TSINGHUA-PRINCETON-COMBUSTION INSTITUTE

2025 SUMMER SCHOOL ON COMBUSTION

Applications of Combustion Science to Fire Safety

José L. Torero

University College London, UK

July 06-12, 2025



TSINGHUA-PRINCETON-COMBUSTION INSTITUTE

2025 SUMMER SCHOOL ON COMBUSTION

<table>
<tr><th colspan="6">Key Activities / 重要活动</th></tr>
<tr><td rowspan="2">July 6
(Sunday)
/7月6日
(周日)</td><td>10:00-17:30</td><td>Registration
注册</td><td colspan="3">Northeast Gate, Lee Shau Kee Sci. and Tech. Building
李兆基科技大楼东北门</td></tr>
<tr><td>18:00</td><td>Welcome Reception
开班仪式</td><td colspan="3">A-278, Multifunction Room, Lee Shau Kee Sci. and Tech. Building
李兆基科技大楼多功能厅</td></tr>
<tr><th colspan="6">Class Schedule / 课程安排</th></tr>
<tr><td rowspan="6">July 7-11
(Monday-Friday)
/7月7-11日
(周一至周五)</td><td rowspan="3">Morning
上午</td><td>9:00-9:50</td><td rowspan="3">Combustion Chemistry
Lecturer: Philippe Dagaut
Jianhua Building
建华楼A109</td><td colspan="2" rowspan="3">Turbulent Combustion
Lecturer: Hong G. Im
Jianhua Building
建华楼LG1-21</td></tr>
<tr><td>10:00-10:50</td></tr>
<tr><td>11:00-11:50</td></tr>
<tr><td rowspan="3">Afternoon
下午</td><td>14:00-14:50</td><td rowspan="3">Dynamics of Flames and Detonations in Premixed Gas
Lecturer: Paul Clavin
Jianhua Building
建华楼A109</td><td rowspan="3">Advanced Laser Diagnostics for Chemically Reacting Flows
Lecturer: Mark Linne
Jianhua Building
建华楼A404</td><td rowspan="3">Applications of Combustion Science to Fire Safety
Lecturer: José L. Torero
Jianhua Building
建华楼LG1-11</td></tr>
<tr><td>15:00-15:50</td></tr>
<tr><td>16:00-16:50</td></tr>
<tr><th colspan="6">Special Activities / 特殊活动</th></tr>
<tr><td>July 6
(Sunday)
/7月6日
(周日)</td><td>13:30-17:30</td><td colspan="2">Art Museum Visit / 艺术博物馆参观</td><td colspan="2">Tsinghua University Art Museum
清华大学艺术博物馆</td></tr>
<tr><td>July 7
(Monday)
/7月7日
(周一)</td><td>17:00-17:30</td><td colspan="2">Group Picture Taking / 暑期学校合影</td><td colspan="2">The open-air plaza next to the New Tsinghua Auditorium
天大广场(新清华学堂露天广场)</td></tr>
<tr><td>July 8
(Tuesday)
/7月8日
(周二)</td><td>17:00-18:00</td><td colspan="2">Campus Tour / 校园游览</td><td colspan="2">Tsinghua University
清华大学</td></tr>
<tr><td>July 9
(Wednesday)
/7月9日
(周三)</td><td>18:30-19:30
19:30-21:00</td><td colspan="2">Poster Presentation / 海报展示
Career Panel / 职业发展论坛</td><td colspan="2">B-518, Lee Shau Kee Sci. and Tech. Building
李兆基科技大楼B-518会议室</td></tr>
<tr><td>July 10
(Thursday)
/7月10日
(周四)</td><td>18:00</td><td colspan="2">Farewell Reception / 欢送会</td><td colspan="2">Guan Chou Yuan Restaurant
观畴园餐厅</td></tr>
<tr><td>July 11
(Friday)
/7月11日
(周五)</td><td>8:00-18:00</td><td colspan="2">Program Certificate Distribution / 学习证书发放</td><td colspan="2">Jianhua Building
建华楼</td></tr>
<tr><td>July 12
(Saturday)
/7月12日
(周六)</td><td>9:30-11:30</td><td colspan="2">CCE Laboratory Tour / 燃烧能源中心实验室参观</td><td colspan="2">Northeast Gate, Lee Shau Kee Sci. and Tech. Building
李兆基科技大楼东北门</td></tr>
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Combustion Fundamentals of Fire Safety



José L. Torero, University College London, United Kingdom

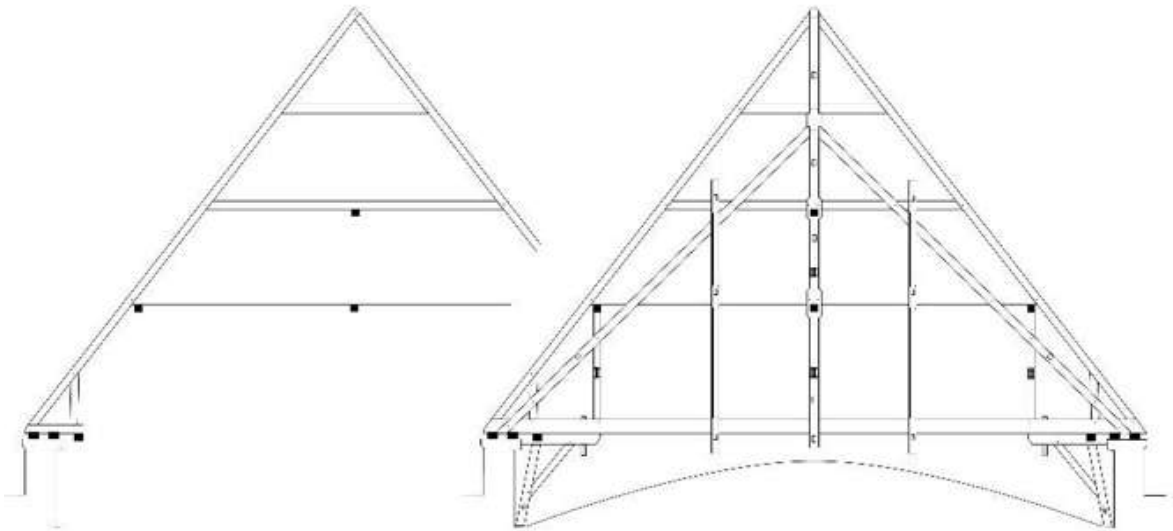


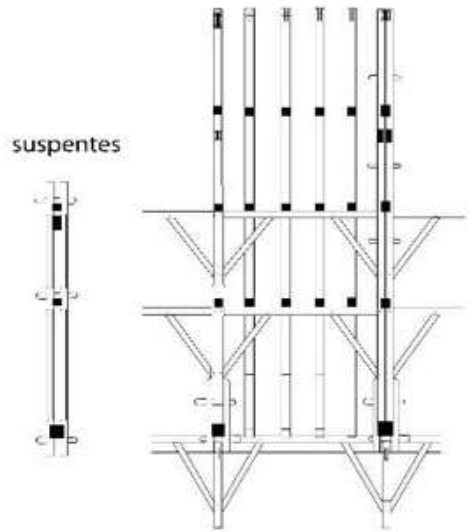




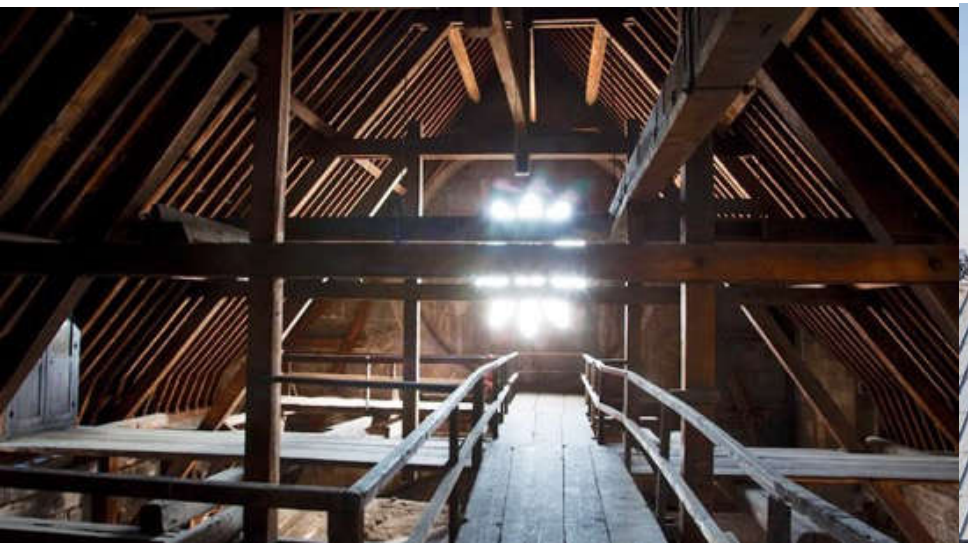




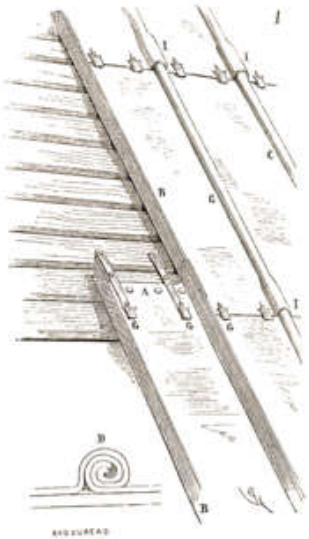



suspentes


5m.
0







WHAT IS THE ROLE OF COMBUSTION IN FIRE SAFETY?



A British Example

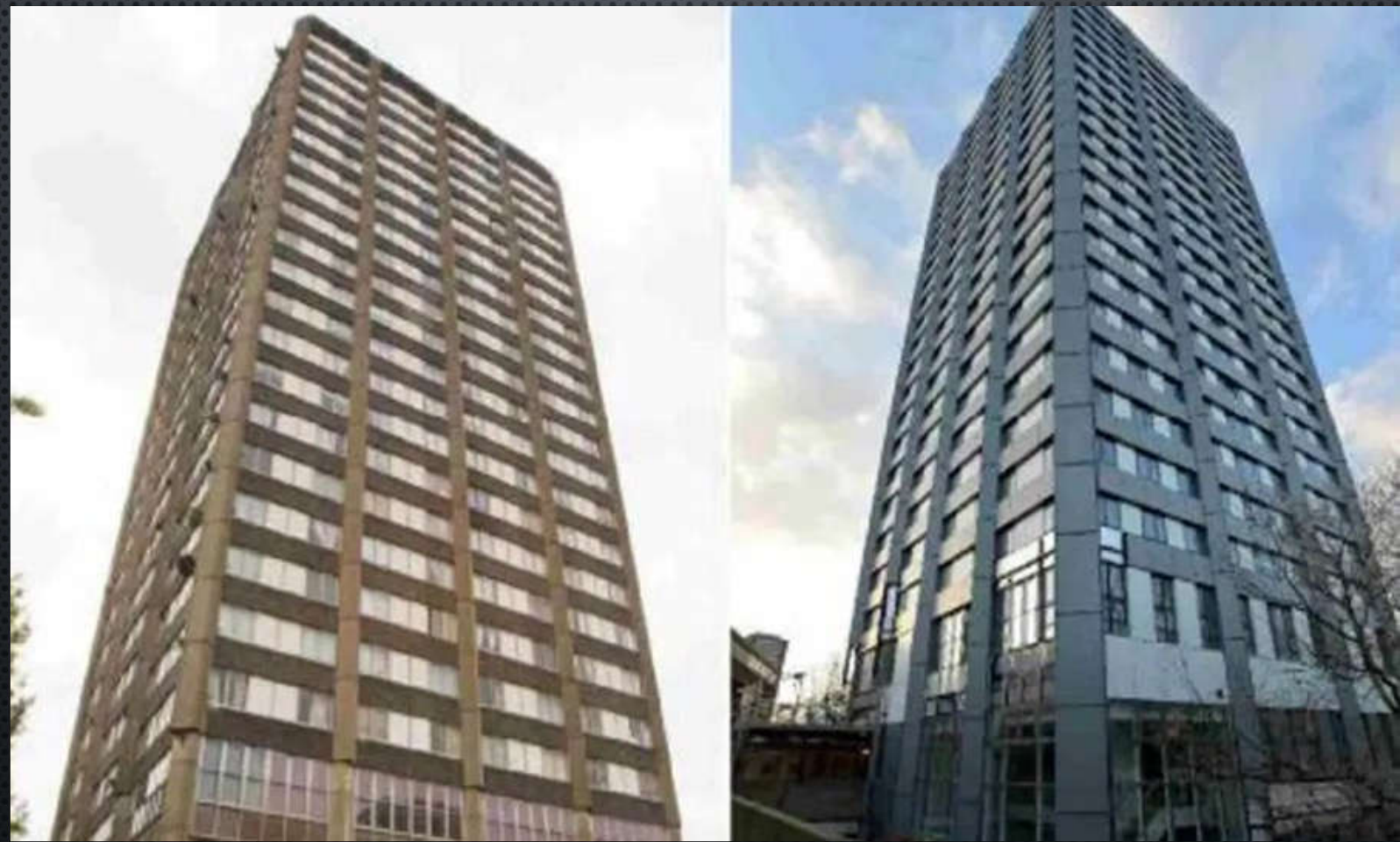


Grenfell Tower

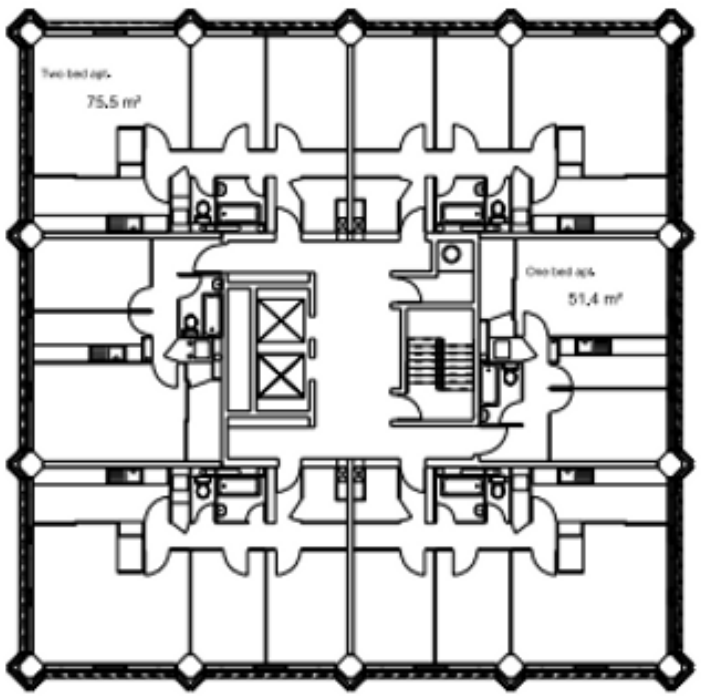
- Grenfell Tower was part of the Lancaster West Estate, a council housing complex in North Kensington.
  - 24-storey tower block
  - designed in 1967 in the Brutalist style of the era by Clifford Wearden and Associates
  - constructed by contractors A E Symes of Leyton from 1972 to 1974
  - 67.30 m tall
  - The lower four storeys were originally used for non-residential purposes
  - The upper 20 (of 24) storeys were residential floors
  - contained 120 one-bedroom and two-bedroom flats. two lower floors were converted to residential use, bringing the total to 129 apartments, housing up to 600 people
  - Grenfell Tower underwent a major renovation, announced in 2012 and conducted over 2015–2016
  - The tower received new windows, a water-based heating system for individual flats and new aluminum composite rain screen cladding. According to the application, the purpose of the cladding was to improve heating and energy efficiency, and external appearance.
- Was designed to be operated under a "stay put policy" in the event of fire.
- There was no centrally activated fire alarm and only a single central staircase.

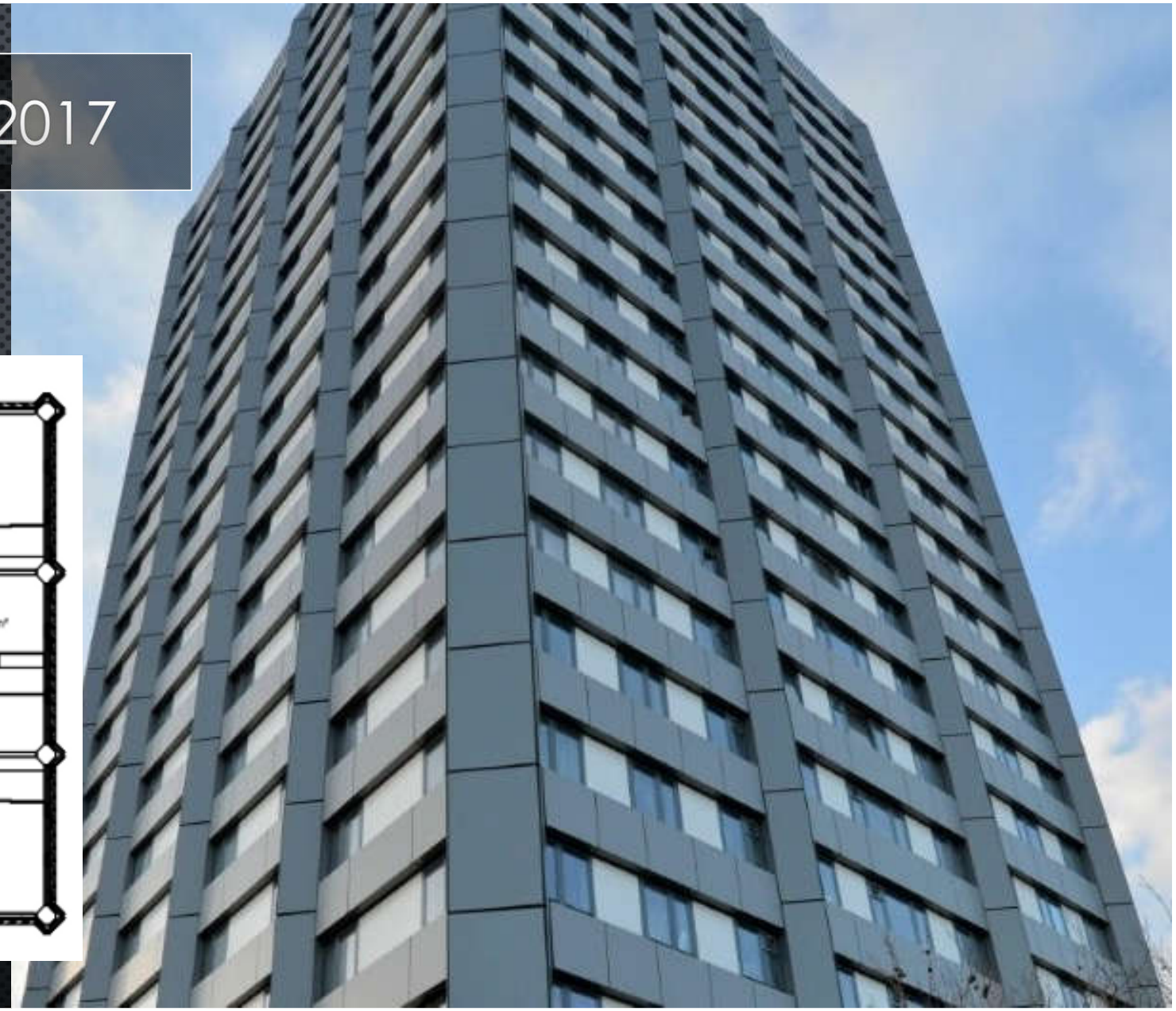
PRE-2017

POST-2017

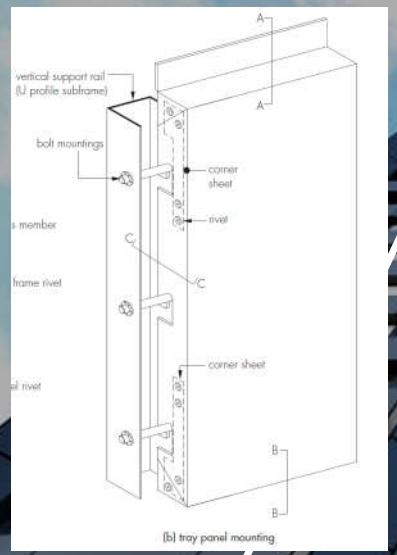


GRENFELL TOWER - 2017

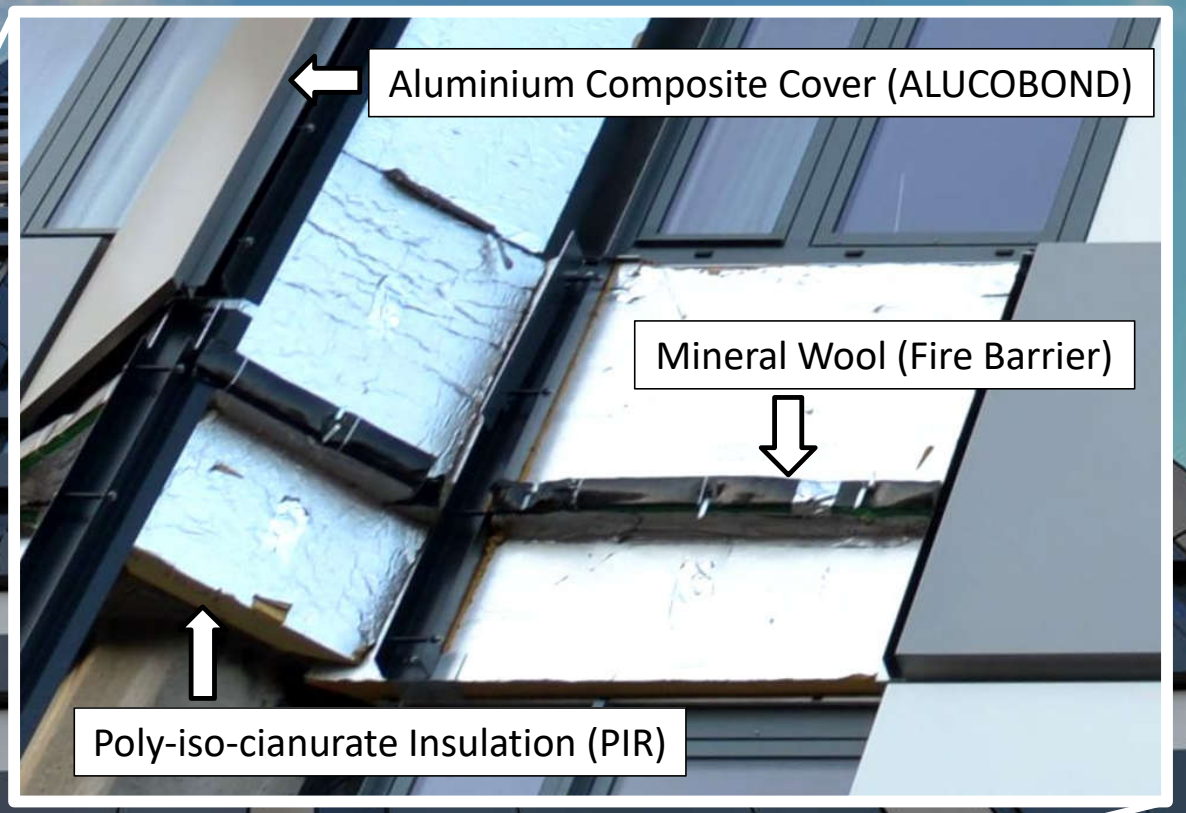


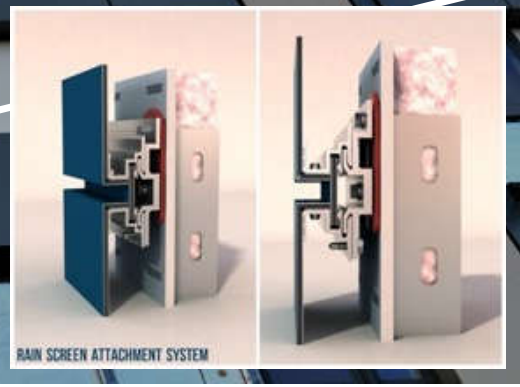


THE CLADDING SOLUTION



(b) tray panel mounting





PRECEDENT

TIMELINE

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



ARCONIC'S REYNOBOND PE



- Polyethylene
  - Heat of Combustion: 44 MJ/kg
  - melting point: 120 to 130 °C
  - Ignition Temperature: 320 to 340 °C
  - Critical Heat Flux for Ignition: 11 kW/m^2



The Address Downtown Dubai

- Fire: 31st December 2015
- Arconic's Reynobond PE
- One of many iconic fires

JUNE 14TH, 2017 – 00:54:29 (1ST 999 CALL) BY MR. BEHAILU KEBEDE INFORMING LFB OF A FIRE IN THE KITCHEN OF FLAT 16 (4TH FLOOR)

JUNE 14TH, 2017 – 01:00:00 – 2 FIRE PUMPS ARRIVE

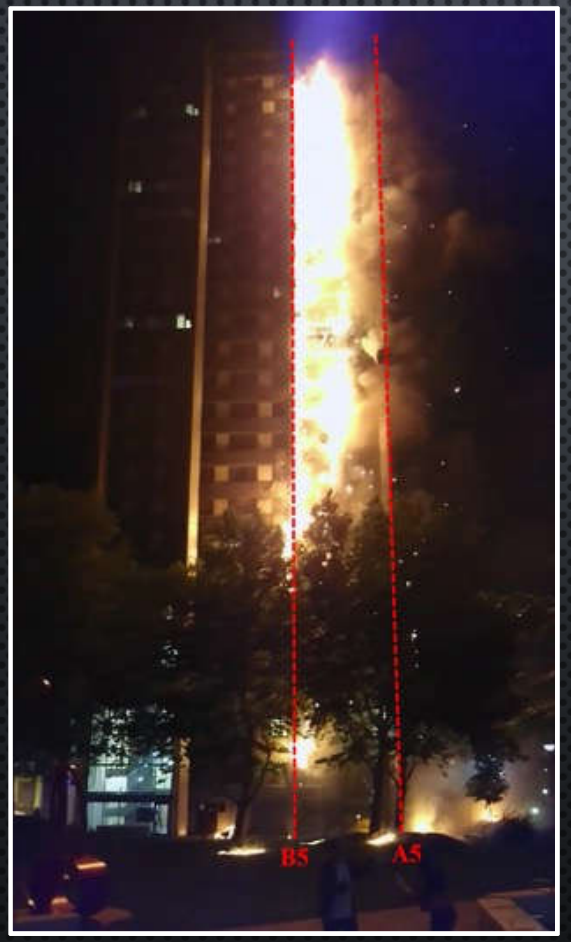
JUNE 14TH, 2017 – 01:15:00 – FIRE IN FLAT 26

JUNE 14TH, 2017 – 01:30:00 – FIRE AT ROOF LEVEL

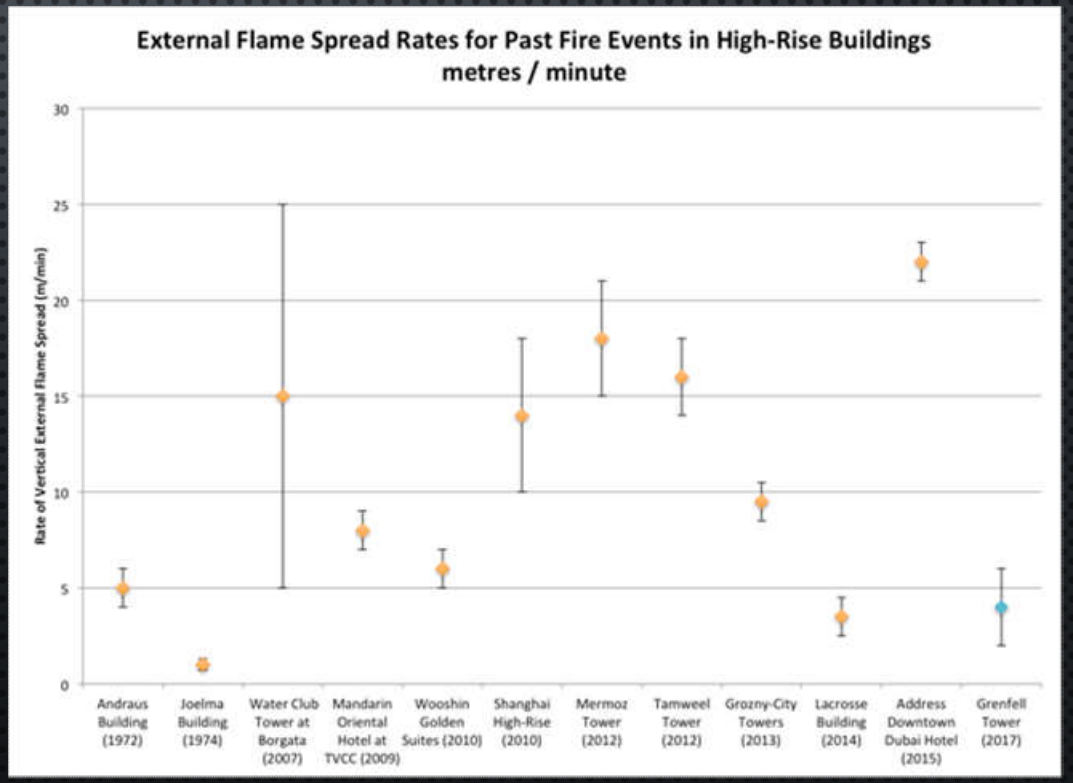
JUNE 14TH, 2017 – 01:18 TO 01:38 – 110 ESCAPE

JUNE 14TH, 2017 – 01:38 TO 01:58 – 20 ESCAPE

UNUSUAL?


BS
AS


METROPOLITAN POLICE
METROPOLITAN POLICE


External Flame Spread Rates for Past Fire Events in High-Rise Buildings
metres / minute
Rate of Vertical External Flame Spread (m/min)
0
5
10
15
20
25
30
Andraus Building (1972)
Joelma Building (1974)
Water Club Tower at Borgata (2007)
Mandarin Oriental Hotel at TVCC (2009)
Wooshin Golden Suites (2010)
Shanghai High-Rise (2010)
Mermoz Tower (2012)
Tamweel Tower (2012)
Grozny-City Towers (2013)
Lacrosse Building (2014)
Address Downtown Dubai Hotel (2015)
Grenfell Tower (2017)

JUNE 14TH, 2017 – 02:47 – "STAY-PUT" POLICY REVOKED

- What Happened?

HOW DO WE STOP THIS FROM HAPPENING AGAIN?

Responsibility

- Responsibilities of a Designer
- Responsibility for Management

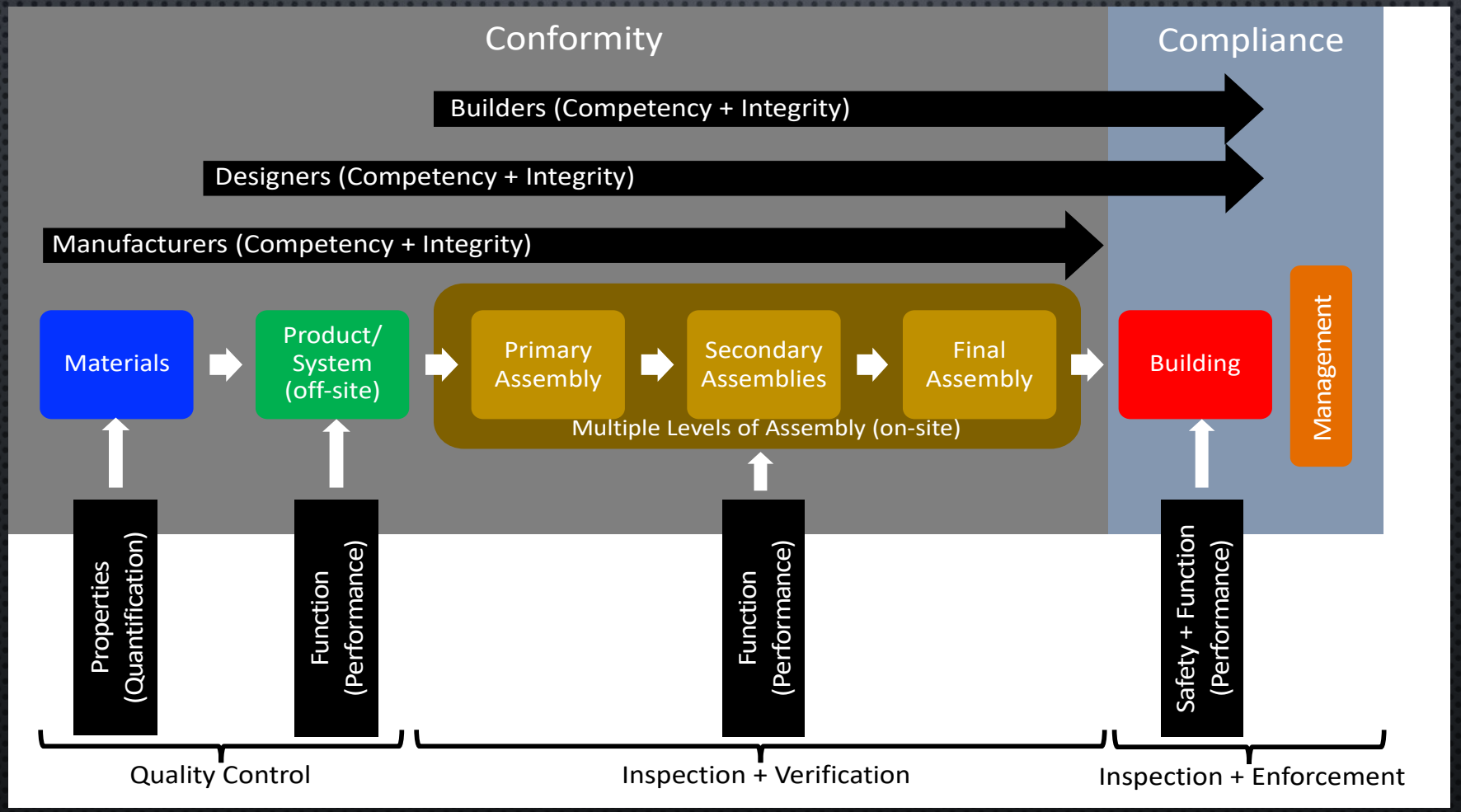
- What do you need to know to competently discharge your responsibilities?

MANY COMBUSTION PROFESSIONALS END UP WORKING IN THE FIELD OF FIRE SAFETY

WHAT DO THEY NEED TO KNOW TO COMPETENTLY WORK IN THE FIELD OF FIRE SAFETY?

WHAT IS COMPETENCY?
WHY IS IT NECESSARY?
HOW IS IT DEFINED?
WHO DEFINES IT?

COMPLIANCE & CONFORMITY

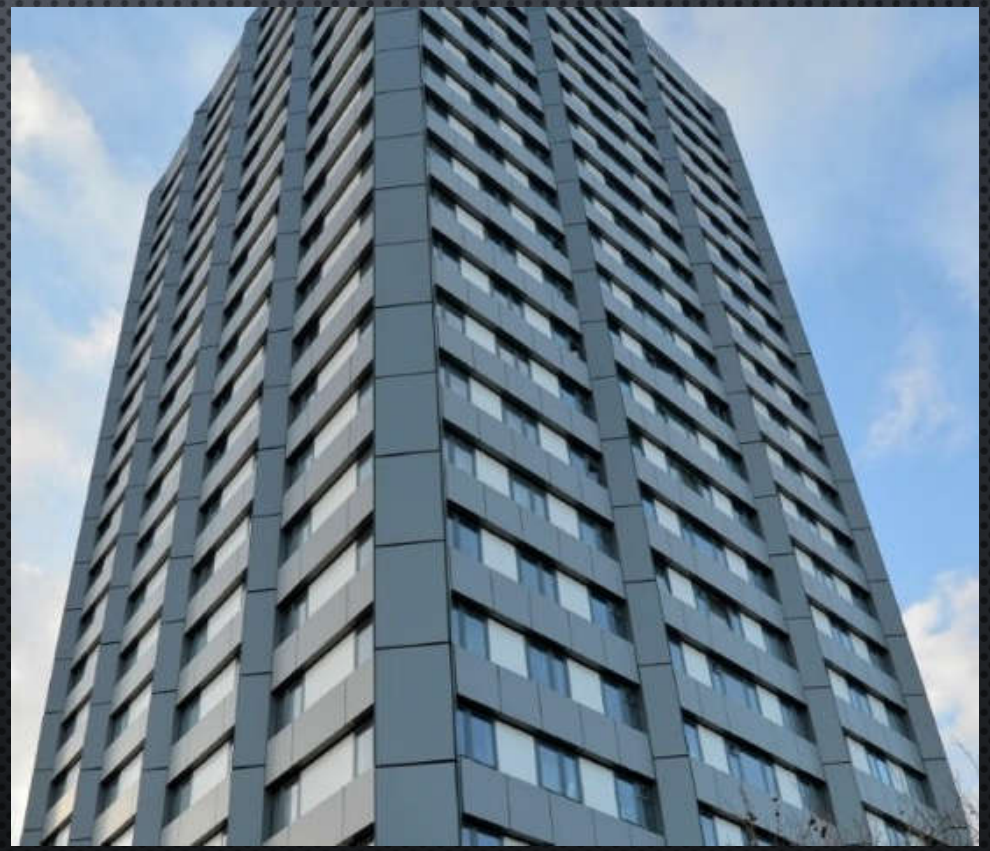


DEPENDING ON WHAT TASK YOU ARE UNDERTAKING YOU NEED DIFFERENT KNOWLEDGE: **FIRE SAFETY IS A TEAM RESPONSIBILITY**

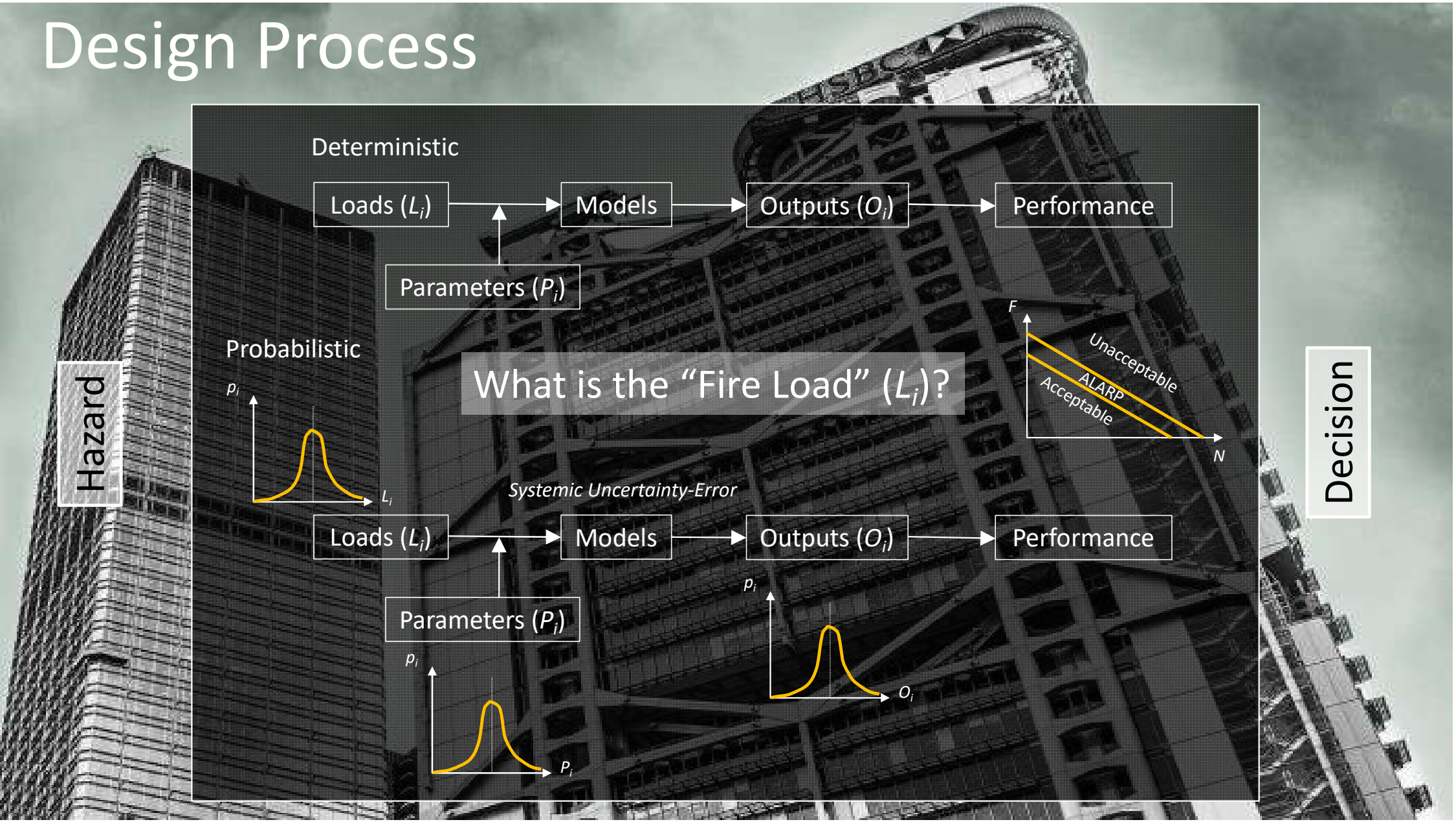
THE BUILDING IS COMPLIANT – **NO PARTIAL COMPLIANCE!**

EXPLICIT PERFORMANCE OBJECTIVES

- WHAT IS A FIRE SAFE BUILDING?

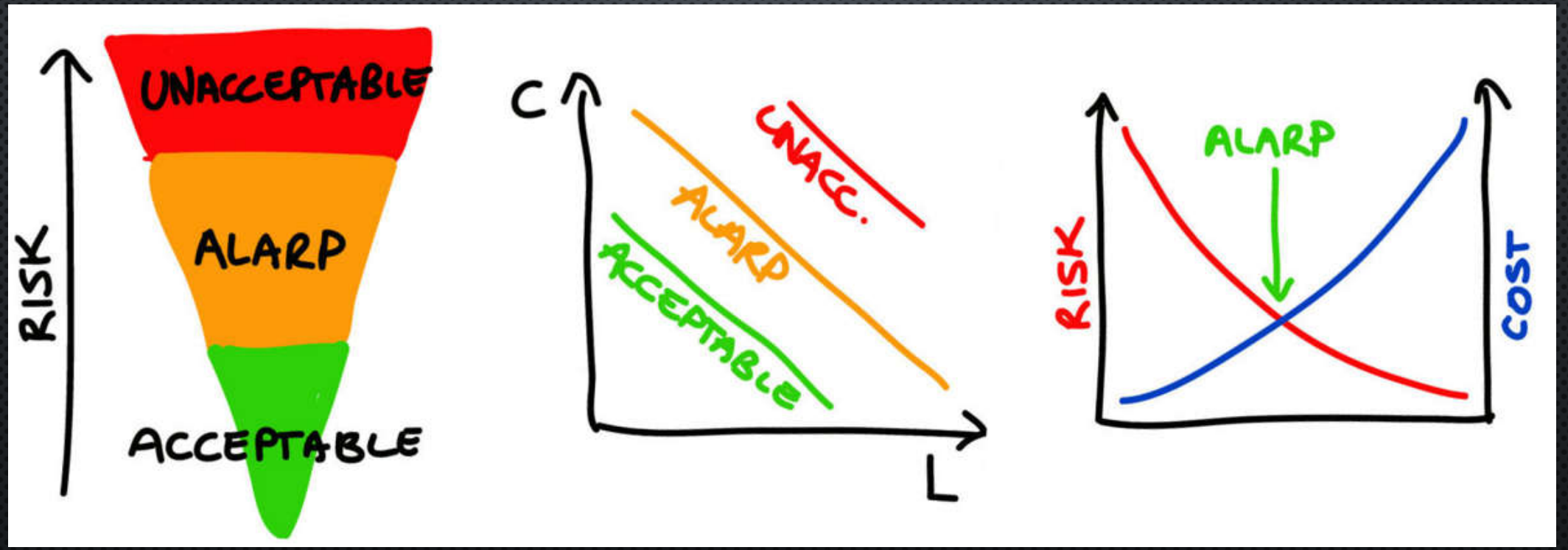


Design Process



OBJECTIVES: WHAT CAN SOCIETY ACCEPT

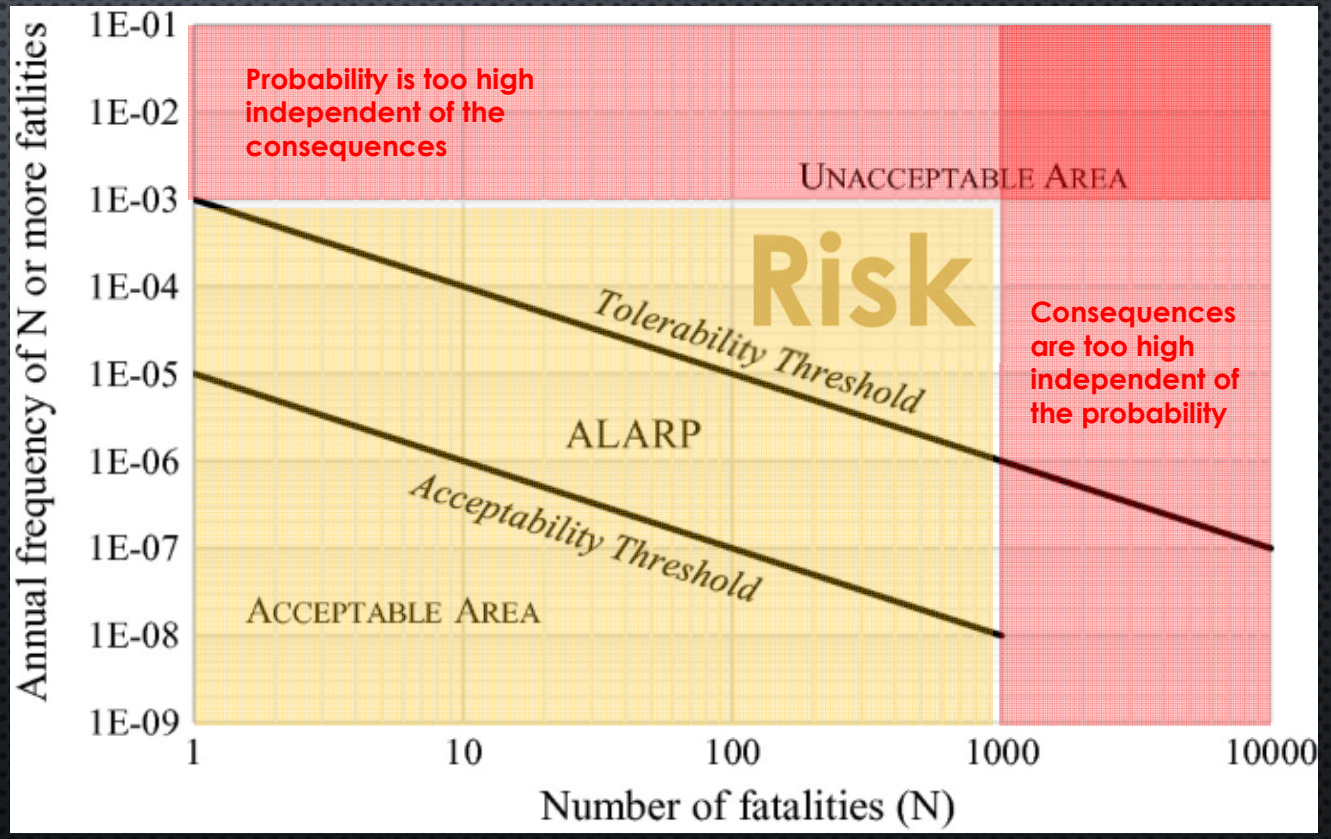
"As Low as Reasonably Practical" (ALARP)



LIFE SAFETY

$$Risk = Probability\ x\ Consequence$$

- What is Society Willing to Accept? **A Political Decision**
  - OHS- One in a million for workers
  - Car crash – One in a thousand
  - Fire – One in 100 thousand
  - Nuclear power plant – 10^{-12}
  - Etc.



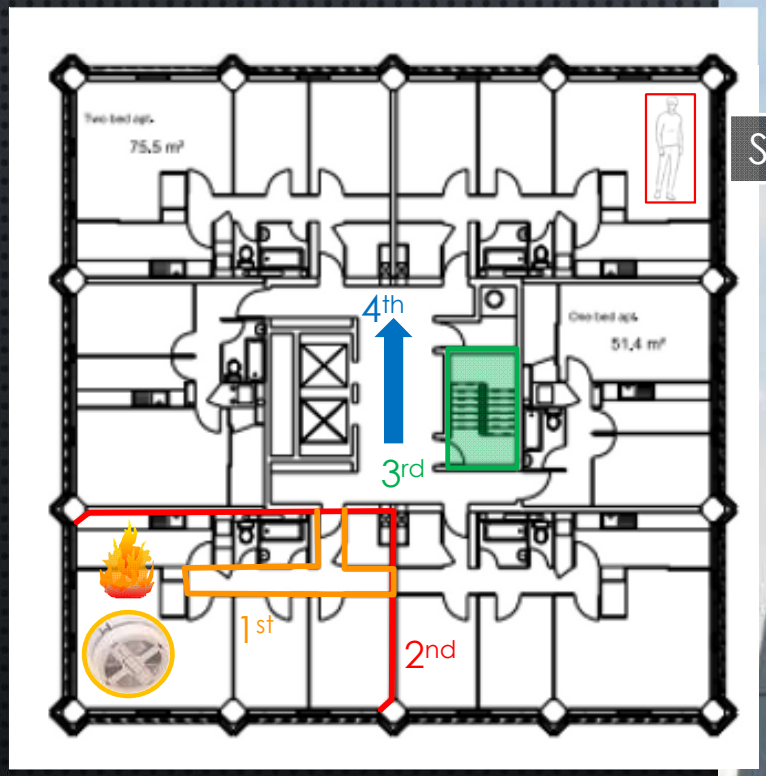
IN FIRE SAFE DESIGN WE DESIGN A ‘FIRE SAFETY STRATEGY’ IS DEFINED TO CONTROL THE EVOLUTION OF THE FIRE (I.E. THE FIRE LOAD)

THE GRENFELL FIRE SAFETY STRATEGY

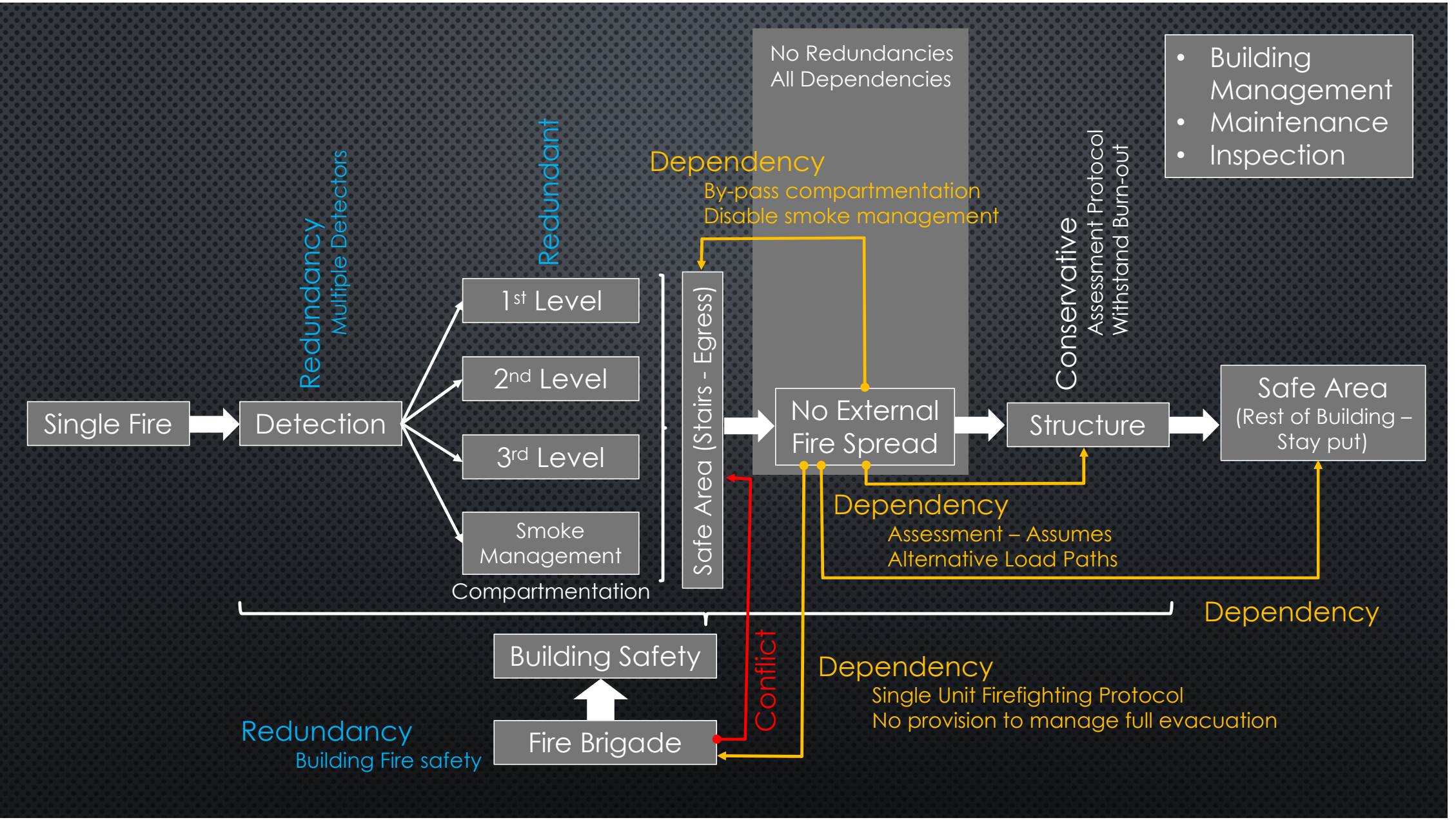
OBJECTIVE: TO GIVE ALL OCCUPANTS THE BEST POSSIBLE CHANCE FOR SAFETY

⟺

FIRE LOAD: THE ONE UNIT FIRE

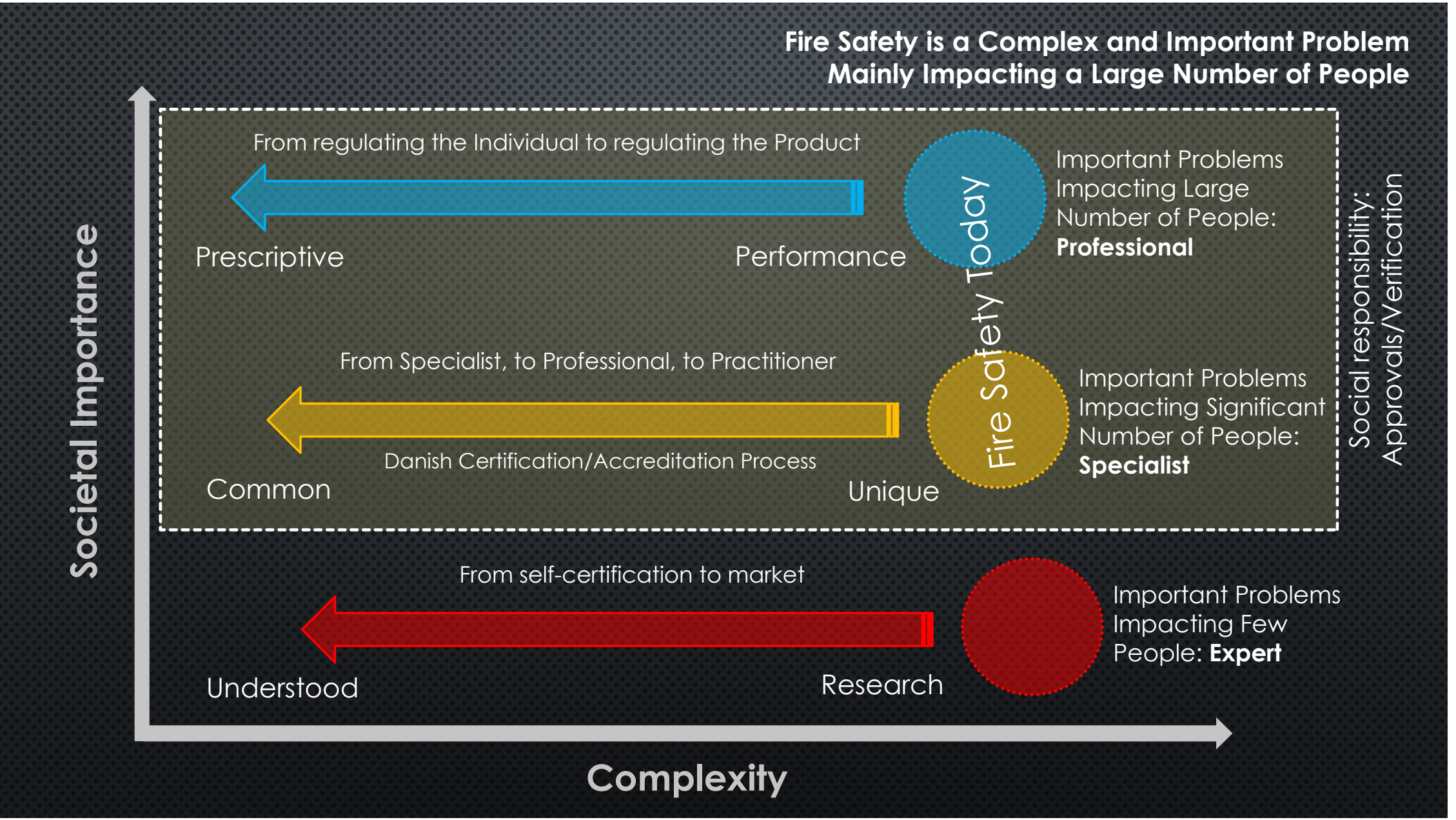


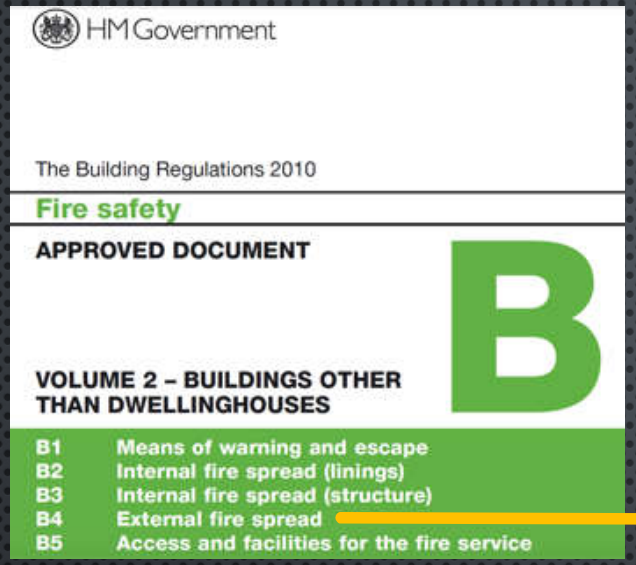
Stay Put


No Redundancies
All Dependencies
• Building Management
• Maintenance
• Inspection
Redundancy
Multiple Detectors
Redundant
Dependency
By-pass compartmentation
Disable smoke management
Conservative
Assessment Protocol
Withstand Burn-out
Single Fire
Detection
1st Level
2nd Level
3rd Level
Smoke Management
Compartmentation
Safe Area (Stairs - Egress)
No External Fire Spread
Structure
Safe Area
(Rest of Building – Stay put)
Dependency
Assessment – Assumes Alternative Load Paths
Dependency
Building Safety
Conflict
Dependency
Single Unit Firefighting Protocol
No provision to manage full evacuation
Redundancy
Building Fire safety
Fire Brigade

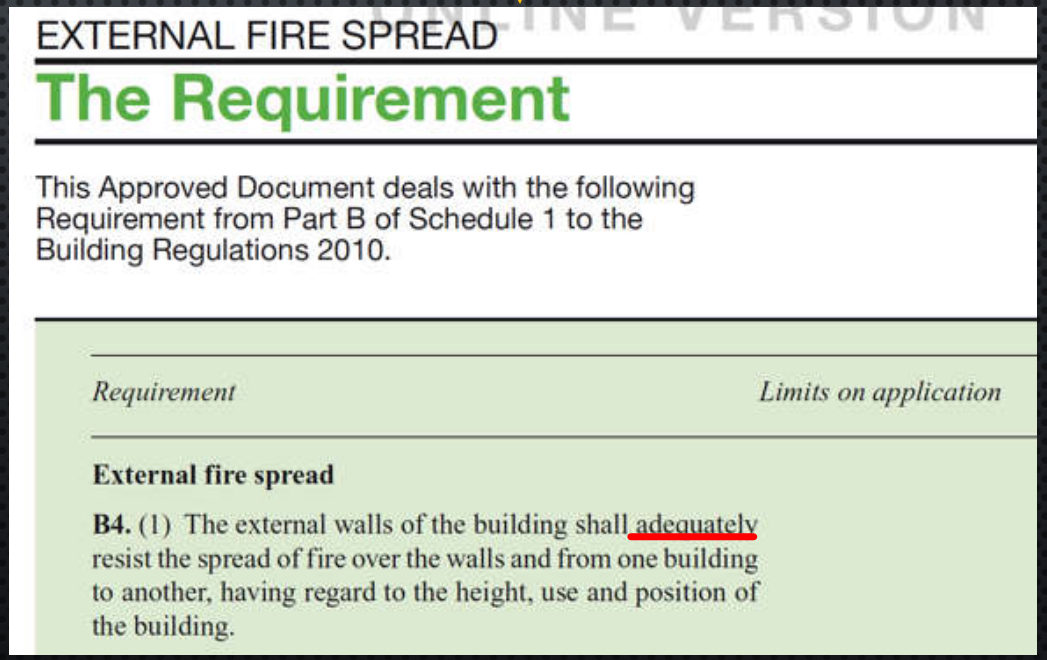
WHAT IS THE ROLE OF COMBUSTION IN DEFINING AN ADEQUATE FIRE SAFETY

REGULATION


Fire Safety is a Complex and Important Problem
Mainly Impacting a Large Number of People
From regulating the Individual to regulating the Product
Prescriptive
Performance
Important Problems Impacting Large Number of People: Professional
Fire Safety Today
From Specialist, to Professional, to Practitioner
Danish Certification/Accreditation Process
Common
Unique
Important Problems Impacting Significant Number of People: Specialist
Social responsibility: Approvals/Verification
From self-certification to market
Understood
Research
Important Problems Impacting Few People: Expert
Societal Importance
Complexity



Approved Document B has no overall safety objectives



RESPONSIBILITY: UNDEFINED

Objectives

Compliance → Fire Safety Strategy

Overall Objective & Fire Safety Strategy (Undefined)

THE REQUIREMENT

- B1 - Means of Warning and Escape
- B2 – Internal Fire Spread (linings)
- B3 – Internal Fire Spread (structure)
- B4 - External Fire Spread
- B5 – Access and Facilities for the Fire Service

BUILDING REGULATIONS PLACE AN ENORMOUS WEIGHT ON PROFESSIONAL COMPETENCY

Guidance

Potential Approaches

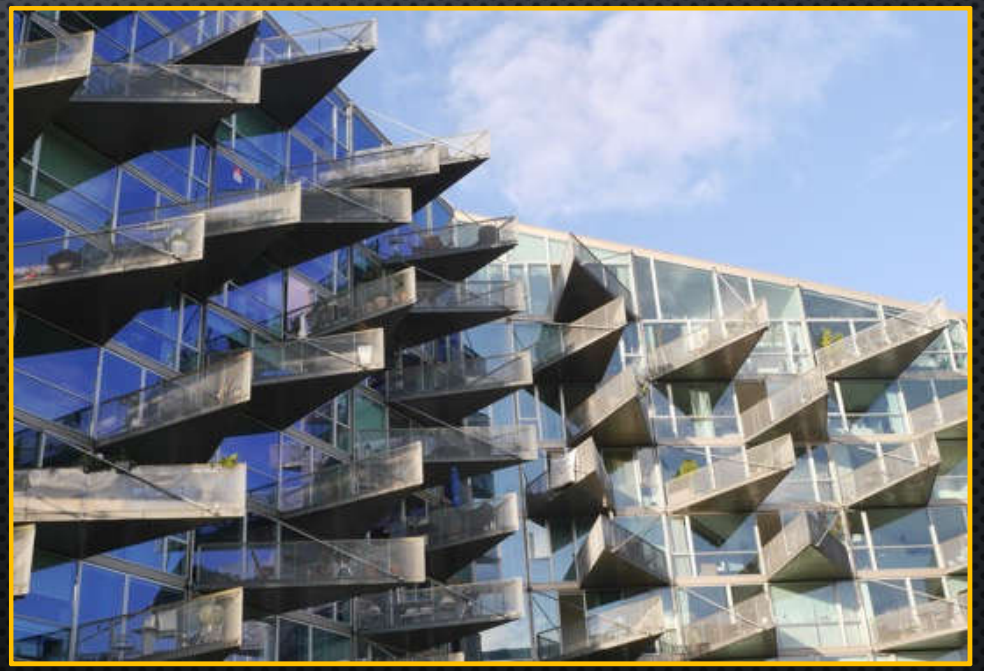
PROFESIONAL: BOUNDARIES: UNDEFINED

WE REGULATE TO ALLOW FOR COMPETENT PRACTICE

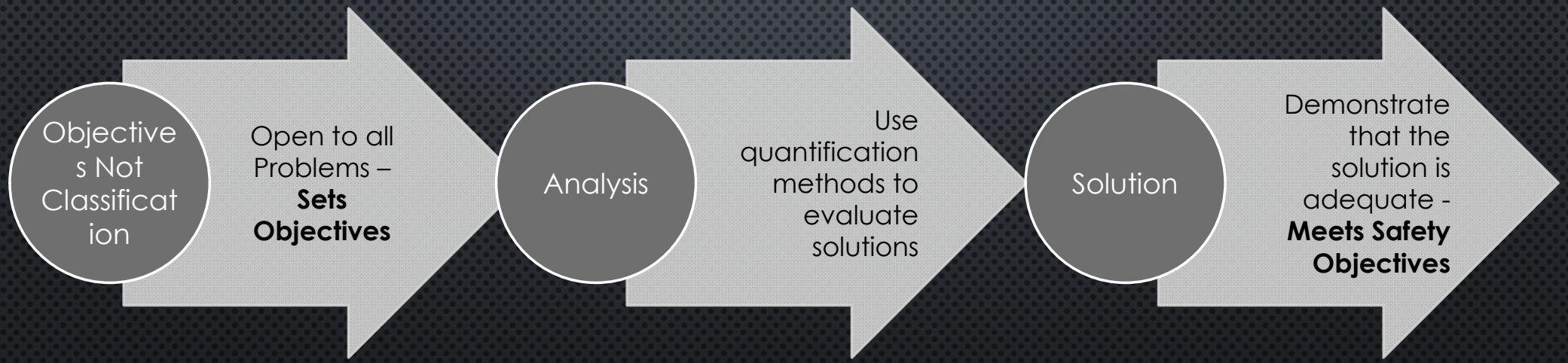
REGULATORY MECHANISMS

REGULATING COMPETENCY ON THE BASIS OF THE PRODUCT OF THE DESIGN PROCESS IS VERY DIFFICULT – WHICH IS THE MOST COMPLEX BUILDING?

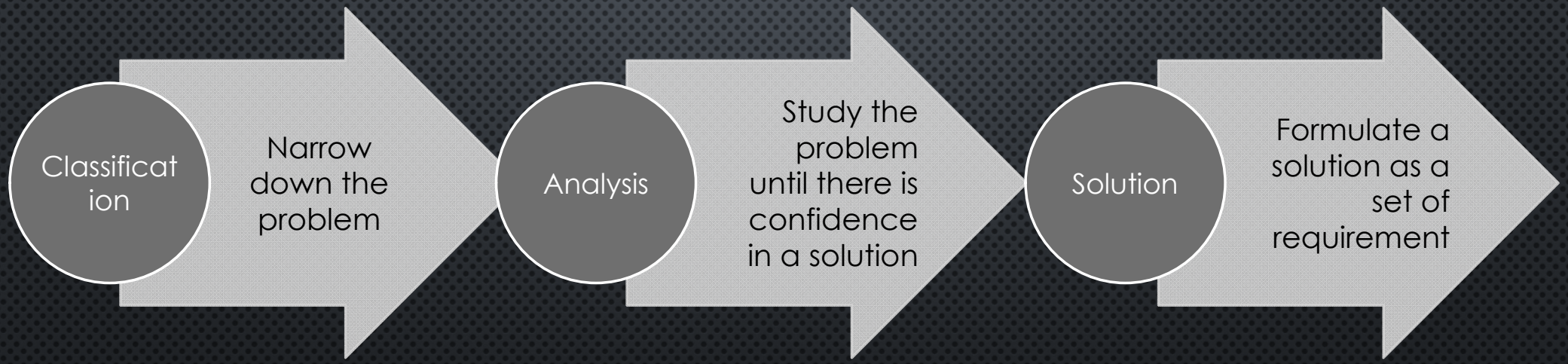




PERFORMANCE BASED SOLUTIONS – FUNCTIONAL REQUIREMENTS



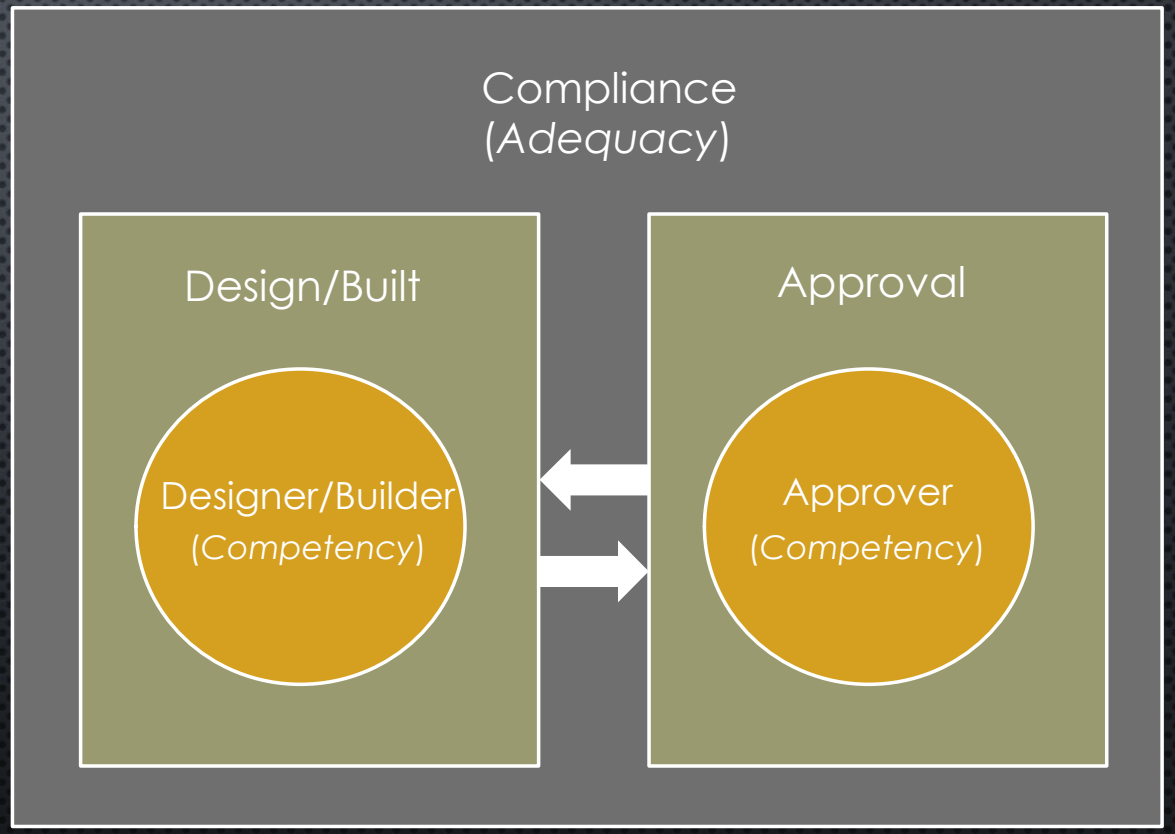
PRESCRIPTIVE SOLUTIONS

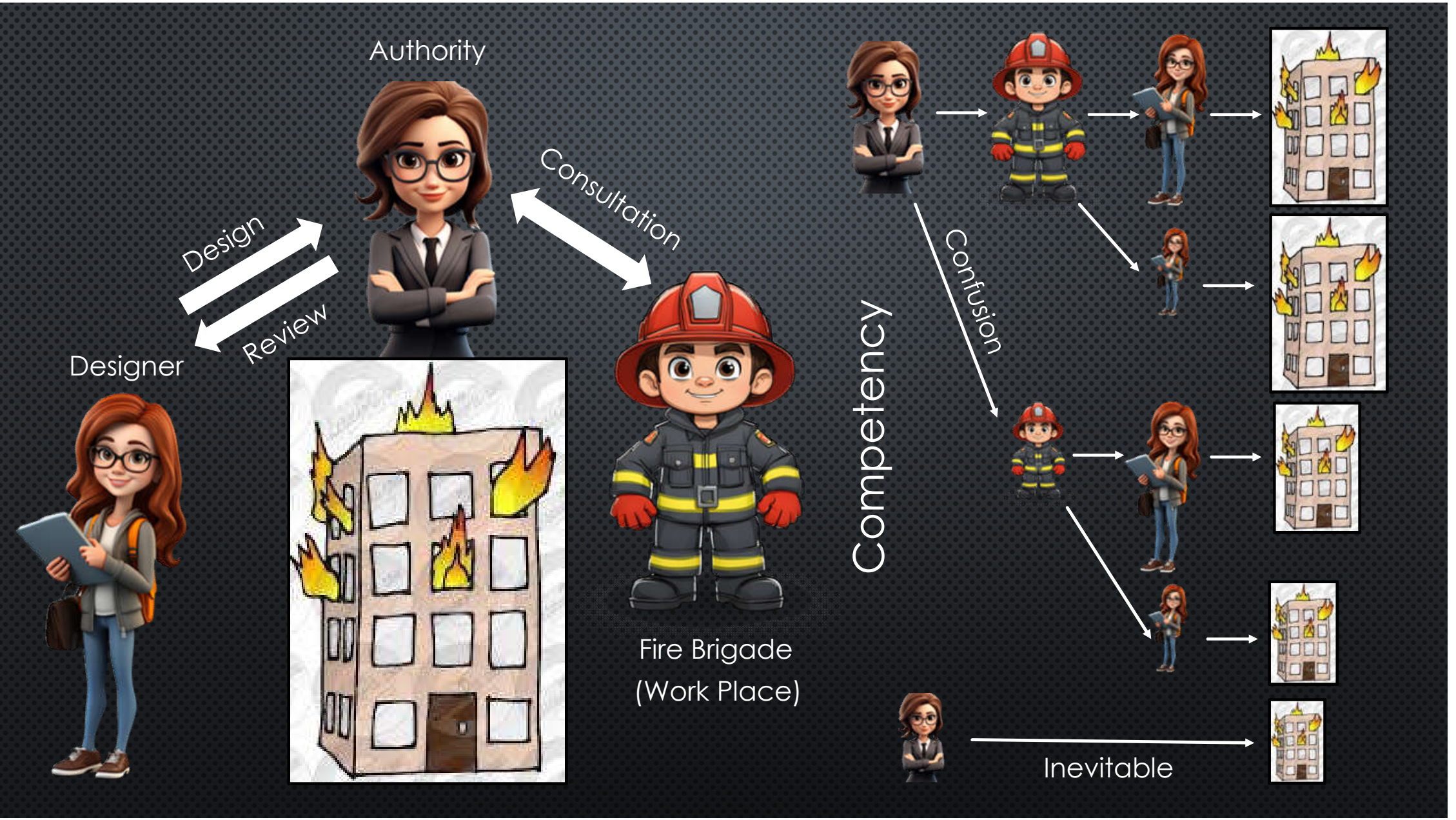


THE NATURE OF COMPETENCY IS VERY DIFFERENT GIVEN THE PROBLEM TO BE ADDRESSED AND THE REGULATORY FRAMEWORK BEING APPLIED

PRINCIPLES OF APPROVAL

- APPROVAL IS THE DIALOGUE BETWEEN TWO COMPETENT PROFESSIONALS THAT ENABLES TO ESTABLISH THE ADEQUACY OF A DESIGN/BUILT: **COMPLIANCE**

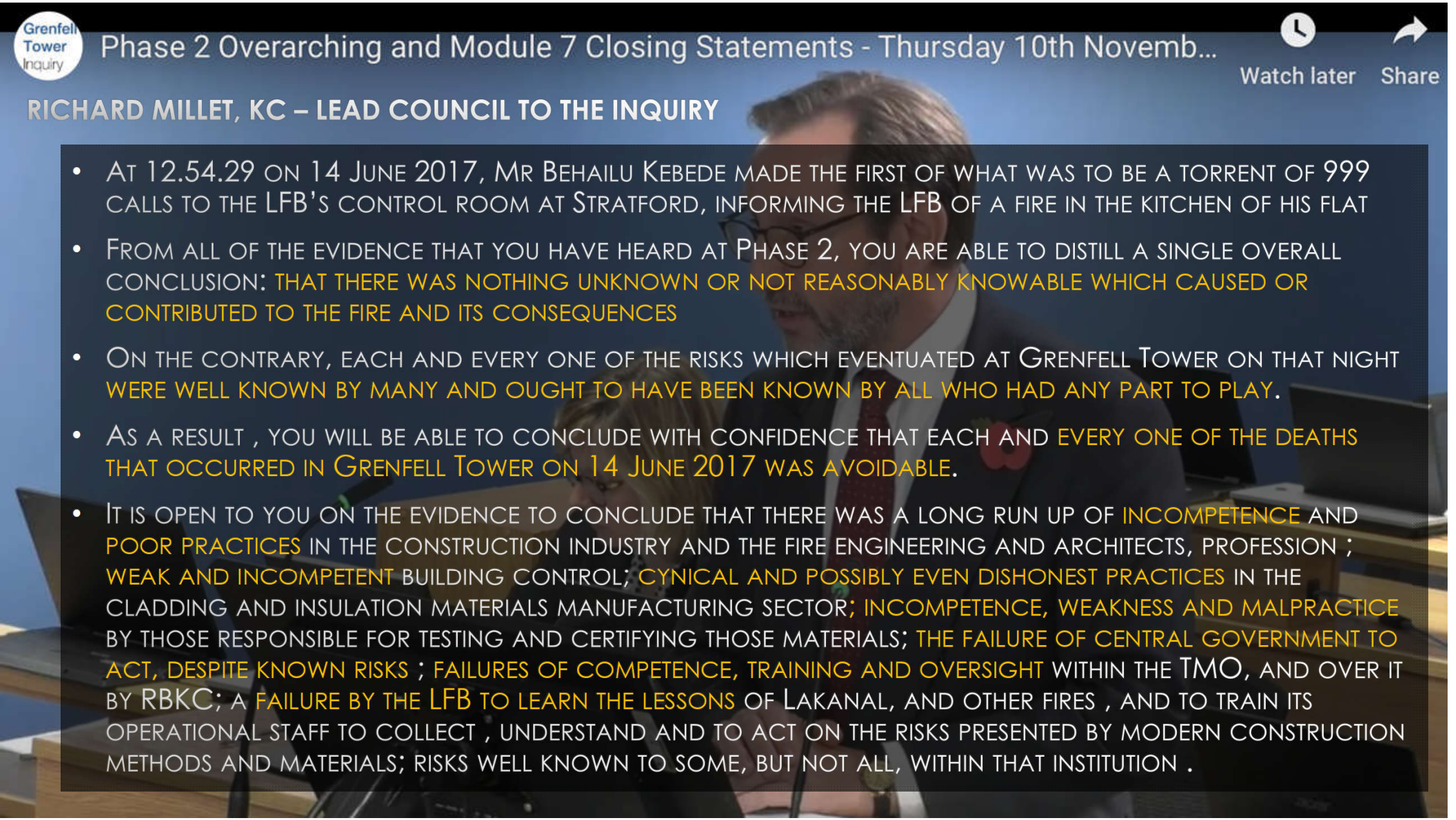


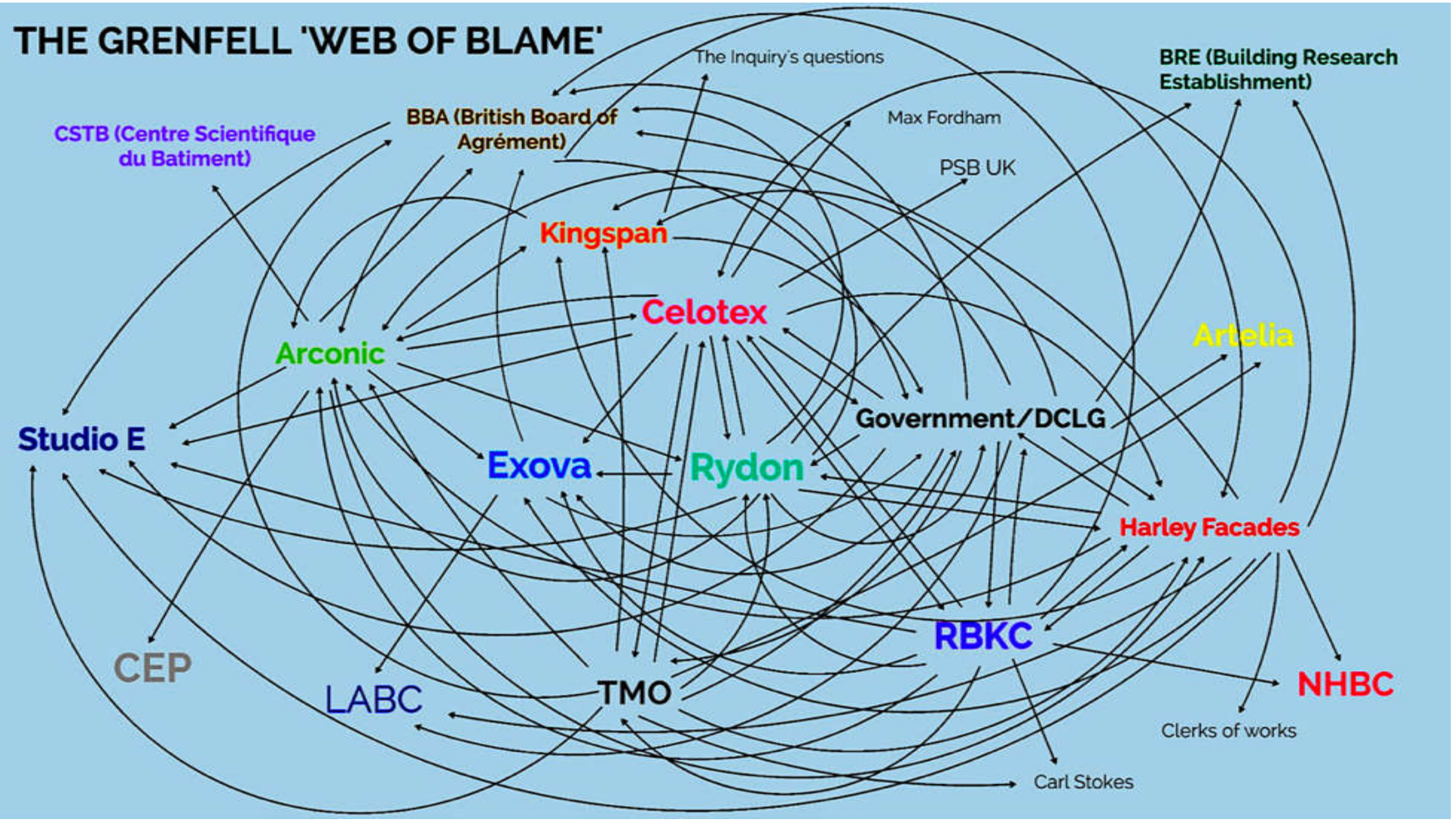

Authority
Design
Review
Consultation
Designer
Fire Brigade
(Work Place)
Competency
Confusion
Inevitable

FIRE SAFETY: COMPETENCY NEEDS TO BE REGULATED

REGULATING THE INDIVIDUAL AND NOT THE PRODUCT

Inconsistency - Current Building Regulations put an extraordinary weight on competent professional practices – This is inconsistent with the weak professional competency framework currently in use


Grenfell Tower Inquiry
Phase 2 Overarching and Module 7 Closing Statements - Thursday 10th Novemb...
Watch later
Share
RICHARD MILLET, KC – LEAD COUNCIL TO THE INQUIRY
• At 12.54.29 on 14 June 2017, Mr Behailu Kebede made the first of what was to be a torrent of 999 calls to the LFB's control room at Stratford, informing the LFB of a fire in the kitchen of his flat
• From all of the evidence that you have heard at Phase 2, you are able to distill a single overall conclusion: that there was nothing unknown or not reasonably knowable which caused or contributed to the fire and its consequences
• On the contrary, each and every one of the risks which eventuated at Grenfell Tower on that night were well known by many and ought to have been known by all who had any part to play.
• As a result , you will be able to conclude with confidence that each and every one of the deaths that occurred in Grenfell Tower on 14 June 2017 was avoidable.
• It is open to you on the evidence to conclude that there was a long run up of incompetence and poor practices in the construction industry and the fire engineering and architects, profession ; weak and incompetent building control; cynical and possibly even dishonest practices in the cladding and insulation materials manufacturing sector; incompetence, weakness and malpractice by those responsible for testing and certifying those materials; the failure of central government to act, despite known risks ; failures of competence, training and oversight within the TMO, and over it by RBKC; a failure by the LFB to learn the lessons of Lakanal, and other fires , and to train its operational staff to collect , understand and to act on the risks presented by modern construction methods and materials; risks well known to some, but not all, within that institution .


THE GRENFELL 'WEB OF BLAME'
The Inquiry's questions
BRE (Building Research Establishment)
CSTB (Centre Scientifique du Batiment)
BBA (British Board of Agrément)
Max Fordham
PSB UK
Kingspan
Celotex
Arconic
Artelia
Government/DCLG
Studio E
Exova
Rydon
Harley Facades
RBKC
CEP
LABC
TMO
NHBC
Clerks of works
Carl Stokes

“DEREGULATION BY INCOMPETENCE”

Complexity + Regulatory Ambiguity + No Competency = Social Inequality

Low Income

- Small low quality architectural firm unaware of details – low budget
- Small engineering budget – inexperienced, lack of competency, lack of attention to detail – low budget
- Standardized design – authorities not paying attention – mass approvals – low budget
- Poor quality - unsafe

High Income

- Rafael Vignoli – Leading architect very experiences and competent in details – large budget
- Irwin Cantor, etc. – Experienced, high competency, high attention to detail, - large budget
- Unique design – authorities paying great attention to detail – large review budget
- High quality - safe

WE FAILED TO MEET SOCIETY'S EXPECTATIONS

WE RENDERED OURSELVES INCOMPETENT

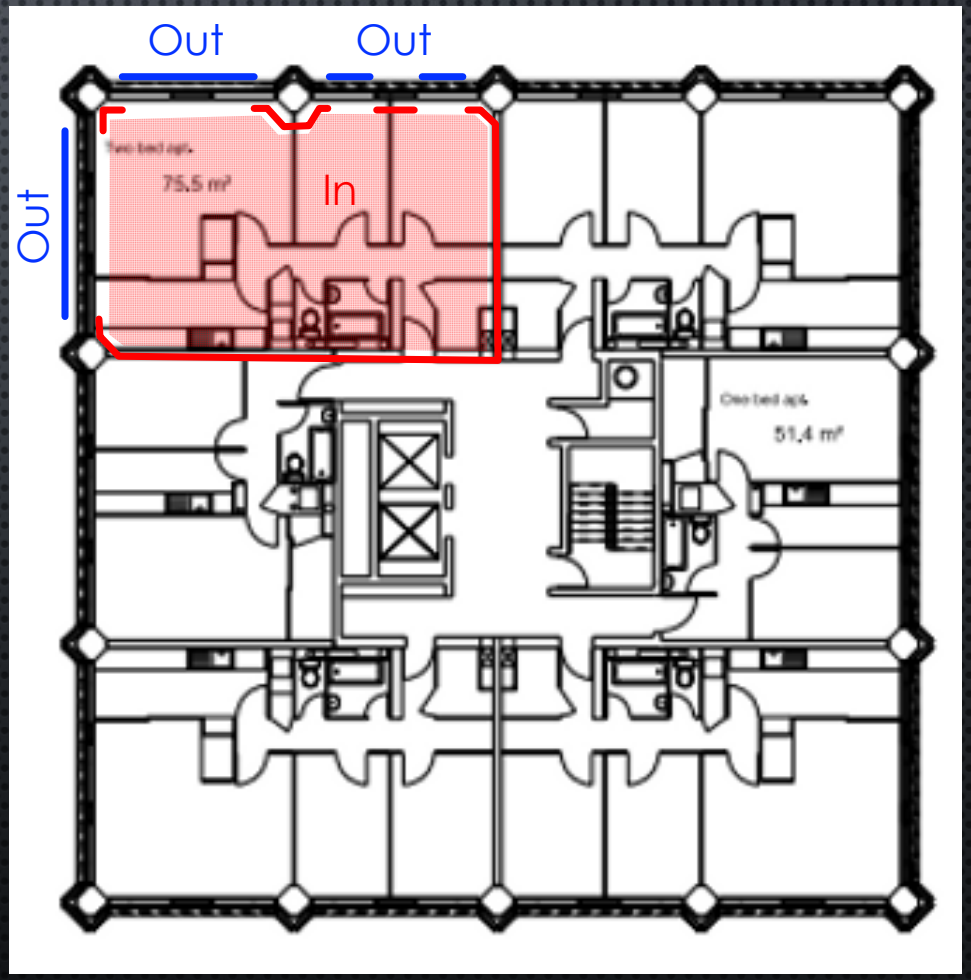
THE LOSS OF TRUST

HOW DO YOU RECOVER TRUST?

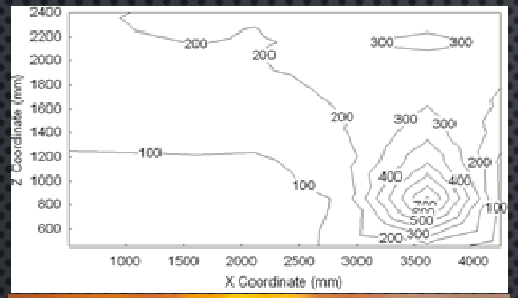
WHAT SHOULD WE HAVE KNOWN?
IS THERE A ROLE FOR COMBUSTION SCIENCE?

IN OR OUT: DEFINING THE BOUNDARY

A Combustion Problem?

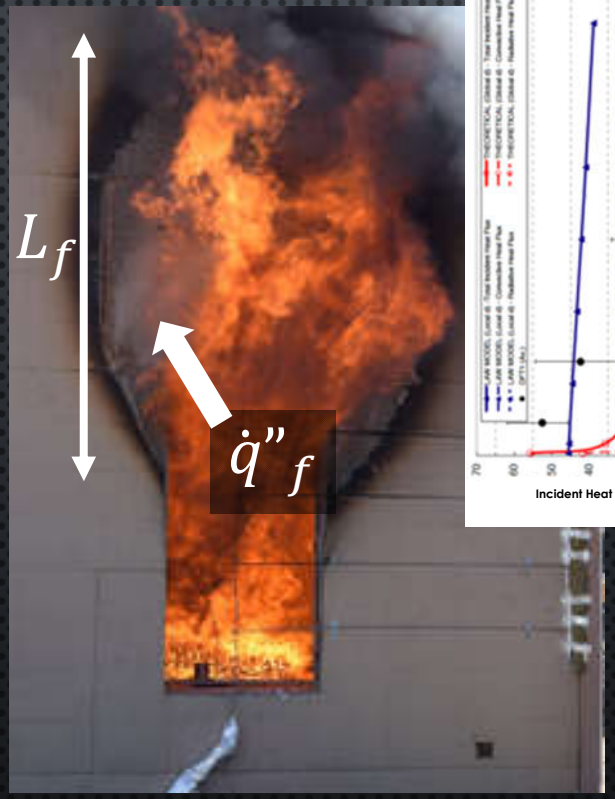


IN OR OUT: QUANTIFYING THE HEAT SOURCE

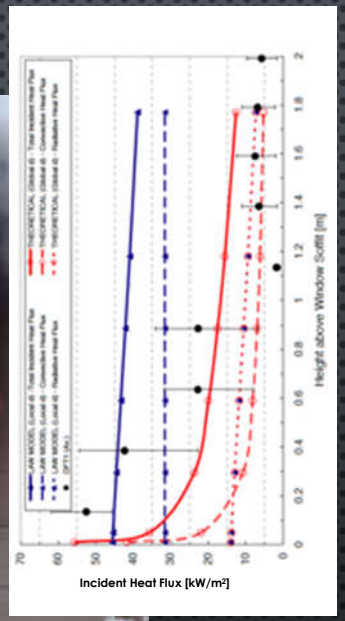


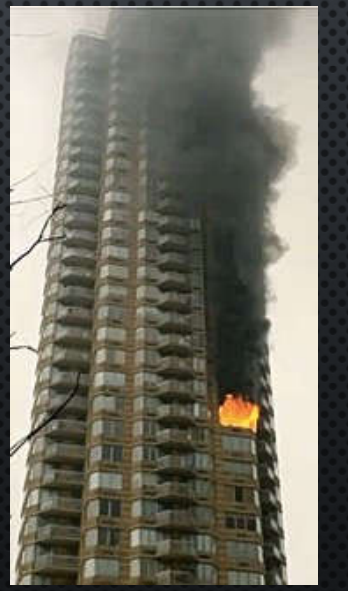


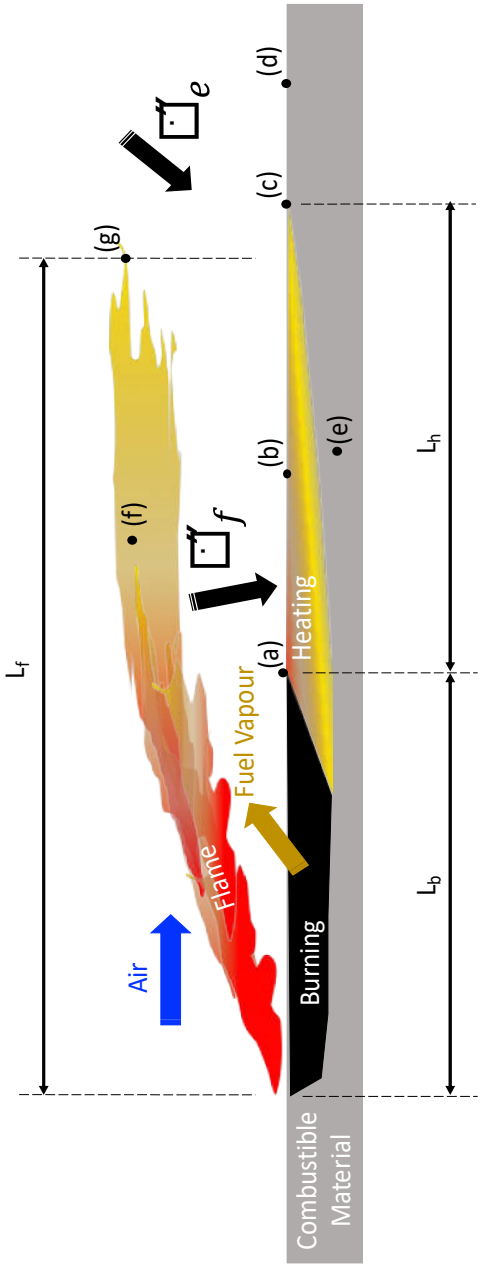
Internal



External

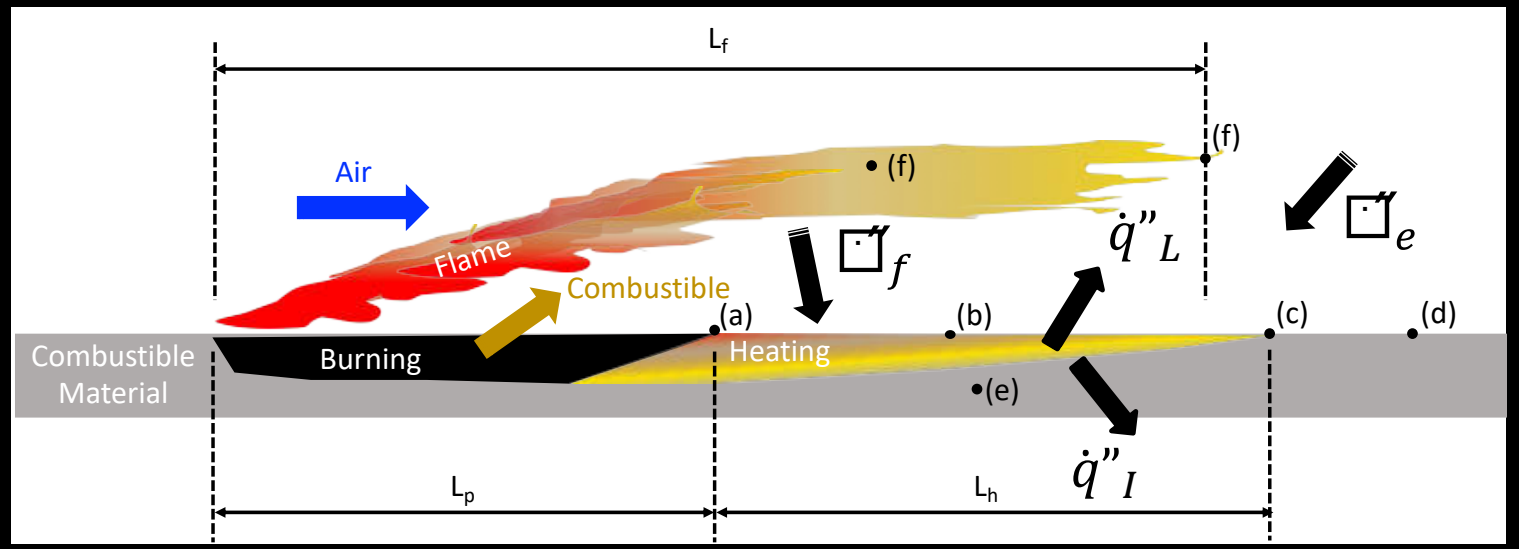






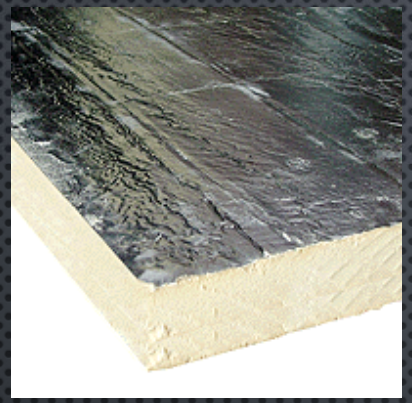
External Flame Spread: How do I quantify this?

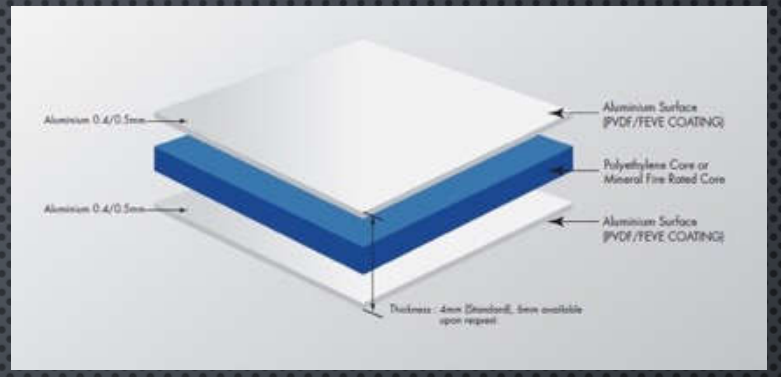
$$V_S = \frac{L_f - L_p}{t_{ig}}$$

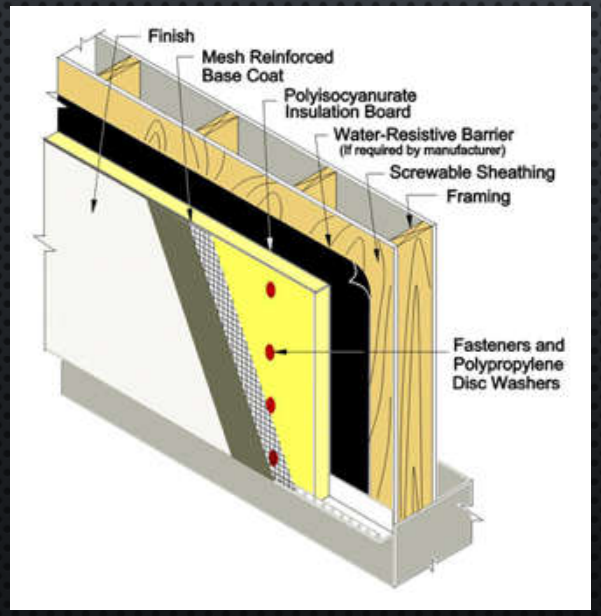


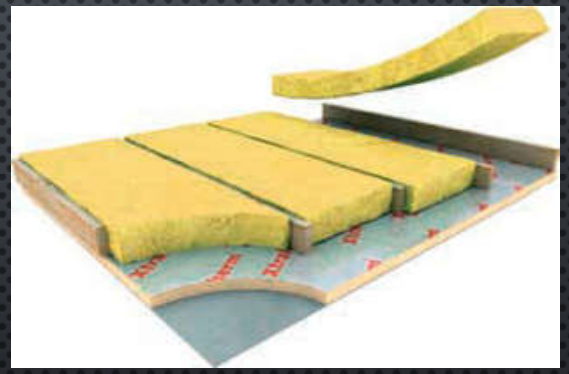
A COMBUSTION PROBLEM?

COMPLEXITY

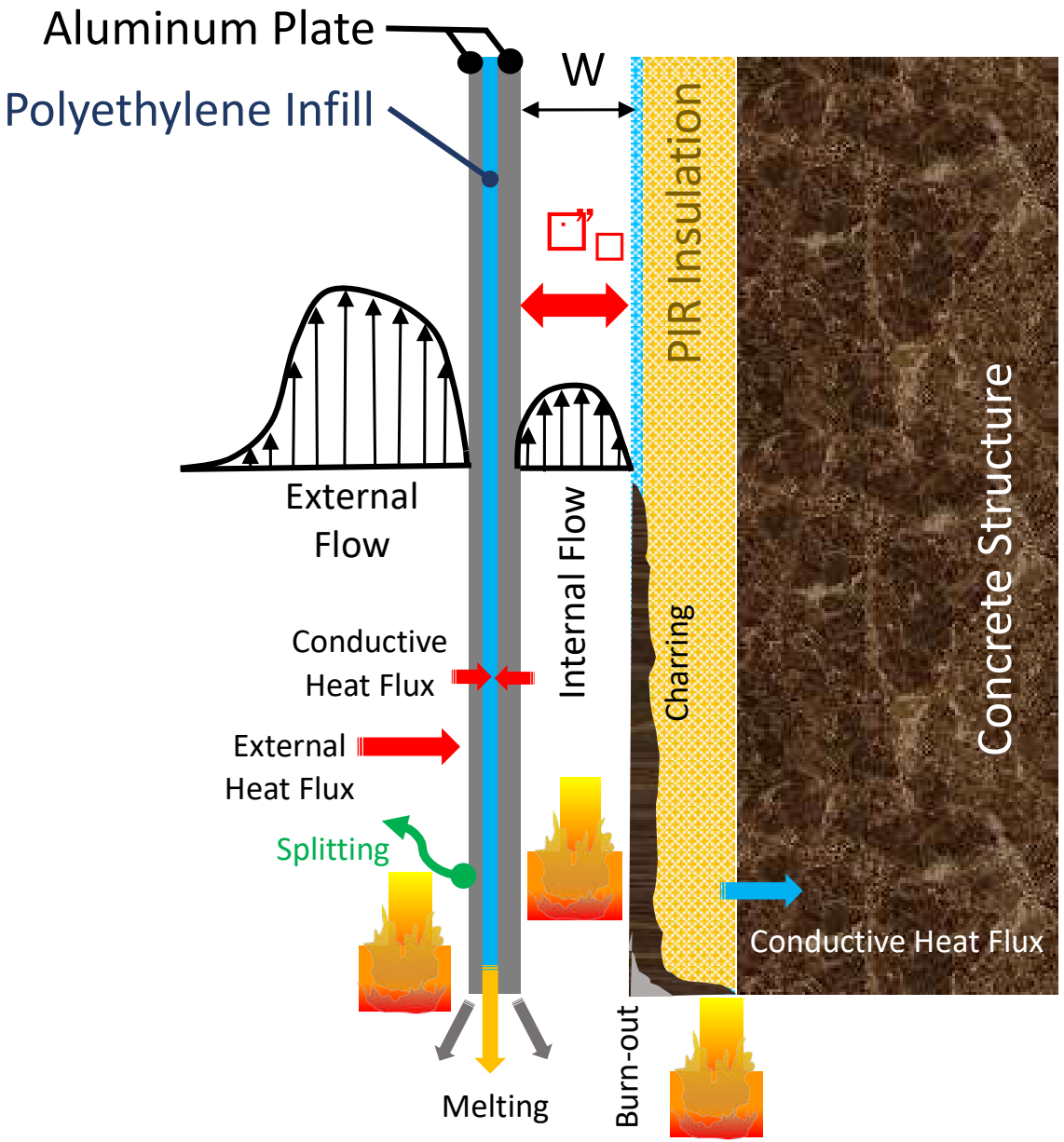



Aluminium Surface
(PVDF/FEVE COATING)
Polyethylene Core or
Mineral Fire Rated Core
Aluminium Surface
(PVDF/FEVE COATING)


Finish
Mesh Reinforced
Base Coat
Polyisocyanurate
Insulation Board
Water-Resistive Barrier
(If required by manufacturer)
Screwable Sheathing
Framing
Fasteners and
Polypropylene
Disc Washers







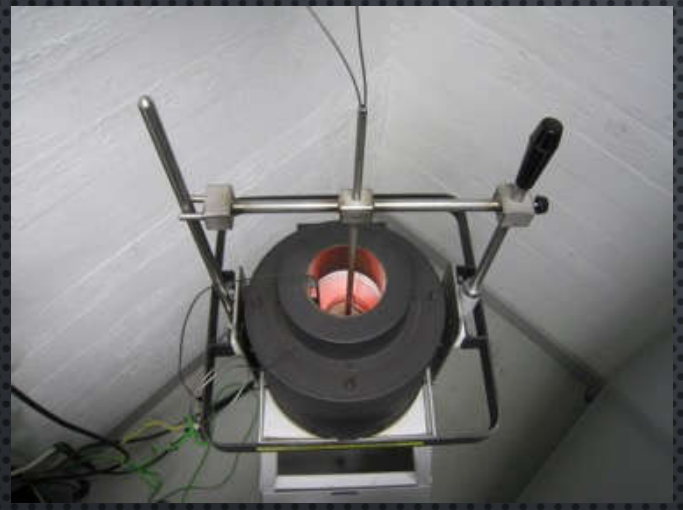
Complexity

- 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?

A COMBUSTION PROBLEM?

IS TESTING A WAY TO QUANTIFY PERFORMANCE?

WHICH TEST?





ISO-1182

Calorimetry
ISO-1716



Spread?
BS-476, ASTM-E-119



TGA-DSC

IS THIS A SOLELY A MATERIAL FLAMMABILITY ISSUE?



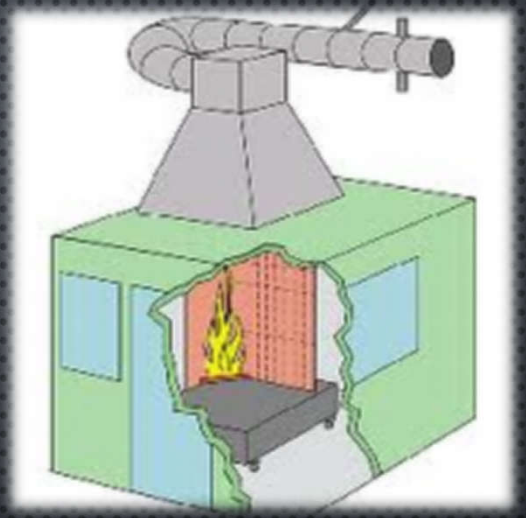
LARGER SCALE FLAMMABILITY TESTS?

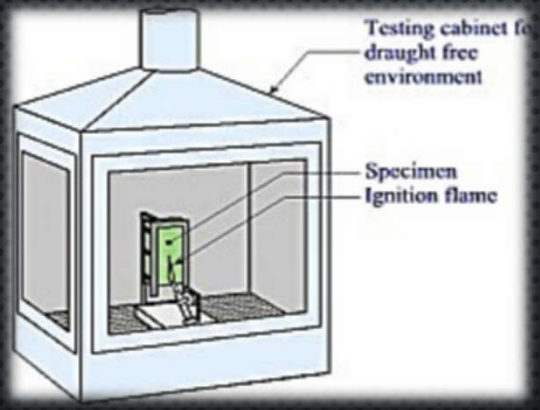
Are we truly testing "system" behaviour?

Reaction-to-fire Classification: A1, A2, B, C, D, E

f(…, FIGRA, SMOGRA, …)

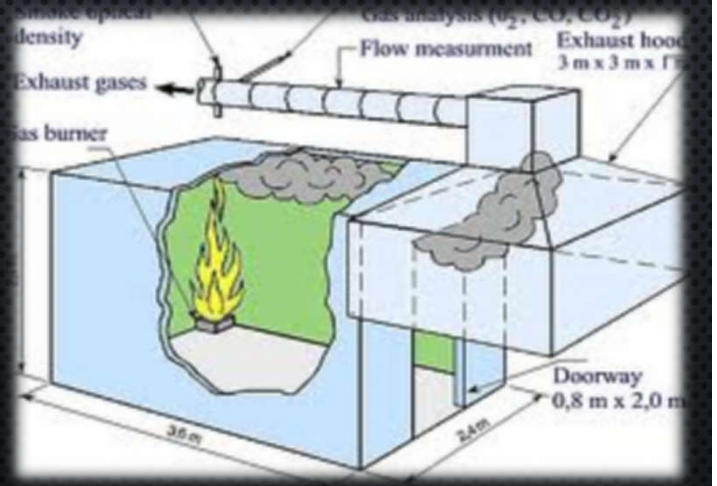
SBI (ISO 13823)



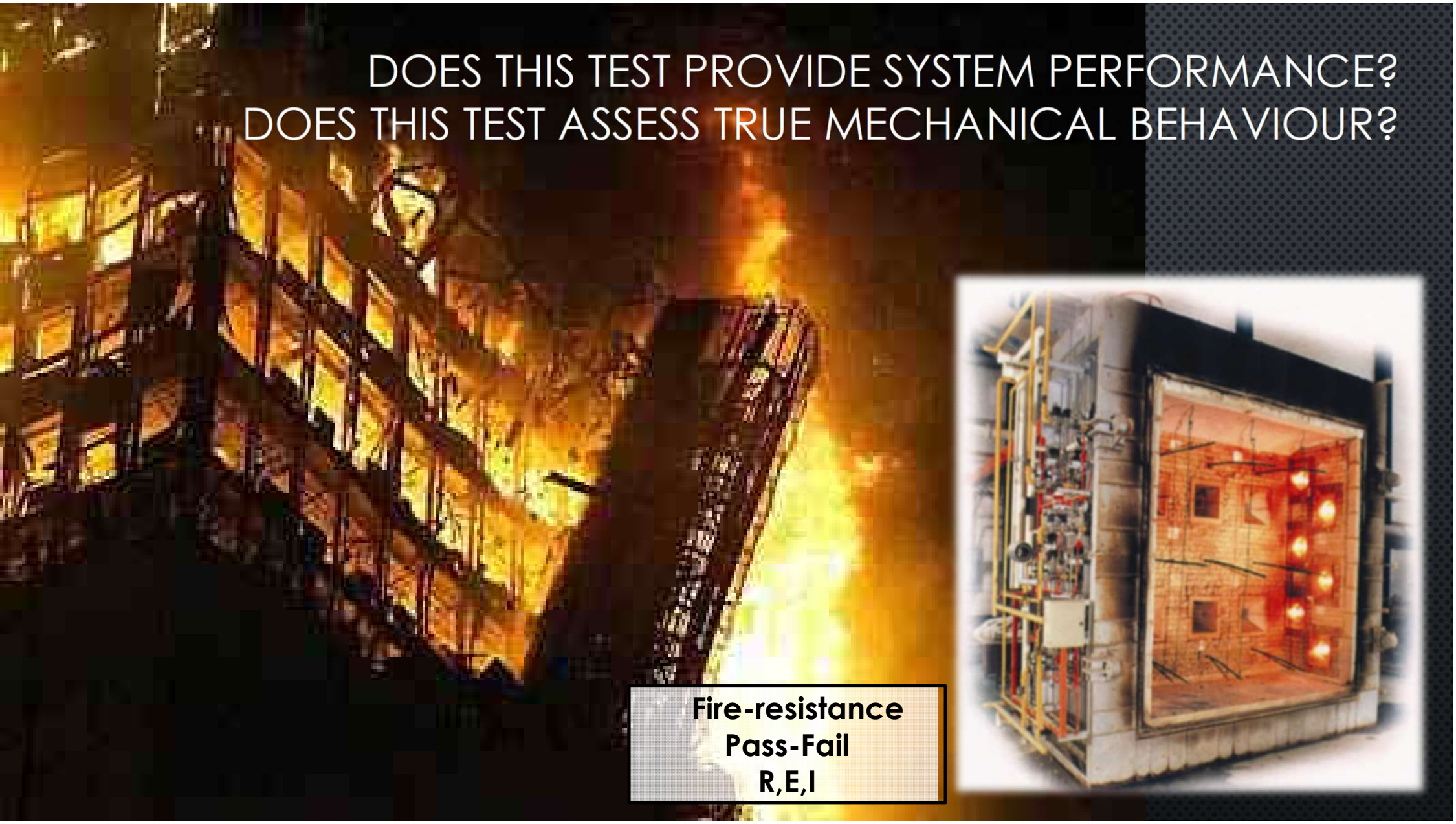


Ignitability test (ISO 11925-2)

Room corner test(ISO 9705)



DOES THIS TEST PROVIDE SYSTEM PERFORMANCE?
DOES THIS TEST ASSESS TRUE MECHANICAL BEHAVIOUR?

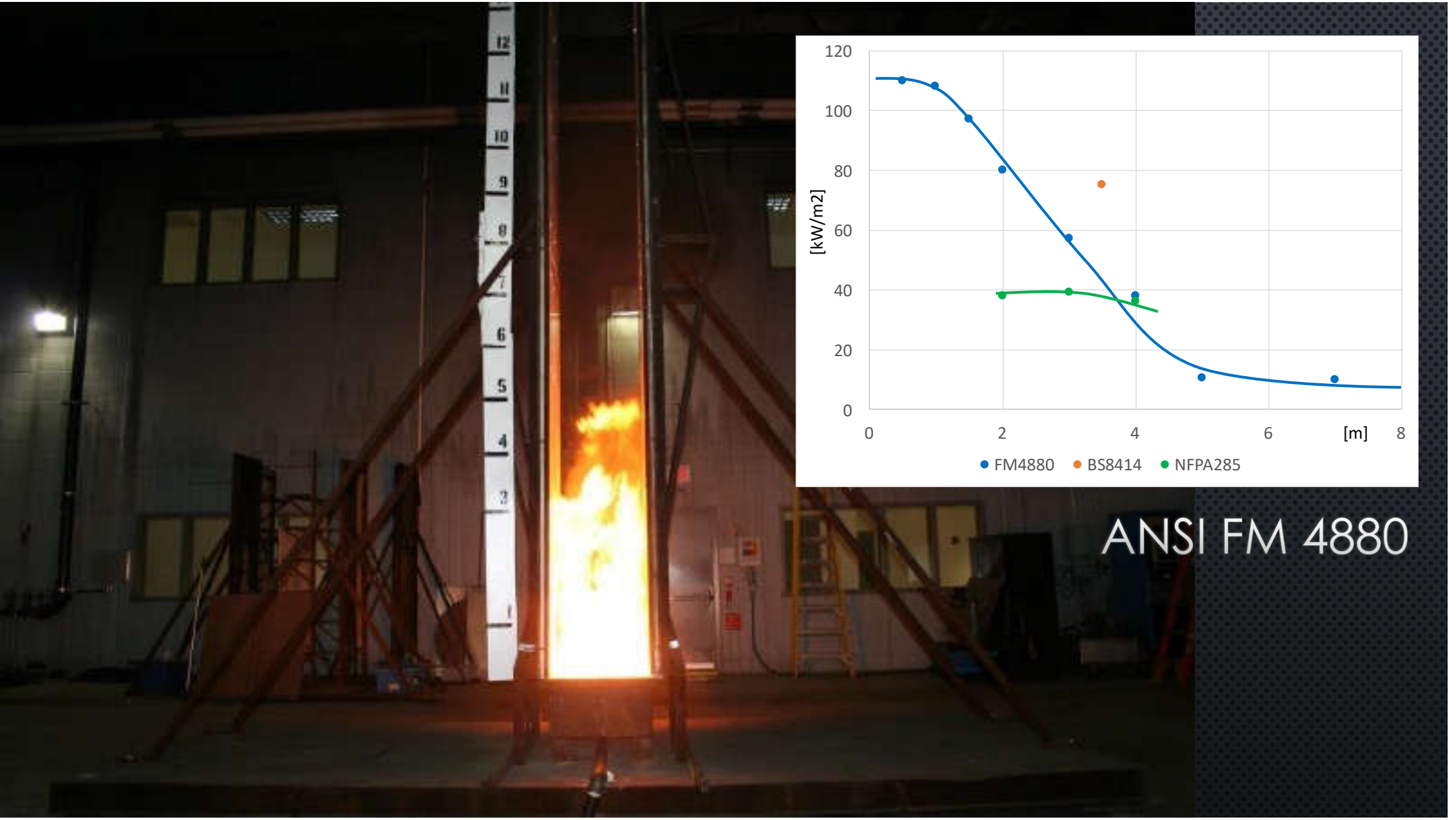


Fire-resistance
Pass-Fail
R,E,I

ARE THESE THE RIGHT TESTS?







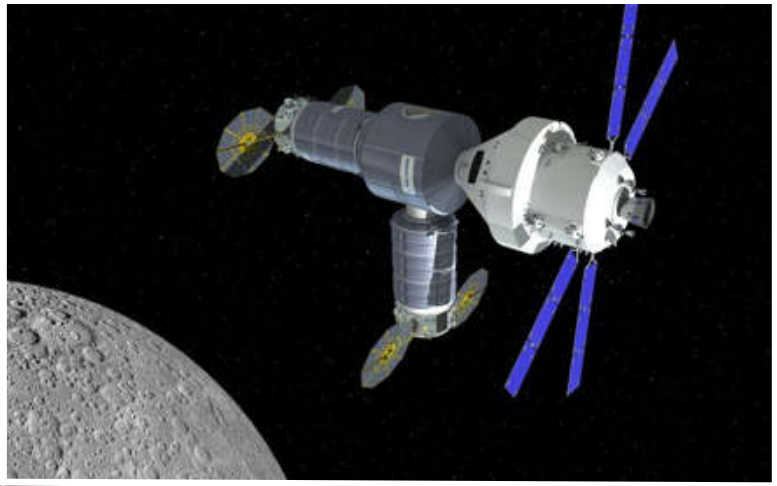
ANSI FM 4880

IS THIS ALL WE NEED OR WE NEED A BETTER UNDERSTANDING OF THE COMBUSTION PROBLEM?

HOW MUCH DO WE NEED TO KNOW TO INTERPRET THESE TESTS PROPERLY?

IS THIS ALL SOCIETY WANTS FROM US?

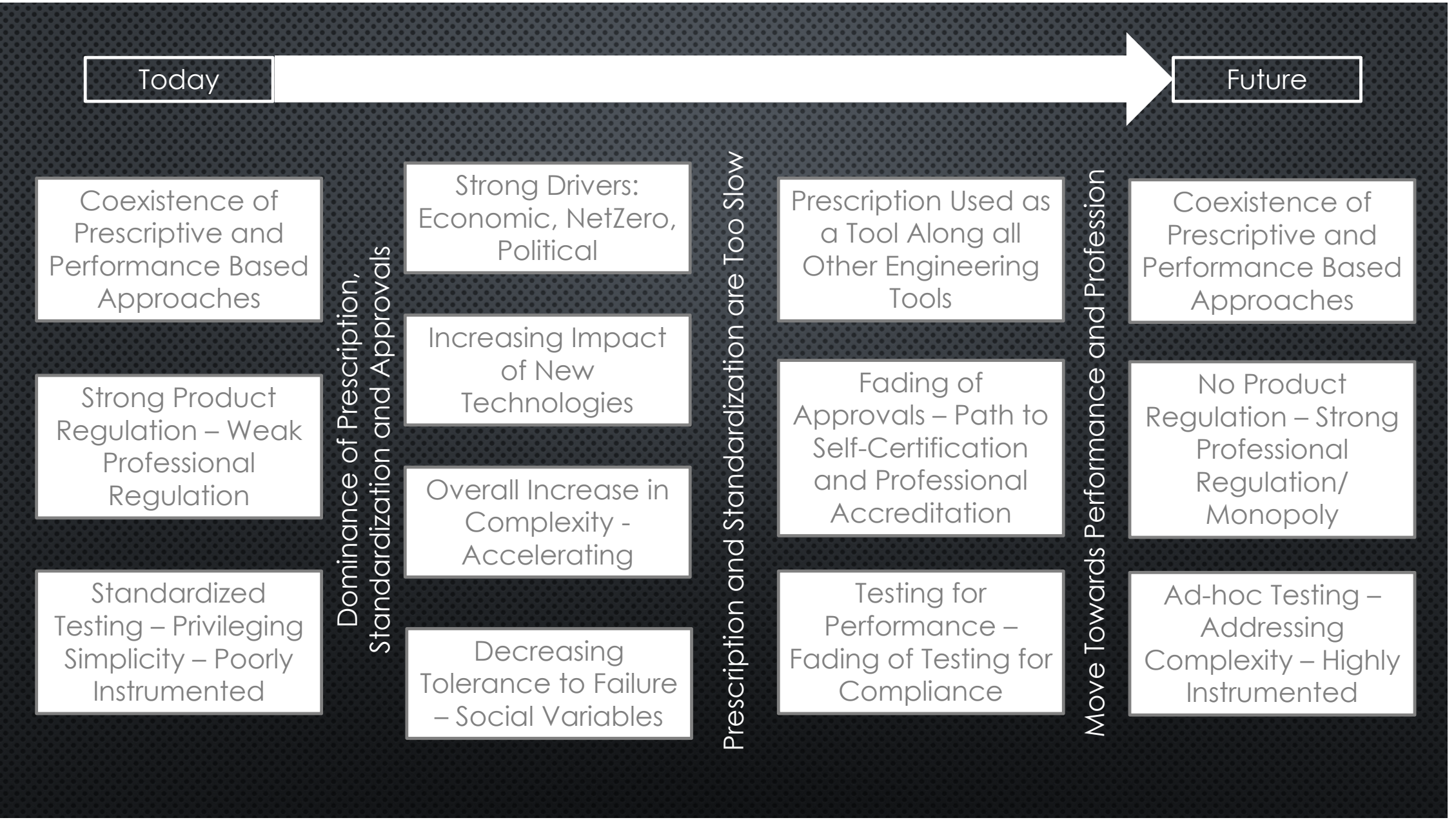







SOCIETY WANTS MORE FROM US

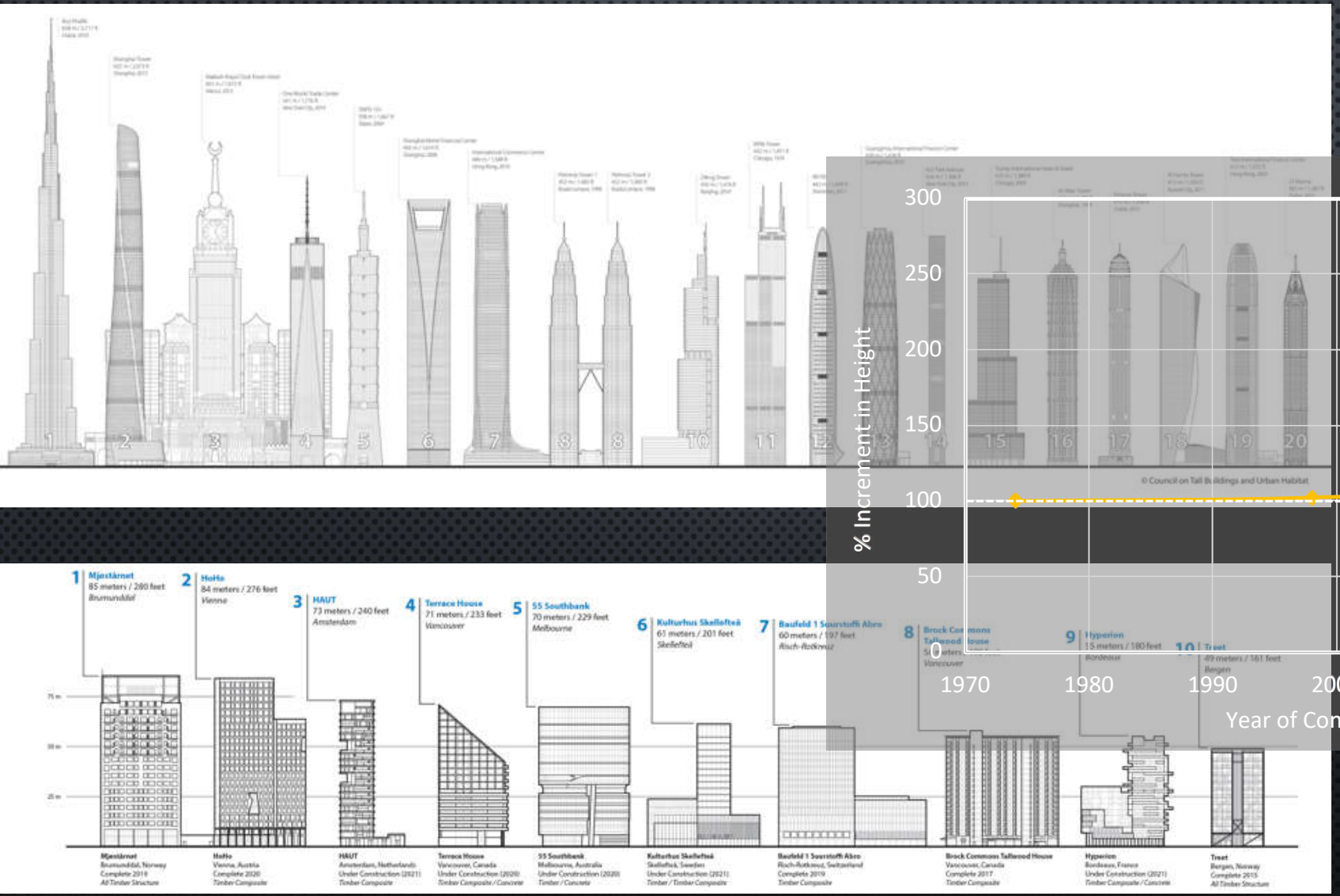

SOCIETY NEEDS MORE FROM US

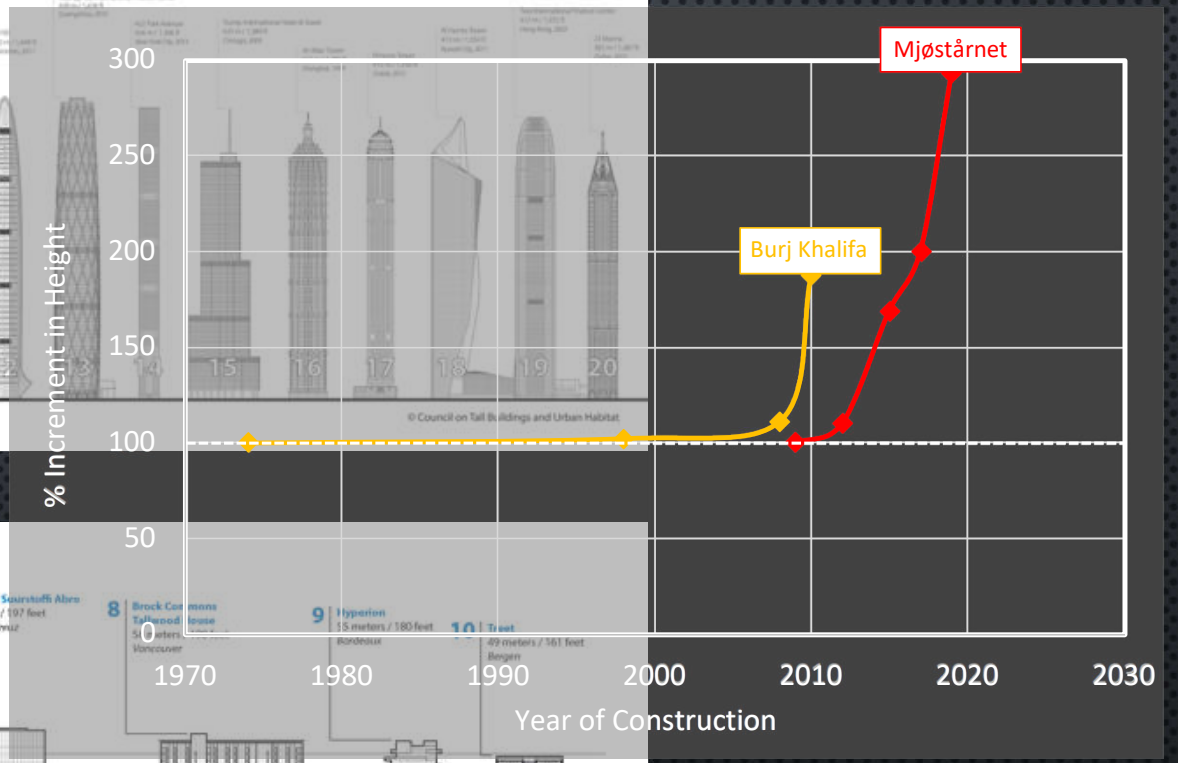

Today
Future
Coexistence of Prescriptive and Performance Based Approaches
Strong Product Regulation – Weak Professional Regulation
Standardized Testing – Privileging Simplicity – Poorly Instrumented
Dominance of Prescription, Standardization and Approvals
Strong Drivers: Economic, NetZero, Political
Increasing Impact of New Technologies
Overall Increase in Complexity - Accelerating
Decreasing Tolerance to Failure – Social Variables
Prescription and Standardization are Too Slow
Prescription Used as a Tool Along all Other Engineering Tools
Fading of Approvals – Path to Self-Certification and Professional Accreditation
Testing for Performance – Fading of Testing for Compliance
Move Towards Performance and Profession
Coexistence of Prescriptive and Performance Based Approaches
No Product Regulation – Strong Professional Regulation/ Monopoly
Ad-hoc Testing – Addressing Complexity – Highly Instrumented

TALL TIMBER

ALL BUILDINGS, INDEPENDENT OF WHAT MATERIALS ARE USED, SHALL BE DEMONSTRATED TO HAVE AN EQUAL AND ACCEPTABLE LEVEL OF SAFETY. WHETHER THE BUILDING STRUCTURE IS MADE OF COMBUSTIBLE OR NON-COMBUSTIBLE MATERIALS THE BUILDING SHOULD ACHIEVE THE SAME LEVEL OF SAFETY

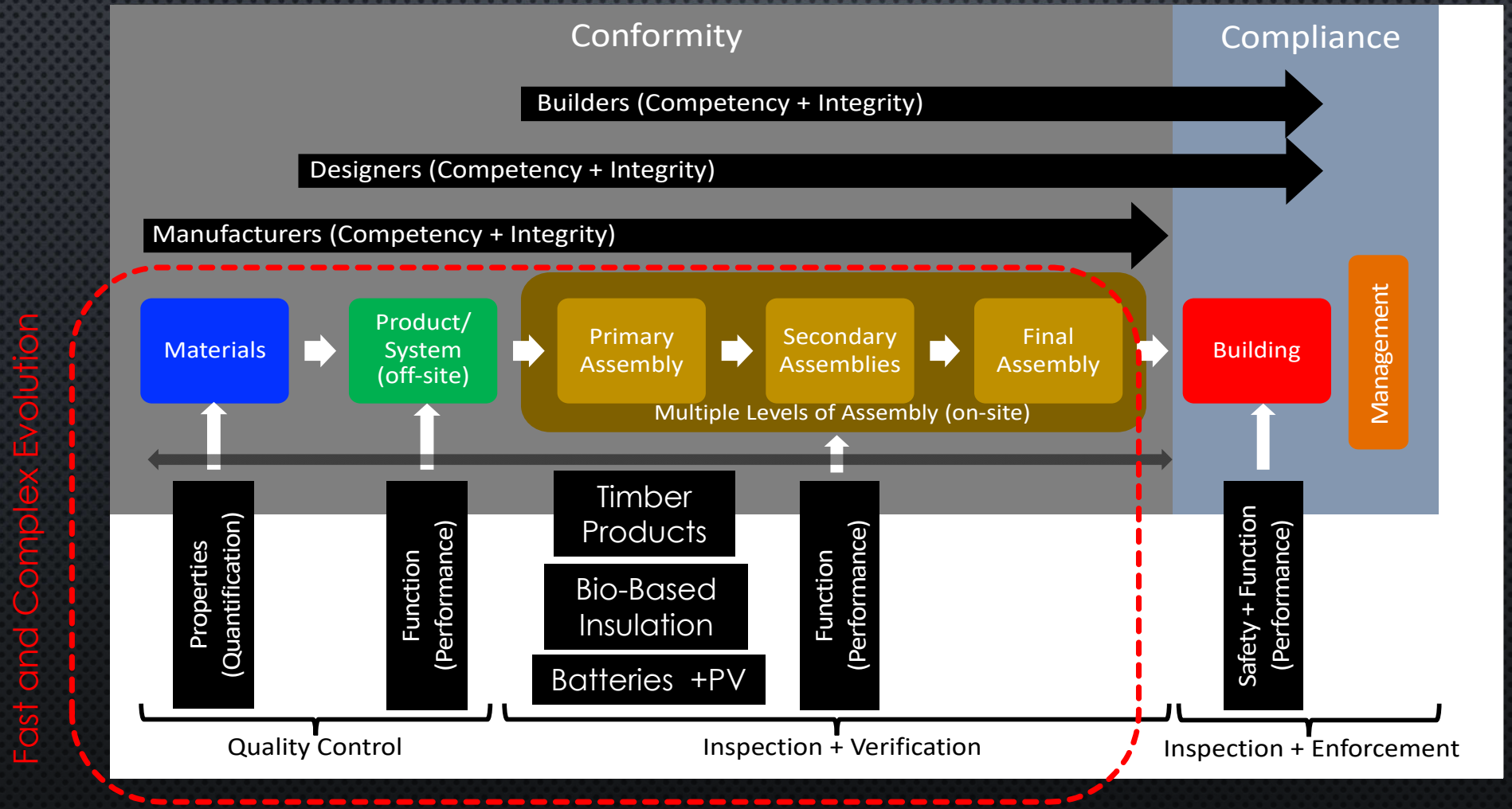
CHANGE IS TOO FAST





ARE WE RENDERING OURSELVES INCOMPETENT AGAIN?

COMPLIANCE & CONFORMITY: NOT THE MATERIAL BUT THE BUILDING



POTENTIAL CONSEQUENCES

A SENSITIVITY/CONSEQUENCE ANALYSIS THAT FOCUSES ON DAMAGE POTENTIAL SHOULD EXPLICITLY ESTABLISH POTENTIAL CONSEQUENCES FOR ALL POTENTIAL FAILURE MODES. THIS SENSITIVITY/CONSEQUENCE ANALYSIS SHOULD INCLUDE THE IMPACTS OF A FIRE ON THE BIO BASED STRUCTURE, AS WELL AS ON ALL SURROUNDING BUILDINGS AND ON FIREFIGHTER INTERVENTIONS







Understanding Consequences

Charlotte, USA – 18 May 2023









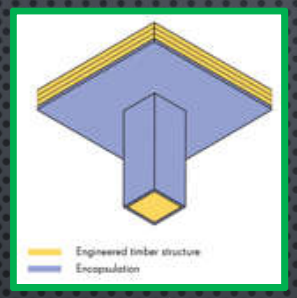
Potential Challenge to the design concept of “Separation Distances”

THE NEW MODEL BUILDING
DEVELOPING A PRESCRIPTIVE DESIGN

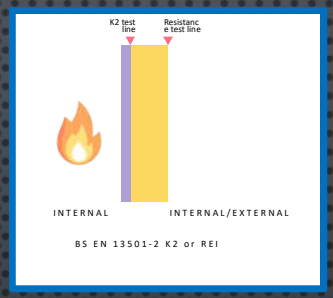


WAUGH THISTLETON ARCHITECTS

35 PITFIELD STREET LONDON N1 6HB +44(0)2076135727 WAUGHTHISTLETON.COM



Encapsulation

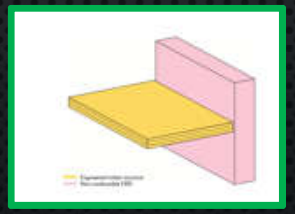


K2 (60 min)-Encapsulation

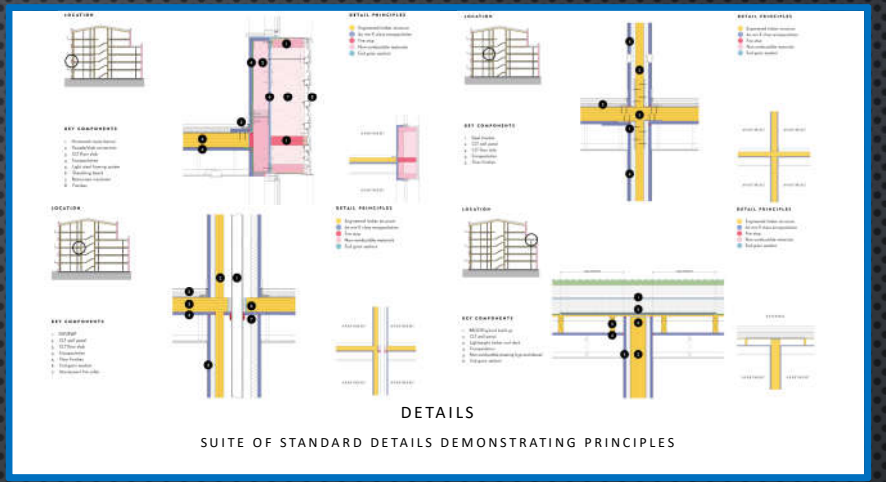


Non-Combustible Building Envelope

Sprinklers



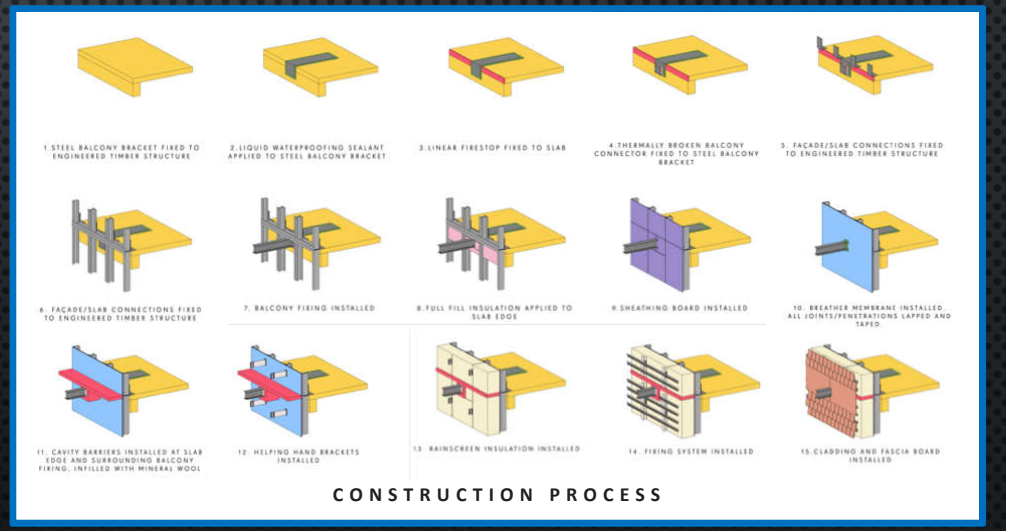
The Most Onerous Condition Always Applies
No Vertical Fire Spread



DETAILS

SUITE OF STANDARD DETAILS DEMONSTRATING PRINCIPLES

Over specify Construction Process to Reduce Dependency on Trade Skills



CONSTRUCTION PROCESS

NOT THE BUILDING WE WANT TO DESIGN BUT THE BUILDING WE CAN EXPLAIN

EXPENSIVE
INFLEXIBLE
DIMINISHED ENVIRONMENTAL BENEFIT

CAN WE DO BETTER?

ALLOW THE TIMBER TO IGNITE?



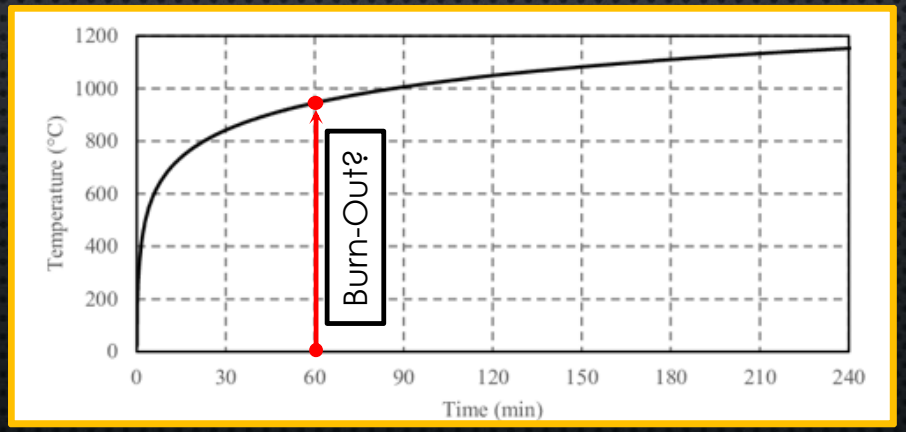
REI (60 min)-Encapsulation



REI (60 min)-Encapsulation + Self-Extinction



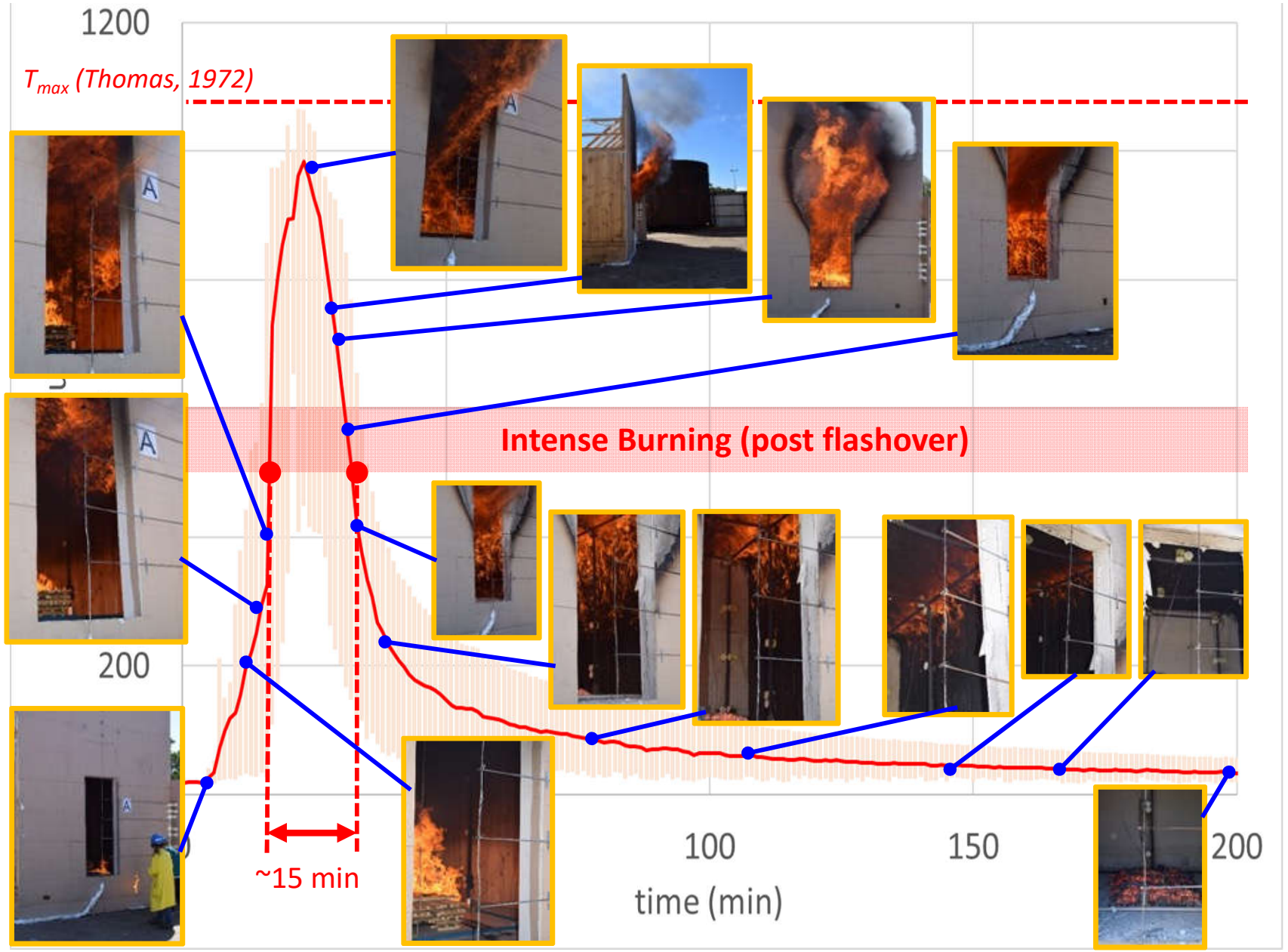
K2 (60 min)-Encapsulation



IS THIS THE CORRECT EXPOSURE?


WHAT IS **'FAILURE'**?
IGNITION?
CONTINUOUS BURNING?
UNEXPOSED SURFACE TEMPERATURE THRESHOLD?
FAILURE OF THE GLUE-LINE?
DELAMINATION?
FAILURE OF COMPARTMENTATION?
STRUCTURAL FUNCTIONAL FAILURE?
ETC.
CAN WE PROPERLY ASSESS **'FAILURE'** USING STANDARDIZED TESTS?

Large Scale Test: Learning Form the Test or Demonstrating What We Already Know?



DESIGN FOR EXPLICIT PERFORMANCE

IT IS THE COMPETENT PROFESSIONALS' PREROGATIVE TO DEVELOP A FIRE SAFETY STRATEGY, TO QUANTITATIVELY DEMONSTRATE ITS ADEQUACY AND TO DECIDE WHAT TOOLS ARE NECESSARY FOR THIS DEMONSTRATION.

COMPETENCY IS A LIFE LONG PROCESS

WE DECIDE WHAT COMPETENCY IS AND WE DEEM PROFESSIONALS COMPETENT

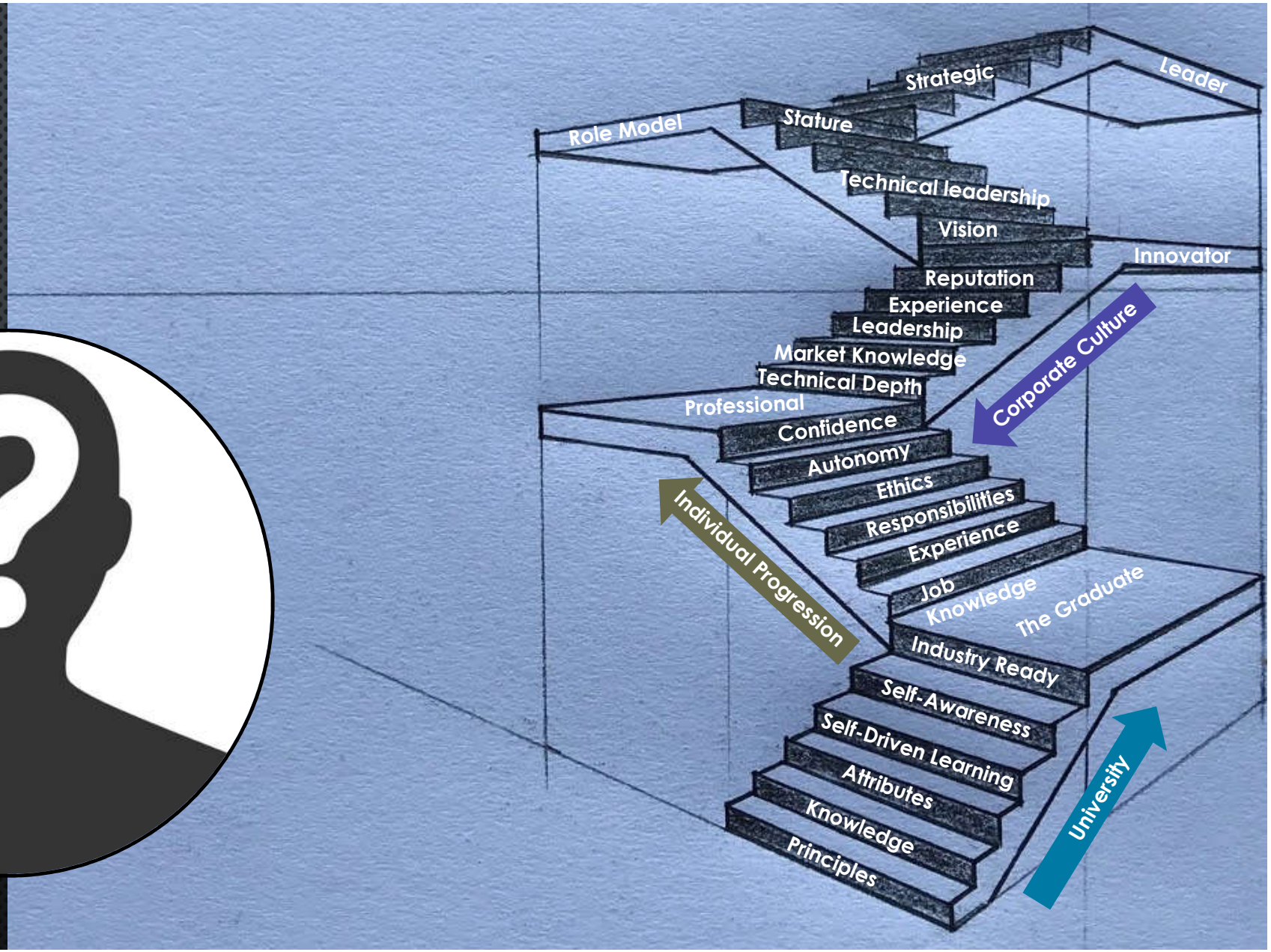
THE MORE WE TRIVIALIZE THE PROBLEM IN AN UNWARRANTED MANNER THE MORE WE ALLOW THE INCOMPETENT TO RULE

THE MORE WE TRIVIALIZE THE PROBLEM IN AN UNWARRANTED MANNER THE MORE WE ENABLE THE INCOMPETENT TO DECIDE WHO IS COMPETENT

BUT WE WILL CARRY THE BURDEN OF FAILURE

Building the Professional Pipeline





Competence:

- Necessary Knowledge
- Necessary Attributes
- Proficient use of Available tools
- Capability to continue learning
- Certification & Enforcement

William F. Baker, NAE (SOM)



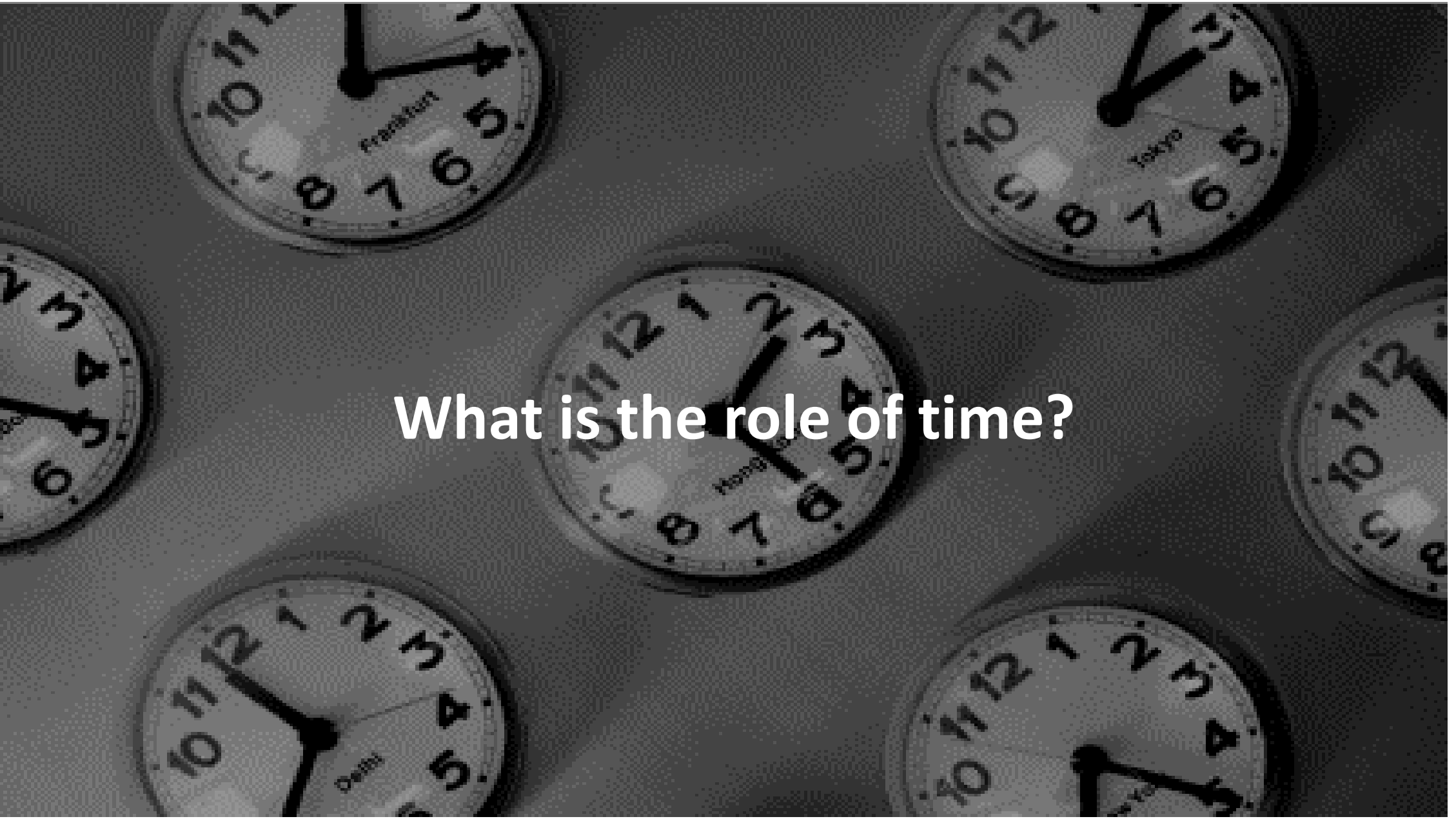

Thankyou!

Fire Dynamics



José L. Torero
University College London
United Kingdom

Lecture -2


What is the role of time?

Objectives

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

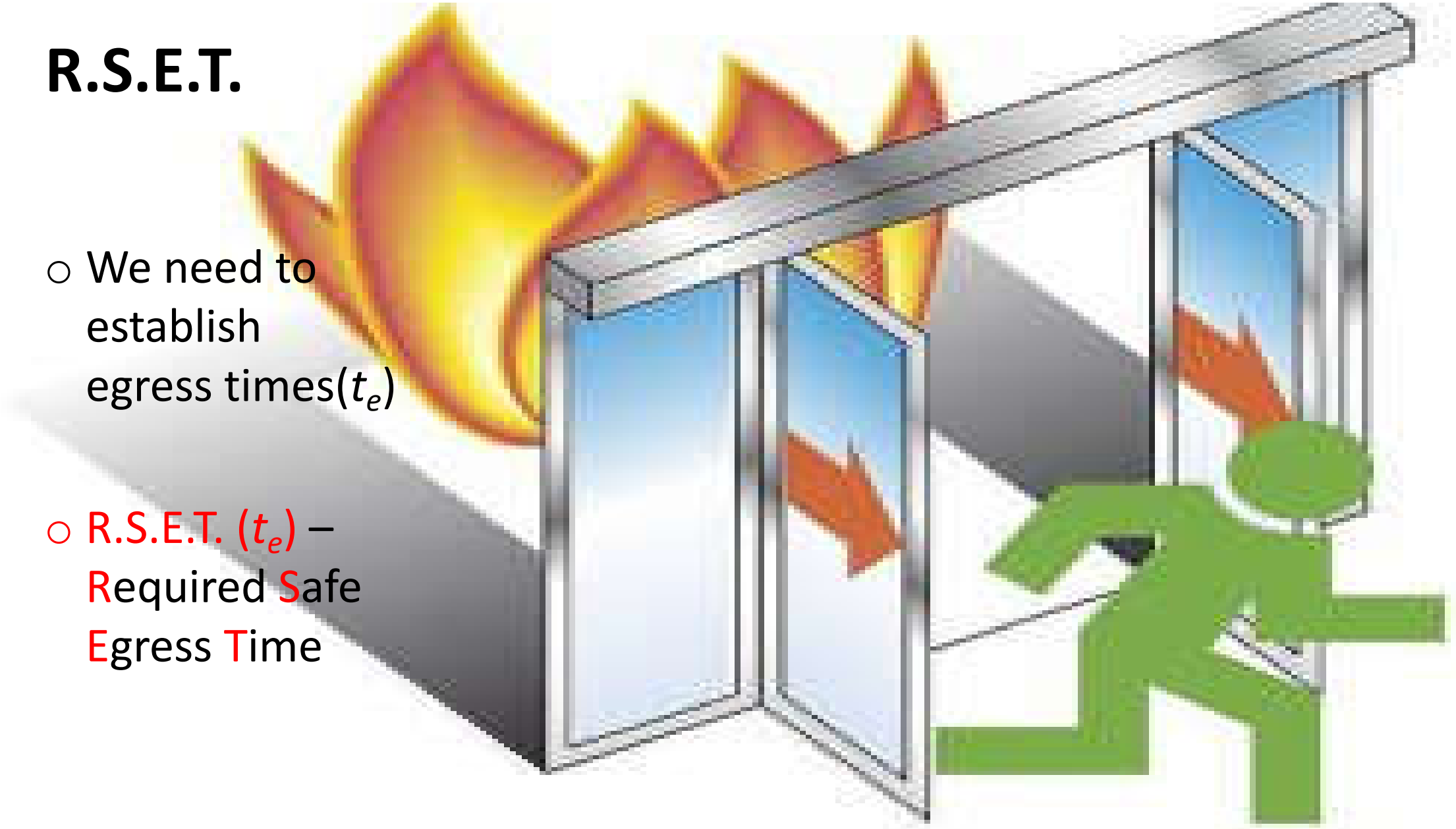
$t_e <<<<< t_S$

$t_s \rightarrow \infty$

Fire Safety Strategy

R.S.E.T.

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



ASET



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

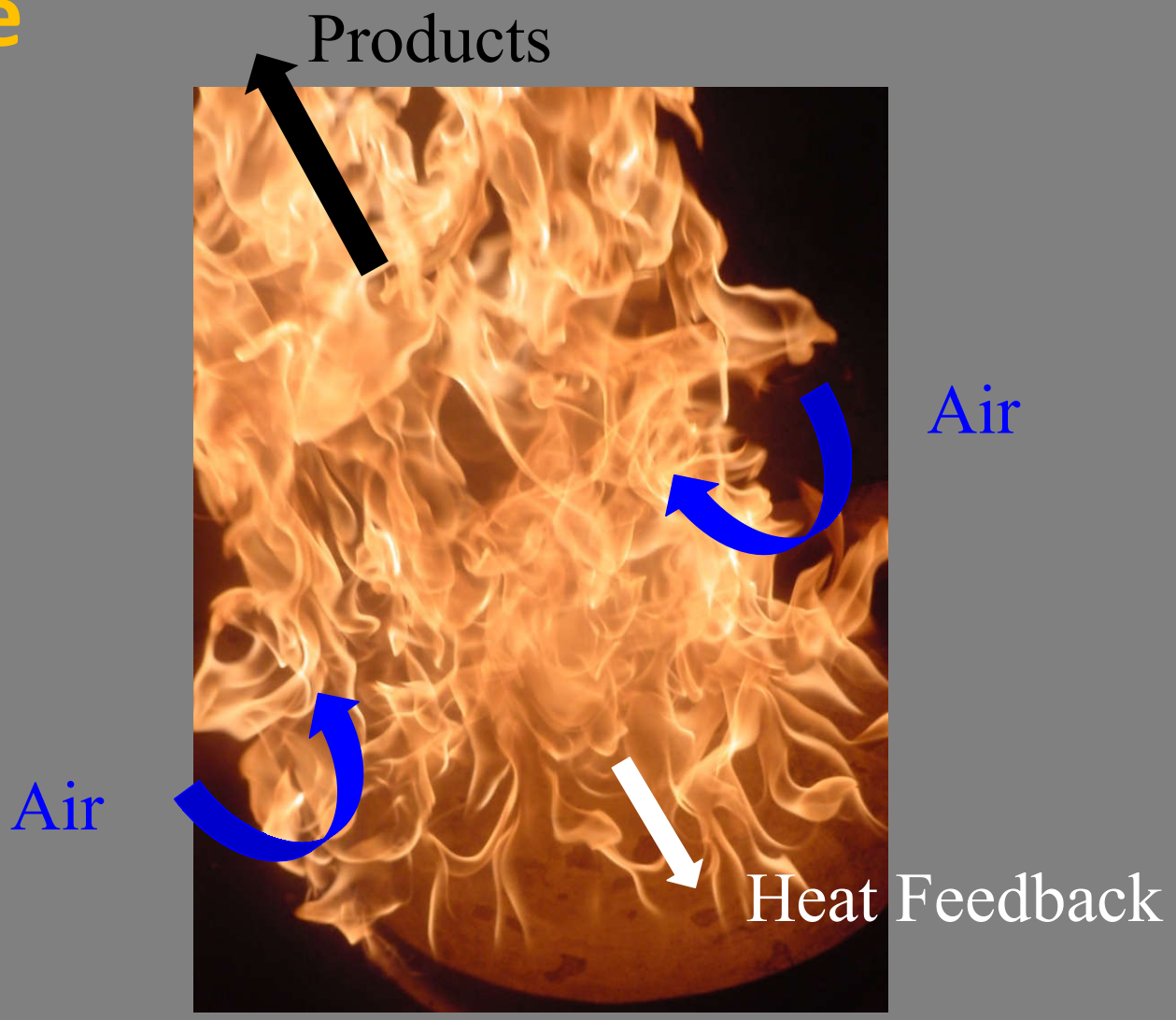


Explosion?

- 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 $t \rightarrow 0$


FAST FRAMES
T4

Diffusion Flame



Motion Only Through Spread

Burke-Schumann

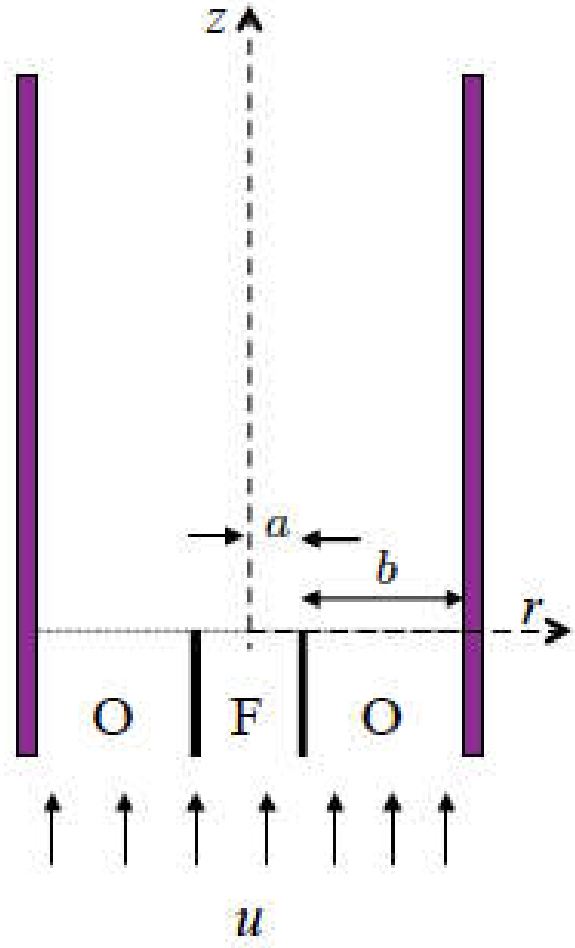
- Flame Sheet Approximation
  - $Y_F = 0 \rightarrow for\ the\ oxidizer\ side$
  - $Y_O = 0 \rightarrow for\ the\ fuel\ side$
- $x_f \rightarrow Flame\ location;\ Y_F = Y_O = 0$

$$\phi = \frac{Y_{Fo}/\upsilon_F W_F}{Y_{Oo}/\upsilon_O W_O}, \nu = \frac{Y_O W_O}{Y_F W_F}, \psi = Y_F - \frac{Y_O}{\nu}, \frac{\partial \psi}{\partial z} - \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial \psi}{\partial r} = 0\right), c = \frac{a}{b}$$

- Solution:

$$\psi(r,z) = A_0 + \sum_{n=1}^{\infty} A_n J_0(\lambda_n r).e^{-\lambda_n^2 z}$$

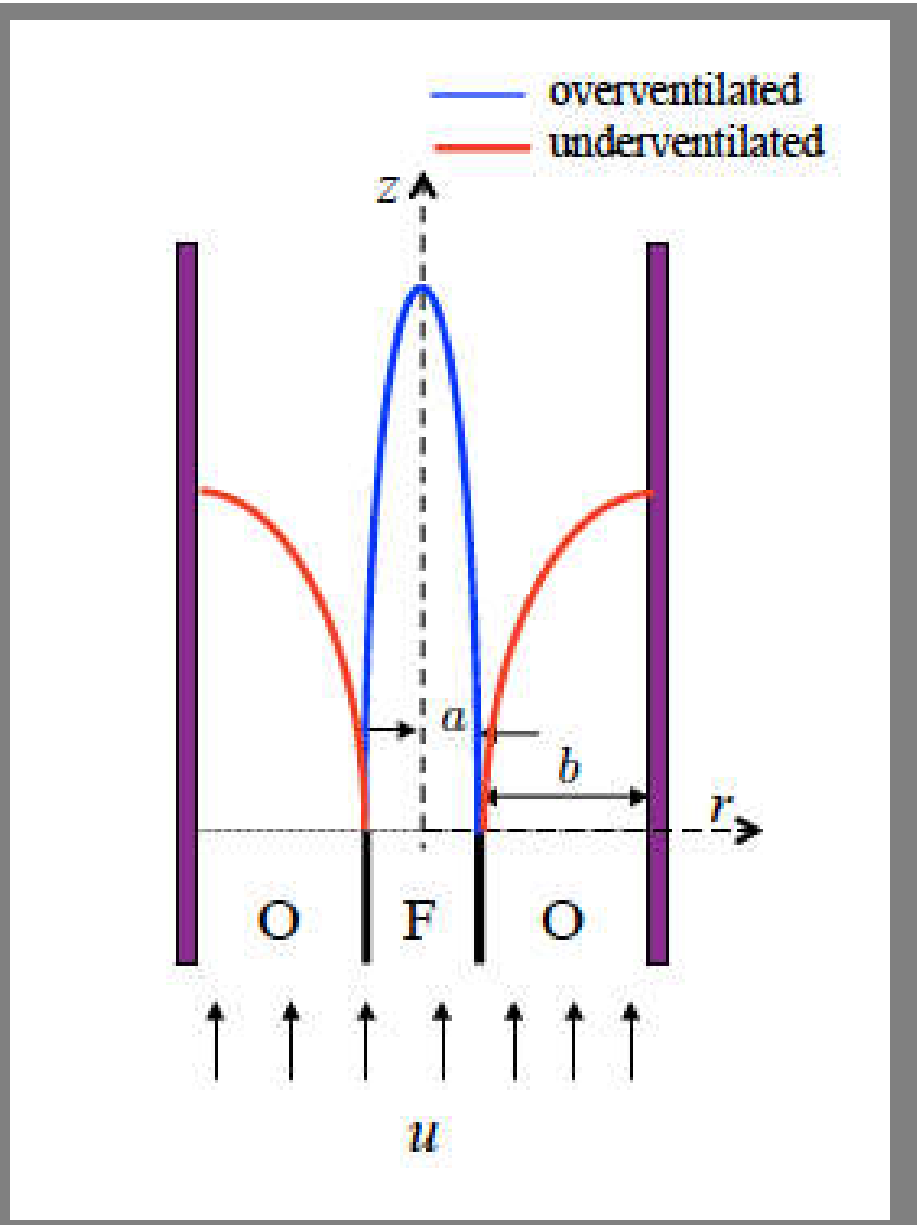
$$A_0 = \left(1+\frac{1}{\phi}\right)c^2 - \frac{1}{\phi}, \quad A_n = \frac{2\left(1+\frac{1}{\phi}\right)c}{\lambda_n J_0^2(\lambda_n)} J_1(c\lambda_n)$$



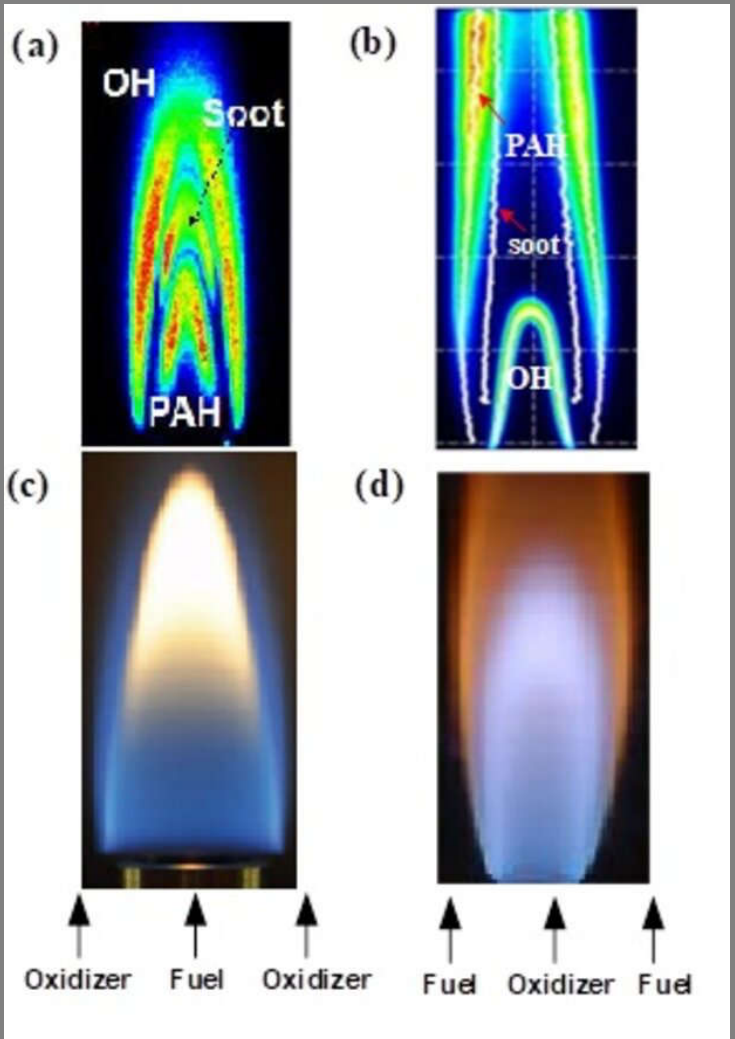
Matalon

Flame Location

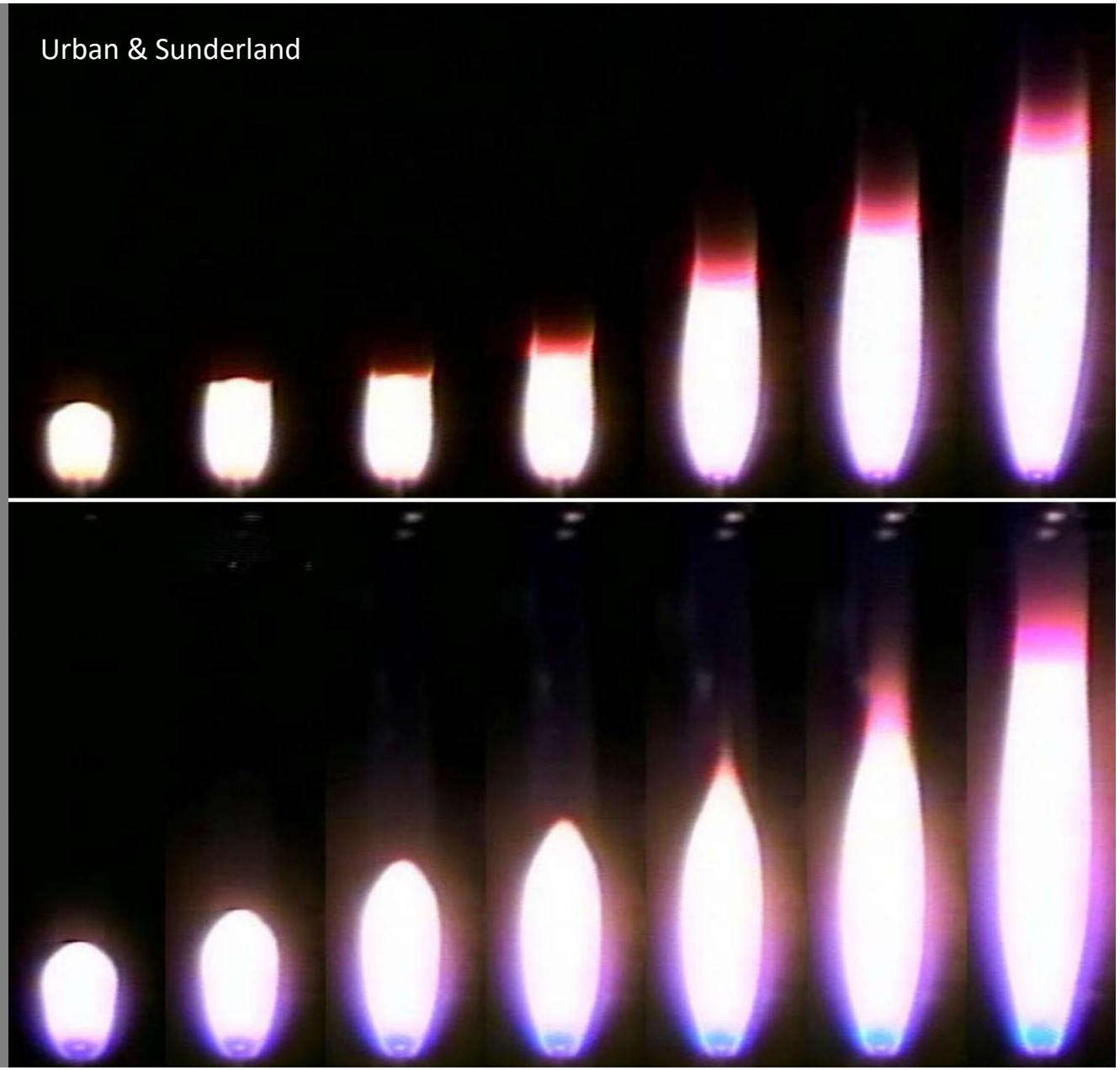
$$F(r,z) = A_0 + \sum_{n=1}^{\infty} A_n J_0(\lambda_n r).e^{-\lambda_n^2 z} = 0$$



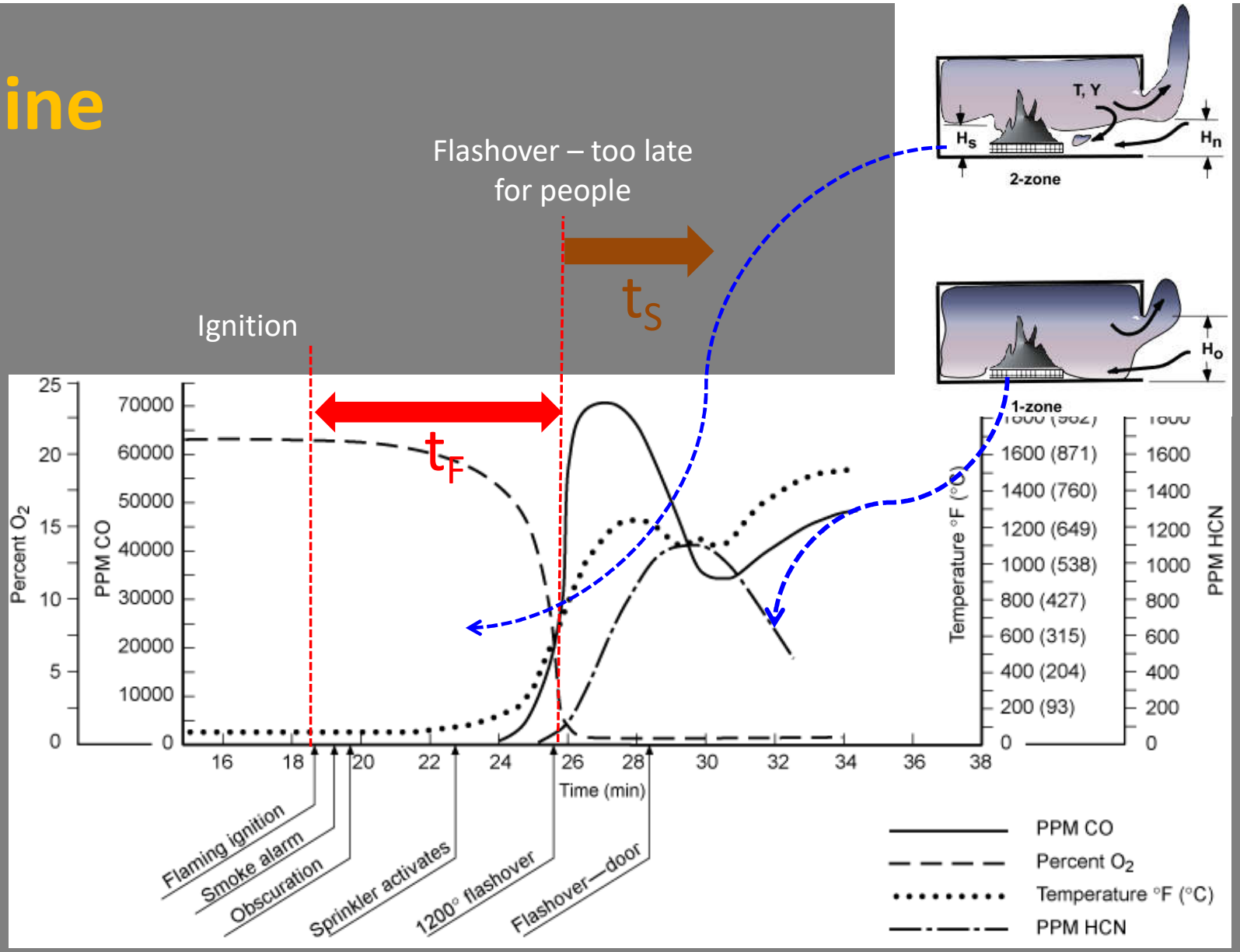
Smoke Point



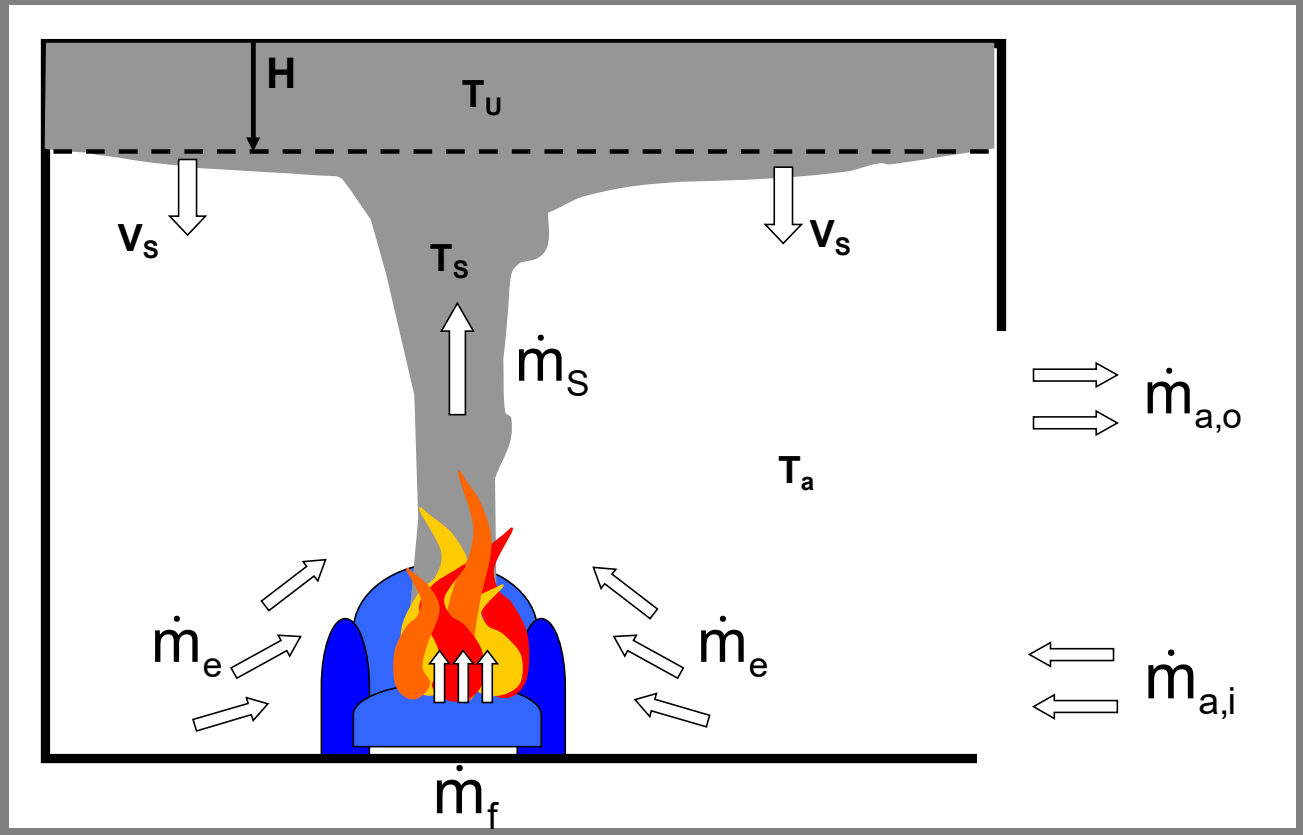
Mikofski et al



Timeline


Flashover – too late for people
Ignition
t_S
t_F
T, Y
H_S
H_n
2-zone
H_o
1-zone
Percent O_2
PPM CO
Temperature °F (°C)
PPM HCN
Time (min)
Flaming ignition
Smoke alarm
Obscuration
Sprinkler activates
1200° flashover
Flashover—door
PPM CO
Percent O_2
Temperature °F (°C)
PPM HCN

The Pre-Flashover Compartment Fire

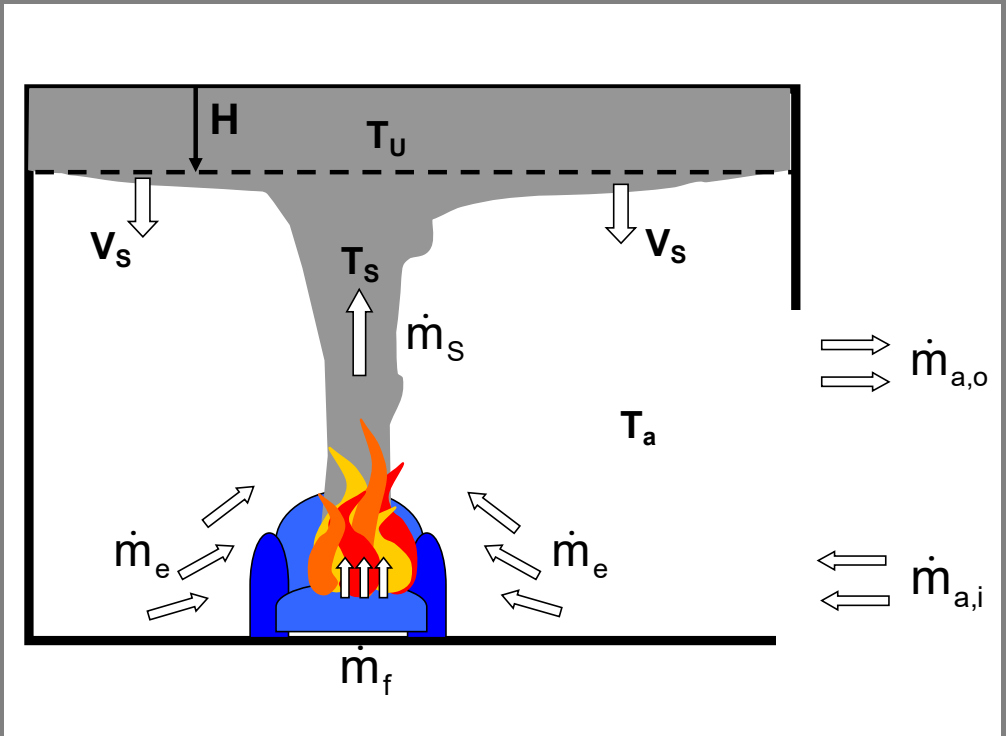


Approach

- 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:
    $V_S = \frac{dH}{dt}$

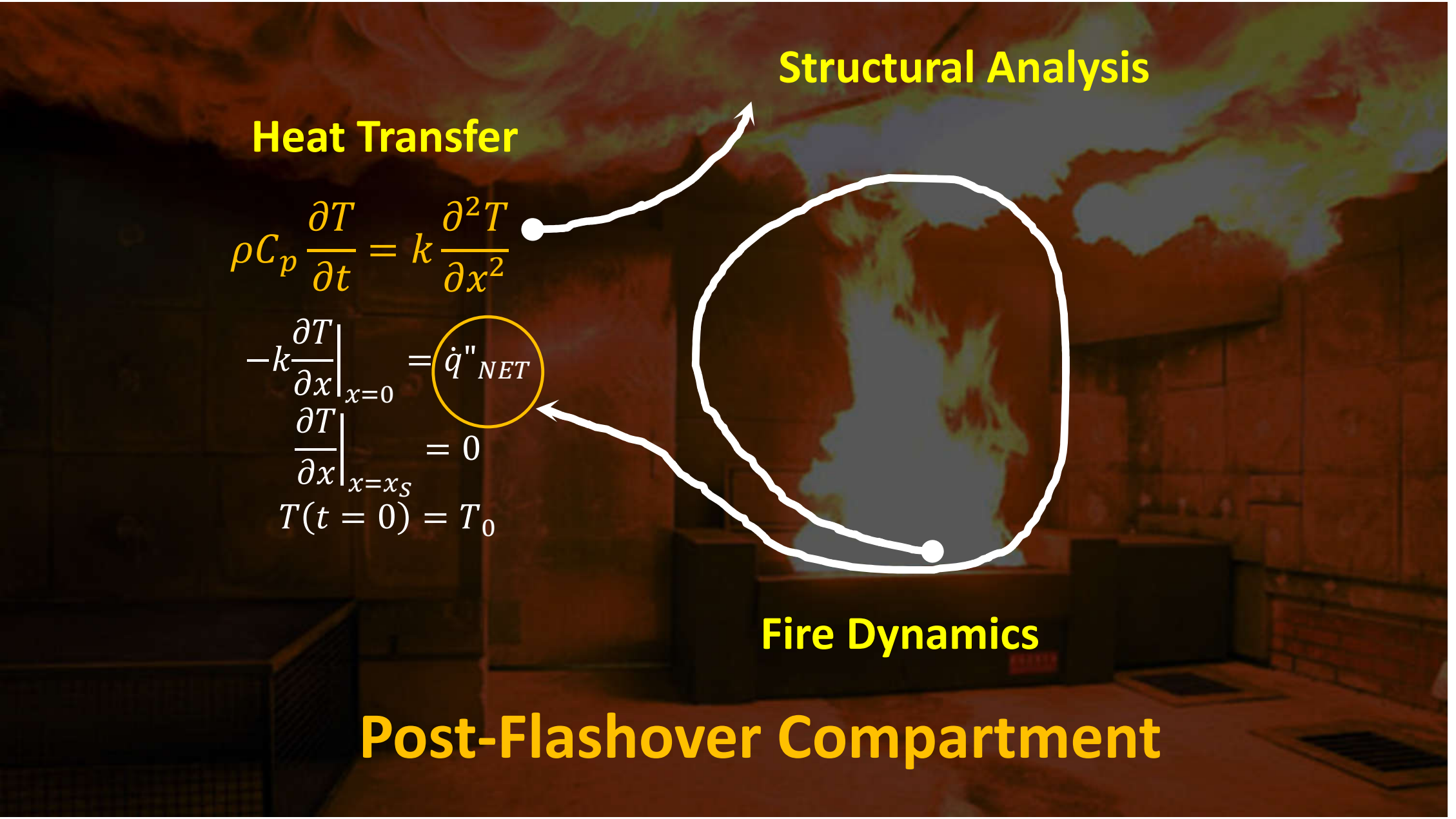
Conservation Equations

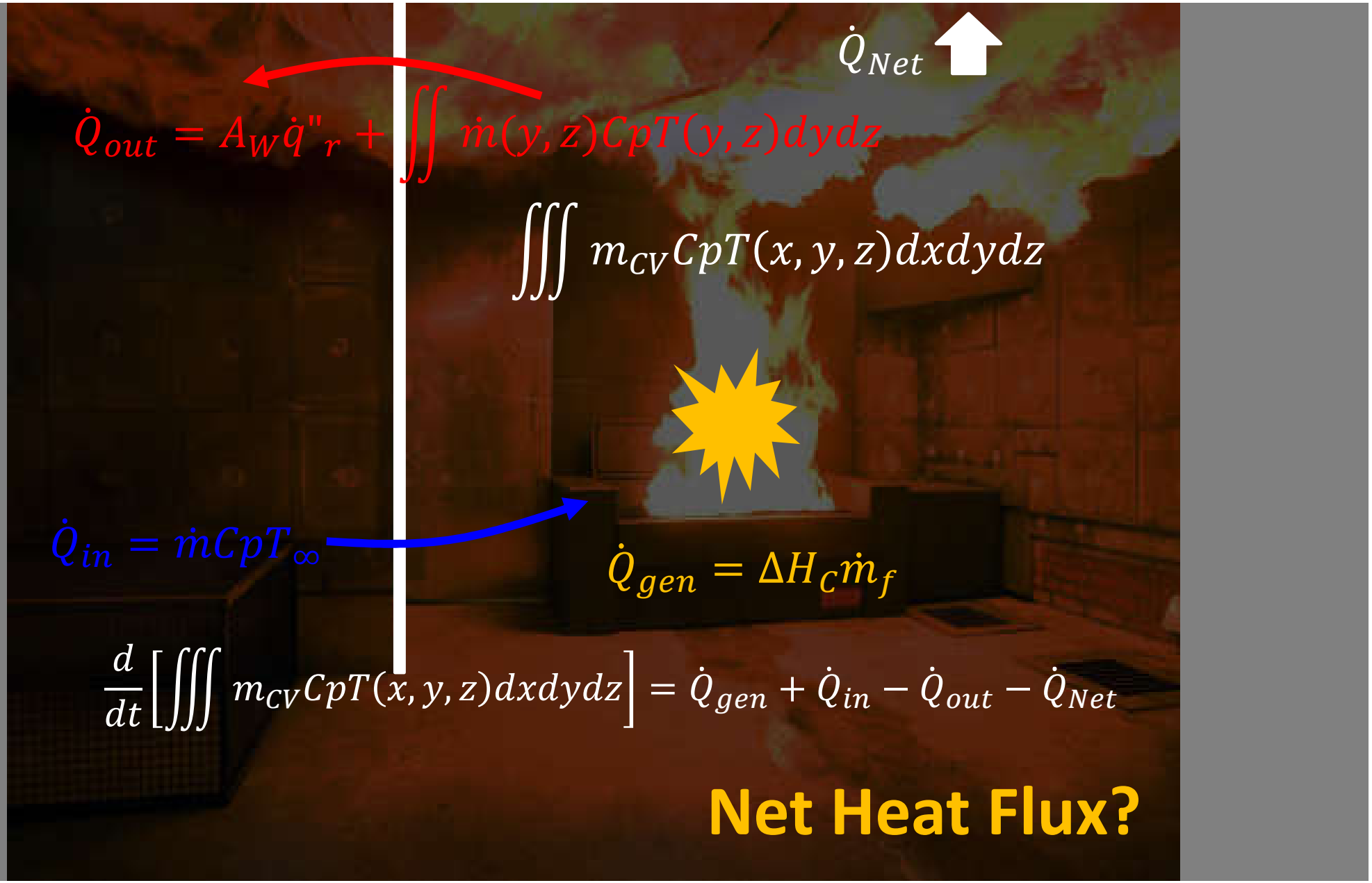
- These parameters can be obtained from, the ideal gas law and conservation of mass and energy in the Upper Layer

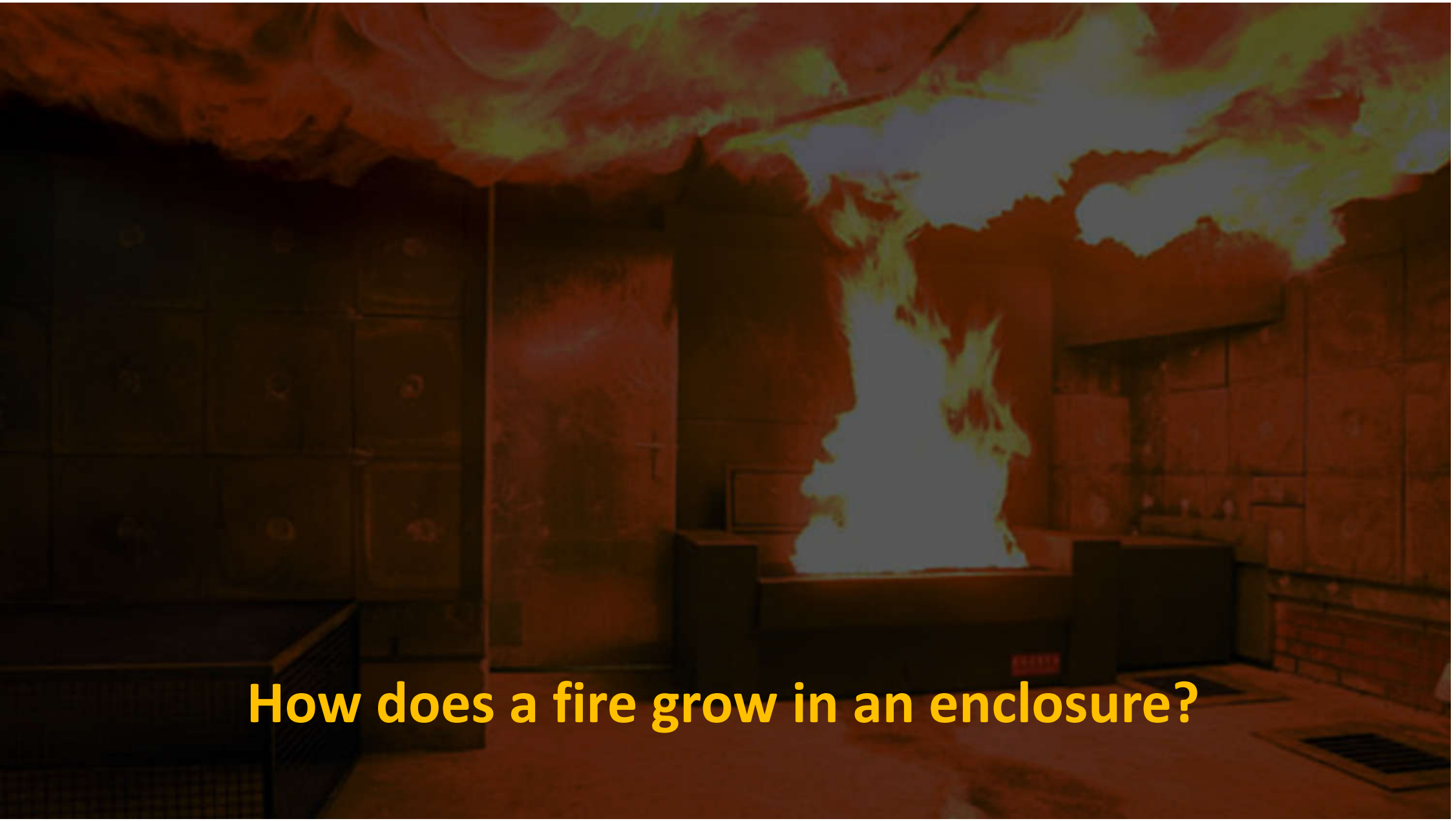
$$P = \rho R T_u$$

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

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


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
Post-Flashover Compartment

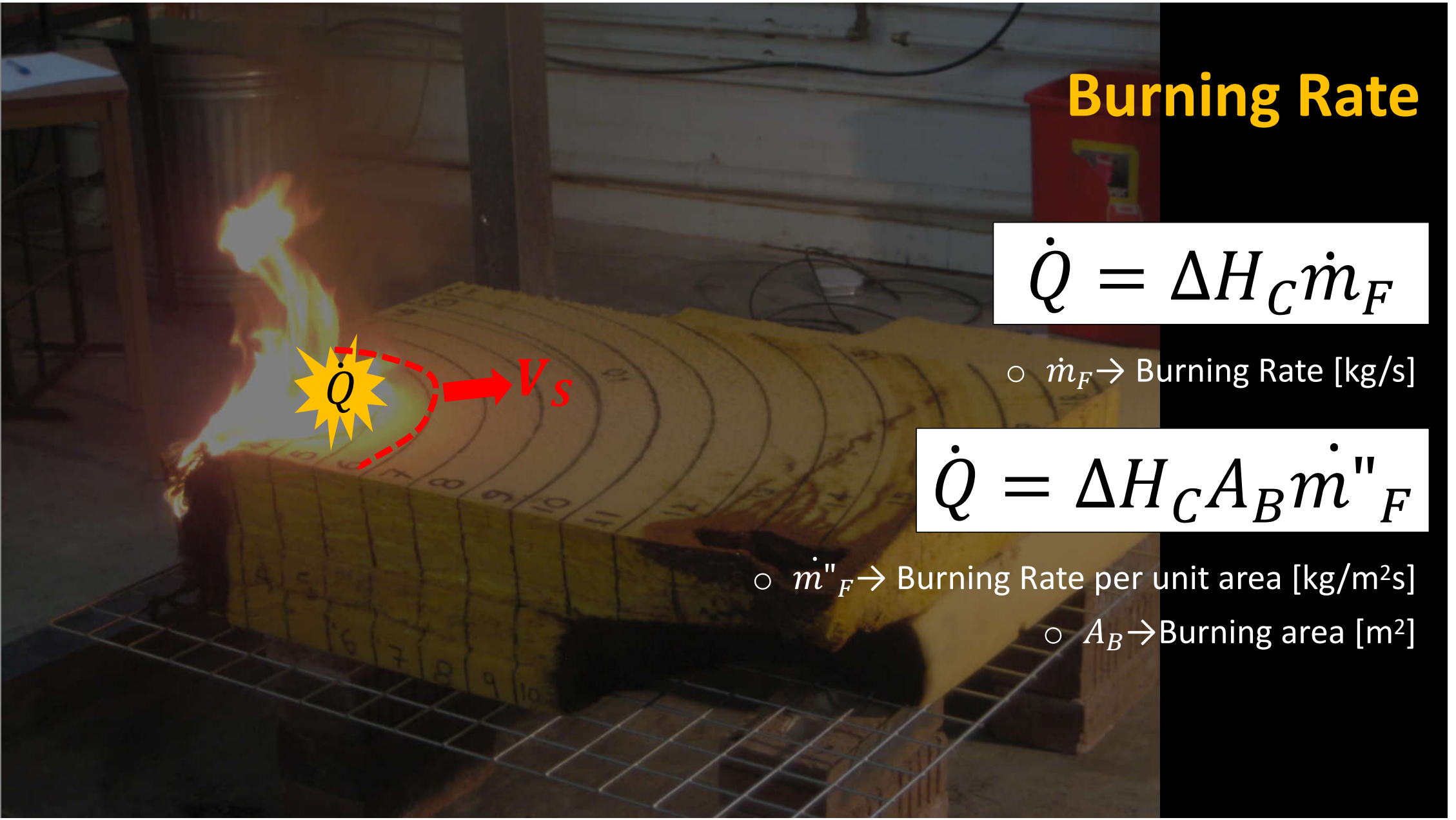

$\dot{Q}_{Net}$
$\dot{Q}_{out} = A_W \dot{q}"_r + \iint \dot{m}(y,z) CpT(y,z) dydz$
$\iiint m_{CV} CpT(x,y,z) dxdydz$
$\dot{Q}_{in} = \dot{m} CpT_\infty$
$\dot{Q}_{gen} = \Delta H_C \dot{m}_f$
$\frac{d}{dt}\left[\iiint m_{CV} CpT(x,y,z) dxdydz\right] = \dot{Q}_{gen} + \dot{Q}_{in} - \dot{Q}_{out} - \dot{Q}_{Net}$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

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

- $\dot{m}_F$ → Burning Rate [kg/s]

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

- $\dot{m}''_F$ → Burning Rate per unit area [kg/m²s]
- A_B → Burning area [m²]

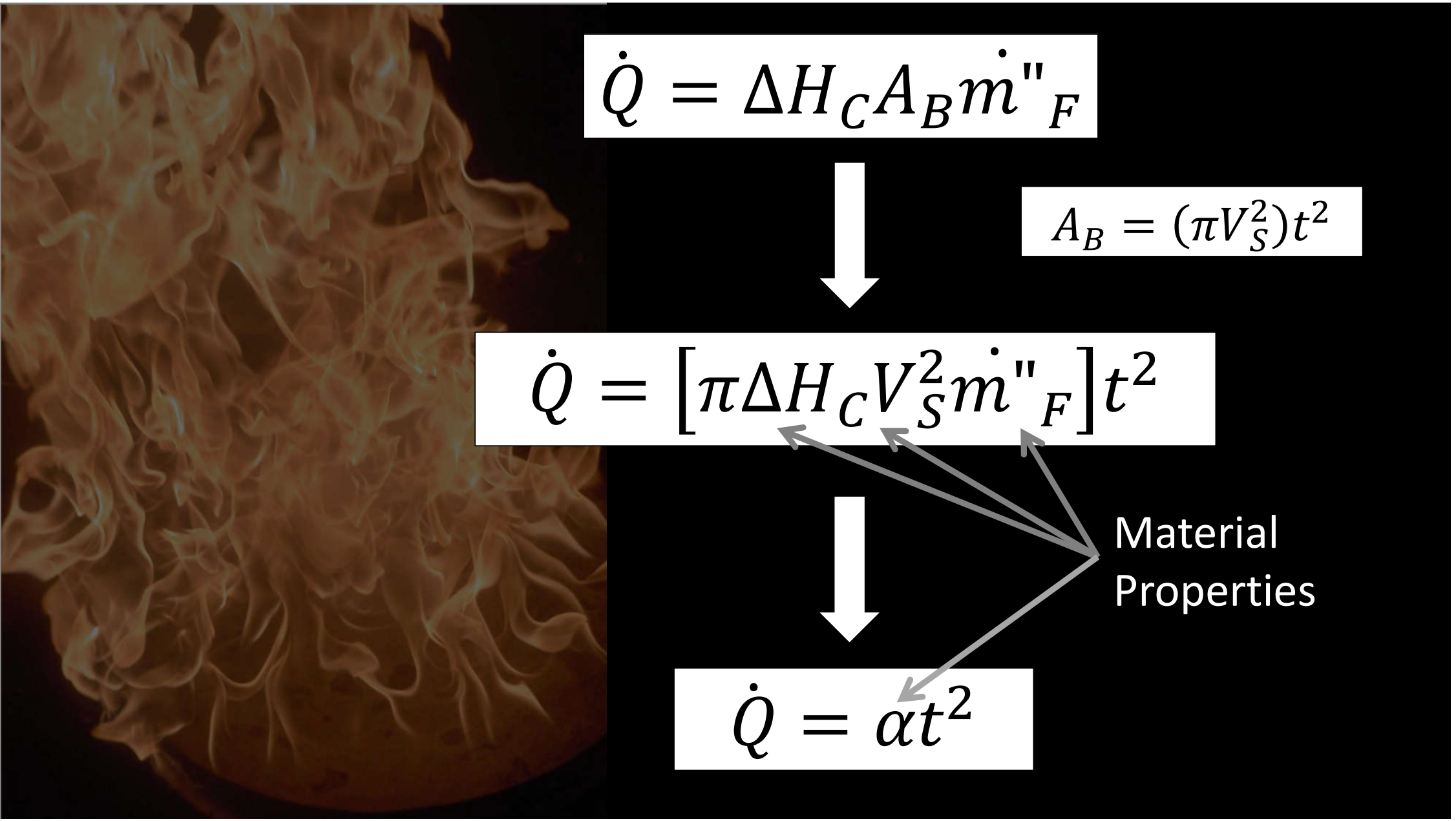
Design Fire

- $A_B = \pi r_B^2$
  - r_B →burning radius

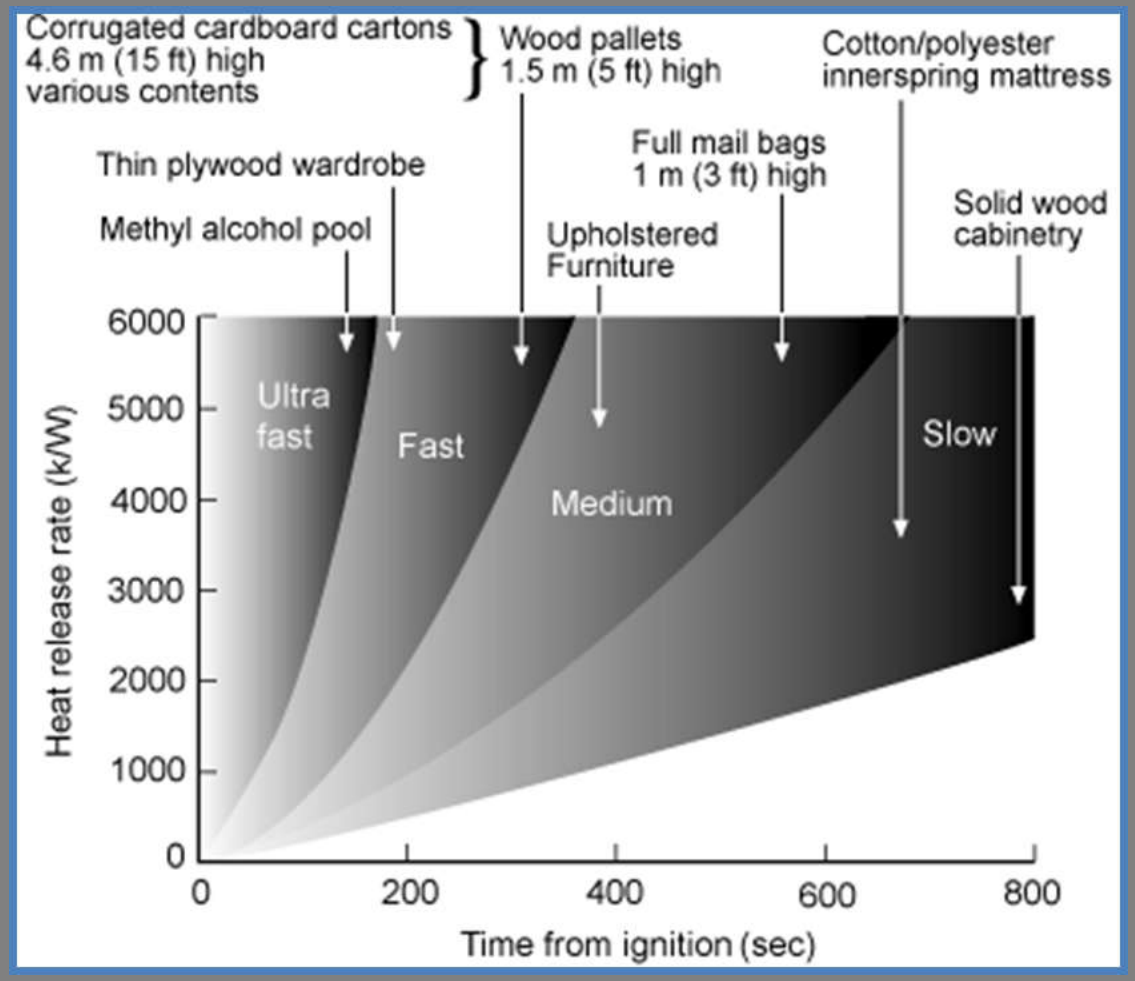
- $r_B = V_S t$
  - V_S→Flame spread velocity
  - t→time

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




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

Normalized Design Fires



Class	α
Ultra Fast	0.1876
Fast	0.0469
Medium	0.0117
Slow	0.0029

Conservation of Mass

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



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

≈ 0

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

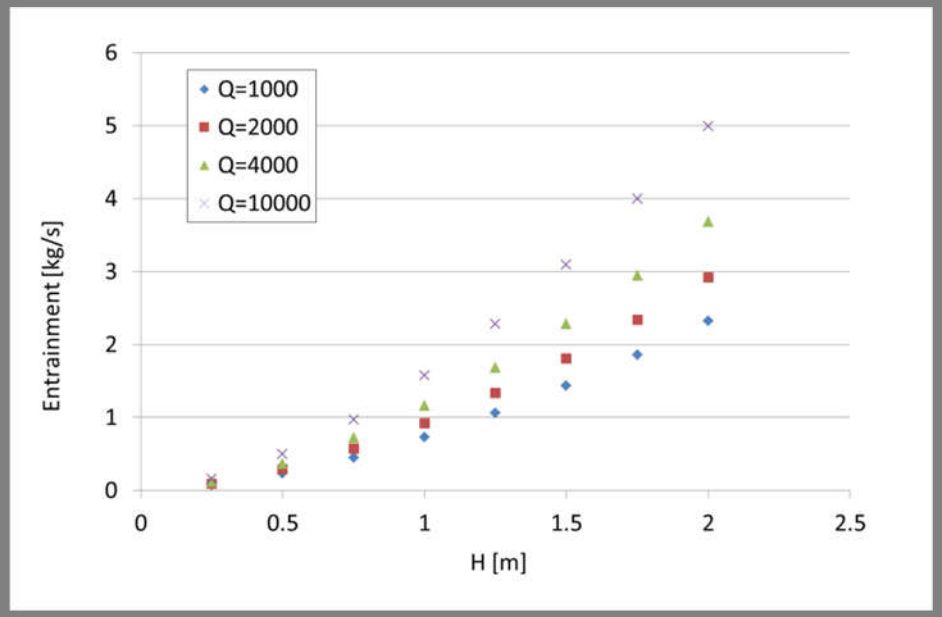
$$\dot{m}_S \approx \dot{m}_A$$

Conservation of Energy

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

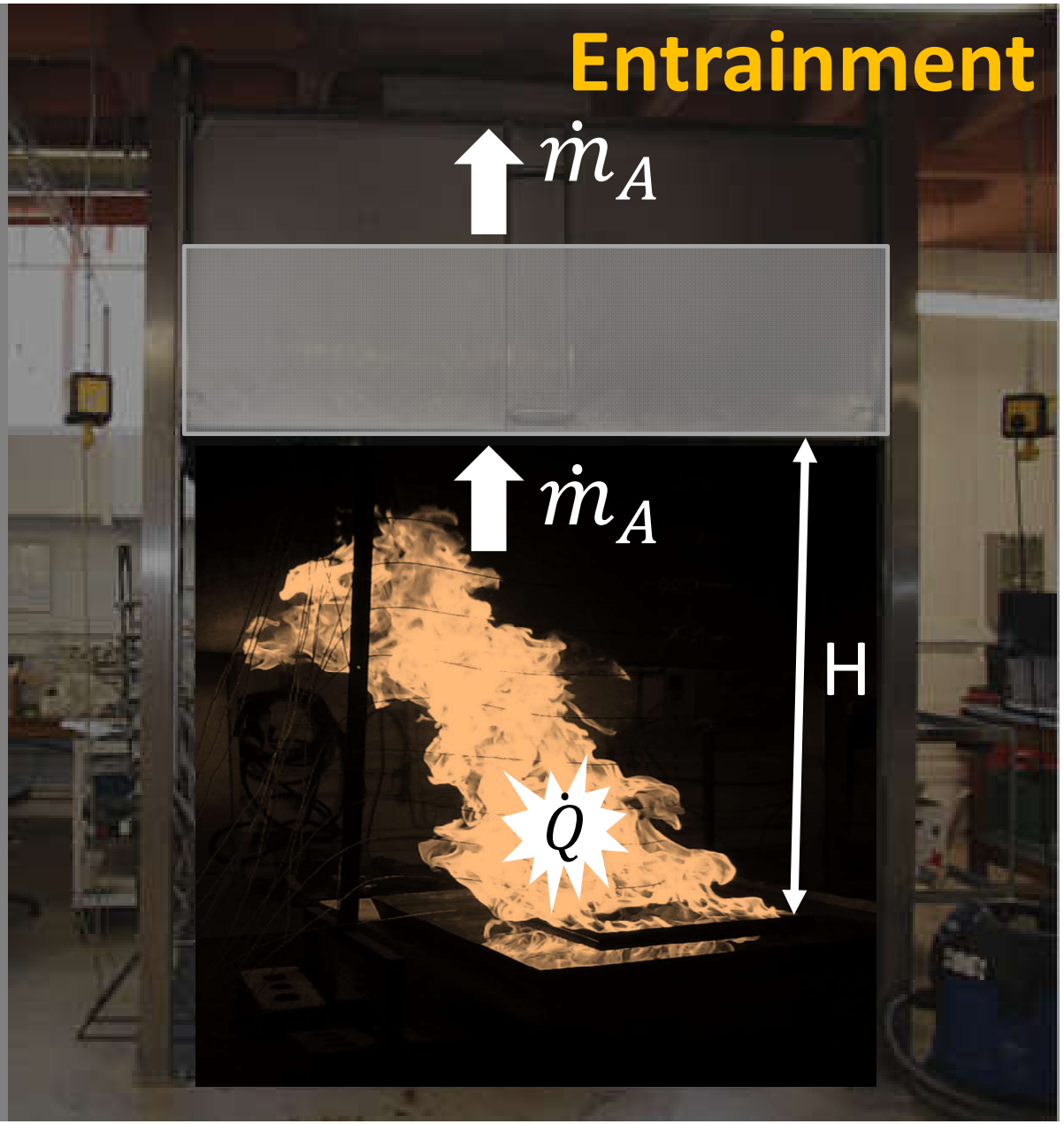
- C_p → Specific Heat (J/kgK)
- T_S → Smoke temperature
- T_A → Ambient temperature

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



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

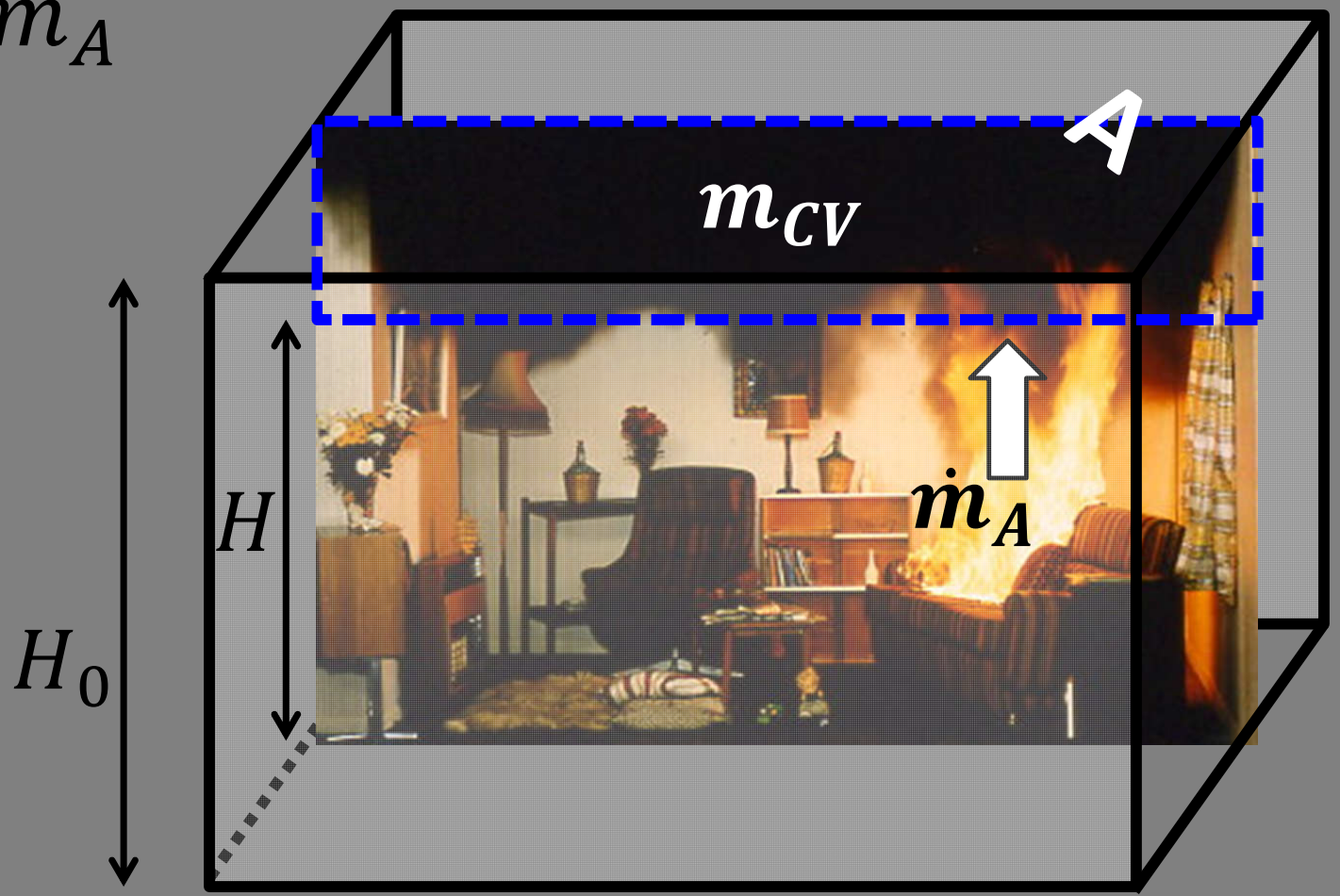
- ρ_A→Ambient density
- g→gravity (9.81 m/s²)
- $E = 0.2$→Entrainment constant
- H→ Entrainment height



Conservation of Mass: Hot Layer

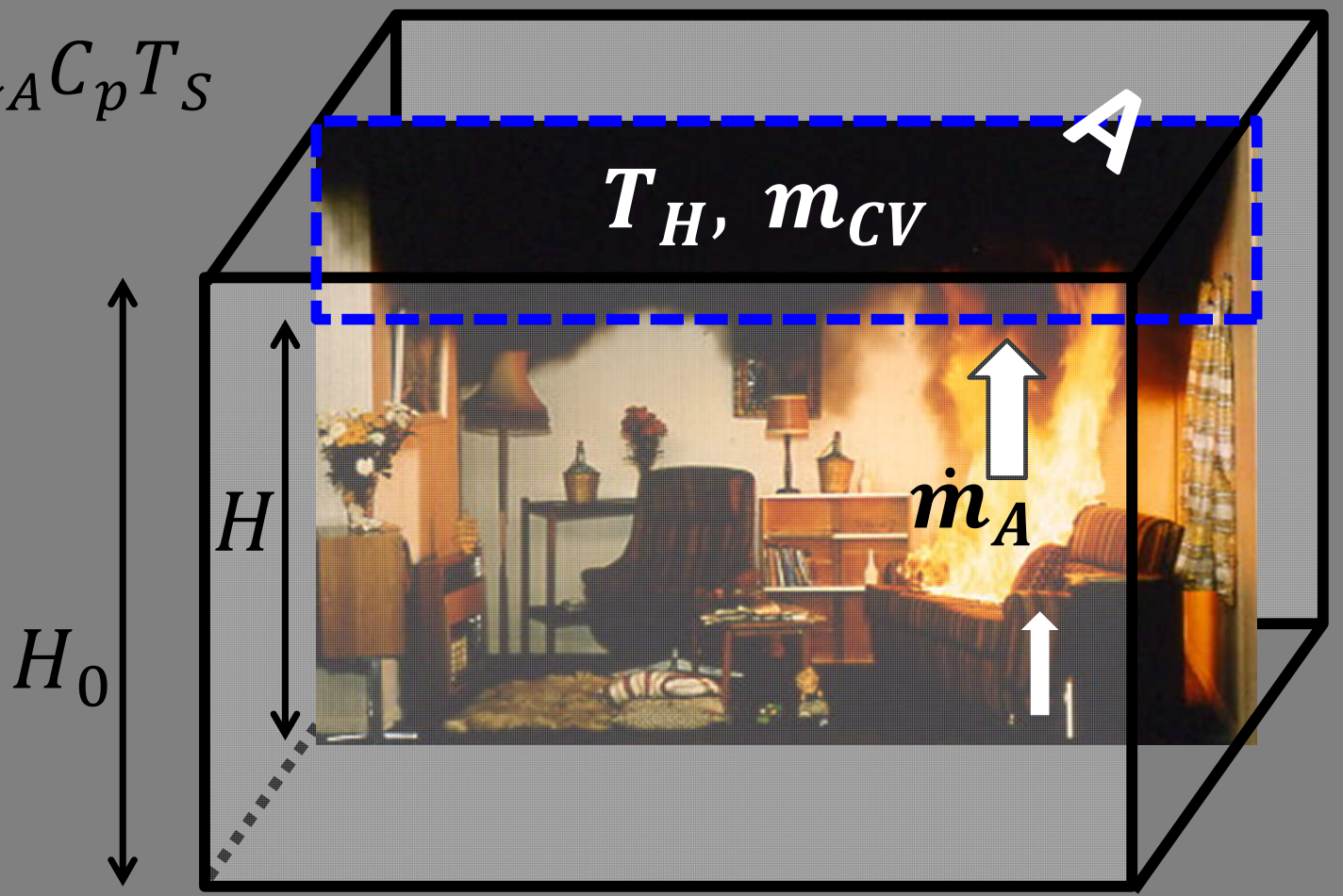
$$\frac{dm_{CV}}{dt} = \dot{m}_A$$

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



Conservation of Energy

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

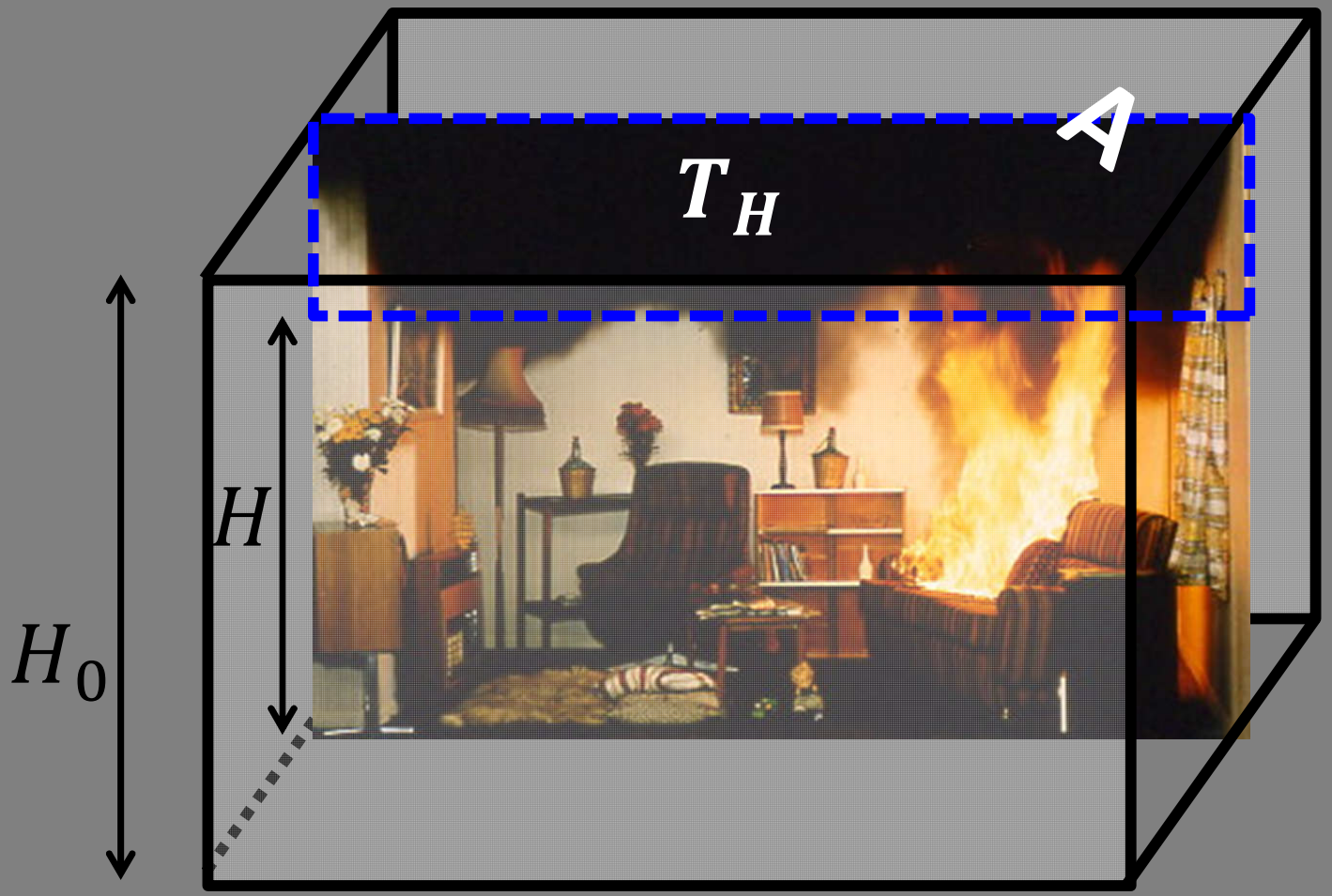


Can be solved using an Excel Spreadsheet

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

Example: Slow Growing Fire

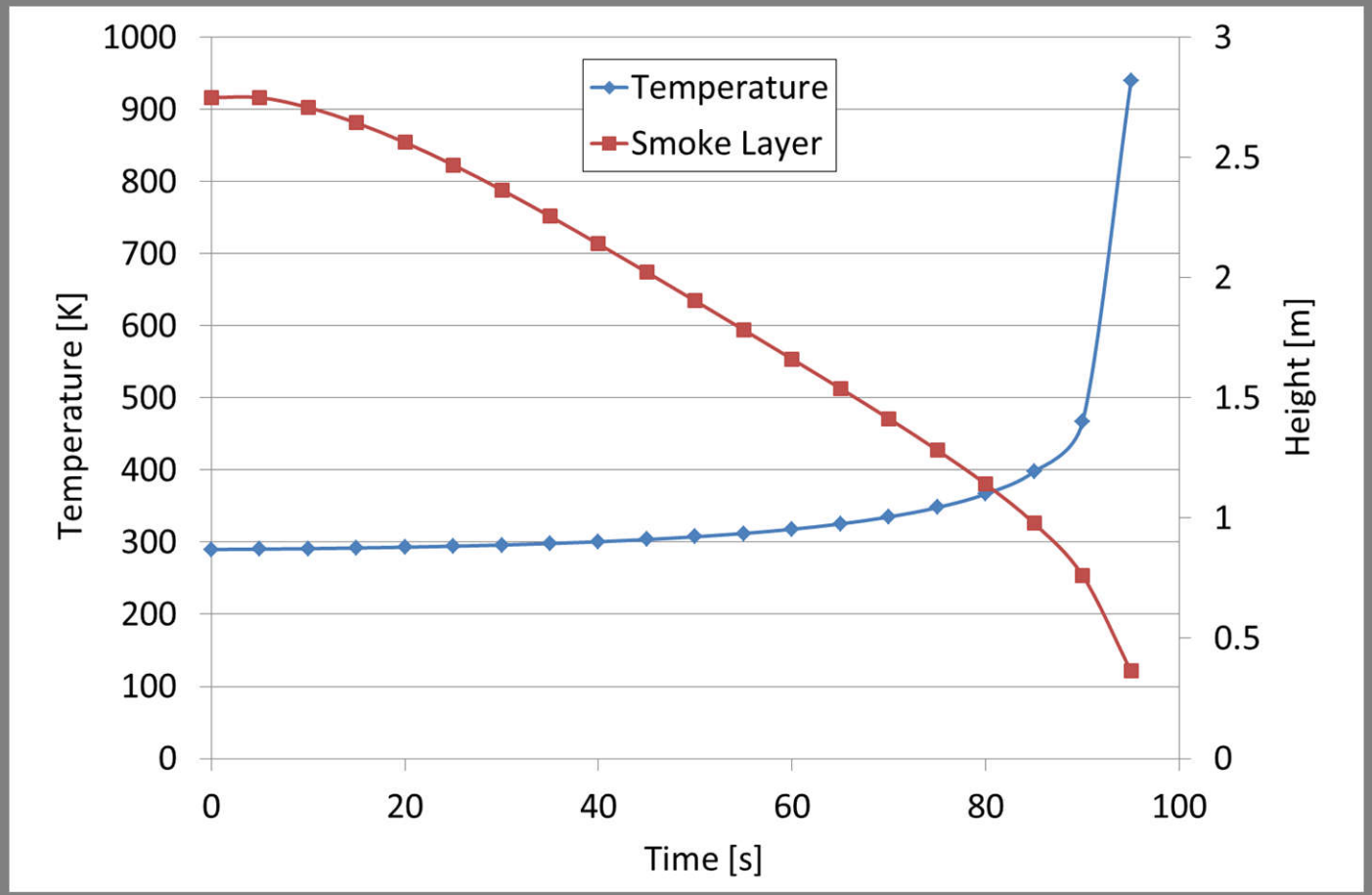
$H_0 = 2.75\,m,\ X_0 = 4.75\,m,\ Y_0 = 3.5\,m$



Implementation

α(slow)	0.0029	W/s2		H0	2.75	m	$E\left(\frac{g\rho_A^2}{C_pT_A}\right)^{1/3}$					
E	0.2			X0	4.75	m		0.073042309				
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										
			$t_{t+1}=t_t+\Delta t$	$\dot{Q}=\alpha t^2$	$H_{t+1}=H_0-\Delta H_t$	$\dot{m}_A=E\left(\frac{g\rho_A^2}{C_pT_A}\right)^{1/3}\dot{Q}^{1/3}H^{5/3}$	$T_S=T_A+\frac{\dot{Q}}{\dot{m}_AC_p}$	$m_{CV,t+1}=m_{CV,t}+\dot{m}_A\Delta t$	$T_{H,t+1}=\frac{m_{CV,t}T_{H,t}+\dot{m}_A\Delta tT_S}{m_{CV,t+1}}$	$\rho_2=\frac{T_1}{T_2}\rho_1$	$\Delta H_t=\frac{m_{CV,t+1}}{A\rho_2}$	
			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



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United Kingdom

Lecture-3

Burning Rate



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

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/m²s]

○ A_B→Burning area [m²]

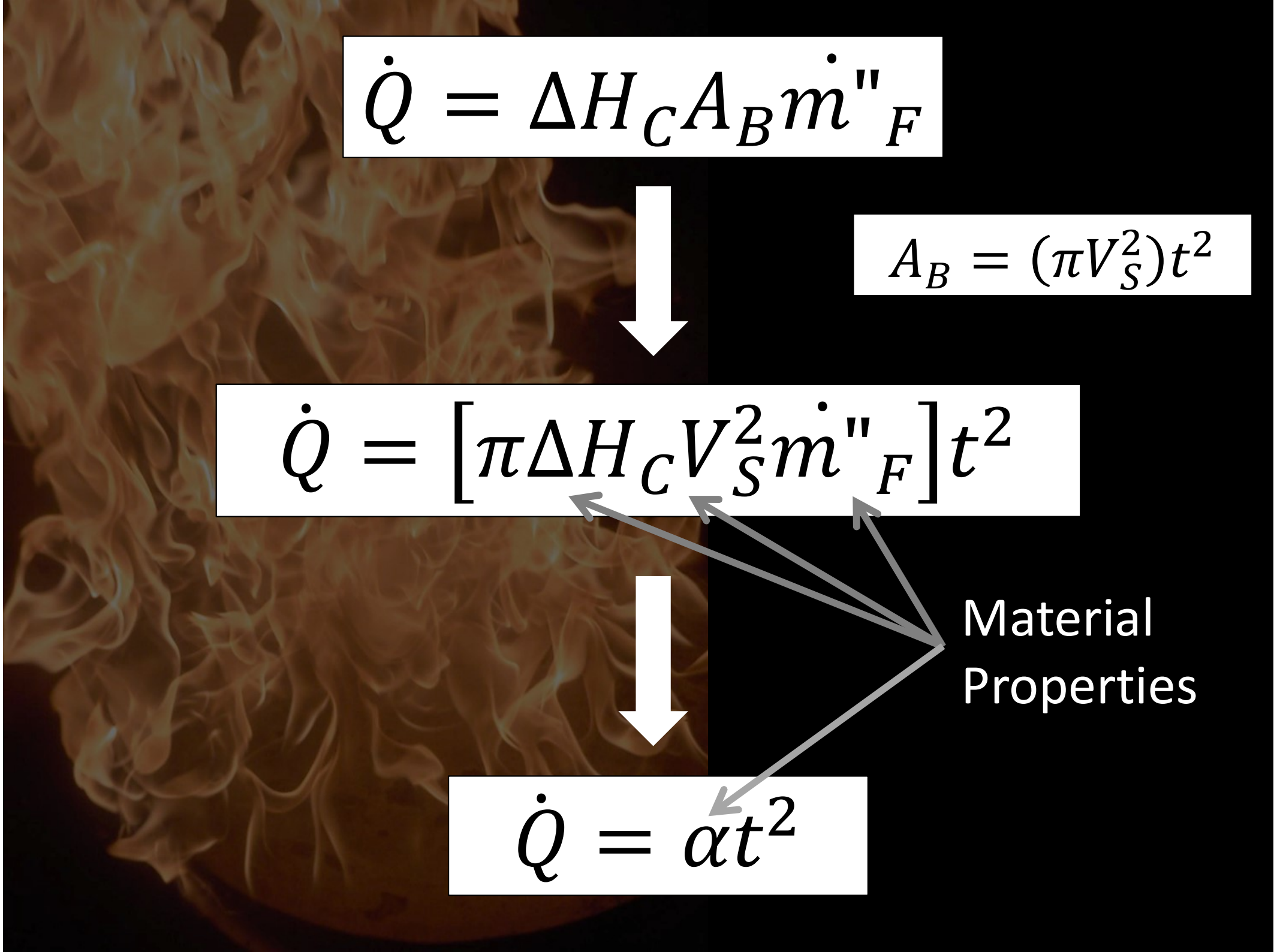
Design Fire

- $A_B = \pi r_B^2$
  - r_B →burning radius

- $r_B = V_S t$
  - V_S→Flame spread velocity
  - t→time

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



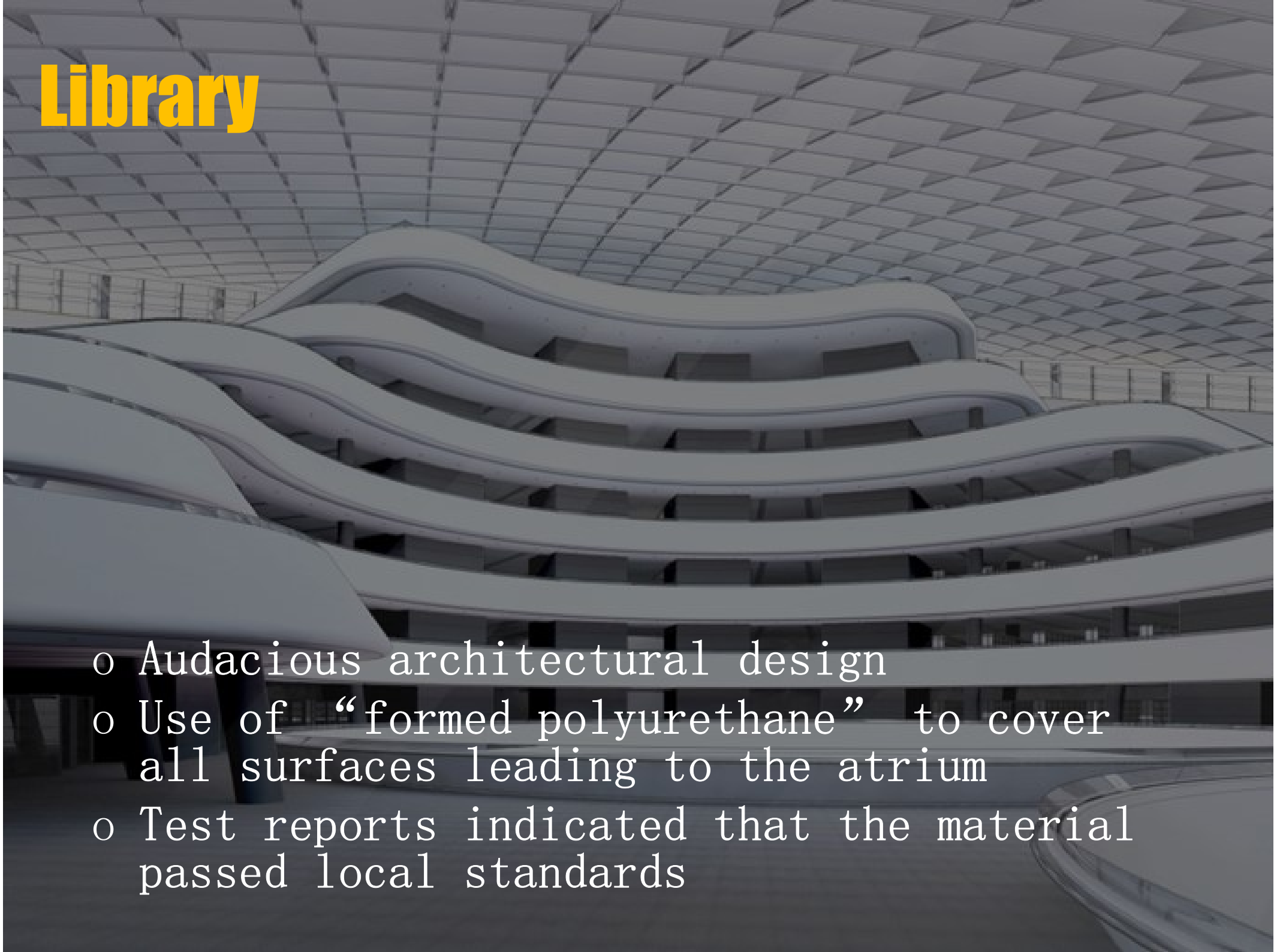

$\dot{Q} = \Delta H_C A_B \dot{m}''_F$
$A_B = (\pi V_S^2) t^2$
$\dot{Q} = [\pi \Delta H_C V_S^2 \dot{m}''_F] t^2$
Material Properties
$\dot{Q} = \alpha t^2$

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

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

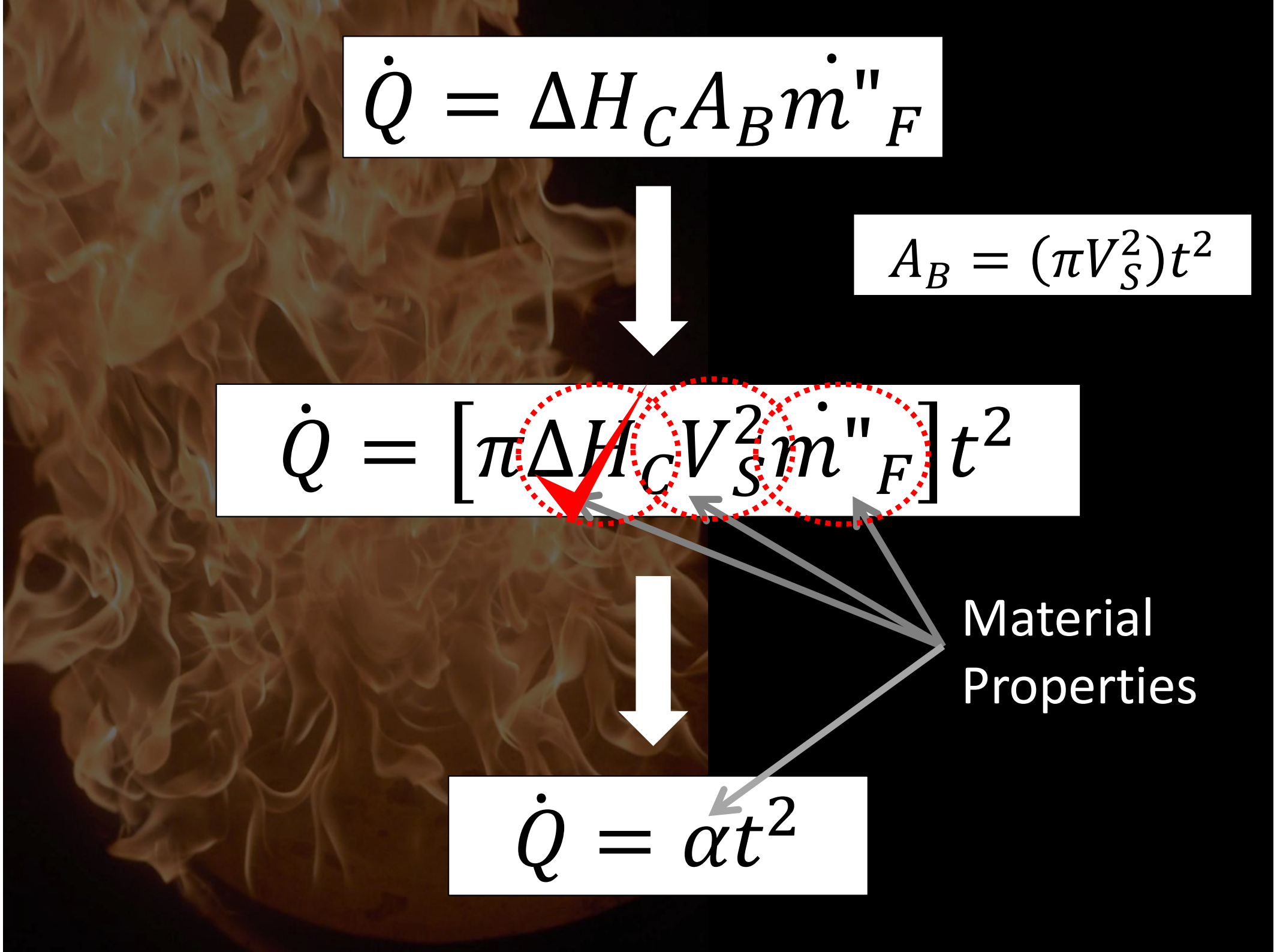
Timber



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)

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

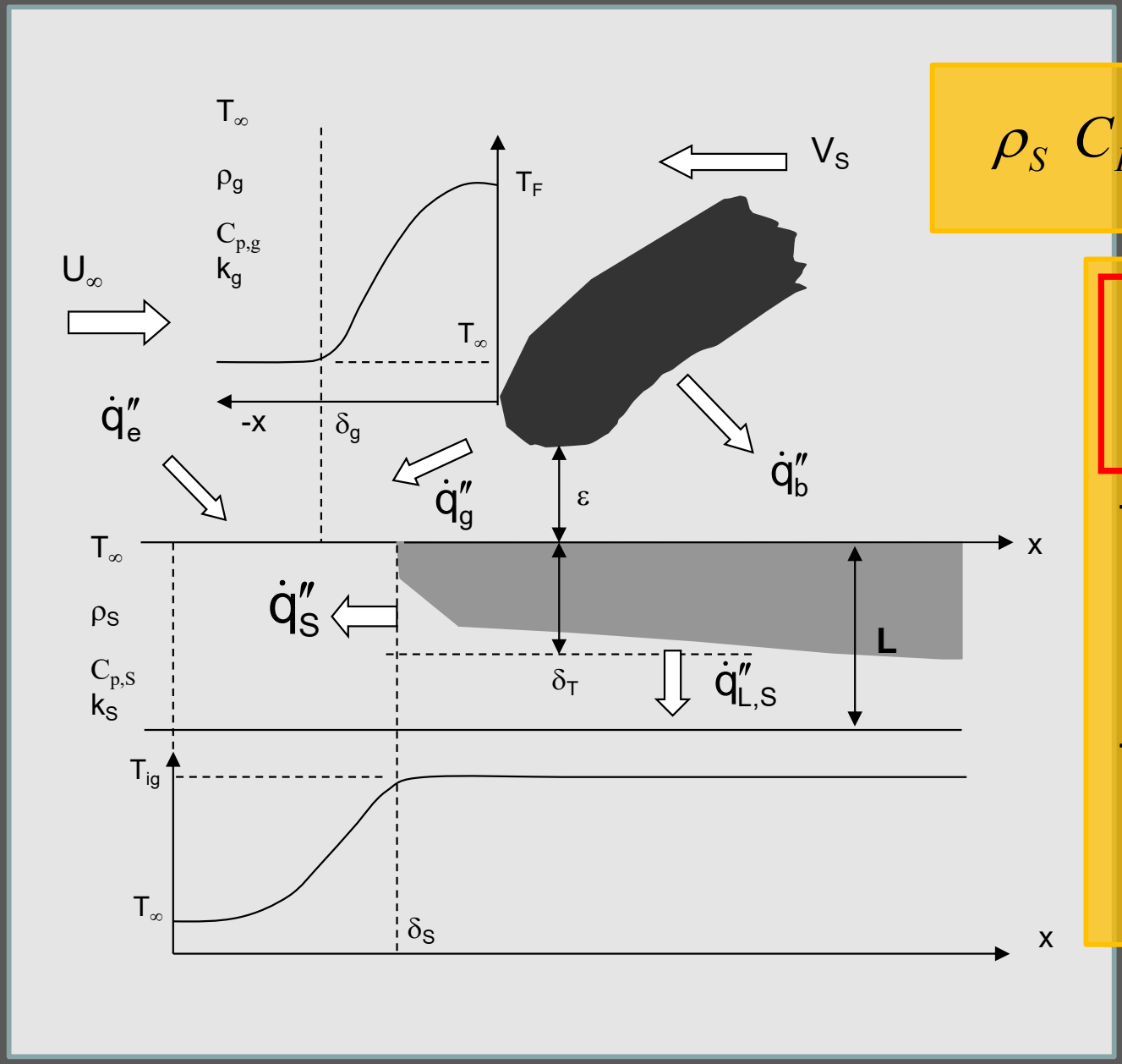
- What do we need to determine the flame spread velocity (V_S)?

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



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

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

Thermally Thick

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

Thermally Thin

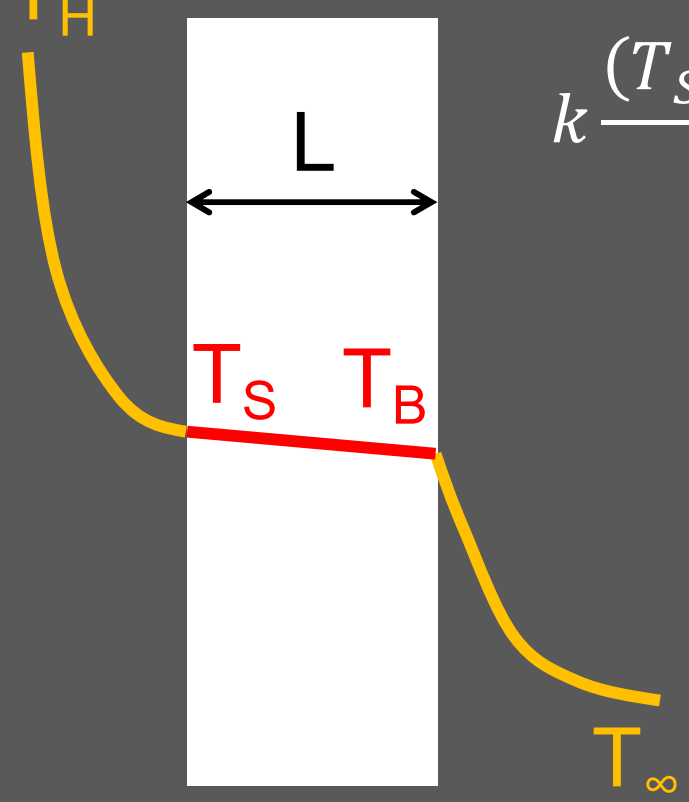
$$\delta_T = L$$

Thermally Thick vs. Thermally Thin

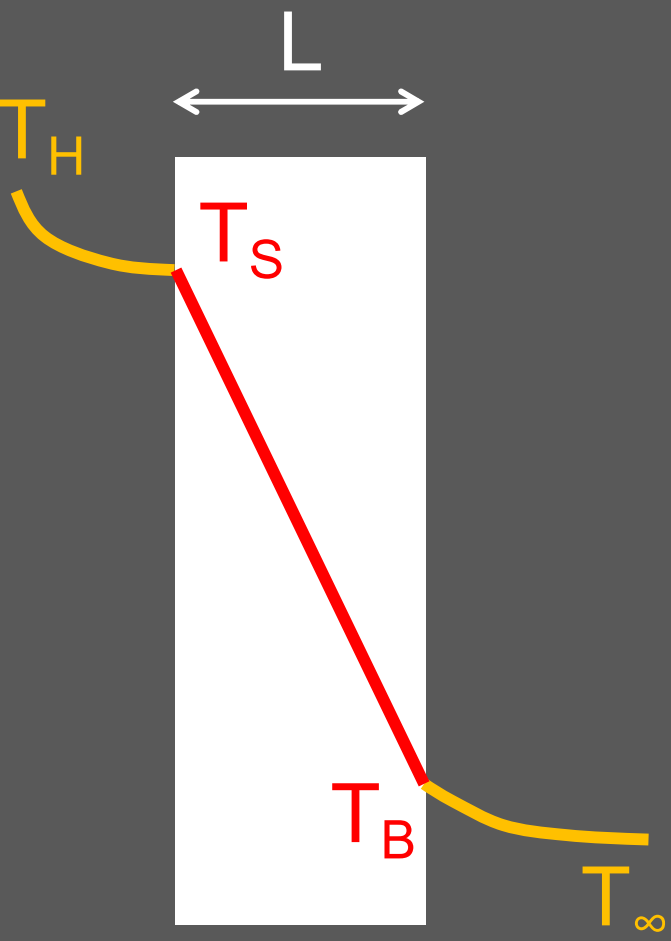
$$-k\frac{\partial T}{\partial x} = h_T(T_H - T_S)$$

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

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



Thermally Thin



Thermally Thick

Biot Number

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

$Bi \ll 1$ (Thermally Thin)

$Bi \geq 1$ (Thermally Thick)

Thermally Thick

- Most materials behave as thermally thick

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

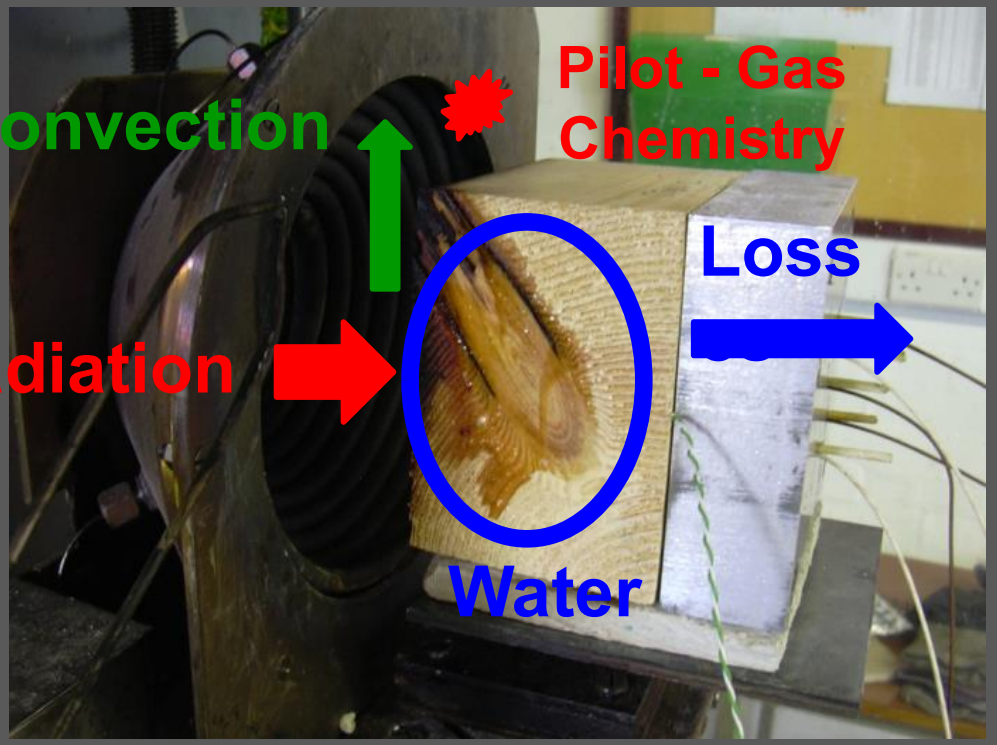
$$V_S = \frac{\dot{q}''^2_g \delta_S}{k_S \rho_S c_{P,S} (T_{ig} - T_\infty)^2}$$

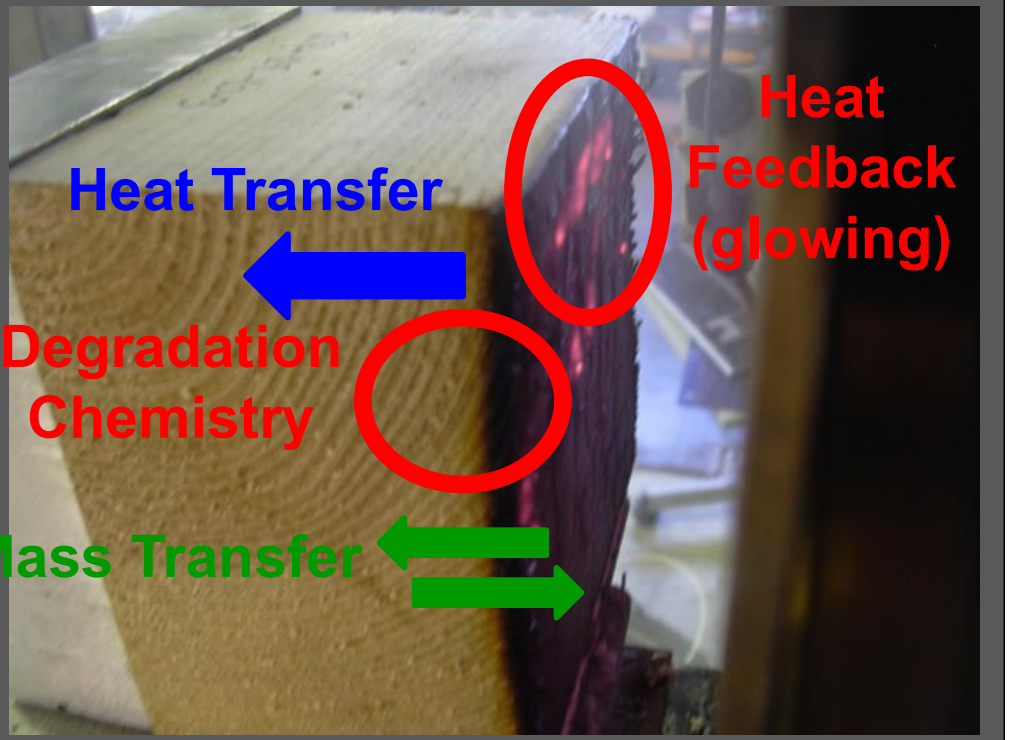
Material Properties

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

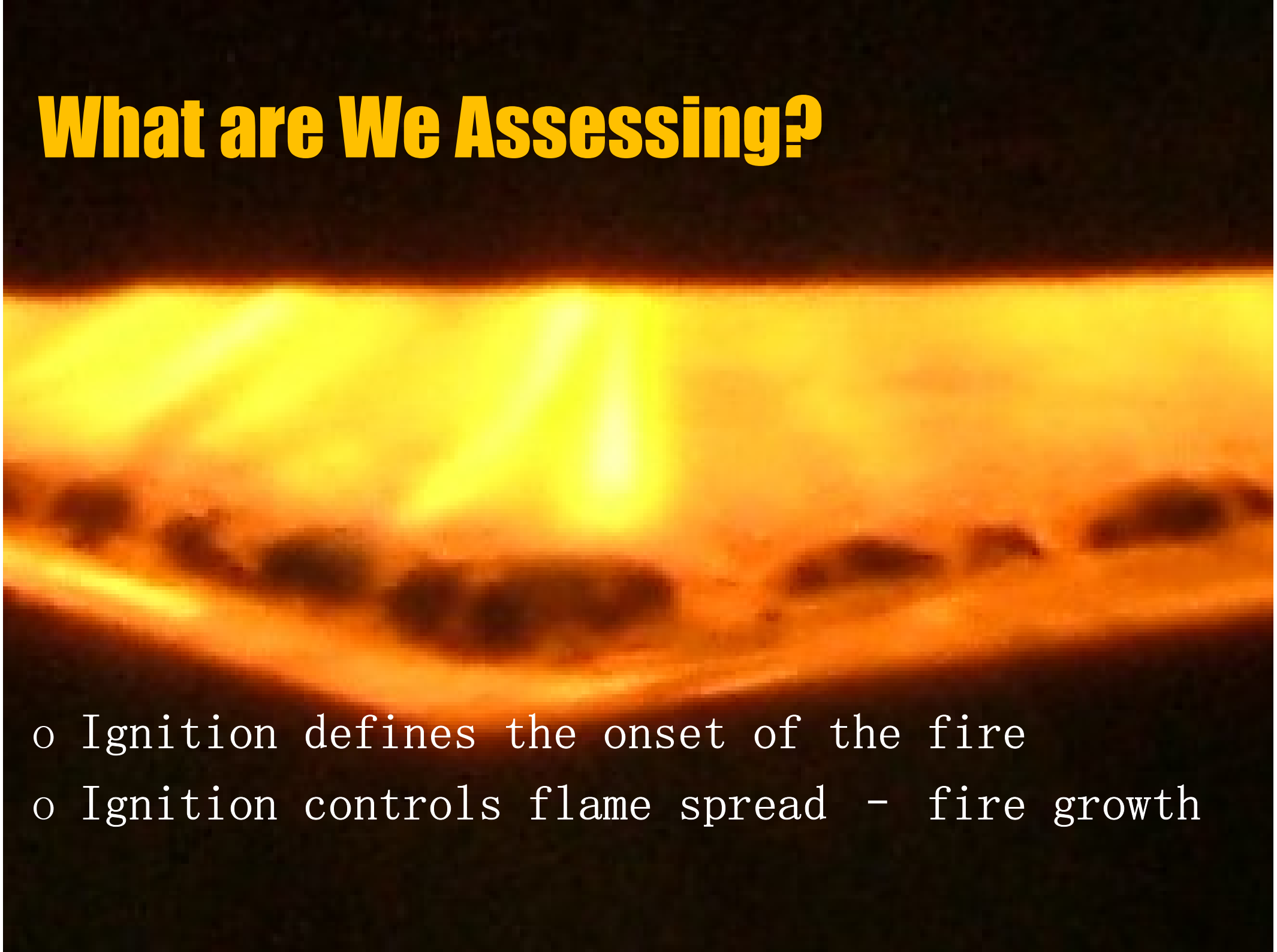
Ignition

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





What are We Assessing?



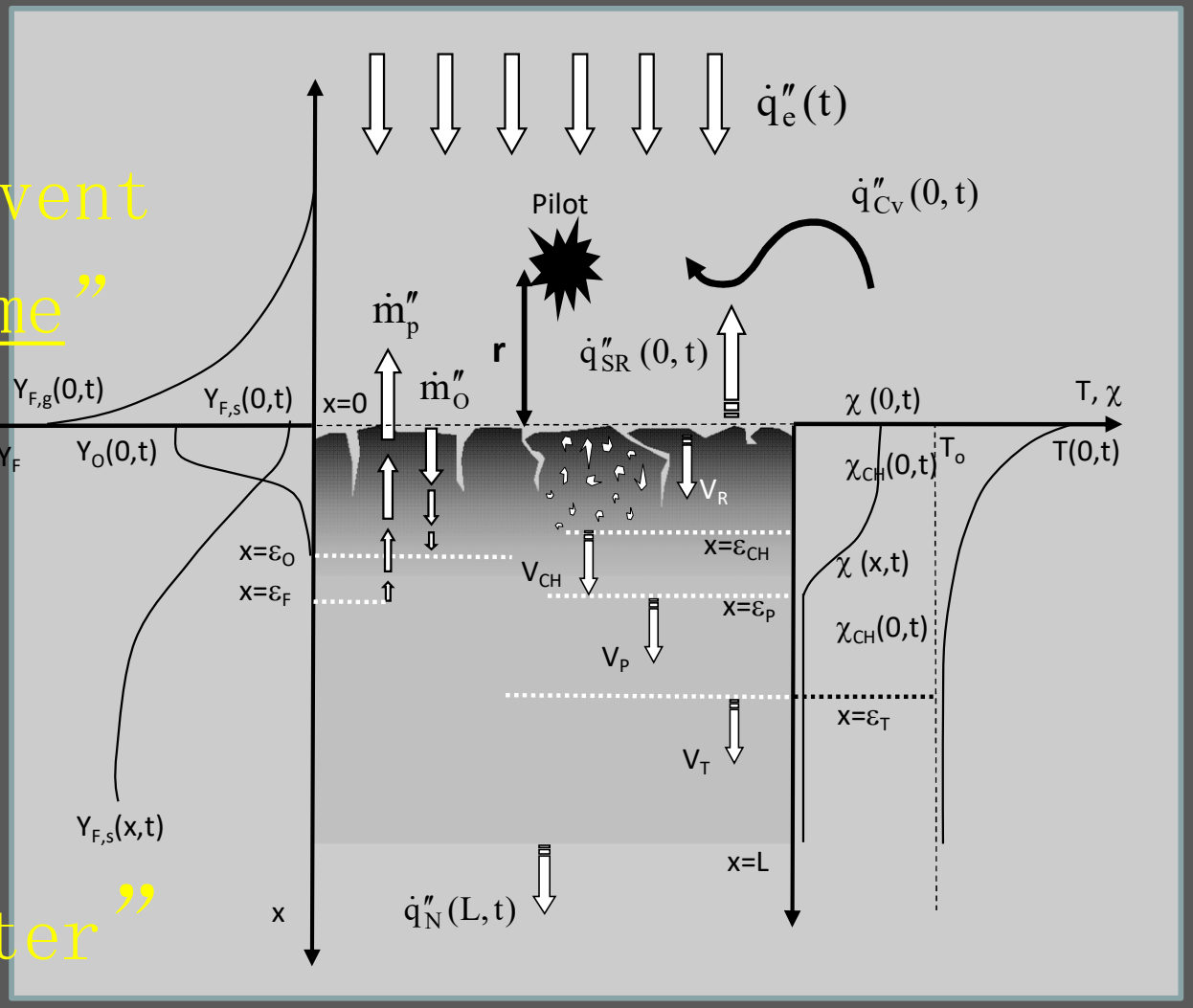
- Ignition defines the onset of the fire
- Ignition controls flame spread - fire growth

Processes

- t_{ig} → observable event

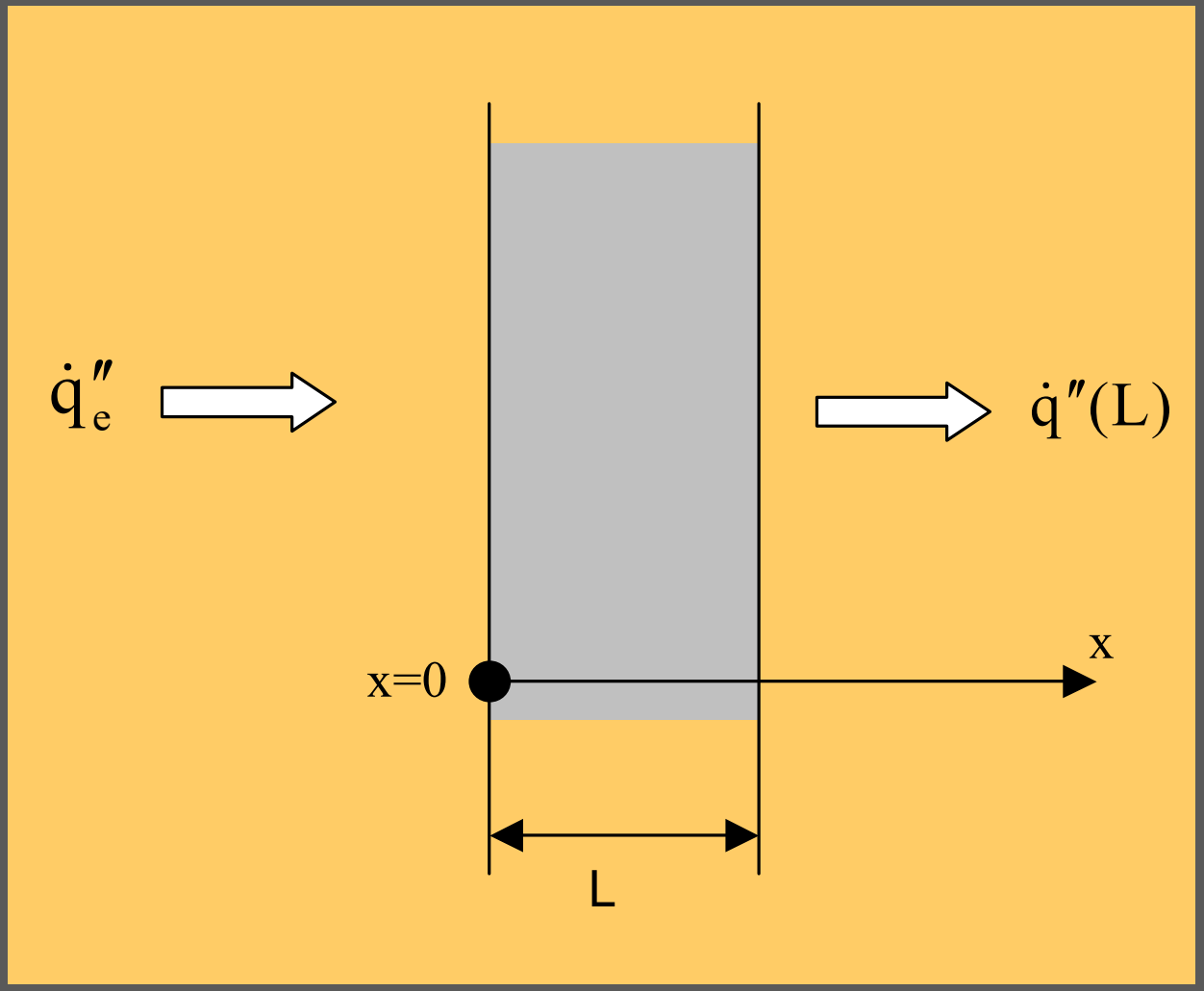
  "Ignition delay time"





- "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

$$t = 0 \qquad T = T_i$$

$$x = 0 \qquad -k_s \left.\frac{\partial T}{\partial x}\right|_{x=0^+} = \alpha \dot{q}''_e - k_g \left.\frac{\partial T}{\partial x}\right|_{x=0^-} - \dot{q}''_{S,R}$$

$$x = L \qquad -k_s \left.\frac{\partial T}{\partial x}\right|_{x=L^-} = \dot{q}''(L)$$

Fuel Generation

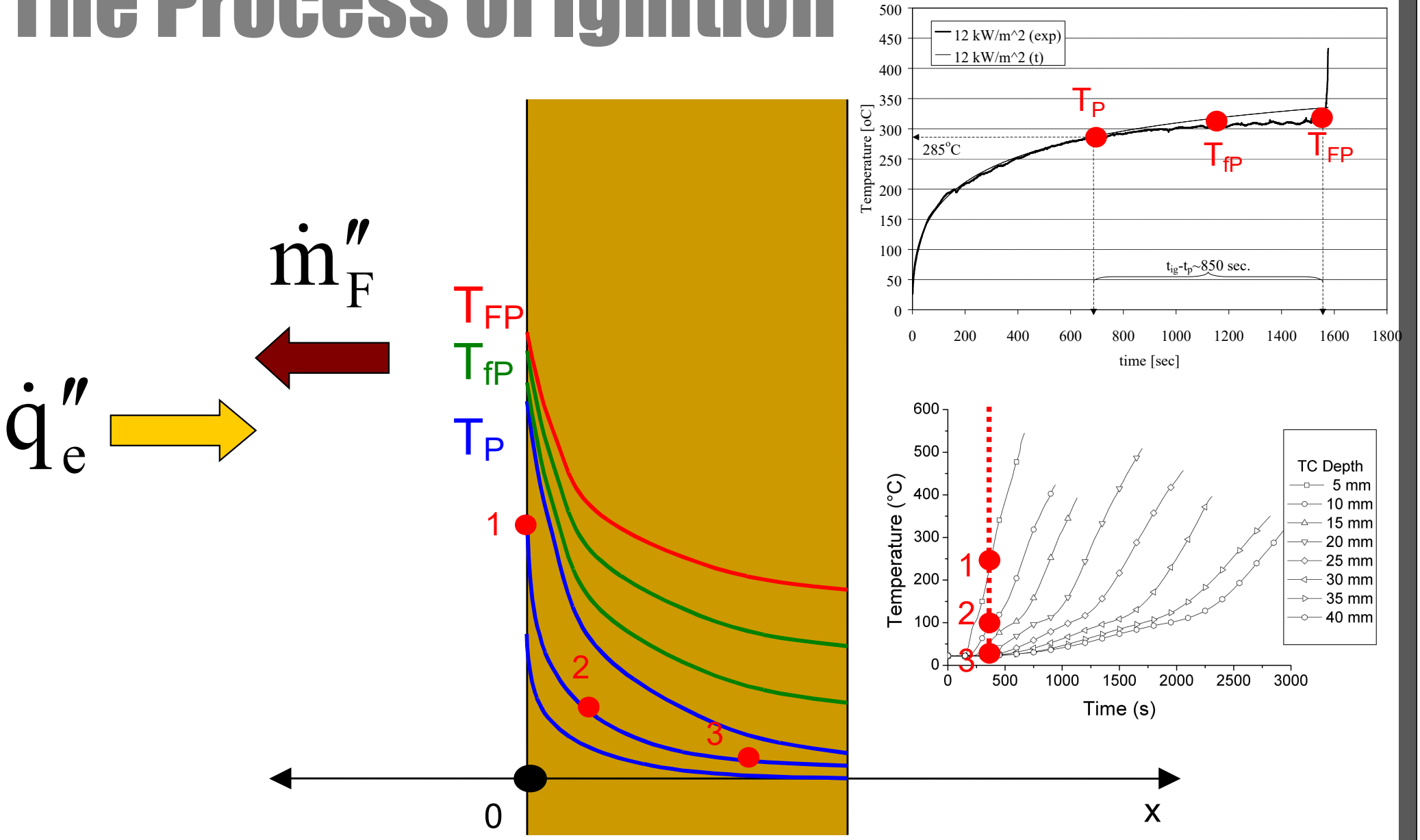
$$\dot{m}''_F = \int_0^L \chi(x) Y_F(x) \sum \rho_S A_i e^{-E_i/RT} dx$$

- 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

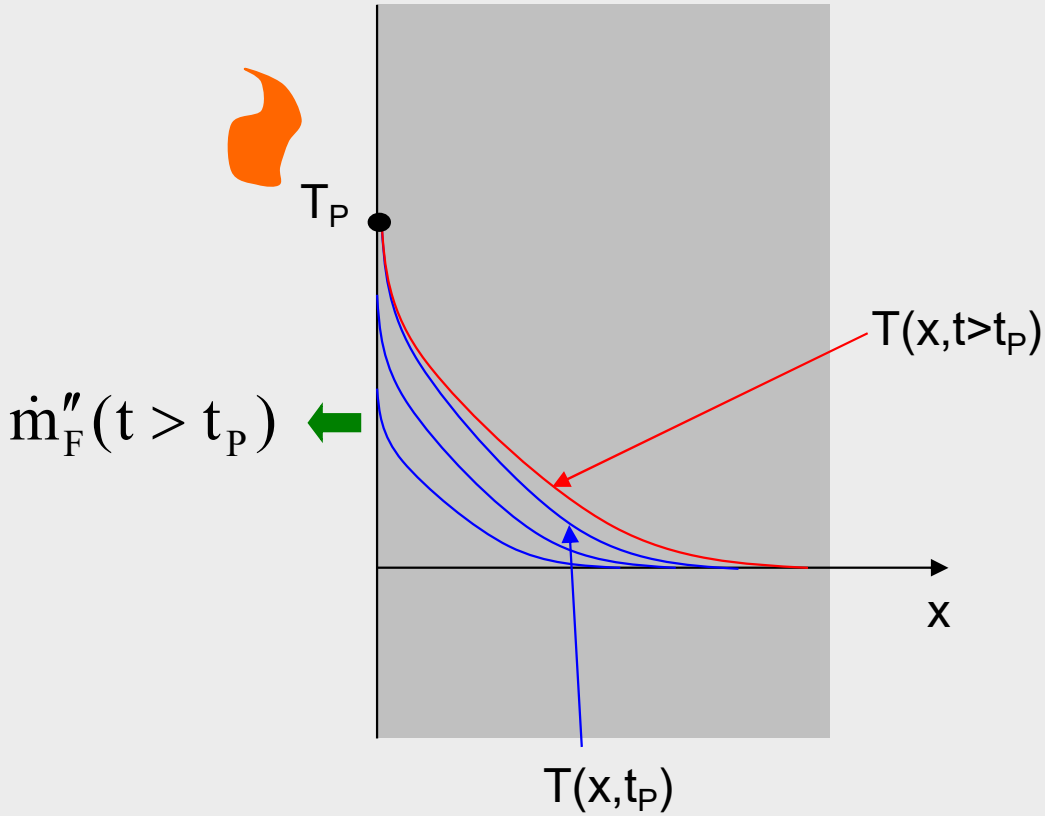
- A simplified solution is necessary

Piloted Ignition

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

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

$$t_{ig} \approx t_p$$



$$T_{ig} \approx T_p$$

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

$$t = 0 \qquad T = T_i$$

$$x = 0 \qquad -k_s \left.\frac{\partial T}{\partial x}\right|_{x=0^+} = \alpha \dot{q}''_e - k_g \left.\frac{\partial T}{\partial x}\right|_{x=0^-} - \dot{q}''_{s,R}$$

$$x = L \qquad -k_s \left.\frac{\partial T}{\partial x}\right|_{x=L^-} = \dot{q}''(L)$$

Semi-Infinite

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

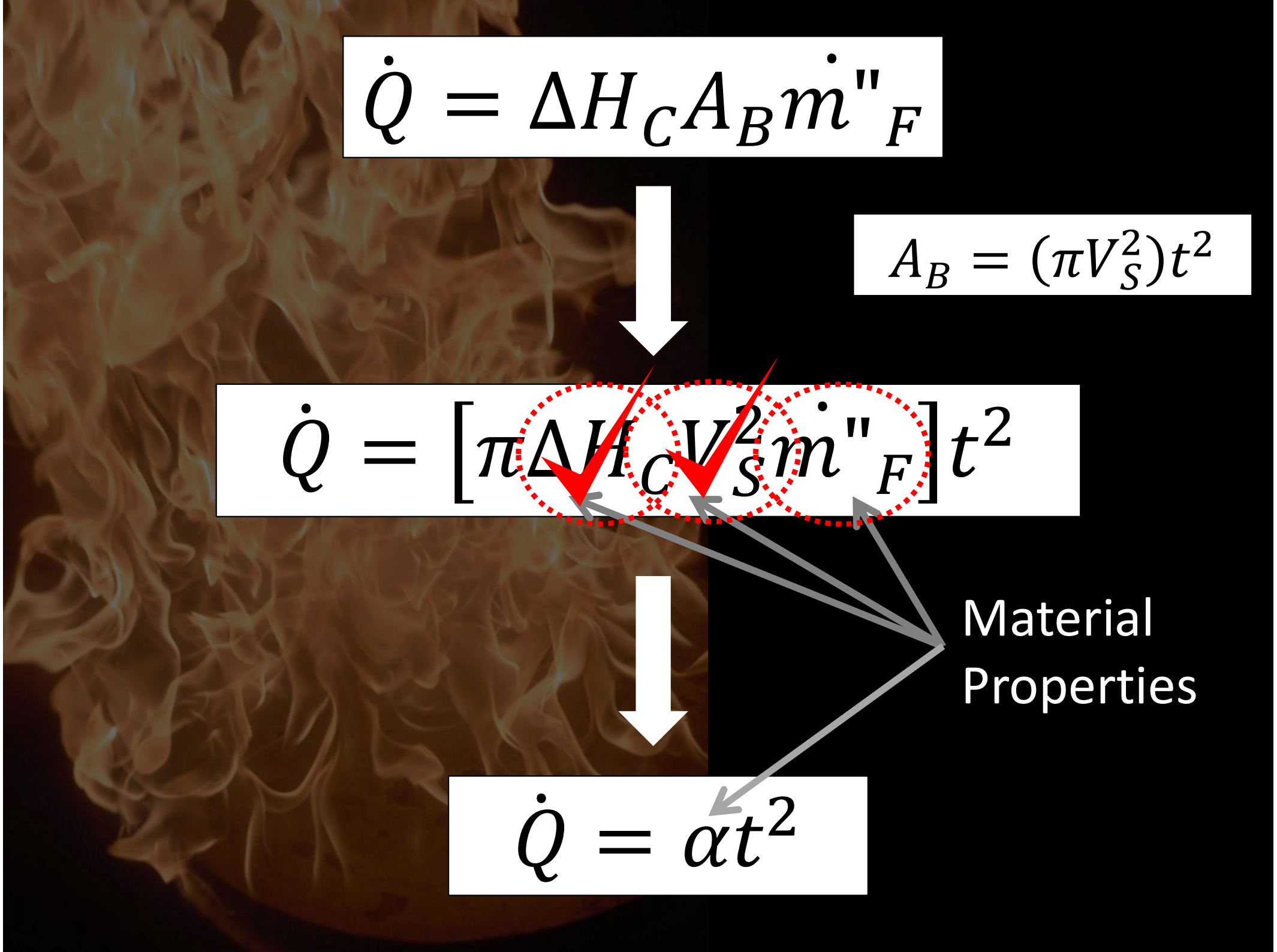
Simplified Problem

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

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

Material Properties

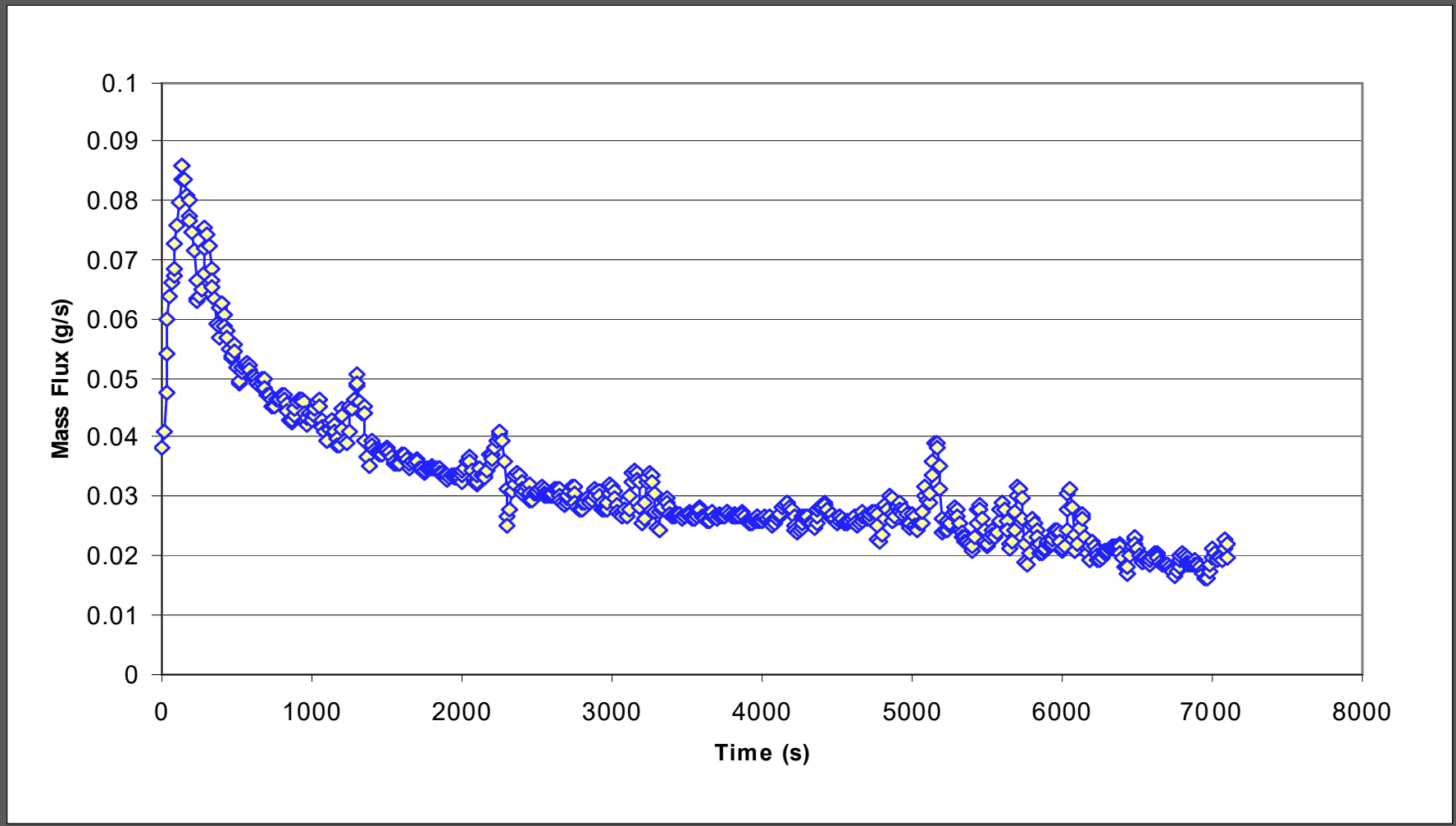
$$t_{ig} = \frac{\pi}{4} k_S \rho_S C_{P,S} \left(\frac{T_{ig} - T_\infty}{\dot{q}''_e} \right)^2$$


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

Burning Rate

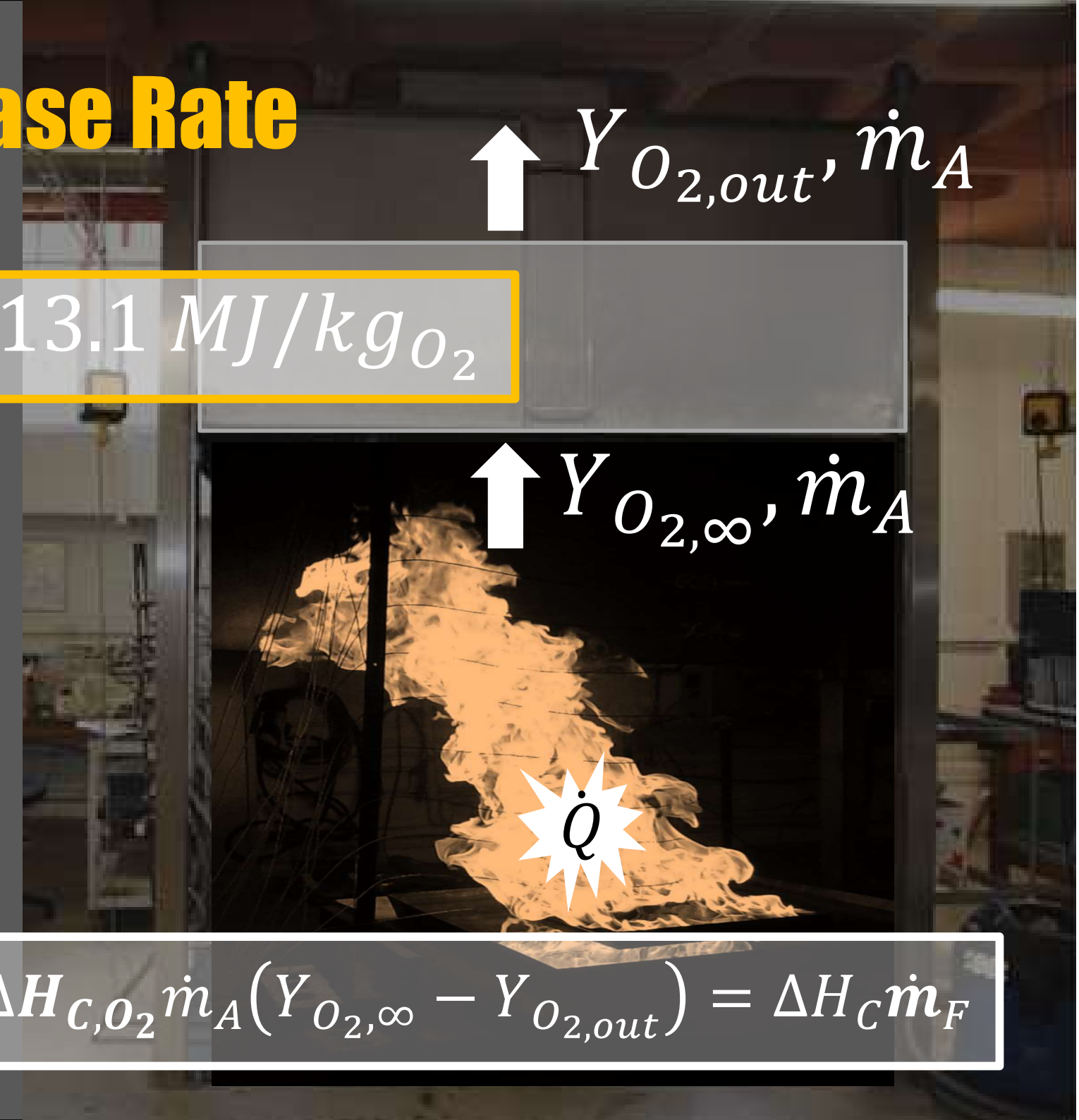
o Temporal

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

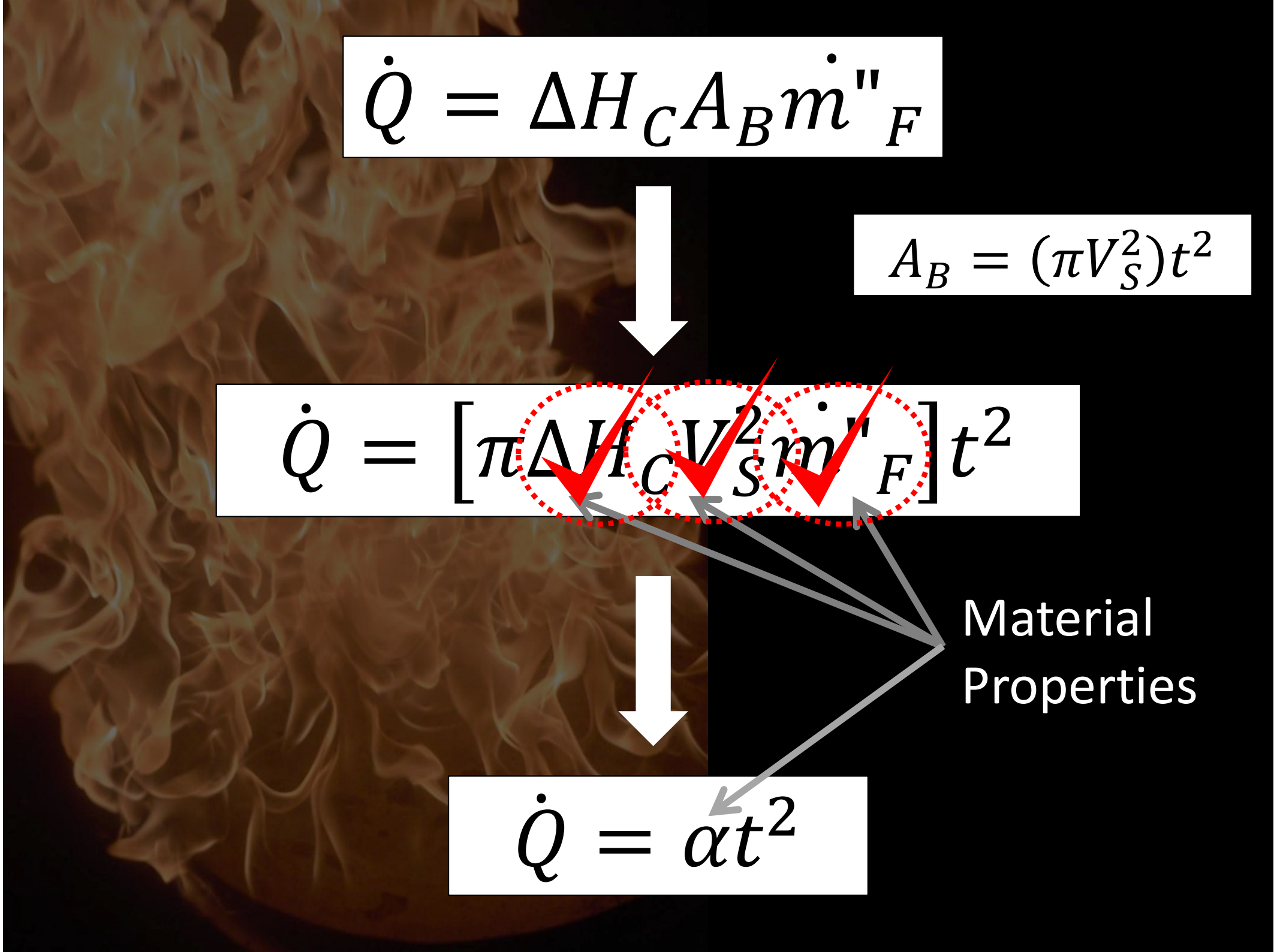


Heat Release Rate

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



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


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

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

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

$\phi = \dot{q}''^2_g \delta_S$
$k_S \rho_S C_{P,S}$
T_{ig}

} Material Properties

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

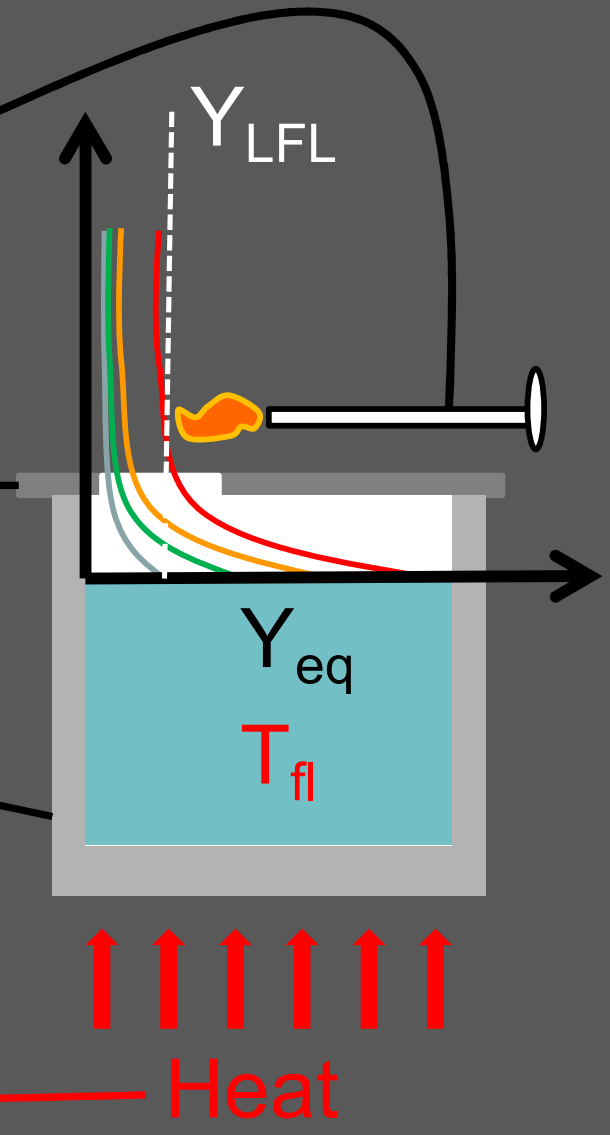
$\dot{Q}$ } Material Property

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.

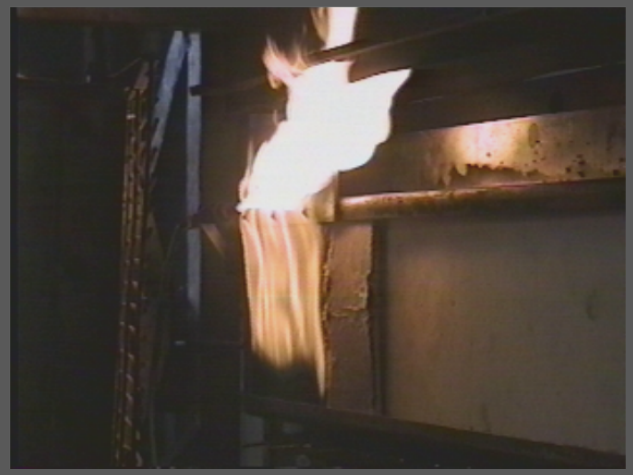
Typical Data

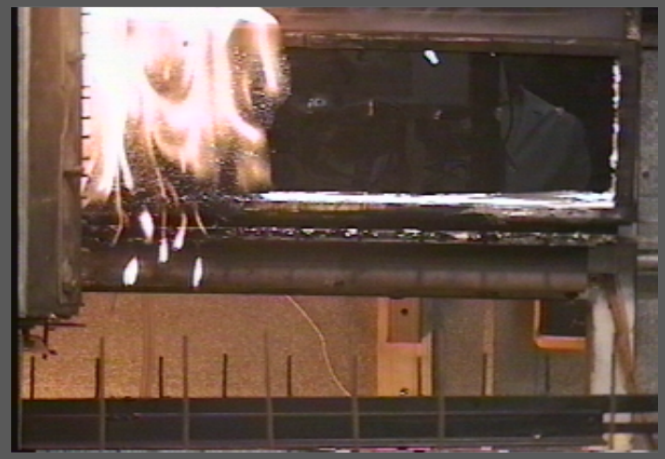


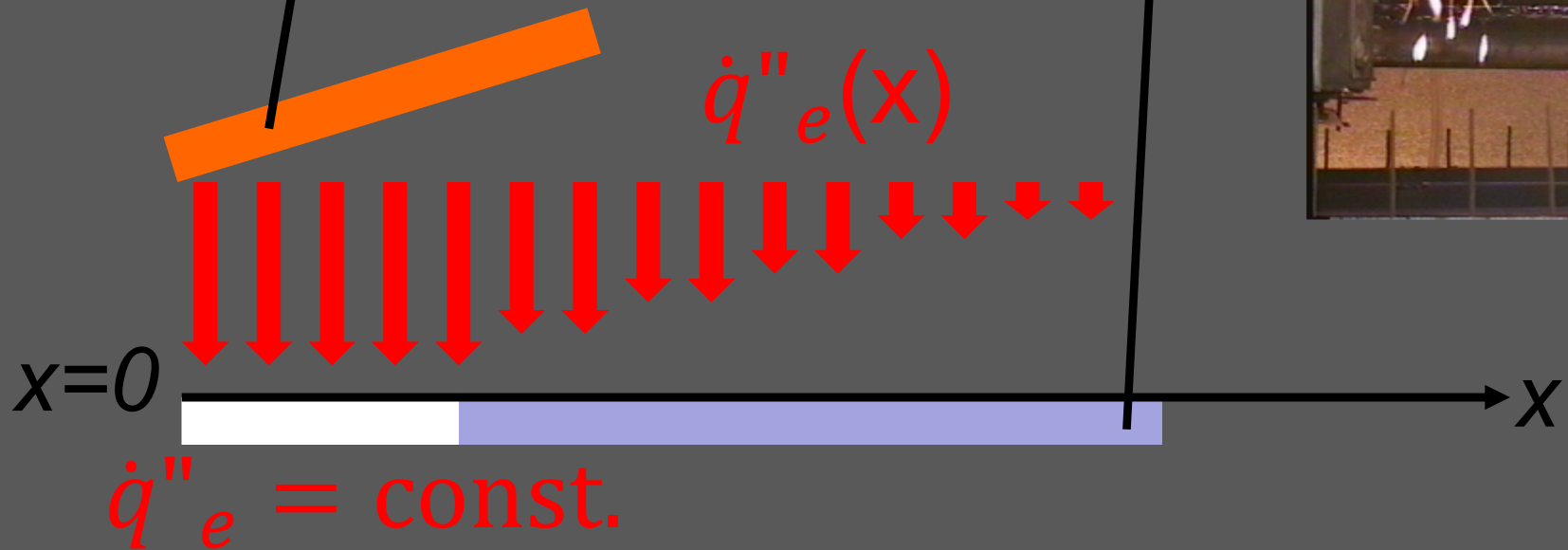
	NFPA Rating	Flash Point (°C)	Boiling Point (°C)
Acetaldehyde	4	-37.8	21.1
Acetic Acid (glacial)	2	39	118
Acetone	3	-18	5607
Acetonitrile	3	6	82
Carbon disulfide	3	-30.0	46.1
Cyclohexane	3	-20.0	81.7
Diethylamine	3	-23	57
Diethyl ether	4	-45.0	35.0
Dimethyl sulfoxide	1	95	189
Ethyl alcohol	3	12.8	78.3
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)



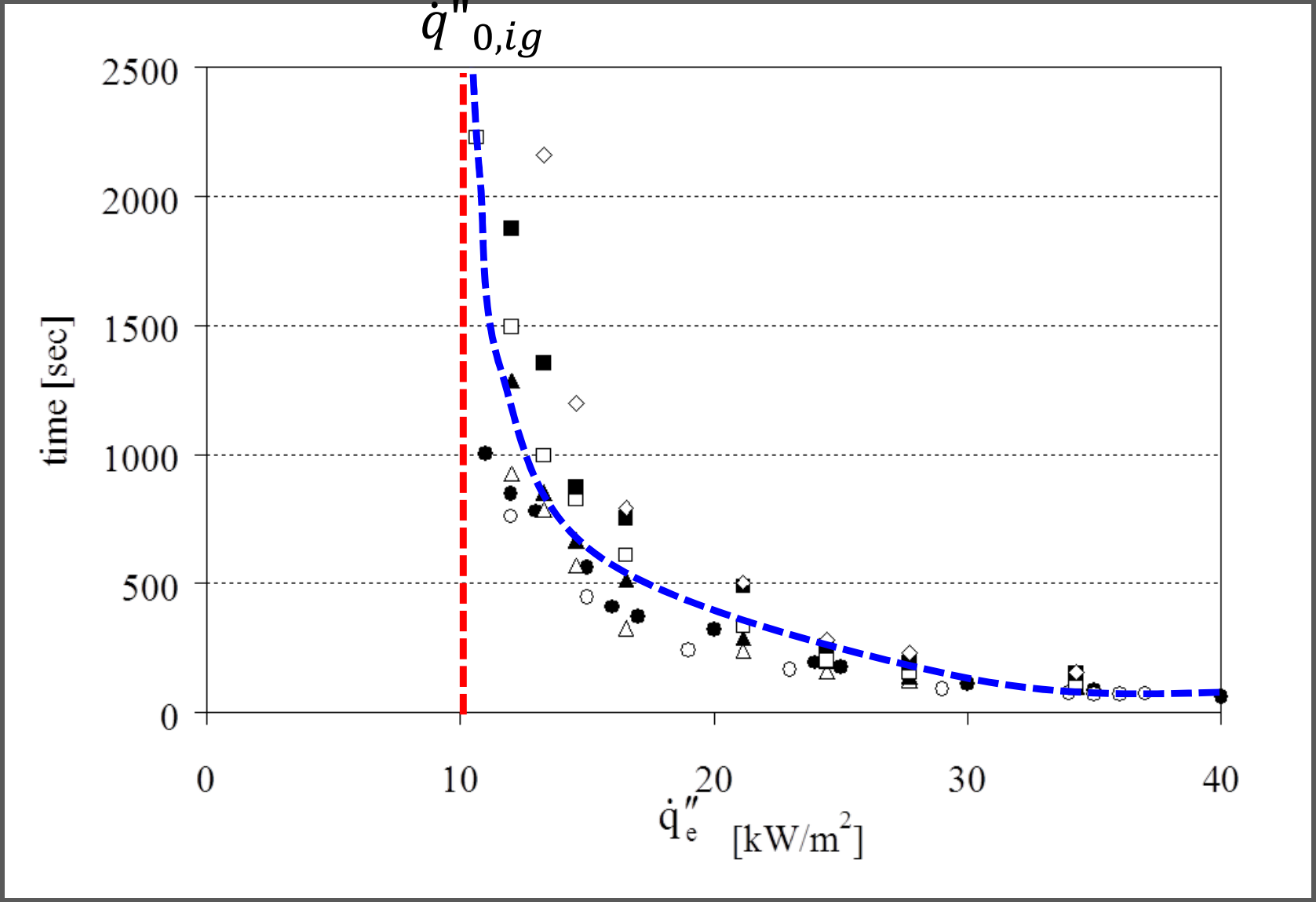






Ignition

Critical heat Flux for Ignition



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

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

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

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

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

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

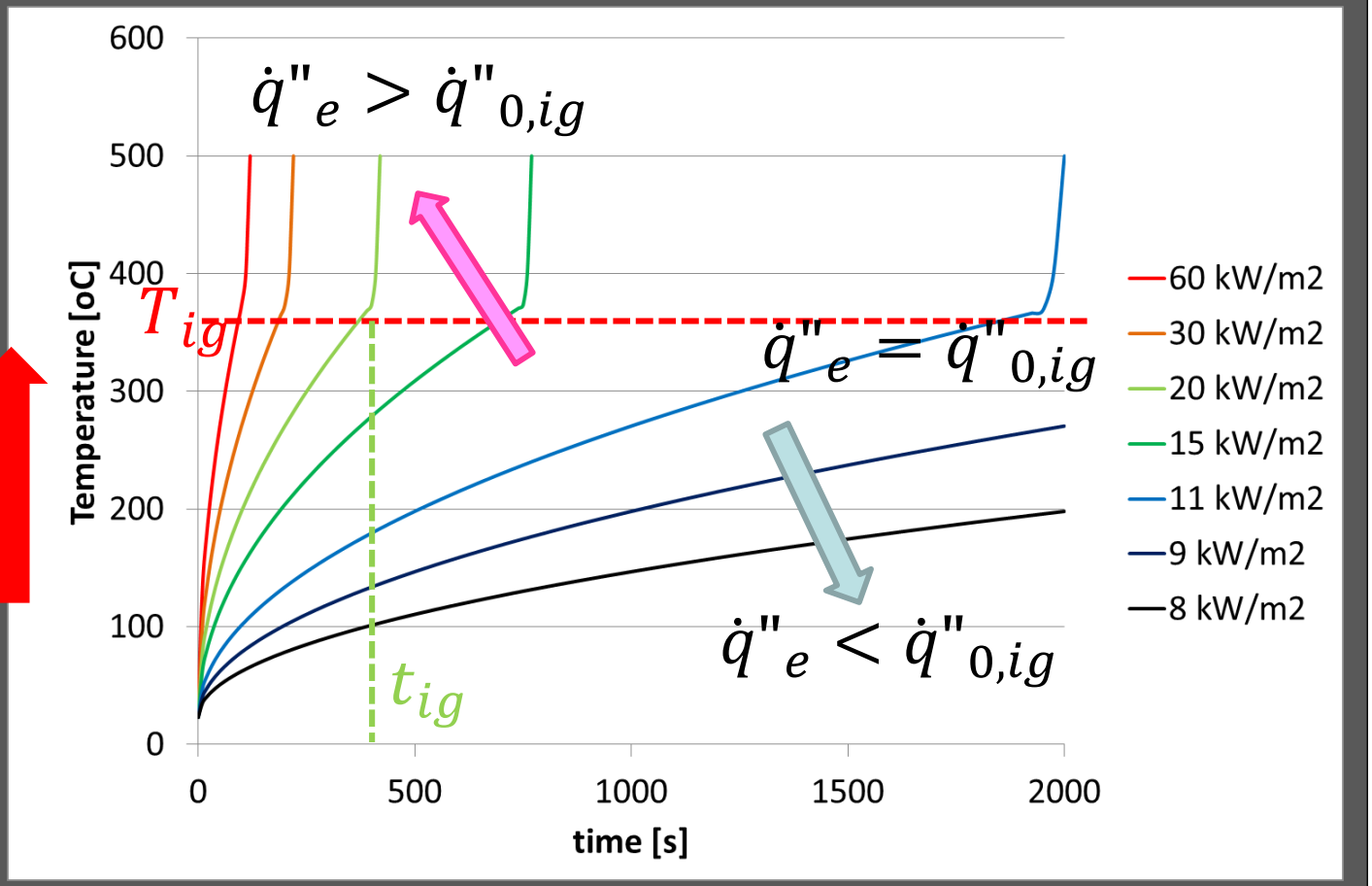
Test Value

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

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

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

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



Thermal Inertia

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

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

$$y = Ax + B$$

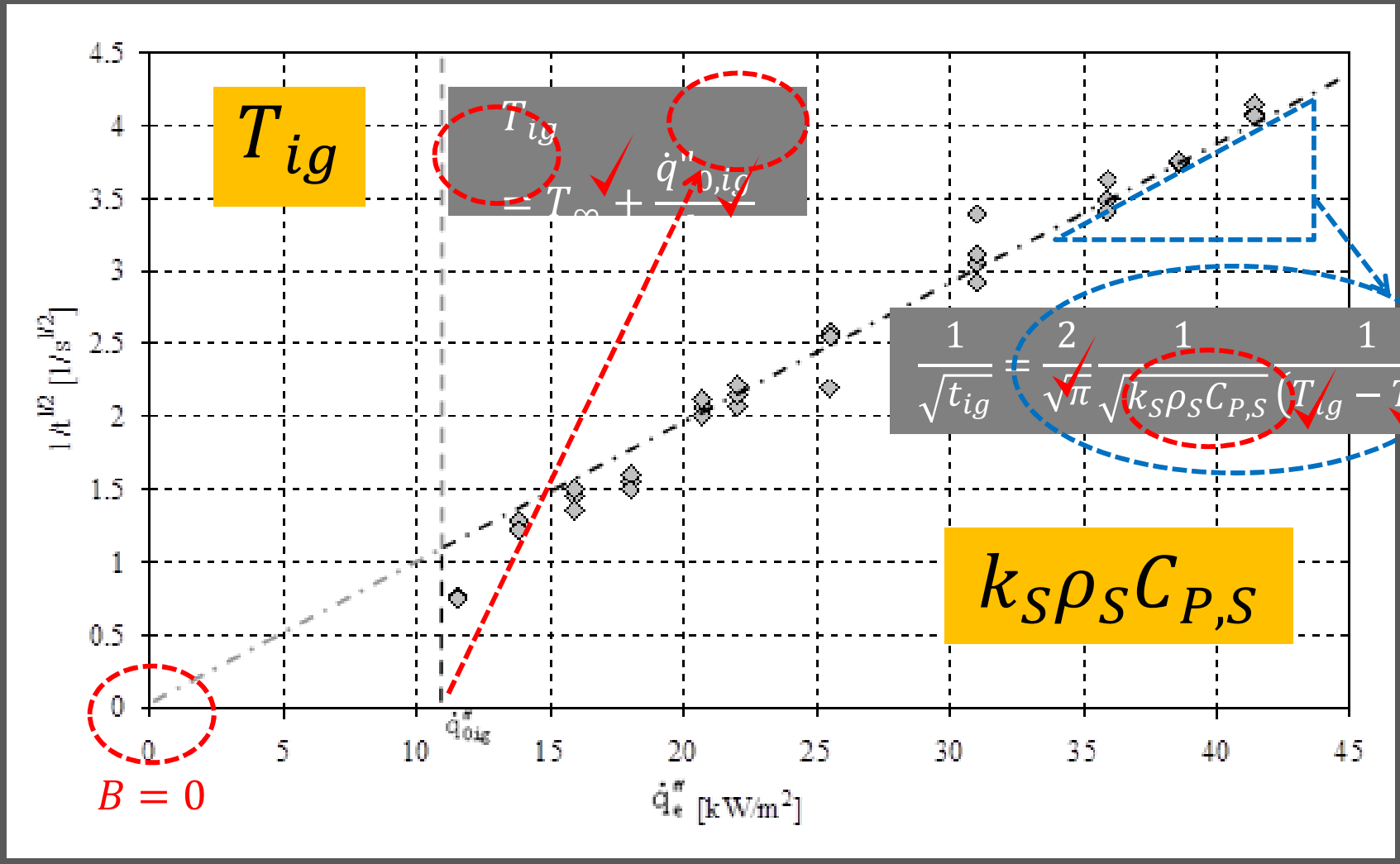
$$y = \frac{1}{\sqrt{t_{ig}}}$$

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

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

$$B = 0$$ ← Intercept

Material Properties

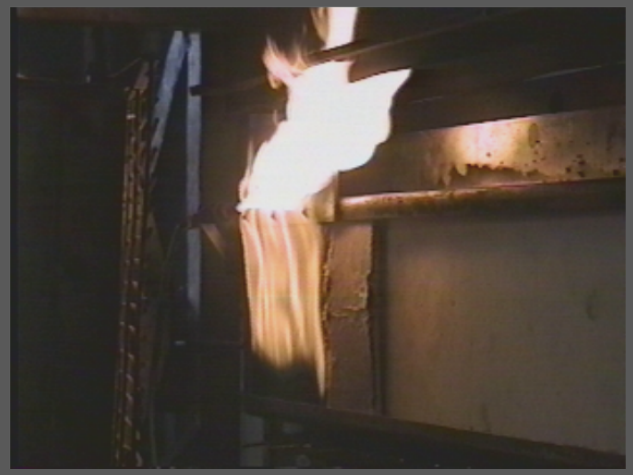


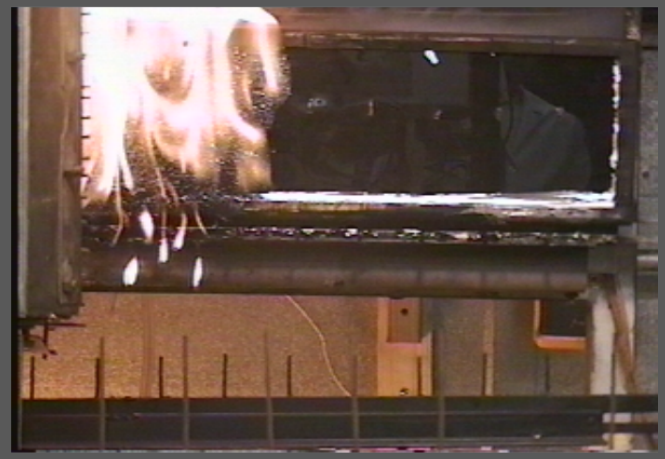
Data

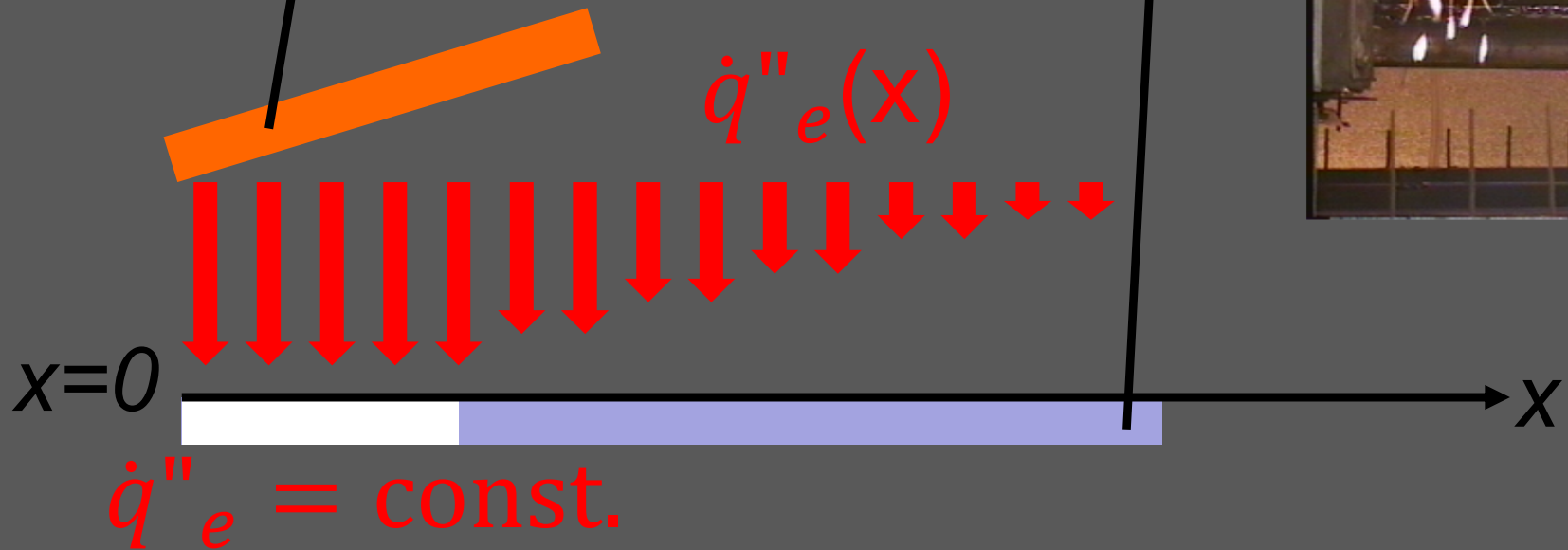
Material	T_{ig} [^{o}C]	$\overline{k_s \rho_s C_s}$ [$(kW/m^2K)^2.s$]
Wood fiber board	355	0.46
Wood hardboard	365	0.88
Plywood	390	0.54
PMMA	380	1.00
Flexible Foam Plastic	390	0.32
Rigid Foam Plastic	435	0.03
Acrylic Carpet	300	0.42
Wallpaper on Plasterboard	412	0.57
Asphalt Shingle	378	0.70
Glass Reinforced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

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

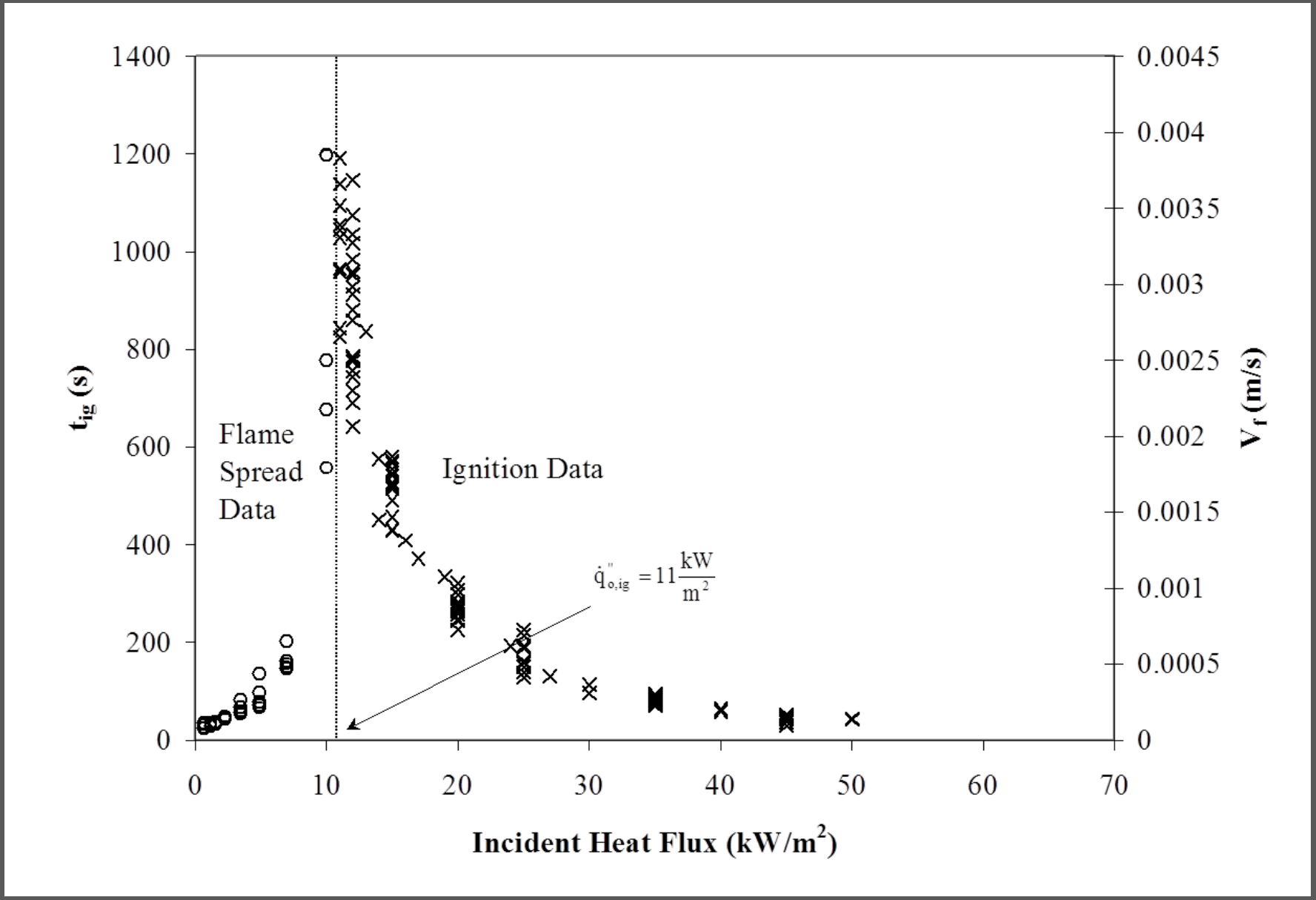








Flammability Diagram



Surface Temperature (T_S)

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

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

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

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

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

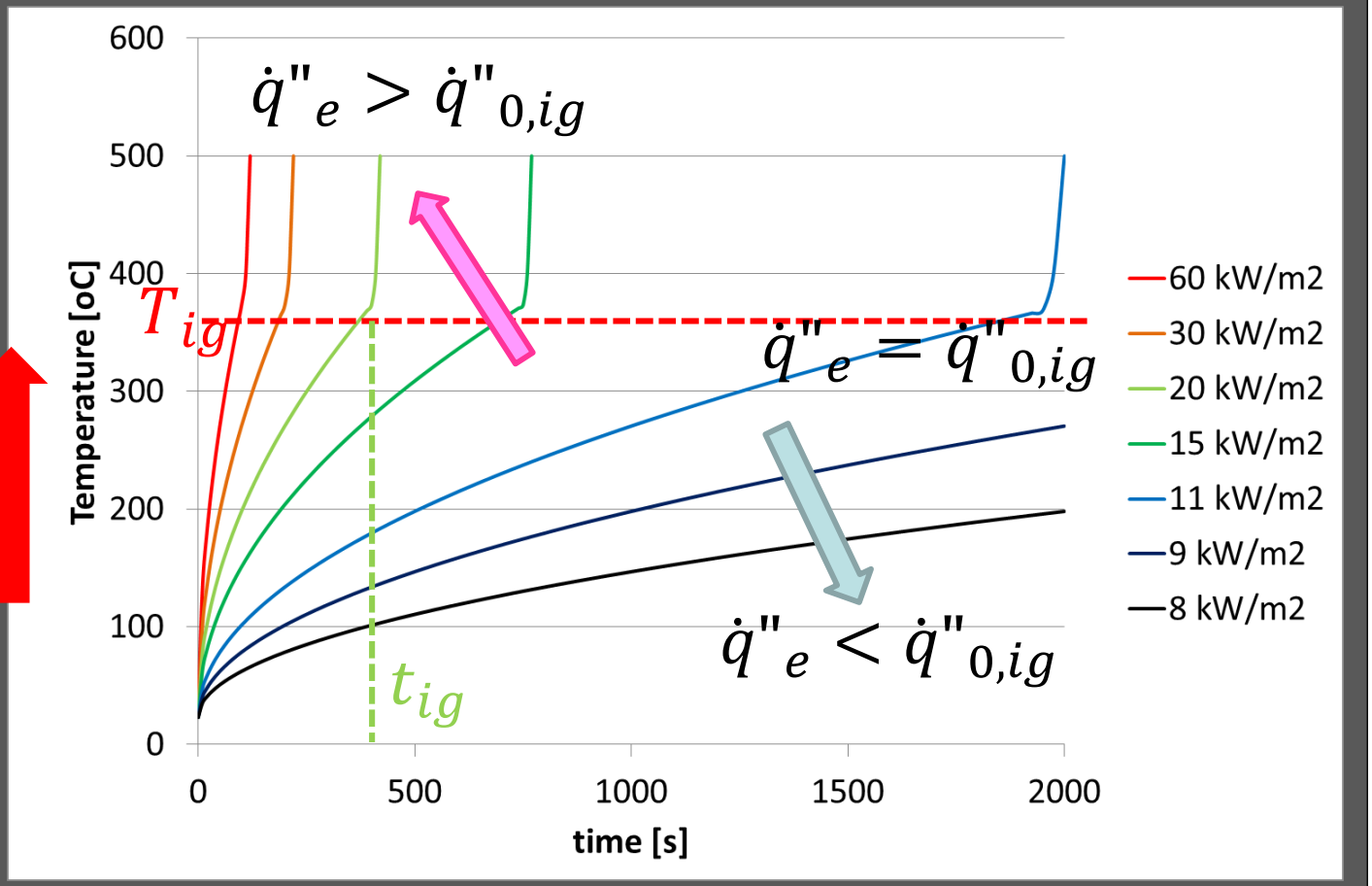
Test Value

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

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

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

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



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

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

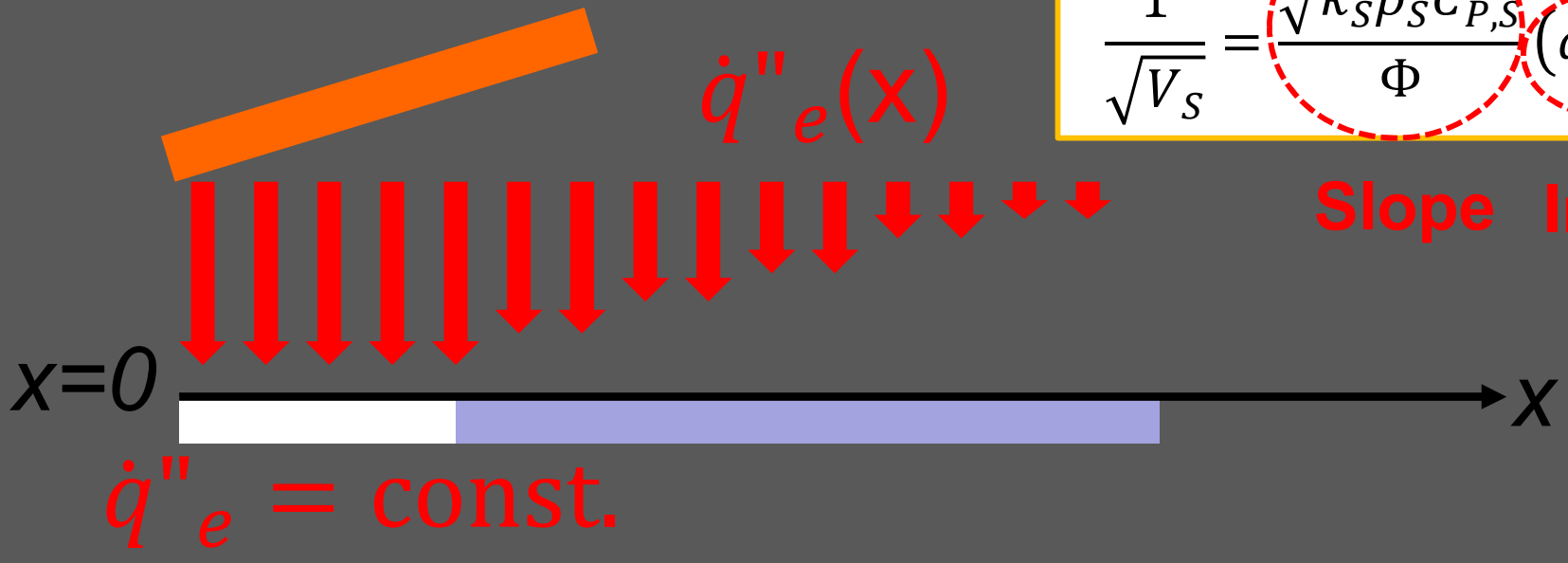
o $$V_S = \frac{\dot{q}''^2_g \delta_S}{k_S \rho_S C_{P,S}\left(T_{ig} - T_S\right)^2}$$

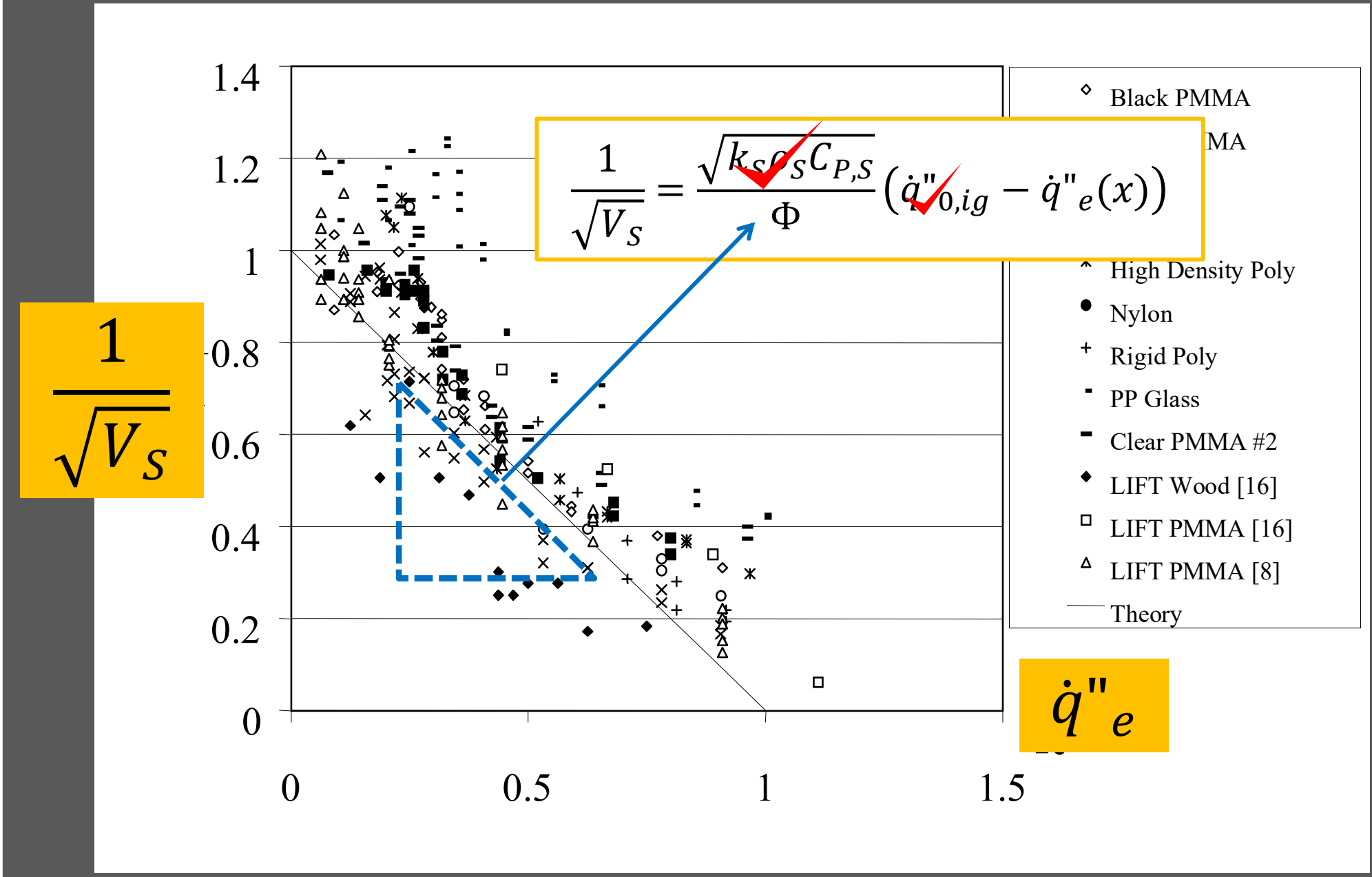
o $$V_S = \frac{\dot{q}''^2_g \delta_S}{k_S \rho_S C_{P,S}\left(T_{ig} - T_\infty + T_\infty - T_S\right)^2}$$

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

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

Slope Intercept



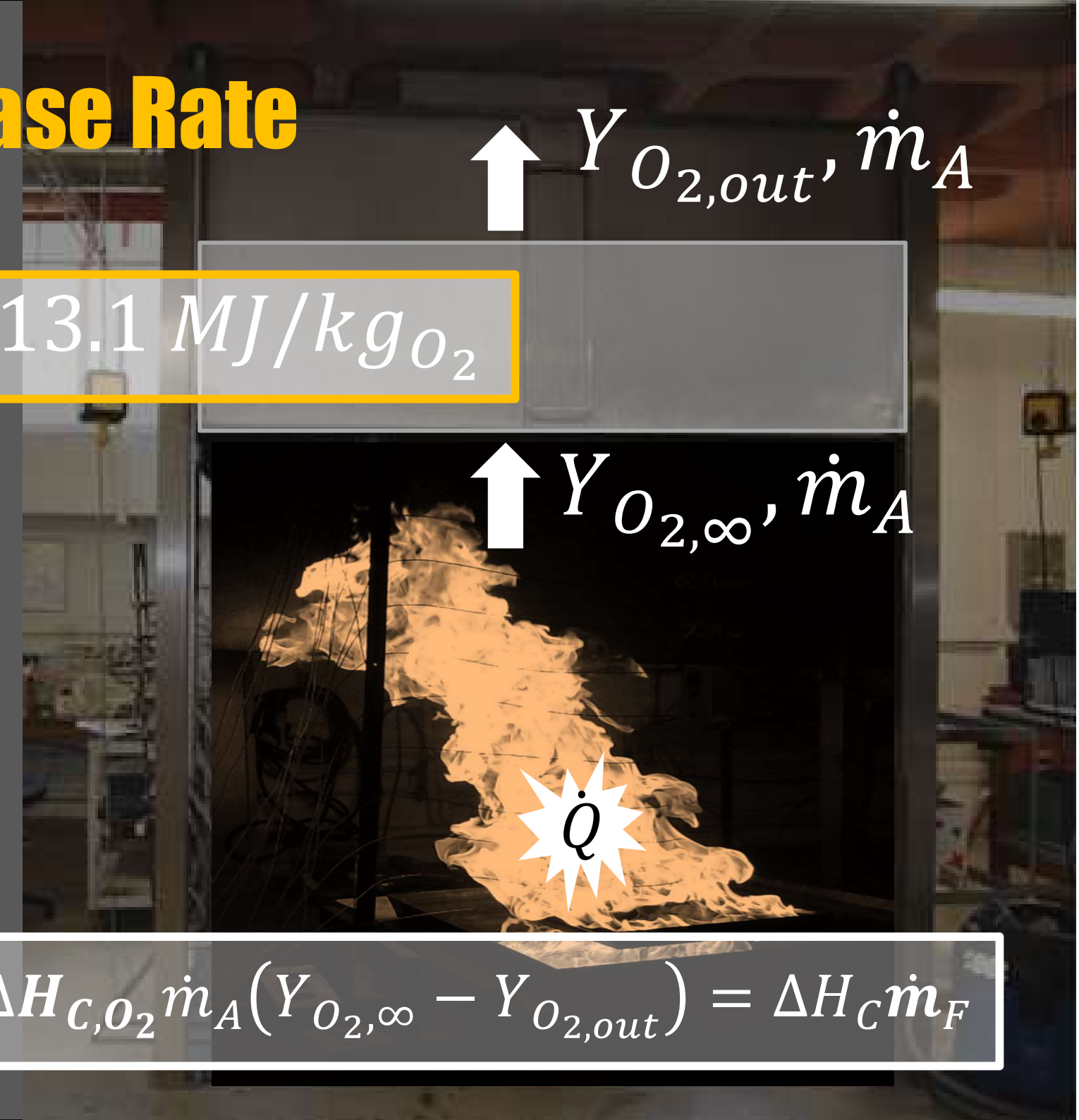

$\frac{1}{\sqrt{V_S}}$
$\frac{1}{\sqrt{V_S}} = \frac{\sqrt{k_S \rho_S C_{P,S}}}{\Phi}\left(\dot{q}''_{0,ig} - \dot{q}''_e(x)\right)$
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
0.5
1
1.5
$\dot{q}''_e$
Black PMMA
MA
High Density Poly
Nylon
Rigid Poly
PP Glass
Clear PMMA #2
LIFT Wood [16]
LIFT PMMA [16]
LIFT PMMA [8]
Theory

Data

Material	$(\Phi_{O,S})$ (kW^2/m^3s)
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

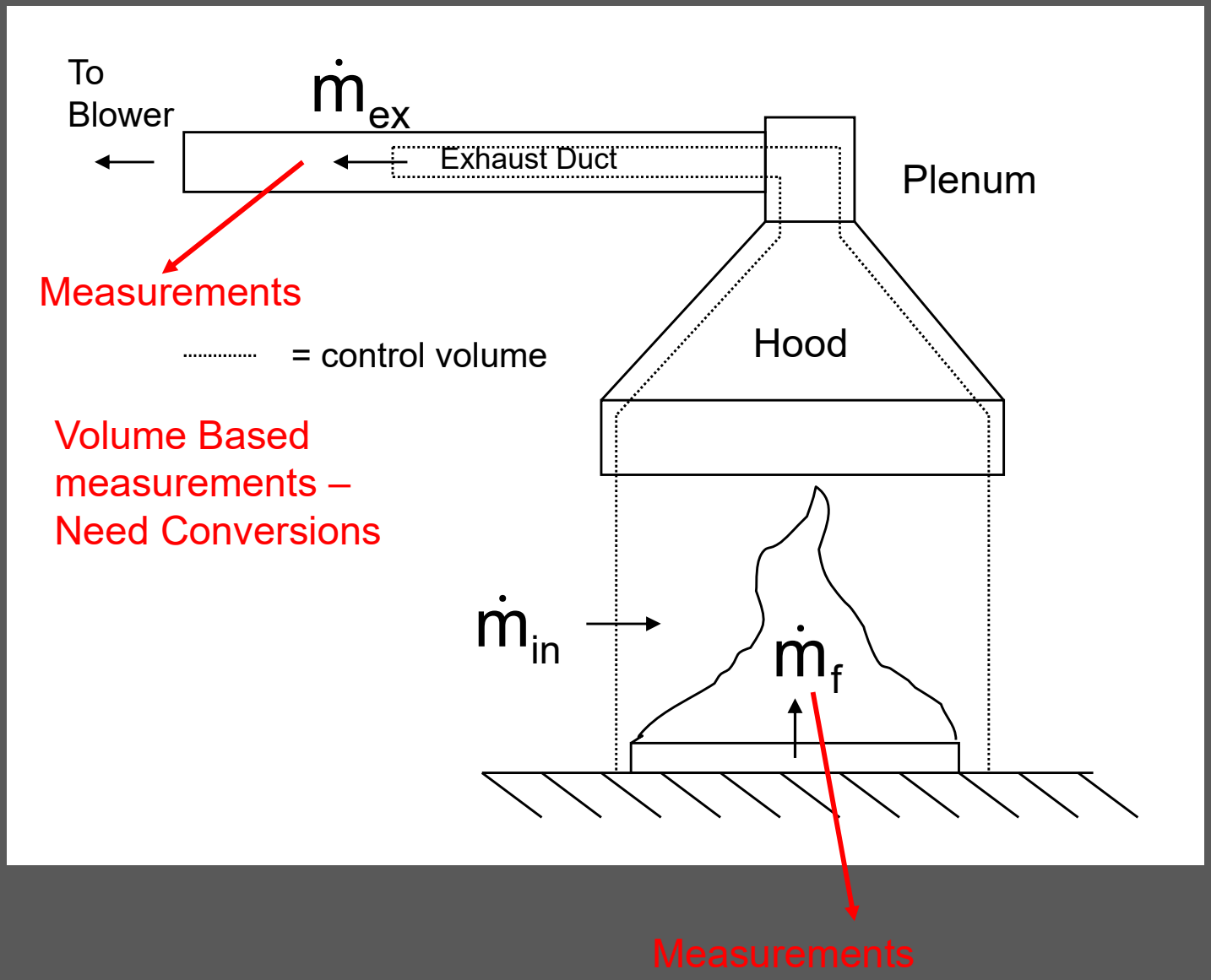
Heat Release Rate

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



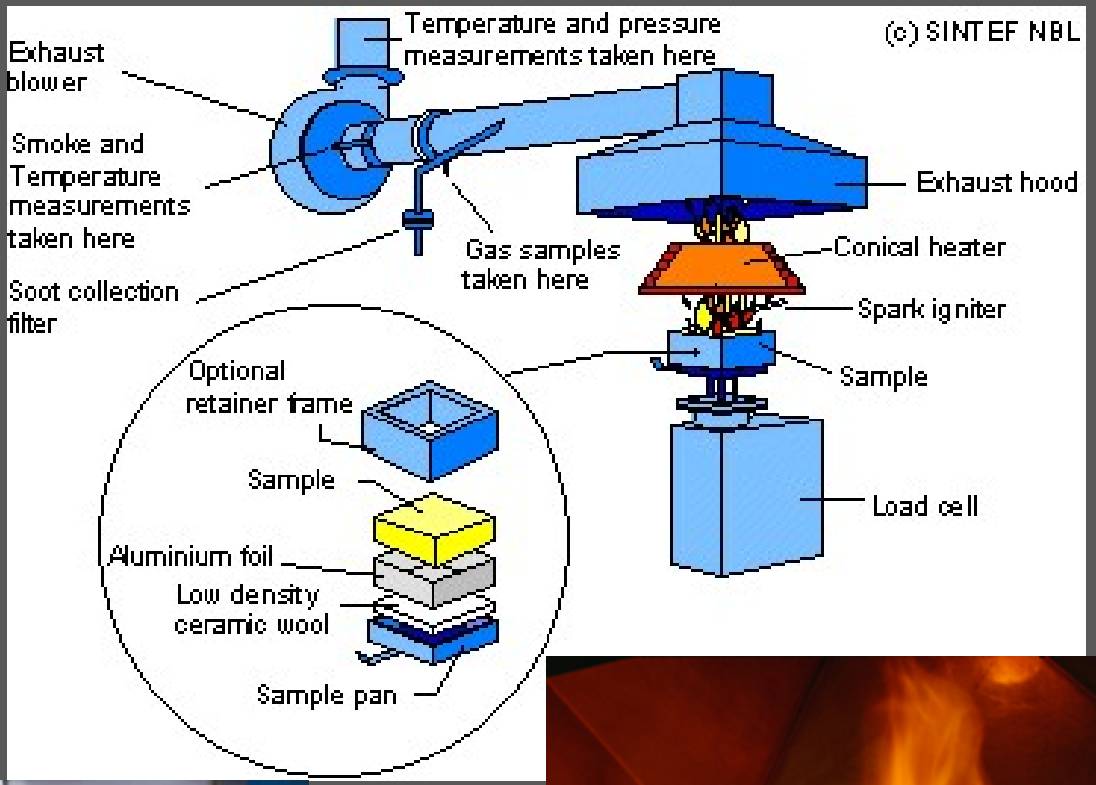
$$\boldsymbol{HRR = \dot{Q} = \Delta H_{C,O_2} \dot{m}_A \left(Y_{O_{2,\infty}} - Y_{O_{2,out}}\right) = \Delta H_C \dot{m}_F}$$

O_2 Consumption



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




(c) SINTEF NBL
Exhaust blower
Temperature and pressure measurements taken here
Smoke and Temperature measurements taken here
Exhaust hood
Gas samples taken here
Conical heater
Soot collection filter
Spark igniter
Sample
Optional retainer frame
Sample
Load cell
Aluminium foil
Low density ceramic wool
Sample pan

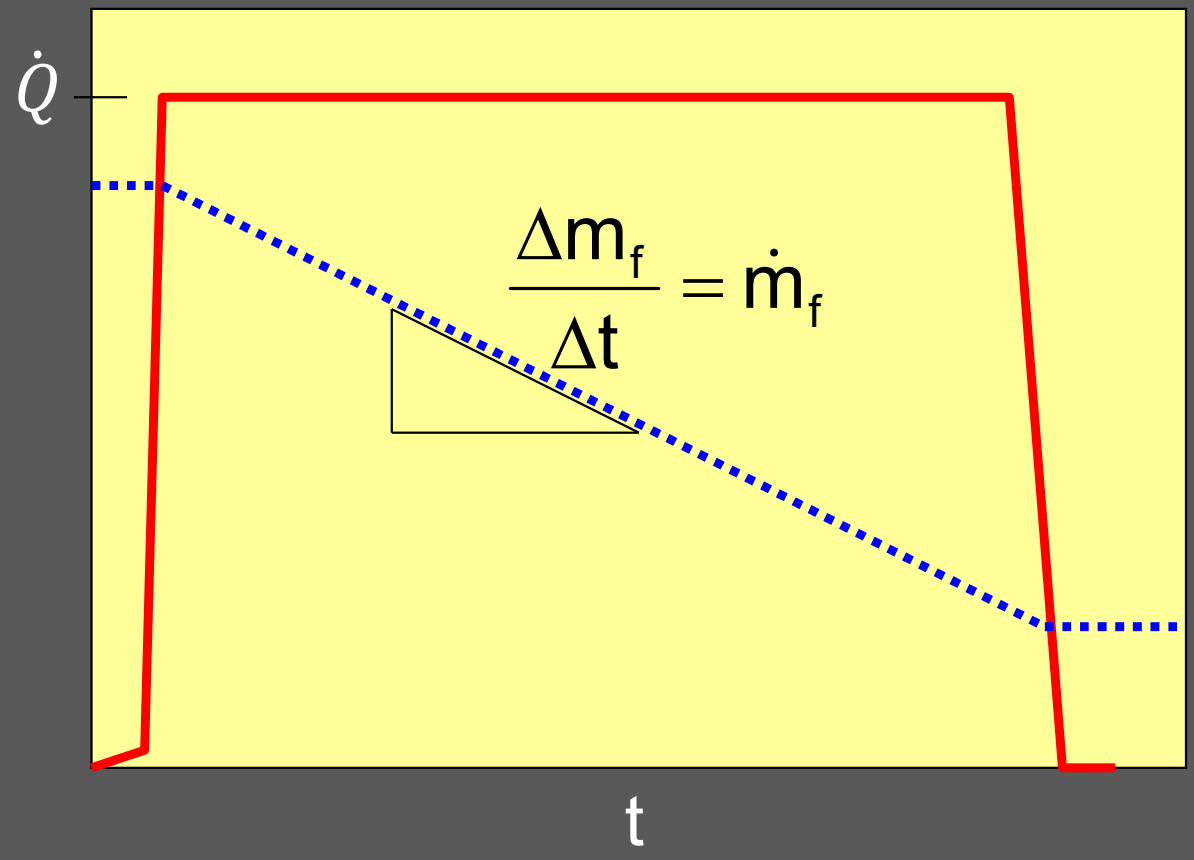




Experimental Results

- Ideal Scenario:

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

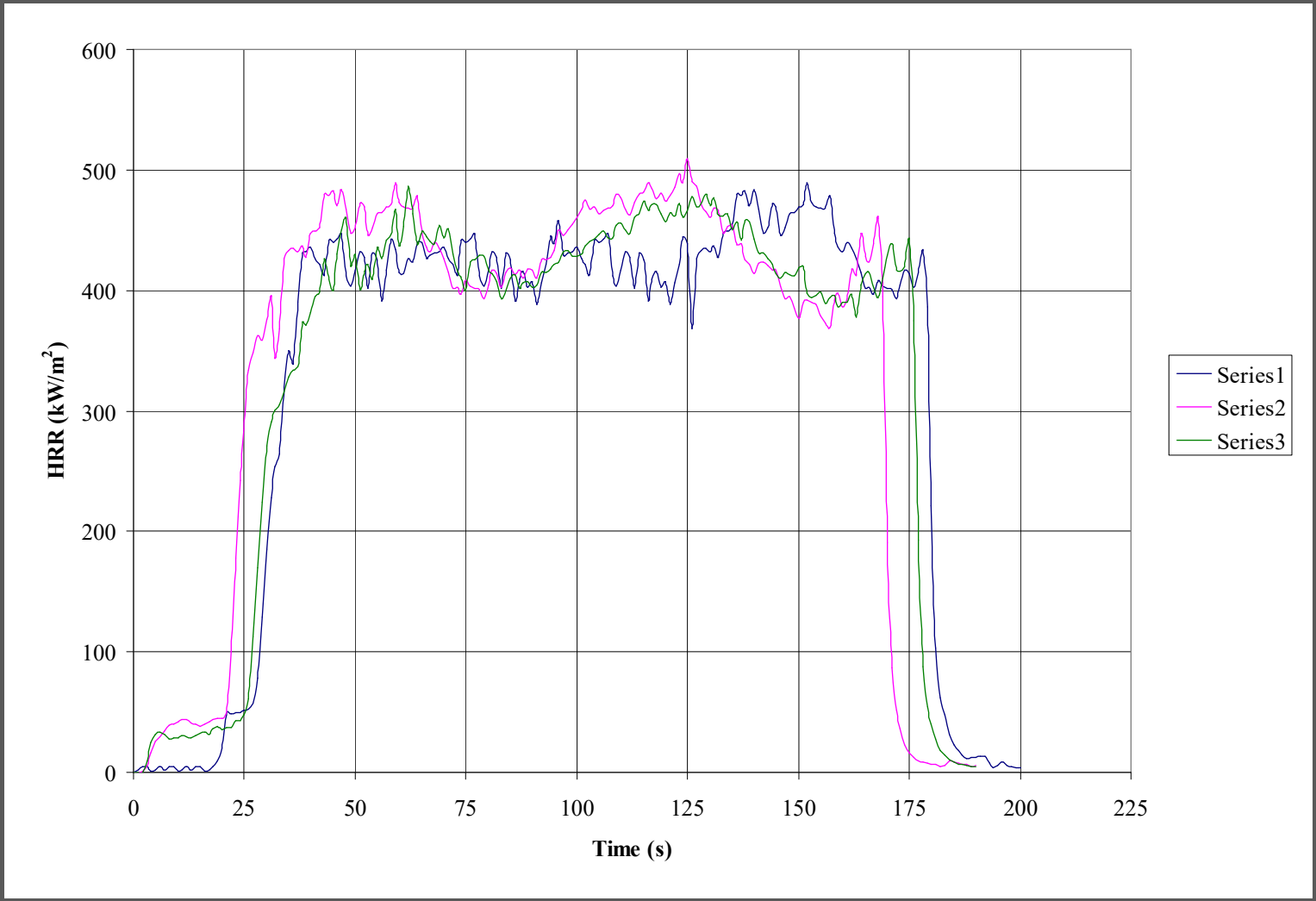


$$\Delta H_C = \frac{\dot{Q}}{\dot{m}_f}$$

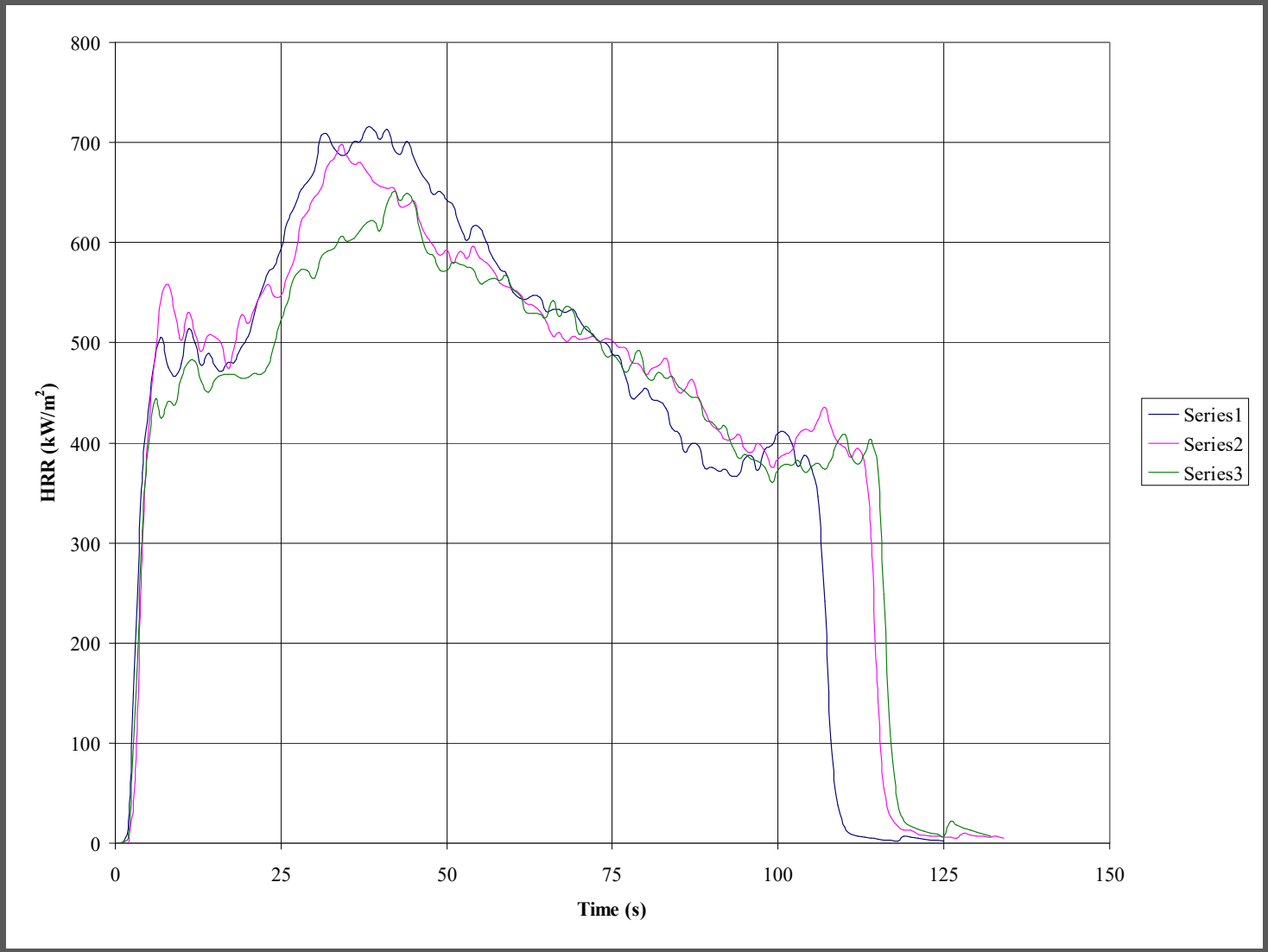
$$HRRPUA = \dot{Q}'' = \frac{\dot{Q}}{A_S}$$

$$A_S = 100\ cm^2$$

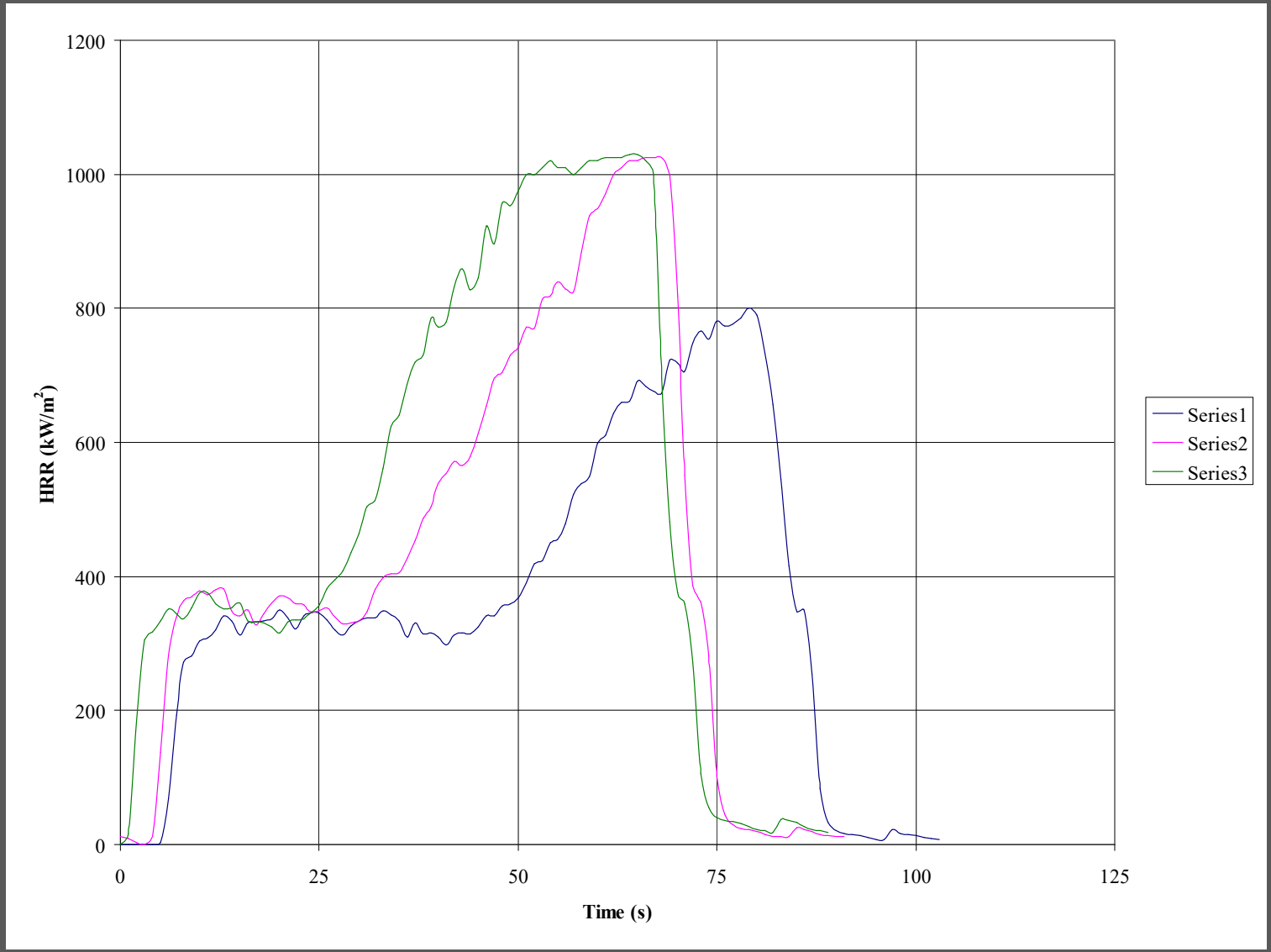
Kerosene


600
500
400
300
200
100
0
HRR (kW/m2)
0
25
50
75
100
125
150
175
200
225
Time (s)
Series1
Series2
Series3

Gasoline


800
700
600
500
400
300
200
100
0
HRR (kW/m2)
0
25
50
75
100
125
150
Time (s)
Series1
Series2
Series3

Naphthalene (I)



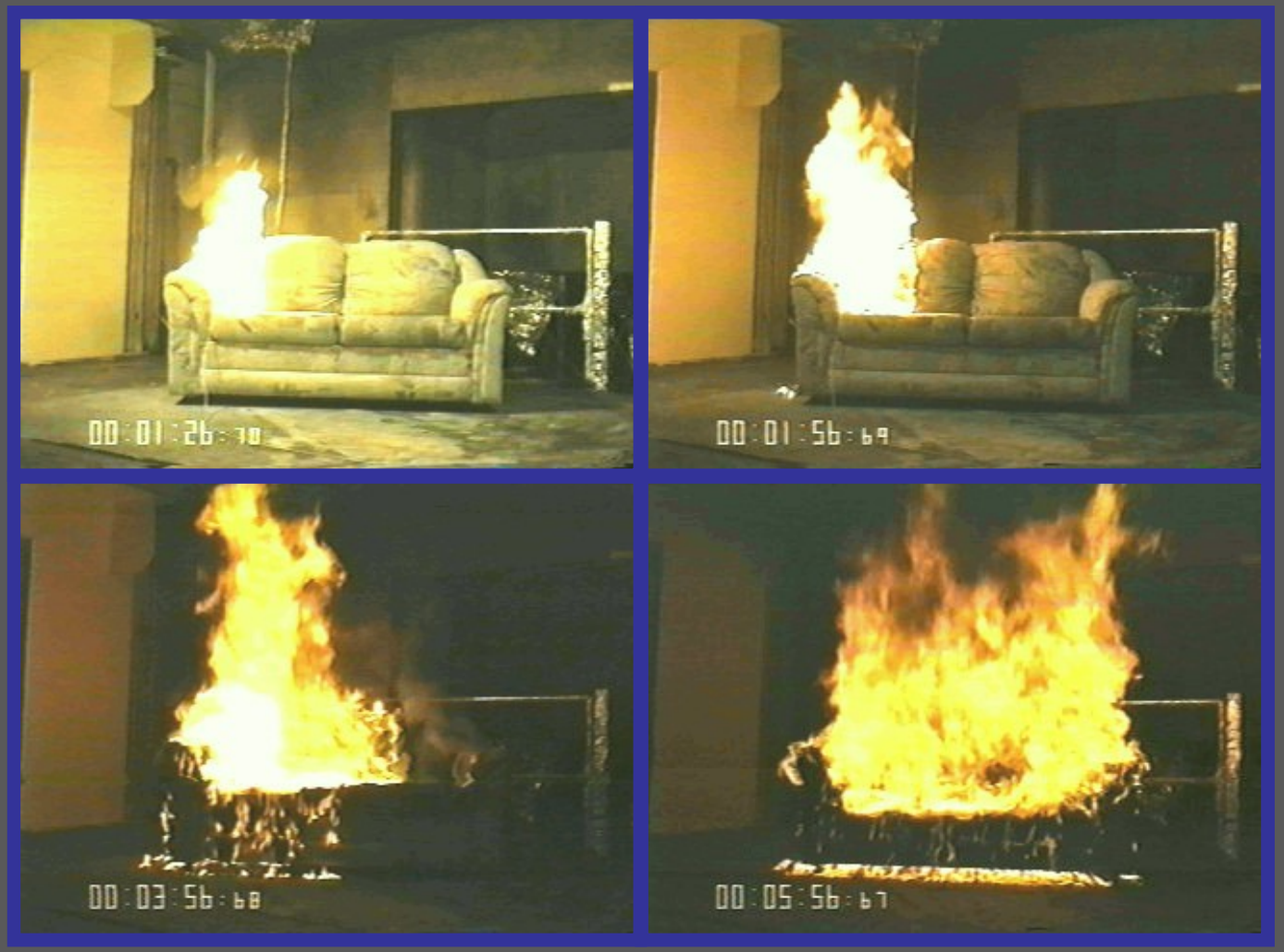
The Real Scale Application

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

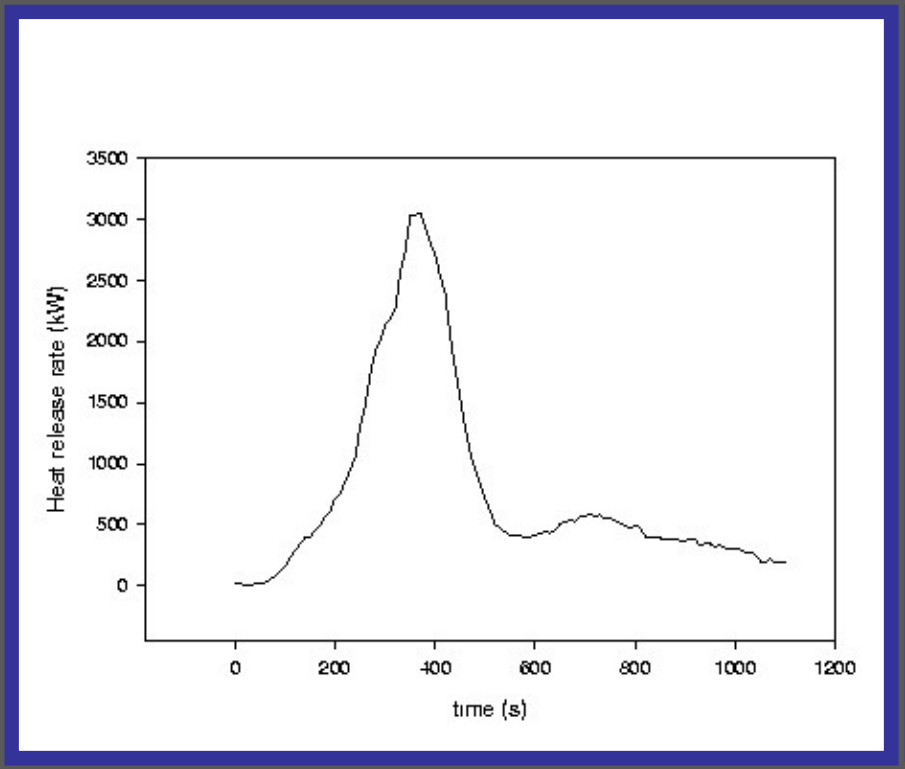




Loveseat



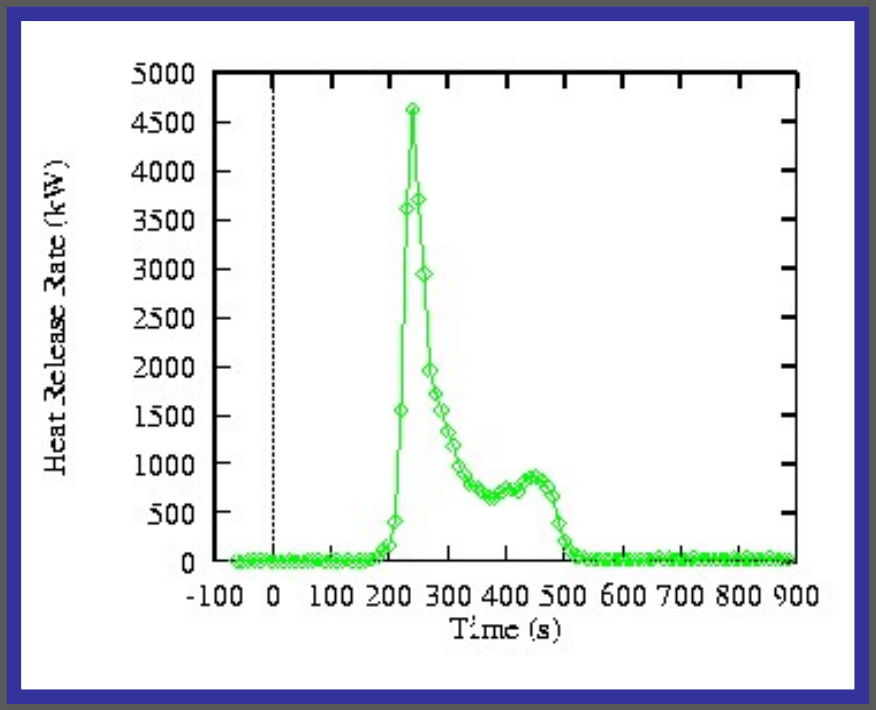
Loveseat


Heat release rate (kW)
3500
3000
2500
2000
1500
1000
500
0
0
200
400
600
800
1000
1200
time (s)



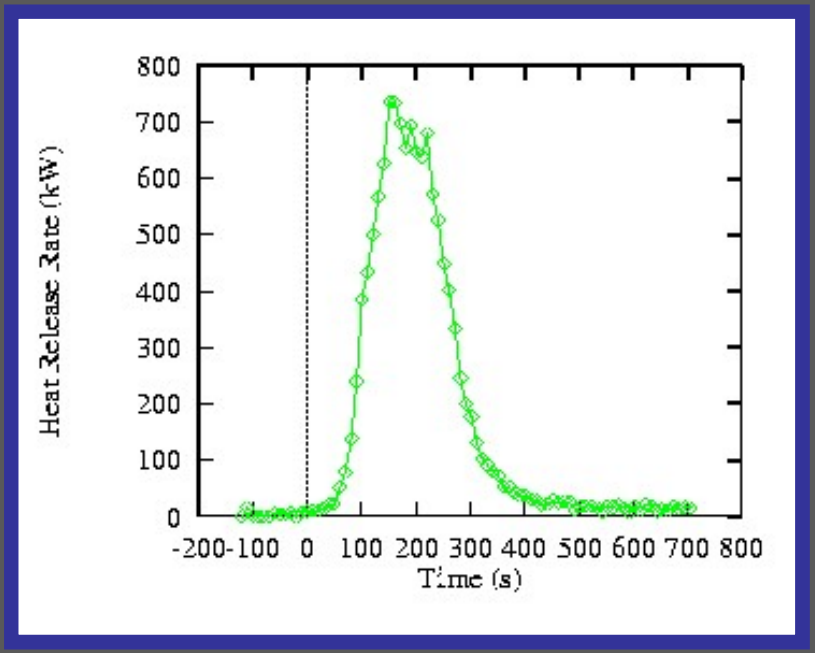
Bunk bed





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

Mattress


Heat Release Rate (kW)
800
700
600
500
400
300
200
100
0
-200-100 0 100 200 300 400 500 600 700 800
Time (s)



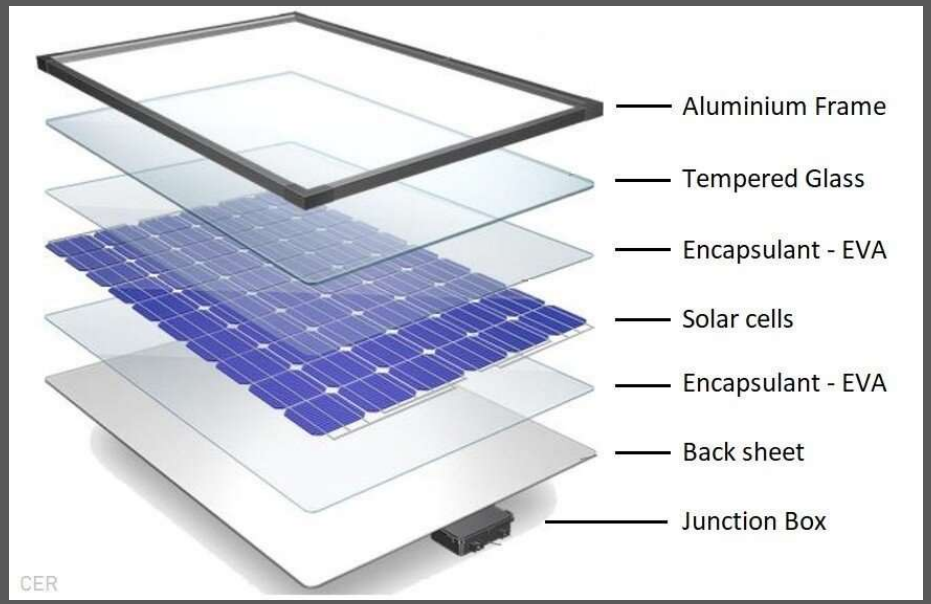
HRR data resources

- 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

Photovoltaics

- How does the configuration affect the flammability of solar panels?







a) Time of ignition



b) 300 s after ignition



c) 450 s after ignition



d) 510 s after ignition



e) 570 s after ignition

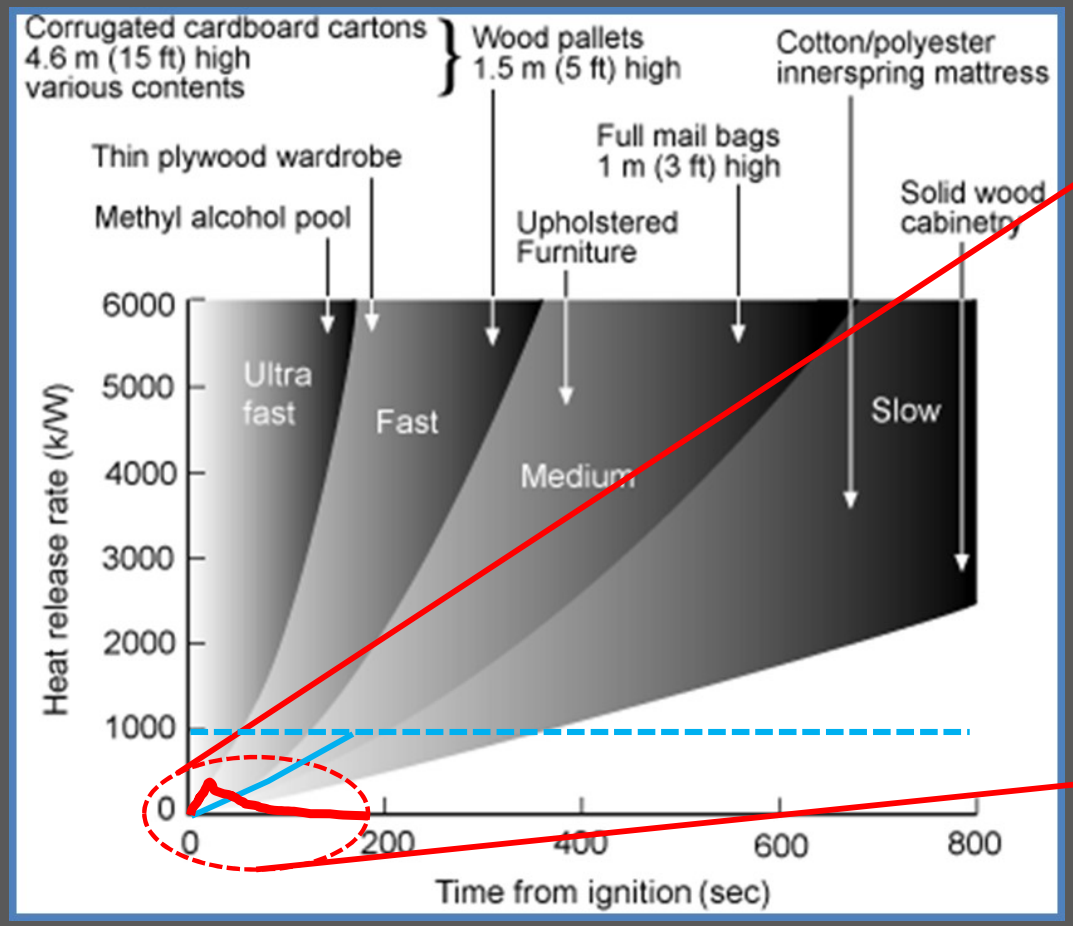


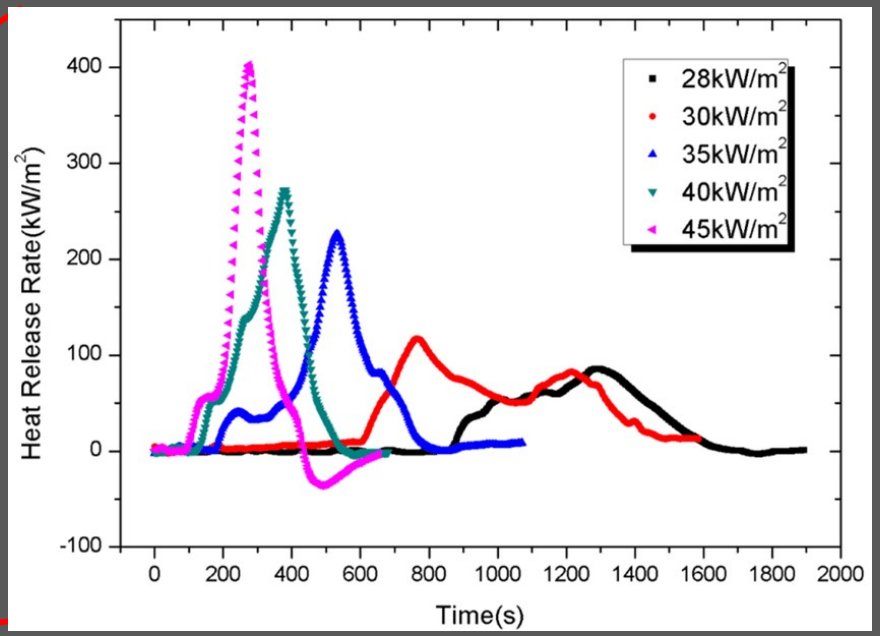
f) 630 s after ignition



g) 690 s after ignition

HRR – Do we design for this?





Fundamentals of Smouldering Combustion



Lecture- 4

José L. Torero, University College London, United Kingdom

Smouldering – A Fire Problem

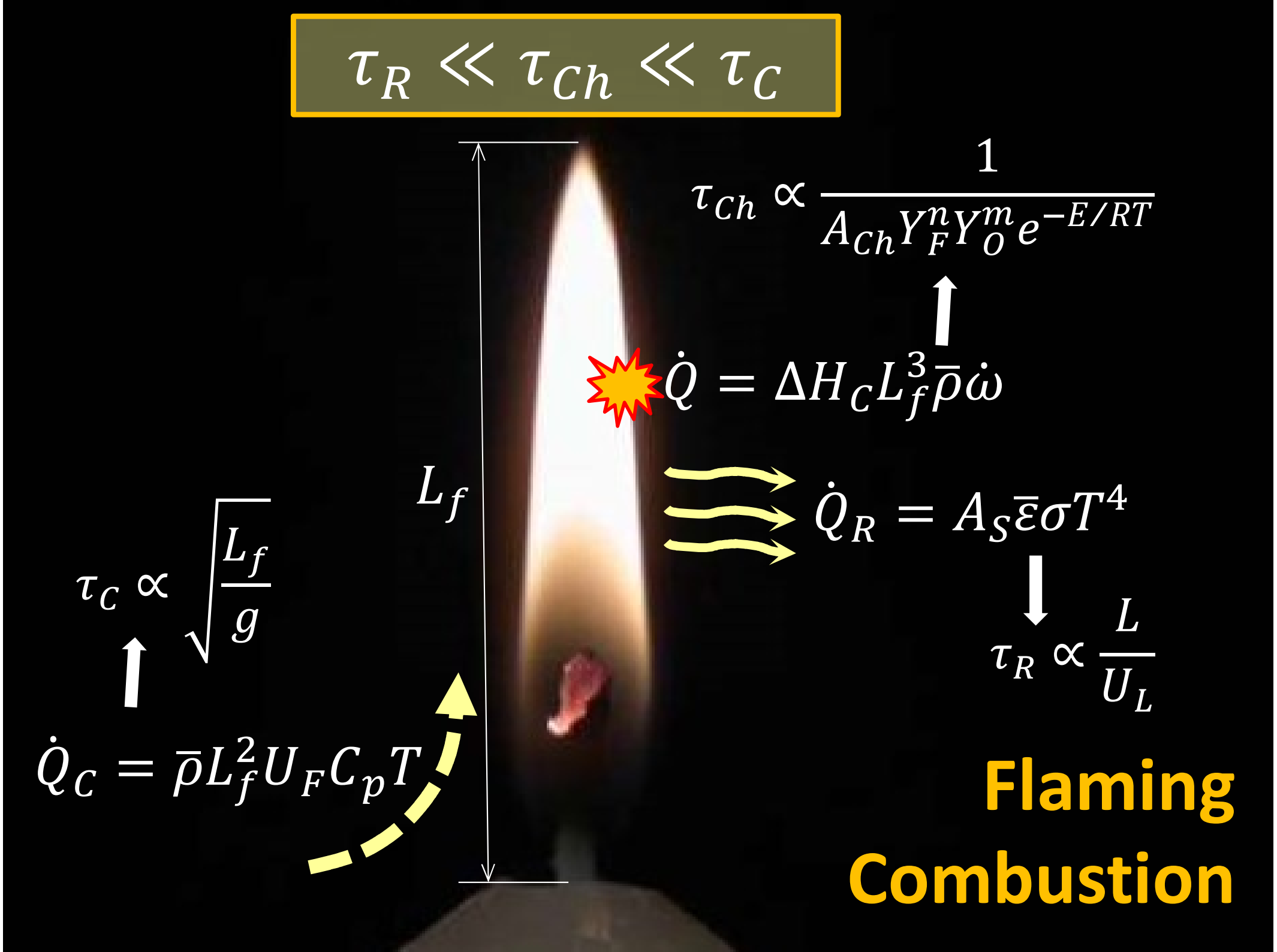
- Very common form of burning – Fire Hazard
  - Coal
  - Foams
  - Cigarette … etc.



Why is this a problem?



- Large quantities of combustion products – they can represent from 5%-40% of the global annual fossil fuel emissions
- 2%-5% of all abandoned coal mines lead to subsurface fires
- Very difficult to extinguish – the oldest subsurface fire has been burning approximately 6,000 years
- Contamination of underground water – i.e. large amounts of mercury being transported
- Lead to forest fires and destruction of the ecosystem
- Subsidence of the ground
- Complete social disruption, etc.


$\tau_R \ll \tau_{Ch} \ll \tau_C$
$\tau_{Ch} \propto \frac{1}{A_{Ch} Y_F^n Y_O^m e^{-E/RT}}$
$\dot{Q} = \Delta H_C L_f^3 \bar{\rho} \dot{\omega}$
L_f
$\dot{Q}_R = A_S \bar{\varepsilon} \sigma T^4$
$\tau_C \propto \sqrt{\frac{L_f}{g}}$
$\tau_R \propto \frac{L}{U_L}$
$\dot{Q}_C = \bar{\rho} L_f^2 U_F C_p T$
Flaming Combustion

Smouldering Combustion

$$\tau_{Ch} \propto \frac{d_P^2}{D\Delta Y_O}$$

$$\tau_C \propto \frac{d_P}{U_F}$$

$$\dot{Q} = \Delta H_C d_P^3 \bar{\rho} \dot{\omega}$$

$$\dot{Q}_R = k_R \frac{T}{d_P}$$

$$\dot{Q}_C = \bar{\rho} d_P^2 U_F C_p T$$

$$\dot{Q}_{CD} = k_{CD} \frac{T}{d_P}$$

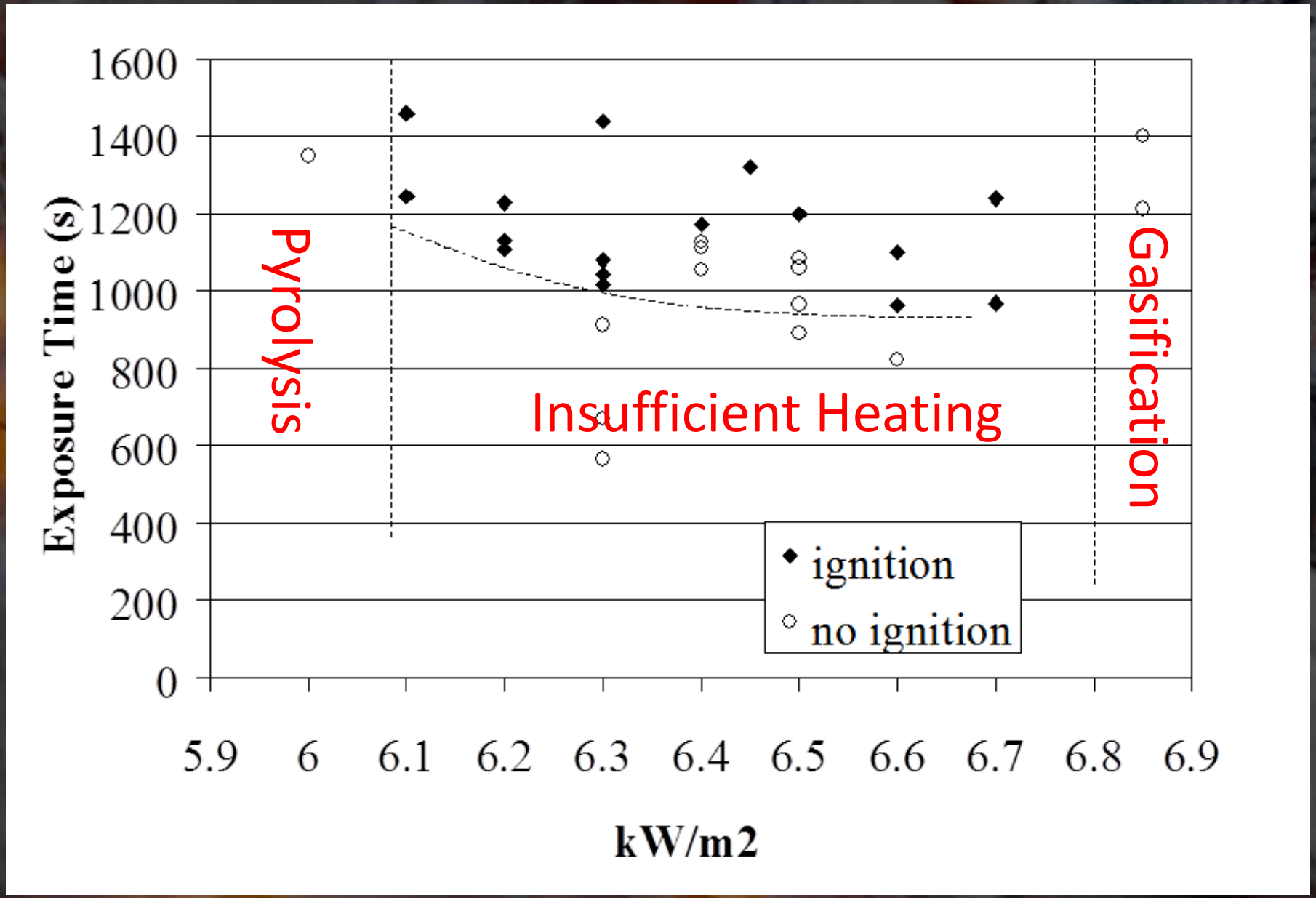
$$\tau_T \propto \frac{d_P^2}{\alpha_T}$$

$$\tau_T \approx \tau_{Ch} \approx \tau_C$$

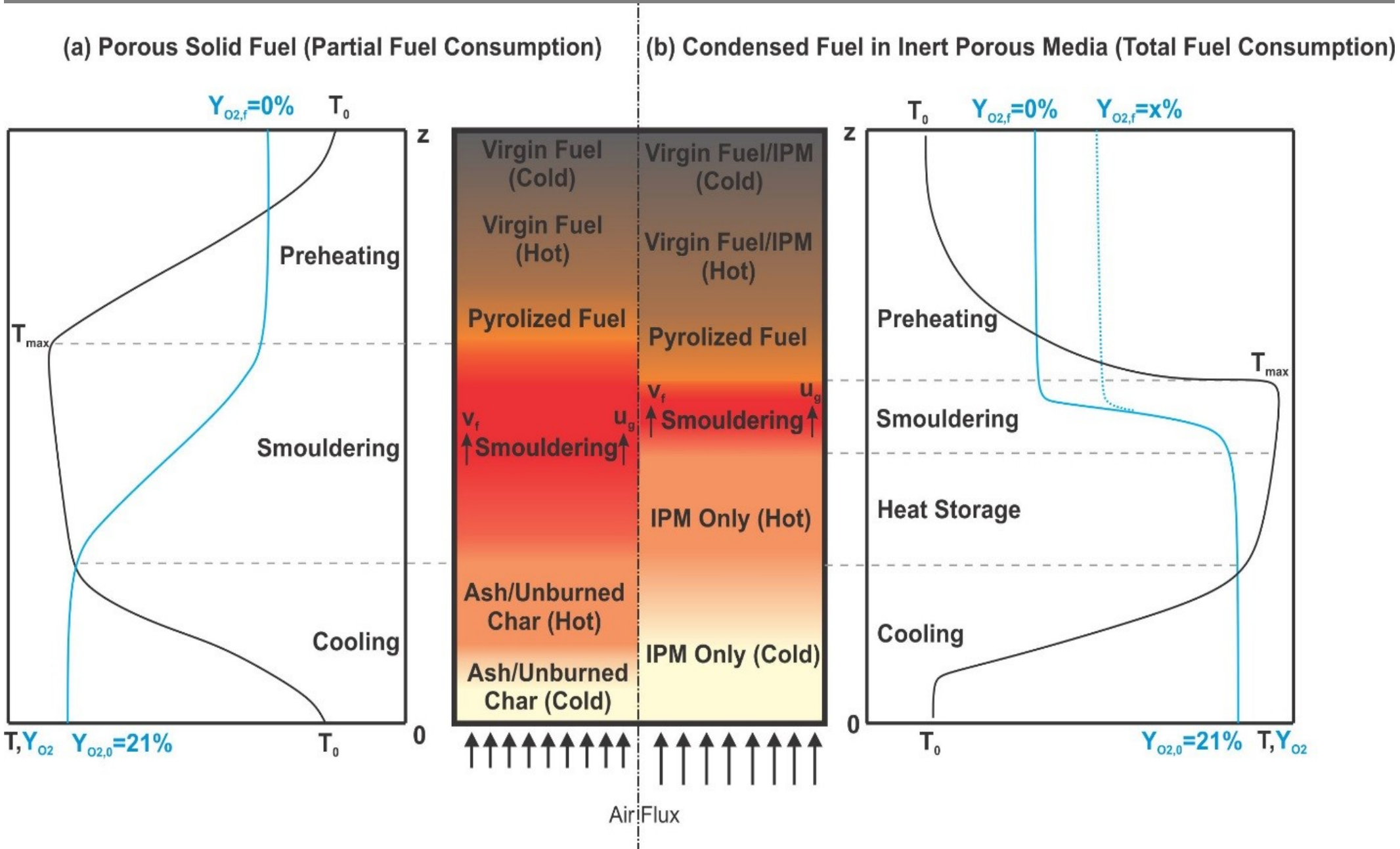
$$k_R = \frac{16\sigma T^3}{3}$$

Acc.V Spot Magn Det WD Exp 500 µm
10.0 kV 5.0 50x GSE 9.8 1 0.6 Torr

Smouldering Window

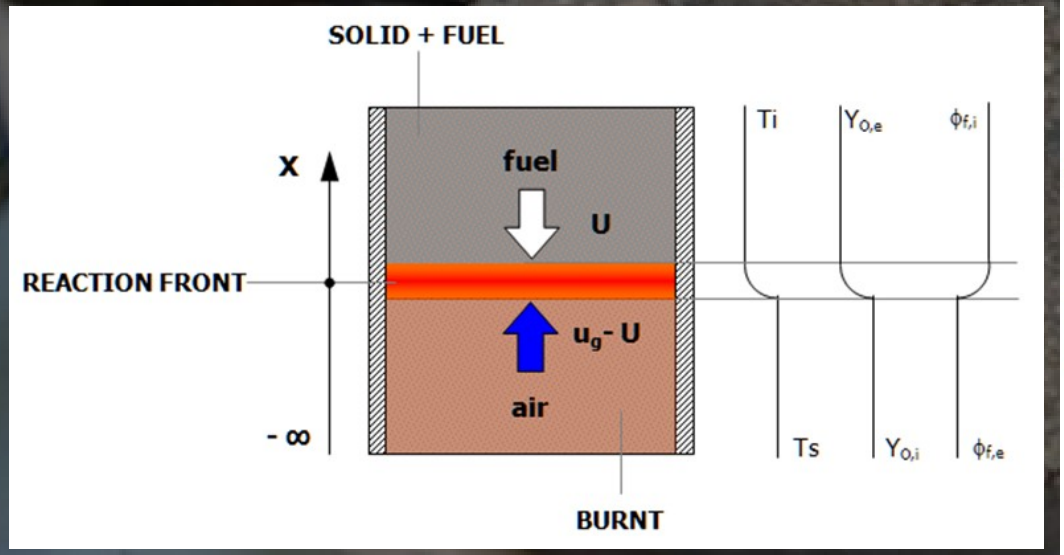


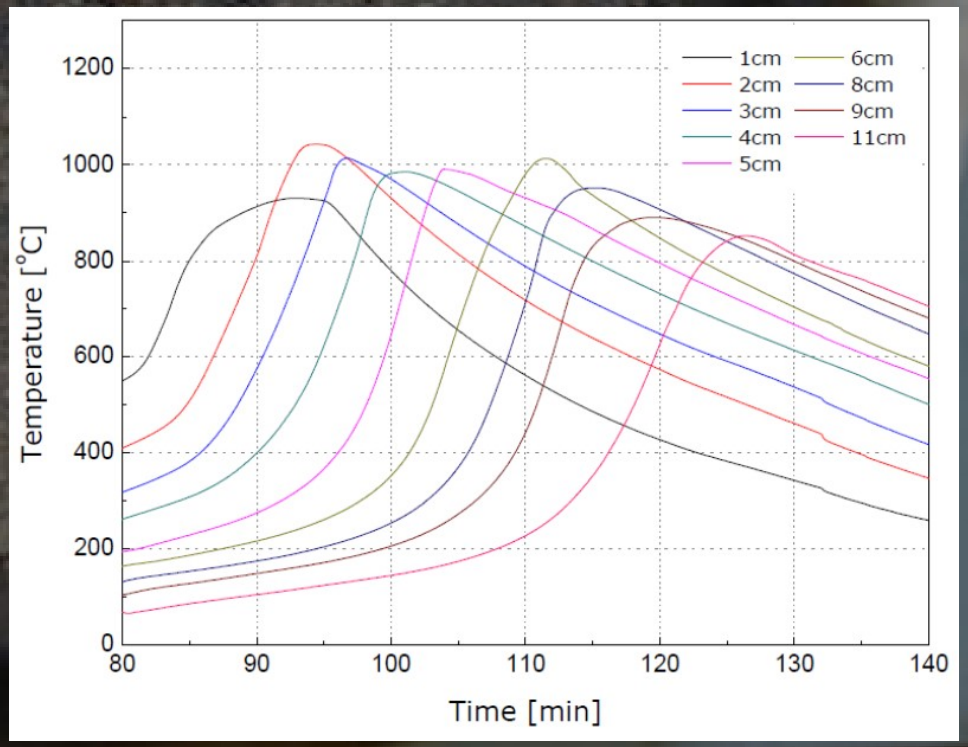
Forward Smouldering



Example: Smouldering of Contaminated Soil

- Contaminated Soil ignited allowing a smouldering reaction to propagate
- At the small scale thermocouples and CO/CO_2 ratios can be used to control propagation, destruction rates and quenching

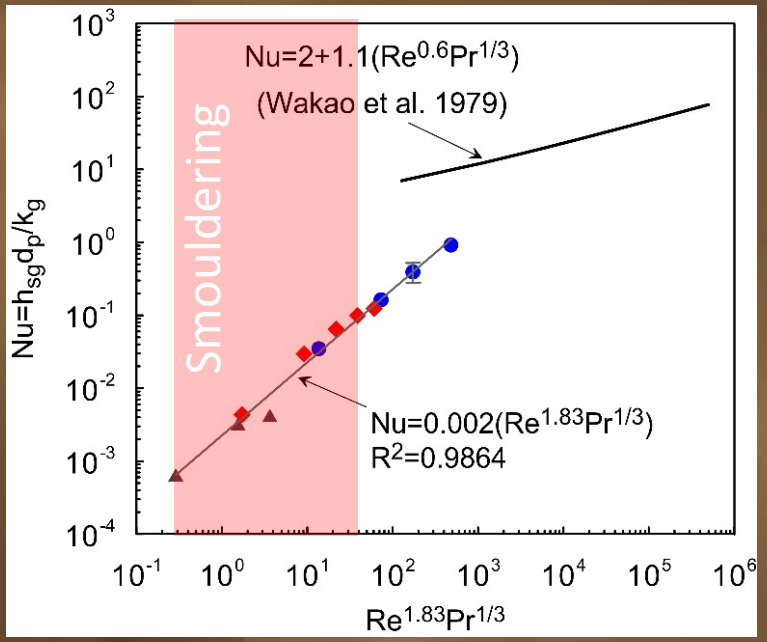




Results



What is still to be learnt?



$$(1-\phi)(\rho_s C_{p_s})\frac{\partial T_s}{\partial t} = (1-\phi)\frac{\partial}{\partial x}\left((k_s + k_{rad})\frac{\partial T_s}{\partial x}\right) + U\left(\frac{A_{s,c}}{V_c}\right)(T_s - T_\infty) + h_{sg}\left(\frac{A_{s,sp}}{V_{sp}}\right)(T_g - T_s)$$

$$\phi(\rho_g C_{p_g})\frac{\partial T_g}{\partial t} + \rho_g C_{p_g} u_g \frac{\partial T_g}{\partial x} = \phi\frac{\partial}{\partial x}\left(k_g \frac{\partial T_g}{\partial x}\right) + U\left(\frac{A_{s,c}}{V_c}\right)(T_g - T_\infty) + h_{sg}\left(\frac{A_{s,sp}}{V_{sp}}\right)(T_s - T_g)$$

- We know how to write the equations
- We do not know what to fill for the parameters …

Smouldering Chemistry?

- Robust smouldering can be modelled as a thermal wave with heat generation governed by oxygen supply
- Weak smouldering/extinction requires a more detailed description of the chemistry – significant advances have been extensively reported in the last 15 years
- Oxygen mass transfer into the fuel remains an unresolved challenge

Post-Flashover compartment Fire



José L. Torero
University College London
United Kingdom

Lecture - 5

Assessing Structural Behavior



Fire Resistance

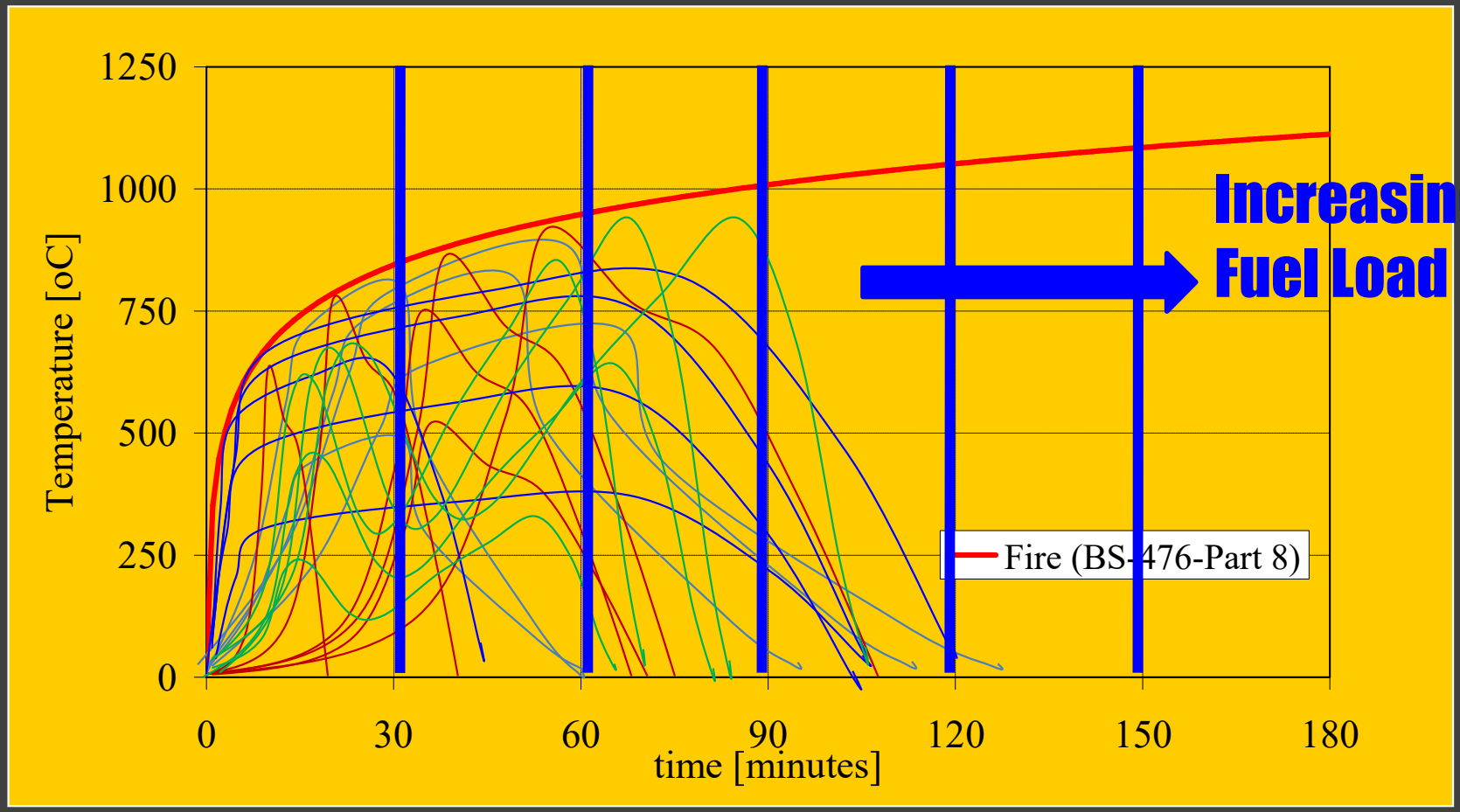


- Current approach is “Fire Resistance” (Ingberg S.H., “Fire loads: Guide to the application of fire safety engineering principles,” *Quarterly Journal of the National Fire Protection Association*, **1**, 1928.)

Origins

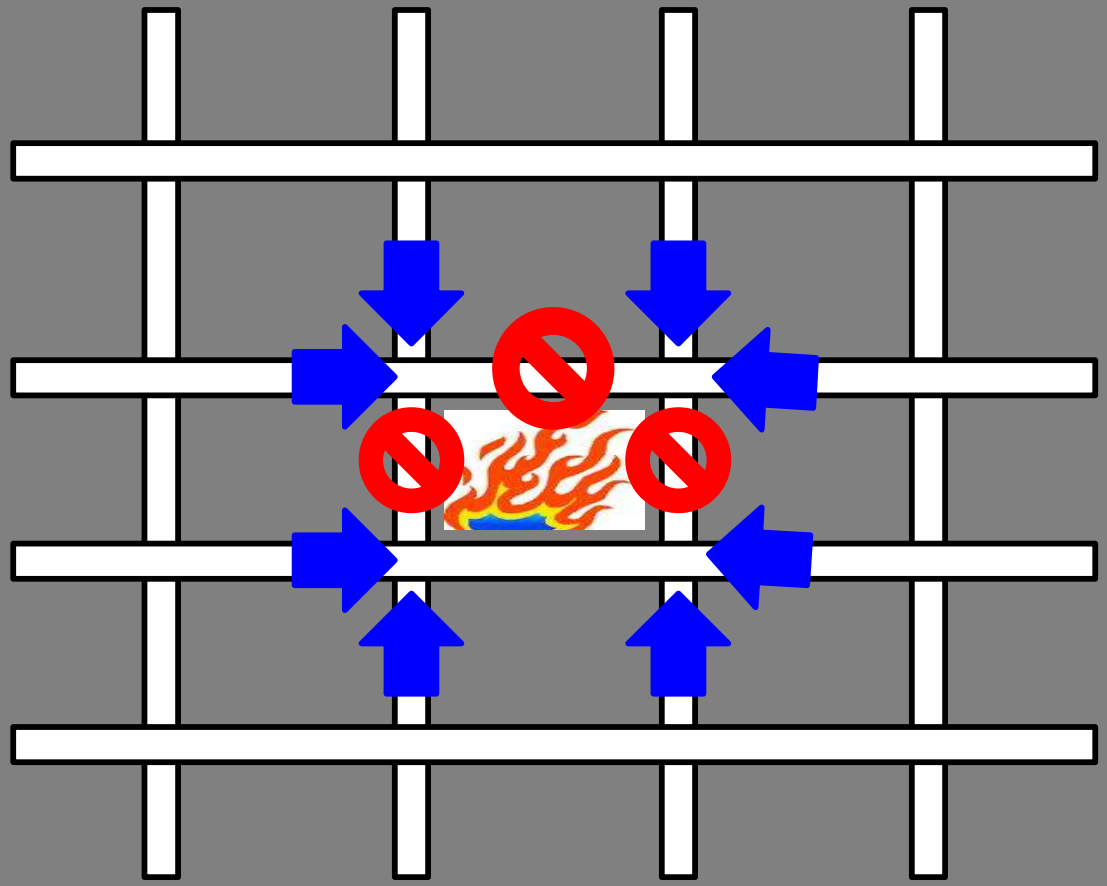


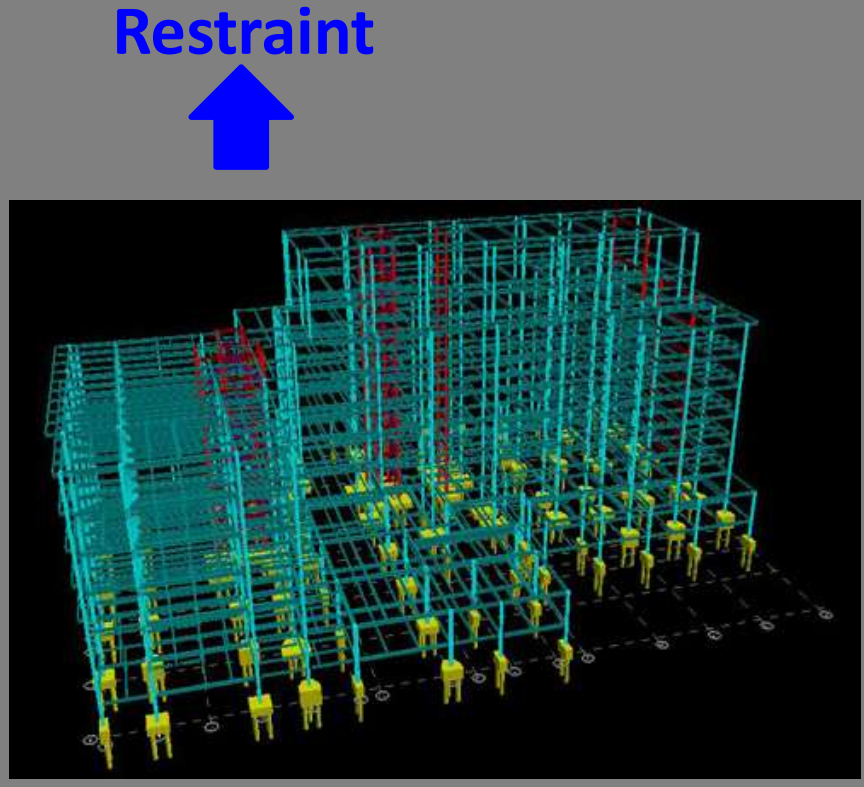
- Worst Case Scenario
- Curve defined by envelope to all fires
- Required Rating defined by total fuel consumption



Restraint

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

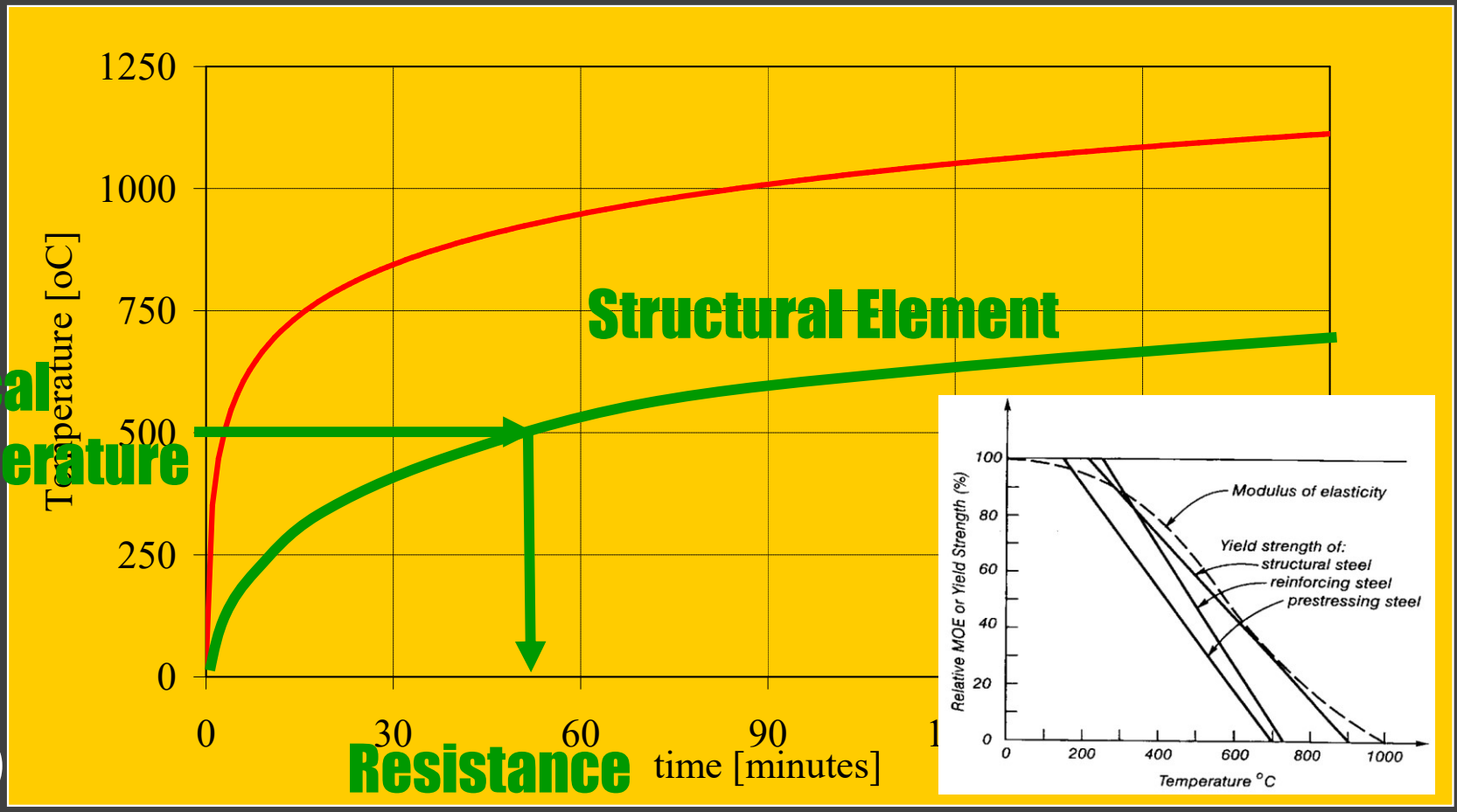




Standard Fire

- Furnace to reproduce compartment
- Single element tested





(Ingberg, 1928)

Large Safety Factor?

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









What is the expected performance of encapsulation?

The Brock Commons Test Results



"This passive protection is achieved through charring at the surface of the wood members which protects the remaining structurally sound wood." (2018-IBC proposal)



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

Existing Framework



1962-1972



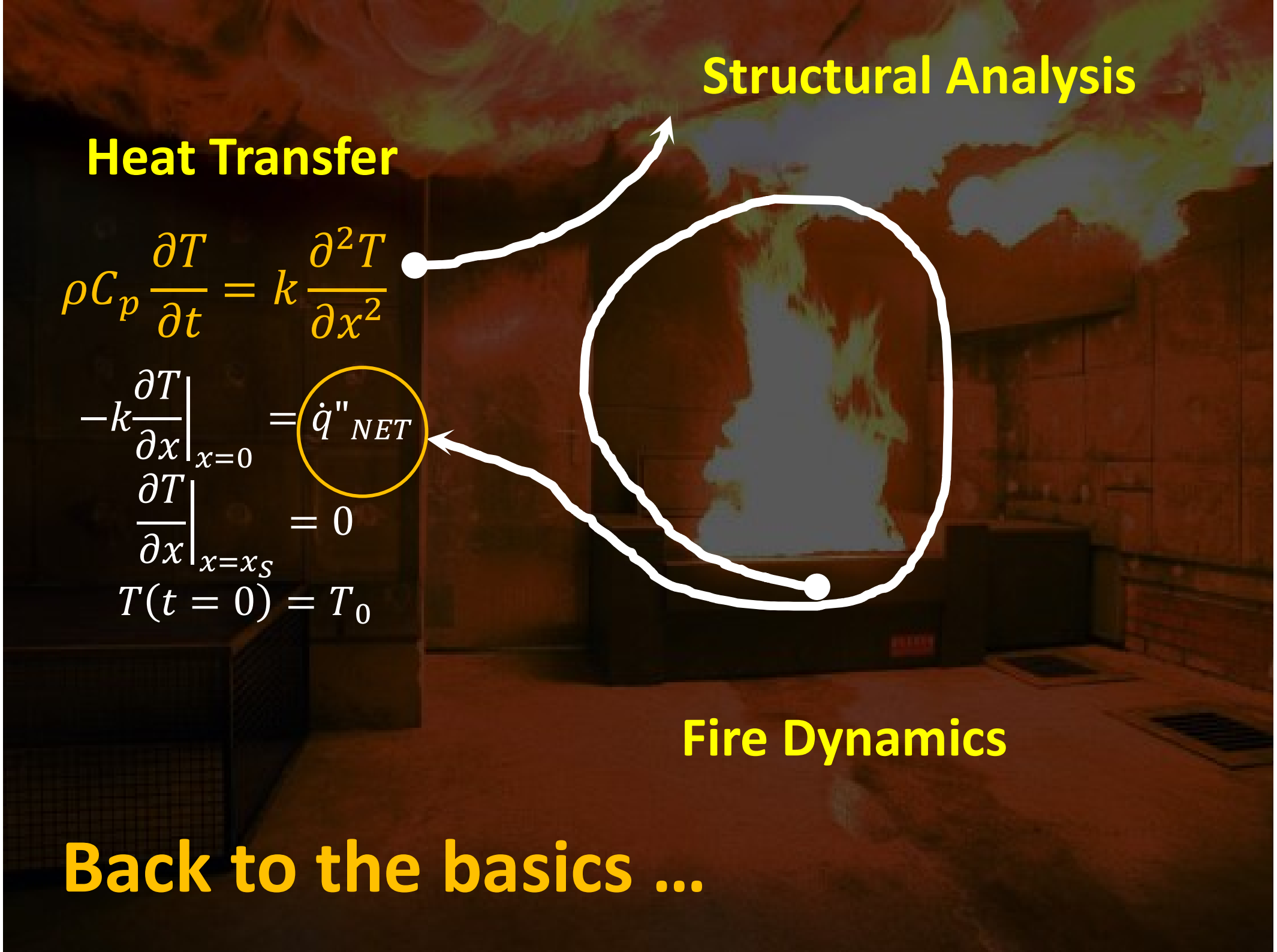
1969-1976

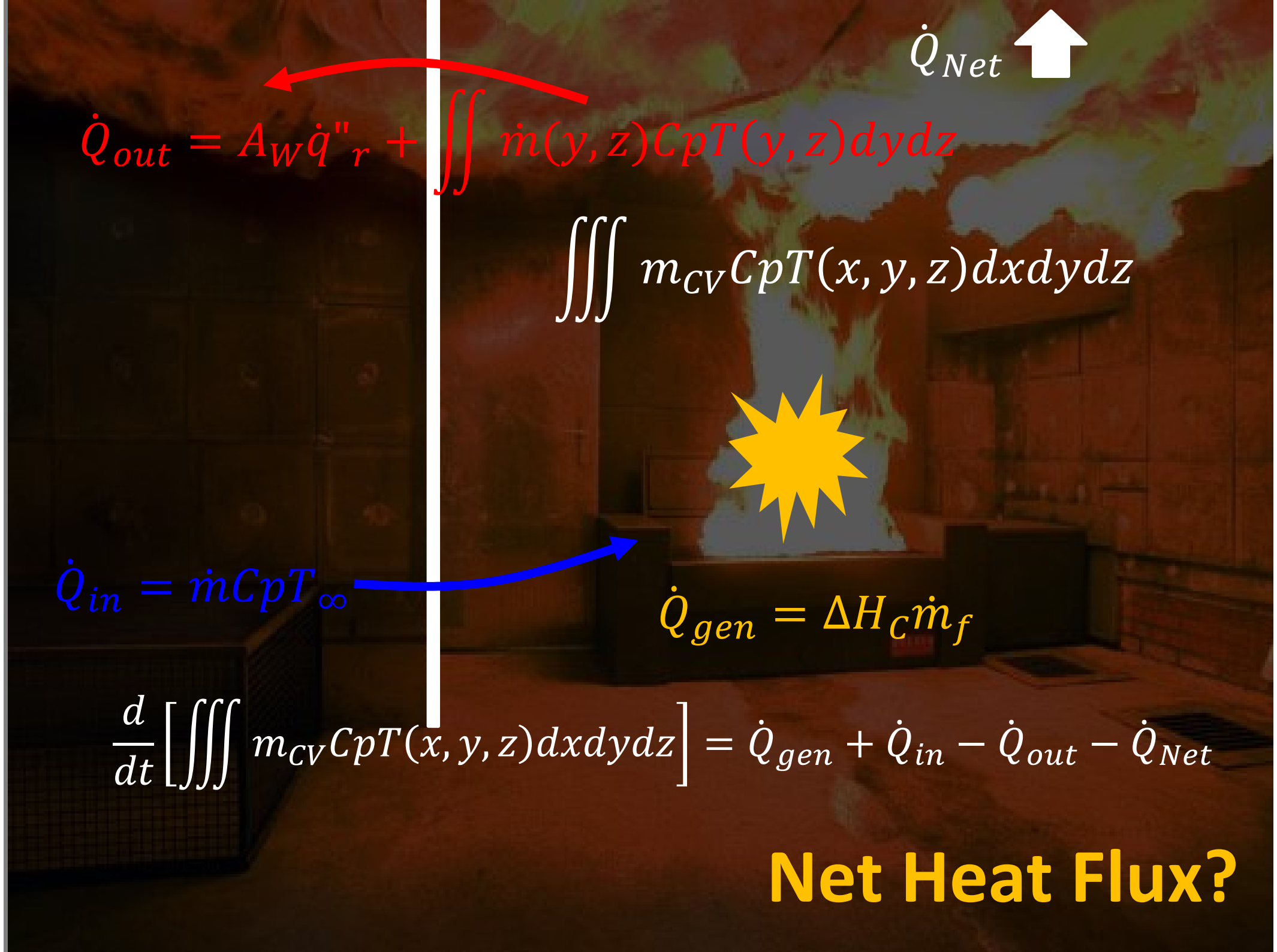


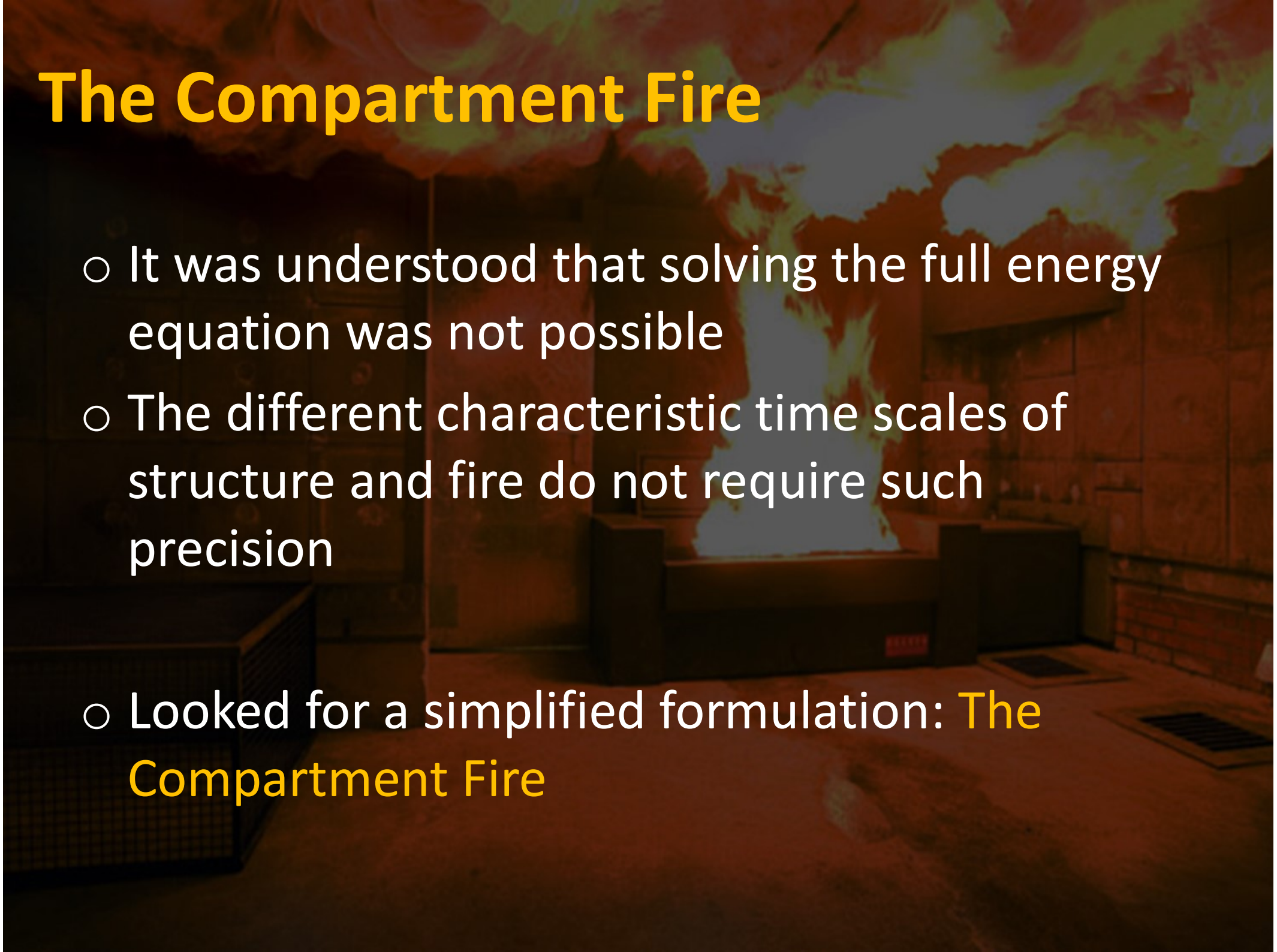
1958



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 …


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



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

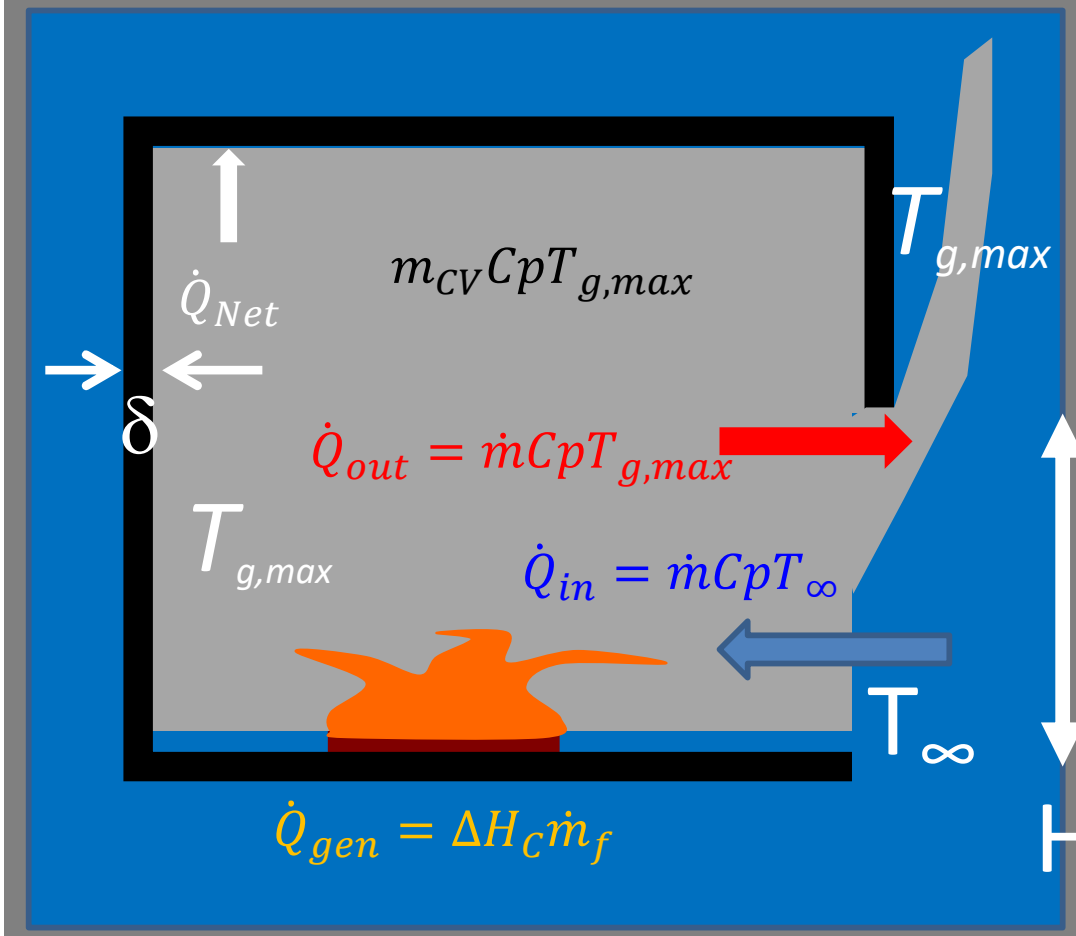
- The heat release rate is defined by the complete consumption of all oxygen entering the compartment and its subsequent transformation into energy, $\dot{Q} = \dot{m} Y_{O_2,\infty} \Delta H c_{O_2}$.
  - Eliminates the need to define the oxygen concentration in the outgoing combustion products
  - 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.

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



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

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

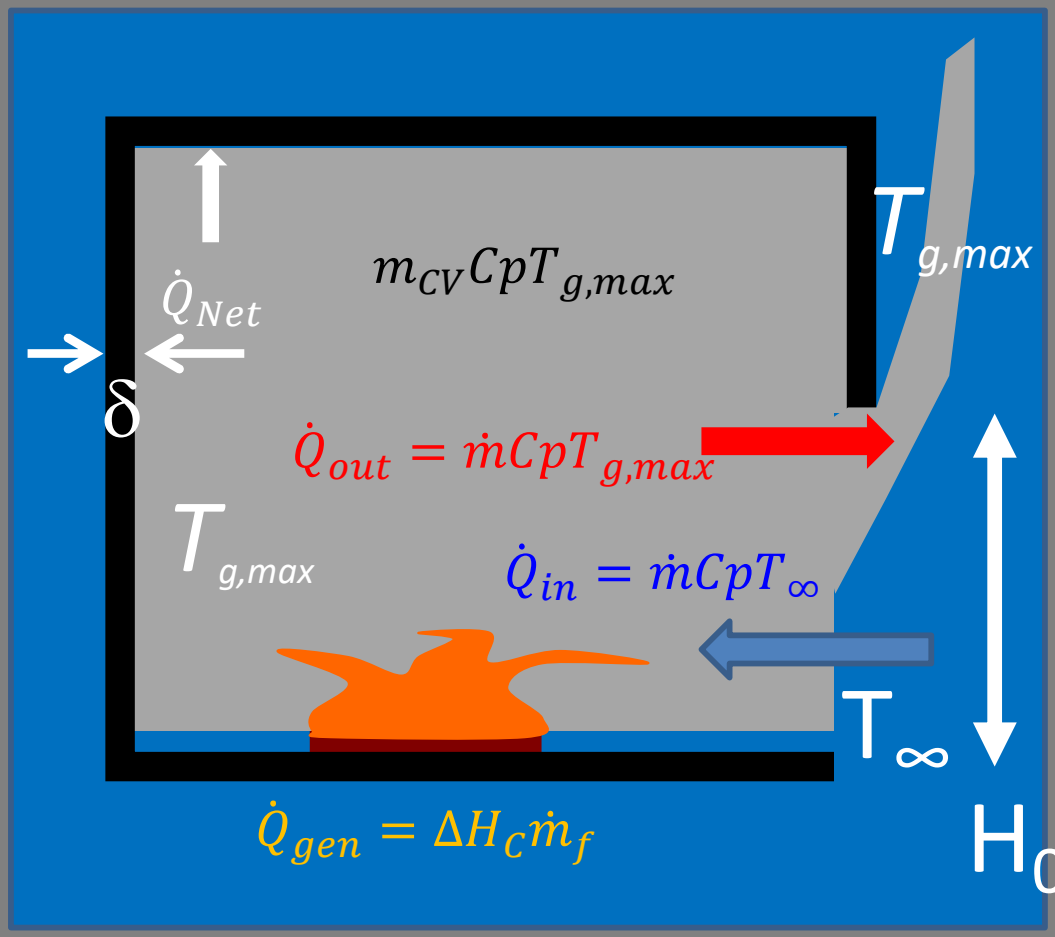
$$\dot{Q}_{out} = \dot{m}C_pT_{g,max}$$

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

Maximum Compartment Temperature

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

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



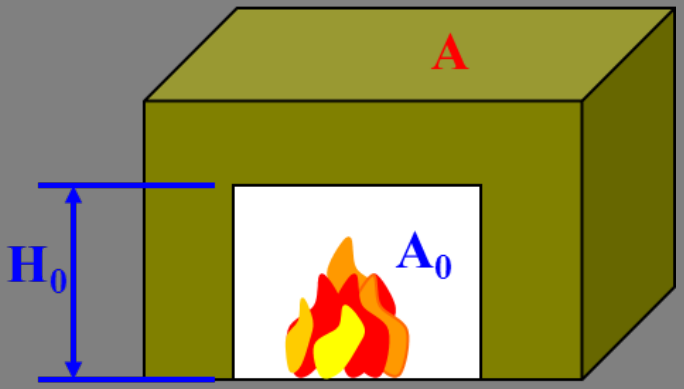
$$T_{g,max} = \left(\frac{1 + \frac{T_{\infty}}{T_{CD}}}{1 + \frac{T_F}{T_{CD}}} \right) T_F$$

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

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

The Data





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

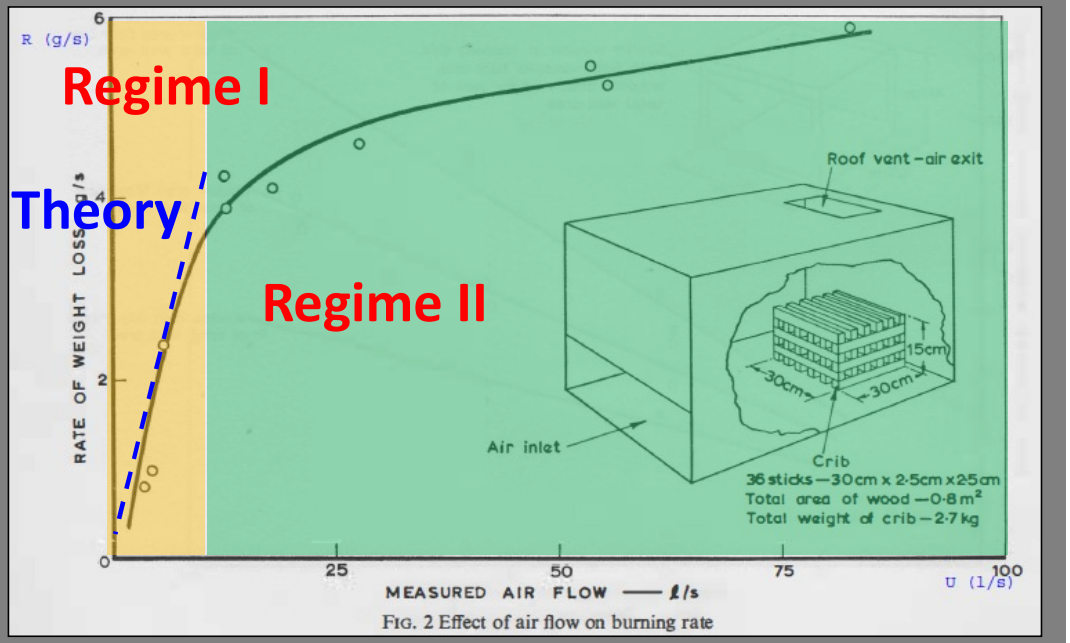
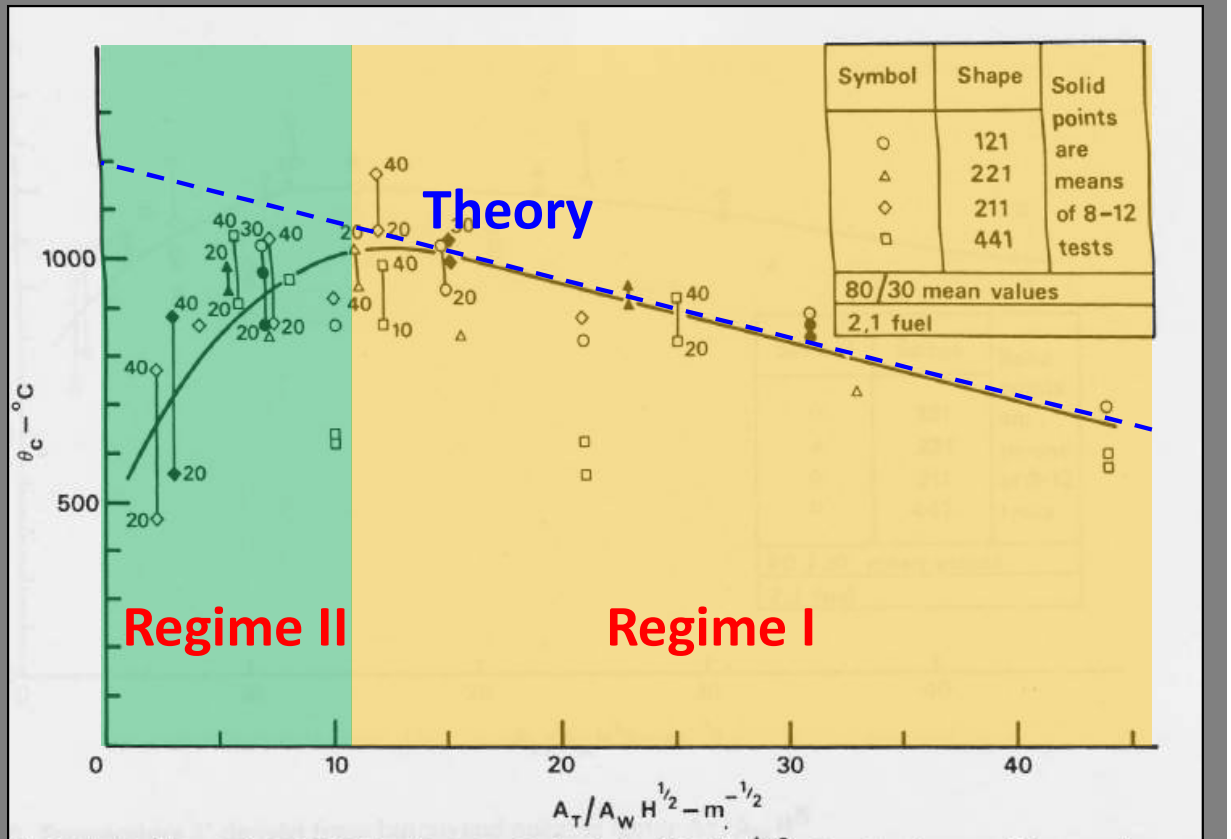


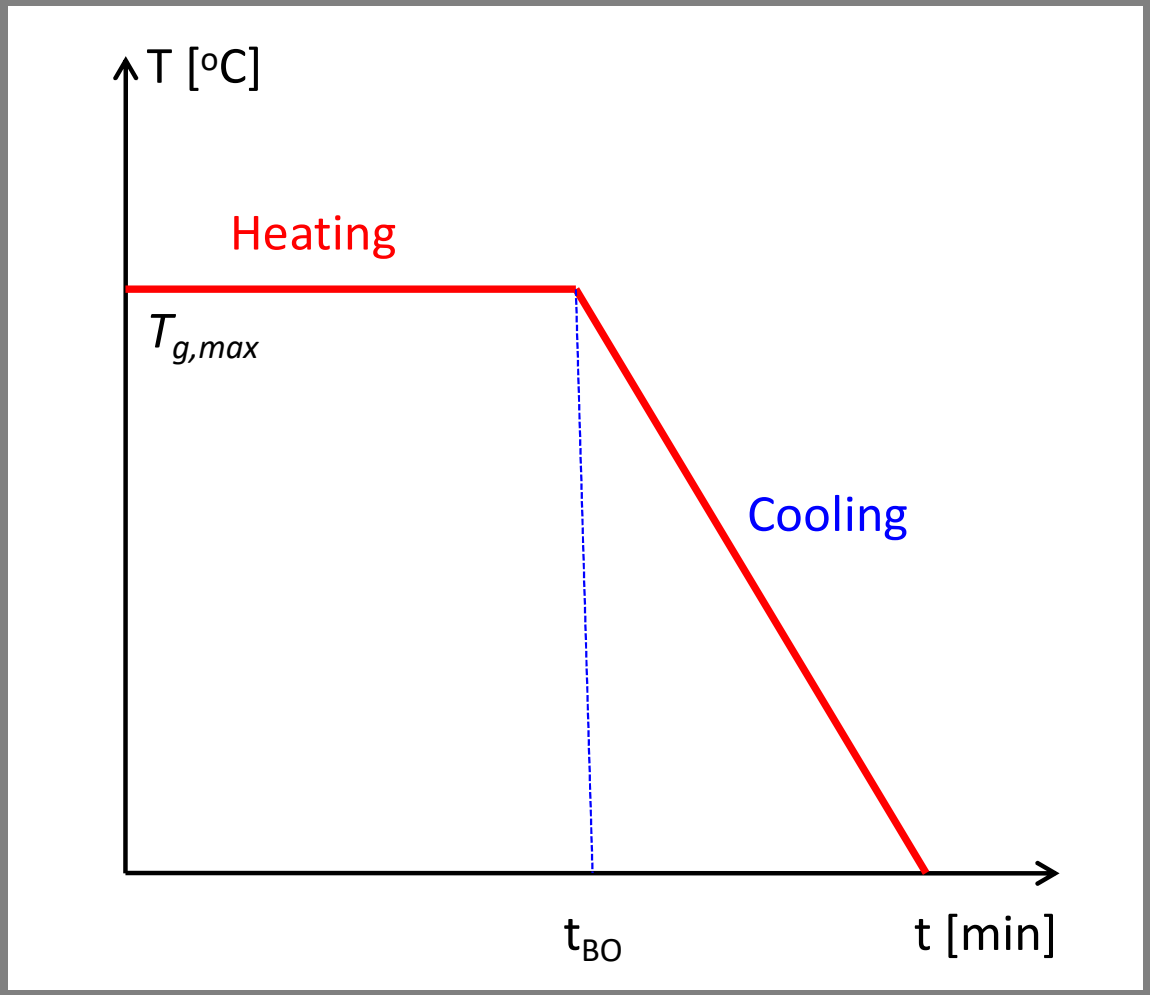
FIG. 2 Effect of air flow on burning rate

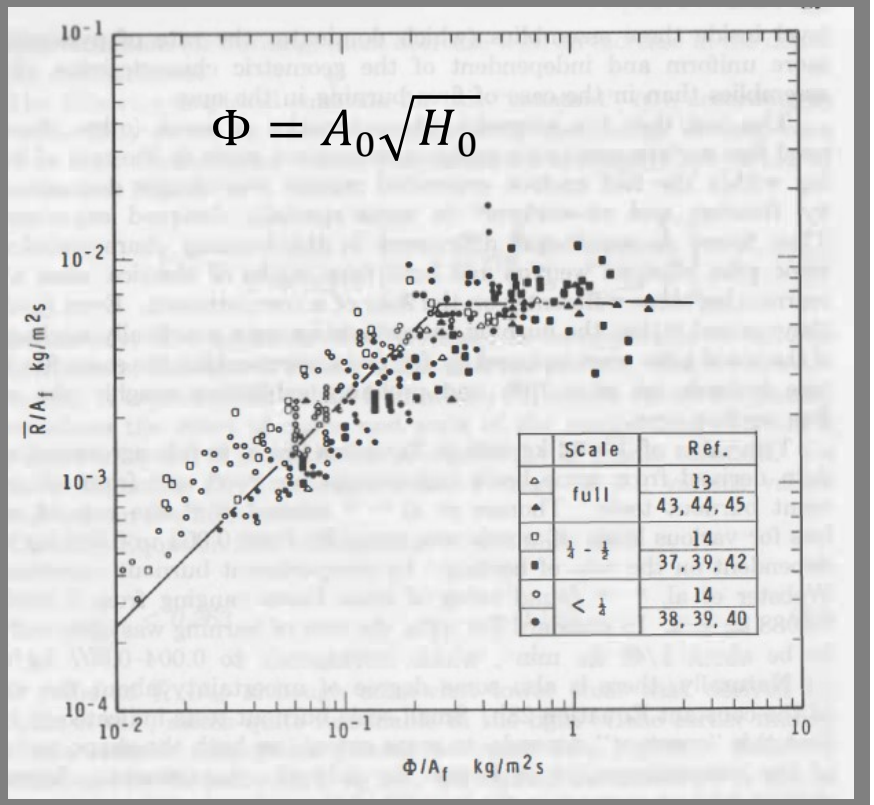


A_T excludes floor and opening. Numbers are fire load densities (kg/m²) at ends of range of temperatures

Design Method

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





$R = 0.1\ A_0 H_0^{1/2}$ (kg/s)

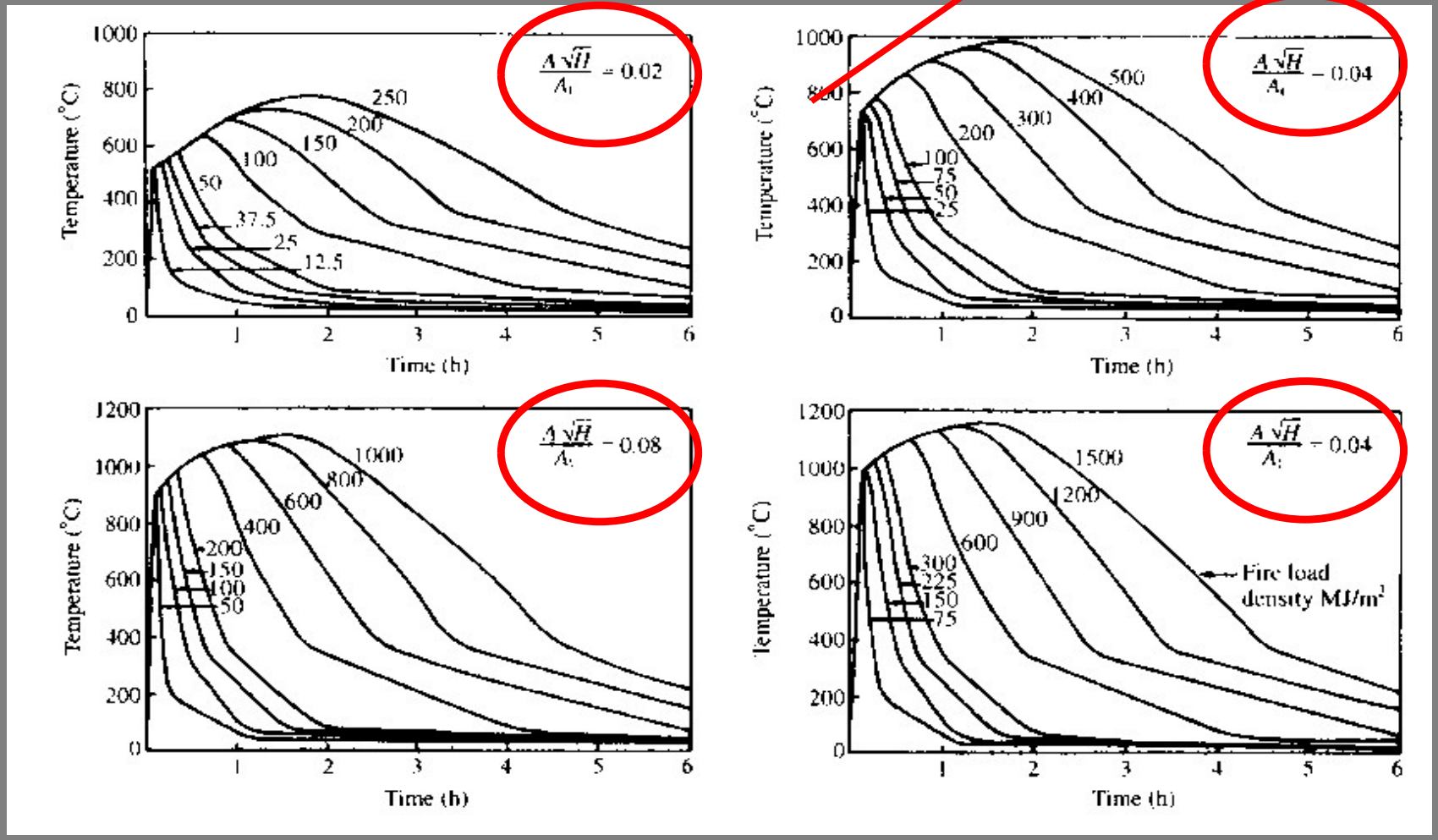
Kawagoe (1958)
Thomas & Heselden (1972)

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

Parametric Fires

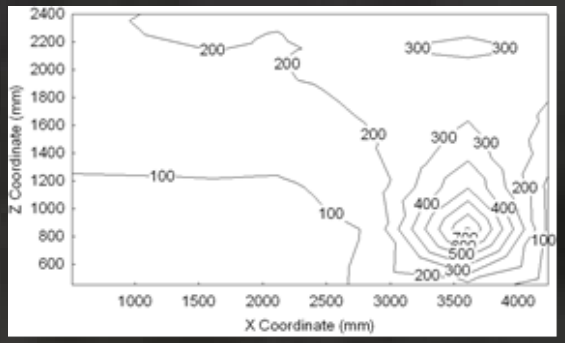
(Pettersson, O. Magnusson, S. E. and Thor, J. "Fire Engineering Design of Steel Structures," Stockholm, Jun. 1976.)

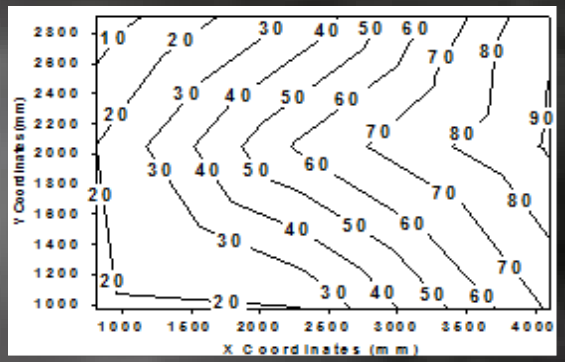
$\dot{Q}_{Net}$

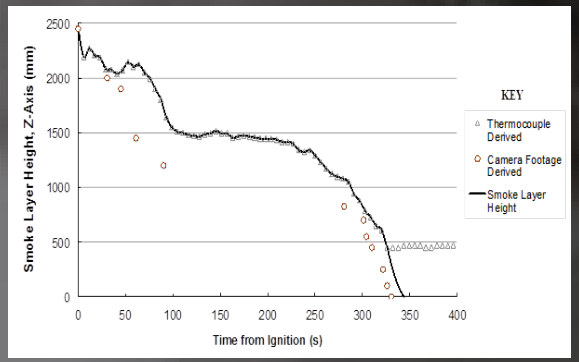


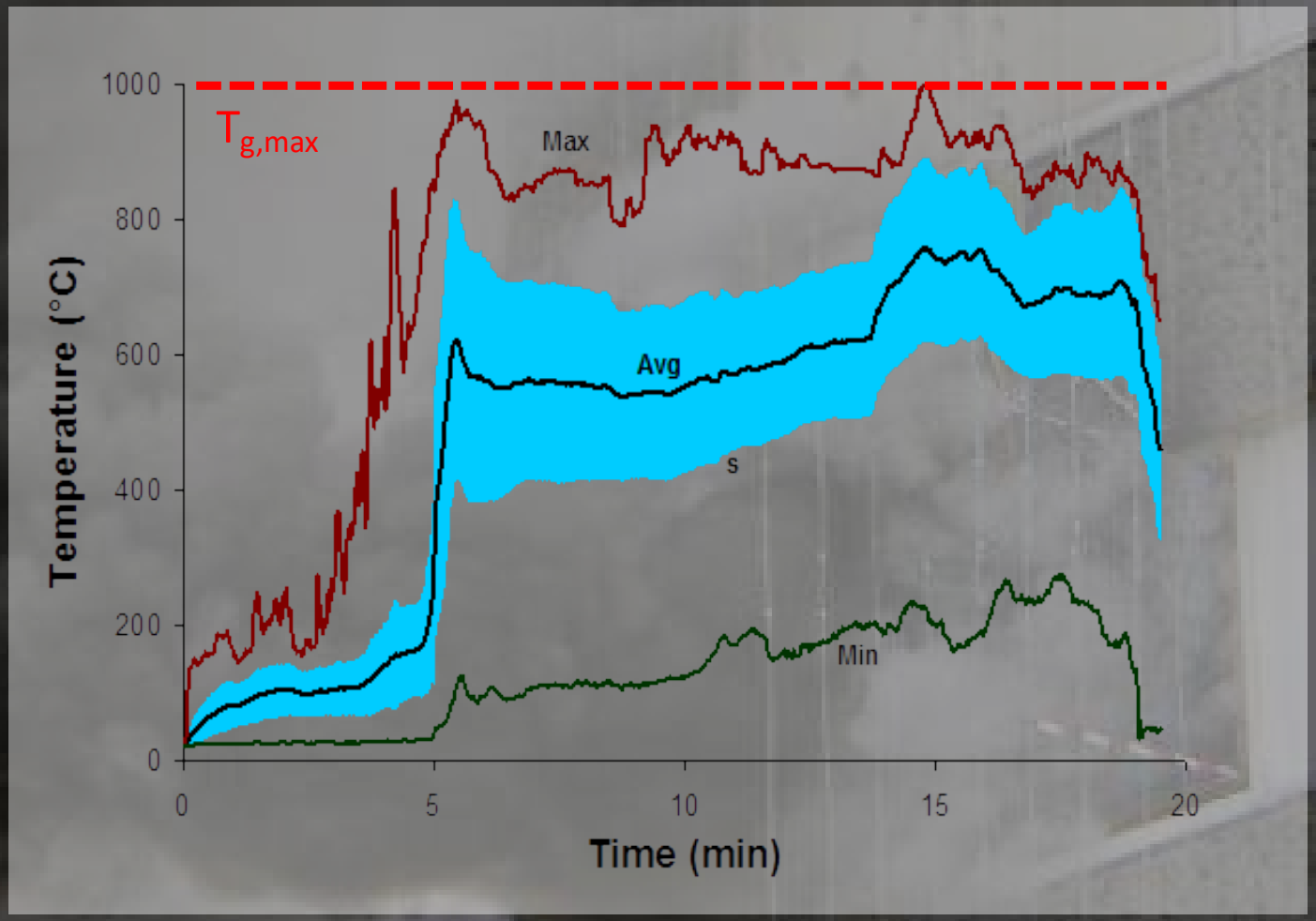
- Recorded temperature evolution – effect of structural heating
- Average temperature – single thermocouple rack (6 – TC)

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

Executive Summary

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

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

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

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.

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

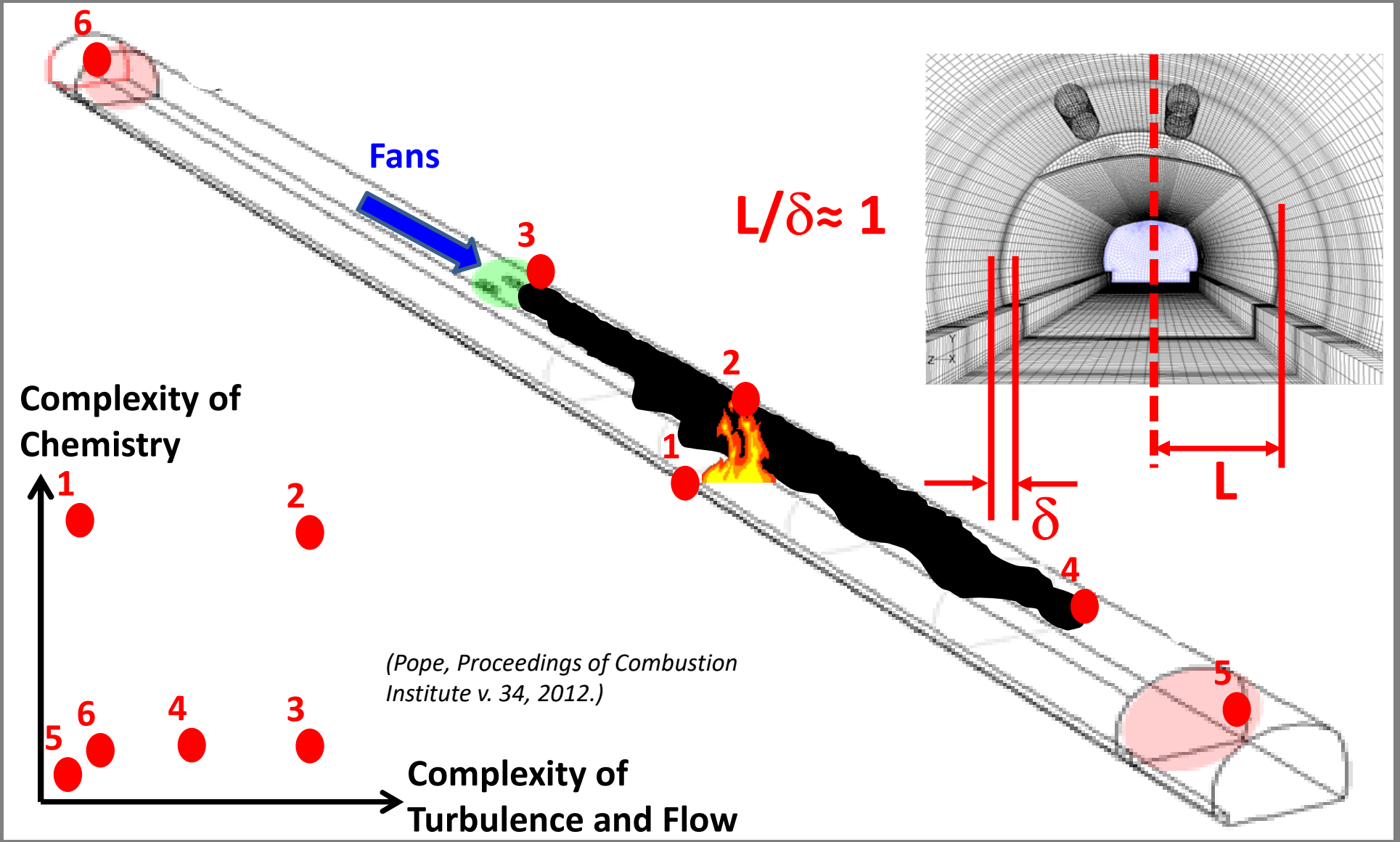
↓

Heat Transfer

↓

Air Entrainment

Complexity


6
Fans
3
2
1
4
5
L/δ≈ 1
δ
L
Complexity of Chemistry
1
2
6
4
3
5
Complexity of Turbulence and Flow
(Pope, Proceedings of Combustion Institute v. 34, 2012.)

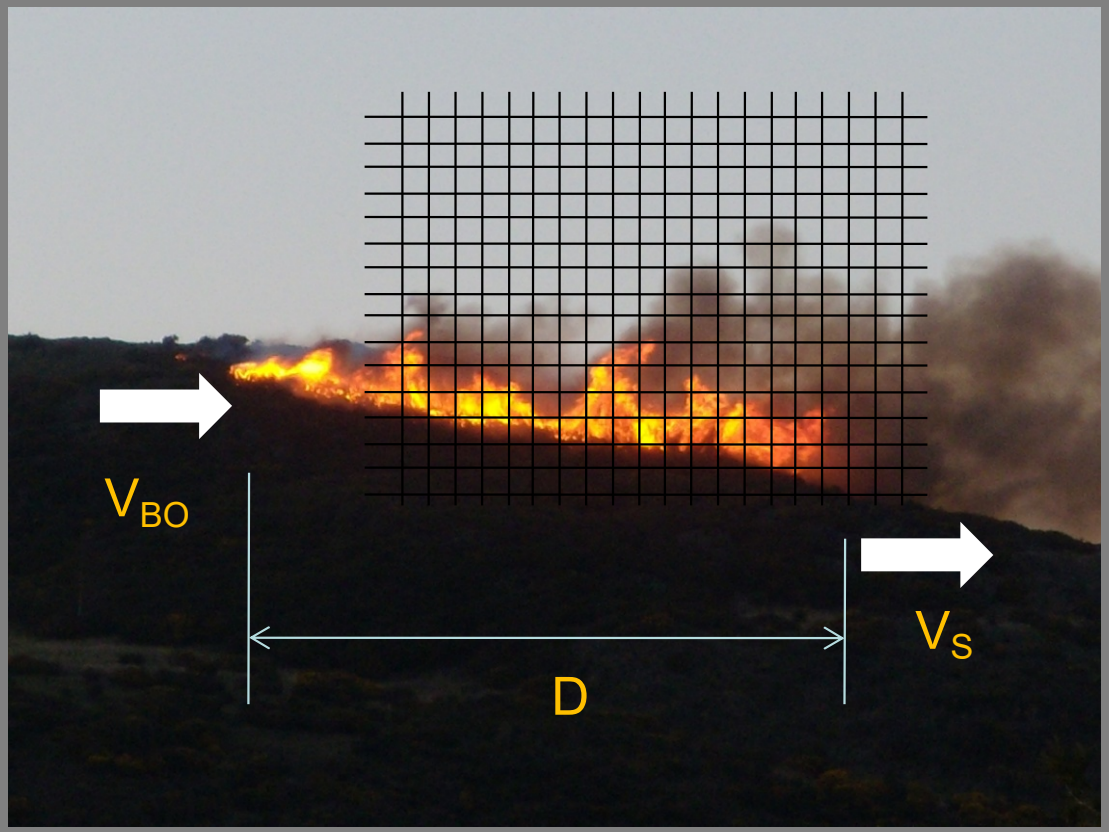
Incompatibility of Scales

Type	Time Scale (s)	Vertical Scale (m)	Horizontal scale (m)
Combustion	0 . 0 0 0 1 – 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

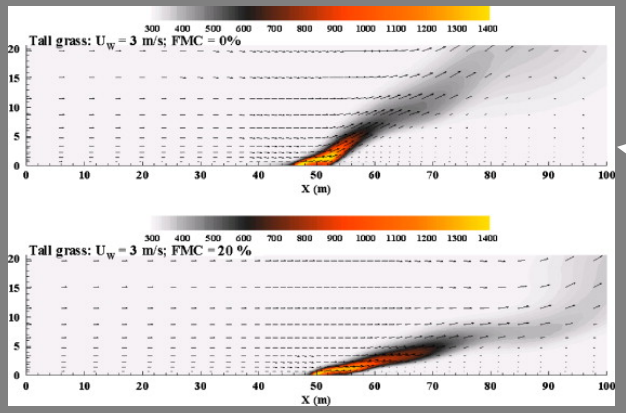
Sullivan, A., "A Review of Wildland Fire Spread Modelling, 1990-Present, 1: Physical and Quasi-Physical Models", arXiv:0706.3074v1[physics.geo-ph] (2007).

Classic Scaling-Up

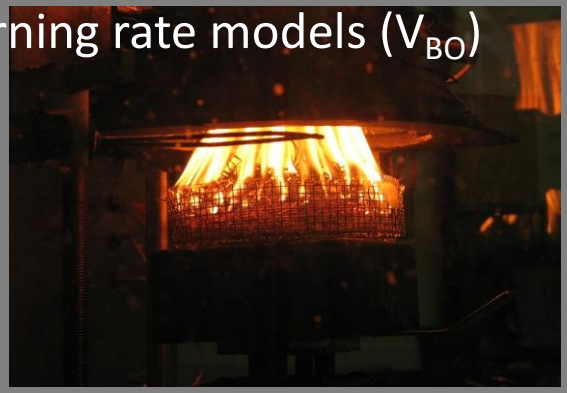
- Uncouple processes
- Develop simplified models
- Feed Models with experimental data



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



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



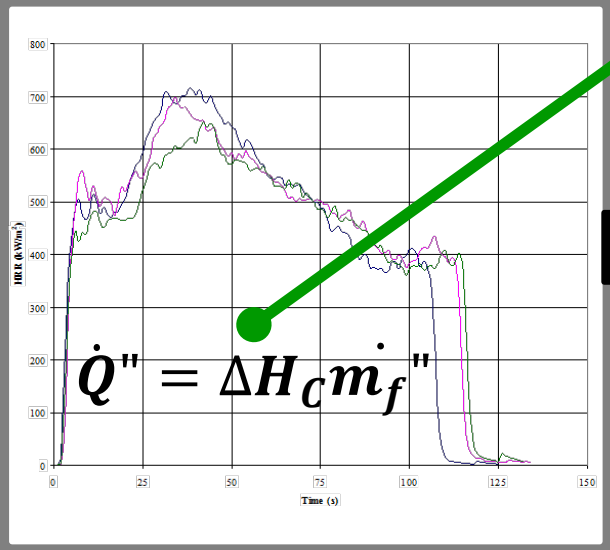
$\dot{Q}$, D

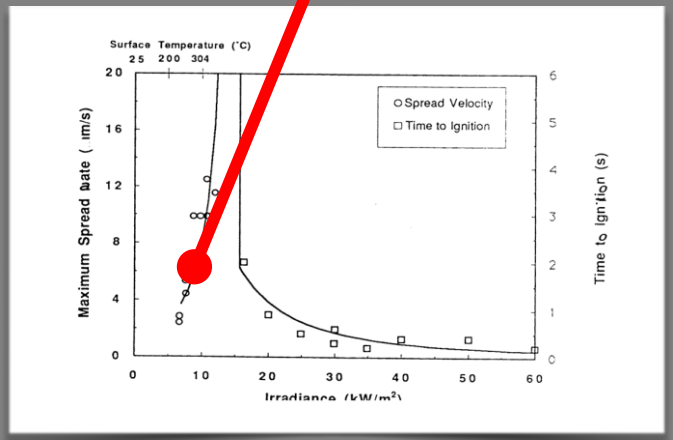
Compartment Fire

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

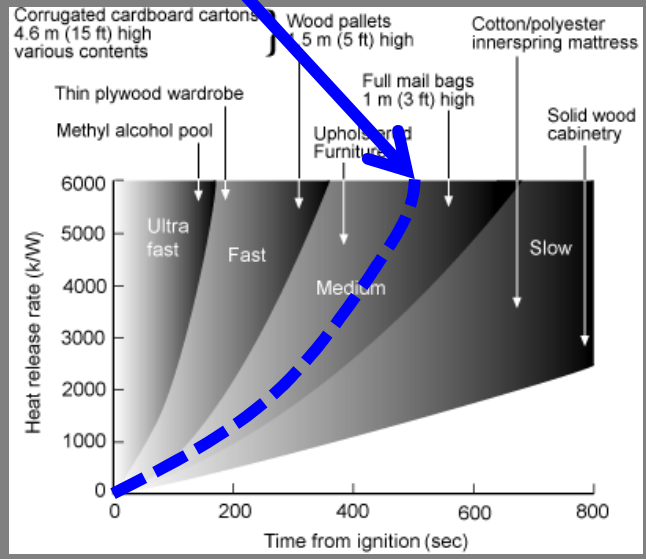
$$A_B = \pi r^2 = \pi (V_f t)^2 = (\pi V_f^2) t^2$$

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



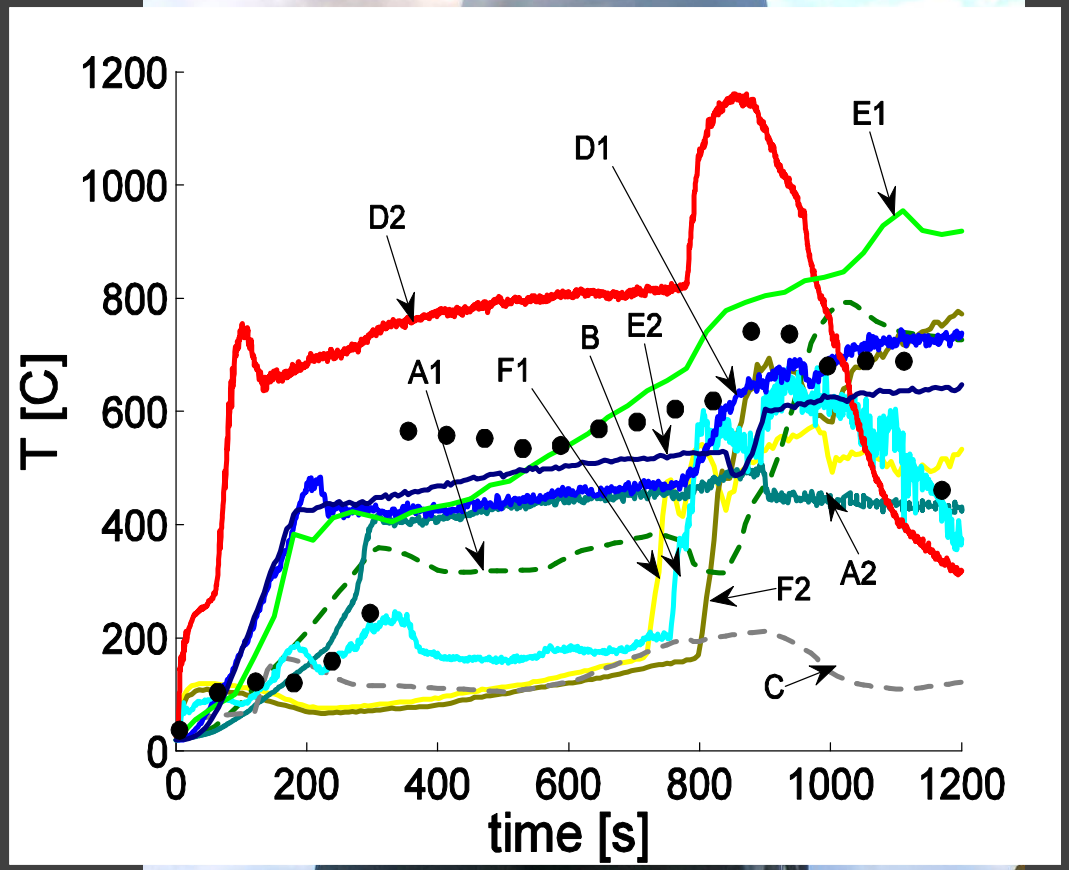


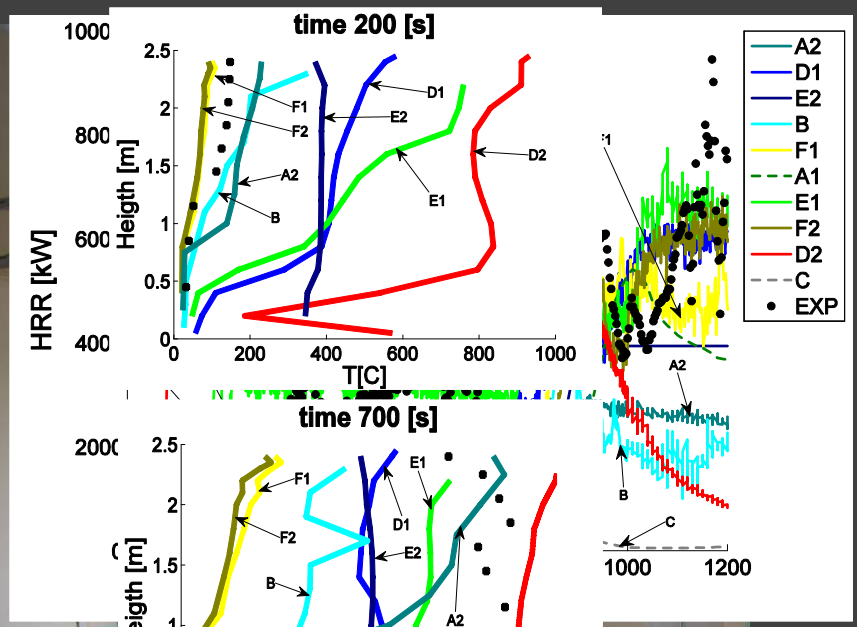
(Quintiere, 1998)



(SFPE, 2009)

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

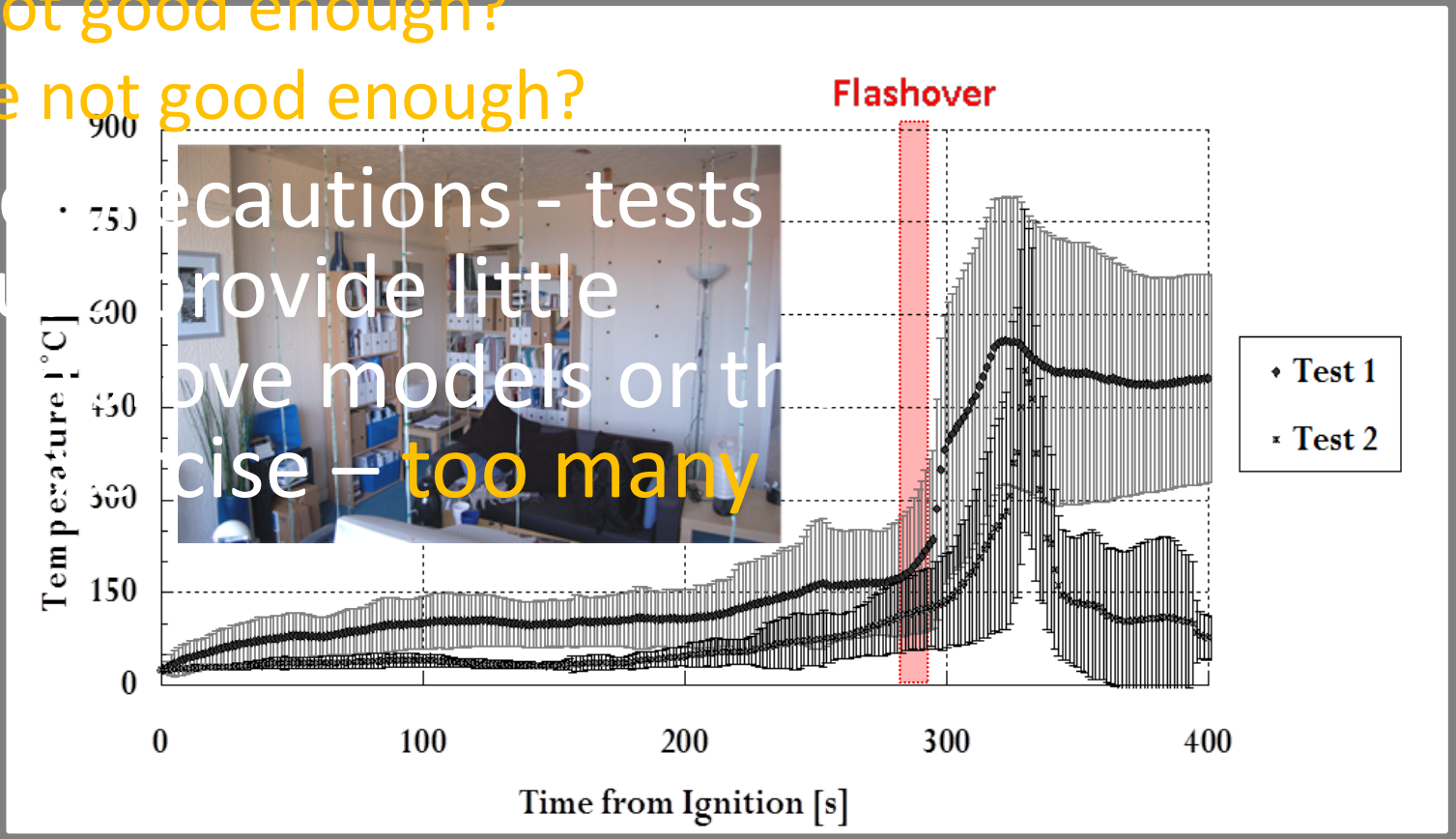




(Rein et al. 2009)

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 th ecautions - tests of this natu rovide little insight to i ove 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



Fire Safety of Historical Buildings: Principles and Methodological Approach

José L. Torero[1]

Abstract. This paper addresses an issue rarely contemplated in the management of historical buildings, fire safety. There is an implication that "compliant" means "safe" and that the goals and objectives of compliance are perfectly aligned with those of fire safety. In the case of historical buildings, this is a mistake that has resulted in the loss of major historical buildings through the centuries. This paper presents a framework of analysis that uses adequate tools to evaluate and establish true performance assessment. The objective is to adequately define and implement the goal of fire safety. This paper is not a traditional research paper in that it does not describe experiments, computations or analysis. Instead, this paper proposes, through an example of application, a critical overview of problems incurred when evaluating fire safety on the basis of solutions issued from prescriptive approaches. In the process, this paper highlights the value of a comprehensive performance-based approach. A performance-based analysis emphasizes an approach to design that values the inherent features of historic buildings. This could potentially result in minimum and rational alterations that meet the goals of fire safety while also achieving other restoration objectives.

Keywords: fire safety, fire protection, regulatory compliance, fire dynamics, life safety.

1 Introduction

The implementation of fire safety in the built environment has been traditionally a very prescriptive process. The goal is one of protecting life against the hazard of fire. While fire safety is directly related to the laws of physics and the management of human behavior in a high-risk situation, these laws of physics are rarely invoked and instead its implementation is generally associated to code compliance. Codes, incorporate elements of human behavior and fire dynamics, nevertheless they are the result of multiple compromises, many of which are associated to a temporal perception of safety, the available tools and the construction typologies. What was perceived as safe in the past might not be perceived as safe today. Buildings are thus constantly being retrofitted so as to be updated to new code requirements. These code requirements, in turn, are deemed to provide an acceptable level of safety as it is perceived today. The implication is that compliance means safe and that any building that is not code compliant, to the current prescriptive requirements, is therefore unsafe and needs to be retrofitted. Obviously, there is a limit to this approach. Many times, buildings cannot be retrofitted and therefore codes provide provisions for grandfathering non-compliant structures as well as for the use of performance based tools. Grandfathered buildings will never be perceived as safe and therefore many concessions on the building use become necessary. Performance based design is rarely used as such, and when it comes to historic

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buildings, its use is mostly directed towards obtaining certain specific equivalencies that allow to ascertain that omissions to the codes are acceptable.

When it comes to historic buildings, the building incorporates a contextual value that is generally not accounted by codes. Certain features of the building (ex. architecture, ornaments, construction techniques) cannot be modified without diminishing the value of the building. Furthermore, many times the building will house inherently valuable objects that are part or not of the fabric of the building (ex. murals, paintings, art object, religious objects, etc.). Many of these objects and their use can represent a hazard themselves (ex. preservation fluids in a natural history museum, fabrics in a textile museum, candles in a church, etc.). These features of historic buildings make them a challenge because it becomes unacceptable to alter the building to include modern fire protection features (ex. smoke detectors, sprinklers, fire rated stairs, etc.) and it is many times impossible to manage hazards in a manner consistent with code assumptions (ex. no combustibles in egress paths, fuel characteristics corresponding to the assumptions embedded in the design of fire protection systems, etc.). Thus, the fire safe design of a historic building represents a challenge. The challenge is based on the need to achieve an adequate level of safety, in a building that has many alteration constraints and where common tools for fire protection become unacceptable.

The conventional approach of attaining compliance or to implement equivalent solutions by means of bridging performance-based design has proven inadequate resulting in many losses where the final explanation is that the building was non-compliant and therefore the failure should be expected.

Detailed reviews of many aspects of fire safety in the context of historical buildings have been written [1] and the unique features of historical buildings that affect fire safety have been recognized by many and have been discussed many times in great detail. Nevertheless, these reviews focus on framework type explanations of the different problems but do not offer a means to take advantage of the inherent features of the historical buildings.

Carattin and Brannigan [2] provide one of the most eloquent reviews of the complexities associated to the implementation of fire safety in historical buildings. Not only they address the multiple variables of the problem, the major constraints associated by the nature and value of the buildings but they also study in detail the many limitations of the analytic tools commonly used for establishing if a building is fire safe. Carattin and Brannigan establish in their review [2] the weakness of codes and standard design practices when addressing historic structures. Their concern is summarized when they state that: “because they are called “buildings,” designers and code writers and enforcers routinely assume that they are simply older versions of the modern buildings they work with. But they are not.” The review covers several examples and relevant issues nevertheless is centered around life safety and only briefly discusses other issues associated to the fire safety strategy.

The focus of most of the work on fire safety of historical buildings remains on life safety and the means to quantify in a comparative manner the importance of the building and its contents is not clearly discussed. A very good example of this approach is the review by Bernardini [1] where, after a detailed explanation of the

issues, the focus is placed back on effective means of wayfinding as a mechanism to aide egress without major modifications to the building fabric. Reviews that address recent advances in codes and legislation treat fire in a simple manner and remain focused in the adaptation of buildings to meet current standards while taking into account the desire to minimize intervention ("older versions of the modern buildings" [2]). None of these changes take advantage of the inherent safety of the historic buildings or propose novel approaches towards a quantitative analysis of safety [3].

Studies have addressed management as a means of improving life safety in historical buildings, but the principles evoked are a simple and direct extrapolation of approaches used for modern buildings [2] without a direct link to the inherent features specific to historic buildings [4].

The review by Marrion [5] attempts to describe performance criteria that could be used as a basis for design. In this review a lessons-learnt approach is presented, where a series of assumed causes for fires are presented but which are not based on thorough fire investigations. Thus, the link to adequate intervention is tenuous. Methods to deliver performance based designs have even been codified [6, 7], nevertheless as described by Watts and Solomon [8], much of what is presented in NFPA 914 [6] relies on judgments that are partly subjective and on agreement of the involved parties, including the authority having jurisdiction. The focus therefore still reverts back fully to life safety and is tainted by expert judgement. Carattin and Brannigan [2] warn against expert judgement as a means to address fire safety in historic buildings.

One of the clearer attempts to use a performance approach towards the analysis of a historic building addresses the refurbishment of the "Teatro Comunale Niccolò Piccinni" in Bari [9]. Here, a combination of fire protection measures and calculation tools are used to deliver what is deemed as an acceptable solution. This solution incorporates structural components, new compartmentalization requirements, active fire protection measures and major modifications of the architecture (stairs). Despite the detailed explanations provided on the measures taken, there is no quantitative assessment on how the objectives of the refurbishment were attained or on how the inherent features of the building supported the proposed solution. The exception is the structural analysis where performance criteria are defined but they are established either in regulatory terms (i.e. Fire Resistance [10]) or by means of arbitrary thresholds (i.e. 400ºC fires). These criteria are valuable in that they serve to assess the robustness of the structure but do not take account the actual fires possible within the building. In some manner, the treatment of the historic building remains as that of an older version of a modern building [2].

Approaches that deviate from life safety have also been published. Many of these studies have produced frameworks that analyze in a systematic manner risk within historic buildings or the potential upgrade options that can be used to upgrade the fire safety of historic buildings. These studies use complex tools such as Analytic Hierarchy Process [11] where all options are tested against constraints such as cost or valuable historical attributes. Many of these studies rely on expert opinion but do not define what constitutes an expert (against the warnings of reference [2]) or how the risk assessment can be transformed into design approaches that take

advantage of the inherent features of the building [12]. In some cases, these risk assessment tools have even been incorporated into Geographic Information Systems (GIS) [13] without resolving the basic principles of fire safety and many times defining fire safety on the basis of incorrect principles such as ignition risk. In a similar manner, studies have suggested the use of BIM for the purposes of addressing fire safety, in particular the Historical Building Information Modelling (H-BIM) approach. While accurate digital representations of historic buildings will be with no doubt valuable to achieve an optimized approach to fire safety, none of these approaches has yet incorporated any of the fundamental issues of fire safety [14]. These studies fail in several manners, first they do not establish in a quantifiable manner the safety objectives, second, they do not take into account the beneficial attributes of the building and finally they do not address in a quantifiable manner the impact of proposed modifications. In the absence of these three fundamental features these approaches cannot be used.

What would be discussed here is an alternative approach that puts forwards the fact that life safety and fire dynamics are processes that evolve in space and time and that are governed by the laws of physics and by well characterized human behavior. A such, if the objectives are clearly established and the tools are mastered by competent professionals, a safe but non-compliant historic building can be obtained with minimum intrusion to the historic value and significance of the building and without limiting its use or contents.

2 Current Approach to the Fire Safety Strategy

2.1 Fire Risk Analysis

Currently, a prescriptive fire safety strategy is based on the following premises. A building is expected to have a fire in its life. Fires, if considered in the most general way, are much higher event probabilities for a building than any other hazard. Therefore, the probability of a fire is effectively one. This is very important because it changes the concept of risk. Normally, risk is defined by equation (1) [15]

$$R_g = P_g \, x \, C_g = P_f \, x \, C_f \approx C_f \qquad \textbf{(1)}$$

where R_g is defined as the general risk, P_g is the probability of the event and C_g the consequences. The sub-index "f" corresponds to a fire where $P_f \approx 1$ and therefore risk in the event of a fire is purely the management of consequences.

The assumption that a fire will occur equates to the acceptance that an ignition event will happen. This does not imply that this event will have significant consequences, but simply that it will happen. What is termed here as a fire event includes all possible scenarios and thus is an event that precedes the progression of the fire. For an ignition event to become a fire scenario, there have to be interactions between the fire, the building fabric, the fire safety measures and potentially the occupants. Form this initial fire event, scenarios will develop and there will be some that are more probable than others. Nevertheless, for the purpose of this paper, the evolution towards a scenario will be incorporated in the analysis of consequences.

This approach to event probabilities is not common when analyzing other hazards like earthquakes or floods. In these fields, the consequences need to be managed but they are generally subordinated to the evaluation of the event probability [1]. For other hazards, we design for events of a certain acceptable probability and therefore we can define loads against which we can evaluate the design (ex. one in one-hundred-year event). Therefore, performance assessment becomes a natural path. In the case of fire, the objective is simply to manage the consequences of an event that will happen. In the absence of a fire safety strategy many fires will result in unacceptable consequences, so the purpose of the fire safety strategy is to manage the consequences in a manner such that the probability of a fire resulting in unacceptable consequences is sufficiently low. The manner by which codes establish what is a probability that is low enough that it can become acceptable to society is integrally based on life safety [16-18]. In the case of historical buildings, given the value society assigns to the building and its contents, this approach is insufficient.

The focus on life safety has limited the capacity to develop fire safety strategies that carefully incorporate the characteristics and value of the building and its contents. This is a fundamental weakness when it comes to respectful restoration but also limits the rigor applied to the development of strategies that pertain the approaches used towards safe management of restoration sites.

2.2. Current Prescriptive Approach

Prescriptive approaches will manage fire events by first defining the characteristics of the event. First, the event will be considered a single accidental fire that will be placed and defined according to scenarios that are considered possible. For example, if a building includes a kitchen, a kitchen fire becomes part of the consideration. Multiple events are excluded by separating them as criminal events (i.e. arson). A designer is therefore not required to design for multiple events. Many historical monuments have been destroyed in acts of war by circumventing this assumption [19] which demonstrates that proactive introduction of multiple events fully dismantles the fire safety strategy [20].

Buildings are classified as a function of their occupancy. Occupancy not only defines the use of the building but also defines the type and quantity of combustibles that will be expected to be present. Statistics have been developed for traditional occupancies (ex. assemblies, residential, hotels, hospitals, etc.) determining typical fuels and typical quantities. Thus, by providing a classification the potential fires against which the countermeasures will be defined are fixed. Codes will define then the fire growth as a function of tabulated fires. The most common approach is presented in equation (2) [21]:

$$\dot{Q} = \left[\pi \Delta H_c \dot{m}''_f V_s\right] t^2 = \alpha t^2 [kW] \quad \textbf{(2)}$$

where $\dot{Q}$ is the heat release rate and is the primary quantity that characterizes the fire size, ΔH_c (heat of combustion), $\dot{m}''_f$ (burning rate) and V_s(flame spread rates) are material properties that define the propensity of a combustible to release energy. "t" corresponds to the time from ignition and represents the rate of growth. All material properties are then integrated into a global parameter, α , which is then classified. Most codes will

classify materials as sustaining a slow growing fire ($0.0029 \leq \alpha < 0.0117\ [kW/s^2]$), medium growing fire ($0.0117 \leq \alpha < 0.0469\ [kW/s^2]$), fast growing fire ($0.0469 \leq \alpha < 0.1876\ [kW/s^2]$) and ultra-fast growing fire ($0.1876 \leq \alpha\ [kW/s^2]$)[21].

The classification of the fire event (as a pre-defined evolution of the heat release rate in time) allows to establish the event that is to be used as input when analyzing the impact of a fire on a building and its occupants. As explained before, the primary objective of a fire safety strategy is life safety. Thus, a primary objective of a fire safety strategy is to allow people to evacuate safely. Given the occupancy, the characteristics and quantity of people will be defined and thus typical egress times can be established. To guarantee appropriate notification of the occurrence of a fire, so that the onset of egress can be well controlled, building regulations will require appropriate detection and alarm systems. These systems are consistent with the occupancy, so while in residential buildings point detectors will alarm the residents and only the residents, in hospitals, smoke detectors will be connected to alarm systems and to building managers for a coordinated egress approach. Many variables will affect egress, these include behavioral variables as well as building characteristics [1,2]. These egress times are called the Required Safe Egress Time (RSET) [22]. The building will then be designed in a manner such that a fire that follows a certain growth classification will not attain untenable conditions anywhere in the building before all occupants have evacuated. Tenability is difficult to define but in general terms means conditions that challenge the safety and wellbeing of occupants or that are perceived as challenging by occupants. As such, carbon monoxide concentrations can be used as a tenability criteria because it can incapacitate occupants but also visibility because occupants will feel challenged by waking into a smoke laden space. Many guidelines will provide quantitative criteria on tenability mostly based on carbon monoxide concentrations, temperatures and visibility [21].

The Available Safe Egress Time (ASET) is the time required for any specific environment in a building to attain untenable conditions. In a building deemed to be safe ASET will always be much greater than RSET [22]. When the fire grows too fast and the occupants do not have sufficient time to evacuate then other provisions have to be put in place. If spaces are too large and therefore travelling distances are too long, then compartmentalization can be introduced either to protect egress paths or to stop smoke from entering adjoining spaces. The fire growth rate can also be controlled to increase the ASET. Sprinklers can be used to reduce the fire growth rate while requirements for fuel control can also be introduced. Both will effectively reduce or limit the value of "α" (Equation (2)). Compartmentalization is generally referred to as passive fire protection while sprinklers as active fire protection. Engineering tools can be used to determine different combinations of active and passive measures that deliver an adequate level of safety.

Compartmentalization includes all components of the barriers including doors and service penetrations. To guarantee compartmentalization strict rules of testing are implemented to provide certification to all building components. Certification is attained by means of fire resistance testing [10] which is a furnace test that is intended to reproduce a worst-case scenario and provide a time to failure for all components (i.e. a time to attain a critical failure temperature).

To facilitate egress all paths (ex. corridors, stairs, doors, etc.) for evacuation have to be designed ergonomically so that people can flow freely. The direction of egress shall also be signaled appropriately.

Redundancies have to be introduced, so compartmentalization is supported by active control of pressure in areas that need to be free of smoke so that air flows from the safe place towards the fire and not the opposite (ex. Pressurized stairs). Means of egress can be duplicated in case one is blocked by smoke or fire. The fire service is the ultimate redundancy to the overall strategy. Details on the components and implementation of a fire safety strategy can be found in reference [22].

Redundancies and factors of safety are introduced not only to provide robustness to the design but also to compensate for variability and uncertainties. The development of a fire as well as the behavior of people carry significant uncertainties. Any analysis needs to consider these uncertainties. In the case of prescriptive design, the treatment of variability and uncertain is implicitly incorporated in the code provisions, while in the case of performance based design appropriate treatment of uncertainties is part of professional practice. Given that this paper focuses on establishing a methodological approach, there will be no further discussion on variability and uncertainties, nevertheless, their appropriate treatment is clearly part of the methodological approach.

Through the entire egress process the structure needs to maintain stability, so all load bearing structural components will be thermally protected so that their temperature does not reach critical values were significant reduction of structural strength occurs. The required thermal performance is defined once again as a fire resistance by means of large scale testing [10]. Under these circumstances, codes will establish that there is no need to check for stability of the structure under the effects of a fire [23]. A fire that can challenge stability and is capable of leading to progressive collapse is therefore considered as an extraordinary (i.e. low-probability) event. Buildings have included an explicit structural performance analysis for fire only in the last 20 years and even then, only unusual, highly important or unique buildings have justified this engineering effort [24].

2.3 Outcome of a Fire Safety Strategy

A key weakness of the fire safety prescriptive approach is the fact that the overall outcome is never assessed. Codes will deliver solutions that are fitting to the classification, nevertheless, these solutions are not solutions to the fire safety strategy but to the components of the strategy. As an example, the National Fire Protection Association (NFPA) in the USA [25] has two opening codes NFPA1 and NFPA101, NFPA1 states the life safety goals of the code and NFPA 101 the different classifications and the basic principles of the solutions proposed. Other documents within the code will describe in more detail some special classifications (ex. hospitals, industrial facilities, etc.) but in general most other documents within the code will prescribe detailed solutions to the different protection components. As such, documents like NFPA 13 will describe sprinkler systems, NFPA 72 Detection and Alarm systems, etc. Compliance with the code is therefore defined as incorporating the correct components and implementing them adequately. There are no explicit objectives of overall fire safety defined by the codes. Given this approach, it is extremely complex to establish an “equivalent level of safety.” For historic buildings this is paramount because code compliance then is only possible if all the protection

measures prescribe by the code for the occupancy are implemented and implemented according to the requirements of the code.

3. Historic Buildings

Historic buildings differentiate themselves from other buildings in that the building in itself has sufficient value that it not only needs to be preserved in as intact a manner as possible but also needs to be explicitly protected. In contrast to conventional code compliant buildings, where life safety is the primary and single goal of compliance, in historic building other objectives gain significant importance. Life safety will remain a primary goal but it is no longer the single primary goal of fire safety. Historic buildings are part of national patrimony, many times hold objects of unquantifiable value and in most cases buildings and contents are irreplaceable. This added constraint requires changes to the approach towards fire safety. This change has to improve the strategy to account for the protection of the building and objects of material and historic value [1-9].

3.1. Fire Growth and Fire Damage

Fire growth no longer can be assumed simply as a function of material properties and a growth rate that is allowed to increase as a function of time. In a conventional building fire growth will, when unattended, lead to flashover. Flashover corresponds to the moment when the smoke layer produced by the fire reaches a sufficient temperature and soot volume fraction that results in enough radiation so that all other combustible objects ignite. At this point the compartment gets filled with hot smoke. The fire in this case will result in major damage to that compartment and all its objects [26]. Figure 1(a) shows a typical photograph of the aftermath of a post flashover fire. As it can be seen, all objects within the compartment have been destroyed and it is very likely that significant structural damage would have occurred. If this would have been a historical building, it is very likely that this type of fire would have resulted in unacceptable damage, even if life safety was not compromised. In a conventional building this might not be a major issue but in a historic building this could potentially represent a major loss. Thus, for historic, buildings a fire generally cannot be allowed to grow. There are two means by which fire growth can be controlled, by means of compartmentalization and by means of active fire suppression. Compartmentalization is many times impossible in a historic building because the structure cannot be modified, thus the importance of fire suppression increases. There is generally reluctance to introduce fire suppression systems in historic buildings for two primary reasons. The first is that it represents an intrusion to the architecture, and this is many times unacceptable. Second, in case of an accidental sprinkler activation, water damage can be as devastating as a fire [2]. The second issue is truly not a significant one. While conventional suppression systems might experience these problems, tailor made systems should not. A dry pipe with higher level of reliability and multiple activation devices is always a possibility [25]. The first issue is more relevant and needs to be carefully considered. Concealed sprinklers are possible but still represent an intrusion to the architecture and many times it is impossible to introduce the piping without damaging valuable features of the building.



(a) (b)

Figure 1. Consequences of a fire (a) a post flashover fire with generalized damage [27] (b) a fire that not reached flashover with localized damage (University of Geneva) [28]

3.2. Controlling Fire Growth

As an example, Figure 1(b) presents an image of the University of Geneva building after a significant fire [28]. In some areas of the building the fire reached flashover damaging objects but also the fabric of the building. Sectors of the roof were severely damaged and require complete replacement. Instead, other areas, like those illustrated on Figure 1(b) only showed localized damage. Thus, the loss was not complete and many valuable elements of the architecture could be cleaned and reconditioned during the 2014 rehabilitation of the building [28]. This example serves to illustrate that given certain characteristics of a building, conditions might be such that flashover will not occur. While this example will be discussed in much more detail later, it is useful to show that these characteristics can be exploited to protect the building.

The main reason why flashover did not occur is because of the large volume of the public areas. Flashover requires for the smoke to reach a certain temperature (generally assumed to be around 600°C [6,7]) and contain a certain concentration of soot. The soot volume fraction defines the emissivity of the smoke and the temperature its radiative power [21]. Radiation from the smoke layer delivers heat to all combustible materials and once a critical value for ignition is attained, all combustible materials will ignite and flashover will occur [26]. The temperature and species concentrations of the smoke layer are defined by the smoke migrating upwards from the fire and into the smoke layer. The temperature of the smoke and species concentrations are correlated through energy and mass conservation equations [21]. Equation (3) shows an example of the energy conservation equation for the smoke

$$T_S = T_\infty + \frac{\dot{Q}_c}{\dot{m}_A C_p} \tag{3}$$

Where T_S is the temperature of the smoke, T_∞ the ambient temperature, $\dot{Q}_c$ is the fraction of the energy released by the fire delivered to the smoke, $\dot{m}_A$ is the mass of air entrained by the fire and C_p the specific heat capacity of the smoke. A similar conservation equation can be constructed for the soot volume fraction showing

that it will also depend on the heat released by the fire ($\dot{Q}_c$) and the mass of air entrained ($\dot{m}_A$). The mass of air entrained can be obtained by a simple correlation of the form [29]

$$\dot{m}_A = C\dot{Q}_c^{\,1/3} H^{5/3} \quad \textbf{(4)}$$

Where C is called the entrainment constant and is an empirical value corresponding to a specific type of fire and H is the smoke free height between the floor and the smoke layer. This height will initially be the floor to ceiling height of the room but later as the smoke accumulates it will decrease. Combining Equations (3) and (4) it can be established that the temperature (and similarly concentrations) will increase as the fire increases in size and will decrease as the floor to ceiling height increases. Conventionally, sprinklers will be used to reduce the fire size and thus prevent flashover but also the building design can be used to increase the floor to ceiling height and also prevent or delay flashover. While this analysis is simplistic in nature it shows that a feature of an existing building, such as the floor to ceiling height, can be used to compensate for the omission of a sprinkler system.

3.3. Compartmentalization and Life Safety

Compartmentalization is also a very important issue when it comes to historic buildings. General building code requirements worldwide will indicate the need to use protected means of egress (ex. [25]). This generally means that emergency stairs need to be provided and that these have to be introduced with a predefined separation that does not excide prescriptive maximum egress distances. Emergency egress paths have to be enclosed by fire resistant construction. The layout of most historic buildings was defined most times prior to the introduction of maximum egress distances in the codes (in most countries these requirements appear no earlier than 1920's [19, 20]). Therefore, most historic buildings do not have provisions of enclosed stairs. Adding or enclosing stairs generally requires extraordinary interventions. When addressing a historic building, it is therefore necessary to establish if these enclosed stairs are necessary and what alternative means and provisions can be used to compensate for the absence of such enclosures. In a similar manner, corridors many times exceed maximum egress distances, thus codes will require barriers to break the corridor to guarantee safe egress. Again, these barriers represent major intrusions and therefore need to be addressed with some care. The management of smoke to allow for extended travel distances and unenclosed stairs in a historic build will be used as an example of the type of analysis required.

It is important to clarify, that smoke management is used here only as an example of an alternative form of intervention. There will be situations or potential occupants groups that will not benefit from this specific approach. A detailed performance analysis should take into account all those considerations.

3.3. Fire Resistant Doors

A critically important feature of compartmentalization are the doors. Performance assessment of fire doors requires testing of a door system that includes the door, the frame, the hinges and all other fixtures. The system

needs to protect the safe are from ingress of fire and smoke. In historic buildings, doors are many times, inherent fixtures of the architecture and therefore it is desirable not to intervene to attain a required level of fire resistance. Figure 2 shows a good example of such doors. The doors come from the same building at the University of Geneva and during the refurbishment it was highly desirable not to alter the doors and fixtures. Maintaining these doors requires a detailed analysis of their capacity to withstand the penetration of smoke and flames. In general, it is easy to demonstrate that massive timber doors are capable of sustaining the heat fluxes of a generalized fire for an adequate period. It is much more difficult to address their capacity to contain smoke. It is very common that minor modifications, that introduce adequate seals and manage the relative motion between frame and door, will be required and therefore detailed dialogue with other stakeholders (i.e. architects and heritage experts) will be necessary.



Figure 2. Historic doors and detail of fixtures used at the Bastions Building, University of Geneva

3.4. Fire Resistance and Structural Integrity

When following a prescriptive approach, structural integrity and compartmentalization is guaranteed by means of fire resistance testing. Structural elements and compartmentalization components need to be tested in a destructive manner to establish their fire resistance. This will generally be impossible for historic buildings. Structural solutions of historic buildings tend to be very different from current constructive methods. Therefore, these solutions have never been tested for compliance and therefore do not represent rated construction. Code compliant constructive solutions are generally included within official listings [30] that describe performance as obtained through testing. Figure 3 shows examples of structural systems with protection dating to the 19th century. A system of the nature of Figure 3(b) will most likely achieve the required fire resistance, nevertheless

it will not be certified (and therefore non-compliant) and will require cover if the building was to be rehabilitated. As structural system like Figure 3(a) is very similar to that of 3(b) but it has no fire protection. This system will also be deemed non-compliant. Both cases are different but will both be treated in a similar manner by codes. Detailed Finite Element Models (FEM) can establish the structural behavior of these systems. To establish if the structural behavior meets the needs, a temperature distribution for the structural system is needed [31]. The temperature distribution of the gas phase and associated heat transfer coefficients can be obtained using Computational Fluid Dynamics (CFD) models but in most cases (due to the simple geometries and very different time scales for the heating of solids and gases) much simpler models can also be used [26]. A simple zone model will be illustrated in the next section [21]. A subsequent heat transfer analysis will then deliver the temperature evolution of the structural elements. The FEM models can serve to provide a time equivalency for the structure that defines what could be the potential fire rating for a historical structure. As indicated above, this is a significant departure from prescriptive methods where performance assessment of the structure is not required.



(a)

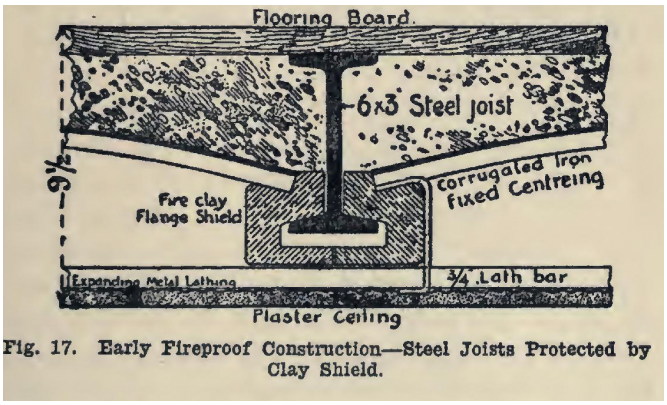


Fig. 17. Early Fireproof Construction—Steel Joists Protected by Clay Shield.

(b)

Figure 3. Historic structural slab (a) photograph of a historic vaulted ceiling (b) Section of a 19th century protected beam

An important aspect of structural assessment is the determination of the thermal solicitation potentially imposed by a fire. Structural analysis traditionally uses a concept of a load being applied to the structure. This load will follow a probabilistic distribution that will be defined within a code or a guideline. In the case of fire, this is not the case. The nature of the fire is affected by the building and the fuel available. As indicated by Equations (3) and (4) temperatures depend on geometrical features such a floor to ceiling heights. Furthermore, the nature of the constructive materials (ex. Wood) might make the construction part of the available fuel. All these aspects need to be carefully considered. Once the temperature evolution within the building is established and heat transfer to the structural systems is calculated, then the structure will evolve as the temperature increases. The evolution can result in the deterioration of mechanical properties (ex. As indicated in Eurocode 5 [31]) but also thermal expansion and thermal bowing can result in the generation or relaxation of mechanical loads. This opens the possibility to the introduction of structural interventions, of minor impact to the historic value of the building, that could nevertheless reduce the loads generated during a fire. While the potential for this type of intervention exists and could be immensely valuable to the preservation of a historic building, to the knowledge of

the author, this approach has never been implemented. Instead the conventional approach is to ignore all the potential benefits of the existing structural design and to either replace it by a rated alternative or to add encapsulation to a level where the thickness of the encapsulation is in itself sufficient to comply with the prescriptive requirements. In the domain of structural integrity, current prescriptive practices in the structural and fire safety engineering community have not evolved in a manner that enables the use of modern analytical tools to determine the true capacity of a historical structure to withstand a fire.

4. Example – Smoke Management for The Bastions Building University of Geneva

Overall, the basic principle of analysis of fire safety for historic buildings implies the migration from "compliance" to "performance" and the acceptance of a much more complex series of safety objectives. Life safety needs to be accompanied by property protection and the implicit safety associated to code compliance has to be substituted by a detailed assessment of performance using state of the art engineering tools. This section will provide a simple example to illustrate a methodological approach. This example is not intended to be exhaustive nor to solve the fire safety strategy in its integrity. Instead, it takes some aspects of the comprehensive analysis to highlight the value of a performance-based approach.

4.1. Brief Description of the Building

The Bastions Building at the University of Geneva was constructed between 1869-1871undergoing two series of renovations a first renovation of the Aula Magna in the period 1940-1944 and a retrofit of the roof in the period 1961-1963. The renovation of the Aula Magna changed its layout and introduced a series of vitreaux considered to be unique glass work from Geneva. The building has a central building and two wings covering a total surface area of 25,000 m^2. Figure 4 shows an image of the building and Figure 5 images of some of the vitreaux. The building is not only a remarkable example of classic architecture of the late 19^{th} century but also houses murals, stone work and woodwork of exceptional value. Rehabilitation of the building will require adaptation to modern codes that not only implied significant reconfiguration of space but also the potential elimination of the vitreaux to maintain compartmentalization of the means of egress. This example does not correspond to any existing analysis or official documentation associated to this renovation. It is an independent alternative approach that is only used for illustration.

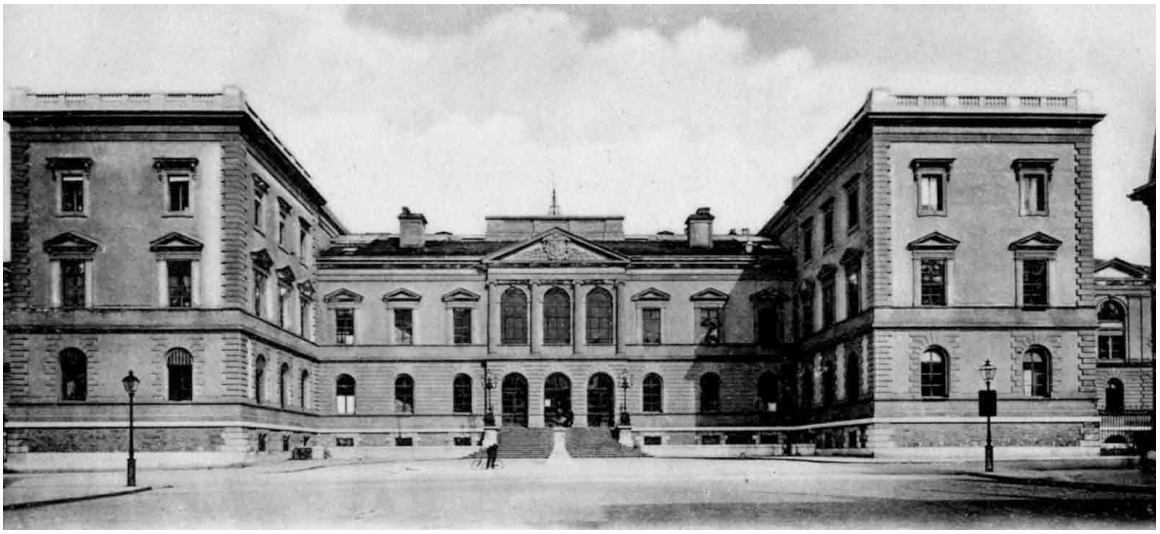


Figure 4. Photograph of the Bastions Building before the 1940 renovation work

4.2. Proposed Compliant Solution

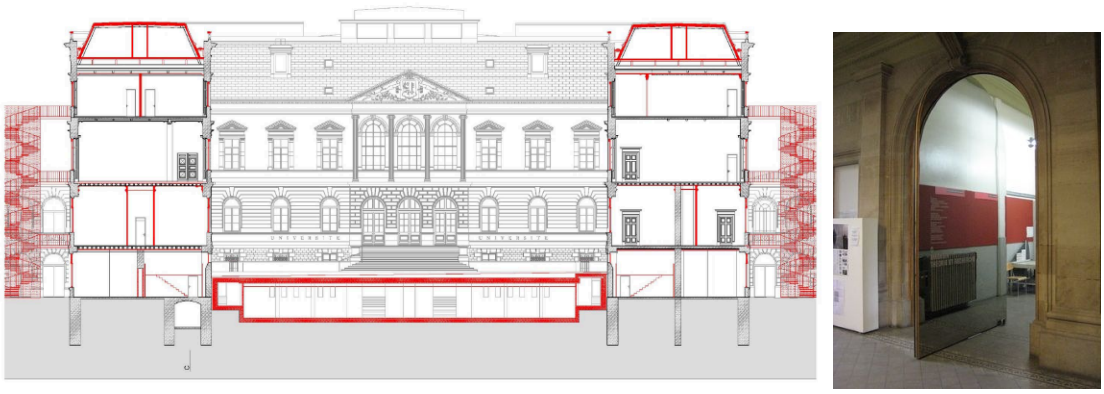
Extracts from an existing code compliance analysis [32] are presented here to describe a series of modifications that will enable the building to comply with current building regulations. Figure 6 shows the existing building layout (ground floor). The main transit area is completely open and it includes the vitreaux with the second set of vitreaux forming part of the Aula Magna. The building in its current form has multiple deficiencies when it comes to addressing the egress of people. Addressing these deficiencies could potentially imply covering or eliminating the vitreaux to ensure fire resistance compliance. The corridors in all floors exceed maximum travel distances – 30 m.

A solution implemented in a very similar building of the same complex compartmentalizes the corridors by means of an electrically activated mirror door that is intended to vanish by reflecting the corridor (as seen in Figure 6(b)). This type of solution has a questionable impact on the internal architecture of the building but also deteriorates circulation during normal operation of the building. As an emergency solution is not ideal because it relies on a mechanical device to close the door and compartmentalize the corridor in the event of a fire. Normally, solutions that require many moving parts are not deemed as robust and generally require high levels of maintenance.

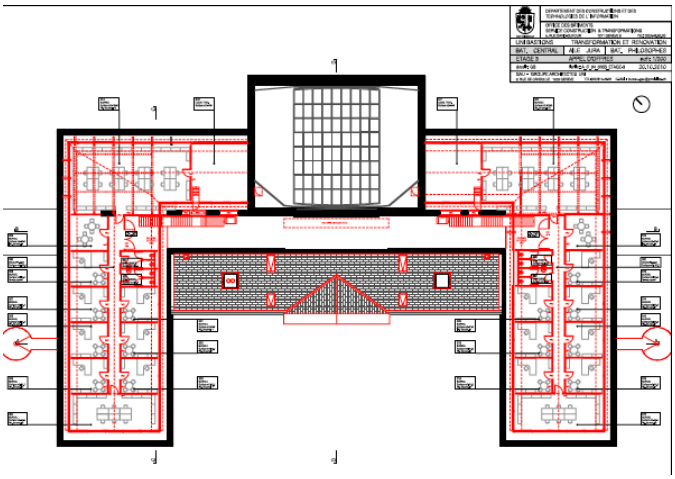


Figure 5. Vitreaux in the monumental stair and Aula Magna by Emilio Beretta (1958) and Alexandre Cingria (1940) [32]

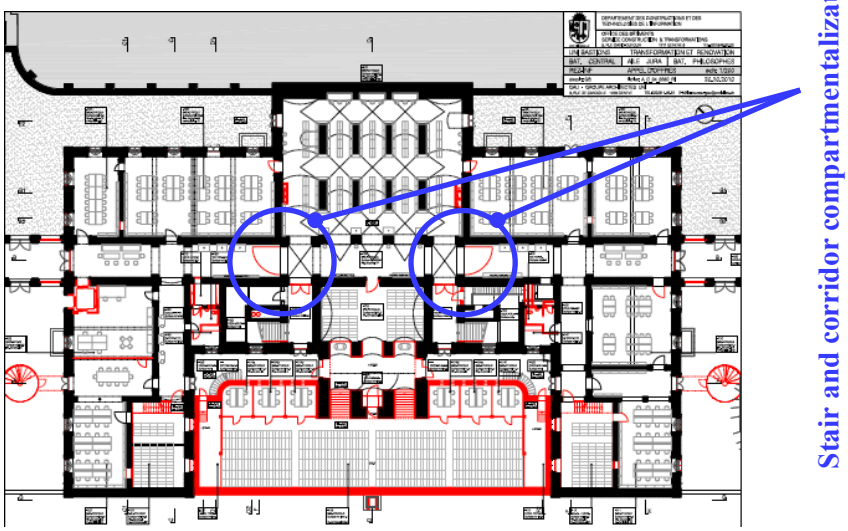
The monumental stair (Figures 6(c) and 6(d) and Figure 7) cannot be fully enclosed therefore cannot serve as a means for emergency evacuation. As can be seen in Figure 6(d) there are attempts to partially enclose the stairs, but given the ceiling height and the architecture of the stair, these will all be very intrusive. Thus, alternative egress paths need to be constructed. Figure 6(a), 6(c) and 6(d) shows the proposed alternative and the location of two external stairs. In red are the modifications required. As it can be seen, the addition of external means of egress implies significant alteration to the façade which represents a potentially unacceptable intrusion on the architecture of the building. It is also important to note that internal stairs are generally a preferred solution for egress because smoke can be better managed and adequate egress conditions are easier to guarantee, particularly in areas where extreme weather conditions are possible [22]. Codes like NFPA [25] will normally suggest internal stairs.



(a) (b)



(c)



(d)

Figure 6. Proposed addition of new emergency egress paths and fire resistant structural elements [32] (a) front elevation (b) alternatives for compartmentalization used in similar building renovations in Geneva (mirror door) (c) Plan layout of the first floor showing in red fire resistant construction ad added emergency stairs (d) Plan layout of the ground floor showing in red fire resistant construction and the proposed compartmentalization of corridors and the monumental stair (blue circles).

4.3. Alternative Approach to Smoke Management

The alternative approach to introducing the mirror doors and the external escape stairs is to evaluate the potential fire growth (Equation (2)) use a zone model [21] to establish the time required for the smoke layer to descend to a point where it interacts with occupants. This is clearly a viable proposition because the floor to ceiling height is approximately 6 m and the corridors can be as wide as 7 m, which gives a very significant volume. The larger the volume the slower the descent of the smoke layer and the easier to manage egress. The objective would be to achieve egress without any physical intervention on the building. The zone model was built specifically for this application based on the equations of reference [21].

A series of fires were analyzed and an example of the results is presented in Figure 8. The egress time has been calculated using simple empirical data for displacement velocities [22] and pre-movement times corresponding to educational facilities [22]. For the example illustrated in Figure 8 the egress time (RSET) is between 180-240 sec. These values were calculated using extremely conservative estimates. The methodology used is based on a free flow approach for the corridors and a density based approach for doors. It is important to note that the calculations presented in Figure 8 are only used for illustration purposes and are not intended as definitive quantifications. While sensitivity analyses were conducted with the fire and the parameters associated to egress, the presentation of these details goes beyond the scope of this paper.

The red and black curve correspond to the height of the smoke layer and the temperature of the smoke layer. The value of "$\alpha = 0.00833$" which corresponds to a slow growing fire. The corridors are almost free of combustibles; therefore, a slow growing fire is an acceptable growth rate. As can be seen from Figure 8, the smoke layer will descend (z(t)) to approximately to 3 m from the floor when everyone has already evacuated (most conservative). This means that people and smoke will not interact.



Figure 7. Existing building layout (ground floor). Inserted photographs of the egress paths.

Furthermore, the temperature of the smoke layer would have not reached 100°C by the time everyone has left the building. This is a smoke layer temperature that will still maintain safe conditions for occupants. This analysis demonstrates that the building design (i.e. geometry), while not compliant with building regulations, still provides a safe environment for occupants. It is important to note that this example is only presented to illustrate an alternative approach. In an analysis of this nature it is essential to demonstrate adequacy for numerous scenarios under different conditions. Furthermore, it is essential to take into account numerous variables including occupants with limited mobility, redundancies etc. Nevertheless, this example demonstrates that by taking advantage of the geometric characteristics of the building, it is possible to demonstrate that the building is safe while not being compliant.

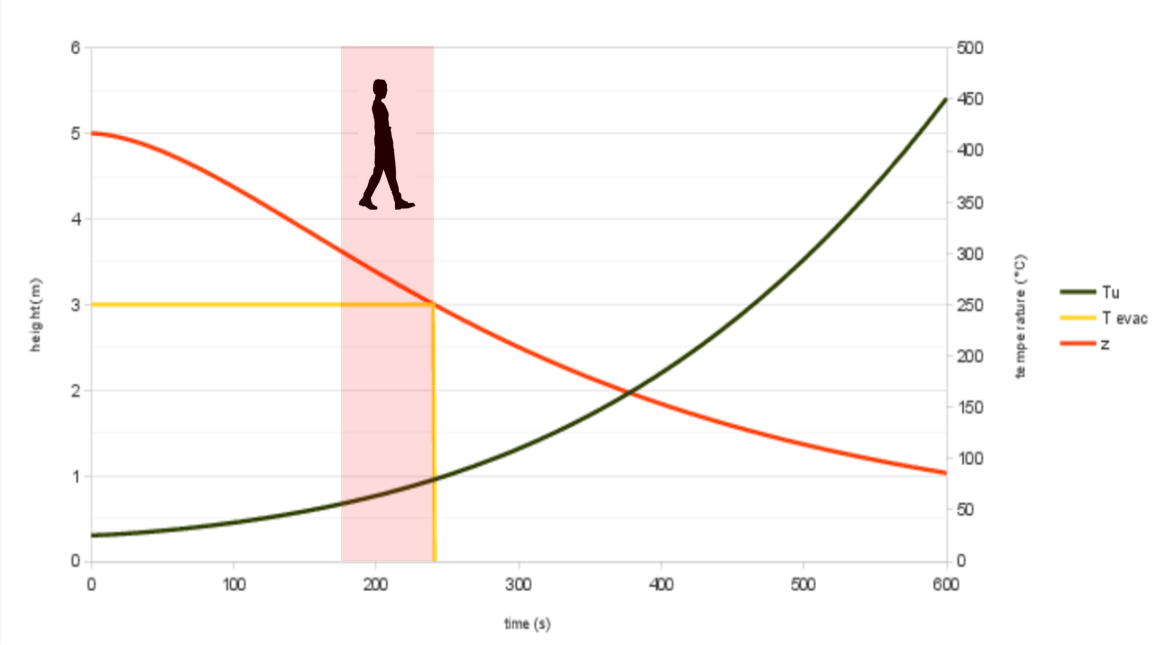


Figure 8. Performance evaluation of the egress paths.

In a similar manner, a fire dynamics analysis was conducted to demonstrate that flashover will not occur in any of the compartments. The ceiling height is sufficiently large that common furniture and contents of this building cannot generate sufficient heat to enable flashover to occur. This is of extreme importance because it shows that temperatures within the compartment will not reach values that will threaten the structure nor ignite timber. A compliant solution would require a fire resistance rating for all structural elements in red (Figure 6(a), 6(c) and 6(d)), this will have most likely implied encapsulation or replacement that might have include particularly valuable elements such as the vitreaux. The premise behind the fire resistance rating is the exposure of a structure to a post-flashover fire for a duration capable of consuming the integrity of the fuel content (i.e. time to burn-out) [10]. Given that the fire will not reach flashover, temperatures of the smoke layer can be estimated using a zone model and in this case indicate that they will never exceed 300ºC. This is consistent with values presented in the literature [29]. A detailed heat transfer and structural analysis could have been performed to demonstrate that the building structure offers adequate strength, nevertheless the estimated temperatures rendered this analysis unnecessary. Instead, only a heat transfer analysis was performed to establish any areas where a temperature increase, even mild, could create potential structural problems. This analysis identified no areas of concern. The focus then became compartmentalizing the smoke, which implies a detailed inspection of any possible smoke migration paths. Filling these paths to avoid smoke migration is most definitely a much less intrusive intervention.

For the doors, an extremely conservative assessment was made to establish that the doors were thick enough even if extreme charring rates were used to calculate fire damage. Despite the fire not reaching flashover, a localized fire can require the doors to withstand an intense fire for periods much longer than the egress times. So no modifications to the structure are required nor the replacement of the doors. Given that occupants can exit

without any interaction with the smoke means that no intervention is necessary. The vitreaux can remain, the mirror doors are not necessary and the two proposed new means of escape can be omitted.

Identifying which compartments can attain flashover and establishing typical compartment temperatures allows to identify which sectors of the building are susceptible to significant damage. This is important because it allows to identify which areas of the building will put at risk valuable objects, thus will inform where valuable objects might have to be actively protected or displaced.

5. Conclusions

The solution to fire safety for historic buildings requires a performance assessment to explicitly demonstrate that the necessary fire safety objectives have been met. In the case of historic buildings, the fire safety objectives include life safety but also need to include adequate protection of the patrimony. Currently, the Fire Safety Engineering profession has adequate tools to conduct these analyses, allowing for unprecedented freedom in the manner in which adequate levels of safety are delivered. To be able to implement these tools it is necessary to understand that safety is not only attained by compliance and furthermore that compliance does not mean safety. Many historic buildings have features that make them inherently safe despite not being compliant with current codes. This paper has used an existing renovation as an example to illustrate this. This paper does not intend to question or analyze the approach used for the Bastions Building at the University of Geneva, but to use alternative analyses to demonstrate the options available towards a renovation that will be most respectful of the historical building.

6. Acknowledgments

This work was conducted while on sabbatical at Ecole Polytechnique Fédéral de Lausanne funded by the Landolt & Cia Chair in Innovation for a Sustainable Future. The support of Dr. Michael Woodrow (Foster & Partners) in the analysis of the building is much appreciated. The collaboration of the conservation authorities of the Ville de Genève is also acknowledged. This analysis is not intended to question or to conduct a rigorous fire safety engineering analysis of the buildings discussed but to use them as an example to illustrate a methodological approach.

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Scaling-Up Fire

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Abstract

The role of combustion research in fire safety is revisited through the process of **Scaling-Up** fire. **Scaling-up** fire requires the adequate definition of all the building blocks and couplings associated with the construction of a fire model. The model then has to deliver predictions of the evolution of a fire and its environment with the precision, completeness and robustness relevant to fire safety. Areas of combustion research relevant to the development of fire models emerge from an assessment of methodology, complexity, incompatibility and uncertainty associated to the **Scaling-Up** process.

Relevance

The evolution of a fire in any realistic context (building, vehicle, forest, underground, etc.) is an extremely complex process where it could be suggested that predictions of accuracy, completeness and robustness relevant to fire safety are impossible. Relevant accuracy, completeness and robustness is defined as the ability to quantitatively predict all the variables necessary for design or performance assessment to a level of precision and robustness that justifies using these predictions. The value associated to knowledge gain is established by how this gain can be linked to a quantifiable improvement in the accuracy, completeness or robustness of the prediction.

The gain associated with an enhancement in knowledge can be easily established when the full process is completely described and the areas where the sub-processes that are coarsely represented have been clearly identified. This procedure starts with the more fundamental processes, linking them to generate more complex systems that in turn are further linked until the full process is described and an output can be obtained [1]. Refinement can then be punctually applied and clearly linked to an improved output. This building strategy will be defined here as **Scaling-Up.**

In extremely complex problems, the link between the sub-processes and the output is not always clear. The sub-processes and couplings between sub-processes tend to be coarsely modelled making it difficult to identify the consequences of a change. In this case, deterministic **Scaling-Up** is very difficult but probabilistic assessment can be an effective way to achieve the same objective. In probabilistic assessment, a refinement is introduced and the outcome is then monitored. If this is repeated a sufficient number of times, and if there is a consistent outcome, then the refinement can be deemed to result in a quantifiable gain without necessarily understanding the path followed. This approach is mostly statistical and therefore requires large populations to gain sufficient confidence. To obtain a large population, the process under study needs to remain stable until the link between a component and the outcome is established.

The most difficult category corresponds to complex systems where processes and their links are still coarsely described and where each system to be modelled has a very small population. These are systems that evolve fast or are unique therefore the population

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available for study at any specific moment is always small. A general overview of the issues associated to the statistical treatment of these complex systems is provided by Neyman [2].

It has been suggested that fire problems belong to the last category [3, 4]. Our understanding of the processes involved in fire is very coarse, nevertheless, the outcome is extremely sensitive to multiple variables resulting in many cases in drastic bifurcations (ignition, extinction, flashover, backdraught, etc.) therefore most fundamental processes need to be refined and coupled in precise and complex manners. Unfortunately, many of the links and couplings between these processes are unknown, thus it is currently not possible to relate improvements in the understanding of the fundamental processes to benefits for the outcome. Thus, it can be claimed that deterministic **Scaling-Up** of fires is currently not possible.

When addressing the problem via probabilistic tools, the evolution of our habitat (e.g. novel construction materials such as phase change insulation, discontinuation of fire retardants, new construction systems such as curtain walls, etc.) is much faster than the evolution of the fundamental science associated to fire [5, 6]. This is in contrast to other disciplines such as medical research where the evolution of the subject, the human, is in the order of thousands of years. Thus, the problem in question will drastically evolve before science has been able to mature. Within the evolving habitat there is an infinite variation of specific scenarios making each overall process to be modelled unique. So, from the perspective of predictive capabilities, it can be claimed that each fire scenario has a population of one and the conclusions of one event cannot be used for a general assessment of benefit. Thus, statistical analysis as a **Scaling-up** method for fire predictions will inevitably result in a low confidence output.

It is therefore clear that the **relevance** of research leading to the refinement of a specific component is linked to our capability to **Scale-Up**. Nevertheless, **Scaling-up Fire** appears as the insurmountable challenge of fire safety. Combustion is one of the fundamental processes within the description of a fire and a component that could be refined by means of research. But given the difficulties associated to **Scaling-Up Fire**, the **relevance** of combustion research for fire safety seems questionable. This paper will discuss the **relevance** of combustion research in fire safety through a better understanding of the process of **Scaling-Up Fire**.

Scaling-Up Fire

Fire safety involves a broad range of disciplines tied by a combustion process, “the fire” [7-14]. The combustion reaction will result in species and energy being released in an uncontrolled manner. The release of energy and species will negatively affect structures, people and the environment but will also activate countermeasures and result in human response (evacuation, intervention) intended to minimize the negative impact of the combustion process. A feedback loop exists by which the structure, people and countermeasures will also impact the combustion process. Therefore, fire safety can only be quantitatively assessed if the combustion process can be modelled within the context of its environment. The modelling of the combustion process within the context of its environment will be referred to here as “fire modelling.”

Currently we have many models that attempt the **Scaling-Up** of fire [12, 15]. These models can be deterministic, probabilistic and in some cases system models [16]. These models provide outputs with a specific level of precision, completeness and robustness and in all cases they include a representation of the combustion processes involved.

The simplest form of fire models are prescriptive regulations. For certain environments that share common characteristics a specific design form has been studied and

its performance established and deemed acceptable. Different tools are then used to establish to what extent the context can be changed without exceeding the acceptable outcomes. Among these tools many incorporate combustion principles (classification of flammable liquids in relationship to ignition, hazard classification in relation to fire spread, sprinkler classification in relation to burning rates and heat of combustion, etc.). Once the potential context variation is defined then a classification emerges that provides the context bounds to which the solution can be applied. Therefore, the core of prescriptive design is the classification. If a designer follows a set of prescriptive rules that create the context where a solution is known to yield and adequate outcome then, another set of rules that implements the predefined solution guarantees performance. **Scaling-Up** is simply the extrapolation process that enables the use of the same solution in a context that lies within the bounds of the classification.

Fire models can also be explicit representations of the event and their outputs can be physical parameters such as velocities, temperatures, concentrations, stresses, strains, displacements, heat release rates etc. **Scaling-Up** becomes the explicit integration of all the fundamental processes involved. There is a very large body of literature focusing in the development of explicit fire models, their predictive capabilities and different validation strategies for many relevant fire scenarios [7-14, 17]. This paper does not intend to be a review of this literature instead a systemic view of the issues associated to fire models is presented.

A final set of models are the system models [16]. In system models the fire is also represented in an explicit manner but is only a small component of a scenario analysis. The focus is on the interrelation of the different components with the components described in very simple terms. Nevertheless, system models still rely on an explicit representation of each of the components. **Scaling-Up** remains the explicit integration of all the fundamental processes involved.

Independent of the model, the model output is used for the purpose of designing or assessing the performance of a fire safety strategy. Therefore, it is necessary to establish if the outputs are precise enough, complete enough and robust enough. If they are not precise, complete or robust enough then a compensation strategy needs to be implemented. The most common compensation strategy is the safety factor. The safety factor implies that during implementation, the calculated outputs will be exceeded to compensate for lack in precision, completeness or robustness. The poorer the quality of the output the larger the necessary safety factor, the safety factor can therefore be seen as wasteful use of resources thus a motivation for research.

In prescriptive design, the safety factor is implicit and cannot be quantified. It is embedded in the constraints associated to the definition of the classification and in the implementation of the solution. The implemented solution is deemed to carry a significant safety factor because it has to be robust to the variations permitted within the bounds of the classification. While prescriptive solutions will not be discussed any further, it is clear that research supports the improvement of prescriptive rules. Rules are (in principle) derived from knowledge, thus more knowledge has the potential for better rules, therefore the discussion below will also apply to the potential gain associated to the improvement of prescriptive rules. The nature of prescriptive rules and classifications inevitably imply constraints and large safety factors. Thus the explicit assessment of performance is seen as an effective alternative that enables the reduction of safety factors. Explicit performance assessment enables to break with the constraints imposed by the classification and can refine the safety factor to the specific scenario studied. In a world where sustainability is paramount, waste is

unacceptable and explicit fire modelling represents the only viable option. The remaining sections of this paper will focus on explicit **Scaling-Up Fire**.

The Complexity of Explicit Fire Modelling

Explicit fire modelling is by nature of great complexity because of the unavoidable relationship between the combustion phenomenon and its environment [12, 14, 18, 19]. The relationship between the combustion reaction and its environment introduces two major complexities. First, the environment imposes length and time scales that bound the problem while the underlying physical and chemical processes (that have their own natural length and time scales) still need to be resolved. For example, forest fires are defined by weather and terrain phenomena of kilometre length scales and underground smouldering fires by diffusion rates characterized by century long time scales nevertheless, in both cases the resolution of the fluid mechanics, heat transfer and chemistry associated to the combustion reaction still requires nanometre length scale and microsecond time scale precision [20, 21]. Extensive range and incompatibility of scales is an unavoidable complexity of explicit fire modelling. Second, within a fire, the mass and heat transfer environments result from a self-defined and uncontrolled combustion process that can be deeply affected by the context in which it occurs. The fire will provide the necessary energy to sustain its growth via the degradation of further combustible materials but also the energy to induce buoyancy driven flows that in most cases dominate the nature of fuel and oxygen supply to the combustion reaction [11, 13, 22-24]. Buoyancy defines the location and geometry of the flames, the aerodynamic characteristics of the flow and the kinetic structure of the reactions. The flames will then affect the environment in which the fire develops, which in turn can affect the nature of the combustion process (i.e. heat feedback). Context variables such as the nature and quantity of the combustible materials, the failure modes of structural elements, human behaviour and the activation of the different countermeasures introduce local and/or global changes that will have an obvious and potentially dramatic impact on the fire.

When **Scaling-Up** fire, processes such as chemistry, heat and mass transfer, fluid and solid mechanics are brought together within the context of a model to predict in a quantitative way the evolution of a fire and its impact (interaction) on (with) its environment. Even in this context, **Scaling-Up** does not have to be purely deterministic. Deterministic modelling can always be modulated by different forms of statistical treatment that enable addressing issues of uncertainty [25]. Other elements such as human behaviour and the physiological and psychological reaction of people to the fire are also of great importance and can be incorporated but will not be addressed here. The focus here will be in the non-human related aspects of the problem.

Despite the complexity of the problem, explicit fire models with different levels of detail have been constructed. The simplest models tend to neglect (and thus avoid describing) many processes of lesser importance [12], thus tend to be robust and require simple inputs but have narrow ranges of application and carry significant error bars. Furthermore, they tend to focus on individual processes and scales ignoring (or simplifying) the couplings between processes and the interactions between different scales. Entrainment correlations, relative flammability tests, statistical flame spread models all belong to this category [11, 12]. The application of simple closed form models tends to be restricted and when used for design purposes, merit large factors of safety.

For more than five decades analytical formulations and empirically based correlations have been used to **Scale-Up** fire. In the last thirty years computer models have entered fire

safety, first as simple energy and mass conservation models (zone models), and later through different forms of computational fluid dynamics (CFD) [4, 18, 19]. The scientific literature is currently populated by studies that attempt to improve, verify or validate these models and the practise has made them of mainstream use. Notable to all these models is the Fire Dynamics Simulator (FDS) which currently is used, for the most diverse applications, by thousands of scientists and practitioners [26]. Other models that range from the general to the specific are also in use, both as alternative to FDS or for specific applications where their performance is deemed more relevant [15, 27-38].

More complex models incorporate a more complete description of the processes and the interactions involved. They tend to allow a broader utilization and a reduction of factors of safety. In contrast, complex models require more, and many times more complex, inputs and can only be as robust as the least robust process/interaction formulation. In fire, it is often the case that the complexity of the models to be used is not defined by the capability to mathematically formulate the process but by the impossibility to obtain the inputs required. The descriptions of combustible material degradation [39-45], soot formation [46] and radiative heat transfer [47-50] are among the most common processes where the complexity of the models used is limited by the availability of inputs.

Given the importance of the context in the modelling of fire, it is common to reach the conclusion that complex models are not justified because unavoidable scenario uncertainties lead to output variations much larger than those associated to errors induced by the simplifications introduced in simple models. Furthermore, countermeasures can be over-designed in a manner such that their effect on the combustion process is so overwhelming that detailed modelling of the interaction between the fire and the countermeasure can only be justified when seeking a reduction in the factor of safety [51].

When designing or assessing the performance of a fire safety strategy in an explicit manner, fire models are incorporated in tools intended to enable the quantification of safety. Combustion research, in the context of fire safety, is thus only justified if it can be demonstrated that enhancements in the understanding of relevant combustion process can lead to subsequent improvements in fire modelling and ultimately if the tools, in which fire models are embedded, can deliver a more effective fire safety strategy.

The Fire Safety Strategy

Despite the numerous fire modelling alternatives and the fact that there is always room for improvement, it is important to address if existing fire modelling tools can be improved to deliver a gain that justifies the investment. The gain has to be linked to a more effective fire safety strategy and has to remain even in the presence of the unavoidable scenario uncertainties. If safer environments can be demonstrated or current safety factors can be significantly reduced by gaining precision, completeness and robustness then improvement is justified.

A fire safety strategy consists of numerous components that deliver a fire safe environment. These components are structured around life safety, property protection and business continuity. People in contact with the fire event need to be protected or delivered to areas of safety (life safety), the impact of the fire on its environment needs to be minimized (property and environmental protection) and the fastest return to its original condition needs to be guaranteed (minimization of business interruption). For this purpose a fire safety strategy is put in place. This applies to public and industrial buildings as well as wild land or wild land urban interfaces (WUI). In the absence of a fire safety strategy, life loss will most likely occur and potentially unacceptable property losses and business interruption will result.

In explicit terms, the fire strategy intends to affect the evolution of the fire, reduce the interaction of people with the heat and combustion products and define the environment in a manner that the impact of the fire is reduced to a level where the integral cost of failure is much smaller than the investment on protection.

Fire growth can be controlled in a passive manner by compartmentalizing the space introducing physical barriers that can contain the fire and smoke. These barriers can be fire doors and windows, fire resistant walls and floors as well as non-flammable claddings. The fire can also be affected in an active manner by means of suppression systems (water, gas, powder, etc.) that introduce heat sinks and chemical inhibitors that will negatively impact the combustion processes. The fire service can be considered a mode of active fire suppression.

The interaction of people with the heat and products of combustion is also minimized by means of compartmentalization and fire suppression. The barriers will not only prevent the fire from migrating outside the compartment of origin but will also reduce the dispersion of smoke. Fire suppression will limit the size of the fire, thus the release of heat and combustion products. A complement to these elements of the fire strategy is detection and alarm. Heat, products of combustion, electromagnetic waves or visible images can be used to identify the presence of a fire and provide an alarm so that people can initiate displacement away from the fire. This applies to buildings as well as external environments where evacuation procedures associated to forest fires or large external fires can displace entire communities away from the event [52].

An effective way of managing the interactions between people, heat and products of combustion is by inducing flows that will prevent smoke from reaching certain areas (pressurization of stairwells, downward flow for clean rooms, smoke fans for tunnels, etc.) or by extracting the smoke away from occupied areas or areas to be protected.

Infrastructure can be designed in such a manner that its response to the fire is optimized. Structural systems can be designed and protected to minimize unwanted behaviour (large deformations, progressive collapse, connection failure, breach of compartmentalization, etc.) and building materials can be selected to prevent or reduce fire spread (wall linings, external cladding, roofing materials, etc.). In some cases, such as industrial facilities, structural systems can even be designed to fail prematurely to guarantee the evacuation of smoke and heat. The evacuation of the smoke minimizes the areas affected by the fire and facilitates fire fighting.

In summary, the Fire Safety Strategy is a compendium of measures that are designed to achieve a socially acceptable outcome in the event of any possible fire. The evolution of the fire, the behaviour of structural systems, the response of countermeasures and the migration of people will all evolve in time, thus the evaluation of a fire safety strategy needs to be done within the context of a timeline. Predictions therefore need to be made as a function of time and performance can be established as a relative function of time (Required Safe Egress Time (RSET) vs. Available Safe Egress Time (ASET), RSET vs. Structural Fire Resistance (SFR), detector activation times vs. time to flashover, etc.) [53]. Given that all the components of the strategy are either activated or affected by the fire, to be able to quantify the outcome in an explicit way, the first step is to be able to understand the time evolution of the fire within the context of its environment, thus the “Fire Dynamics” [11, 54].

A Short History of Fire Dynamics

When defining a fire strategy it is essential to be able to characterize the time evolution of the fire and the associated outputs that are to be used to assess performance. For example, to define detection it is necessary to establish the velocity profiles in the vicinity of

the detectors as well as the different species concentrations that are required to activate the detector [55, 56]. When addressing sprinkler performance, velocity and temperature distributions in the immediate region of the sprinkler head are required to calculate the activation time [12], the capability of a water spray to extinguish or control the fire is defined by the trajectory and evaporation rates of the droplets [57-59], the interaction between the droplets and combustible and non-combustible surfaces is necessary to quantify the heat exchange that enables flame spread and the interaction between the water droplets, pyrolyzing surfaces and flames is required to assess the fate of the combustion process. To establish the evolution of structural components detailed heat transfer calculations between the gas and solid phase are necessary. All the parameters associated with convective and radiative heat transfer are required to establish the thermal boundary condition used by structural engineers as input to conduction heat transfer and solid mechanics models [14, 60, 61]. It is clear that none of these outputs can be obtained if the fire cannot be modelled with enough precision and robustness and in a manner that delivers the complete set of data required.

As seen through the examples, for each aspect of the fire strategy there are a multiplicity of aspects that need to be evaluated to establish if the modelling outputs have the required precision, completeness and robustness. In general, transport processes, combustion chemistry and the technology used as a countermeasure are all intimately coupled thus it is impossible to look at each aspect in isolation. Nevertheless, for the purpose of illustration, it is useful to concentrate on some specific aspects of the problem. This paper will only focus on the modelling of the fire.

The Standard Fire

The history of explicit fire modelling is not very old with the first attempts done at the beginning of the 20th century but only formalized in the 1960's and 70's [62]. Probably the first descriptions of the fire are associated to fire resistance and attempts to guarantee adequate structural behaviour. In the absence of most of the fundamental knowledge of combustion, heat and mass transfer, the fire was modelled by attempting to reproduce reality within a furnace [63]. A combustion reaction was sustained within a realistic scale compartment in which the structural element was introduced. Heat transfer was bypassed by measuring directly the temperature of the structural element and the fire was generalized by attempting a "worst case" condition. The worst case condition was generated by reproducing the fastest possible temperature rise to the highest possible temperature. This "worst case" fire was formalized as the "standard fire" and the "standard fire" gave birth to the "structural temperature vs. time" concept. The "standard fire" could then be reproduced in a furnace according to a pre-defined "temperature vs. time" and structural systems tested within that furnace. No real fire could produce a faster temperature rise nor attain the temperatures obtained in the furnace. The exposure time was defined on the basis of attaining burn-out of the estimated fuel load, thus no real fire could last longer. The time required for burn-out was labelled the required structural fire resistance rating. While this "worst case" scenario allowed for confident extrapolation, it is clear that an important safety factor was embedded in this primitive form of fire modelling.

Understanding of structural behaviour at high temperatures was limited to the characterization of the material properties as a function of temperature. Typical safety factors for structural design established how far the loss of mechanical properties could be tolerated. This loss of mechanical properties was then correlated with a temperature resulting in a failure temperature criterion. The time necessary for the structural element to attain this critical temperature in the furnace was then established as the failure time. If the failure time

was greater than the required fire resistance rating then the structural element could be used without any thermal protection, if not, thermal protection should be added in quantities that enabled the time to attain the failure temperature to exceed the required fire resistance rating [9, 12].

An important concept associated to the extrapolation between thermal behaviour in the furnace and real fire behaviour was the compartment size. While there was no clear understanding of the role of compartmentalization, it was inferred that extrapolation could only be robust if the conditions of burning were similar. Furthermore, accepting that single element behaviour, based only on material properties, could be extrapolated to real scale structural behaviour could only be tolerated heating was localized. If a zone of comparable size to the furnace was the only heated area, then the surrounding structure will remain cold and maintain its strength. Any stresses generated in the heated area could then be transferred (redistributed) to the rest of the building and will be of lesser magnitude than those tolerable by the cold structure. In modern terms this represents a requirement of mechanical restraint that is guaranteed by effective compartmentalization. As a consequence, very restrictive compartmentalization requirements were imposed by building codes of the time.

A similar analysis can be done with life safety, where compartmentalization was used to restrict the progress of the fire and combustion products to guarantee the safe egress of occupants. Sprinklers were introduced at the end of the 19th century using a modelling approach very similar to the standard fire. Sprinkler performance was tested using a "worst case" fire within a compartment consistent with the application. Complex industrial conditions where compartmentalization was not possible were addressed by reproducing the environment in a laboratory and testing the sprinklers at the real scale. When the water supply was sufficient to control the fire and maintain it at a manageable size the sprinklers were deemed to perform adequately [64]. For sprinkler and structural performance fire modelling was mostly a trial and error process.

Combustion science progressed through the 20th century nevertheless these issues will not be revisited until the 1960's. Advancement in the understanding of fluid mechanics, heat transfer and combustion did not permeate into fire modelling because the complex problem of fire could not be effectively linked to fundamental knowledge in any of these areas. **Scaling-Up** fire from fundamental principles was not possible, the gain was not evident and the existing design methods seemed to provide satisfactory results. At the time excessive safety factors were not a matter of consideration.

Compartment Fire Dynamics

The 1960's brought two fundamental changes to the construction industry, (1) the relaxation of compartmentalization and (2) the introduction of plastic materials. In the past, "worst case" fires were defined on the basis of burning wood and were limited to a compartment of a size and characteristics regulated by building codes. As buildings became more complex and features such as ventilation ducts and false ceilings were introduced, it became unclear how to maintain compartmentalization. Given that the link between compartmentalization and fire safety performance had not been established on the basis of fundamental principles, it was difficult to establish the implications of the changes associated to new forms of construction. The loss of some level of compartmentalization occurred unnoticed. The consequences of losing compartmentalization were made evident in several tragic fires [64]. In a similar manner, the migration towards plastics introduced novel failure modes induced by physical phenomena such as melting or dripping. These failure modes resulted in burning conditions that were different to those defined by the burning of cellulosic materials (e.g. wood). The need to better **Scale-Up** fire by incorporating these new features

became the driver to a significant research effort that for the first time brought combustion knowledge into fire safety [64].

In an attempt to describe the complexity of the fire in combustion terms, the problem was broken down into numerous components. The interaction between the compartment and the combustion reaction was named compartment/enclosure fire dynamics [65]. The link between the fire and stoichiometry was established by quantifying buoyant flows that serve to supply oxygen to the pyrolyzing fuel (entrainment). The compartment itself was also linked to stoichiometry by quantifying heat transfer from the fire to the walls and from the walls to the fire (feedback). As the fire heats the walls, radiative feedback to the fuel increases leading to an increasing supply of gaseous fuel to the compartment. The global stoichiometry of the compartment then drifts from the lean to the rich and the transition results in the migration of the flames from the interior of the compartments towards the openings. Terminology such as flashover, oxygen limited and fuel limited fires were introduced to describe these phenomena [66-72].

Smoke Management

Through the study of compartment fires it was observed that in the fuel limited regime (early stages of the fire) the energy produced by the fire is controlled by the amount of fuel produced. Buoyant entrainment can deliver enough oxygen to the flames to maintain the global stoichiometry lean. The energy released and the mass of combustion products is controlled by the fuel supply [66] but the amount of smoke produced by buoyant entrainment of air [12, 13, 73-75]. In the fuel limited regime the objective is to establish how long would it take for the compartment to fill with smoke and how much smoke will be spilled into areas surrounding the burning compartment. Simple two zone models [65] were developed for this purpose computing variables such as smoke temperature and time to flashover. After flashover the compartment, and not the fire, becomes the source for buoyant entrainment and heat feedback from the hot gases to the fuel determines the burning rate. Similar expressions for temperatures, air and smoke flows were developed [66-73]. The qualitative nature of the fuel rich post-flashover combustion could not be resolved by these models, thus empirical yields were used to **Scale-Up** species production. With this information, the absence of compartmentalization could be quantitatively addressed. Buoyant entrainment, energy release rate and species yields became the sub-processes introduced into models and used to **Scale-Up** the fire and deliver temperatures and the quantity and composition of the smoke. With these tools smoke management was introduced as a strategy to increase the available egress time (ASET) in non-compartmentalized environments. Smoke management enabled the construction of modern shopping centres, hotel atria and numerous other architectural features that are now common. Furthermore, it allowed improving building codes to enforce compartmentalization when smoke could not be managed. The acquired knowledge resulted in a clear gain that could be directly linked to the understanding brought by the application of combustion principles [76].

Material Flammability

An even more important gain was established when quantifying the energy released by the pyrolyzing fuel. In the lean regime, energy release is associated to the consumption of the fuel. Thus the nature of the fuel is of preeminent importance. The introduction of plastic materials required a better understanding of the differences associated to different materials used in the built environment. Flammability tests had existed for many years nevertheless they were only simplified and reduced representations of reality [12]. Combustion principles allowed to separate the different processes involved in the production of fuel and the release of energy. The formalization of the transport mechanisms by which the flame transfers heat

to non-burning fuel lead to the first definitions of flame spread. Numerous studies established the nature of flame spread and linked it to concepts such as gas phase ignition and extinction [77]. It was identified that flame spread was strongly dependent on the magnitude and nature of the buoyantly induced air flows, therefore, the understanding of the role of complex buoyancy induced flows and turbulence in heat transfer, completeness of combustion, soot production and extinction set hard limits to the **Scale-Up** process. The size of the fire could only be established if the effect of buoyancy could be incorporated into fire models [78]. At this stage, two fundamental approaches were followed, the first was to introduce buoyancy induced flows by means of empirical correlations and the second was the development of computational fluid dynamics models.

It is at this stage that flammability tests acquire a different meaning. Before combustion principles were introduced, flammability tests were simplified representations of reality that allow to rank materials of very similar nature (mostly cellulosic) on the basis of variables that were explicitly related to the application scenarios. Once combustion principles were incorporated, flammability tests could be used to extract "global material properties" that could be incorporated in fire models to define the size of a fire and the energy being released. For example, the Lateral Ignition and Flame Spread Test provided a thermal inertia ($k\rho C$), and ignition temperature (T_{ig}) and a flame spread parameter (ϕ) describing heat transfer from the flame to the fuel that could be directly incorporated into a mathematical formulation that allowed the calculation of flames spread velocities [79, 80]. While this formulation can be seen as oversimplified, it appeared consistent with more fundamental studies on flame spread that serve to support the simplifications embedded in the flammability tests [81]. Oxygen consumption calorimetry [82, 83] was derived from the fundamental fuel oxidation principles developed by Thornton [84] and adapted by Hugget [85] delivering from a test the energy release rate per unit area of burning fuel (mostly known as the Heat Release Rate per Unit Area ($\dot{Q}$")) that could then be incorporated directly into entrainment models to deliver the mass of smoke produced. These tests were directed to deliver the parameters that could feed empirical correlations and zone models.

Equation (1) summarizes the process by which the Heat Release Rate ($\dot{Q}$) is defined on the basis of properties extracted from flammability tests.

$$\dot{Q} = A.\dot{Q}" \tag{1}$$

The heat release rate per unit area is obtained directly from oxygen consumption calorimetry and multiplied by the burning area (A). The burning area is a function of the flame spread rate (V_S), thus it can be represented as a function of the flame spread rate and time (t). While this function is complex and dependent on fuel geometry and flow field it can be argued that a worst case scenario could be represented by radial spread over a fuel surface where the area is equal to the area of a circle of radius r ($A=\pi r^2$). Then the radius is a linear function of the flame spread velocity and time ($r=V_S t$) that when substituted into Equation (1) results in a simple expression for the heat release rate

$$\dot{Q} = A.\dot{Q}" = \pi V_S^2 t^2 \dot{Q}" = \alpha t^2 \tag{2}$$

where the parameter $\alpha = \pi V_S^2 \dot{Q}''$ and the flame spread velocity (V_S) and energy release rate per unit area ($\dot{Q}''$) could be obtained from the flammability tests. Thus the tests could be summarized into a single criterion (α) that within Equation (2) provides the evolution in time of the heat release rate. This is a practical means by which designers could incorporate the heat release rates into fire models and smoke management calculations [12].

The formalization of material flammability fed smoke management models but also allowed a more comprehensive classification of materials that enable capturing specific features of complex materials such as plastics. The plastics industry adopted the heat release rate per unit area ($\dot{Q}''$) as a direct target for the design of fire retardant formulations opening the market to numerous products [86]. While the gain is evident, once again, the full resolution of the induced buoyant flow disabled the **Scale-Up** process by which the fire models, with inputs from the test, could be used to predict the behaviour of the real event.

Using test results as inputs for fire models is complex because the test themselves are influenced by buoyant flows, thus the interpretation of the tests required detailed modelling of the gas phase. This was not recognized at the time and tests were only conceived on the basis of providing realistic, reproducible, simplified and standardized conditions. Flammability tests were not analyzed or instrumented to truly separate the solid from the gas phase. As a result, all properties extracted from the tests remain hybrids that blend flow and material characteristics. While many attempts have been made to use test properties to **Scale-Up** fire from first principles [87, 88], success has never been truly achieved and the potential gain associated to this effort remains uncertain.

Fully-Developed Compartment Fire

In the oxygen limited regime, the stoichiometry is rich, thus excess fuel is being produced and combustion is limited by the oxygen supply induced by buoyancy through the compartment openings. Buoyancy induced flows are displaced from the fire and calculated at the vents and the energy source is directly linked to the consumption of the available oxygen. The temperature of the compartment is then established by balancing the energy generated by combustion of the incoming buoyant flow, the energy lost by the combustion products leaving the compartment and heat transfer through the compartment boundaries [67-72].

The focus of the oxygen limited regime was to calculate the gas phase temperatures of the compartment and the duration of the fire. The objective was twofold, (1) to calculate the mass of smoke spilling into the adjacent compartments once the fire had reached the oxygen limited condition in the compartment of origin, (2) it aimed to establish a set of more realistic conditions (temperature vs. time) curves that could allow the assessment of structural behaviour in fire [89]. While the first objective had a clear gain associated to smoke management and was almost immediately formulated to engineer smoke extraction systems, the second was of restricted application [76].

The determination of more realistic temperature vs. time fire curves seems to be a very direct way of reducing unrealistic safety factors without violating the principles of a “worst case” scenario and design for fuel burnout. Nevertheless, the acceptance of this approach encountered much resistance. The bridge between structural and fire safety engineering is the standard furnace [90]. Structural engineers were not educated to understand – or even be aware of- the differences between the standard fires and the more realistic descriptions of the fire. Nor are architects who are typically the people assigned to prescribe the required insulation.

The first attempt to compare the standard fire with a realistic fire dates as early as Ingberg [63] who defined the concept of time equivalency. Time equivalency is based on a

simplified linearization of heat transfer that allows defining the "fire load" as the integral of the temperature vs. time curve. The concept of equal areas under the temperature vs. time curve implying equal fires builds a bridge between the furnace test and real fires. Nevertheless, the first true application of this concept dates only to the design of the Georges Pompidou Centre in Paris where Margaret Law demonstrated that the external structure could be designed without any fire proofing [76]. The energy transferred from the fire to the external steel structure until burnout of the fuel was much less than the energy transferred by the furnace for the required rating therefore fireproofing could be eliminated exposing the structure as requested by the architects. Following this application, the realistic curves developed by Pettersson et al [89] where formalized in the Eurocodes [91] as the "parametric curves." These curves offer an array of temperature vs. time curves obtained for different fuel loads and ventilation conditions that define a more realistic temperature vs. time formulation.

There are several weaknesses to the "parametric curves" approach: (1) while the "parametric curves" are extracted from experimental data and the gas phase temperatures can be deemed as realistic, the heat transfer between the fire and the structures is not fully resolved, (2) the "parametric curves" represent a fire within a specific compartment size and are not easy to extrapolate to spaces with different dimensions [92] and (3) the critical structural temperature (resulting from a material property) concept depends on the unrealistic assumption that compartmentalization and load transfer to adjacent cold structural elements allow to extrapolate global structural behaviour from single element behaviour [9, 93]. Time equivalency, as a methodology to **Scale-Up** the influence of the fire on the structure, remained incomplete. Robustness, precision and completeness of the model could not be demonstrated and therefore the value of the refinement remained questionable.

Despite the limitations of the tools conceived in this period, it was clear that the calculation methods developed made possible a significant reduction of safety factors and enabled many architectural solutions that would not otherwise be permitted by the existing prescriptive framework. The understanding of fire dynamics established how context variables affected the combustion processes making every environment unique. The result was not only the continuous evolution of building codes, but more fundamentally, the breakdown of the classification framework. Infrastructure did not have to be classified so that a standardized solution could be prescribed by a building code, but it could be treated as a unique problem whose performance could be quantitatively assessed. As a result many building codes incorporated a performance based design clause that enabled the use of engineering tools to demonstrate if a design met an acceptable level of performance [94].

In parallel to the development of tools directly linked to the application, a better understanding of many combustion processes associated to fire was achieved. But despite the quality and fundamental nature of most of this work it has found very little **relevance** within the context of the definition of a fire safety strategy. Eventually, it was impossible to demonstrate the gain associated with these fundamental combustion studies and the links between combustion and fire modelling weakened bringing us to ask if a better understanding of combustion still has a place in the **Scaling-up** of fire?

Computational Models

The last decade has seen how traditional fire tools such as empirical correlations, experimental data, zone models, etc. have been substituted by Computational Fluid Dynamics (CFD). Tools of general use such as smoke management calculations and large scale experiments are being replaced by CFD. Classic smoke management calculations are based on entrainment correlations that are limited by simple geometries and tend to use worst case entrainment scenarios. The result is very large extraction flows and significant questions on

the universality of the results. In contrast CFD can deliver computations for specific scenarios that can potentially optimize smoke extraction rates. In a similar manner, sprinkler performance is commonly established on the basis of large scale testing but these tests are an expensive and inefficient process that will always leave the question of how far the tests can be extrapolated. Computational tools have the potential to provide this assessment in a cost effective and efficient way, but most important, they allow an explicit extrapolation of a much reduced number of test results to any scenario that is deemed within the bounds of validity of the models. A similar case can be made for most elements of the fire strategy, where three dimensional and temporal resolution of the transport equations can quantify all the variables required to assess the performance of complex scenarios or novel technologies in a manner that no other tool can achieve.

One of the most dramatic shifts in the methods used to establish a fire safety strategy is the evolution of the performance assessment of structural systems. The last decade has seen a dramatic evolution of our understanding of the behaviour of structures in fire [9, 93, 95]. The evolution of Finite Element Modelling (FEM) has allowed the analysis of complex structural systems showing that critical structural failure temperatures cannot be established simply on the basis of material properties. For most real building systems, the failure temperatures depend much more on the interaction of the different structural systems within a full structure than on the specific material properties of the building's constituents. For a given structural system, features such as restraint and load redistribution can deliver considerable additional load carrying capacity even at very high temperatures [60, 93, 95]. Thermal expansion results in deformations that enable the use of the compressive and/or tensile membrane action established in composite slabs resulting in failure temperatures that far exceed those linked to the degradation of material properties or to the performance of similar elements tested in furnaces. Other structural systems such as long span beams or light weight trusses can potentially introduce failure mechanisms that appear at temperatures significantly below those established from the decay of the material properties. Furthermore, temperature gradients and heating rates have significant impact on composite systems, where high thermal conductivity materials such as steel work in a composite manner with low thermal conductivity materials such as concrete and thermal insulation. Given the evolution of the heat transfer within the structural systems, deformations will change resulting in different load distributions and thus different failure mechanisms. The refinement of structural modelling for fire requires a higher resolution of the fire and the heat transfer that cannot be delivered by any of the conventional "temperature vs. time curves." CFD is the only mechanism by which temporal and spatial resolution of the heat flow from the fire to the structure can be attained, thus the gain associated to using these methods to **Scale-Up** seems significant [14, 61]. This paper will not discuss FEM models because the combustion **relevance** to these models relies within the definition of the thermal boundary condition provided by the CFD models.

As defined above, the use of CFD as a basis for the **Scaling-up** of fire has a very clear gain and therefore there is a strong motivation for the development and improvement of these tools. Classic tools, while still relevant, will be limited to the simpler and more conventional applications leaving little motivation for further refinement. There are numerous CFD tools available, some of general use and some specific to fire. They all have advantages and disadvantages and a detail discussion of the tools is not the subject of this paper. What is central to this paper is establishing if there is a gain in the further refinement of existing CFD tools. CFD tools are broadly used in the practise of fire safety thus there is a clear perception of their adequacy and a sentiment that further refinement will deliver little to no gain.

Nevertheless, it is not clear that our current CFD tools provide a set of outputs that is precise, robust and complete enough.

Performance Assessment of CFD Fire Models

The fundamental premise behind the development of fire related CFD tools is to be able to reproduce reactive flow fields where buoyancy plays a significant (and many times dominant) role. Furthermore, the models need to be able to include interactions between the combustion process and its environment; the environment being a test, a building, terrain or weather conditions. CFD fire model development focused initially on the gas phase, first as a means to calculate transport of heat and species with an imposed energy source term and only later resolving combustion. These first generation models incorporated extensive knowledge on turbulent flow formulations as well as effective numerical schemes but treated the environmental context only as an imposed boundary condition. It was only much later that CFD models begun to incorporate reactive condensed phase boundaries and to carefully resolve heat and mass transfer at the boundaries. These developments attempted to provide a better definition of the fuel generating boundaries for the CFD. With the incorporation the implementation of turbulent combustion formulations, pyrolysis models, and the refinement of heat transfer within the gas phase and with the boundaries that CFD evolved to become a fire model.

Many exercises of validation and verification have been presented showing different levels of agreement between experimental data and model predictions for many of the variables required as inputs for a fire safety strategy [17, 26]. Despite the extensive effort devoted to these exercises, in most cases, it has been difficult to establish, from the experimental data, the elements of the CFD models that were providing precise enough computations and those who were introducing observed output errors. An exhaustive analysis of all verification and validation studies that establishes the achievements and limitations of individual fire models is yet not available. While the NRC-NIST [17] study is the closest attempt to do this, it still does not analyze in sufficient detail the experiments used and the model output to establish the link between output and model component that will allow establishing where refinement will lead to gain. This is not a criticism to the work because there are two fundamental reasons that disable these verification and validation studies to achieve the full objective, them being:

- Most of the experimental data base used was not developed for the purpose of validation and verification of CFD models. Experiments used were mostly developed to either validate analytical formulations or zone models [96] or as forensic representations of particular scenarios [60]. Thus the resolution and type of data obtained is not targeted for the purpose and in general is too coarse or incomplete to conduct an analysis with the required level of detail.
- Given that a fire model needs to be assessed within the context of its environment, the experimental and numerical burden is very high, thus concessions on grid resolution, modelling detail, experimental control, repeatability and measurements need to be made, creating unavoidable limits to what can be concluded.

Once more the issue of **relevance** appears. Fire tests that are specifically designed for the validation and verification of CFD fire models that are of a scale and complexity that enables an adequate assessment of the performance of the model within the context of its environment seem necessary. Nevertheless, it is not clear if it is **relevant** to conduct large scale tests. Large scale tests introduce several complex issues: (1) the number of tests

required to ensure repeatability, (2) the implementation of diagnostics that can produce the necessary data and (3) the magnitude of the test that guarantees that all necessary model/environmental context interactions required are present. Large scale fire tests are only **relevant** to the validation and verification of CFD models if they can deliver adequate repeatability, the correct data at the correct level of precision and if they can test a scenario that includes the necessary level of interaction between the reactive flow and the environment. Otherwise, the tests will remain simply demonstrations where repeatability, data and scenario can always be questioned. Currently, it can be said with confidence that no large scale fire test has fully delivered a set of data that satisfies all these three conditions. A striking contrast can be established when comparing the needs of fire models with turbulent combustion models where experimental studies such as the Sandia flames [97, 98] provided the correct experiments for the validation and verification of combustion turbulence and chemistry models [99, 100].

In parallel to the development of the CFD framework there has been extensive work within the combustion community to understand specific components of fire models. These studies have targeted the development of sub-components for fire models but also used combustion CFD models for the better understanding of the different sub-processes present in a fire model. Extensive work has focused on specific scenarios where idealized conditions have been defined to understand the key phenomenological features of some individual sub-components of fire models without the complexity introduced when incorporating the full context. An excellent example of these type of studies is the work conducted in micro-gravity combustion and that is summarized by Ross [101]. Here buoyancy was removed allowing analysing fire related processes with a flow field that could be varied in a controlled manner. It is difficult to establish how much of that work has permeated into fire models, but it is clear that the development of fire models is strongly influenced by some of that work. What is not clear is how much more of this detailed work can ever make its way into fire models once the extensive constraints of the environmental context are incorporated. The issue of **relevance** becomes once more an important aspect that needs to be understood. Is it **relevant** to further develop the understanding of fundamental processes if these understanding can never be transported in to a fire model? Is it **relevant** to extrapolate idealized scenarios to a fire model if the added complexity invalidates the extrapolation?

A final issue that needs to be addressed is the robustness of the model. Robust models will deliver results that are invariant when aspects of the modelling process that are extrinsic are changed. This statement can generally be directed towards the user of the model but it could also refer to the computational hardware and software (compilation, platform, etc.). Issues such as robustness to computational hardware and software are generally simple to address and are part of the standard model development procedures, issues associated with the user are more complex. In the case of the user, with a robust model competent users will always reach the same conclusion regarding the manner in which a specific scenario should be addressed (i.e. grid resolution to obtain a grid independent result, input values such as heats of combustion, heats of pyrolysis, thermal properties, etc., constants such as turbulent invariants, laws of the wall, etc. or boundaries). At the end it will be expected that outputs obtained varying these extrinsic aspects should be similar and their variance will define the robustness of the model. As models evolve, a continuous assessment of robustness is always **relevant** because it directly establishes the validity of the output.

The Dalmarnock Fire Tests

The previous section discusses in general terms the **relevance** of large scale tests and sub-process analysis to the development, validation and verification of CFD fire models. This

section considers a specific scenario to illustrate the different issues that emerge when attempting to create a scenario that fulfils all of the necessary requirements for repeatability, data quality and density and environmental context.

The minimum cell that provides a realistic context for a fire model is the compartment. Here, the classic definition of compartment used in most classical studies is used. The compartment represents a small (approximately 100 m^3), quasi-cubic space surrounded by non-flammable boundaries (walls) and with a small number of openings (i.e. doors, windows). While the classic compartment might be perceived as an over simplification it does provide the minimum level of complexity that a fire model should be able to reproduce, thus an ideal place to start. Other real scenarios such as large industrial volumes or atria might provide less (or more) of a challenge to the models; nevertheless, in the immediacy of the fire it is most likely that all the features of a compartment fire will be present. It is clear that many real scenarios will result in further challenges to the fire model, thus the compartment can only be treated as a minimum representation of the problem.

The issue of repeatability is a major concern because tests of this magnitude can only be conducted in a reduced number. Thus the luxury of repeating the test until the same result can be attained in a consistent manner is one that will never exist. For fire models a different approach is necessary. An alternative way of attaining repeatability is by designing a scenario where the importance of the dominant sub-process is emphasized. This process is then meticulously controlled in a manner that when tested independently (much smaller test) the results are consistent. As a means of establishing repeatability, the sub-process next in importance is then varied within an extreme range to establish the magnitude of the impact of this variation. While not ideal, this approach allows reducing the number of large scale tests to a minimum of two (extreme bounds of the secondary sub-process) but it is restricted to serve as a scenario that only validates or verifies the performance of the fire models when the specific sub-process dominates. It is obvious that more tests will always deliver a better sense of repeatability, nevertheless, under these conditions two tests does attain the objective of establishing consistency among the results.

Finally, there is the issue of quality and quantity of the data. Complex diagnostics in a fire environment are extremely difficult to implement. While there are excellent examples of the state of the art measurements made under difficult fire conditions, these examples are always limited to very specific scenarios. The problem is one of extracting the minimum amount of useful data relying on diagnostics that are viable within the context of the particular environment.

The Dalmarnock fire tests [102, 103] are probably one of the few scenarios that explicitly attempted to follow this strategy. Other tests have probably delivered the same results nevertheless they were not explicitly structured for this purpose. The detailed discussion of the large experimental data base available is avoided here only on the basis that the Dalmarnock fire tests explicitly acknowledge the purpose of their design and thus can be used as an example that helps illustrate the challenges associated to validation and verification of CFD fire models.

Description of the Tests

Two tests were conducted in a derelict building in Dalmarnock (Glasgow, UK) in identical compartments. The tests were designed to the constraints typical of a classic compartment. The dimensions of the room where 2.45m high, 3.50m by 4.75m and the compartment included three vents; a window and two doors. The fuel corresponded to realistic office furniture and objects in quantities that would be typically found in any modern work environment. The most important features of the test were the sensor density and the fire that was designed for the test. Figure 1 shows two views of the compartment and Figure 2

a detailed legend for all sensors displayed within the compartment. The Dalmarnock fire tests are described in some detail by Rein et al. [104] and in greater detail in Abecassis-Empis et al. [102] and Rein et al. [103]. Here only a brief description that highlights the aspects best linked to the discussion will be presented.

Given that the objective of the test was to provide a data set that could be used for the purpose of validation, verification and improvement of CFD models it was considered that the type and resolution of the data had to be consistent with standard CFD model outputs and resolution. For this purpose four outputs were selected, temperatures, heat fluxes, light obscuration and velocity. Within the compartment 240 thermocouples were distributed (Figure 2) in as homogeneous a manner as possible. Similarly, 80 thermocouples were placed outside the window to reconstruct the fire plume. Nine thin-skin calorimeters were used to measure heat flux to the compartment ceiling and 16 heat flux gauges were mounted on the partition wall shared with the kitchen. Eight lasers used to measure light obscuration were set in emitter-receiver pairs, such that five were horizontally aligned and three were vertically aligned. Three bidirectional velocity flow probes, were placed in both the doorway leading to the flat corridor and in the doorway to the kitchen and a further eight probes were placed outside the compartment window. Six web-cameras were also used to monitor the fire growth and all data collected was time stamped, both camera and data logger clocks (for all other measurements) having been synchronised prior to ignition.

The thermocouples allowed producing three-dimensional isotherms as a function of time that could be directly compared to a CFD model at equal level of precision and resolution. The heat fluxes to a wall and the ceiling also provided two-dimensional contours of the heat flux as a function of time with a resolution and precision consistent with a CFD model. Light obscuration measurements could only be collected for a few points therefore only characteristic measurements were expected. Also, light obscuration is not a direct output from the model therefore path integration of the model output had to be conducted for comparison. The velocity measurements were a different form of compromise in that only one component of the velocity vector could be obtained for a much reduced number of locations all at the compartment boundaries. The choice of location was given by the performance of the probes but also because it was deemed important to be able to reconstruct a mass balance that established the global heat release rate of the fire. Here, a further assumption needed to be made, which is total consumption of all the oxygen entering the compartment. The global heat release rate is no longer a variable that is directly related to the CFD output, but CFD models are expected to be able to reproduce the time evolution of this variable. The most important limitation of the data was the absence of any gas analysis. This represents a real limitation that could not be resolved given the budget available and the constraints imposed by the test environment. As can be seen, the complexity of the environment not only limits the nature and quantity of the sensors but also introduces compromises on the nature of the measurements.

(a)



(b)



(c)



Figure 1 Photographs of the Dalmarnock compartment (a) view of the front of the compartment towards the only window (b) view of the back of the compartment. (c) a view of the back of the compartment showing the two doors at the right hand side of the compartment. Figure 2 indicates the direction of the three views.

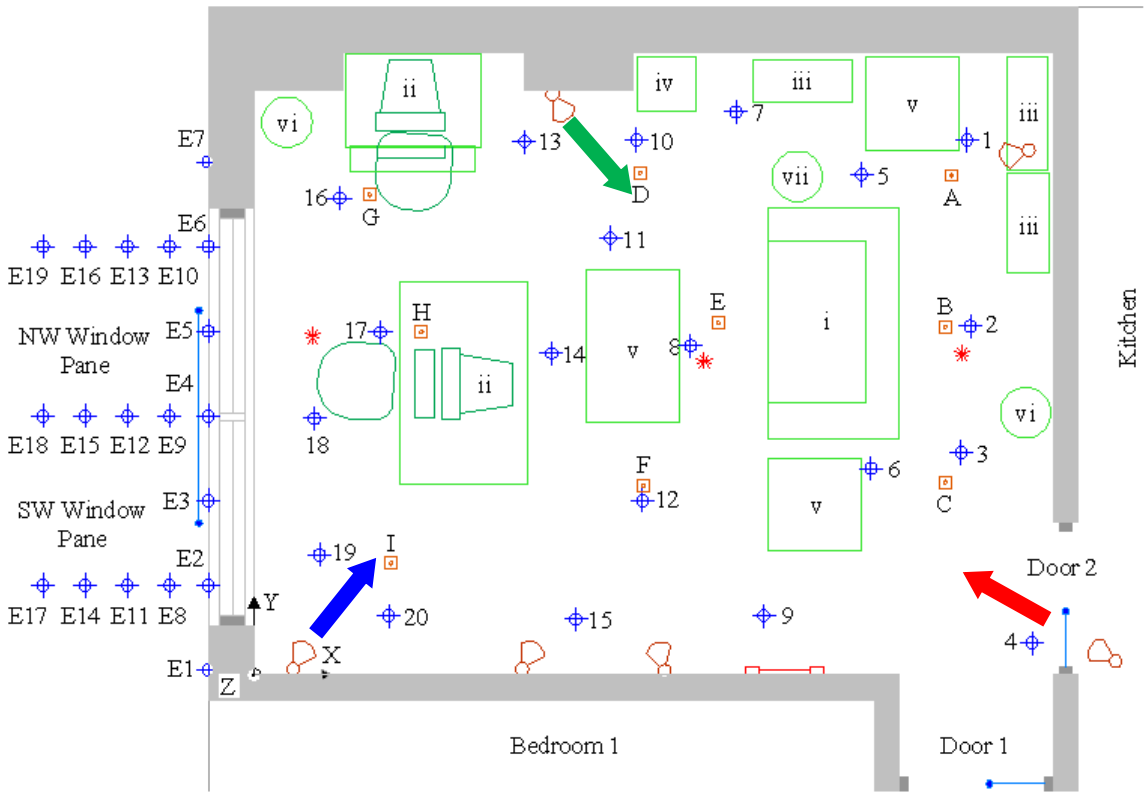
A typical set of thermocouple data for a plane perpendicular to the window wall (3.10 m from the Bedroom 1 wall) is presented in Figure 3 showing the spatial distribution of isotherms for an individual plane at a specific point in time. As shown in Figure 3 these isotherms provided a level of resolution consistent with typical CFD fire models that resolve the combustion and smoke regions. Similar sets of data were constructed for other planes as well as for other times. Data sets for all other measured variables were also obtained with resolutions consistent to the limitations of each measurement. This resolution not only enables a clear understanding of the evolution of the fire but also allows a more detailed comparison with the CFD fire models. More complete sets of data can be found in Abecassis-Empis et al [102] and Rein et al [103, 104].

The boundaries of the compartment (walls and ceiling) were instrumented with thermocouples embedded in the concrete structure as well as strain gauges and displacement sensors. These measurements were intended for comparison with FEM models of heat transfer through the solid boundaries and of structural evolution. Furthermore, the measurements allowed establishing the integrity of the compartment so that the boundary conditions for a CFD model could be specified with certainty.

Repeatability

The repeatability of the test was established by designing the fire in a manner that enabled as consistent of an outcome as possible. The principle behind the design of the fire was to address all major sources of uncertainty. The first source of uncertainty is the ignition protocol. The evolution of a fire can be defined by ignition, especially for a fuel of complex nature, such as furniture. Modern furniture is designed to minimize the potential for ignition, thus barriers are placed on the sides of the furniture protecting the cushions that are generally made of polyurethane covered with fire retarded fabric. Common ignition sources such as waste paper baskets will burn-out before penetrating the barriers thus preventing the flames from propagating towards the polyurethane cushions. Several tests were conducted prior to the test with identical pieces of furniture that allowed a consistent and repeatable ignition protocol that bypassed the barriers and resulted in an almost instantaneous ignition of the polyurethane [102, 103]. Under these conditions, the ignition delay time could be assumed as zero and the magnitude of the fire was large enough from the onset so that the subsequent propagation was observed to be repeatable.

The main piece of fuel was the sofa (Figure 1) which is labelled (i) in Figure 2. Ignition was induced on a waste paper basket filled with paper and a predefined quantity of heptane (labelled (vii) in Figure 2). While burning of the sofa had the potential to induce flashover within the compartment, spread rates will be dominated by many variables of which the inclination of the flame and heat feedback from the smoke and the ceiling were deemed to be the most important. Both variables introduce significant uncertainty given that they will be the result of the balance between the energy generated by the fire and the nature of the ventilation. By igniting the sofa on one end, the leading edge of the flame controlled flame spread (opposed flame spread), thus the influence of the inclination of the flame on propagation rates was minimized. The influence of heat feedback was reduced by inducing flashover before the upper layer temperature increased to a level where radiative feedback became significant. This was achieved by guaranteeing that the flames from the sofa tilted towards a second fuel package that could sustain fast upward flame spread.



SENSOR KEY

8	Thermocouple Tree
E3	External Thermocouple Tree
E	Heat Flux Gauge
	Horizontal Obscuration Sensor
	Vertical Obscuration Sensor
	Air Velocity Probe
	Camera

FURNITURE KEY

i	Sofa
ii	Desk, Computer and Chair
iii	Bookcase
iv	Cabinet
v	Coffee Table
vi	Tall Plastic Lamp
vii	Waste-paper Basket

Figure 2 Sensors distributed within the main compartment. The red arrow indicates the view corresponding to the image of Figure 1(a), the blue arrow corresponds to the image of Figure 1(b) and the green arrow to the image of Figure 1(c). The sensor key indicates the type of sensor and the symbol next to it corresponds to the nomenclature used.

Three bookshelves filled with loose paper and cardboard were used as the second fuel package. The bookshelves were placed strategically in a corner of the room (labelled (iii) in Figure 2 and visible in Figures 1(b) and 1(c)) with the sofa between the vents and the bookshelves. Individual testing of the bookshelves established that once ignited upward flame spread will engulf the entire bookshelf in a very short period of time (~10 seconds) generating sufficient energy to induce flashover in the compartment (>0.5 MW). So once the length of the sofa flame was enough to ignite the bookshelves flashover will be induced instantaneously and the fire will progress to a fully developed fire. It is clear that the present scenario emphasizes the sub-processes associated to secondary ignition (i.e. material properties of the fuel in the shelves, radiative and convective heat transfer from the primary flame, etc.).

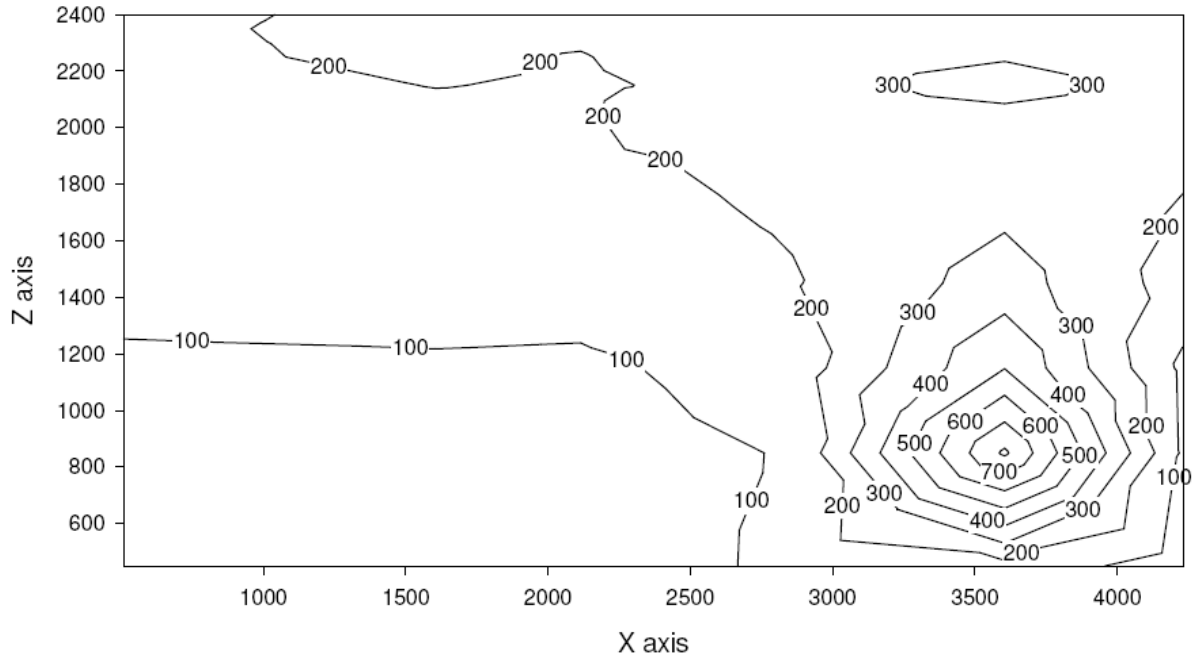


Figure 3 Temperature isotherm for a plane parallel to the side wall where x=0 is the plane of the window and x=4,750 mm the plane of the back wall. The plane is 400 mm away from the side wall and the data was taken 251 seconds after ignition. Data used for the plot was adapted from reference [103].

Once the fire had attained flashover and entered the fully developed phase ventilation becomes the controlling parameter. The two doors were left open and the window was broken at a pre-specified time eliminating the uncertainty of window breakage [103]. The doors were buffered from the environment by other rooms (kitchen and bedroom in Figure 2) and the widows were left open in both adjacent compartments. This allowed enough air to flow into the compartment but sufficient pressure drop to minimize the influence of outside flows. Figure 4 shows a sequence of events using an average compartment temperature as a reference. It can be seen that temperatures before flashover are very low (<150^{o}C) minimizing radiative feedback, flashover occurs almost instantaneously and once the compartment reaches fully-developed conditions it attains an almost steady state until the window is broken (800 sec). After the window is broken, a second steady-state period is observed that eventually is terminated by the fire-fighters. It is important to note that the fire had almost consumed all the available fuel at this point.

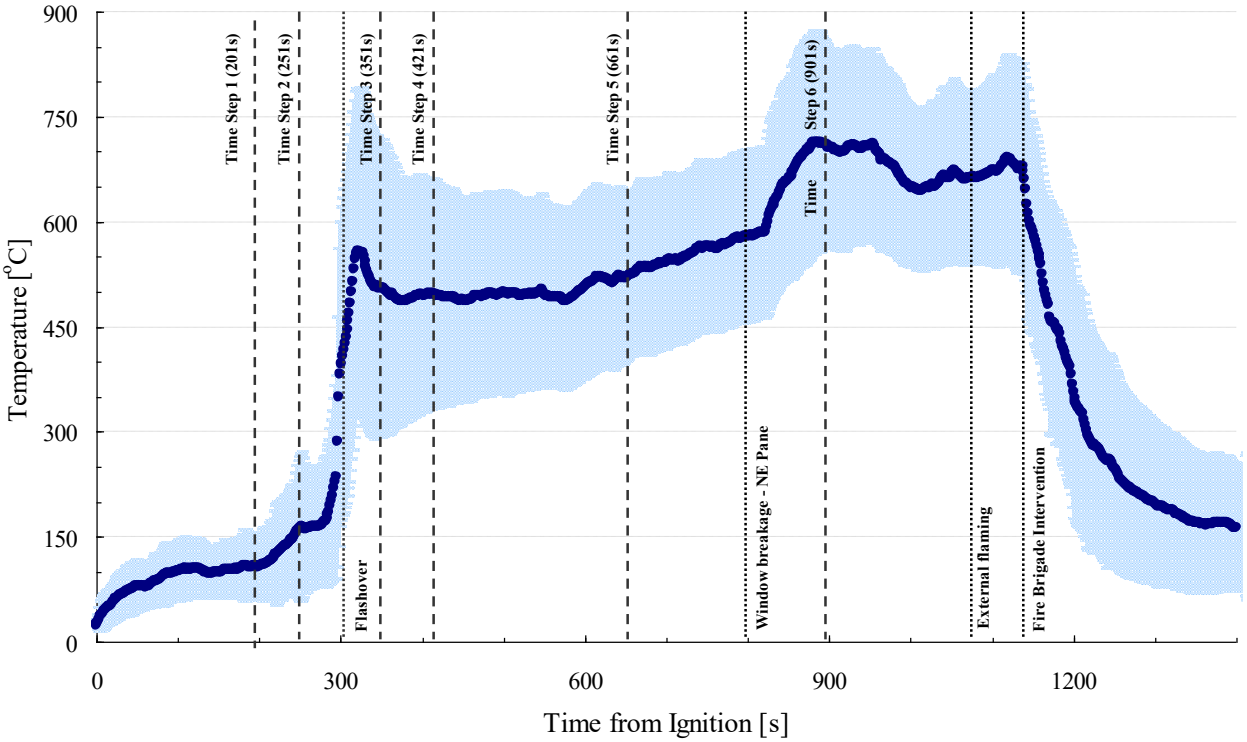


Figure 4 Gas-phase average compartment temperature-time variation (thick line) with the standard deviation of temperature throughout the compartment (shaded). Vertical lines indicate times at which significant events occurred and times at which the data was analyzed spatially. Data for the plot was adapted from reference [103].

A second test was conducted to verify the repeatability of the results. The criteria chosen to establish consistency was time to flashover and the parameter varied was the ventilation. Ventilation will control the inclination of the flame and the temperature of the compartment, thus the radiative feedback. To enhance the ventilation the window was opened early in the test and a large perforation (1.2 m by 1.2 m) was made between the compartment and the bedroom allowing direct access of air from the window in the bedroom to the compartment. This represented a drastic departure from the first test imposing the greatest possible challenge to the repeatability of the test. Given the specific characteristics of the compartment there was no other change that could have a bigger impact. Establishing repeatability for the post flashover stage was not possible given the significant differences in ventilation, nevertheless it was considered that post-flashover conditions are more consistent if the fuel load, type and distribution remains the same. Thus Test 2 was extinguished after flashover was attained. It is clear that further tests could have been carried to guarantee repeatability of the post-flashover scenario. These would have fixed ventilation and vary fuel load and distribution. Nevertheless, once again constraints associated to large scale experimentation limited the number of tests possible. Figure 5 shows the comparison between the two tests. As expected, Test 2 shows lower temperatures throughout the entire pre-flashover period nevertheless flashover occurs almost at exactly the same time and following very similar characteristics. Comparison of video images shows that the evolution of the sofa flame in both tests is very similar and that flashover is, in both cases, induced by the ignition and rapid upwards flame spread of the bookshelf.

Summary

The Dalmarnock fire tests represent a good example of the different measures necessary to achieve large scale tests that can be deemed as **relevant** to the validation and verification of CFD models. While in its minimum expression, these tests are of a scale and complexity that enables an adequate assessment of the performance of the model within the context of its environment. Every effort was made, within unavoidable limitations, to deliver the correct data at the correct level of precision and density. Finally, an adequate scheme was developed to deliver confidence on the repeatability of the tests. While many things could have been improved, and many criticisms can be made to many of the choices, these tests are important in that they represent an explicit attempt to provide data that is **relevant** to the validation and verification of CFD models.

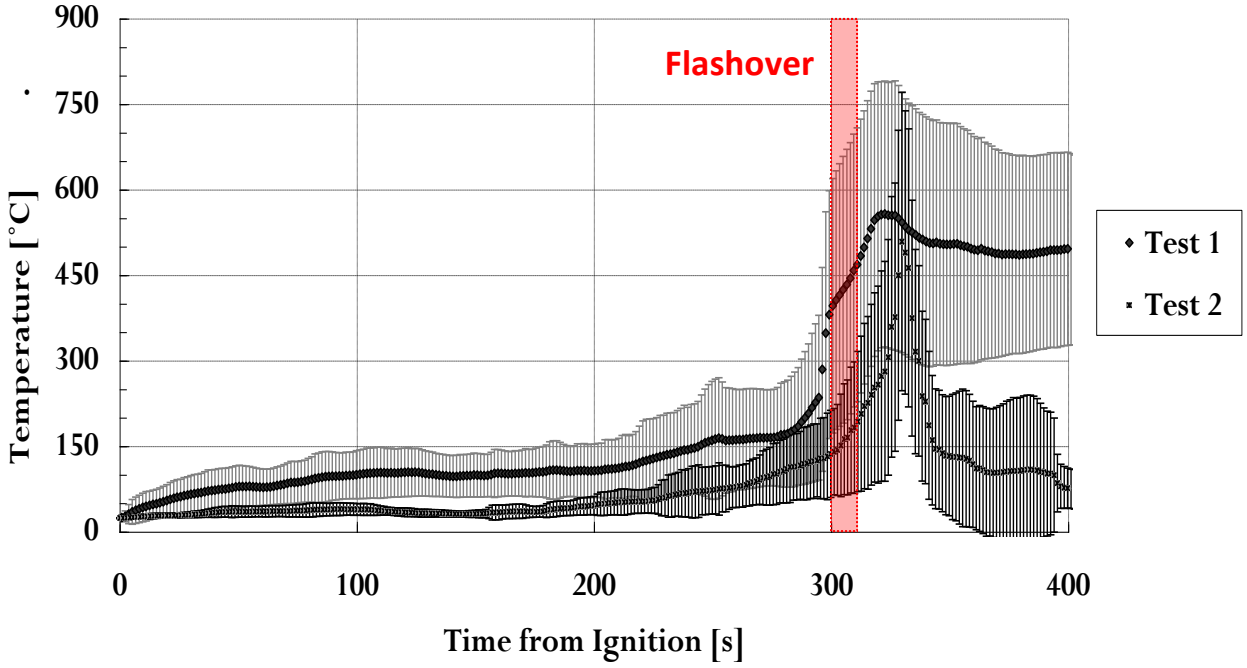


Figure 5 Comparison of the experimental average room temperature (˚C) variation in time (s) of Test One and Test Two. Data is only presented until extinction of Test Two (400 seconds). Data for the plot adapted from reference [103].

Modelling Study

Validation, verification and improvement of fire models require experiments and model output to be compared at many levels. Components of the fire model can be studied by conducting idealized experiments where individual processes or couplings are tested. Several studies of this nature are present in the literature; i.e. The capability of the numerical model to resolve the transport of energy and species can be studied by means of well defined burners where the flames are consistent in nature and buoyant entrainment can be modelled free of any other influences [105-108]; flame spread models can be studied by means of wind tunnels that establish well defined boundary layers where buoyancy is subdued to a forced

flow [109-112] or the accuracy of pyrolysis models can be explored by means degradation experiments where combustion is prevented and substituted by a fixed heat flux [113-116].

The study of the coupling between the sub-processes and their interaction with their environment is then necessary to truly address the validity of a fire model. To achieve this, several approaches need to be explored. A first strategy consists to attempt reproducing existing data to identify sub-process or couplings that are properly modelled or that introduce significant departures from the model output, this is generally referred to as *a posterior* modelling. This can be difficult given the numerous sub-processes and couplings and it can therefore require several experiments. Experiments need to be designed with a clear objective and simplifications have to be introduced in a manner such that the effect of the sub-process or coupling on the output can be isolated. The literature has very few examples of fire experiments specifically designed for this purpose. The study of fire models has been conducted mostly using experimental data obtained in the past with very different objectives [26], thus the identification of target sub-processes and couplings is rarely possible. Instead, most studies of this nature conform themselves with establishing acceptable agreement but are not capable of addressing the reasons for the agreement or the weaknesses in the sub-processes or couplings that result in departures. With a problem that has such a large and complex parameter space, this exercise is like shooting in the dark where even if the target is reached it is impossible to define why.

A final exercise relates to the validation of the model and its robustness. Once sub-processes and couplings have been refined to a sufficient level it is important to conduct blind or *a priori* comparisons. The output of the model is obtained first and then the experiment is conducted to establish by means of a comparison of the relevant parameters the level of precision of the model output and the confidence on the modelling results. On a first instance a single model user should conduct the calculations followed by a Round Robin. The two studies will separate the model capabilities from the robustness of the model to the user. These protocols for validation, verification and improvement have been standardized and are presented in a much more rigorous manner in many publications [117], nevertheless it is important to reformulate them here in the context of fire models and the example presented.

The "A Priori" Round Robin

A Round Robin study was organized in conjunction with the Dalmarnock fire tests [104]. The tests, as explained above, were deemed to be appropriate for this objective, nevertheless assumed that the models to be used already incorporated in an adequate manner all sub-processes required, all necessary couplings among the different sub-processes and with the environmental context and that single user validation had established that the models were capable to provide an output of **relevant** precision. In other words, the exercise assumed that fire models were ready to be used for their intended application. The fundamental driver behind this study was the verification that existing fire models were extensively used for scenarios very similar to the Dalmarnock fire tests (in most cases much more complex). Thus, the objective was simply to establish the robustness of the models to the user.

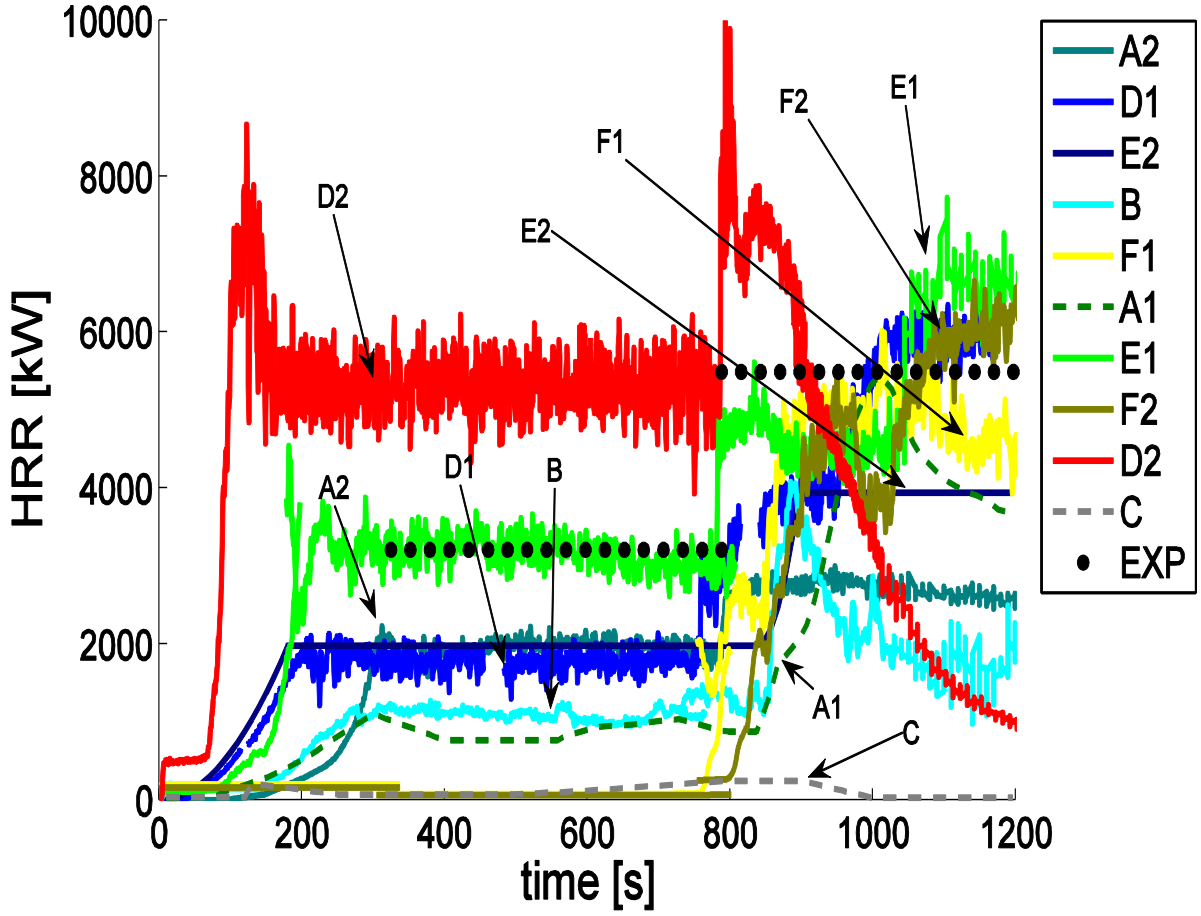


Figure 6 Heat release rate in the whole compartment. Legend for the different curves; continuous line for CFD models, dashed line for zone models, and dots is for experimental data. Data adapted from reference [104]. A1 and C correspond to zone models and all the other data was obtained using CFD models.

The details of the Round Robin and the comparisons between the different submissions and the experimental results can be found in Rein et al. [104]. As an example the comparison corresponding to the heat release rate (HRR) is presented in Figure 6. The heat release rate is a global variable that fire models are expected to be able to predict, because it represents the source term to be used for any interaction between the compartment and the environment external to it. As can be seen in Figure 6, notable are the differences between experimental data and the model output, the differences between different model outputs and the fact that the output from CFD models blends with that of much simpler models (zone models). These observations are consistent among all variables measured with no specific model output being systematically better. While Figure 6 shows E1 as the result closest to the experiment, for other data a different set of predictions will take this role [104].

While the exercise is of great importance, it is not the results that matter, but what can be inferred from the results. Clearly, the objectives were not met and the model outputs did not deliver adequate predictions of the different variables **relevant** to fire safety. The authors of the Round Robin argue that the scatter and randomness in the outputs originated in the different assumptions introduced in the input parameters indicating that the large number of inputs and the variability observed in literature values associated to this inputs can lead to a large variance in the results. This is clearly a possibility but not the only one. It is also

possible that the sub-processes emphasized in the Dalmarnock fire tests are not well described in existing fire models or that the couplings between these sub-processes have not been properly modelled. The model outputs and the comparison between the different submissions do not shed light on this issue because the modelling study was not designed for that purpose. It assumed that these sub-processes and couplings were properly included in the fire model and that they were robust to the user. Finally, the experiments can be questioned. As indicated in the previous section, the experiments were deemed, within the scale and complexity, to be repeatable and the data was deemed sufficient and precise enough. Nevertheless, the experiments were limited in that they over emphasized a specific sub-process (the secondary ignition of the bookshelf) thus were designed with only two possible objectives, to establish the accuracy of the sub-processes and couplings involved in the secondary ignition of the bookshelf or to establish a realistic and repeatable scenario to test the robustness of the overall fire modelling process to the user. The later was explored unsuccessfully by the *a priori* Round Robin but the former needs to be explored by means of an *a posterior* modelling analysis that focuses on the secondary ignition process.

The "A Posteriori" Modelling Study

Several studies have been reported where the scenario of the Dalmarnock tests were modelled after the event and with the data available [19, 118-120]. These studies explore, in more or less detail, the different variables influencing the computational outcome. In all cases some level of agreement between model output and data is demonstrated. The agreement observed, while still showing departures, is to a level much greater than that obtained for any of the models in the *a priori* study. The studies concluded that:

- Reducing the qualitative and quantitative disagreement between experiments and model outputs requires significant effort beyond the standard grid sensitivity and parameter selection process. Some of the inputs need to be explored in greater detail and with the information available parameters need to be tailored to the specific application. A typical set of data is presented in Figure 7 showing the comparison between two modelling scenarios for bounding conditions that could possibly represent the test and the experimental data.
- The common practise of prescribing the heat release rate as the source term that enables the introduction of fuel is not sufficient. For the particular scenario it is necessary to correctly specify the area through which the fuel is incorporated. If this is not done with precision then the flame height is not predicted correctly and heat transfer to the bookshelf is misrepresented and secondary ignition is not predicted adequately. Given that this is the dominant sub-process for the particular scenario, changes in this specific output result in drastic changes in the overall outcome. Thus, for the Dalmarnock scenario it is essential to be able to properly predict flame spread. In the simulation by Jahn et al. [120] the burning area was established from video images, thus an effective correction was introduced on the basis of sensor data.
- Very small scenario changes (e.g. a blanket) can result in a significant difference in the overall results [120].
- Discrepancies were of a quantitative and qualitative manner. When field comparisons were made it was established that energy distribution within the compartment was not necessarily correct. Some of the values were within acceptable error bars others were not. Figure 7 shows how the upper layer temperatures were within the bounds of the models while the lower layer temperatures were not. Field comparisons

provided an added value to the study because they allowed identifying detailed discrepancies.

- It was not possible to identify the sources of error because of the many variables with direct impact on the outcome and the untraceable link between the sub-processes and the outcome. Reference [26] establishes that in this context simulation of fire growth was significantly sensitive to location of the heat release rate, fire area, flame radiative fraction, and material thermal and ignition properties, but these are just a few of the possible sensitivities of the models.

While the *a posterior* exercise remains of value and it is worth reporting, it highlights a fundamental problem that is the essence of the point being made here, validation, verification and improvement experiments need to be defined for a specific purpose that is consistent with the state of the art of the models. The Dalmarnock fire tests, even with all the precautions taken and the extensive data collected, were not designed for the purpose of learning about the model. The tests were designed for a scenario that assumed that all the model sub-processes, input data and couplings were formulated to a level of precision that was **relevant** to fire safety. Thus, fuel packages introduced too much input data uncertainty and the many sub-processes and couplings included in the scenario made it impossible for the modeller to trace back the sources of error. The *a posterior* modelling study only served to highlight the sensitivity of the outcome to several sub-processes (e.g. flame spread) and the fact that small uncertainties in the definition of the scenario can result in major discrepancies in the output. From the perspective of the modeller, this was probably already known and of little help, from the perspective of Fire Safety, it is a reminder that much work still needs to be done in fire modelling.

A final issue of importance is the scenario uncertainty. Fire safety carries, by nature, a significant scenario uncertainty, thus from the present study it can be concluded that detailed CFD modelling is of no **relevance** to fire safety and that further improvements in the sub-processes will always be overruled by the inherent uncertainties of the scenarios studied. From the perspective of the author, this is an incorrect interpretation of the results of this study. What this exercise demonstrates is that variations in the scenario introduce such differences to the outcome that they need to be incorporated in the modelling process. As an example, if the surface area covered by the flames is not predicted correctly, the outcome is drastically different and the potential consequences for fire safety are extraordinary. As clearly demonstrated in Figure 6 where the predictions of the heat release rate (**relevant** variable) cover several orders of magnitude. Thus, being able to establish accurate flame spread rates is essential. Furthermore, the study showed that sensor data (such as video recordings) can be used effectively for this purpose.

Predictive Modelling or Inverse Modelling for the Scaling-Up of Fire

Most current modelling efforts are directed towards predictive modelling. Thus the focus is on improving the models to achieve more robust and precise predictions of a fire event. While this is clearly a necessary approach it does not always lead to results that can be deemed of direct **relevance** to fire safety. The entire process of fire model development, validation, verification and improvement is a tedious, long and expensive process that can only be justified if the improved results lead to a more effective definition of fire safety. This is clearly not the case where variability in the scenario can create errors much greater than the errors associated to the pure modelling exercise. Fire is not the only field where this is a possibility. Other fields such as weather predictions [121] or biological flows [122] also

encounter similar problems because the changes in the initial or boundary conditions can generate massive changes in the outcome. Thus the impact of model refinements is negligible when compared to that of scenario changes. It is therefore essential to be able to incorporate the particular characteristics of the scenario into the model. Given that the scenario can evolve in time it is necessary to be able to capture the scenario at the onset of the model and through the time period that the model is trying to predict.

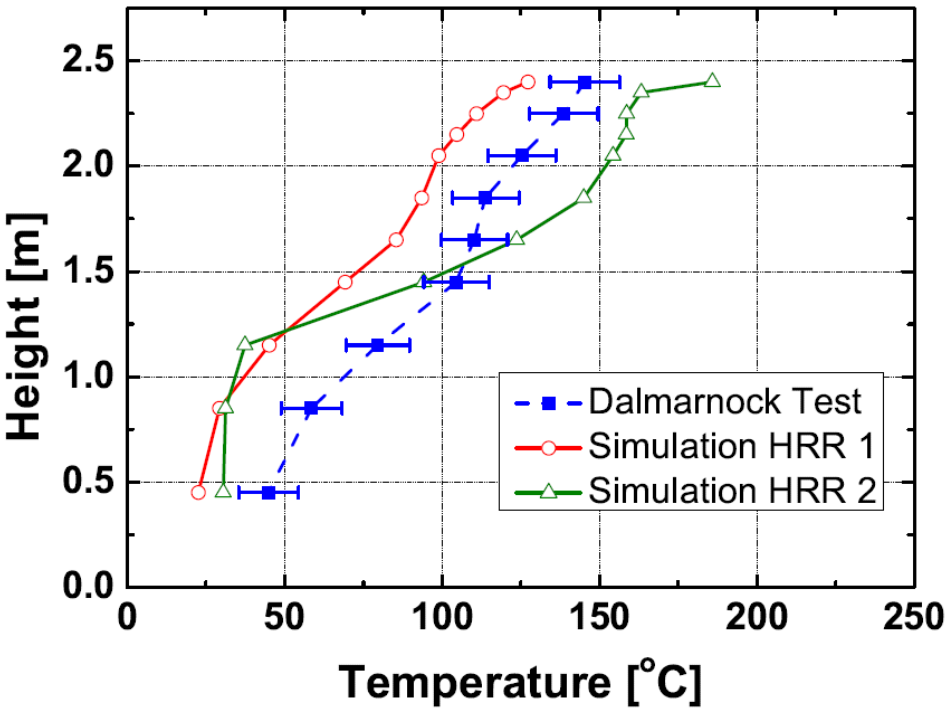


Figure 7 Vertical temperature distribution at a specific time as measured by one of the thermocouple racks of the Dalmarnock Test and as predicted by the model using two bounding heat release rates. Data adapted from reference [120].

Predictive modelling has yet another problem, gas phase (combustion chemistry, heat transfer and fluid mechanics) and solid phase processes (pyrolysis chemistry, phase change, heat transfer, solid mechanics) can have very different characteristic length and time scales, thus fully resolving and coupling all the processes can represent an insurmountable computational burden that requires input parameters that in many cases cannot be obtained. Thus comprehensive fire modelling cannot be justified as **relevant** to fire safety. The common solution to this problem is to simplify certain components of the model. Some simplifications are simple filters that generate compatibility between otherwise incompatible length and time scales (e.g. LES models, Favre Averages, PDF's, etc.[18-21]), some simplifications are physically based and rely on some of the sub-processes being established as negligible (e.g. Low Mach number formulations [18,19], Laminar Smoke Point [123], infinite chemistry [18, 19], etc.), some of them are mathematical leading to solvers that allow coarse grid resolution [29, 35] and some of them simply substitute entire processes by empirical formulations (source terms as empirical burning rates or heat release rates, laws of the wall, etc.[18,19]). An excellent example of the range of simplifications possible is the comparison between the mathematical representation of the problem derived through the development of the Fire Dynamics Simulator [26] (and WFDS [33]), the fire variant of openFOAM [27], the Utah C-SAFE modelling effort [32] or any of the other available

computational tools. Each model incorporates numerous simplifications of different nature leading to models with very different limitations, versatility and application prospects.

The author does not intend to state that comprehensive modelling of the type commonly done in the study of combustion (DNS studies, high level combustion chemistry studies, detailed local heat transfer analysis for flame quenching, etc. [20, 21]) has no place in fire safety, nevertheless its role is primarily to inform fire models and not to be fire models. Fire models should introduce simplified sub-processes that are developed from a combination of canonical experiments and detailed models. Only the combination of both will deliver sufficient understanding of the sub-process, provide direct validation and verification of the model and enable the reformulation of sub-process in a simplified manner that is amenable for introduction in the broader framework of a fire model. Important examples of the detailed analysis of these sub-processes abound in the micro-gravity combustion literature [101] and are of great value to the understanding of the sub-processes nevertheless very few of these studies have aimed to deliver a simplified formulation that then can be introduced into a fire model. Removing the dominant role of buoyancy delivered the canonical experiment that enabled to explore in great detail numerous fundamental processes that are masked in a buoyantly dominated fire model. These processes, while masked by buoyancy, still have an important influence on the overall progression of the fire.

When exploring the literature on the advances of chemical kinetics and their contributions to combustion modelling, the use of canonical experiments like the perfectly stirred reactors allowed the development of combustion chemistry under constant turbulence conditions [124]. These studies delivered simplified chemical kinetic models and constants that then could be introduced into detailed combustion models to study the role of turbulence in combustion [125, 126]. Subsequently, reduced mechanisms and turbulent models were applied successfully to realistic problems such as turbine engine combustion [127]. This approach is not only less frequent in fire, but it is less comprehensive, when a simplified model is developed from a combination of a canonical experiment and detailed modelling, it rarely makes its way to the fire model.

With the exception of a few notable cases, much of the knowledge acquired has not managed to migrate into fire models. This is not because the knowledge acquired is not good or relevant but because it has not been possible to demonstrate its **relevance** to fire safety. The argument is simple, what is the point to further understand these sub-processes or their couplings to deliver a better fire model if at the end, scenario variables will introduce variants that will completely overrule the improvements associated to a better definition of the sub-process? As a result fire models continue to rely on simplifications that were developed on the basis of very strong, scenario specific or unverified assumptions. These simplifications (and their coarse nature) were introduced for models with a different level of resolution, where the framework did not merit the detail (e.g. analytical or zone models). Decades of research have demonstrated that more detailed and better defined models cannot produce results that are more **relevant** to fire safety. Scenario uncertainty has always overruled the need for more understanding or better resolution of the sub-processes and their couplings.

Given that fire modelling is no different than any other complex process, predictive modelling requires understanding of the fundamental sub-processes and their couplings. With this understanding, simplifications can be introduced to enable modelling of the combustion process within the context of its environment [128]. It is the fundamental understanding that will deliver the required robustness and will enable linking the sub-processes and couplings to the outcome. Nevertheless, this fundamental scientific path can only be deemed **relevant**

to fire safety if the impact of scenario uncertainty is reduced to a level smaller than the uncertainty of the model.

The answer to the problem of scenario uncertainty was first established within the weather forecast community several decades ago. Weather data from all over the world is used to initialize (data assimilation) a model prediction. The model then extrapolates the evolution in time of the weather patterns. As new data is collected, a new model is launched with a new set of initial conditions and a new extrapolation is derived. Most modern weather prediction models assimilate observations during a certain period of time (assimilation window) before starting the forecast. This is done in order to account for the dynamic coupling of the involved processes [129]. When consistency between predictions and acquired data is obtained, then it can be deemed that there is a period of time where the model can effectively reproduce reality with a **relevant** precision (lead time). While this approach is consistent with the needs of fire modelling, the extrapolation from one field to another is not straight forward. In fire, like in weather, conditions evolve in time, thus initializing the simulation by means of data is necessary but not sufficient. The scenario uncertainties are embedded in the boundary conditions but also the fire influences the time evolution of the boundary conditions. Thus, the data being assimilated needs to be sufficient to recreate initial and boundary conditions at a **relevant** level of precision. In this manner the breakage of a window or the presence of a blanket (boundary conditions) can be deducted from the combination of data and modelling.

Several inverse modelling studies have been undertaken in the last few years. Richards et al. [130, 131] used a zone-type model and experimental ceiling jet temperatures to estimate the location of a fire and the coefficient of a quadratic fire growth function such as that presented in Equation (2). The experimental data was obtained from the literature and by using temperature sensitive plates and cameras. The model used an axis-symmetric plume as source term, ceiling jet correlations to establish the spatial decay of the smoke temperature and an optimization algorithm to establish a best fit between sensor data and a library of solutions to the zone model. This data allowed using the model to determine a unique fire size and location at the moment when a detector was activated (temperature criterion). The authors found that the accuracy of the fire growth estimations was very sensitive to the nature of the physical model but that the location of the fire could be established in a much more robust manner. While the study discusses numerous ways to quantify errors they do not establish how the limitations of the physical model, the different sub-models (plume, ceiling jet, etc.) and the nature of the data assimilated affected the potential for the combined data and model to deliver predictions.

Similar zone models were used by Leblanc and Trouvé [132] and by Koo et al. [133] In the former study pre-runs were fed to the model to extract successful estimations of the heat release rate evolution while the latter used experimental data to progressively steer the fire simulations towards the experimentally measured temperatures. Koo et al [132] use a Monte Carlo approach where a set of initial parameters was used for random generation of scenarios. In both cases the data (real or simulated) was used to quantify a series of constants that allow to reproduce the variables of interest but it was not established if these constants were invariant, thus providing a data calibrated model that could deliver a prediction. This final point is of critical importance because, if the physical processes are described with sufficient accuracy and completeness, then the calibrating parameters should attain a constant value after sufficient data has been assimilated. Jahn et al. [134] follow a similar approach but described in an explicit manner three invariants, "α" as per Equation (2), an entrainment constant (C) and a time delay intended to displace the onset of the fire growth curve (Equation (2)). The data used for assimilation was obtained from the results of a CFD

simulation for a very simple scenario of a small compartment with homogeneous fuel distribution where the fire spread in a radial manner at a pre-specified rate. Even with a simple formulation, such as a zone model, Jahn et al. [134] managed to establish that convergence of the constants could be achieved. It is clear that the simple nature of the scenario is best fitted for the zone model, thus these results do not necessarily demonstrate that a zone model provides all the necessary physical complexity required for a case such as the Dalmarnock tests. A follow-up to this work used a similar approach but instead of a zone model used a CFD model with a coarse grid resolution [135]. The description of the fire source was initially similar to that presented in the earlier work and the data to be assimilated was generated by a more refined CFD computation. The assimilation process delivered more precise resolution of the different variables albeit at a much higher computational cost. In a final study the same authors use the same model with the Dalmarnock fire data to deliver accurate predictions of all relevant variables with an effective lead time [136]. In this latter scenario it is necessary to introduce a more detailed fire growth formulation that incorporates geometrical features and a flame spread velocity. The flame spread velocity is then addressed independently [137] to demonstrate that a simple model [13, 81] can be used with relevant data to predict the spread of a flame. Only when these components are introduced the invariants converge indicating that the physical processes used suffice to deliver adequate predictions of all **relevant** outputs.

These initial studies have demonstrated that by assimilating sensor data into models it is possible to account for scenario induced uncertainties, but only if the processes and couplings involved are described with sufficient level of detail. Furthermore, the assimilation of data into models enables a better interpretation of tests results, identification of controlling mechanisms and improvement of the sub-processes involved and the couplings that eventually lead to a fire model.

Conclusion

Fire Safety can only be **Scaled-Up** if the combustion process involved can be modelled within the context of their environment (fire modelling). Many forms of fire models exist but only the use of explicit fire models is acceptable in a world that strives for sustainability. Being combustion one of the fundamental processes within fire modelling and a component that could be refined by means of research. The **relevance** of combustion research to Fire Safety is defined by the transparency by which this research can be linked to the precision, completeness and robustness associated to the **Scaling-Up** of Fire.

The link between refinements in the combustion processes involved in fire modelling and the potential improvements in a fire safety strategy is generally blurred by the complexity of the processes involved, the natural incompatibility of time and length scales and the unavoidable scenario uncertainty. In this context the use of CFD as a basis for the **Scaling-up** of fire has a very clear gain. Classic tools, while still relevant, will be limited to the simpler and more conventional applications leaving little motivation for further refinement.

Predictive modelling requires understanding of the fundamental sub-processes and their couplings. With this understanding, simplifications can be introduced to enable modelling of the combustion process within the context of its environment.

Adequate experimentation is critical not only to develop the necessary understanding but also for validation, verification and improvement of fire models. Combined use of models and experiments requires multiple strategies:

- The study of sub-processes in isolation.
- The study of the coupling between the sub-processes and their interaction with their environment using experimental data obtained specifically for the purpose of model validation and of a scale that incorporates relevant complexity and captures all couplings and interactions
- *A priori* studies with a single user should be conducted to assess model capabilities and a Round Robin to establish the robustness of the model to the user
- *A posteriori* studies should be conducted to identify sub-process or couplings that are either properly modelled or that introduce significant errors
- Validation, verification and improvement experiments need to be defined for a specific purpose that is consistent with the state of the art of the models.

Currently, fire models have not been tested following this level of rigour and available experiments have not been defined with this methodology in mind.

In the last 20 years many fundamental studies have been conducted to achieve a better understanding of the sub-processes involved in fire modelling. Nevertheless, most of this knowledge has never been transferred to fire models because its **relevance** has been challenged by the overwhelming impact of scenario uncertainty. Thus, scenario uncertainty represents a major challenge to the **relevance** of combustion research for Fire Safety applications.

An effective means of tackling scenario uncertainty is data driven inverse modelling. Data driven inverse modelling requires the assimilation of adequate input data but also fire models that are specifically designed for that purpose. Through the assimilation of **relevant** data the output will be no longer subdued to scenario uncertainty.

It is at the level of the fundamental processes that predictive fire modelling and data driven inverse modelling meet. A fundamental understanding of the combustion processes enables the introduction of all the necessary variables that affect the outcome of a specific sub-process as well as the couplings between the sub-processes. It is this understanding that then enables confident reformulation of the model in a manner that provides the resolution required by a fire model or in a form that is amenable for data assimilation. The link between the sub-processes, their couplings and the output can then be established through a fire model and any improvements or refinements can be directly linked to an improved output. The improved output can then be used for a better definition or assessment of a fire safety strategy establishing the **relevance** of combustion research in Fire Safety. It is by means of this approach that **Scaling-Up** of fire can be achieved.

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Applications of Heat Transfer Fundamentals to Fire Modeling

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Abstract

The fire industry relies on fire engineers and scientists to develop materials and technologies used to either resist, detect, or suppress fire. While combustion processes are the drivers for what might be considered to be fire phenomena, it is heat transfer physics that mediate how fire spreads. Much of the knowledge of fire phenomena has been encapsulated and exercised in fire modeling software tools. Over the past 30 years, participants in the fire industry have begun to use fire modeling tools to aid in decision making associated with design and analysis. In the rest of this paper we will discuss what the drivers have been for the growth of fire modeling tools, the types of submodels incorporated into such tools, the role of model verification, validation, and uncertainty propagation in these tools, and possible futures for these types of tools to best meet the requirements of the user community. Throughout this discussion, we identify how heat transfer research has supported and aided the advancement of fire modeling.

Introduction

On this occasion of the 75th anniversary of the ASME Heat Transfer Division, we provide an overview of the fire industry and discuss how heat and mass transfer fundamentals are applied in fire modeling. The fire industry, which will be discussed shortly, relies on fire engineers and fire scientists to advance materials and technologies used to either resist, detect, or suppress fire. Fire, as a phenomenon, might be considered wild and untamed combustion. So, while combustion processes are the drivers for fire phenomena, the engineering of systems to address the fire's development is central to fire engineering. The fire industry is a vast enterprise that touches on many aspects of the economy. Starting with manufacturing companies, one finds that there is a supply chain that continuously evaluates how fire impacts their products. Chemicals and materials companies form one group of companies in the fire economy. These enterprises seek to deliver materials that are more resistant to thermal degradation and subsequent ignition. Manufacturers of finished products, whether consumer goods or industrial goods, are constrained in their choices of designs and materials by the effect that these choices might have on the ignition and burning characteristics of the delivered product. The construction

industry, both for residential and commercial structures, is strongly constrained through building codes to produce structures that meet underlying life safety requirements. To make the built environment safer, there are product companies that continue to innovate in fire detection, alarm, and suppression systems. While many of these technologies are intended to operate autonomously, there are also fire mitigation technologies intended for use by the fire service. In the United States alone there are over one million fire fighters who use continually improved tools and equipment to fight fire. The service component of the fire industry includes public safety personnel, research and testing organizations, standards organizations, insurance firms, legal firms, and others. For the various stakeholders in the fire economy, answers are sought on how fire affects the particular issues that they deal with.

Much of the knowledge of fire phenomena has been encapsulated and exercised in fire modeling software tools. Over the past 30 years, participants in the fire industry have begun to use fire modeling tools to aid in decision making associated with design and analysis. In the rest of this paper we will discuss what the drivers have been for the growth of fire modeling tools, the types of submodels incorporated into such tools, the role of model verification, validation, and uncertainty propagation in these tools, and possible futures for these types of tools to best meet the requirements of the user community.

Why Model Fires?

One of the primary drivers for development and use of fire models has been the growth of the fire protection engineering field. Fire protection engineering - the design of buildings to protect people and property from fire - is at the beginning of a major evolution. This evolution is moving away from designing buildings based on specific rules and towards designing based on predictions of what would happen in the event of a fire. This evolution is changing the codes and standards used to regulate building construction from "prescriptive" to "performance based." Advances in fire modeling capabilities plays a key role in enabling and facilitating this change. This evolution is not unique to fire protection engineering. Other engineering disciplines evolved in response to advances in understanding of their underpinning science. Over the past century, fields like mechanical engineering and structural engineering have evolved as new materials, manufacturing processes, and engineered systems pushed the boundaries of existing knowledge and technical capabilities. These changes facilitated innovation in those disciplines. Similarly, fire protection engineering has been influenced by improvements in the understanding of fire science and societal desire for new, cost effective, and innovative building designs.

Almost all buildings today are designed and constructed to meet the provisions of prescriptive codes and standards. These prescriptive codes and standards describe what is acceptable or not acceptable in specific terms. Fire safety provisions include what types of fire safety systems should be installed in buildings and acceptable building geometries. Most engineering design resources are expended on commercial properties, and commercial properties perform very well in fire. For example, in 2011, there were 3,005 civilian fire deaths in the United States. Of these deaths, 2,520 (84%) occurred in a home (Karter, 2012). Fire protection

engineering is generally not applied in the design of residential buildings, but is used in the development of tests for characterizing the construction materials and finished products used in a house. The economics of the fire industry are staggering. In the United States alone, direct and indirect fire costs represent approximately 2% of the GDP (Hall, 2012). These costs range from the cost of fire protection and mitigation to the additional costs of construction associated with adherence to fire safety provisions to the cost of fire losses.

Blind adherence to fire provisions that have not necessarily evolved with changes in materials, technologies, and knowledge has negative consequences. One fundamental tenet of engineering is providing the necessary level of safety at the most reasonable cost. While the buildings to which engineering has traditionally been applied have an excellent history of fire performance, they also have an unknown safety margin. Ideally, model-based fire design would be useful to assessing the marginal cost for a specified level of safety. The use of performance-based design and fire models would allow the fire protection that is provided in a building to be tailored to the characteristics of the building, the items stored within the building, and the people that would use the building.

Another fundamental tenet of engineering is to incorporate the best available scientific knowledge into tools and processes. Application of prescriptive design typically is accomplished with minimal reference to the engineering and scientific literature. This results in an unknown and inconsistent level of safety. Structural fire resistance can be used as a case study. Consider three relatively recent fires that occurred in the United States – One Meridian Plaza, Philadelphia, 1991 (Routley *et al*., 1991); First Interstate Bank, Los Angeles, 1988 (Routley, 1988); and the World Trade Center towers, New York City, 2001. In the case of One Meridian Plaza and the First Interstate Bank, both buildings withstood fires of very long duration. However, the World Trade Center towers collapsed after 102 minutes and 57 minutes of fire exposure, respectively (Milke, 2003). While the fires in World Trade Center were ignited by aircraft collisions, the bulk of the fire exposure resulted from ordinary combustible material and not jet fuel (Milke 2003). Although the fires did not start in the same manner, each of the fires in these buildings was similar in magnitude, but may have provided a different thermal load to the structural components. Regardless of the performance intended by compliance with prescriptive codes, these buildings did not all perform in a similar manner. Heat transfer processes couple the fire to the structure and should be modeled in a meaningful way for inclusion in structural performance-based design. Through a validated performance-based design process, structures could be designed such that structural fire performance would meet the needs of the community and the building owner in the most efficient means possible.

Early (pre-1900's) fire protection requirements were generally prescriptive, with such requirements as the permissible materials from which building exteriors could be constructed or the minimum acceptable spacing between buildings. It is notable that while not explicitly identified, the choice of building materials and the spacing requirements were associated with underlying heat transfer processes. Most modern building and fire code requirements more explicitly have some element of performance associated with them, which can enable the use of

fire models. Performance-based approaches for designing building fire protection can be traced to the early 1970's, when the Goal-Oriented Approach to Building Fire Safety was developed by the United States General Services Administration (Custer and Meacham, 1997). The GSA approach was developed to help the United States government evaluate fire safety in high-rise buildings. Over the 1970's, the GSA work continued to evolve, spawning the Fire Safety Evaluation System (ultimately published as NFPA 101A), the Building Fire Safety Engineering Methodology, and the Fire Safety Concepts Tree (NFPA 550).

The GSA and subsequent works were published as guidelines, meaning that they could be used as a voluntary alternative to strict compliance with prescriptive codes. In 1985, the first performance-based code was published – the performance-based British Regulations. New Zealand published a performance-based building code in 1992, and Australia followed suit in 1995. Other major developments in performance-based design include the following publications:

- First edition of the *SFPE Handbook of Fire Protection Engineering*, 1988
- *Performance Requirements for Fire Safety and Technical Guide for Verification by Calculation* by the Nordic Committee on Building Regulations in 1995
- Performance option in the NFPA *Life Safety Code* in 2000
- *SFPE Engineering Guide to Performance-Based Fire Protection Analysis and Design of Buildings* in 2000
- Japanese performance-based Building Standard Law in 2000
- *ICC (International Code Council) Performance Code for Buildings and Facilities* in 2001
- Performance option in the *NFPA Building Code* in 2003

Each of these published documents facilitated the use of fire models in the design of buildings.

Beyond the design of structures, fire models are increasingly used in forensic analyses. A fire loss may be analyzed to determine the cause and origin and contributing factors. Fire models allow the analyst to hypothesize a scenario and determine if the modeled results of the scenario are consistent with observations from the fire. Forensic analysis in fires is an extremely challenging inverse analysis process since the fire destroys much of the evidence of the factors that created it. Nevertheless, the fire leaves signatures even after consuming many parts of the structure. The National Fire Protection Association's Guide for Fire and Explosion Investigations (NFPA 921) provides guidance to fire investigation professionals to improve the overall quality of the fire investigation process. The fire investigation process is used to assess if improvements can be made in codes and standards after major losses have occurred. The process is also used in civil litigation and criminal prosecution to determine culpability when fire has caused damage, injury, or death. In the civil litigation context in the US, while insurance companies will likely issue some initial settlements, the subrogation process is used to assess

responsibility to the various parties involved in the litigation. In the litigation, fire investigators, fire engineers, and fire scientists serve as expert witnesses using their expertise in fire evolution to propose or refute various hypotheses on how some aspect of the fire took place. Experts serve in similar capacity in criminal prosecution in the US, but unlike in civil cases, a defendant in a criminal case could be given a death sentence based on evidence and witness testimony. The gravity of this consequence should require a process and standard for hypothesis testing that is as stringent as can possibly be devised. Fire models are more routinely being used in both civil litigation and criminal prosecution. There should be a path forward on how to incorporate the uncertainty inherent in any given model into a hypothesis testing standard.

Physics and Submodels

The typical structure fire in the United States takes place in a single family residence. While the most likely room for a fire to start is the kitchen, these fires tend to be more monitored than fires that begin in other parts of the home. Undetected fires often begin when a heat source such as a compromised electrical connection, unmonitored candle, or improperly discarded cigarette heats up some organic mass of material. The heat source heats the material until the material begins to pyrolyze wherein volatile material is released from it. Depending on the local flow conditions, type and arrangement of the material, and intensity of the heat source, the pyrolysis process could lead to smoldering combustion or transition into gas phase flaming combustion. If a flame develops, the flame spreads over the fuel surface in what is essentially a continuous ignition process. With increased flame spread and as more of the fuel material is consumed by the fire, the fire products and plume can begin to accumulate in sufficient concentration in the upper regions of the room that the heat transfer from this region begins to affect the overall heating rate of all fuel material within the compartment. The upper layer radiative heating increases the burning rate dramatically, if there is enough oxygen within the room. Fire models have been developed to predict the evolution of any given fire scenaro. Deterministic fire models have evolved over the past 40 years to the point where there are three basic types: empirical correlations, zone models, and computational fluid dynamics (CFD) models. The correlations were developed in the 1970s and 1980s as a combination of classical buoyant plume theory and well-stirred reactor concepts. Using estimates of the fire's heat release rate and the basic compartment dimensions and material properties, it became possible to predict average hot gas layer temperatures, sprinkler activation times, and the time to flashover (where the compartment becomes oxygen limited and engulfed in flames). These correlations are simple, robust, and remain to this day a primary component of any fire protection engineering design. However, the correlations were limited to single compartments and very simple geometries, and there soon became a need to model a series of compartments or even an entire building. Thus, in the 1980s, the two-zone models were developed. The basic idea of these models is that a fire creates two distinct thermal layers in a compartment, and pressure differences between compartments drive heat and smoke from one to the other. A zone model is essentially a stiff system of ordinary differential equations that can be solved in seconds to simulate the spread of

smoke and heat throughout a building. As zone models became widely used through the 1990s, geometrical limitations once again drove the profession towards more complex modeling tools. Computational fluid dynamics (CFD) codes were soon being developed for fire specific problems. An overview of the issues in CFD modeling of fire is provided by McGrattan (2005). With CFD, there is no need to limit the computational domain to conform to the basic two layer concept, and, thus, a much wider array of applications opened up, coinciding with the architectural trend towards unconventional building design.

Regardless of type, what distinguishes a fire model from any other type of simulation tool is the source term in the energy conservation equation; namely the fire. The fundamental physical process that drives fire phenomena is the combustion process which can occur either in the gas phase, or within a porous medium, or on the surface of a material. In the overall evolution of a fire, the gas phase flaming reaction represents only one part of the overall dynamic. Torero (2012) detailed the role of combustion science in fire safety engineering. The following discussions consider the same physical processes noted by Torero, but more narrowly discuss the roles of heat and mass transfer analysis to the overall system level modeling. The discussion also identifies the role of data reduction models, many of which require heat and mass transfer models, in advancing the theoretical bases used in fire modeling.

Pyrolysis

In fire applications, the fuel is often an inhomogeneous condensed phase material. A significant part of fire modeling is characterizing the thermophysical and chemical properties of arbitrary engineered materials. One requirement of the modeling process is to be able to describe solid thermo-chemical pyrolysis. While the chemistry and the mechanical evolution of the materials have a significant effect on pyrolysis, the amount of fuel produced is also strongly coupled to complex heat and mass transfer processes. The temperature of the material, initially at ambient, increases with convective and/or radiative heating of the material's surface. Because the radiative heat flux in fire scenarios is often larger than the convective flux, it can be important in some scenarios to properly couple the details of the radiative heat flux to the condensed phase fuel. The evolved pyrolysis products from the condensed phase decomposition may modulate the incident radiative field near the condensed phase interface. Typically, the highest temperatures will be achieved close to the surface, but energy transfer in-depth will result in a spatially and temporally varying internal temperature distribution. For some scenarios, it is important to characterize the radiative field coupling within the condensed phase. In general, however, for a decoupled analysis of solid pyrolysis, the evolution of the in-depth temperature field is modeled using an energy balance in a control volume limited by the surface of the material for which the surface energy balance sets a boundary condition.

Pyrolysis tends to be an endothermic process controlled by many chemical reactions which are strong functions of the temperature. Most pyrolysis reaction rates tend to be described by Arrhenius type dependence on the temperature. Depending on the fuel, heating characteristics, and local gas phase species constituents, the pyrolysis process can follow

distinctively different paths. Because it is difficult to in-situ sample pyrolysing materials in the same way that one can probe gas phase systems, a much less resolved picture exists of the chemical pathways. These paths can be a compendium of numerous reactions that could be sequential or compete against each other. Furthermore, the chemical pathways can be strongly influenced by the presence of oxygen (Hirata et al. 1985, DiBlasi et al, 1993). The effect of oxygen on the degradation kinetics emphasizes the importance of mass transfer effects within the material. In-depth oxygen diffusion is controlled by the structure of the solid. Some materials are highly permeable and allow unrestricted transport of species in and out of the solid. The permeability of the fuel can be a function of many variables including the degradation and consumption of the material and has deserved very little attention in the fire literature. Oxygen concentrations will be controlled by the local permeability and by production/consumption rates, thus indirectly by the temperature distribution. The effects of permeability and pressure are combined in a complex manner to define the flow within the porous fuel medium. This remains an unresolved problem.

For charring materials, pyrolysis leads to the production of gaseous fuel (pyrolyzate) and a residual solid phase char. The char is mainly a carbonaceous solid that could be further decomposed. The secondary decomposition could be complete, leading to an inert ash or to a secondary char that can be further decomposed in a single or multiple steps. Non-charring materials decompose leaving no residue behind. One approach to providing global characterization of the pyrolysis process is to apply thermal analytical methods to thermally decomposing materials.

Often, the kinetics of degradation are parameterized using experiments like thermogravimetric analysis (TGA). In TGA a sample of a material is subjected to a heating history while the mass of the sample is measured as the sample thermally decomposes. Typically, sample sizes for these materials are considered to be sufficiently small that transport time scales are fast relative to chemical decomposition time scales. Hence, the samples can be considered to be thermally and chemically lumped. By assuming that heat and mass transfer processes within the sample are fast relative to the chemical time scales, the mass loss rate is then controlled by the decomposition kinetics. Rate parameters can then be derived from the mass loss rate data, but there are concerns that such data do not adequately represent the true decomposition processes associated with heating rates associated with fires (Conesa, 1996; Burnham and Weese, 2004; Bruns and Ezekoye 2009). Additionally, as research progresses on the effects of inorganic micro and nanoscale additives on flammability, questions are being raised on the role of heat and mass transfer physics on experimental observations (Kashiwagi et al., 2005).

Other details of the decomposition process can be found from tests like differential scanning calorimetry (DSC) (Höhne et al., 2003, Stoliarov, 2008). In DSC two cells, one with a reference material and the other with the sample under consideration are heated with a prescribed temperature time history. Differences in the amount of heating required between the two samples is used to infer the effective thermodynamic parameters of the sample in question. The

data reduction model for the DSC could either be limited to the sample model or could include the furnace and reference material models. Both TGA and DSC based studies tend to produce the relevant constants for reduced chemical mechanisms that represent the complex degradation process. Given that the reaction rate is a strong function of temperature, it is clear that the adequate resolution of the energy equation is paramount in defining the degradation rates.

Prediction of evolved species from the degrading material is important in the ignition phase of a material and may be important in describing the products of flaming combustion. As in other heat and mass transfer applications, computations and models at atomic and molecular scales have begun to play an ever increasing role in characterizing physical processes. The connection between macroscopic and continuum descriptions of material evolution and atomistic descriptions has been made using modified classical molecular dynamics simulation concepts. Various flavors of reactive molecular dynamics (MD) simulation tools and techniques have evolved wherein the electronic and atomic potential energy surface modifications are included in classical MD models as submodels to describe bond breakage steps (Stoliarov et al., 2003; Nyden et al., 2004; Smith et al., 2011). Quantum chemistry calculations are performed offline using either ab-initio tools or hybrid approaches like density function theory to inform the reaction chemistry of the models (Car and Parrinello, 1985).

Because the chemical pathways leading to the pyrolysis of most solid fuels of interest in fire are unknown, many studies have sought to develop reduced chemical mechanisms for the pyrolysis of specific solids following the initial approach of Rein et al. (2006) and Lautenberger et al, (2006). Even for reduced mechanisms, there is still great uncertainty on the chemical pathways, the number of reaction steps required and the parameters associated with them. Data reduction models, used to test these mechanisms and fit the parameters, rely on complex heat and mass transfer models that are coupled with the reduced chemical degradation models containing the unknown parameters. Because of the large number of parameters and degrees of freedom that need to be explored by the optimization process, the required amount of experimental data required in the optimization process (TGA, DSC, cone calorimeter) often becomes infeasible. Even the nature of these experiments and associated uncertainty in the data propagates further uncertainty into the calibrated parameters (Carvel et al., 2011 and Rogaume et al., 2011).

At the continuum scale, fuel decomposition models should also be able to describe heat and mass transfer processes within arbitrary condensed phase materials undergoing thermal degradation. While a framework exists to model such processes using, as an example, the formalism developed for porous media heat and mass transfer (Kaviany, 1991), the details associated with characterization of thermophysical and transport properties remain a challenge. Further, it is generally unclear how to properly specify the appropriate level of complexity required in any particular analysis of a complex composite system in which there are synergistic effects between the materials due to manufacturing features etc. The coupled effects of decomposition and transport are evident when one considers the range of actual degradation behavior that potentially exists in fire scenarios. Common polymeric materials in fire environments range from thermoplastics to thermosets. There are materials that melt and drip,

while others form a char layer. These gross changes to physical configuration of the material often affect the overall evolution of the fire (Ohlemiller, 2000). At the fundamental level, melt flow depends on the temperature, morphology, and molecular weight distribution of the polymeric system (Berry and Fox, 1968). The fluid mechanics, heat transfer and materials processing literature has developed various ways to model melting and flowing polymeric systems (Denn, 1990; Jaluria, 2001). Because of melting and melt flow, a localized fire could spread by burning droplets or a flowing melt stream to other adjacent fuel packets.

Ignition

Ignition is a competition between the exothermic energy release rate and heat losses from the reacting gases to unreacted gas and to the condensed phase fuel. Obviously, a flammable mixture is required before flaming ignition can occur. Before flaming ignition can occur, a sufficient concentration of fuel vapor needs to be available in the gas phase. The solid decomposition products in the gas phase depend on many factors and might be a combination of solid phase pyrolysis and oxidation products. Thus, the product composition might include fully oxidized compounds such as carbon dioxide (CO_2), partially oxidized gases such as carbon monoxide (CO) and other molecules that can have varying levels of partial oxidation. As an example, Kashiwagi and Nambu (1992) studied the degradation products of cellulosic paper showing that there is a significant presence of inert gases like water vapor, fully oxidized gases like CO_2, partially oxidized products like CO and unoxidized species like CH_4 and H_2. There is very little data available on the degradation products of most materials relevant to fire, therefore, the mass fraction of flammable gases present in the local products of degradation is generally described by means of a global contribution of all compounds that can be further oxidized. This suggests that together with the gas phase reaction rates, the decomposition products concentration must be known to model ignition.

After pyrolysis gas begins to emerge from the fuel surface, the emerging fuel will encounter the ambient oxidizer and possibly produce a flammable mixture. Given that a complex fuel flow is migrating into the oxidizer flow, the definition of a flammable mixture region is not a simple one. In standard test methods the ambient flow is well defined but in real fires, flow fields are defined by the flames themselves and by the geometry of the environment (obstacles, fuel geometry, etc.) with the possibility of complex flow patterns. After a flammable mixture has been attained, this mixture needs to increase in temperature until a combustion reaction can occur. This process is described in great detail by Fernandez-Pello (1995). Niioka et al (1981) identify an induction time and a pyrolysis time. The pyrolysis time corresponds to the time required to attain a flammable mixture while the induction time is the time for the mixture to reach a temperature at which ignition can occur.

The amount of energy required for ignition can be associated to a Damköhler number (Williams, 1985). The Damköhler number corresponds to the ratio between local residence and chemical times. The chemical time represents the necessary time for the reaction chemistry to occur and is expressed as the inverse of the reaction rate. A critical Damköhler number for

ignition can then be established, above which a combustion reaction can proceed. This is probably the most precise way to describe ignition but it requires the full resolution of the flow and temperature fields as well as comprehensive knowledge of the kinetic constants associated to the combustion reaction. While the flow field can be resolved by means of Computational Fluid Dynamics (CFD) the chemistry of most fire related fuels still remains uncertain. Qualitative assessment of the Damköhler number for ignition has only been achieved for a few very well defined experimental conditions such as stagnation flows or boundary layers (Quintiere, 2006).

Auto-ignition in its simplest form is a competition between the exothermic energy release rate associated with oxidation and heat losses from premixed fuel charge. Data on auto-ignition is generally reported as Auto-Ignition Temperatures (AIT) which corresponds to a recorded temperature at the moment where ignition of a flame is first observed. A summary of much of the data available is presented by Babrauskas (2003). Given the complexity of the processes leading to auto-ignition, these values can only be taken as reference values that are a direct function of the specific test conditions. Generally, significant discrepancy is found in the literature with reported Auto-Ignition Temperatures varying more than 150 ^{o}C for a given material.

In practice, ignition is initiated by a pilot flame, hot gases, or hot element. From the perspective of ignition, the exposed solid surface represents not only a boundary between the gas and the solid, but also a potential ignition site. While regression rates can be very different between charring and non-charring materials, at the surface, the main difference between the two material types is the temperatures that can be achieved during pyrolysis. Carbonaceous chars in ambient oxygen environments can reach much higher temperatures than non-charring surfaces. In many cases, vigorous oxidation often termed surface glowing, can initiate gas phase ignition. The actual temperatures reached by the oxidizing char are controlled by heat transfer through the char, transpiration cooling by the fuel produced in-depth, and radiative losses from the glowing surface char.

The presence of a pilot can simplify modeling of the gas phase ignition processes and somewhat reduces the influence of environmental variables. Characterization of the flow field is still required to establish the presence of a flammable mixture and heat transfer between the hot element and adjacent premixed fuel mixture. For some global models, ignition can be assumed to occur at the moment where the lean flammability limit (LFL) is attained at the location of the pilot. To attain the LFL at the pilot location it is necessary to resolve the momentum and mass transport equations simultaneously with the surface boundary conditions.

Given a flammable mixture and an ignition source, the pyrolysis rates at the moment when the flame is established will determine if a flame can continue to exist or if the combustion reaction will cease after the premixed gas mixture is consumed. The feedback from the ignited flame will enhance pyrolysis, but usually, the relatively large thermal inertia of the solid will result in a slow response, therefore it will be necessary for pyrolysis rates to already be sufficiently large even in the absence of the flame heat feedback. If pyrolysis rates are not sufficient, the flame will extinguish and continuous pyrolysis will lead once again to the

formation of a flammable mixture and subsequent ignition. This manifests itself as a sequence of flashes that precede the establishment of a flame over the combustible solid. This process is identical to the "flash point" generally associated to liquid fuels and for solid fuels has been described in detail by Atreya (1998).

The transition between the "flash point" ignition and the established flame, which could also be named the "fire point" in an analogy with liquid fuels, deserves especial attention. The characteristics of the diffusion flame established on a solid fuel surface are defined by the flow field and the supply of fuel. The rate at which both reactants reach the flame zone defines the flame temperature and thus the characteristic chemical time. If the amount of fuel reaching the flame is small, then the flame temperature will be low and the chemical time will be long. As described above, the flow field defines the residence time. A second critical Damköhler number appears, but this time is one of extinction. This concept has been described many times explicitly in the combustion literature (Williams, 1985) but only implicitly in the fire literature. In most discussions simplifications have been assumed leading to simpler parameters that can serve as surrogates for the Damköhler number. Williams (1985) discusses a critical gas phase temperature below which extinction will occur. If the residence time remains unchanged, then extinction is only associated to the chemical time, thus can be directly linked to a critical gas phase temperature. It can be further argued that extinction is much more sensitive to temperature than to flow, thus only radical changes in the residence time need to be addressed making this criterion a robust one. A more practical surrogate to the Damköhler number is a critical fuel mass flux criterion. The concept of critical fuel vapor mass flux for ignition resembles elements of premixed flame quenching. The attainment of a critical mass flux of fuel will be the single parameter defining the flame temperature and thus the Damköhler number (Rasbash et al, 1986). Furthermore, under more restrictive conditions the critical mass flux can be associated to a critical solid phase temperature (Thomson et al., 1988).

Combustion

Once gas phase ignition has occurred heat and mass transfer processes allow the flame to creep across the fuel, this process is referred as flame spread and has been the subject of many studies in the literature. Flame spread is effectively a sequence of ignitions, therefore will not be described here. A summary of the different flame spread studies is provided by Drysdale (2011).

A flame is described by thermal and diffusive balances with extremely sensitive temperature dependent reaction terms. The characteristic length scales in flames defined only once one appropriately characterizes the thermal and mass transport thermophysical properties. Because of the disparate length scales in a practical fire scenario, the length scale ratio between a typical flame thickness and the compartment geometry typically preclude the ability to describe the flame with adequate resolution. There are many issues to address when describing the gas phase chemistry evolution in fire models. More important than the details of the flame is that a model should be able to describe the gross heat release rate which produces the density change and dilatation in the velocity field. Depending on the quantity of interest from the fire model,

this may not be the most important chemistry issue to address. Much of the hazard posed by fires is associated with the toxicity of incomplete products of combustion such as carbon monoxide, hydrogen cyanide, and soot coated with hydrocarbons (Pitts, 1995). Unlike many scenarios studied in combustion science, in fire modeling, the incomplete products of combustion, particularly CO, are non-negligible in their impact on the overall heat release rate of the combustion process. Significant amounts of carbon monoxide are produced in a typical compartment fire because of the relatively large global fuel to air ratio. Once a condensed phase fuel has ignited, the inefficient mixing of air and fuel in the fire produces copious amounts of incomplete products. Proper description of the evolving product soup requires knowledge of the chemical composition of the condensed phase fuel and its pyrolysis products. These are typically relatively large hydrocarbons that may be also bound to various trace chemicals used as flame retardants etc. Because gas phase combustion in fire is predominantly in non-premixed flames, the pyrolysis gases evolve in high temperature environments and begin to form soot. The kinetic description of soot evolution is extremely complex even for very simple fuels. One description is that polycyclic aromatic hydrocarbon molecules, formed in the pyrolysis gas mixture, coagulate to form nascent soot particles that then grow by surface addition of smaller hydrocarbon molecules and polycyclic aromatic hydrocarbons (PAHs) and by agglomeration (Frenklach, 2002; Öktem, et al., 2005) . Predicting soot evolution is extremely important in fire modeling because the radiation heat transfer in fire is primarily associated with the soot species and because soot impacts sensor activation, human visibility, and respiratory irritation. Even for relatively simple and lower molecular weight fuels, it is very difficult to predict soot volume fractions in a flame to within a factor of two (Mehta et al, 2009, Saffaripour et al, 2011). In-situ measurements have been useful in better characterization of soot evolution.

Thermal Radiation and Soot

Fire evolution and spread is mediated by heat transfer rates. In practical fire modeling scenarios, radiation is the dominant mode of heat transfer (Sacadura, 2005). If one assumes a gray gas model for the gas mixture, and uses a Planck mean absorption coefficient for typical combustion product gases, one can easily show that when the soot volume fraction exceeds approximately 1 ppm, the soot absorption coefficient is larger than the gas absorption coefficient. In most practical fire conditions the soot volume fraction is much larger than 1 ppm in most of the fire. An exception to this rule is very near the surface of a liquid fuel pool. Because the fuel vapor has not necessarily had time to breakdown into soot, there is an abundance of fuel vapor that participates with the incident radiation. It is in this near surface region that a gray gas model might be most limited. Work in the heat transfer literature has been useful in parameterizing fuel spectral absorption coefficient models (Fuss et al, 1997). The spectral details of the absorption coefficient and its modification of the radiative intensity determine the true incident flux on the fuel surface. Depending on the interface's radiative properties, these spectral effects could be important.

Typical measurements used to characterize the soot properties are laser based extinction experiments and laser induced incandescence experiments. Both extinction and LII measurements are grounded in heat and mass transfer fundamentals. Considerable effort has gone into developing detailed descriptions of soot morphology with a goal of better characterization of the soot radiation properties and soot transport physics. Sorensen and co-workers (e.g., Cai et al, 1995), Faeth and coworkers (e.g., Köylü and Faeth, 1994), and Mulholland and coworkers (Zhu et al., 2000) characterized the mass fractal and optical properties of soot aggregates. The morphological characteristics of soot aggregates somewhat modify their radiative emission properties but do not markedly change the absorption properties if reasonable approximations are made about the soot primary particle size and volume fraction. These changes in radiative properties are neither significant for measuring soot volume fraction by extinction nor for simulations of most compartment fires. Where these morphological effects do matter is in models for smoke detection systems. Smoke detectors sense smoke using either optoelectronic or mobility principles. In both cases, the morphological properties of the smoke play a role in the detection sensitivity. A model for the radiative scattering processes in smoke detector activation was reported by Upadhyay and Ezekoye (2005), and the role of soot fractal dimension on detector processes was discussed. For LII, Knudsen number effects on the cooling rates and subsequent interpretation of LII signal outputs have been useful in validating experimental techniques (Daun et al, 2007).

While soot primarily absorbs thermal radiation, water droplets from sprinkler and mist fire suppression systems scatter radiation. From a fire design perspective, water sprays/curtains are sometimes used as radiation shields. The heat transfer submodel in a fire model should be able to model droplet scattering physics (Dembele et al., 1997). Depending on the characteristic length scales of the droplet cloud, particles can either be modeled using either a Rayleigh limit or a geometrical optics limit. For intermediate scales, full Mie analysis may be required, but approximations are often made in the specification of the phase function Additionally, the effects of both water vapor and water droplet size distribution may be included in the analysis as was done by Dembele et al.

Turbulence radiation interactions have been investigated in the literature to determine if including improved estimates of temporal and spatial temperature fluctuations affects radiative heat transfer predictions (Li and Modest, 2002). The nonlinear dependence of radiative intensity on temperature implies that for some applications, there will be significant deviation between the temporally and spatially averaged radiative emission relative to estimates based on the temporally and spatially averaged temperature.

In depth radiative transfer in some materials, particularly many polymer systems, has been shown to affect the thermal degradation and ignition characteristics of the material. As an example, Bal and Rein (2011) recently noted the importance of including in-depth radiation modeling to properly predict the ignition time of polymethylmethacrylate using a thermal ignition model. Thermal radiation induced damage and heating has also been important to characterize and analyze in the development of increasingly burn resistant protective garments

for firefighters and warfighters. Mell and Lawson (2000) applied heat transfer fundamentals to characterize the mechanisms controlling the protective properties of firefighter personal protective equipment.

Smoke and Convective Heat Transport

Fire modeling has contributed to and borrowed from developments in computational fluid dynamics in developing gas phase flow models (McGrattan, 2005). In many respects, this is one area in which fire modeling has the strongest validation. While the turbulent flow processes can be quite complex and involve variable density and composition, there is an underlying physical model (i.e., Navier Stokes) that describes the flow evolution over a range of scales. The challenge in this area of modeling is in developing submodels for physics that occur at scales smaller than the computational grid. Fire gas phase flow modeling typically takes place in compartments with characteristic length scales on the order of meters. Dissipative length scales (whether Batchelor or Kolmogorov) are often millimeter or sub-millimeter for the velocities encountered in compartment fires. It is currently infeasible to simulate processes across the range of scales. There are many approaches to modeling subgrid scale mixing in CFD, but fire modeling has traditionally looked to the meteorological literature because of its emphasis on low speed, buoyancy-driven flow (Smagorinsky, 1963; Deardorff, 1972; Germano *et al*., 1991).

Structural Response

Structural components can be compromised either by high heat fluxes or by oxidative damage. It is necessary to be able to couple the combustion evolution with descriptors of structural evolution. The overall time scales over which structures evolve are considerably longer than the time scales associated with the flow processes. On the other hand, the spatial resolution required to model structural component thermomechanical evolution is at much more resolved scales than what is typically available from fire simulation. As such, sensible ways of coupling the fire flow evolution to the structural evolution are necessary. For many scenarios, the structural evolution can be decoupled from the fire flow evolution. There are, however, scenarios in which fire induced changes in the structure strongly modify the evolution of the fire. One obvious case in which the fire affects the structure which in turn affects the fire is window glass failure. As already noted, fuel loads for typical fire compartment scenarios are globally rich. In the fire literature, the resulting fires in such compartments are said to be ventilation limited. For ventilation limited fires, the heat release rate within a compartment is controlled by the oxygen mass flow rate into the compartment. Thus, a change in the availability of oxygen entering the compartment associated with a window breaking or a door being opened dramatically impacts the fire evolution. Time scales over which a door might be breached by a fire are considerably longer than the times required to fail a window. Simple models are available for window breakage that rely on the heat transfer rates to the window, the geometry and constraints on the glass (Cuzillo & Pagni, 1998). Given the variability in window types, age, and condition, one can perhaps only view such models as being statistically descriptive. Glass breakage models rely

on thermomechanical models for the glass and window system. Glass heating by convection and radiation is important to the overall model. Details like the insulating properties of the window cladding strongly affect the crack growth and propagation. Initial microscale features of any particular glass sample provide a state of stress on the boundaries (e.g, associated with the glass being cut) and in the interior that affect breakage. In spite of this complexity, it is extremely important to provide a means for implementing window/glass breakage into fire models because of how dramatically such failures affect the subsequent fire evolution.

A slightly simpler problem is the modeling of the behavior of structural systems in fire. In this case, the potential of a structural system to affect the nature of the fire is only as a thermal boundary condition until major structural collapse (usually late in the fire evolution) occurs. By exploiting the time scale differences, one can decouple the gas phase evolution and the solid phase and the fire becomes only the forcing for the heat transfer to the solid mechanics models (generally finite element models) that are normally used to establish the evolution of a structure (Usmani et al. 2001). Interestingly, the detailed mechanical properties of common building materials are not well known at elevated temperatures associated with fire (Hu et al, 2009).

To be able to define the temporal and spatial evolution of a structure during the event of a fire, the following issues need to be resolved:

1. The temporal and spatial evolution of the gas phase fire thermal, flow, and species fields should be known.
2. The evolution of the gas phase fields determines the temporal and spatial evolution of the heat exchange between the structural elements and the gases.
3. With thermal boundary conditions defined on the structural elements, detailed analysis can then take place for the structural elements. For materials like steel the transient energy equation consists only of heat conduction and enthalpy terms with variable thermal properties, but for other more complex materials such as concrete or plaster board, complex mass transfer equations need to be resolved to account for the vaporization enthalpy as well as moisture migration.
4. The spatial and temporal evolution of the temperature of the structural elements affects the material and mechanical properties of the solid which determine stresses and deformations within the structure.
5. The results of these calculations can be used to establish quantitative failure thresholds.

The comprehensive formulation of the problem requires the coupling of the gas and solid phases. Explicit finite element models coupled with transient CFD models become a necessity if the complete interaction is to be resolved. Despite many attempts to do this, there is currently no combination of models that solves the coupled effects of fire and structure. Furthermore, there is currently no CFD model that comprehensively resolves the fire at the necessary scale and with full detail. Finite element models are more advanced but many of the mechanical and thermal properties that serve as inputs are still unavailable.

Numerous alternative approaches can be found in the literature, some of them are well argued simplifications that use the characteristics of the problem to either relax the coupling between gas and solid phase or simplify certain terms of the equations. Among these simplifications are simplified connection models, constitutive property models, total heat transfer coefficients and spatial and temporal averaging of the gas phase. These simplifications take advantage of the very different time and length scales of the solid and gas phase problems to decouple and simplify many of the processes. When correctly argued these approaches are perfectly valid and provide a true assessment of the performance of the structure as well as quantified error bars linked to uncertainties and simplifications (Buchanan, 2002).

The equations used in simple numerical methods are derived from simplified heat transfer approaches. For example, a quasi-steady-state, lumped heat capacity analysis can provide the temperature rise of unprotected steel members, while for protected steel members, the thermal resistance provided by the insulating material can be accommodated by empirically derived correlations (c.f. the Structural Eurocodes methodology (CEN, 2005)). These approximate methods allow the designer to use any appropriate gas-phase temperature-time curve, but their generality remains uncertain.

Advanced models based on numerical heat transfer methods provide a more general approach and are becoming increasingly popular both in a research and industrial context (Cox and Kumar, 2002). Their advantages lie in the ability to define an arbitrary gas-phase boundary condition and to perform conjugate heat transfer calculations in which the surface temperature is obtained from the balance of the gas- and solid-phase thermal conditions (Patankar, 1980). The analysis is typically performed in three-dimensions, thereby overcoming the limitations of simpler approaches which consider only the in-depth direction. There is a significant challenge in achieving sufficient grid resolution within the solid, where much smaller cells are normally required due to the steep thermal gradients, especially when structured meshes are adopted (which may demand a similar cell size in the gas and solid phases) (Kumar et al., 2005); this can be overcome using unstructured meshes, or by coupling to an independent high resolution mesh within the solid, though in the latter case there will still be limitations associated with the resolution of the surface cells, e.g. where these are not able to fully resolve the details of the geometry, such as an I beam. In addition, temperature-dependent properties can easily be incorporated into the calculations for greater accuracy.

The resolution of the thermal gradients is necessary to model structural behavior in fire. Without precise thermal gradients phenomena such as connection behavior, thermal expansion, thermal bowing or tensile membrane action cannot be reproduced. These phenomena determine the evolution of the structure as it is being heated and allow identifying potential forms of failure (Usmani et al, 2001). Furthermore, the potential for concrete spalling is strongly defined by temperature gradients.

A second approach that is equally valid is that of establishing a series of constraints in the form of codes and standards. These constraints guarantee a simplified environment that can be quantified by means of a simple representation. The most common of these code based

constraints are the requirements for compartmentalization. By reducing all buildings to a summation of standardized compartments, the evolution of the fire can be reduced to an energy balance and thus both gas and solid phase behavior can be deeply simplified. This particular approach still provides a true assessment of performance. The error bars, in this case, are linked to the simplifications of the physical models defining the gas and solids but also to the deviation of the real compartments from the standardized ones (Thomas and Nilsson, 1973, Harmathy, 1981)

An approach that is acquiring popularity is that of using simplified models coupled with probabilistic estimations of error. These methods, based on theories of risk and reliability, are only valid if the representation of the physical phenomena incorporates in a correct manner all the necessary variables and couplings and the probabilistic distributions for all poorly defined properties are available. In this case a probabilistic distribution of true performance can be established.

A final method is the relative assessment of performance. This method creates a realistic scenario and assesses the performance of a system against it. The realistic scenario can be a standardized temperature vs. time curve, a parametric temperature vs. time curve to provide a relative performance of a structural component or system but also a standardized compartment to assess the relative severity of a fire given different fuels. While this approach can be used for the purpose of understanding or for classification, it will never provide true performance assessment.

Human Behavior and Egress

Modeling human activity in fires has primarily considered the effects of fire on civilian occupants within structures. The type of civilian action in fires that has been most examined has been egress modeling, where the time necessary to evacuate a building is predicted (Gwynne, 2001). One of two different approaches is used in an egress model: either (1) predicting occupant movement speed by using a hydraulic analogy, or (2) assigning each occupant its own behavioral characteristics. The hydraulic analogy predicts movements speeds based on the width of the egress component and the density of occupants within that component. Behavioral models rely simple rules based upon the location of exits, amount of heat or smoke, and assumed mobility data to characterize the evacuation of a structure. Building occupants can affect the fire conditions in a building by actions such as opening doors, windows etc. Similarly, firefighters affect the fire by changing the ventilation in the structure and also by application of water and other suppressants to the fire. However, the effects of occupants or the fire service on the progression of fire are generally not modeled. There is an opportunity for coupling egress models with fire simulations to improve the quality of simulation and support firefighting training and post incident reviews.

Modeling Engineering Subsystems

The range of engineered systems that are frequently encountered in compartment fires has motivated the development of submodels for heating ventilation and air conditioning systems

(Gaunt, 2000), sprinkler activation (Heskestad and Bill, 1988), and smoke detection (Cleary *et al*., 1999). Typically, these submodels are in the form of an ordinary differential equation involving a handful of empirical parameters. Ideally, these parameters are obtained via a standard test, like the RTI (Response Time Index) of a sprinkler.

In addition to fire protection and building systems, models of measurement devices are commonly added to fire models. For example, gas temperatures are typically measured with bare-bead thermocouples which do not actually measure the true gas temperature but rather the small bead of metal itself. A fire model can easily incorporate simple models of a thermocouple (Welsh and Rubini, 1997) so that model predictions can be compared directly with measurements for validation purposes. Another useful measurement device that can be easily modeled is a plate thermometer, a thin, insulated inconel plate useful for monitoring standard furnace tests (Wickström *et al*., 2007). These simple models of measurement devices help the model user to report the computed quantity in a way that an experimentalist would so that there is less confusion when comparing model and experimental results.

Model Verification and Validation

The use of fire models currently extends beyond the fire research laboratories and into the engineering, fire service, and legal communities. Sufficient evaluation of a model is necessary to ensure that users and regulatory authorities can judge the adequacy of its technical basis, appropriateness of its use, and confidence level of its predictions. This is ever more true due to the emergence of performance-based design as an alternative to prescriptive regulations.

The model evaluation process consists of two main components: verification and validation [ASTM E 1355]. Verification is a process to check the correctness of the solution of the governing equations. Verification does not imply that the governing equations are appropriate, only that the equations are being solved correctly. Validation is a process to determine the appropriateness of the governing equations as a mathematical model of the physical phenomena of interest. Typically, validation involves comparing model results with experimental measurement. Differences that cannot be attributed to uncertainty in the experimental measurements are attributed to the assumptions and simplifications of the physical model.

Consider in turn the three basic classes of fire models. Empirical correlations are typically presented in the form of simple formulae or equations that require, at most, a spreadsheet program to calculate a result. Verification of such models is trivial. Validation is often assumed, given that the models are typically based on full-scale experiments. However, there have been efforts in recent years to compare classic empirical correlations with experiments that were not used in their original development. One study, sponsored by the United States Nuclear Regulatory Commission and the Electrical Power Research Institute [Hill et al. 2007], considered a number of classic compartment fire correlations and found that these correlations tend to over-predict compartment temperatures. This result is looked upon favorably by regulatory agencies who prefer that these simple models err “on the conservative side.”

Next, consider two-zone models. These models are essentially a set of ordinary differential equations for the average upper and lower temperatures and pressures within a set of compartments. Again, verification of the governing equation solver is straightforward, and this procedure is supplemented by global checks of mass and energy conservation within each "control volume." Validation of zone models has traditionally consisted of comparing model predictions with the results of full-scale experiments in compartments that conformed to the basic assumptions of the model; that is, relatively flat, unobstructed ceilings and simple geometries. More recent validation work [Hill et al. 2007], however, has documented more challenging fire scenarios that highlight the strengths and weaknesses of these models.

Finally, verification and validation of CFD fire models has dominated this area in the past decade. Neither is trivial. Verification of these models takes on many forms, from grid resolution (convergence) studies to checks of the conservation laws of mass, energy and momentum. Validation of CFD models is similar to that of the simpler models -- comparisons with full-scale experiments. Given the abundance of fire test data, it is more practical to compare model and experiment rather than to dissect the model into its constituent parts and evaluate each separately using various analytical techniques. For other fields of CFD, this is unavoidable, but for obvious reasons fire science has yielded a wealth of test data with which to evaluate the models. In addition, regulatory authorities are typically not experts in CFD and prefer simple comparisons of model predictions with experimental measurements as a means of assessing the accuracy of the model.

So what are the challenges associated with fire model V&V?

1. Even though there is an abundance of fire test data, many of these past experiments were not intended for model validation. This means that the experiments are not well-documented, experimental uncertainties are not reported, and the test results are often presented as simple pass/fail judgments with limited data to use for model validation.
2. Experiments conducted prior to the advent of oxygen consumption calorimetry do not provide accurate measurements of the fire's heat release rate. Without this key input parameter, these experiments can only serve as a rough qualitative check of the model.
3. Model validation cannot be static; that is, with each new version of the model, developers need to re-run and re-document the results of the V&V studies. From a regulatory standpoint, if a particular version of the model has been validated, this is the version that shall be used until a new validation study is performed. To address this problem, a substantial repository of validation data is being collected and archived at NIST and an automated procedure has been developed to continually re-run a suite of V&V cases so that model users can cite up to date estimates of model uncertainty.
4. Standards like ASTM E 1355 do not explicitly state how the results of model V&V studies are to be reported, and it does not specify what level of accuracy constitutes "validation." It is left to the model user to decide how to report the results of the study, and it is up to the AHJ

(Authority Having Jurisdiction) to decide if the model is appropriate for the given application. In the NRC/EPRI fire model validation study [Hill et al. 2007], the NRC and interested industry and research collaborators developed a relatively simple methodology for reporting model uncertainty. In brief, for a given model and given predicted output quantity, there is a reported relative bias and relative standard deviation that is based on comparisons to a wide range of full-scale experiments. This methodology has been applied in various ways over the years and it is now typical for a validation study to conclude that Model X over or under-predicts Quantity Y, on average, by Z %, with a relative standard deviation of sigma %.

5. From the discussion above, it is apparent that there are fairly well accepted methods for performing model V&V. These methods, however, only quantify *model uncertainty*; that is, the uncertainty in the model prediction due to assumptions and simplifications of the model itself. The issue of *parameter uncertainty*, the uncertainty related to the input parameters, is receiving more attention for two reasons: First, as models become more accurate, the relative contribution of parameter uncertainty to the overall uncertainty increases. Second, the increased use of CFD means that conventional techniques for propagating parameter uncertainty are now much more difficult to apply. Empirical correlations and to some extent zone models lend themselves nicely to the various analytical methods to assess the influence of input parameters on the resulting prediction. CFD does not because these models incorporate more detailed physics and require hours or days of computational time. Adjoint based models are gaining acceptance in many areas of CFD, and such models are likely to be incorporated into fire modeling such that sensitivities can be extracted in computationally efficient ways. In evaluating the uncertainties in model parameters, there are many ways that parameter inference can be performed. One approach gaining favor is the use of Bayesian inference in parameter estimation (Tarantola, 2005). The Bayesian formulation naturally leads to the specification of a probability density function in the parameter being evaluated (Upadhyay et al., 2011). Knowledge of the statistical distributions of the uncertain parameters provides a basis for propagating said uncertainties through the fire model to determine a risk informed quantity of interest (Upadhyay and Ezekoye, 2008).

Based on this list of challenges, there are a number of potential areas for future research. First, consider the need for experiments. There exists a considerable number of experimental data sets in which the temperature, heat flux, species concentrations, and other quantities are measured within a compartment with a controlled fire, usually a gas or liquid fuel spray burner whose heat release rate is accurately measured. These experiments are ideal for assessing the capability of the models to transport and distribute the heat from the fire throughout the compartment. What is lacking are carefully designed experiments in which the fire's heat release rate is not a specified input parameter, but rather a predicted output quantity. The most obvious example is a room filled with furniture, and certainly many experiments of this type have been conducted for various reasons, but the results of these experiments are not particularly useful for model validation because the material properties are typically not measured. Even if they are measured, to some extent, the uncertainty related to the prediction of the heat release rate of a growing, spreading fire overwhelms all other sources of uncertainty to the point where the model

at best makes a very rough qualitative prediction of the outcome. What is needed are a series of experiments of increasing complexity that can be used to assess the model capabilities step by step -- first, how well the model predicts the burning rate of a given object, second, how well the model predicts the spread of the fire from object to object, and finally, how well the model predicts the transition from small fire to flashover and beyond. Combining all of these phenomena into a single experiment does not allow for a systematic assessment of the sub-models that are adequate and those that are not and need improvement. A key component of this analysis is the propagation of parameter uncertainty. The rate of fire growth and spread is very sensitive to the material properties -- temperature-dependent thermal conductivity, specific heat and density; the choice of reaction mechanism and associated parameters; geometric complexity of the burning object.

Inverse Analysis

Inverse analysis generally refers to analysis in which the usual ideas of causality are reversed. In the heat transfer literature there has been a large body of work on development of computational techniques for inverse analysis (Beck et al., 1985; Ozisik, 2000). These approaches have been applied to parameter estimation, boundary condition estimation, and source estimation. One can arrive at an inverse solution either through an optimization process in which one seeks to minimize an objective function, defined as the difference between a forward model and some measured or desired. Alternatively, one can formulate a model in an inverse sense and use one of many approaches in the literature to generate the solution. Typically, problems formulated in an inverse sense are mathematically ill-conditioned. For problems developed as a system of equations as might be generated from differential operators or from Fredholm integral equations, an ill conditioned system is identified by the ratio of the largest to smallest singular value for the system (Hansen, 1987). Hansen discusses several approaches to regularization of the system of equations such that meaningful solutions that are less sensitive to measurement noise can be computed. Optimization based inverse analysis has been applied to problems of interest in fire scenarios (Richards et al, 1997, Jahn et al, 2011, Overholt and Ezekoye, 2012). In each of these studies, the authors used forward models for fire evolution to predict compartment fire behavior. Fire researchers at the National Institute of Standards and Technology, among others, have begun to frame a discussion on the use of building fire sensors with very fast computational models for fire for fire growth modeling for firefighter operations (Evans,2003 ; Jones et al., 2001).

Measurement systems for fire systems have also benefitted from inverse analysis techniques. Boundary condition estimation techniques for conduction analysis have been useful in development of heat flux measurement gauges in fires (Lam and Weckman, 2009). In the heat transfer literature, much of the source estimation and boundary condition estimation analysis has occurred for temporally evolving physical systems. Approaches like that of Erturk et al (2002) may be useful in better characterization of furnaces used to characterize material fire resistance and in development of fire detection analysis.

Forensic analysis in fire scenarios challenges the limits of inverse analysis techniques. For such problems, the fire often has destroyed much of the evidence associated with its evolution. The National Fire Protection Association's fire investigation reference document (NFPA 921) details the types of signatures that fire forensic analysts should consider in determining the cause and origin of a fire. These so-called fire-patterns include burn patterns on walls, depth of char on wood, spalling of concrete or masonry, glass breakage location, and other damage indicators. Many of these damage processes are thermally mediated, and any model based reconstruction of the fire should be able to predict the observed damage. The implication is that there should be available submodels to predict fire damage assessment as part of the hypothesis validation steps in forensic reconstruction.

Conclusions

Fire modeling represents a broad set of tools at various scales, with different underlying physical models used to design materials resistant to fire, model fire testing equipment, and predict fire ignition, spread, and damage in the built environment. Proper characterization of heat and mass transfer processes is critical to the predictive capability of these tools. In this paper, we have outlined different ways in which ongoing heat and mass transfer research plays a role in advancing fire models.

Several critical areas of research are evident to advance fire models. Perhaps the greatest current need in fire modeling is the need to be able to reliably predict burning rates of real materials. To do so is an interdisciplinary endeavor that requires a more nuanced view of the coupling of experiments and testing with modeling. At the heart of this endeavor is the need for improvements in condensed phase materials evolution models. Such improvements have many possible side benefits including closer integration in use of tests and models for product design. Translation of inverse modeling approaches to fire scenarios could revolutionize fire arson investigation. Fire investigation had traditionally been conducted by nontechnical investigators. Given the potential disastrous impact of an incorrect fire evolution hypothesis being accepted, the need to improve this capability is evident. Development of a fire inverse analysis framework is another interdisciplinary endeavor that will require closer coordination between experimental and computational research. On the computational and modeling side, the largest computational effort for smoke and heat transport or forensic analysis or any compartment scale analysis is the computational fluid dynamics model. Development of low dimensional models for fire flow processes would significantly improve the ability to make multiple runs for either design or forensics applications. As the overall predictive reliability of fire models improve and computing power increases, one envisions routine use of fire models to aid evacuation and firefighting operations during fire hazards.

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Revisiting the Compartment Fire

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ABSTRACT

Understanding the relevant behaviour of fire in buildings is critical for the continued provision of fire safety solutions as infrastructure continually evolves. Traditionally, new and improved understanding has helped define more accurate classifications and correspondingly, better prescriptive solutions. Among all the different concepts emerging from research into fire behaviour, the "compartment fire" is probably the one that has most influenced the evolution of the built environment. Initially, compartmentalization was exploited as a means of reducing the rate of fire spread in buildings. Through the observations acquired in fires, it was concluded that reducing spread rates enabled safe egress and a more effective intervention by the fire service. Thus, different forms of compartmentalization permeated through most prescriptive codes. Once fire behaviour within a compartment was conceptualized on the basis of scientific principles, the "compartment fire" framework became a means to establish, under certain specific circumstances, temperatures and thermal loads imposed by a fire to a building. This resulted not only in improved codes but also in a scientifically based methodology for the assessment of structural performance. The last three decades have however seen an evolution of the built environment away from compartmentalization while the "compartment fire" framework has remained. It is therefore necessary to revisit the knowledge underpinning this seminal approach to initiate discussion of its continued relevance and applicability to an increasingly non-compartmentalised built environment. This paper, through a review of classic literature and the description of some recent experimentation, aims to inform and encourage such discussion.

KEYWORDS: compartment fires; fire dynamics; design fires.

INTRODUCTION

Predicting the progression of a fire is inevitably the starting step of any form of performance based design. Defining the time evolution of all relevant variables (temperatures, velocities, species, etc.) is the initial challenge that a Fire Engineer faces when attempting to quantify the performance of a system and all countermeasures introduced to mitigate the impact of a fire. Decades of research have focused on the different processes linked to the characterization of a fire environment and numerous engineering methods have been developed to enable engineers to quantify the performance of a design. This is particularly true when focusing on the evolution of a fire within buildings.

The evolution of a fire within a building is characterized by the coupling between the building and the combustion process. The environment resulting from the interaction of building and combustion can then be used to establish its influence on egress, countermeasures (detection and suppression) or on structural behaviour. Each component of a fire safety strategy is drastically different from the others therefore the evaluation of the performance of each component needs to be done in a manner consistent with the specific processes involved. A comprehensive assessment of the evolution of a fire and its interactions with people and buildings has long been recognized as an intractable problem. And while in recent years complex computational tools have been developed for all aspects of a fire strategy, it is still necessary, for the purpose of design, to develop simplified methods that allows an effective but manageable design process.

A common mechanism to simplify the design process is to separate the different components of the problem by linking specific processes to specific characteristic times within a fire timeline. For example, the characteristic timescales associated to egress and the activation of countermeasures are relatively small, therefore the assessment of their performance will emphasize the understanding of the earlier phases of a

fire, i.e. fire growth time and time to flashover. In contrast, when addressing structural behaviour, growth and flashover occur within time scales that are much smaller than those required to significantly affect the mechanical strength of structural systems, thus the focus has been on fully developed fires. While a similar analysis could be done for each process, this paper focuses on the interaction between a fire and the structure. The simplified framework of a fully developed fire will be used to initiate the discussion. That being said, it is important to accept that this is already a simplification that excludes scenarios where the concept of a fully developed fire is not relevant.

The understanding of the thermal interaction between a fire and a structure has been explored since the late 19th century. Bisby *et al* [1] provide a comprehensive review of the associated literature. The main achievement of the earlier stages of research was the definition of the standard temperature *vs* time curve as a general description of the fire environment [2]. This definition enabled structural engineers to establish methods to protect structural systems from a fire. The recognition that further understanding of the fire environment is necessary to quantify structural behaviour only emerges through 30 years of research encompassing the period from 1960-1990. In this period, a series of seminal studies authored by the fathers of fire safety science provided the foundations for our current engineering methods. Kawagoe questions the physical basis of the standard temperature *vs* time curve and is the first to intuitively establish the concept of the compartment fire [3]. Through experimental observations he defines the link between ventilation, gas phase temperatures and burning rate. Thomas and co-workers [4, 5] extend and formalize the experimental database into a series of engineering expressions that characterize the maximum temperature within a compartment and, given a fuel load, the potential duration of the a fully developed fire. Thomas's formulation de-emphasizes time and provides a worst case time invariant temperature regime for the fire until total burn-out of the fuel. At this point research bifurcates, while Petterson *et al* [6] extend the empirical data base by re-emphasizing the time evolution of the fire, Emmons *et al* [7] and McCaffrey *et al* [8] refine Thomas's formulation by further describing the different processes and adding more experimental data. It is important to note that only Petterson *et al* [6] emphasize the time evolution of the fire while all others focus on the worst case condition. Of notable importance are the studies by Harmathy *et al* [9], Law *et al* [10-12] and Tanaka *et al* [13-17] who attempted to translate the acquired knowledge into design methodologies with an emphasis on structural performance. Numerous complementary studies were conducted in this period providing refinements and extensions to the existing methods but emphasizing the validity of the fundamental approach initiated by Kawagoe [3].

In 1998 the SFPE Task Group on Fire Exposures to Structural Elements chaired by Prof. J.G. Quintiere started to develop the SFPE Engineering Guide for Fire Exposure to Structural Elements that was finally published in 2004 [18]. This guide provides a comprehensive review of the different methods used in the calculation of how fires thermally affect structures. This guide was followed in 2011 with the SFPE Engineering Standard on Calculating Fire Exposures to Structures [19] developed by SFPE Standards-Making Committee on Calculating Fire Exposures to Structures chaired by J. K. Richardson. The SFPE Engineering Standard draws on the information of SFPE Engineering Guide to provide a method that enables the engineer to establish the evolution of the thermal boundary condition for a structure subject to a fire. Given a well-defined set of boundary conditions, the evolution of the transient temperature distribution of a structure can be established by means of a heat conduction analysis [4, 5, 9, 19-23]. These temperature distributions are then used as inputs for a structural analysis that determines the performance of a structural system in fire [23, 24]. There are other methods available in the literature [25-29] nevertheless, the comprehensive nature of the SFPE Guide and Standard make it a good starting point for this paper.

In parallel to the development of design methods, significant advances in the development of Computational Fluid Dynamics (CFD) models for fire applications have been reported. These models allow a significant level of refinement that enables a much more detailed treatment of the thermal boundary conditions for the structure. Successful applications have populated the literature in the last 10 years [30, 31]. CFD has a fundamental role in enabling better understanding of the physical processes [32] but it is recognized that there are still many uncertainties in the models. In what concerns the use of CFD for design, the utilization of the models can be too complex to be practical for main stream design and the drastic differences between solid and gas phase time scales do not necessarily justify the level of precision

brought by the utilization of CFD [33]. This paper will not address further the use of CFD, this is a subject of enough complexity to merit its own individual work.

It could appear as if by 2011, date of the publication of the SFPE Engineering Standard on Calculating Fire Exposures to Structures [19], that research had matured to a level where the thermal boundary condition for a structure was fully defined. Existing design methodologies, albeit conservative, provided a robust solution to the thermal boundary condition for performance assessment of a structure in fire.

A review of the classical studies on which existing design methodologies are based serves to clarify the limitations of existing design methods and the areas where further research is necessary. Some new experiments will be presented to provide evidence towards the need for further research.

THE COMPARTMENT FIRE FRAMEWWORK

The temperature evolution within a building enclosure is defined by a compendium of complex processes occurring simultaneously. Fuel is pyrolyzed at a rate determined by the characteristics of the material and the net heat exchange between the fuel, the fire, the enclosure, the exterior environment and gas phase (hot and cold). The fuel mixes with oxidizer flowing through the compartment leading to a combustion reaction whose characteristics are defined by the relative quantities of fuel and oxidizer (local stoichiometry) as well by heat exchange with the enclosure and the exterior environment. The heat generated by the combustion reaction is partially lost at the openings, partially transferred to the enclosure and to a minor extent fed back to the fuel. The relative importance of all these terms defines the energy accumulated in the compartment and thus its temperature evolution. The resulting gas phase temperature will most likely be a function of all three spatial coordinates and time ($T_g(x,y,z,t)$) and the consequence of complex heat and mass transfer processes. The characteristic time scales of combustion, flow and heat transfer can be very different, thus significant simplifications are potentially possible. Given the complexity of the processes an *a priori* assessment of the possible simplifications is not possible without a detailed quantification of each term.

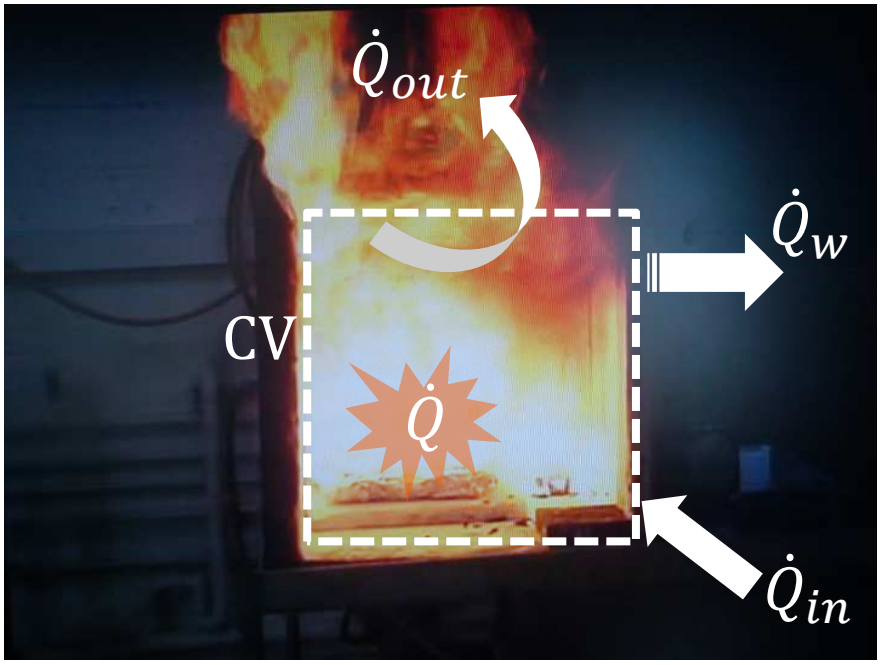


Fig. 1. The “Compartment Fire” framework.

The “Compartment Fire” framework is based on a series of observations that emerged from numerous experiments conducted by Kawagoe [3] and later by Thomas *et al.* [5]. These experiments were then complemented by results of Harmathy [9]. The principle behind the method is that characteristic time scales for combustion are very short thus energy is assumed to be released as a function of reactant supply,

i.e. oxygen in the case of an oxygen-limited reaction and fuel in the case of a fuel-limited reaction. The characteristic time for heating of the enclosure is extremely long compared to all gas phase processes, therefore the gas phase can be assumed to be quasi-steady. The characteristic time for fuel pyrolysis is comparable to that of solid heating therefore a single characteristic time describes both. The burning rate will attain steady state conditions at the same time as the enclosure reaches thermal equilibrium with the gas phase. Under those circumstances a maximum gas phase temperature will be achieved (and maintained) beyond the transient heating of the enclosure. The steady state condition implies a constant heat transfer to the walls, a constant generation of heat, and a constant flow of heat out of the enclosure. The main consequence of this approach is that the geometry of the enclosure (dimensions, aspect ratio and openings) defines the relative importance of each term and therefore the value of the equilibrium gas phase temperature ($T_{g,max}(x,y,z)$). Thomas explores all three parameter spaces emphasizing the role of each of them [4, 5].

As explained above, depending on the availability of air the generation of heat is either controlled by fuel supply (fuel limited) or air supply (oxygen limited). This distinction is important in that it determines the form the energy source takes when introduced in the energy equation. Nevertheless, it does not eliminate the need to resolve the transport processes that bring fuel and oxidizer towards the reaction zone. Thomas *et al.* [4] describe the role of transport by establishing two limit regimes, *Regime I* and *Regime II*. Harmathy [9], offers a similar discussion using a different terminology ("ventilation controlled," "fuel-surface-controlled") but identical concepts.

Thomas *et al.* [4] describe *Regime I* as the case where the vents are small enough that they allow for the compartment to fill with smoke. In this case, at steady-state oxygen supply is limited, combustion is rich and soot concentrations are high. A significant amount of the energy released by combustion occurs outside the compartment and the flow field within the enclosure is dominated by thermal expansion of the gases allowing the assumption that momentum within the enclosure is negligible. Momentum and mass is only exchanged at the openings therefore it can be characterized by static pressure differentials across the openings. If a fixed fraction of the energy released is lost through the openings then the maximum temperature distribution ($T_{g,max}(x,y,z)$) will only be a function of the equilibrium heat exchange with the enclosure and the heat generated, where the heat generated is directly related to the mass flow of oxygen through the vents. Given the high soot concentrations (the optical depth is very small) and low velocities a linearized approximation for total heat transfer is acceptable. This enables not only the formulation of heat exchange through the walls by simple expressions [18, 33] but also the expression of the burning rate as a direct function of the gas phase temperature. As Thomas *et al.* [4] and Harmathy [9] point out, the equilibrium temperature, and consequently all other characteristic values, are defined by the relative magnitude of the three main terms of the energy equation, heat generation, heat transfer to the enclosure and heat losses through the vents. The relative values are therefore strongly dependent on the geometry of the compartment. While the validity of the framework extends to all geometries that comply with the assumptions, the resulting values are defined by the complex heat and mass transfer processes that remained unresolved. All unresolved processes are substituted by experimental values therefore the quantitative values extracted from experimentation are only applicable for the characteristic geometries reported in the tests.

In the case where the vents are sufficiently large, the smoke evacuates the enclosure with little resistance allowing for the fire to draw air. If the pressure differentials generated by the fire dominate over the static pressure differentials, the combustion products are expelled from the enclosure as fast as air is drawn into the enclosure. Complex heat and mass transfer processes dominate over this regime that Thomas *et al.* [4] label *Regime II*. No simple theoretical analysis can be defined for *Regime II*. Characteristic heat transfer times are short, soot concentrations are low therefore heat exchange from the fire to the structure was deemed to be less severe than for *Regime I* [4]. Harmathy [20] argues theoretically the lower severity of *Regime II* showing that the large velocities and vent size result in a major fraction of the heat being expelled through the vents, a decreased net heat accumulation in the enclosure and lower gas phase temperatures. Quantification of the actual heat transfer to the structure and the fuel is highly dependent on the geometry of the enclosure and extrapolation is extremely difficult under these circumstances. If quantification of the environment is desired, *Regime II* needs to be avoided.

From a design perspective different approaches can be followed. Code based restrictions on vent and compartment size can be imposed to avoid either regime. Through Thomas's work it is generally implied that *Regime I* is more severe than *Regime II* (albeit never truly quantified) therefore building design can be done under the quantifiable worst case conditions of *Regime I*. In other words, the building geometry can be restricted so that only *Regime I* fires are possible and structural design can be done to withstand the thermal load of such fires. Alternatively, an even more conservative approach can be followed which is to quantify *Regime I* as a worst case condition but require building characteristics consistent with *Regime II*. A final approach was strongly advocated by Harmathy [20-22] who embraced Thomas's conclusion on the greater severity of *Regime I* and encouraged designers to increase venting as an effective means to reduce fire proofing. The following quote is extracted from Reference [21]: "The simplest way of improving fire safety is to reduce its destructive potential in the "fire cell" (space on fire) by ensuring that the fire, if it occurs, will be fuel-surface-controlled (i.e. *Regime II*), in other words, by using large window areas, whenever possible, it becomes possible to replace fire resistance requirements with ventilation requirements. This means that the designer is entitled to decide whether to choose between buildings built with small windows and heavy fire-rated walls and floors, and buildings with large windows and lighter non-combustible, non-fire-rated elements." Whatever approach is followed, it was recognized that this is only valid within the context of the specific geometries studied [5, 9].

An important point regarding the differences between *Regime I* and *Regime II* is highlighted by Harmathy [20]. The mechanisms linking compartment temperature and burning rate are only valid for *Regime I* and not for *Regime II*, in particular, the inverse relationship between the maximum average gas phase temperature ($T_{g,max}$) and the duration of the fire. In Reference [20] Harmathy indicates: "The conclusion reached so far is that well-ventilated fires, i.e., fuel-surface controlled fires, not only burn at lower temperatures (in general), but also are very short. The common belief that compartment fires are either short and hot or long and relatively cool is, therefore, completely wrong." This observation seems to have been forgotten and it has become common to describe both regimes as being defined by the same interaction of physical processes [34] without remembering that *Regimes I and II* are two limit forms of behaviour that are the result of neglecting different processes and having the remaining ones interacting in a very specific manner.

In summary, the "Compartment Fire" framework is a robust representation of the behaviour of a fire in an enclosure. There is no fundamental weakness in the approach but the quantitative results are intimately linked to the geometry of the compartment (size, vent size, aspect ratio). The geometry will define if the conditions are consistent with the assumptions of the analysis but most importantly, it will establish the relative magnitude of the heat flow in and out of the enclosure (terms in Figure 1), which in turn defines the equilibrium temperature. Currently, the relative distribution is not defined in an analytic way but by means of experimental values. Extrapolation of these experimental values requires geometrical consistency. The SFPE Engineering Guide for Fire Exposure to Structural Elements [18] addresses this issue as early as the Executive Summary, nevertheless it addresses the influence of the geometry on the validity of the different methodologies employed in terms that are relevant only to *Regime I* fires, in other words as a function of the Opening Factor ($A/A_0\sqrt{H_0}$). The following section will define this terminology and address the fundamental differences between both regimes.

Energy Balance in a Compartment Fire

A compartment will be used as a control volume to describe the mechanisms by which energy can be transferred in and out of the control volume resulting in temperature distributions within the compartment. Friction work will be neglected and the volume of the compartment will be assumed constant. The energy conservation equation for the fixed control volume of Figure 1 can be represented as:

$$\frac{dQ_{CV}}{dt} = \dot{Q}_{in} - \dot{Q}_{out} + \dot{Q} - \dot{Q}_w \tag{1}$$

Where $\dot{Q}_{in}$ is the enthalpy entering the control volume with the reactants per unit time, $\dot{Q}_{out}$ is the enthalpy leaving the control volume with the products per unit time, $\dot{Q}_w$ represents the heat losses to the enclosure

boundaries and $\dot{Q}$ the total heat release rate within the enclosure by the fire. To understand better the role of each term it is useful to normalize the Equation (1) by the heat release rate.

$$\frac{1}{\dot{Q}}\frac{dQ_{CV}}{dt} = 1 + \frac{\dot{Q}_{in}}{\dot{Q}} - \frac{\dot{Q}_{out}}{\dot{Q}} - \frac{\dot{Q}_w}{\dot{Q}} \tag{2}$$

Given that the addition of mass into the enclosure associated to the fuel's mass loss rate is negligible in comparison to the air mass inflow and gas mass outflow rates (estimated between 16% [9] and 18%[4]), the rate of change of mass within the control volume can be considered close to zero (i.e. $\frac{dm_{CV}}{dt} \approx 0$), therefore the transient term of the conservation of mass equation can be neglected resulting in:

$$\dot{m}_{in} = \dot{m}_{out} = \dot{m} \tag{3}$$

Given the significant temperature differences between the reactants and products it is possible to establish that $\frac{\dot{Q}_{in}}{\dot{Q}} \ll \frac{\dot{Q}_{out}}{\dot{Q}}$. This simplification is not necessary for the rest of the analysis but it will be retained here for consistency with the original presentation. Simple scaling analysis establishes that the characteristic heating times for the solid walls is at least two orders of magnitude longer than that of the combustion products allowing to assume quasi-steady conditions, i.e. $\frac{1}{\dot{Q}}\frac{d\dot{Q}_{CV}}{dt} \approx 0$. On the basis of these simplifications equation (3) can be rewritten as

$$1 = \frac{\dot{Q}_{out}}{\dot{Q}} + \frac{\dot{Q}_w}{\dot{Q}} \tag{4}$$

It is important to note that until this point no strong assumptions have been made and Equation (4) can be satisfied by any enclosure subject to a fire. What follows is a series of assumptions that enable the transformation of Equation (4) into a set of very simple expressions that serve to characterize the enclosure fire under *Regime I* conditions. The assumptions are:

(a) The heat release rate is defined by the complete consumption of all oxygen entering the compartment and its subsequent transformation into energy, $\dot{Q} = \dot{m}Y_{O_2,\infty}\Delta Hc_{O_2}$. Where the ambient oxygen concentration is given by $Y_{O_2,\infty}$ and the heat of combustion per kilogram of oxygen consumed is given by ΔHc_{O_2}. This assumption not only eliminates the need to define the oxygen concentration in the outgoing combustion products but also eliminates the need to resolve the oxygen transport equation within the compartment. Implicitly this assumption limits the analysis to scenarios where there is excess fuel availability, chemistry is fast enough to consume all oxygen transported to the reaction zone and the control volume acts as a perfectly stirred reactor. It is important to add that if the heat of combustion is assumed to be an invariant then the level of completeness of the combustion process is assumed to be independent of the compartment.

(b) Radiative losses through the openings are assumed to be negligible [4] therefore $\dot{Q}_{out}$ is treated as an advection term. Harmathy [9] provides an estimate for the radiative losses of approximately 3% of the total energy released.

(c) There are no gas or solid phase temperature spatial distributions within the compartment. The gas phase equilibrium temperature is therefore defined by a single value, $T_{g,max}$, and the equilibrium surface temperature of all solid surfaces also by a single value, T_w. $\dot{Q}_{out}$ and $\dot{Q}_w$ can then be strongly simplified. If the specific heat is assumed to be a constant then $\dot{Q}_{out} = \dot{m}C_pT_{g,max}$. $\dot{Q}_w$

can be simplified in several manners depending on the objectives of the simplification. The simplifications associated to $\dot{Q}_w$ require more detail and are addressed later.

(d) Mass transfer through the openings is governed by static pressure differences therefore a simple orifice plate expression can be used to evaluate the mass flow of air through the openings, $\dot{m} = CA_O\sqrt{H_O}$, where A_O and H_O are the opening area and height respectively and C is a constant that amalgamates all other constants including the orifice plate coefficient and gravity. It is important to note that this assumption requires all velocities within the compartment to be negligible. Different values of the constant were derived by Harmathy [9] and calculated by Thomas [5] for different experimental conditions.

The classical approach is to define $\dot{Q}_w$ as conduction losses through the boundaries of the compartment. While more complex formulations are possible, a simple steady state approximation will be used to quantify conductive losses:

$$\dot{Q}_W = Ak\frac{(T_{g,max} - T_\infty)}{\delta} \tag{5}$$

Where A is the area through which heat is being transferred, k an effective thermal conductivity of the compartment boundaries, δ a characteristic thickness of the boundaries and T_∞ the ambient temperature. It is important to note that this approximation is quite coarse in that it assumes the temperature difference between the interior and the exterior of the compartment boundaries ($T_{g,max} - T_\infty$) as the maximum possible value i.e. T_∞ does not rise due to heat transfer through the walls, therefore the resulting heat transfer to the boundaries is maximized and the compartment temperature is minimized as a consequence of these maximal heat losses. While this approximation might not be conservative it is useful to establish the relationship between the gas phase temperature, the air intake and the compartment geometry. Substituting equation (5) into equation (4) and solving for the steady state gas phase temperature the following expression is obtained:

$$T_{g,max} = \left(\frac{1 + \frac{T_\infty}{T_{CD}}}{1 + \frac{T_F}{T_{CD}}}\right)T_F \tag{6}$$

Where $T_F = Y_{O_{2,\infty}}\Delta Hc_{O_2}/C_p$ is a characteristic flame temperature and $T_{CD} = \frac{CY_{O_{2,\infty}}\Delta Hc_{O_2}}{(k/\delta)}\left(\frac{A_O\sqrt{H_O}}{A}\right)$ is a characteristic conduction temperature. It is important to note that under the present assumptions all terms of equation (6) are constant with the exception of the classic opening factor $\left(\frac{A_O\sqrt{H_O}}{A}\right)$ and the thermal conduction heat transfer coefficient (k/δ) both properties of the compartment.

An alternative approach to define the heat transfer through the walls is by means of a convective boundary condition. In this case heat transfer through the walls can be described by

$$\dot{Q}_W = Ah_T(T_{g,max} - T_W) \tag{7}$$

Where h_T is a total heat transfer coefficient and T_W the interior surface temperature of the compartment boundaries. Once again, this is a very simple expression that establishes a different form of the steady state gas phase temperature:

$$T_{g,max} = \left(\frac{1 + \frac{T_W}{T_{CV}}}{1 + \frac{T_F}{T_{CV}}} \right) T_F \tag{8}$$

Where $T_{CV} = \frac{CY_{O_2,\infty} \Delta Hc_{O_2}}{h_T} \left(\frac{A_O \sqrt{H_O}}{A} \right)$ is a characteristic convection temperature. While both expressions (equations (6) and (8)) are very similar and depend on the opening factor $\left(\frac{A_O \sqrt{H_O}}{A} \right)$, equation (8) also depends on a gas phase parameter which is the total heat transfer coefficient. This only becomes interesting when the asymptotic conditions are attained.

If $\frac{T_\infty}{T_{CD}} \ll 1$ and $\frac{T_F}{T_{CD}} \ll 1$ (i.e. large opening factor and insulating walls) then equation (6) results in

$$T_{g,max} = T_F \tag{9}$$

If $\frac{T_\infty}{T_{CD}} \gg 1$ and $\frac{T_F}{T_{CD}} \gg 1$ (i.e. small opening factor and non-insulating walls) then equation (6) results in

$$T_{g,max} = T_\infty \tag{10}$$

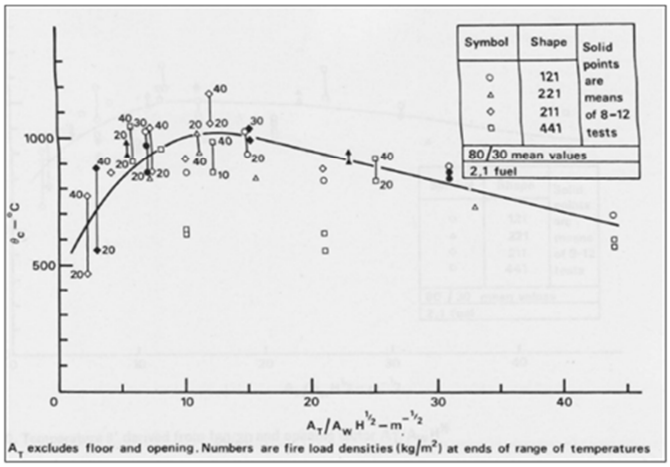


Fig. 2. Average compartment temperature for the CIB Tests, extracted from [5].

Similarly, if $\frac{T_\infty}{T_{CV}} \ll 1$ and $\frac{T_F}{T_{CV}} \ll 1$ (i.e. very large opening factor and weak total heat transfer) then equation (8) results in

$$T_{g,max} = T_F \tag{11}$$

But if $\frac{T_\infty}{T_{CV}} \gg 1$ and $\frac{T_F}{T_{CV}} \gg 1$ (i.e. very small opening factor and strong total heat transfer) then equation (8) results in

$$T_{g,max} = T_W \tag{12}$$

It is important to note that the asymptotic values associated with equation (6) (i.e. equations (9) and (10)) directly relate the gas phase temperature to the two hard limits, the ambient and characteristic flame temperatures. Therefore, this equation is very useful when addressing the evolution of the gas phase temperature as a function of the opening factor. In the work by Thomas *et al* [4] it is stated that the quantitative values of $T_{g,max}$ will be dependent on the conduction heat transfer coefficient (k/δ) and that a conservative characteristic value can be taken for testing leading to a conservative empirical evolution of $T_{g,max}$ as a function of only the opening factor. Figure 2 shows the plot extracted from reference [5] where the right hand side of the curve shows the evolution of $T_{g,max}$ as a function of the inverse of the opening factor. Extrapolation of the trend in this region in both directions will lead towards the asymptotic values defined by equations (9) and (10). The asymptotic limit defined by equation (9) will not be attained. Towards the left of the maximum temperature (Figure 5) the conditions are representative of *Regime II* which does not comply with the assumptions of this analysis and therefore deviates from the trends defined by equation (6) and the asymptotic limit defined by equation (9).

Finally, Kawagoe [3] establishes that from equation (5) and from the fact that the burning rate is proportional to the heat transfer rate to any of the boundaries of the compartment, that the burning rate is proportional to $A_O\sqrt{H_O}$.

In contrast to equation (6), equation (8) has a different asymptotic term for the case where heat transfer between the gas and compartment is high. In this case the gas phase and wall temperatures are the same (as represented by equation (12)). This observation is significant in that it focuses on the temperature of the structure and indicates that given the right heat transfer conditions, the thermal characteristics of the structure can dominate the minimum temperature of the gas phase and the balance of the two right hand terms of equation (4).

In summary, the compartment fire framework allows, by means of several strong assumptions, a representation of the maximum steady state temperature, $T_{g,max}$, of a compartment simply as a function of the opening factor $\left(\frac{A_O\sqrt{H_O}}{A}\right)$ and the burning rate, *R*, as proportional to the ventilation factor $A_O\sqrt{H_O}$. Those assumptions are consistent with *Regime I*, and while remaining within these assumptions, simple expressions (equations (6) and (8)) can be used to link $T_{g,max}$ to the opening factor. Outside the validity of the fundamental assumptions the theoretical link between temperature, burning rate and opening factor does not exist.

THE RANGE OF VALIDITY OF THE COMPARTMENT FIRE FRAMEWWORK

The Original Experiments

To understand the range of validity of the expressions presented above it is important to discuss the experiments that led to this analysis. Two series of large scale experiments provide the initial set of data used to develop the Compartment Fire framework: those by Kawagoe [3] and those of the CIB study [4, 5]. The CIB programme summarizes Kawagoe's experiments therefore will be used to describe the nature of the tests. The shape of the compartments used in the CIB Programme was rectangular, designated by a three figure code representing the three principal dimensions of width, depth and height (where all dimensions are normalized by the height). Thus, a 211 compartment measured 2 units wide, 1 unit depth and 1 unit height. The four shapes of compartment examined were 211, 121, 221, and 441. The overall scale of the compartment was taken as the compartment height, and scales of 0.5, 1, and 1.5 meter were employed. Therefore, the larger compartment size was 6 m x 6 m x 1.5 m height.

The data obtained through these experiments are mainly burning rates and average compartment temperatures ($T_{g,max}$). The weight of the fuel was obtained throughout each test either by weighing the whole compartment or by weighing the floor separately. The temperatures were recorded by only two thermocouples placed at ¼ and ¾ of the compartment height above the centre of the floor. As pointed out by Thomas and Heselden [5], in some cases, the lower thermocouple was laid inside the wood cribs that were used as fuel resulting in a measurement bias for the average temperature.

Although the CIB data for average temperatures vs. the inverse opening factor presented significant scatter, Thomas and Heselden [5] drew a best-fit line through one of the fuel configuration data sets (i.e. the (2,1)

crib configuration, meaning 20 mm thick sticks spaced 20 mm apart) obtaining as a result the very well-known plot presented in Figure 2.

Similar graphs for other fuel crib configurations were presented by Thomas and Heselden [5] but because the (2,1) configuration resulted in higher average temperatures, the data of Figure 2 are generally used for design analysis. It is important to emphasize that the data shows reasonable scatter for *Regime I* conditions but the scatter is very large for *Regime II*. In the case of *Regime II*, factors such as aspect ratio, nature of the fuel and scale were shown by the authors to have a significant effect on the resulting temperatures.

An important finding in the CIB Programme was that high values of the enclosure's depth to height ratio produced non-uniform temperatures horizontally and large windows non-uniformity vertically, with the ceiling temperatures typically being the maximum temperatures found in an enclosure fire.

Non-Uniformity and the "Natural Fire"

Following the observations of the CIB studies, Stern-Gottfried et al. [35] reviews the test literature in an attempt to establish if the assumption of homogeneous temperature distribution within the compartment is valid through the available data. The compiled data showed that for smaller, cubic compartments the assumption of a homogeneous temperature distribution is valid but it breaks down with the size of the compartment and in particular when the aspect ratio deviates from the cubic compartment.

Additionally, Drysdale [36] explains that most of our knowledge of the behaviour of compartment fires comes from experiments with near-cubical compartments, with characteristic dimensions ranging from 0.5 m to 3 m which of course are very different in shape and size compared with typical spaces in modern commercial buildings [37].

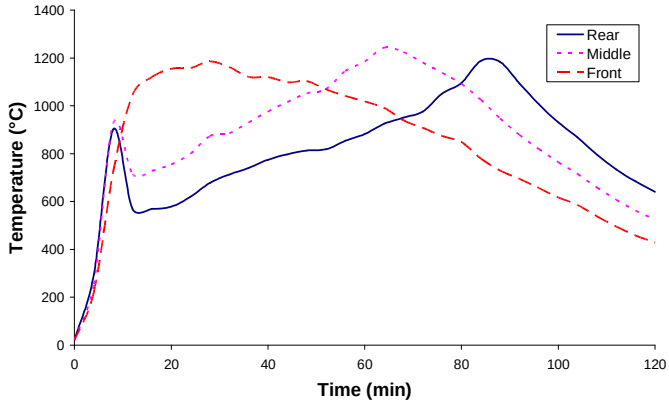


Fig. 3. Temperature distributions for the Natural Fire safety Concept Tests [29]

In 1999, the Natural Fire Safety Concept 2 test series at Cardington [38] included a much greater spatial resolution of instrumentation. The eight Cardington tests were conducted in a room 12 m x 12 m x 3 m with uniformly spaced fuel load packages distributed across the floor. Sixteen thermocouple trees containing four thermocouples each were placed on a uniform grid in the compartment to record the gas temperatures, shown in Figure 3. The tests were conducted with various combinations of fuel type, ventilation distribution, and interior lining material. The tests had liquid fuel channels connecting the fuel packages so that ignition and the subsequent burning could be as uniform as possible.

The Cardington experiments intended to test two types of compartment insulation; "insulating" and "highly insulating". However, after Test 1, the "highly insulating" material was placed on the ceiling for all remaining tests, creating an intermediate level of insulation. The fuel packages were either just wood cribs or a combination of wood and plastic cribs. The ventilation openings were either fully open on the front of the enclosure or fully open on the front and back. As shown in Figure 3 there is a significant evolution in space and time of the temperature. The evolution in time is mostly related to the time lag between heating in the gas phase and the heating of the compartment, thus is related to the level of insulation. This had been

previously extensively studied by Pettersson *et al* [6] when developing the parametric fire curves, nevertheless the Natural Fire Concept tests were the first where the insulation was systematically varied. The evolution in space was observed but not studied in detail due to the restricted amount of instrumentation.

A different form of temperature distribution was reviewed and reported by Clifton [39] who describes fires that spread through a large compartment generating spatial and temporal distributions as a consequence not only of stratification but also of the progression of the fire through the compartment. Clifton [39] emphasizes a simple methodology to model these fires and only presents a limited set of experimental data to validate the analytical approach. While the data are coarse and limited, it does indicate drastic spatial and temperature evolutions throughout the compartment. An earlier study concerning the St. Lawrence Burn project [40] was recently reported by Gales [41] where compartments of dimensions 11.2 m x 12.8 m and 13 m x 9 m respectively were exposed to a propagating fire showing once again significant spatial and temporal distributions.

The Dalmarnock Fire Tests

The Dalmarnock Fire Tests, which provide the greatest instrumentation density to date, were conducted in a real high-rise apartment building in Glasgow, UK [42]. The two tests conducted had a realistic fuel load of typical furnishings. The compartment was 4.75 m x 3.50 m x 2.45 m, containing 20 thermocouple trees, each with 12 thermocouples (placed 0, 0.05, 0.1, 0.2, 0.3, 0.4, 0.6, 0.8, 1.0, 1.3, 1.6 and 2 m from the ceiling). Ignition occurred in the waste-paper basket adjacent to the sofa. Two tests were conducted, Test One was allowed to progress to burn-out while the second test was manually suppressed immediately after flashover. Thus only Test One is of interest here.

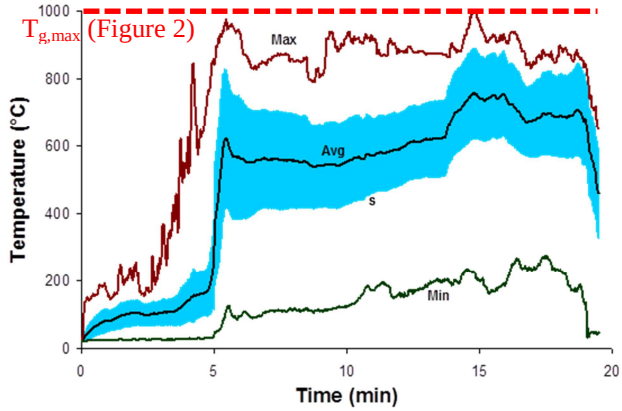


Fig. 4. Experimental results of Dalmarnock Test One [42] showing the compartment average, maximum and minimum temperatures, the standard deviation and the prediction from Figure 2. Flashover occurred at 5 min and the fully developed stage lasted until suppression at 19 min.

The Dalmarnock Test One shows that the temperature distributions, even for a small compartment corresponding to *Regime I*, are lower than the predictions of the CIB and present very large variations in space and time. All it takes is to provide sufficient instrumentation density to spatially resolve the temperature fields. In the Natural Fire Concept tests the compartment was large but all fires were ignited simultaneously, in the Dalmarnock tests the fire was allowed to propagate, but the compartment was small. In the study by Clifton [39] one series of experiments was reported where the compartment was large (44 m x 34 m) and the fire was allowed to propagate, nevertheless, the data has poor resolution and only a single experimental condition is reported. A similar situation occurs with the St. Lawrence Burns Project where only two tests were reported and limited data is available.

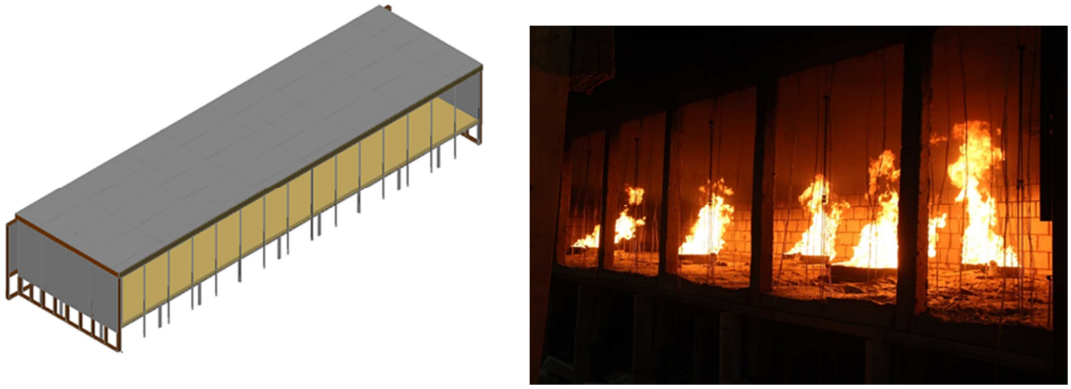
Summary of Existing Evidence

The available experimental data confirm that the observations and analysis first developed by Kawagoe [3] and then by Thomas *et al* [4, 5] can provide a simple yet fundamentally adequate way to describe the

maximum average temperature, $T_{g,max}$, and burning rate as a function of a single parameter, the ventilation factor $\left(\frac{A_O\sqrt{H_O}}{A}\right)$. The SFPE Engineering Guide - Fire Exposures to Structural Elements [18] reviews a large amount of data that validates this approach. The data and analysis is presented in the context of the of the same methodology and while it explores the limits of validity of the approach it does not extended beyond the "Compartment Fire Framework" first formulated by Thomas *et al* [4]. Following on from Thomas *et al* [4], this paper highlights the main assumptions involved in the formulation that leads to the definition of the ventilation factor $\left(\frac{A_O\sqrt{H_O}}{A}\right)$ as the single parameter that characterizes the compartment fire and establishes through a brief review of some experimental data that there is a large body of evidence that demonstrates that the conditions necessary for a *Regime I* fire are not necessarily met in modern building enclosures. Furthermore, the available data is not sufficient to characterize the different forms of behaviour that fires can have in the multiplicity of compartment geometries now common in the built environment. The next section briefly summarizes a series of tests designed to start filling these gaps of knowledge.

THE "TALL BUILDING" TESTS

To respond to the need to better describe the special and temporal evolution of a fire that is allowed to progress in a large compartment a series of tests were conducted in 2013 at the Building Research Establishment in the UK. These tests are inscribed within a larger programme that looks to address fire scenarios for tall buildings, thus will be labelled the "Tall Building Tests."



(a) (b)

Fig. 5. (a) Schematic of the BRE large compartment constructed and (b), a photograph of a characteristic gas burner test.

A compartment of dimensions 5 m x 18 m x 2 m (Figure 5(a)) was constructed and included 15 openings along the front (1.5 m high by about 1 m wide each) that can be open and closed to allow varying ventilation in a systematic way. The tests are heavily instrumented including internal thermocouple trees spaced at 0.7 m in the x-direction, 0.6 m in the y-direction, and at 0.3, 0.6, 0.9, 1.2, 1.4, 1.6, 1.8, and 1.95m in the z-direction. There is also a thermocouple tree in the centre of each opening at z = 0.25, 0.5, 0.75, 1.0, and 1.25m. Outside there is also a thermocouple tree at around 0.4 m from the compartment and aligned with the centre of each opening. These trees have 12 thermocouples each which are spaced as follows: 0.25, 0.5, 0.75, 1.0, 1.25, 1.5, 1.75, 2.0, 2.25, 2.5, 2.75 and 3.0m. 100 thermocouples provide in-depth temperatures (at different depths) along a 3 m wide section of the back wall which is in-filled with non-flammable insulation. Heat flux gauges were placed on all 5 surfaces of the compartment evenly distributed. There are 45 on the floor (3 in x -direction, 15 in y-direction), 45 on the ceiling, 45 along the back wall (15 in y-direction, 3 in z-direction) and 15 (5 in the x-direction, 3 in the z-direction) along each of the side walls. There are also heat flux gauges outside, opposite the centre of each opening, at different distances away from the compartment (in x-direction). Smoke obscuration is measured with 5 laser-receiver pairs in total evenly spaced along the centre of the compartment. Bi-directional velocity probes allow characterizing the in-flow and out-flow of the compartment. There are 2 probes per opening (z =

0.225 m and z = 1.275 m of the opening height, respectively). There are 5 gas-sampling points evenly spaced along the ceiling of the compartment. The gas probes sample O_2, CO_2 and CO to establish completeness of combustion. Five cameras were used to film the compartment from different angles, including one camera at the centre of each of the side walls. An InfraRed camera was also used to film the compartment from the outside.

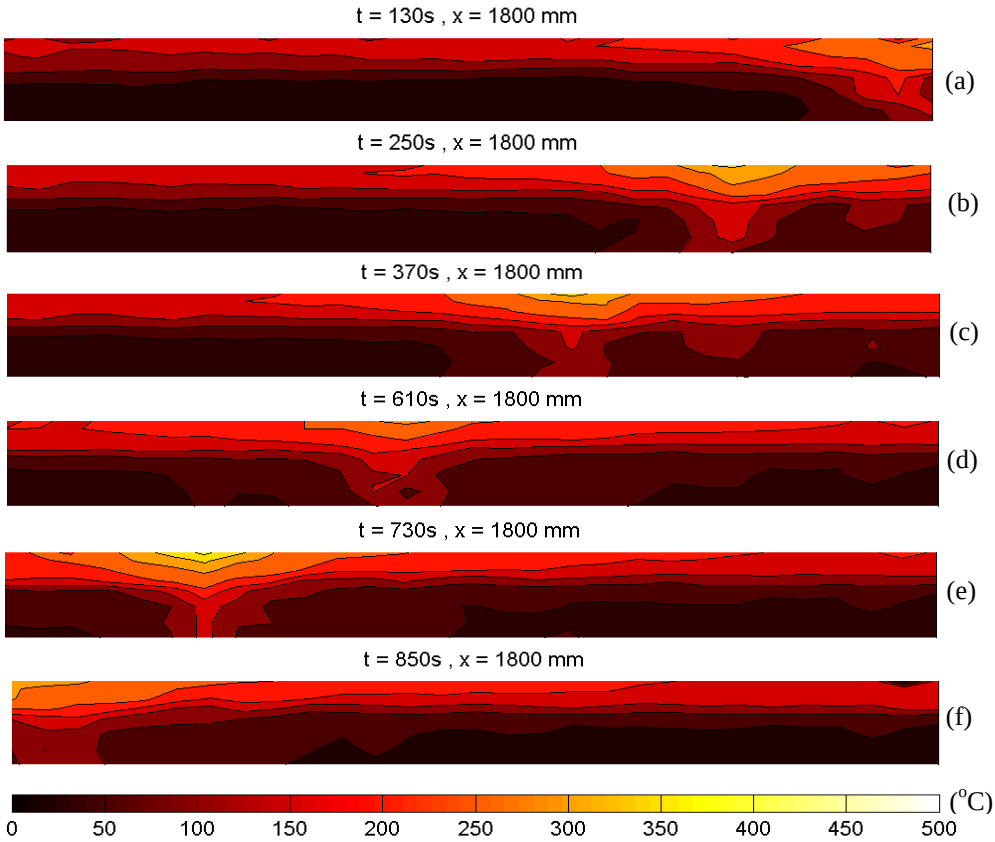


Fig. 6. Temperature distributions along a plane 1800 mm deep and parallel to the open face (in between burners) – the openings were fully open allowing for the maximum evacuation of of smoke.

Two series of tests were conducted, a first series where a sequence of gas burners (12 propane burners, of 0.5 m x 0.5 m trays full of gravel, evenly spaced throughout the compartment in pairs of 2) was ignited progressing from one end of the compartment to the other. Ventilation and fire spread were varied to cover a range that allowed for spread much faster than ventilation opening to spread much slower than ventilation opening. The second series of tests was conducted with wood cribs covering the entire floor and ignited at one end. The ventilation was again varied. For the wood crib tests, the central staging area has been divided into 8 sections that can move up and down independently. These sat on load cell systems that enabled the measurement of mass loss. A photograph of a typical test is presented in Figure 5(b).

While the description of the experimental data is beyond the scope of this paper, it is important to emphasize that the scale and data variety and resolution result in different observed behaviour that not only deviate from the compartment fire framework but that could potentially have a significant impact on the thermal boundary condition used to analyse structural behaviour. Furthermore, current detailed structural analysis requires a level of resolution that cannot be provided by the simple formulation of the compartment fire framework [34, 44]. These tests provide a level of resolution that is more consistent with the needs of such analysis.

Figure 6 shows a series of representative data for an experiment using gas burners ignited in a sequential manner while the panels allowing air were opened fully. The fire is initiated with two burners (front and back –Figure 5(b)) at the right hand side of the compartment. Initially, the ceiling jet propagates across the compartment with no significant accumulation of smoke but very rapidly it covers the entire compartment (<130 sec – Figure 6(a)). The smoke produced by the fire is fully evacuated allowing for the establishment of steady state conditions. The initial burners are turned-off as the next set is ignited and the temperatures once again reach steady-state conditions rapidly. A clear smoke layer can be seen in Figure 6(b). The smoke layer shows very similar temperatures to the ones observed in Figure 6(a).

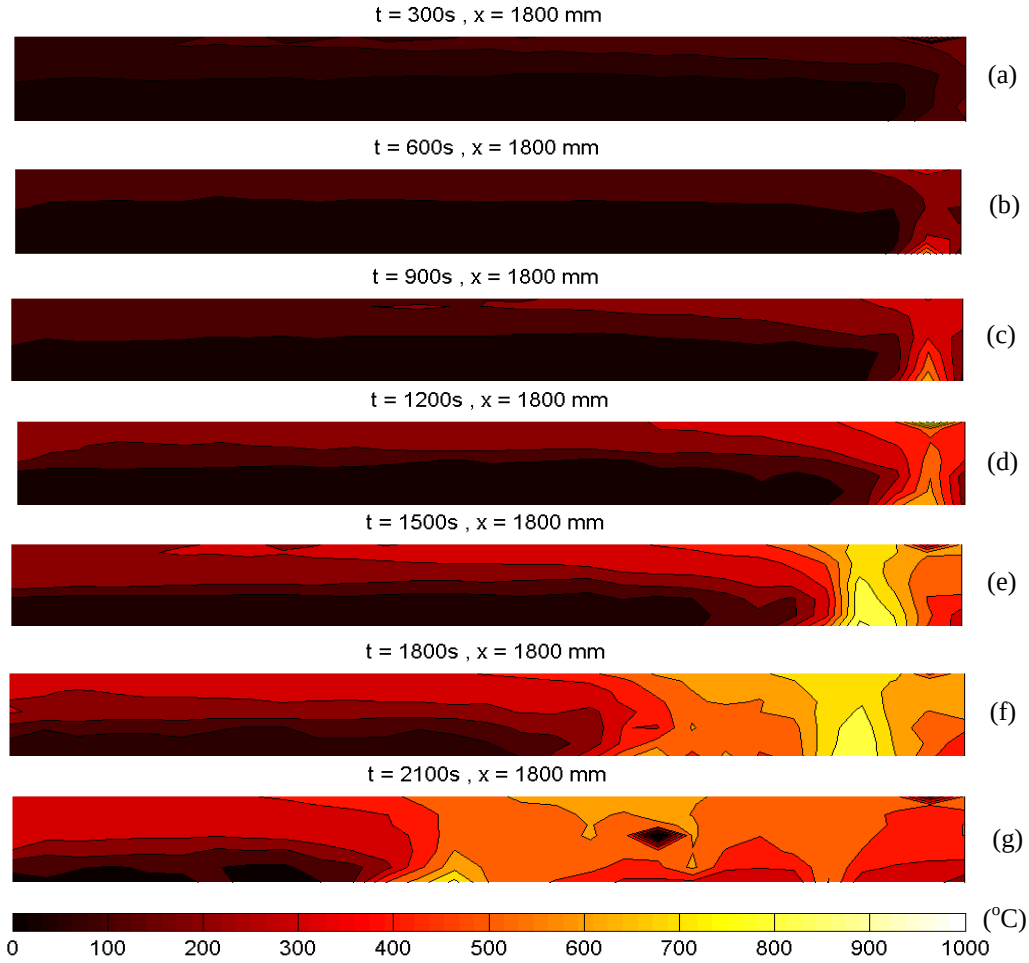


Fig. 7. Temperature distributions along a plane 1800 mm deep and parallel to the open face – the openings were fully open allowing for the maximum evacuation of of smoke and the fuel were wood cribs.

This series of tests shows at each stage conditions very similar to those described by Regime II. These conditions reproduce themselves at each stage of the burning process and the characteristic times scales in the gas phase are short enough that quasi-steady conditions can be established at each stage of the propagation. The burners were ignited at rates consistent with spread rates of typical building fuels, therefore these observations could potentially be extrapolated to fires with realistic materials. While the conditions are similar to those of Regime II fires, the size of the compartment allows for the formation of gradients of temperature not only in the vertical direction but also in the directions parallel to the floor. The data has enough resolution to be able to provide an appropriate boundary condition for structures whose analysis requires spatial distribution.

The rate of ignition of the gas burners as well as the size and location of the openings were varied to establish other potential regimes. The rate of ignition of the burners as well as the size of the fire (i.e. number of burners) did not have a major impact on the nature of the fire in the compartment within the range of conditions studied. A clear smoke layer was rapidly established with the interface dependent mostly on the size of the fire indicating that the capacity of the open face to evacuate smoke exceeded the differences introduced by the changes to the fire. In contrast, as the vents were diminished in size or in number, smoke could not be evacuated and the quasi-steady nature of the process was lost leading to a complex and dynamic interaction between burners and smoke.

An experiment with wood cribs can be used as an example as it encompasses the full potential complexity of the dynamic interaction between the fire, the smoke and the compartment. Figure 7 presents temperature distributions within a plane (1800 mm deep) at different points in time. The fuel is wood cribs and the vents are fully open. The fire was ignited in the right hand corner and allowed to propagate. Initially the ceiling jet propagates across the compartment (Figure 7(a)) until a smoke layer is established (Figure 7(b)). Fire spread is very slow relative to the gas phase processes thus quasi-steady state conditions establish in a similar manner to those presented in Figure 6. As the fire continues to grow the temperature of the smoke layer starts to increase. An important aspect of this is that depending on the size of the fire and the amount of ventilation surface available, the rate at which conditions evolve in the vicinity of the fire is much different to the rate of evolution in the far field (left hand side Figure 7(c)). Furthermore, momentum-driven flows impinging on the walls start affecting the characteristics of the smoke layer (Figure 7(d)). At approximately 1500 second (Figure 7(e)) smoke layer temperatures on the right hand side of the compartment exceed 500^{o}C within approximately a third of the compartment. At this stage rapid ignition of the fuel through almost half of the compartment occurs in a manner that resembles a localized flashover (Figure 7(f)). The fire will continue to burn to the right of the flame front (Figure 7(g)) but the burning rate is maximum at the leading edge of the flame decreasing towards the right of the compartment. For the case where the vents were fully open, the flames continue to spread towards the left of the compartment. Strong air entrainment from left to right and smoke evacuation behind the flame prevented any subsequent instantaneous ignition of the fuel.

The experimental sequence presented above is described only with the purpose of illustrating the complex dynamics of the fire within a large compartment. The different processes explained varied in their significance depending on the ventilation and it was very clear that the temperature distributions were a strong function of the geometry of the compartment. What is clear is that under these conditions the dynamics of the fire correspond to a complex mixture of the limit *Regimes I and II* described by Thomas *et al* [5] and there is no relationship between the overall opening factor $\left(\frac{A_O\sqrt{H_O}}{A}\right)$ and the temperatures or burning rates.

SUMMARY

Upon revisiting the original studies that define the compartment fire framework it is clear that the approach that links an averaged maximum steady state temperature, $T_{g,max}$, and burning rate, R, to an opening factor $\left(\frac{A_O\sqrt{H_O}}{A}\right)$ and an air inflow parameter $\left(A_O\sqrt{H_O}\right)$ respectively, is a simple but robust way to describe the behaviour of a *Regime I* fire. The conditions of a *Regime I* fire are defined by a series of very strong assumptions that guarantee the direct link between ventilation, temperature and burning rate. There is no theoretical link between the opening factor and the gas phase temperature for *Regime II* fires and any experimental evidence of a link is accompanied by great scatter of the data. This is not a new observation, from the very early studies by Thomas *et al*, the scatter of the data within *Regime II* conditions was emphasized.

There is significant experimental data that shows conditions under which the assumptions of the compartment fire framework are not valid but there are no systematic studies that truly address the boundaries of validity of this approach. Therefore, the limits of validity of the methodology are currently unknown.

A critical assumptions associated to the compartment fire framework is the geometry of the compartment. Most of the data that validates the method is with quasi-cubic small (<150 m^3) enclosures. Recent experimental data on well instrumented fires in larger compartments has demonstrated complex behaviour that cannot be described in terms of the compartment fire framework. Many modern building spaces deviate from the small quasi-cubic enclosure therefore there is great need to conduct research that provides physical insight on the dynamics of a fire in complex geometries. High resolution data is necessary for validation of design tools intended to describe the thermal boundary condition for a structure within a fire in a large compartment.

ACKNOWLEDGMENTS

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THE MALVEIRA FIRE TEST: FULL-SCALE DEMONSTRATION OF FIRE MODES IN OPEN-PLAN COMPARTMENTS

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Abstract

This paper presents the characterisation of the fire dynamics in the *Large-Scale Demonstrator Malveira Fire Test*, a full-scale fire experiment carried out in a disused industrial building in Portugal. The Malveira Fire Test is the second stage in the series of full-scale experimental programmes developed for the *Real Fires for the Safe Design of Tall Buildings* project at the University of Edinburgh. This experiment is intended to act as a real-building demonstration of the fire dynamics typical of large open-floor plan compartments and provide a data set for methodologies aiming at design fire inputs representative of real fire dynamics in compartments typical of tall buildings.

The Malveira Fire Test showed three distinct fire behaviour modes characterised by the ratio between the velocities of the fire front (V_s) and the burnout front (V_{BO}); a travelling fire mode with $V_s/V_{BO} \approx 1$, a growing fire mode with $V_s/V_{BO} > 1$ and a fully-developed fire mode with $V_s/V_{BO} \to \infty$. The three modes are found to have a correlation with the incident heat flux onto the surface of fuel caused by the resulting energy distribution within the compartment. A description of the instrumentation and analysis of results are presented to support a theoretical justification for the transitions between fire modes.

Keywords

Enclosure fire dynamics, large-scale experiments, compartment fire framework, tall buildings

1 Introduction

The built environment has seen rapid growth in recent decades as new structures continue to evolve in height, construction materials, compartmental composition and use [1]. This growth shows no sign of slowing as the rate of complex and tall buildings being constructed continues to rise worldwide, with a 402% increase in the number of buildings exceeding 200 m in height in 2017 alone [1, 2]. The forces driving this progression are a combination of financial, political-environmental, and technological factors, which have resulted in significant advancements in construction techniques, cost optimisation, innovative materials, ease of construction, and architectural innovation [1]. One of the key trends of mainstream architecture since as far back as the 1920s is the desire for open, flexible volumes saturated by natural light through multiple large openings [3]. The result of this trend is tall buildings of all occupancies having large open plan compartments.

A thorough understanding of fire dynamics is required so that fire safety engineering principles can adapt to these new rapid developments in construction, consequently providing the overarching objectives of life safety, property protection and business continuity. This understanding is derived from pioneering research predominantly developed between the 1950s and 1990s, brought by the need for more explicit descriptions of the fire environment and engineering methods to assess the performance of fire-resistant partitions and structures. From these works, the *Compartment Fire Framework* was developed, which defined the fire dynamics as a function of restrictions imposed by compartmentation, with limited openings, typical of relatively small compartments [3-4].

At present, the provision of fire-safe designs within tall buildings currently hinges on three essential components [34]:

1. Ensuring effective vertical compartmentation that confines the fire to one floor,
2. Providing structural integrity that extends beyond the burnout of the fuel load, and
3. Maintaining clear egress routes for all occupants.

These three design components strongly rely on the characterisation of the fire dynamics beyond the early growth stage of the fire as the primary input parameter [1]. The *Compartment Fire Framework* still underpins the engineering tools used to quantify all these aspects. In cases where this framework does not apply, the thermal boundary condition imposed on structural systems from the fire is far from being completely resolved [4].

1.1 The Compartment Fire Framework

The origins of fire compartment studies stem from the work of Ingberg in 1928 [5], driven by the high death rate associated with building fires and recognition that they tended to burn until structural collapse [6]. Fire measurements at the National Bureau of Standards (NBS) quantified the duration and intensity of building fires [6], whereas Ingberg's work related these parameters to an equivalent exposure to the standard furnace fire time-temperature curve. Ingberg initiated the pioneering period of fire safety engineering research, which formed the basis of the *Compartment Fire Framework*. The main objective of these key studies was to characterise the behaviour of fully-developed fires within compartments in order to

define the thermal loads for structural assessment. Fujita and Kawagoe's early work [7-9] realised the limitations of the fire resistance test and established that the compartment fire characteristics and their surroundings (i.e. geometry, fuel, ventilation etc.) are intrinsically linked, resulting in a very complex interaction in the event of a fire [10].

Due to the complexity of the coupling between compartment fire dynamics and the compartment itself, the need for simplifications was recognised in order to quantify behaviour for design purposes. This was achieved by Thomas and Heselden [11], who demonstrated that, for a specific range, the compartment and opening geometries completely govern the physical behaviour of the fire as the fire is controlled by the inflow of air into the compartment. Beyond this specified range, the openings are considered sufficiently large enough to no longer be a governing factor. Thus the amount of fuel surface available governs the fire. The former was labelled *Regime I* (ventilation-controlled) fires and the latter *Regime II* (fuel-controlled) fires. The traditional understanding of these fire regimes was expanded on by Harmathy [12], and further revised more recently by Majdalani [3]. A *Regime I* fire compartment fills with smoke due to the limited ventilation, causing rich combustion and high soot concentration. Flow within the compartment is dominated by the expansion of hot gases, allowing to neglect mass and momentum transfer. A key characteristic of *Regime I* fires is that the compartment exhibits high, uniform temperatures and openings must allow for the transfer of mass that is driven by the hydrostatic pressure difference between the inside and outside of the compartment [4]. A *Regime II* fire is also fully-developed, however, it is dictated by the fuel surface area available for combustion. Large openings allow for air exchange with the outside, allowing for high momentum buoyant flows that hinder the correlation between ventilation and fuel burning rate [3]. The significant momemntum prevents the retention of smoke and results in the lack of a smoke layer. Internal temperatures are therefore generally lower.

The *Compartment Fire Framework* in its current form focuses on *Regime I* fires. Researchers, through increased simplifications, were able to articulate it theoretically and the data obtained from testing showed more clear trends in comparison to the large scatter that was associated with results from *Regime II* experiments. Furthermore, due to the higher temperatures observed in the *Regime I*, this was deemed the most 'severe' category for the structure. Advancements in research have typically exclusively focused on characterising the energy exchange and burning rates within a compartment as functions of the opening geometry [4]. Tools were then developed, allowing for rapid application of 'conservative' bounding thermal loads to structural design, which have been integrated into design standards and building practices globally [14]. *Regime II* fires, being more complex, have not been researched and developed theoretically. The *Regime I* design methods assume a worst-case uniform temperature, which is much higher than the range of possible temperatures of *Regime II* fires. The lack of correlation between the actual fire behaviour in open plan compartments and current design fires may lead to inadequately designed structures [13].

Architectural evolution has led to tall, open-plan structures with interconnected compartments being the norm. Nevertheless, as the fire design strictly depends on compartmentation, a clear disparity between contemporary infrastructure and definitions of

compartment fire dynamics has arisen. While fire characteristics of *Regime II* fires have historically been deemed less severe, in contemporary open-plan infrastructure, smoke and therefore heat can be transferred away from the fire yet still remain within the building. It will consequently continue its exchange of energy with the structure and unburnt combustible materials, even in areas that are remote from the fire. This introduces a possibility of spatially variant energy distributions within large compartments, which modern structural fire engineering has shown that can introduce complex thermally induced forces within a structural system, even at lower temperatures [15]. Such loading conditions are not considered by traditional approaches to establishing structural performance under thermal loading. [16].

The more widespread distribution of generated heat can lead to fires in large compartment exhibiting behaviour referred to as "travelling fires", where fuel is burned over a limited area and spreads across the floor plate [17]. Travelling fire theory assumes two regions in the compartment – the near field and the far field. The near field refers to the region where the fire itself is located, while the far field is the areas remote from the fire. These two regions are assumed to remain constant in size but 'travel' through the compartment as the flame spreads and fuel is consumed [18].

Calculation methods to approach "travelling fire" behaviour have been developed in the last decade, e.g. the travelling fires methodology [18-21]. As opposed to [17], where a temperature distribution was extracted from a Computational Fluid Dynamics calculation, these later studies [18-21] employ different correlations and simplified approaches towards defining spatial temperature histories. While this approach allows for a more practical application of the "Travelling Fires" concept, it relies on many assumptions and simplifications that have still not been fully validated with adequate experimental data.

1.2 Real Fires for the Safe Design of Tall Buildings

In recent years, the University of Edinburgh undertook the *Real Fires for the Safe Design of Tall Buildings* (RFSDTB) project, which aimed at producing a methodology that could be used to provide design fire inputs representative of real fire dynamics in large open-plan compartments typical of tall buildings. The RFSDTB project consisted of two series of full-scale experimental programmes, the *Edinburgh Tall Building Tests* and the *Large-Scale Demonstrator Malveira Fire Test*.

In 2013, the Edinburgh Tall Building Tests (ETFT) programme was carried out at the Building Research Establishment, Watford, United Kingdom [22]. The first stage of tests (Jan-May 2013) consisted of gas burner tests in a compartment of internal dimensions 5 m (width) x 18 m (length) x 2 m (height), and where different fire and ventilation modes were replicated. The second stage (May-June 2013) consisted of two wood crib tests in the same compartment with two different static ventilation conditions. The gas burner tests provide characteristic energy distributions for different fire and ventilation modes with precribed energy input (heat release rate). Three different fire modes were studied based on the relationship between the spread velocity of the fire front (V_s) and the spread velocity of the burnout front (V_{BO}):

1. Mode 1: a fully-developed fire where $V_s/V_{BO} \rightarrow \infty$.

2. Mode 2: a growing fire where $\frac{V_s}{V_{BO}} > 1$.
3. Mode 3: a travelling/moving fire where $V_s/V_{BO} \approx 1$.

Three ventilation modes where studied based on the inverse opening factor ($\phi' = \frac{A_T}{A_w\sqrt{H}}$):

1. Static ventilation with $\phi' = 4.1$.
2. Static ventilation with $\phi' = 23.3$
3. Variable with the inverse opening factor transistioning from $\phi' = 23.3$ to $\phi' = 4.1$ (indicating increasing opening area as would be the case with window breakage).

Preliminary results from energy distribution analyses applied for the gas burner stage have been presented by Maluk et al. [23]. These clearly indicate different characteristic energy distributions within the compartment for the aforementioned fire modes and ventilation conditions.

In 2014, a full-scale fire experiment was carried out in a disused industrial building in Póvoa da Galega, Malveira, Portugal. The purpose of this test was to reproduce an open-plan compartment fire within a real building of a similar configuration to the ETFT gas burner stage. This paper describes the experimental compartment in the *LSD Malveira Fire Test*, including installed sensors array, main results and an initial analysis of the experimental output data. Data will be made available through the University of Edinburgh Data Share repository (https://datashare.is.ed.ac.uk/handle/10283/3109) along with data from the *Edinburgh Tall Buildings Fire Tests*.

2 Description of the compartment

The compartment selected for the experiment was originally an office within the building. At the time of the experiment, the compartments of the building were used by the Fire Service of Malveira (Bombeiros Voluntários da Malveira) to practise firefighting techniques and observe fire growth phenomena. The office compartment was selected for this experiment due to its similarity in dimensions and opening characteristics to previous purpose-built experiments from this project [22]. The building was constructed as a concrete frame with masonry block infill. The layout and dimensions of the compartment are described in detail in the following sections.

2.1 Overview, dimensions and coordinate system

The internal dimensions of the experimental compartment were approximately 4.7 m (depth), 21.0 m (length), and 2.85 m (height). In places there were protrusions into this space due to beams, columns and fittings. The compartment along with details of these protrusions are presented in Figure 1. The origin of the coordinates system used to describe locations within and around the compartment is in the rear left corner of the compartment as viewed from the outside looking in (refer to Figure 1). The average floor to ceiling height prior to installation of a false floor (described later) was 2850 mm. This is not inclusive of a 100 mm deep layer of cork insulation covering approximately 60% of the ceiling. This layer was on the right-hand side of the compartment as shown in Figure 1b.

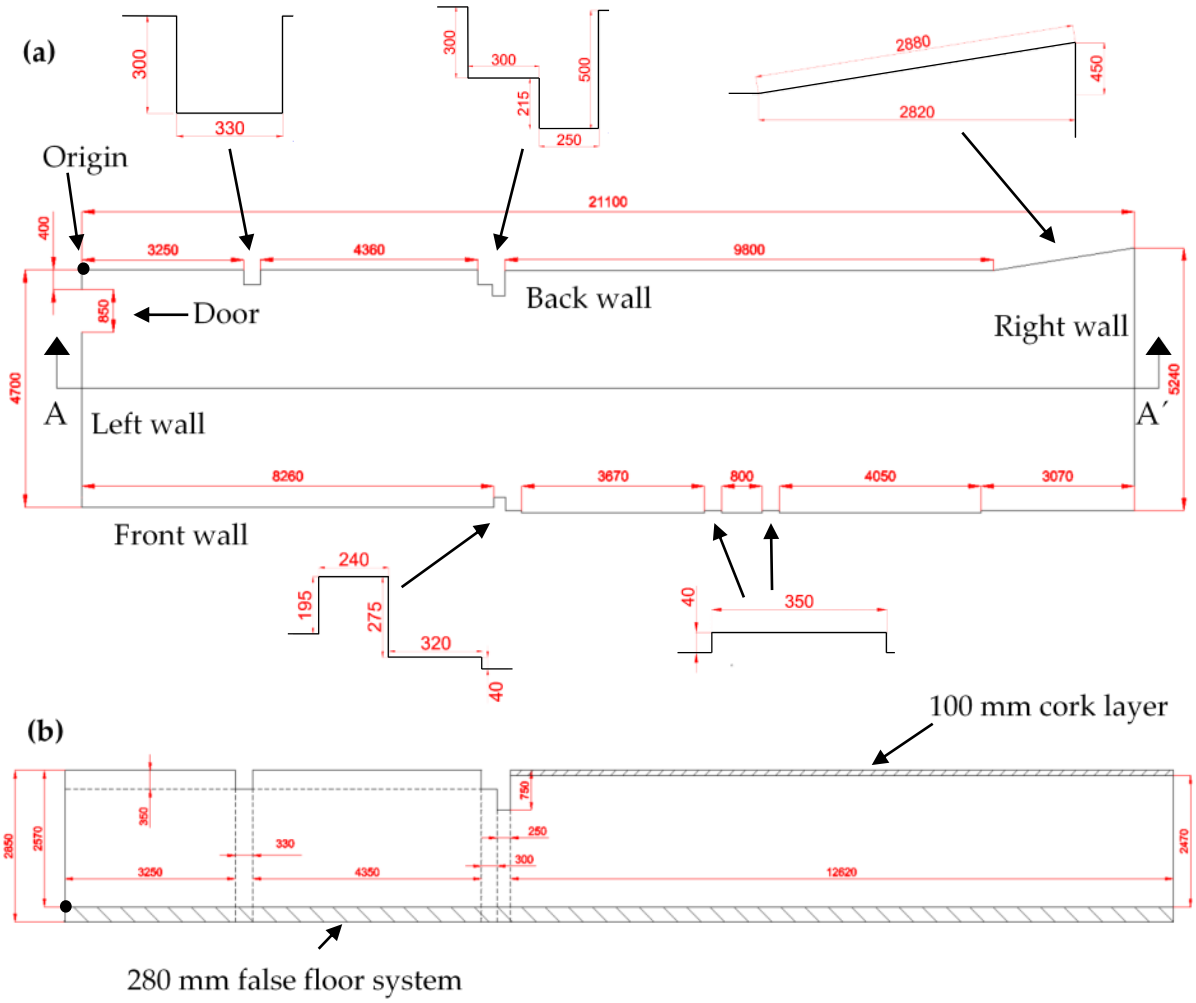


Figure 1. (a) The central diagram shows the floor plan of the compartment with overall dimensions. Surrounding diagrams give details of columns and other protrusions and shape irregularities. (b) Front view, section A-A´: Dashed lines indicate positioning and dimensions of concrete columns and beams against back wall. The layer of cork and false floor are represented as hatched areas.

2.2 Positioning and dimensions of the openings

The primary openings were formed by five windows of varying dimensions, located along a single long wall of the compartment. The positioning and dimensions of these windows are shown in Figure 2. There was one further opening formed by a door. This door was initially closed, however, it was opened during the test to encourage a concurrent flow through the fire and over the fuel bed, and thus encourage more rapid fire growth. The position of this door is shown in Figure 1 and Figure 5 (c). The door opening was 0.85 m wide and 1.72 m high. All other original openings to the compartment were sealed and remained so throughout the test.

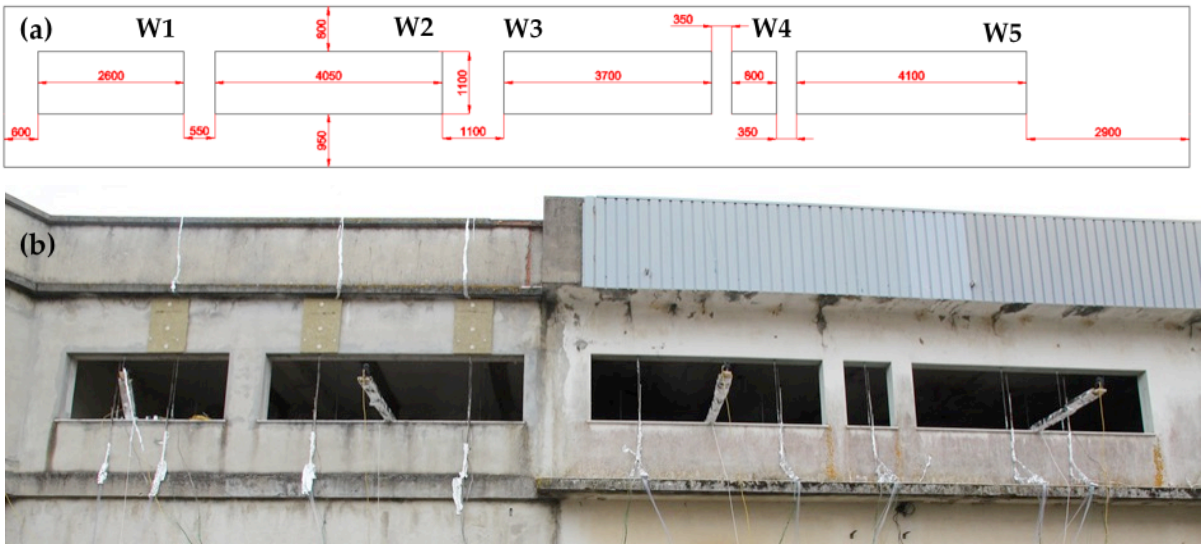


Figure 2. Elevation of the front wall as viewed from outside the compartment. (a) Sketch with location and dimensions of the windows. (b) Picture of the external view of the compartment. External TSCs are present on the façade above windows 1 and 2.



Figure 3. View of the openings W5 (a), W4 and W3 (b) and W2 (c) from inside the compartment. Internal TSCs are visible above and below the openings.

2.3 Floor plan and floor system

The dimensions of the floor of the compartment are shown in plan in Figure 1. A false floor system was designed to enable mass loss measurements whilst maintaining a level floor throughout the compartment. The total height of this false floor system was 280 mm. The floor layer consisted, from top to bottom, of 100 mm of ROCKWOOL CONLIT™, a 10 mm plasterboard, and a 20 mm particleboard. When supported by a mass loss scale, the floor system was attached to a wooden frame that supported the floor 50 mm above the surface of a 100 mm deep mass loss scale. The frame system enabled passage of air beneath the floor and all around the mass loss scales in order to insulate and provide cooling. Elsewhere, the floor layer was supported by evenly distributed feet consisting of 50 mm of ROCKWOOL CONLIT™ and 100 mm deep masonry bricks, again to allow air to circulate beneath. The global height coordinate z = 0.0 m is level with the top of the false floor. Mass loss scales supported floor platforms with dimensions of 1.2 m x 2.4 m. The distribution of floor platforms is shown in Figure 4. The final compartment effective height was thus 2570 mm in the area without cork and 2470 mm in the area with cork.

3 Description of the sensor arrays

A large number of sensors were provided within the experimental compartment and on the external façade. These were designed with the aim of characterising the fire environment at a spatial resolution that enables the benchmarking of tools and or methodologies developed by the RFSDTB project, while at the same time considering the physical and time constraints implied by working within an existing, partially derelict building.

3.1 Gas-phase temperature

1.5 mm bead K-type thermocouples were used to establish the spatial and temporal gas-phase temperature fields inside the compartment and in each of the openings. A total of 24 thermocouple trees, in three rows of eight trees, with each tree containing eight thermocouples were evenly spaced throughout the interior of the compartment. Each tree had thermocouples at 0.77, 1.07, 1.37, 1.67, 1.87, 2.07, 2.27 and 2.42 m above false floor level (z = 0.0 m). The spacing and locations of these internal trees are shown in Figure 4a. A further nine thermocouple trees were located in the window openings. Each of these trees contained five thermocouples at heights 0.15, 0.35, 0.55, 0.75, and 0.9 m above the window ledge, which corresponds to heights 0.82, 1.02, 1.22, 1.42 and 1.57 above the false floor level (z = 0.0 m). The locations of these trees are shown in Figure 4b.

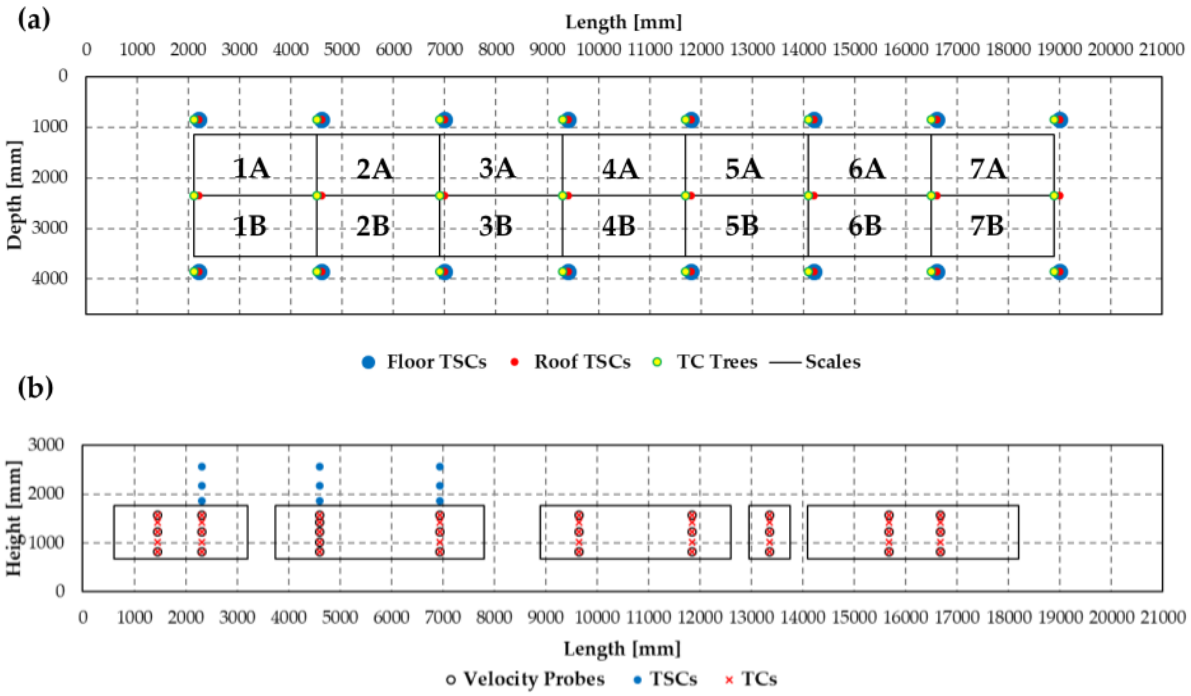


Figure 4. (a) Diagram showing floor, ceiling, gas-phase sensor locations and platform (1A – 7B) outlines. (b) Diagram showing the window and façade sensor locations.

3.2 Incident radiant heat flux

As per previous experiments in the RFSDTB project [22], thin skin calorimeters (TSCs) were used to quantify incident radiant heat flux to solid surfaces. A total of 93 TSCs were located on all internal surfaces of the compartment, with further nine mounted in three columns of

three gauges on the façade above windows 1 and 2. The layout of these TSCs are shown in Figure 5. The external TSCs are shown in Figure 7b.

The TSCs comprised a 10 mm diameter, 0.5 mm thick 304b stainless steel plate, with a KX-type thermocouple welded to the centre of the unexposed face. The plate was embedded in a 80 mm diameter, 25 mm deep Superwool® HT disc. The thermocouple wires pass through the Superwool® HT and exit through the rear. The design was such that a corresponding hole could be cored from the compartment wall, ceiling or floor and the Superwool® HT with TSC imbedded inserted, leaving the TSC flush with the surface of the wall, floor or roof. The calibration of these gauges is given by Hidalgo *et al.* [24].

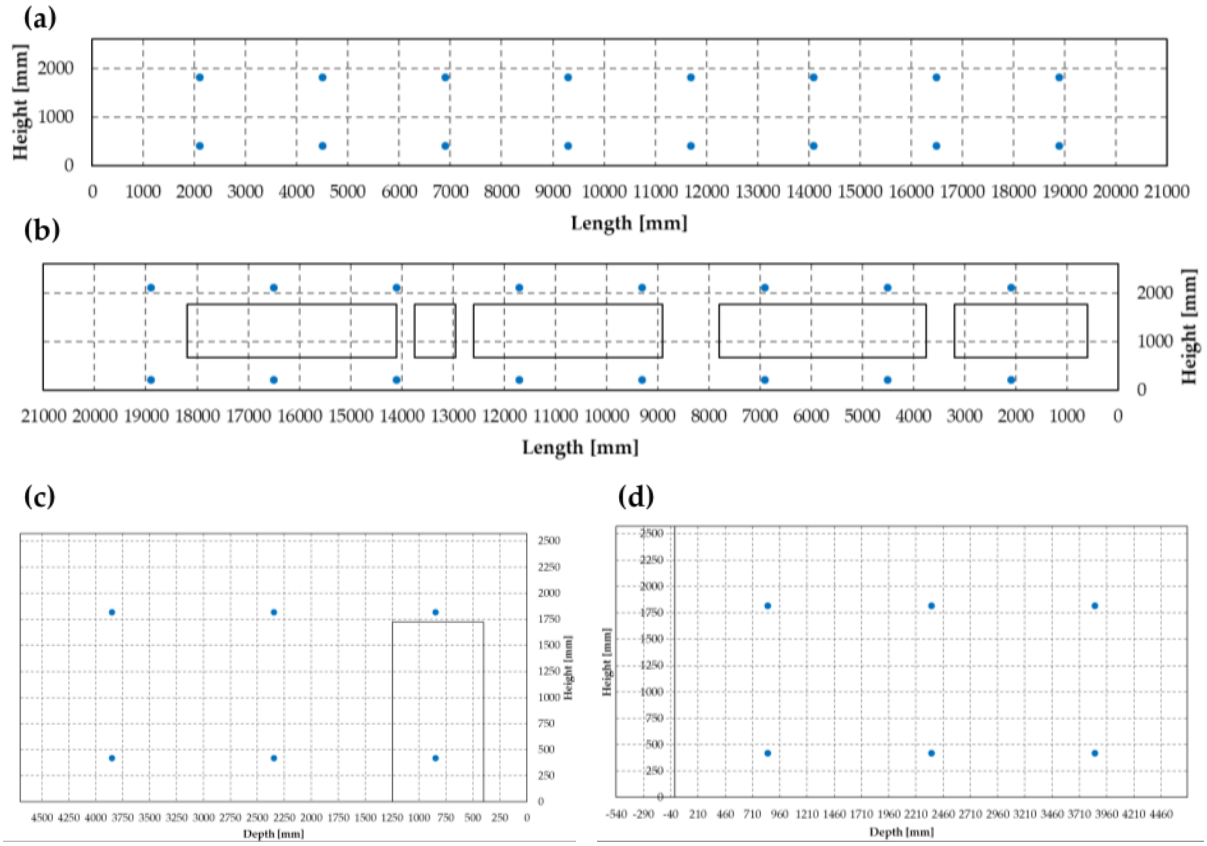


Figure 5. Diagram showing TSC locations on (a) back wall, (b) front wall, and (c) left-end wall and (d) right-end wall.

3.3 Mass loss

A total of 14 scales were distributed beneath the fuel bed to measure mass loss from the wood cribs used as the design fuel load. The scales were a bespoke design for this test, designed, constructed and installed by LEVANTINA DE PESAJE LABORATORIO, S.L.. Each scale was 1 m x 1 m x 0.1 m high and supported a 1.2 m x 2.4 m false floor platform. The arrangement of these platforms and installation are shown in Figure 4a and in Figure 6, respectively. The maximum load capacity of each scale was 300 kg with an expected accuracy in the reading of ± 20 g. The scales were calibrated on-site before the test.



Figure 6. (a) View of the floor from the left end of the compartment, with all the scales in place ready to hold the false floor platforms. (b) View of the floor on the right end of the compartment, with some scales holding the 1.2 m x 2.4 m platforms for the false floor.

3.4 Gas flow velocity at the openings

A total of 29 bi-directional velocity probes [25] were distributed between each of the windows to characterise gas in- and out-flow. The locations of the probes corresponded to the thermocouple trees located there and sit above the external edge of the window sill. Each thermocouple tree location had three corresponding velocity probes except for one which had five velocity probes in window 2. Where three probes were present, they corresponded in height to the upper, middle and lower thermocouples of the window trees. The single location with five probes had a probe at each of the heights of the thermocouples in the corresponding tree. The specific positioning of each probe relative to the windows is shown in Figure 4b. A representation of the system used to install the pressure probes is shown in Figure 7.



Figure 7. (a) Window 1 showing the arrangement of bi-directional velocity probes and the cantilever system for the external network cameras. (b) View of the windows with bi-directional velocity probes and external network cameras, and the façade with thin skin calorimeters above windows 1 and 2.

The bi-directional velocity probes were connected to differential pressure transducers. The set probe-transducer has recently been calibrated in a wind tunnel facility. Detailed results from

these calibrations are presented by Gupta et al. [26]. The relation between velocity and voltage output from the transducers is shown in Figure 8 below.

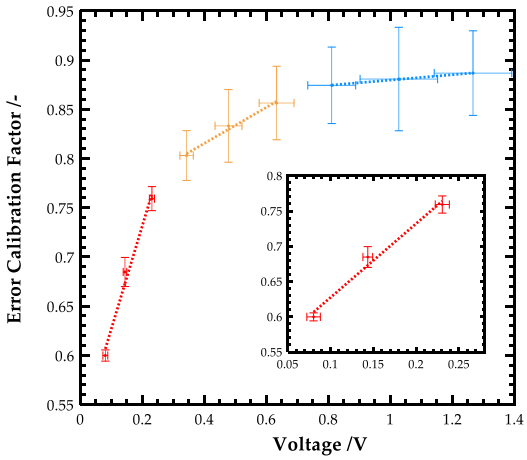


Figure 8. Correction factor for the bi-directional velocity probe and differential pressure transducer setup [26].

3.5 Video imaging

A total of eight network cameras were employed to capture video footage of the experiment. A camera was embedded in each of the end walls looking along the length of the compartment. To enable analysis of the fire and burnout front position, cameras were also placed to look in through each of the four large windows (refer to Figure 7b). These cameras were mounted to an insulated wooden beam cantilevered approximately 2 m out from the corresponding window sill. Two final cameras were positioned on the external façade of the compartment looking along the face of the openings. These cameras were positioned at mid window height in order to provide visual confirmation of neutral plane heights. Further to the network cameras, a digital video camera and a thermal imaging camera were setup on the roof of a building in front of the experimental compartment to provide an overview of events inside the compartment and fully capture any smoke and flames emerging from the compartments front openings.

3.6 Data logging

Data logging was performed by two Agilent 34980A Switch/Measure Units, equipped with 34925A 40/80 Channel Optically Isolated FET Multiplexer modules. Each data logger was fitted with a 4-wire RTD in order to provide an external reference temperature for the thermocouples and connected via LAN cable to a unique PC to ensure that any computer issues had minimal impact on the amount of data recorded. Two PCs were assigned to log data from eight network cameras and a laptop was provided to record data from the thermal imaging camera. A final PC was associated to a bespoke data logging system for the mass loss scales. The bespoke system was designed and installed by LEVANTINA DE PESAJE LABORATORIO, S.L.

4 Fuel, ignition and opening factor

The fuel used in this experiment was wood cribs of Pinus Pinaster, with an assumed density of 510 kg.m^{-3} and a heat of combustion of 18 MJ.kg^{-1} [27]. The intended fuel load was approximately 420 MJ.m^{-2}, average design fuel load for an office according to EN 1991-1-2 [13]. The fuel bed was comprised of three full layers and one-half layer of Pinus Pinaster sticks. Each stick was 1.2 m long with a 5 cm x 5 cm cross section. In full layers, sticks were spaced at 5 cm thus each full layer was comprised of 10 sticks per metre length of fuel bed. In the half layer, sticks were spaced at 15 cm giving 5 sticks per metre run. The overall fuel bed size was 16.8 m long x 2.4 m wide as shown in Figure 9.



Figure 9. The image shows the arrangement of the beams and columns protruding into the experimental volume. It shows the fuel bed with the ignition fuel tray highlighted in red.

Moisture content measurements taken on the day of the experiment suggest an average moisture content of the individual sticks of 19% ± 6%. The average moisture content for the crib measurements along the approximated crib weight on each platform is shown in Table 1.

Table 1. Estimated mass and moisture content measurements for the wood cribs on each platform. Three data points per platform were taken for moisture measurements.

1A	**2A**	**3A**	**4A**	**5A**	**6A**	**7A**
153.7 kg	158.1 kg	166.6 kg	167.9 kg	174.3 kg	166.5 kg	158.7 kg
17% ± 2%	20% ± 5%	22% ± 13%	13% ± 1%	15% ± 1%	16% ± 2%	15% ± 3%
1B	**2B**	**3B**	**4B**	**5B**	**6B**	**7B**
158.0 kg	170.8 kg	164.1 kg	167.2 kg	171.1 kg	159.8 kg	169.7 kg
18% ± 1%	23% ± 12%	20% ± 4%	28% ± 13%	18% ± 4%	16% ± 2%	19% ± 1%

In addition to the wood crib, the only other fuel source available in the compartment was the 100 mm cork layer attached to the ceiling on the right-hand side of the compartment (Figure 1b). The cork layer was an energy efficiency feature of the building. It was decided not remove it in order to provide a different boundary condition which could induce a change in fire mode due to lower heat losses or heat release contribution.

Thermogravimetric studies on the wood and cork were applied to characterise the volatile content and yield residue of both materials. These were tested with a heating rate of 20°C.min^{-1} in three conditions: air, nitrogen, and air after testing in nitrogen. The normalised mass and derivative of the normalised mass versus temperature are presented in Figure 10 below. In nitrogen tests, it is shown that both wood and cork provide a char yield of approximately 20%. The char appears to oxidise above 450°C, whereas the pyrolysis reactions are approximately observed within 200-400°C for wood and 250-450°C for cork. This indicates that pyrolysis and condensed-phase oxidation reactions occur in different domains, thus the burning of both the wood and the cork are identified as very similar charring burning fuels. Additionally, these fuels show similar heat release rate per unit area (120 - 206 kW.m^{-2} for cork [29] and 54 – 177 for Radiata Pine [30]). The differences between the cork and wood fuel are the exposed surface area (much larger in the wood crib) and the material density and thermal conductivity (160 kg.m^{-3} for cork and 430-640 kg.m^{-3} for pine; 0.043 W.m^{-1}.K^{-1} for cork and 0.112-0.147 W.m^{-1}.K^{-1} for pine according to Table A.28 in [28]). Therefore, a lower burning rate is expected from the cork, however, the lower thermal inertia of cork (insulation) implies a faster ignition and flame spread [31, 32].

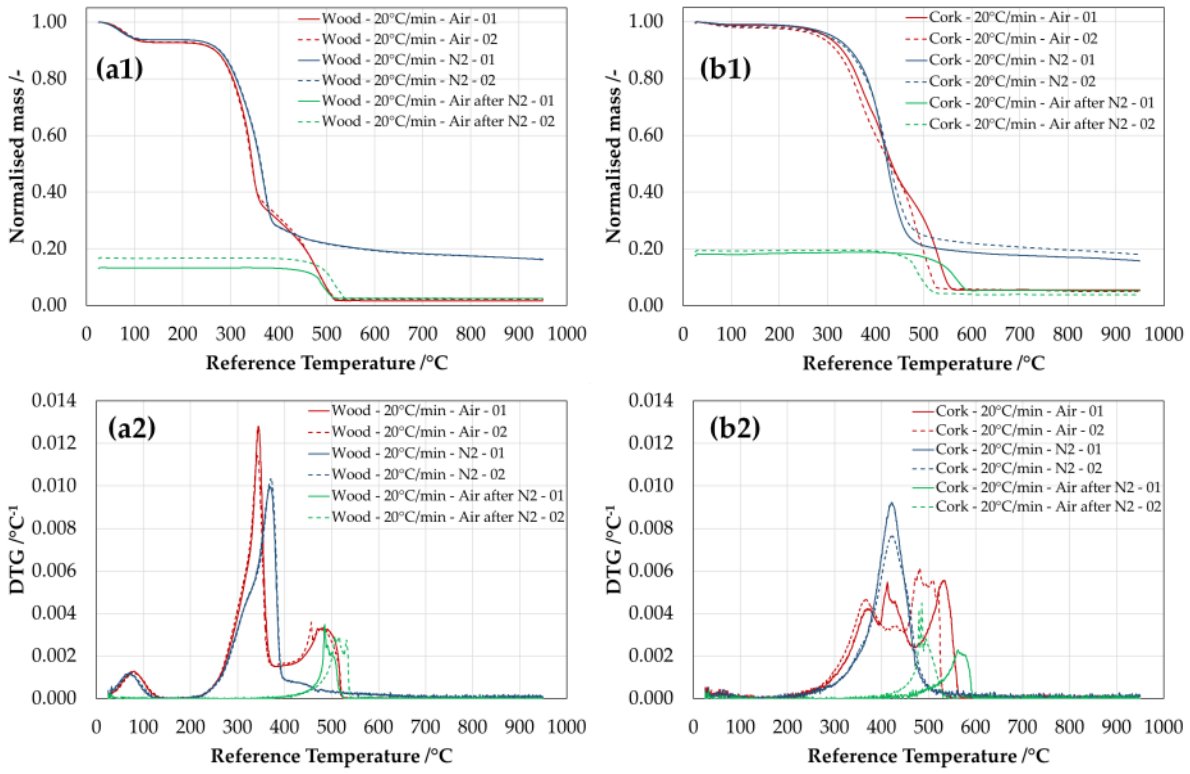


Figure 10. Thermogravimetric analyses of wood (a) and cork (b) used in the test. Plots on the top indicate the normalised mass versus temperature, whereas plots on the bottom

indicate the derivative of the normalised mass versus temperature. Tests were carried out in air, nitrogen, and in air after decomposition in nitrogen at 20°C.min^{-1}.

Ignition of the wood crib was achieved through a 2.4 m line fire. A mixture of 5 litres of kerosene and 0.5 litres of diesel fuel was placed in a 2.4 m long x 10 cm wide and 5 cm high metal tray. This tray was placed at the start of the crib in place of the lowest two sticks, shown highlighted in Figure 9. A blow torch was applied to the liquid fuel mixture until ignition was achieved.

Table 2 shows the inverse of the opening factor calculated for the compartment under different assumptions. For all cases, it is shown that the inverse of the opening factor is below 10 m$^{-0.5}$, where Regime II fires are generally identified.

Table 2. Estimated opening factor for the compartment under different assumptions such as considering the compartment as a whole or separated sections divided by the central 500 mm deep beam dividing the two areas with different ceilings.

Compartment	**Inverse opening factor $\phi' = \frac{A_T}{A_w\sqrt{H}}$ (A_T excludes floor and openings) /m$^{-0.5}$**	**Inverse opening factor $\phi' = \frac{A_T}{A_w\sqrt{H}}$ (A_T excludes wood crib and cork surfaces and openings) /m$^{-0.5}$**	**Inverse opening factor $\phi' = \frac{A_T}{A_w\sqrt{H}}$ (A_T excludes only the openings) /m$^{-0.5}$**
Overall compartment	4.6	6.4	9.5
Left-hand side compartment	4.6	5.9	6.6
Right-hand side compartment	3.4	5.3	10

5 Results

A set of characteristic results that provide an overview of conditions throughout the experiment are presented.

5.1 Principal events and visual analysis of the evolution of the fire

After ignition the fire grew at a slow rate, continuing to travel at an apparent constant rate throughout the left-hand side of the compartment. This was visually confirmed with the fire front and burnout front displacing at a slow rate. The flame height was not uniform along the depth of the compartment. At 148 min after ignition, the door on the left wall of the compartment was opened in order to study whether lateral flow would accelerate the fire front spread velocity. After the door was opened, the computer system shut down, thus interrupting the data logging system. The problem was solved approximately 5 min later, resuming data logging. As the travelling fire approached the beam that differentiated the compartment with and without cork on the ceiling, the fire appeared to grow in size as the flames were apparently larger. After reaching the beam, it was observed that the cork

insulation ignited and soon after the flame on the cork spread vigorously. The fire front on the crib then experienced a quick acceleration; soon the whole wood crib on the right-hand side of the compartment was burning. External flaming was then observed. After two minutes manual extinction was applied by the Fire Service due to the potential risk of collapse of the building. Several instances of spalling were observed from the wall linings and beams.

A list of the major events observed in the test is provided in Table 3 below. Based on these events and the data obtained from the experiments, five distinct time domains are defined to ease the interpretation of results and fire behaviour. The timeframe for each domain is selected based on the trends observed in the burning rate presented in further sections.

Table 3. List of principal events observed in the test and time domains for analysis.

Event	Time	Analysis time domain
Ignition	0 min 0 s (13:10:47)	Domain I (0-19 min)
Burnout front starts to develop	21 min 22s (13:32:09) (estimation)	Domain II (19-152 min)
Opening of door	147 min 57s (15:18:44)	
Generator shut down – data logging stopped	201 min 23 s (16:32:10)	Domain III (152-237 min)
Generator turned on – data logging resumed	206 min 59 s (16:37:46)	
Fire front reaches central frame	224 min 42s (16:56:09)	
Ignition spotted on cork ceiling	228 min 21s (16:59:19)	
Rapid flame spread on the ceiling	237 min 11s (17:07:58)	Domain IV (237-238 min)
Rapid flame spread of the wood crib	237 min 53s (17:08:40)	
External flaming	238 min 0s (17:08:47)	
Extinction by Fire Service	241 min 6 s (17:11:53)	Domain V (238-242 min)

Figure 11 shows the different events and stages of the fire captured from the exterior with video and SLR cameras.



Figure 11. Sequence of images from the front video and SLR camera. (a), (b) and (c) show the travelling fire mode. (d) shows the ignition and fire spread of the cork insulation. (e) shows transitioning to a fully-developed mode as shown in (f).

Using the video footage from the front cameras and a video image processing technique [33], the position of the fire and burnout fronts are estimated for the whole duration of the test (Figure 12a). The length of the fire is calculated as the difference between the positions of these two fronts. Assuming that the fire spread and burned out uniformly along the width of the crib (2.4 m), the length and size (area) of the fire can be estimated (refer to Figure 12b). From the five distinct time domains defined in Table 3, Figure 12 shows clear different growth rates:

- Domain II with 2 mm.min^{-1} (0.005 m^2.min^{-1}), corresponding with the definition of Mode 3 ($V_s/V_{BO} \approx 1$);
- Domain III with 28 mm.min^{-1} (0.067 m^2.min^{-1}), corresponding with the definition of Mode 2 ($V_s/V_{BO} > 1$); and
- Domain IV with 1686 mm.min^{-1} (4.046 m^2.min^{-1}), corresponding with the definition of Mode 1 ($V_s/V_{BO} \to \infty$).

The growth rates for domains I and V are not assessed as for domain I the burnout front was not established yet, whereas for domain V all the wood crib was burning. It should be noted that the chosen trend lines fudge other trends in smaller time scales, e.g. the fluctuations in domain III. Despite the fudging effects, this approach is preferred for easier interpretation of results.

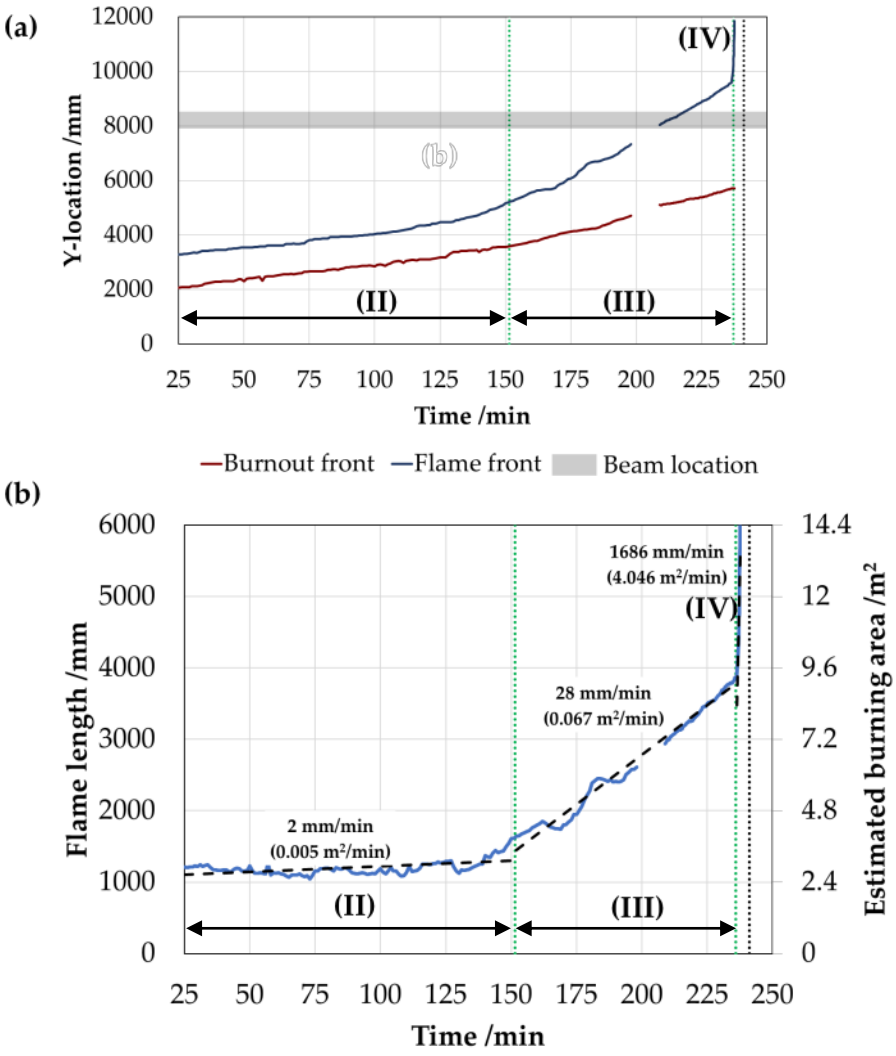


Figure 12. (a) Position of the fire and burnout front obtained with image processing techniques using video footage from network cameras located at the windows. The shading area corresponds to the location of the beam that separates the region of compartment with different ceilings. (b) Estimated length and size of the fire, based on the assumption that the fire grows uniformly along the width/depth of the compartment.

5.2 Mass loss

Figure 13 shows the normalised readings of each of the 14 scales, with 1A and 1B corresponding to the ones on the left-hand side of the compartment next to the wall and next to the window, respectively. The data have been cleaned so that increase of mass due to debris falling onto the scale is minimised. Until 125 minutes, it is shown that only the fuel on 1A and 1B decreases. The mass loss follows a linear decrease, suggesting a steady burning rate. It is also observed that, up to 58 minutes, 1A and 1B experience similar mass loss, however, the burning rate of 1B is slightly higher afterwards. From 125 minutes to 160 minutes, the wood cribs on 2A and 2B appear to be burning along with 1A and 1B, which burn at a very low rate probably experiencing smouldering. After 170 minutes, the wood cribs 1A and 1B appear to be almost completely consumed; instead, 2A and 2B show a linear decrease, suggesting again

a steady burning rate. Although 2A initially shows a lower burning rate, after 160 minutes it appears to be faster than 2B. After 195 minutes, the cribs 3A and 3B start to burn with the same pattern as shown by the previous pair of cribs. It is clearly shown that the slope of 3A and 3B is larger than the slope of 2A and 2B, and the slope of these is larger than 1A and 1B. 3A is also shown to burn much faster than 3B, presumably due to higher radiant feedback as 3A was closer to the wall whereas 3B was closer to the window (refer to section 5.4). After 238 minutes the rest of the cribs start to lose mass significantly faster and at a higher rate, as shown by the drastic loss of mass. This transition is more clearly shown in Figure 13b. At 241 minutes a sudden increase of mass is shown, corresponding to the manual extinction by the Fire Service.

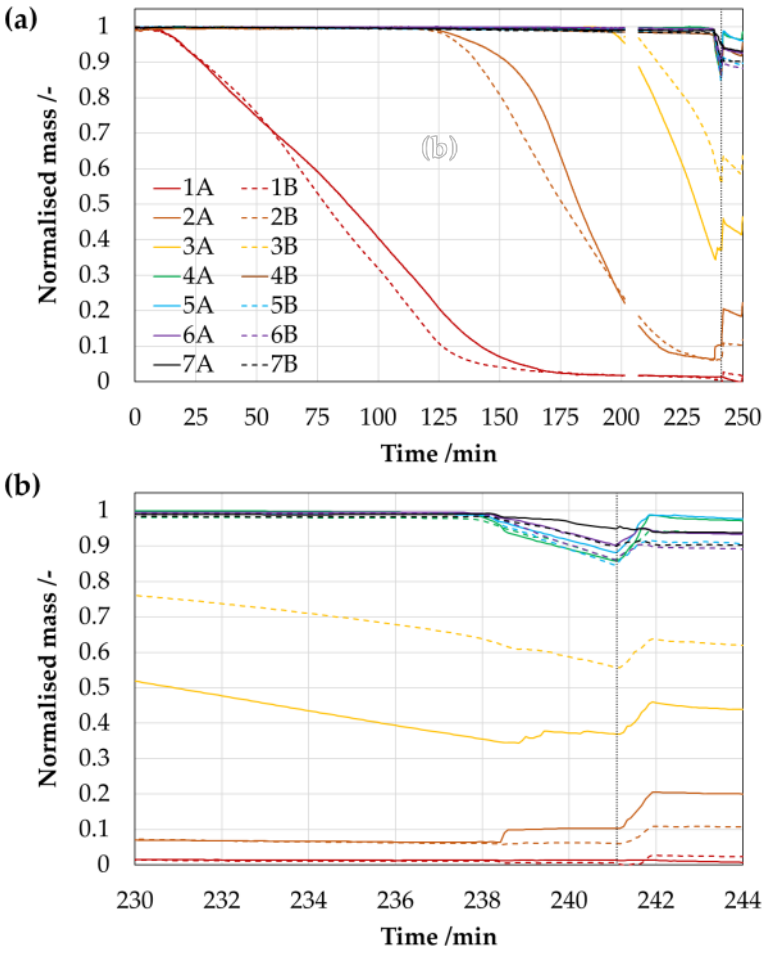


Figure 13. Normalised mass for each platform for (a) the whole duration of the test and (b) for a zoom in at 230-244 minutes. Extinction is shown as a vertical dotted line.

In order to establish a clear burning rate of the overall wood crib fuel in the compartment, Figure 14 shows the total mass loss rate from the wood cribs. Figure 14a shows the five clear domains with significantly different burning rates. These domains are denoted visually with vertical dotted lines. The 'slope' of the burning rate is used to represents the rate of change in the burning rate, which theoretically correlates to the increase of burning surface area as

shown in Figure 12. Note that the odd choice of units, $g.s^{-1}$/min, is justified to provide a better interpretation of the variation in burning rate (normally expressed in $g.s^{-1}$) for a long duration test (easily expressed in minutes).

- **Domain I (0 – 19 min):** an initial peak up to 4 minutes, related to the kerosene-diesel mixture, and a growth up to 19 minutes (refer to Figure 14b).
- **Domain II (19 – 152 min):** from 19 minutes until 152 minutes, the burning rate is lightly increasing from 36 $g.s^{-1}$ to 55 $g.s^{-1}$, thus a rate of 0.14 $g.s^{-1}$/min (refer to Figure 14b).
- **Domain III (152 – 237 min):** after 152 minutes the burning rate experiences a faster acceleration followed by a deceleration; this cycle is observed twice during this period and it is believed to be caused by the varying moisture content of the wood crib in different regions (see Table 1). However, a global (average) linear increase rate of 0.47 $g.s^{-1}$/min can be observed. The region corresponds to the fuel from the pairs {2A,2B} and {3A, 3B} (refer to Figure 14b).
- **Domain IV (237 – 238 min):** at 237 minutes the burning rate accelerates significantly with an approximated rate of 298.35 $g.s^{-1}$/min (refer to Figure 14c).
- **Domain V (238 – 242 min):** a peak mass loss rate of 1.3 $kg.s^{-1}$ is observed at 238 min, with a stabilisation of the mass loss rate around 800-900 $g.s^{-1}$. Data beyond 242 minutes is not shown as the insertion of water inhibits estimating the actual decrease of burning rate (refer to Figure 14c).

It is shown that the variation in burning rate observed for domains II to IV are consistent with those variations in observed fire length and size presented in Figure 12b. Therefore, it can be confirmed that the differences between domains are associated to an acceleration of the fire front.

The fluctuations in fire length and size observed for domain III (Figure 12b) are also observed in the burning rate (Figure 14); even more abruptly. Since these fluctuations occur when only one scale is affected, it is believed that this may not be caused by the transition between scales. Instead, it is believed that this could be caused by areas of the crib with increased moisture content as shown in section 4.

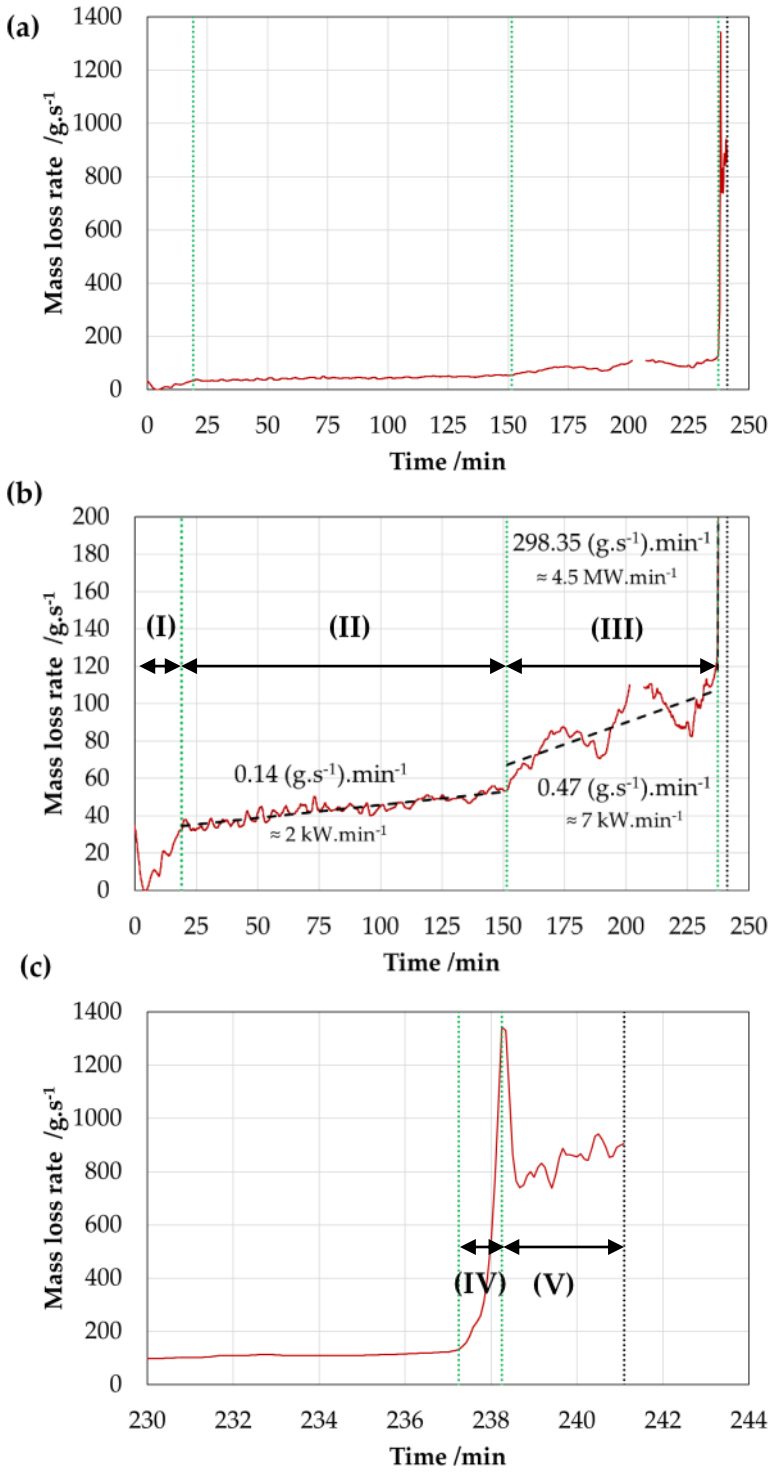


Figure 14. Total mass loss rate from the wood crib measured with the scales. Data has been corrected taking into account debris that fell on the platforms and applying a LOESS filter for different domains independently. (a) Complete duration of the test. (b) Zoom-in for a maximum MLR of 200 g.s^{-1}. (c) Zoom-in for 230-244 minutes. Green vertical dotted lines indicate transitions between domains observed in MLR. Black vertical dotted line indicates the manual extinction by the fire service.

5.3 Gas-phase temperature

The evolution in the gas-phase temperature within the compartment is shown using contour plots based on the data from thermocouple trees. Figure 15 to Figure 18 show the representative thermal evolution for each of the domains observed in the previous section. These contour plots correspond to the centre-line thermocouple trees along the length of the compartment. Linear interpolation is used to represent the temperature in areas between thermocouple trees. White areas are regions where temperature data were not collected. The beam located in between areas of the compartment with and without cork attached to the ceiling is shown as an L-black shape. The cork is shown as a thin brown layer, whereas the thermocouples are represented as green dots. To better describe these plots, each of the domains from II to V are described independently:

- **Domain II (Figure 15, 19 to 152 min):** characteristic temperature fields in the near field and the far field are clearly identifiable. Plots at 19 and 152 min suggest that the fire appears to be travelling, i.e. spreading via Mode 3 ($V_s/V_{BO} \approx 1$), since a distinctive plume temperature field is observed. This is consistent with the slowly growing burning rate of the crib, which grows at a rate of 0.14 g.s^{-1}.min^{-1}. It is observed a slow but consistent increase in the overall gas-phase temperature, both in magnitude and volume of hot areas. Maximum gas-phase temperatures in the ceiling above the near-field are below 300°C.

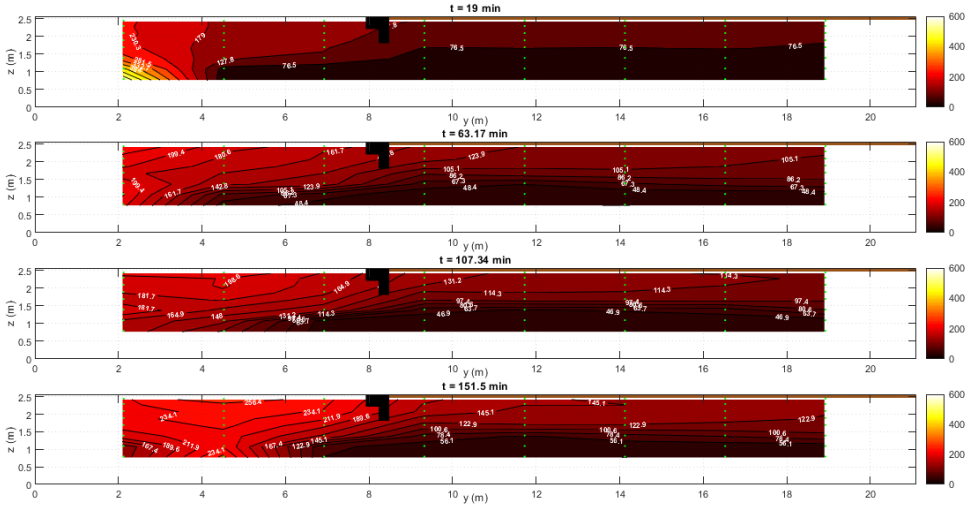


Figure 15. Gas-phase temperature contour along the centre-line of the compartment from 19 to 152 min (domain II).

- **Domain III (Figure 16, 152 to 237 min):** between 160 and 234 min, the fire appears to be travelling as per Domain II, however, the temperatures are increasing. This is consistent with the increase in burning rate, which grows at a rate of 0.47 g.s^{-1}.min^{-1}, and increase in fire size, which grows at a rate of 28 mm.min^{-1} (or 0.067 m^2.min^{-1}) as described in the previous sections. This confirms that the fire is not only travelling but growing in size (surface area) as the burning rate increases – transition from Mode 3 ($V_s/V_{BO} \approx 1$) to Mode 2 ($V_s/V_{BO} > 1$). This behaviour is verified by the increasing area of the near-field temperatures which are characterised by higher temperatures.

Additionally, it is observed that the beam disrupts the ceiling jet, as the temperature distribution observed on the far left-hand side of the compartment are higher than those observed beyond the beam on the right-hand side of the compartment. This behaviour changes from 234 min, when a localised area of the cork ceiling on the right of the beam is increasing in temperature, with temperatures above the maximum temperature below the ceiling on the left of the beam. This is due to local ignition of the ceiling material in that location, which was verified visually. The flame on the ceiling appears to spread as the regions with higher temperature spread towards the right-hand side of the compartment. During this process, the flame is not rapidly spreading over the crib since the temperatures on the bottom thermocouples are significantly lower. At 237 min, the fire on the crib reaches the thermocouple tree located on the right-hand side of the beam (close to y = 9 m).

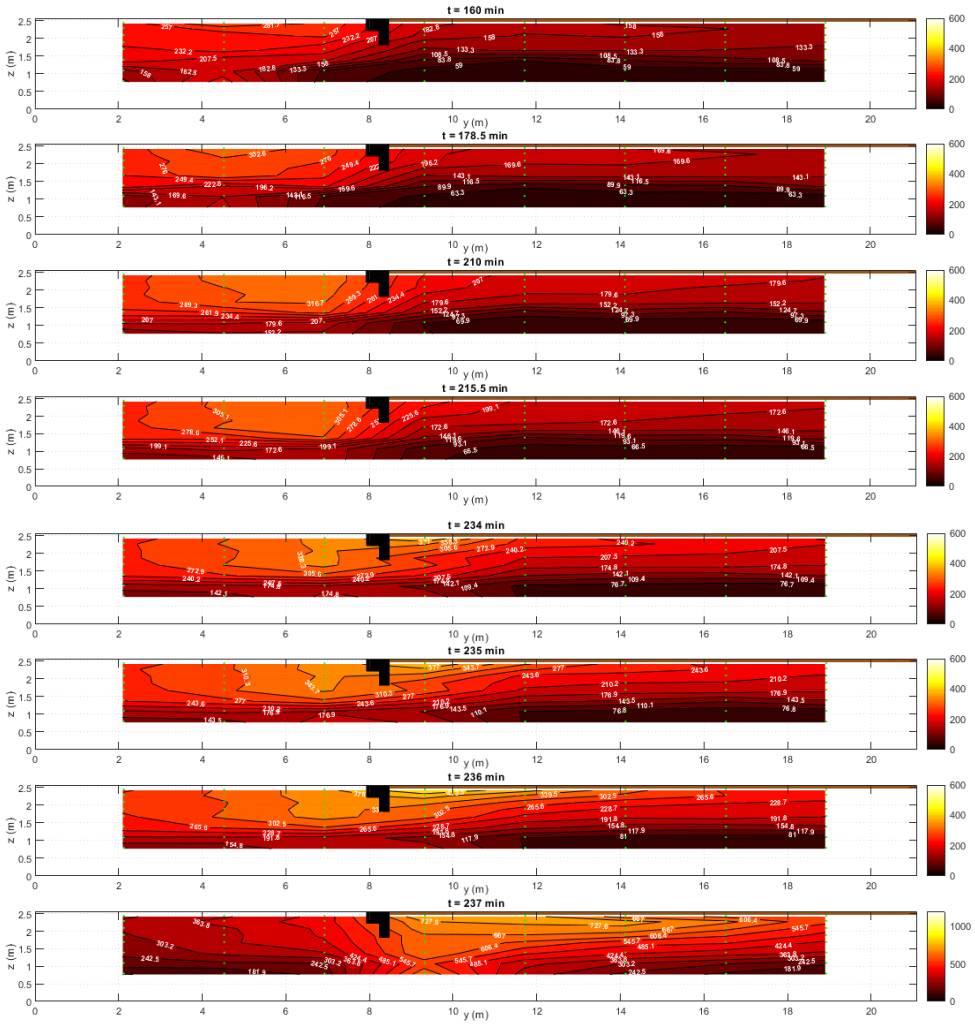


Figure 16. Gas-phase temperature contour along the centreline of the compartment from 152 to 237 min (domain III).

- **Domain IV (Figure 17, 237 to 238 min):** following the ignition and flame spread of the cork insulation attached to the ceiling, after 237 minutes the fire transitions from Mode 2 ($V_s/V_{BO} > 1$) to Mode 1 ($V_s/V_{BO} \rightarrow \infty$), accelerating rapidly over the surface of the

wood crib. This is consistent with the large increase in burning rate presented in previous section, transitioning from a rate of 0.47 $g.s^{-1}.min^{-1}$ to 298.35 $g.s^{-1}.min^{-1}$.

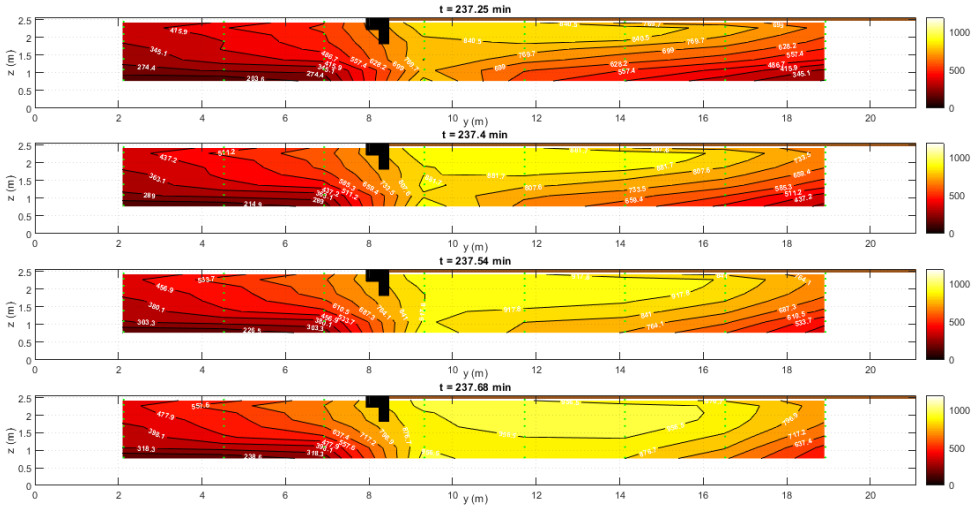


Figure 17. Gas-phase temperature contour along the centreline of the compartment from 237 to 238 min (domain IV).

- **Domain V (Figure 18, 238 min to 240 min):** once the flame of the wood crib has spread up to the right end of the compartment, temperatures on the right-hand side of the compartment are approaching 800-1,000°C, typical of fully-developed fires. The temperatures are more uniform at the centre of the crib (y = [9 m,17 m]), with lower temperatures on at the edges (y < 9 m and y > 17 m), presumably due to air entrainment and the absence of fuel on those areas. On the left-hand side of the compartment, there is a clearly defined two-zone behaviour. Nonetheless, a ceiling jet temperature pattern is observed in the hot layer, with increasing temperatures close to the area where all fuel burning (y > 9 m).

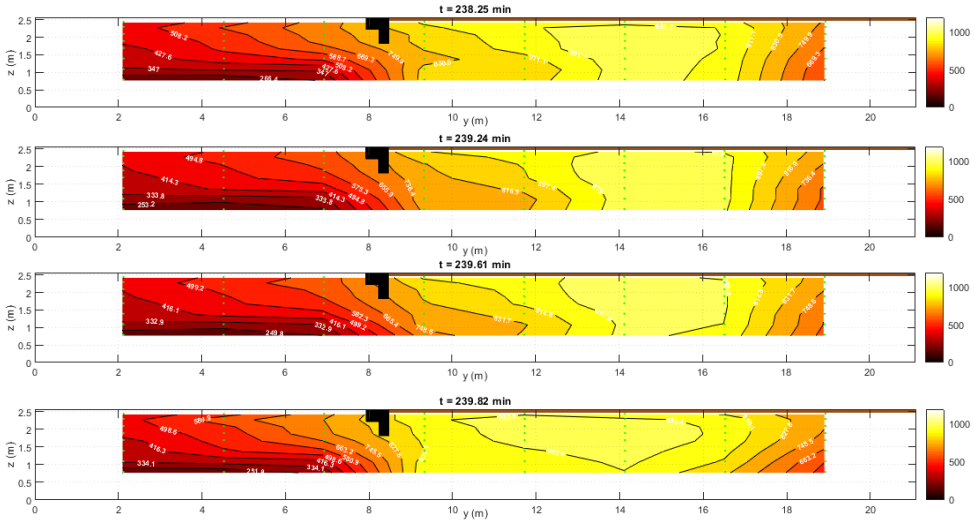


Figure 18. Gas-phase temperature contour along the centreline of the compartment from 238 to 240 min (domain V).

5.4 Incident radiant heat fluxes onto floor

The evolution of the incident radiant heat flux onto the floor are shown in Figure 19. The two rows of TSCs correspond to Row 'Z0-A' and 'Z0-B' which are the rows of sensors along the 850 mm and 3850 mm planes in the x-axis, respectively. For the heat flux calculation using TSCs, it was assumed that the gas-phase at the floor level remained at ambient temperature, since thermocouples were not at the ground level and these would include radiation errors. The plots have been divided into the five domains.

- **Domain I (0 to 19 min)**. It can be seen that the measurements by most sensors are less than 1 $kW.m^{-2}$ with the exception of HF-Z0-A1 and HF-Z0-B1, the TSCs located at x = 2200 mm, and correspond to the sensors closest to the flames at this time. The heat flux of HF-Z0-A1 and HF-Z0-A1 increase from 0 kWm^{-2} to roughly 5 kWm^{-2} and 3 kWm^{-2}, respectively. The heat flux recorded by HF-Z0-A1 is higher than HF-Z0-B1, suggesting that the fire front position is not uniform in width or extra radiative feedback is received near the wall.
- **Domain II (19 to 152 min).** HF-Z0-A1 and HF-Z0-B1 experience a decrease at approximately 20.7 minutes, which corresponds to the time at which the liquid ignition source consisting of the mixture of 5 L of kerosene and 0.5 L burning out, as confirmed visually by the video footage, whereby the production of smoke reduces as the liquid fuel is consumed. All other sensors indicate an increase in heat flux throughout the duration of this Domain. HF-Z0-A2 shows the highest increase from roughly 1 kWm^{-2} to 6 kWm^{-2}. This change is not reflected by HF-Z0-B2, and this sensor reads consistently low values throughout the duration of the test indicating sensor failure. HF-Z0-A3 and HF-Z0-B3 read the third highest values throughout this Domain increasing to roughly 2 kWm^{-2}. These readings correspond to the fire location, which is between y = 2200 and y = 5200 during this domain, meaning the fire is over these sensors at this stage of the test.
- **Domain III (152 to 237 min)**. The period between 192 and 209 minutes is represented by a straight line as this corresponds to the period where the data logger failed and was rebooting, and thus no data was collected. HF-Z0-A2 remains the highest heat flux between 152 and 192.3 minutes as during this stage the fire is still closest to this sensor, as the flame front travels from approximately y = 5200 to y = 7000 mm and the burnout front travels from y = 1650 to y = 2410 mm, and the values remain consistent for the entirety of the Domain. During the period where data was not collected, HF-Z0-A3 and HF-Z0-B3 begin to read the highest heat fluxes up until 236.9 minutes. The peak heat flux recorded during this stage by HF-Z0-A3 and HF-Z0-B3 are 15 and 10 kWm^{-2} respectively. HF-Z0-A4 and HF-Z0-B4 begin to rise rapidly in their heat flux readings at around 220 minutes as the fire reaches the soffit, as confirmed by video footage. HF-Z0-A5 and HF-Z0-B5 show a similar trend, however to a less extent being located further downstream of the fire. Between 221 and 226 minutes the data recorded by HF-Z0-A3 was removed due to artificial noise from the TSC.
- **Domain IV and Domain V (237 to 240 min).** Once the fire rapidly and almost instantaneously spread throughout the right side of the compartment at

approximately 238 minutes, all TSCs failed, as indicated by a drop-in heat flux. Therefore, to reduce artificial data, all data following a decrease in heat flux beyond 238 minutes was removed.

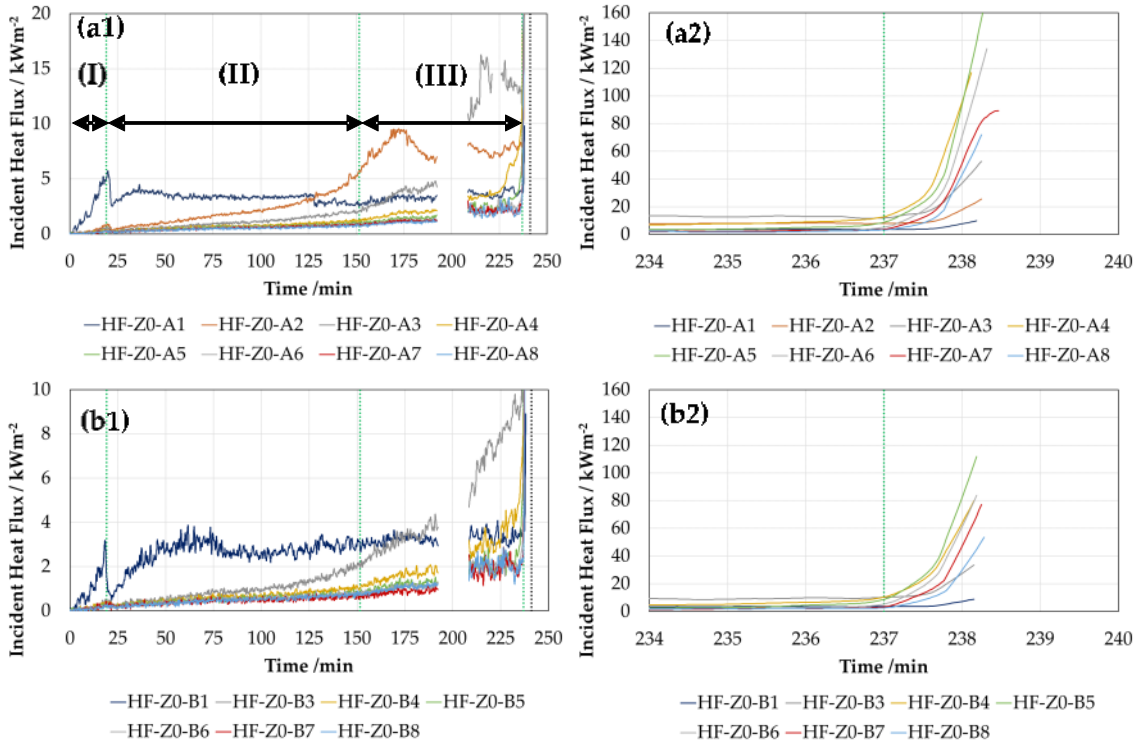


Figure 19. Incident radiant heat flux imposed on the floor along the length of the compartment at x = 850 mm (a – next to back wall) and x = 3850 mm (b – next to window). (a2) and (b2) show a zoom-in for 234 to 240 min, transition from domain IV to V.

Sensors 4 through 6 for both Rows A and B read the highest heat fluxes at this stage, as they are located to the right of the soffit where the fire first rapidly increases in size as it spreads throughout the right side of the enclosure. The peak heat fluxes recorded by each sensor during this Domain are provided in the table below, with the exception of TSC rows 1 and 2 as their peaks were recorded in Domains I and II.

Table 4. Peak heat fluxes recorded by the TSCs during Domains IV and V of the test.

y-position	Row HF-Z0-A - x = 850 mm (kW.m^{-2})	Row HF-Z0-B - x = 3850 mm (kW.m^{-2})
3	49	33
4	117	80
5	139	112
6	107	84
7	75	69
8	64	45

The values recorded by Row B are generally lower, indicating that the flame front position was not constant with depth, and Row B was possibly impacted on by its location being adjacent to the openings.

5.5 Opening Flow Velocities

The evolution of the gas in- and out-flow velocities are shown for each window. The associated thermocouple trees are used in conjunction with the bi-directional probes to calculate the respective density of air. Figure 20 shows the flow velocity of each bi-directional probe located within a vertical array, with a negative flow velocity reading indicating an in-flow, and positive flow velocity indicating an outflow. The transition between the in-flow to out-flow is described as the neutral pressure plane region. Like Section 5.3, each of the plots describe each domain independently.

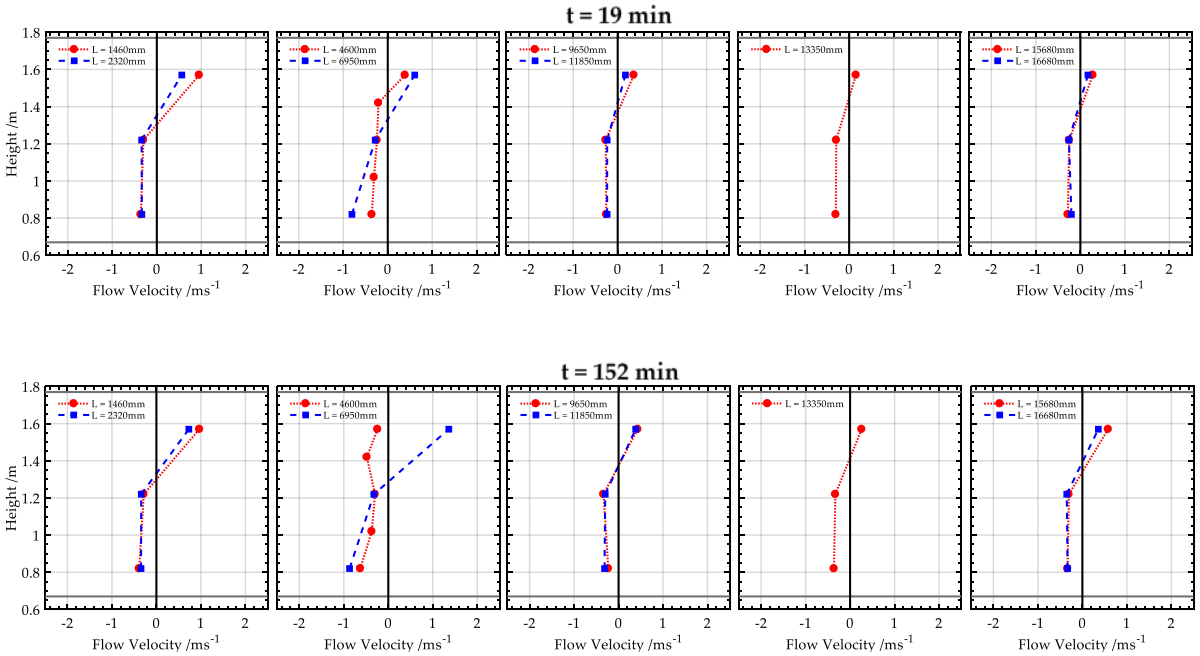
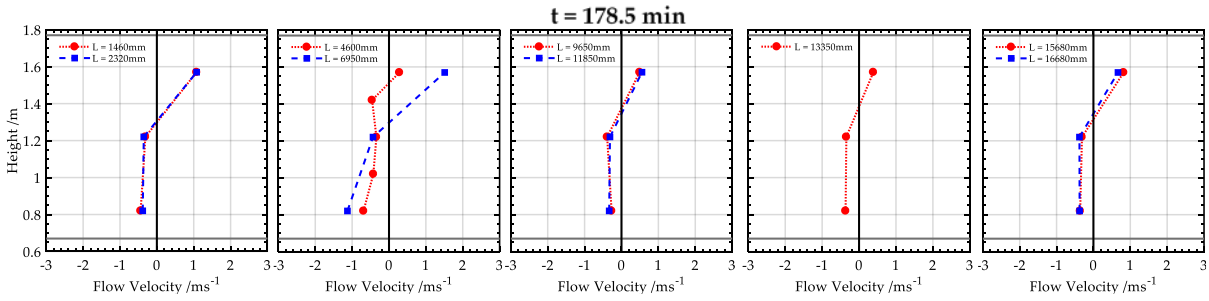
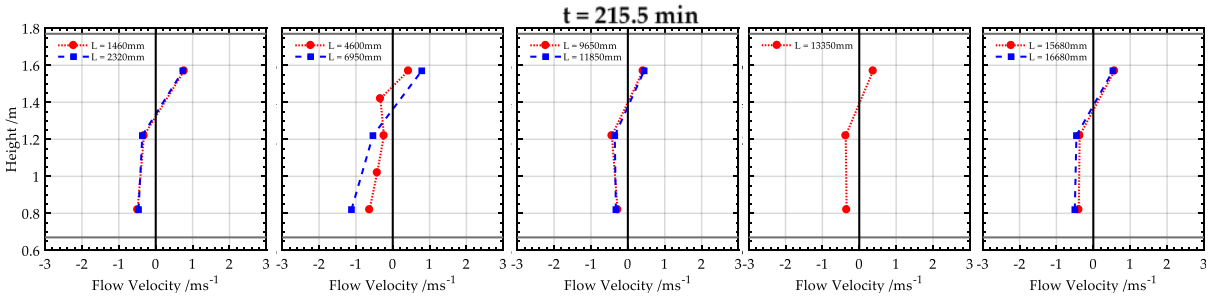


Figure 20. Flow velocities at each of the five window openings during the time of domain II (19 min to 152 min). Each plot represents in ascending order, each opening along the length of the compartment.

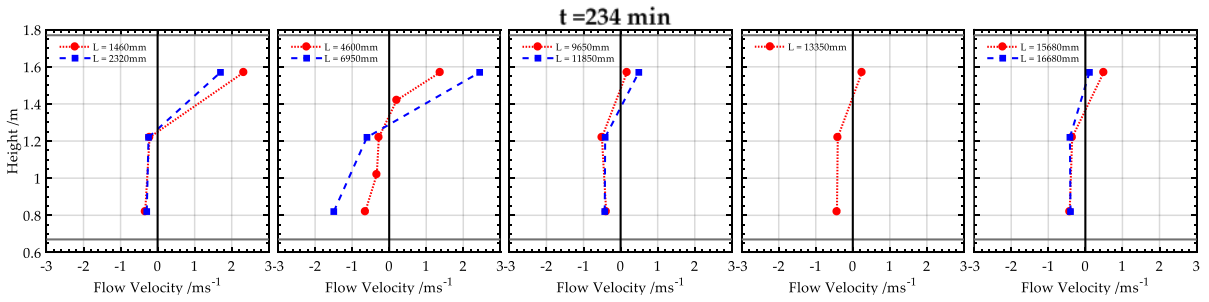
- **Domain II (Figure 15, 19 to 152 min):** at 19 min, characteristic velocities through opening 1 are higher than the other openings for both time steps, indicating that the plume from the fire is starting to develop and hot convective flows are leaving through the openings. Opening 2 shows constant inflow velocities for each height, up until the neutral plane region,H_N, which is defined as the transition region from inflow to outflow velocities and lies in-between 1.42m and 1.57m above the false floor level. The plots at 152 min show that at y = 4.6m, the velocities recorded are all negative (i.e. flowing into the compartment). This could be induced by local entrainment of air from the near-field of the fuel-controlled travelling fire, which is indicative of the region for which the flame front is located. The peak velocity is recorded at 1.4m/s, which is the probe array located just downstream of the flame front (y = 6.95m).


t = 178.5 min
L = 1460mm
L = 2320mm
L = 4600mm
L = 6950mm
L = 9650mm
L = 11850mm
L = 13350mm
L = 15680mm
L = 16680mm
Height /m
Flow Velocity /ms-1

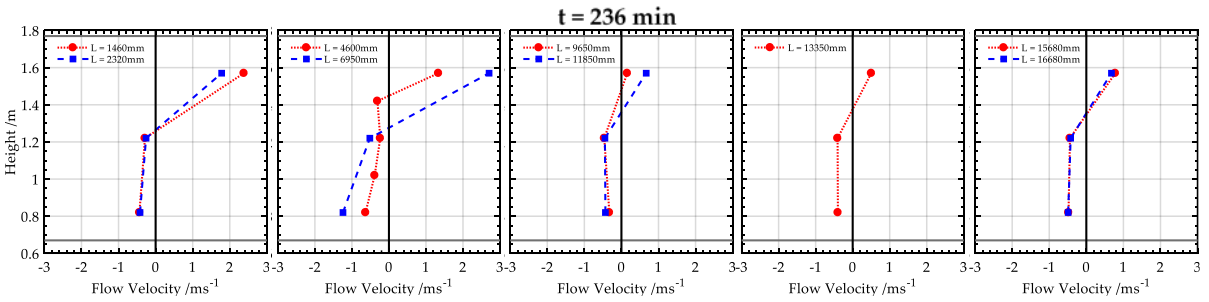
1


t = 215.5 min
L = 1460mm
L = 2320mm
L = 4600mm
L = 6950mm
L = 9650mm
L = 11850mm
L = 13350mm
L = 15680mm
L = 16680mm
Height /m
Flow Velocity /ms-1

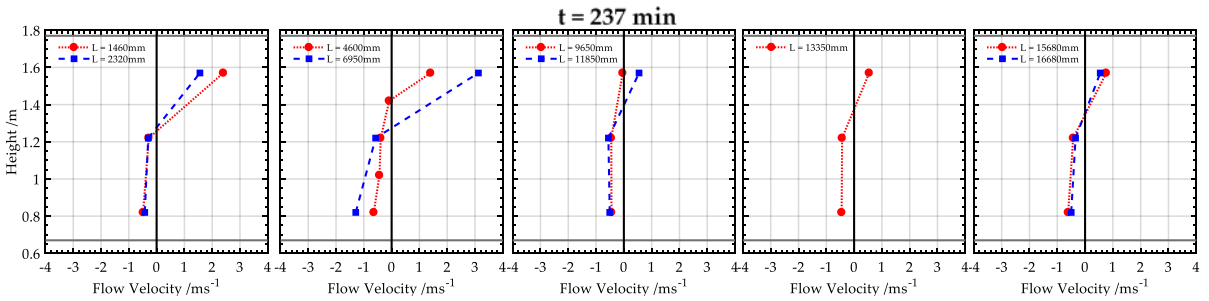
2


t =234 min
L = 1460mm
L = 2320mm
L = 4600mm
L = 6950mm
L = 9650mm
L = 11850mm
L = 13350mm
L = 15680mm
L = 16680mm
Height /m
Flow Velocity /ms-1

3


t = 236 min
L = 1460mm
L = 2320mm
L = 4600mm
L = 6950mm
L = 9650mm
L = 11850mm
L = 13350mm
L = 15680mm
L = 16680mm
Height /m
Flow Velocity /ms-1

4


t = 237 min
L = 1460mm
L = 2320mm
L = 4600mm
L = 6950mm
L = 9650mm
L = 11850mm
L = 13350mm
L = 15680mm
L = 16680mm
Height /m
Flow Velocity /ms-1

5

Figure 21. Flow velocities at each of the five window openings during the time of domain II (152 min to 237 min). Each plot represents in ascending order, each opening along the length of the compartment.

- **Domain III (Figure 21, 152 to 237 min):** between 160 and 215.5 min, the fire front (as defined from the mass loss rate recorded using the scales) is located in-between the two probe arrays in opening 2. This is observed with the low flow readings at L = 4600mm at 160 min, and then at L = 6950 mm at 215.5 min, indicating a local entrainment effect dominating the flow field at the opening of this point. Within this period, the highest flows are recorded at the probes just downstream or upstream of the fire front, followed by opening 1. Between 215.5 min and 237 min, the fire front has transitioned to the region in-between opening 2 and opening 3, with the upstream velocities in opening 1 and opening 2 increasing substantially. At 234 min, the neutral plane height has descended at opening 2, such that the neutral plane region lies in-between 1.22 m and 1.42 m, corresponding with visually observed descending smoke layer triggered by the ignition of the cork ceiling. Peak outflow velocities are recorded in-between 2.5 $m.s^{-1}$ and 2.7 $m.s^{-1}$ at L = 6950 mm, which is the probe upstream of the rapidly expanded fire front, followed by the probes located in opening 1, which range from 1.6 $m.s^{-1}$ to 2.3 $m.s^{-1}$. Near-wall velocities recorded by the probe array at L = 1460 mm consistently records the second highest outflow velocities. It is important to note that inflow velocities through Domain III are shown to be constant, with probes located downstream of the fire, also recording consistent values.

The probe data for domain IV and domain V are not presented herein, as the probes located downstream of the fire were engulfed in external flaming, with the plastic hoses connecting the probes and transducers starting to heat and possibly melting.

5.6 Heat release rate quantification

The heat release rate of the fire is estimated using a mass loss rate calorimetry approach, using the burning rate of the wood crib. A range of [12.8 – 20.4] $MJ.kg^{-1}$ for the heat of combustion of two species of pine wood [28] is assumed to consider the uncertainty in the material and efficiency of the combustion. The HRR is shown in Figure 22, and it can be identified that the transition to fully-developed fire (or flashover/thermal runaway) is shown approximately near 2.1MW. It should be noted that this HRR estimation does not consider the burning of the cork insulation, and therefore the true value would be expected to be higher from 237 min, where the transition is identified.

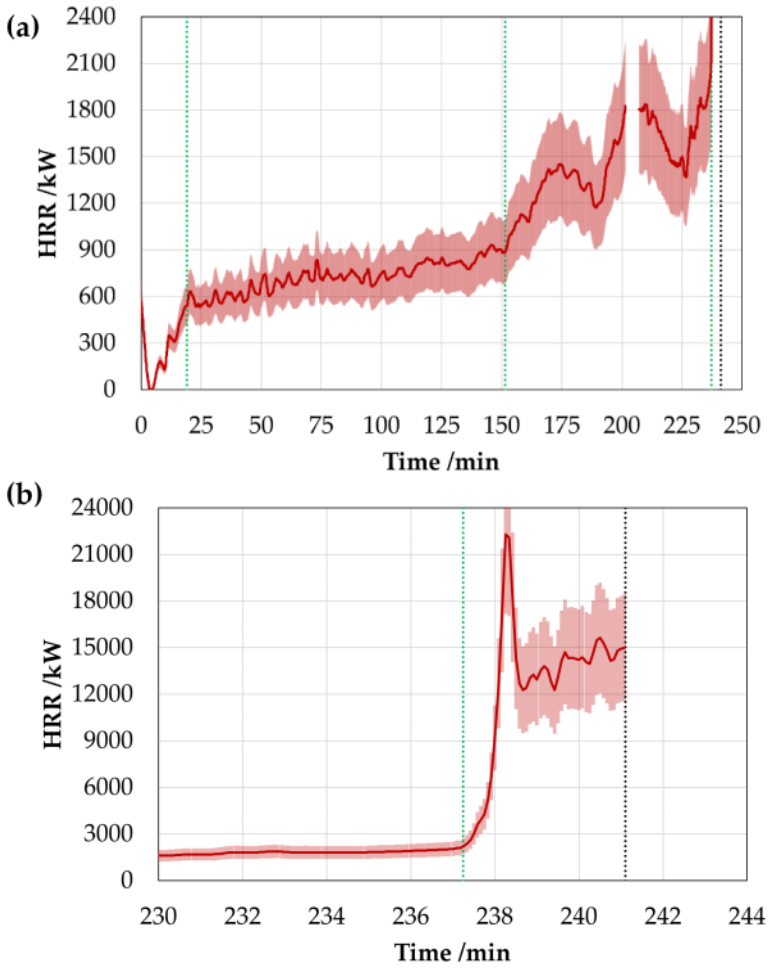


Figure 22. Estimation of HRR based on MLR from scales. Error bars provide maximum and minimum HRR using 12.8 and 20.4] MJ.kg^{-1} as the heat of combustion.

6 Summary and discussion

6.1 Fire behaviour modes

A preliminary analysis of the results presented in the previous section indicates that the compartment fire experienced the three distinct fire modes for the floor fuel load formerly presented by Hidalgo *et al.* [22]. Applying a linear fit to the fire front and burnout front position for each of the domains presented in Figure 12, an average velocity can be estimated using the slope of the linear fit. Average velocities and the ratio between these are presented in Table 5 below.

Table 5. Average fire front and burnout front velocity for each time domain using linear fitting functions. Ratio between these velocities and fire behaviour mode are shown.

Time domain	Fire front velocity (V_s) /mm.min^{-1}	Burnout front velocity (V_{BO}) /mm.min^{-1}	V_s/V_{BO} /-	Fire mode
I	21	0	$\rightarrow\infty$	-
II	13	12	1	$\boldsymbol{V_s/V_{BO} \approx 1}$
III	54	26	2	$\boldsymbol{V_s/V_{BO} > 1}$

IV	2977	26	116	$\boldsymbol{V_s/V_{BO} \rightarrow \infty}$
V	-	-	-	$\boldsymbol{V_s/V_{BO} \rightarrow \infty}$

Each of the fire modes identified were characterised by the following conditions. It should be noted that domain I is excluded from the three modes, since it corresponds to the early transient growth with the burnout front not developed yet.

- A **travelling mode ($\boldsymbol{V_s/V_{BO} \approx 1}$)** corresponding to domain II with a burning rate in the range 36 g.s^{-1} – 55 g.s^{-1} that lasted 133 min. The fire length had an average value of 1.2 m (corresponding to a fire size of 2.88 m^2), which grew at an average rate of 2 mm.min^{-1}. The incident radiant heat flux imposed on the fuel bed ahead of the fire front was below 6 kW.m^{-2}.
- A **growing mode ($\boldsymbol{V_s/V_{BO} > 1}$)** corresponding to domain III with a burning rate in the range 55 g.s^{-1} – 100 g.s^{-1} that lasted 85 min. The fire length had an average growth rate 28 mm.min^{-1} (corresponding to a size growth of 0.067 m^2.min^{-1}). The average rate at which the burning rate grew was 0.47 g.s^{-1}.min^{-1}, caused by an increase in the burning area. The incident radiant heat flux onto the floor ahead of the fire front were below 10-15 kW.m^{-2}.
- A **mode with an extremely rapid to instantaneous spread of the fire front such that the fire immediately covers the entire available fuel surface in the compartment ($\boldsymbol{V_s/V_{BO} \rightarrow \infty}$)**. This corresponds to domain IV with an extremely rapid fire growth (1.686 m.min^{-1} for the fire length and 298.35 g.s^{-1}.min^{-1} for the burning rate) that occurred within a minute and reached a peak burning rate of approximately 1.3 kg.s^{-1}. Subsequently, in domain V, the fire covered the available fuel surface on the floor, for 2 min and an average burning rate in the range 800 – 900 g.s^{-1}. This short duration was due to the intervention of the fire service for safety reasons. It should be noted that this stage would have been expected to continue until the consumption of the fuel load. Incident radiant heat fluxes onto the floor during domain IV were increasing above 15 kW.m^{-2} and reaching maximum values within the range 112 to 134 kW.m^{-2} during domain V until the sensors failed.

6.2 Transition between fire modes

Analysis of the conditions governing the transition between fire modes is of extreme importance towards establishing a comprehensive framework for compartment fires in open-floor plan spaces. This section presents a brief discussion of the conditions observed within each fire mode, and the transition between modes.

The initial mode, the travelling fire mode ($V_s/V_{BO} \approx 1$), was characterised by being almost steady process with very slow increase in burning area and therefore burning rate. It can be assumed that the energy distribution in the compartment enabled a fire front spread velocity equivalent to the burnout front velocity (refer to Figure 12 and Table 5). It is theorised that the principal driver dictating the flame propagation is the local radiation from the flame itself, given that the heat fluxes from the smoke layer onto the floor were relatively low (<6 kW.m^{-2}), with a relatively thin smoke layer. At these heat fluxes, preheating of the crib by the smoke will be very slow and thus not affect the flame spread or burning rates.

The transition from the travelling ($V_s/V_{BO} \approx 1$) to the growing mode ($V_s/V_{BO} > 1$), and subsequently to a fully-developed mode ($V_s/V_{BO} \to \infty$) is justified by an acceleration of the fire front over the burnout front, which is evidenced by the increasing burning area and therefore burning rate. In this stage, the heat from the smoke layer appears to affect more the fire front velocity, i.e. a flame spread surface phenomenon, than the burnout front velocity, i.e. the burning rate phenomenon controlled by charring. The development of an increasing heat flux ahead the fire front was observed, up to 10-15 kW.m^{-2} (refer to Figure 19) before the transition to a fully-developed fire.

Until detailed energy distribution analyses are performed, it can be assumed that the increase of heat flux is due to a change in the energy balance in the compartment. The change in the energy balance may be induced by a reduction of heat losses through the boundaries, trapping or containment of heat in a localised area of the compartment by the physical geometry, and extra heat release contribution within the compartment – essentially all playing the same role. The results presented in previous sections show that both the 500 mm deep soffit beam located at y = 9940 mm and the cork insulation have played a driving role in the transition of fire modes.

It is hypothesised that the transition from the travelling mode (domain II) to the growing mode (domain III) of the test is driven by the presence of the soffit beam. This is illustrated in the temperature contour plots shown in Figure 15 and Figure 16. While domain II displayed a thin smoke layer, as the fire approaches the beam it results in an obstruction that promotes smoke layer accumulation within the left side of the compartment which in turns provide a source of heat feedback into the fire and fuel allowing for the burning rate to increase. For domain II the fire plume temperatures in the nearfield were consistently lower than 200 °C; these near-field temperatures increase to above 300 °C as the fire approaches the soffit.

It is theorised that the transition from the growing mode (domain II) to the fully-developed mode is driven by the presence the cork on the ceiling due to its the low thermal inertia (< 10^4 W^2 s m^{-4} K^{-2} [28]), thus reducing the heat losses and inducing a rapid ignition and fire spread on the ceiling. The cork insulation, although a charring material, can sustain burning if sufficient heat is provided. Ignition and flame spread on the cork have clearly induced a drastic change in the thermal balance in the compartment. Even though cork has been shown by several authors to provide a relatively low HRR (120 - 206 kW.m^{-2} as shown by [29]), this has been shown to have a significant impact, presumably as the energy was released on the ceiling of the compartment, thus reducing heat losses due to lack of entrainment. These two mechanisms of behaviour/contribution from the insulation have previously been discussed by Hidalgo *et al.* [31].

The presence of soffit beam and the thermal insulation material, whereas very characteristic of the scenario studied, evidences the importance of adequately defining the thermal energy balance in the compartment so that realistic fire modes can be used as input design scenarios in open-plan floor compartments.

Further investigation is required to provide a better understanding of the sensitivity of the spread velocity of the fire front (V_s) and the burnout front (V_{BO}) to the external heat flux.

Consolidated research has demonstrated that the flame spread (V_s) is primarily a function of the fuel thermal inertia and the external heat flux whereas the burnout time is a function of the fuel density and mass loss rate per unit area, which depends on the external heat flux [34].

6.3 Identification of fire regime in domain V

The analysis of fire regime is only undertaken for the domain V of the fire. The temperatures observed in the right end of the compartment following ignition of the cork ceiling and rapid flame spread across the right end of the compartment have been compared to the theoretical temperatures in *Regime I* fires using the Thomas plot [11]. The opening factor was then calculated by dividing the enclosure into two compartments (refer to Table 2), as the fire was effectively only taking place in the right end as all fuel on the left of the central beam had been consumed. The temperatures used to compare the experimental results to the '*Compartment Fire Framework*' were taken as the average temperature within the right end of the compartment during the steady-state burning of domain V, which took place approximately between 239 and 241 minutes as shown in Figure 23.

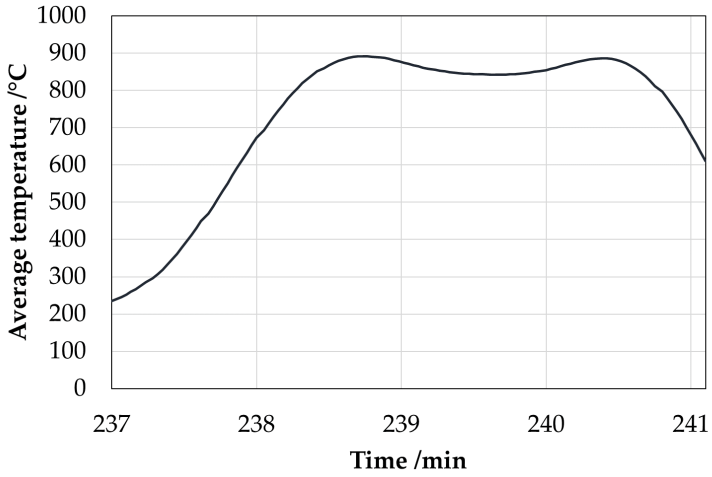


Figure 23. Average temperature within the compartment during domain V.

The average temperature was found to be 862 ± 131 °C. The peak temperature reading throughout the entire test was found to be 1056°C. A comparison of these values to the Thomas plot is shown in Figure 24. Note that the opening factor is computed by excluding the fuel and opening surfaces from A_T. The steady-state fire briefly observed during domain V is shown to be representative of a *Regime II* fully-developed fire, with the average fire temperature during this stage being very closely estimated by the data collected by Thomas and with significant spatial variability. The maximum temperature reading within the compartment is more indicative of a *Regime I* fire; however, this was recorded by thermocouple A5-5 at 239 minutes with similar temperature recorded in Row 5 of the thermocouple trees. It is assumed that this occurred as the flame engulfed the sensors.

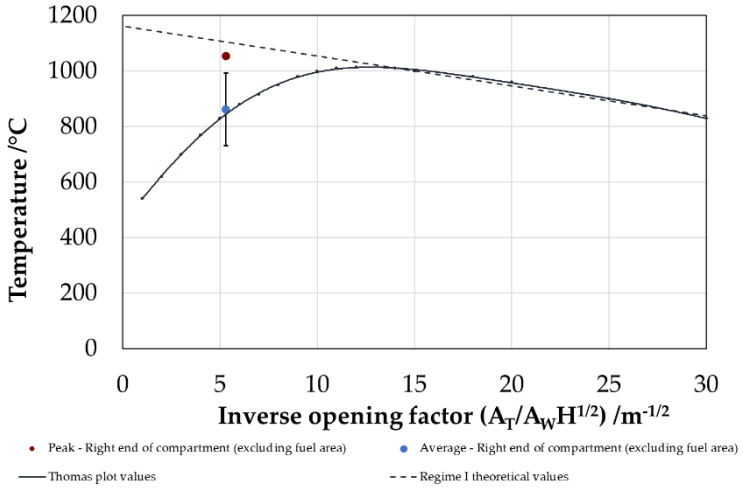


Figure 24. Comparison of experimental results of domain V (fully-developed fire) to the Thomas plot [11] . The blue point represents the average temperature within the compartment during this phase and red the maximum recorded temperature. The dashed line depicts the maximum temperature according to Regime I theory

7 Conclusions

This paper presents the characterisation of the *Large-Scale Demonstrator 'Malveira Fire Test'*, which took place in a well-ventilated, open-plan compartment in Povoa de Galera, Malveira, Portugal in 2014. The principal source of fuel was a continuous bed of wood cribs running the length of the compartment, parallel to the ventilation, closely replicating the setup of the Edinburgh Tall Building Tests. The high level of instrumentation enables significant spatial resolution of the thermal environment and thus enables a quantitative interpretation of the visual observations.

Three fire behaviour modes are clearly identified in the data, corresponding to a travelling fire, a growing fire, and a fully-developed fire, appearing sequentially as the fire moves along the entire length of the compartment. These modes are defined by the ratio of the flame front velocity and burnout front velocity. The transition between fire modes, and thus evolution of energy production appears strongly linked to the spatial redistribution of energy produced, and specifically to the evolution in heat feedback to the unburned fuel. This energy redistribution is strongly coupled with the variation in physical characteristics of the compartment along its length, e.g. openings, thermal characteristics of the boundaries, compartment geometry, etc.

This test illustrates the importance of, and thus need for, accurate characterisation of the dominating mechanisms driving the flows within the fire compartment at each stage of the fire development, as this dictates energy redistribution and therefore the ability of the fire to transition between fire modes. Accurate characterisation of the expected fire dynamics during each expected mode will in turn enable the adequate design of the fundamental elements (pressurisation systems, structural fire protection, etc.) underpinning the success of fire safety strategies for tall buildings.

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TÆC
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GRENFELL TOWER: PHASE 1 REPORT



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EXECUTIVE SUMMARY

A fire originated in the kitchen of Flat 16 of Grenfell Tower on June 14th, 2017. While there are numerous ways in which this fire could have originated, at the date of submission of this report, there is no conclusive evidence that constrains the cause, origin and initial stages of the fire to a single timeline or set of events. Nevertheless, analysis of the evolution of the events and of the observable damage enables a detailed analysis of many of the factors influencing the nature of the event and its consequences.

Fires evolve in space and time leading, in many instances, to a complex sequence of events and multiple processes and activities occurring simultaneously. It is therefore useful to structure these events, processes and activities. So, for the purpose of this report, the timeline of the Grenfell Tower fire will be divided into four stages, each of which reflects a key phase in terms of this particular fire event[1]:

- **First Stage:** From the initiation of the event to the breaching of the compartment of origin
- **Second Stage:** From the breaching of the compartment of origin to the point when the fire reaches the top of the building
- **Third Stage:** The internal migration of the fire until the full compromise of the interior of the building, including the stairs
- **Fourth Stage:** The untenable stage[2]

The geometrical configuration of the kitchen and the available ventilation did not allow the kitchen fire to attain flashover. The temperature of the smoke accumulated below the ceiling of the kitchen will remain within the approximate range of 100-220°C. As will be described below, these temperatures are capable of damaging components of the window, but the accumulated smoke cannot ignite any of the combustible materials in the vicinity of the window or within the façade system.

The temperature of the smoke accumulated below the ceiling of the kitchen is sufficient to heat the uPVC components of the window to temperatures that result in complete loss of mechanical properties (90°C). These temperatures would have been attained within an approximate period

[1] The stages are qualitative in nature therefore no exact times are proposed here, details on times can be found in the body of the report and in references [2], [4] and [5]. The times are roughly First Stage (00:54 - 01:05), Second Stage (01:05 - 01:30), Third Stage (01:30 - 02:30) and Fourth Stage (02:30 - extinction).

[2] The term tenability is intended to describe in a qualitative manner, the conditions within different parts of the building as it pertains to the interactions of the fire and smoke with people. Tenability and safety are difficult terms to define and therefore have to be interpreted in a relative manner. That is because the concept of tenable conditions inside a building will vary between different persons e.g. between adults and children and it is possible to adopt very technical definitions of tenability depending on what is being assessed. For the purpose of this report, I use the phrase untenable conditions to mean conditions that are life-threatening (e.g. high temperatures, high concentration of carbon monoxide, etc.) or perceived by occupants as life-threatening (e.g. poor visibility). In contrast, a tenable or safe environment will be one where conditions remain or are perceived by occupants not to be life threatening. Typical approaches and quantitative data that serve to define tenability are provided in the literature [6] but for the purpose of this report only the qualitative approach described above will be used.

between 5-12 min which is consistent with the time available between the discovery of the fire (initial call to the fire brigade) and the first observation of smoke and burning debris external to the building. The geometry of the uPVC elements and approach used for their fixation would have resulted in the eventual fall-off of these elements. The failure of the uPVC leaves all other combustible components of the façade system exposed.

Flames have higher temperatures than the smoke accumulating below the ceiling of a room. Therefore, an unobstructed fire of 300 kW placed at a maximum distance of 3.1 m from the window would have been sufficient to ignite any of the combustible components of the façade system. A fire of 300 kW is no greater than a fire originating from a pan fire of 40-50 cm radius. A pan fire will cover its entire surface immediately after ignition so it will remain of constant size. In contrast, a fire originating from appliances will ignite and then spread through the different combustible materials within the appliance, thus the fire will grow in time. Appliances with significant mass of combustible materials (e.g. refrigerators) can release heat beyond 1000 kW, while those with less mass of combustible materials (e.g. electrical stoves) might never reach 300 kW.

If the fire was obstructed (i.e. there was an obstacle between the fire and the window) then a 300 kW fire would have had to be placed less than 1 m from the combustible materials of the window if those materials were to ignite. A fire placed further away, capable of igniting combustible materials in the window, would have most likely brought the room to flashover.

Almost any appliance within a common kitchen could have sustained a fire of the size (300 kW) required to ignite combustible components of the façade system if placed close enough to the window. Therefore, the cause an origin of this fire is of minor importance to the outcome. To complete an investigation, it is important to understand how and where the fire started. Nevertheless, the precise cause and origin of this fire is, on one respect, irrelevant to the event which subsequently occurred. From a design perspective, a fire of 300 kW occurring in a residential kitchen, and in the proximity of the window, should be considered to have a probability of one. In other words, a fire of this nature will happen in a residential unit and therefore the building is required to respond appropriately.

Once any of the combustible components of the façade ignited, their proximity and complex arrangement would have inevitably resulted in the ignition of other components leading to external flame spread. This point marks the end of the first stage of the fire.

Through this first stage of the fire the building was operating as intended and in accordance with the assumptions which underpin the existing regulatory framework. Firefighting operations remained within the bounds of conventional practice and the structure could be considered to pose no risk of failure. A “stay put” strategy (i.e. occupants of flats adjacent to the flat on fire or on levels above or below can remain safely within their own flat) would have implied minimum risk to the occupants during the first stage of the fire.

Vertical fire spread characterizes the second stage of the fire. Vertical flame spread is significantly faster and more robust than lateral flame spread, so the fire rapidly propagates upwards but propagates laterally with greater difficulty.

Only in the final 5 – 10 minutes of the second stage (from 01:20 onwards) and before the fire reaches the top of the East façade, was there a significant number of emergency calls indicating smoke or flames within the building. These calls were not related to the original kitchen fire. Video camera

recordings show that during this period, occupants were, for the most part, able to egress with little or no evidence of smoke. With the exception of some short time periods, it can be concluded that the stairs remain safe during this stage of the fire. The moment when the fire reaches the top of the building is defined here as the end of the second stage of the fire.

Through this second stage of the fire the building is operating outside the conditions contemplated by the existing regulatory framework. Firefighting operations are outside the bounds of conventional practice and therefore have to be driven by a dynamic risk assessment. A “stay put” strategy is not consistent with the characteristics of the second stage. To a large extent the building remains tenable and the stairs still retain the characteristics required for them to be a safe egress path. Egress is outside the bounds of conventional protocols, therefore is not free of risk, but nevertheless it can be considered a better strategy than “stay put.” The heating period from the fire, even if an extreme heating rate is considered, is too short to result in structural temperatures that would have posed any challenge to the integrity of the structure. The structure can be deemed safe in this period.

Cavity barriers, no matter how well or badly they were designed and / or implemented, would not have prevented vertical or lateral flame spread in the Grenfell Tower fire. Flames can propagate through the interior cavities of the façade system but can also project over the façade system. Flames in the interior cavities will face and be slowed by the cavity barriers. Flames projected over the façade system will spread unobstructed via the exterior (this includes joints, damaged areas, etc.). Typical flame temperatures are higher than the melting temperature of aluminium (650^{o}C) therefore the aluminium plates of the composite panels would have offered no protection to the combustible materials.

Details of the cladding will have an impact on flame spread rates, although in the case of Grenfell Tower, upward flame spread rates are not uniquely fast. A comparison with other international events shows that upward flame spread for the Grenfell Tower is among the slowest. It is therefore possible to ascertain that detailing of the façade system (as opposed to its material composition) has only a minor impact on the evolution of this fire.

Lateral spread in the initial stages of the fire is much slower than vertical flame spread. Once the fire reaches the top of the building, the fastest rate of spread occurs in the area of the architectural crown. Lateral flame spread results in significant amounts of debris falling downwards igniting the façade system in lower floors of the building. All these fires then proceeded to propagate upward. Therefore, the main mechanism of lateral fire spread is falling debris, and thus the rate of lateral spread is defined by the rate of lateral spread of the fire at the architectural crown.

Different details in the façade system (materials, geometry, cavity barriers, etc.) seem to show different levels of impact on the rate of flame spread. Tests conducted after the Grenfell Tower fire do provide some further information. But the complexity of this façade system is such that observations and tests, such as BS 8414, do not provide sufficient information to be able to reach incontestable conclusions. The specificity of the scenario used for these tests and the quantity and quality of the data recorded does not allow for a reliable extrapolation of the test results. Adequate performance assessment of systems of the complexity of these façade systems require better and more detailed data for a range scenarios and test configurations.

Compliance of the façade design relies on establishing if it "adequately resists the spread of fire.[3]" The only path to compliance is performance assessment "from test evidence[4]" used by a competent engineer using "relevant design guides.[5]" The complexity and importance of the façade system requires more than guides and therefore the reliance is fully on professional competency. There is no clear definition of professional competency, therefore this is a matter that needs to be studied with great attention.

There are no provisions in the Building Regulations that require the designer to control inward penetration of an external fire occurring on the building. Emphasis is given to the risk posed by heat fluxes of a magnitude typical of those received from adjacent buildings (12.6 kW/m^2). Furthermore, given that glazing is an unavoidable part of the function of a residential building it is certain that in the presence of an impinging external flame the glazing will fail. Glazing is generally considered to fail with heat fluxes of 5 - 10 kW/m^2 while external fires occurring on the building have been measured to deliver heat fluxes within a range of 20-120 kW/m^2. It is therefore not reasonable to expect that an external fire occurring on the building will not start internal fires within the building.

In the third stage of the Grenfell Tower fire, internal fires were started at multiple levels as the fire propagated upwards. In a similar manner, but at a much slower rate, internal fires would have been initiated after the fire propagated laterally. Grenfell Tower had multiple pathways for internal propagation, many of them much less robust than glazing (i.e. the extraction fan, window detailing, etc.) and they all contributed to fast ingress of flames into the units.

Analysis of the emergency calls and a damage analysis shows that internal penetration happens in many ways, with a wide range of consequences and in many different locations. Internal penetration occurs first in floors 5, 12 and 22. Rapid internal penetration above floor 20 can be attributed to the presence of the architectural crown and the debris falling from it. Due to immediate proximity to the architectural crown, the upper floors were more readily exposed to the build-up of falling debris on external ledges. Furthermore, a buoyant plume will carry heat upwards further explaining the rapid ingress of flames into the units above floor 20.

Analysis of other international fire events shows that the buoyant plume generated by the fire cannot significantly accelerate lateral fire spread in the absence of other contributing factors. Several international fire events show that once the fire reaches the top of the building it starts to decay, showing only minor lateral fire spread. In some cases, extensive lateral fire spread similar to Grenfell Tower occurred. Most international events are poorly documented therefore it has not been possible to identify any design features that are consistent to all fires where significant lateral fire spread occurred. Nevertheless, the fire occurring at the Monte Carlo Hotel & Casino in Las Vegas showed rapid lateral propagation at the top of the building. This fire serves as an example that illustrates how debris from a high-level fire can initiate multiple lower fires creating lateral fire spread over a more extensive area of the building.

Once the external fires have breached the exterior of further units, they may or may not act as an ignition source for a compartment fire, depending on the layout of the fuel within the breached compartment and the location of the ignition point. At Grenfell Tower, and increasingly with height,

[3] Functional requirement B4 (ADB) and performance criteria specified in Section 12.5 (ADB).
[4] Section 12 of ADB and Appendix A of ADB bullet point (b).
[5] Section 12 of ADB and Appendix A of ADB bullet point (b).

149 the internal fires developed into post-flashover fires, rapidly filling the units with smoke and involving
150 combustible materials within the units.

151 At this point the boundary of the units (i.e. perimeter walls and doors) should act as barriers to the
152 progression of smoke. Several international events have shown that means of egress can be protected
153 effectively by means of compartmentalization[6]. Very large fires, with comparable internal fire spread,
154 have not resulted in penetration of smoke and flames into the stair lobby or stairs.

155 Compartmentalization is a required part of the Building Regulations and it is a critical feature of the
156 design of high-rise buildings. Furthermore, ventilation may be necessary to provide a redundancy that
157 protects the stair lobby[7]. The stairs are further protected by a second redundancy consisting of the
158 stair enclosure (including the doors). Therefore, there is an expectation that smoke can still be
159 prevented from entering the remaining safe area of the building (i.e. the stairs).

160 It has been reported that samples of the Grenfell Tower doors failed a standard test approximately 15
161 minutes into the test. The standard test does not replicate a fire event (in terms of the progression of
162 the fire) but creates conditions whereby there is a steady growth of the temperature in time. In 15
163 minutes the temperature of the standard test would have reached approximately 740^{o}C. In a real fire,
164 740^{o}C is a temperature characteristic of a post-flashover fire. Therefore, it is possible to infer that
165 failure of the doors leading to the lobby would have occurred only after the units would have been
166 fully involved in the fire (post-flashover fire).

167 A feature of these doors is that they are of combustible construction resulting in ignition at failure. If
168 the doors ignite they would have inevitably compromised the lobby. Given such a fire, the cross-
169 ventilation strategy (even if it was operational and well maintained) would not have served as an
170 effective redundancy. Because of the small dimensions of the lobby and the fact that it was
171 surrounded by multiple units burning, it is very likely that the stair doors would have been challenged
172 by impinging flames. Impinging flames would have provided enough heat to possibly challenge the
173 performance of any doors similar to those tested after the Grenfell Tower fire.

174 Inspection of all the doors shows that areas where there was major fire impact (i.e. evidence of high
175 temperatures and significant soot deposition) correlate well with areas where doors are either missing
176 or significantly damaged. Other potential paths for smoke and flames have been identified (e.g.
177 inadequate fire stopping material surrounding service penetrations, absent door seals, etc.)
178 nevertheless no significant compartmentalization deficiencies could be established in the post-event
179 inspections. While any deficiency could have contributed to the migration of smoke into the lobby, it
180 would have been highly unlikely that flames could have migrated into the lobby via these routes to
181 create conditions that could compromise the doors separating the lobby from the stairs.

182 A feature of the Grenfell Tower fire was the observation of smoke escaping from windows opposite
183 to the initial location of the fire (i.e. escaping via the west and south faces of the building). These
184 observations occur as early as 40 min from the reporting of the initial fire in Flat 16. Migration of
185 smoke across the building would have required at least two breaches of barriers that were separated
186 from each other (i.e. two flat entrance doors). No clear explanation can be proposed, nevertheless,

[6] Compartmentalization is a process by which physical barriers (ex. walls, floor slabs, doors, etc.) that can withstand the effects of a fire (for a sufficient period of time) are used to maintain the fire within a unit, therefore not allowing heat and smoke from entering adjacent areas of the building.
[7] Section 2 – Means of Escape from Flats (ADB).

given the information available, it is most likely that this occurred because doors were open. This highlights the importance of self-closing mechanisms for doors.

Once the fire has re-entered the building, compartmentalization is the main line of defence. Compliant systems would have helped to protect egress paths and deliver safe paths for the occupants to evacuate. While the external fire contributes to ignition of the unit furnishings, the energy contribution to the unit from this external fire is limited and localized to the areas around the window. Thus, there is no reason for compartmentalization requirements designed to withstand a post-flashover fire not to be suitable for a fire of the nature of that of Grenfell Tower.

Occupant movement (combined with potential absence of functioning self-closers and therefore leaving doors open) or firefighting operations most likely had an impact on the capability of smoke and flames to migrate from the units towards the lobby and stairs. Nevertheless, this possibility cannot exonerate the need for compliant compartmentalization features (walls, fire doors, fire stop, etc.).

The migration of building occupants was analysed showing that the patterns of descent varied in time. First, people reported a dynamic evolution of the smoke within the building. Within some time periods people migrated downwards showing that the stairs still remain tenable. At other points in time people migrated upwards, reporting that the stairs were filled with smoke. Through the third stage of the fire, tenability evolves in a dynamic manner as the fire spreads laterally and different failures occur. In this period, most of the calls reporting smoke and flames come from floors 10-15 and above floor 20.

Between approximately 60 and 70 min from the initiation of the fire, reports of smoke in the lobby and fire and smoke in units become more generalized. This marks the end of the third stage and can be considered as a point when there is generalized loss of tenability in the building.

Through this third stage of the fire, the building is operating outside the conditions contemplated by the existing regulatory framework. Firefighting operations are outside the bounds of conventional practice. The magnitude of the event has significantly reduced the capacity of the fire service to manage the situation. A thermal analysis of the structure shows that the structure was still safe. Temperatures of the structure would have not reached magnitudes where significant damage would have been expected. A “stay put” strategy is not consistent with the characteristics of the third stage. Tenability of the egress paths is highly questionable therefore egress and rescue both represent a high risk during this stage.

Stage four is characterized by multiple calls indicating critical conditions. Many sectors of the building, including lobbies and stairs are untenable. This stage will also be characterized by multiple forms of failure that could potentially include breaches of the gas lines, penetration of fire stopping, structural deterioration, etc. Given the potential temperatures of the structure, a detailed structural assessment would have been essential to establish the stability of the building. This type of assessment requires inspection and analysis not possible during fire rescue and response activities. During this stage, egress or rescue operations are probably still possible within some sectors of the building, nevertheless these activities would be implemented well outside the scope of any regulated practices and will imply significant risk for occupants and fire fighters. The fourth stage does not guarantee safe firefighting operations inside the building.

The tragic consequences of the Grenfell Tower fire highlight the significant shift in complexity that occurs when intricate façade systems are incorporated into high rise buildings. Functional

requirements, guidelines and simple standardized tests become insufficient tools to establish adequate performance[8] of systems where performance is a function of the interactions of the building and building envelope.

The inadequacy of these methods of performance assessment / regulation is such that systems that introduce obvious dangers can be incorporated by designers in a routine manner. These systems can be used without necessitating sufficient consideration of the effect that that inadequate performance can have on the overall validity of the fire safety strategy[9]. This is despite the explicit understanding that one of the fundamental assumptions backing almost all aspects of a tall building fire safety strategy is that external fire spread shall be prevented.

The regulatory framework relies very heavily on competent professionals to provide the necessary interpretation that will bridge the gaps and resolve the ambiguities left by functional requirements, guidelines and standardized tests. Nevertheless, a competent engineer should be capable of interpreting the requirement to "adequately resist the spread of fire over the walls ... having regard to the height, use and position of the building[10]" within the context of the needs of the fire safety strategy in the case of a specific tall building. In the case of the fire safety strategy of Grenfell Tower, "adequately resist" should have been interpreted as being "no" external fire spread.

There is currently no definition of what is the competency required from these professionals, or skill verification approaches that should be used, so as to guarantee that those involved in the design, implementation, acceptance and maintenance of these systems can deliver societally acceptable levels of safety. There is a need to shift from a culture that inappropriately trivializes "compliance" to a culture that recognizes complexity in "compliance" and therefore values "competency," "performance" and "quality." Otherwise, the increasing complexity of building systems will drive society in unidentified paths towards irresponsible deregulation by incompetency.

[8] Performance is defined as adequately fulfilling all functions that support and enable the fire safety strategy to deliver an acceptable level of safety.

[9] Fire Safety Strategy, as referred here, is not a specific document but a conceptual representation of the ensemble of measures introduced to guarantee adequate fire safety (Section 1.6)

[10] Section B4. (1) External Fire Spread (ADB).

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1 INTRODUCTION

1.1. THE INQUIRY'S TERMS OF REFERENCE

The Inquiry's Terms of Reference have been approved by the Prime Minister and have been published on the Inquiry's website. The Inquiry has also published on its website a detailed provisional List of Issues which identify the matters with which its investigation will be concerned. This provisional List may be revised in due course.

1.2. STRUCTURE OF THE INQUIRY

The Chairman has indicated that Inquiry will be conducted in two phases.

Phase 1 of the Inquiry is intended to investigate the development of the fire itself, where and how it started, how it spread from its original seat to other parts of the building and the chain of events that unfolded during the course of the hours until it was finally extinguished. Phase 1 is also examining the response of the emergency services and the evacuation of residents. The Chairman has noted that it is necessary to address these questions first for two reasons:

1. there is an urgent need to identify what aspects of the building's design and construction played a significant role in enabling the disaster to occur; and
2. until the chain of events is understood, it will not be possible to pinpoint the critical decisions that had a bearing on the fire.

The Chairman asked me to provide a report for Phase 1 on:

(a) The ignition of the Grenfell Tower façade materials.
(b) Fire spread to and on the exterior of Grenfell Tower.
(c) Fire and smoke spread within Grenfell Tower.

The current document is my Phase 1 Report.

1.3. STRUCTURE OF REPORT

The report will be structured around a series of general topics that attempt to describe how a high-rise residential building should have responded to a single fire event (Fire Safety Strategy). A fire is a chemical reaction governed by Newtonian physics, therefore its behaviour can be described in terms that are consistent with this framework. In a similar manner, the response of a building to the fire can be described using basic and well accepted scientific principles. The report will first present the fire safety strategy in these terms. It is clear that the complexity of the interactions is very significant, therefore the description of the different processes will remain general and simplified. It is accepted that the general presentation will not cover some of the important details. These will be left for later sections.

Building Regulations provide structured approaches that address the progression of a fire and its interactions with a building. Building Regulations accept that a single fire event will occur in a building. Then, the objective of Building Regulations is to manage this fire event in a manner such that the consequences are acceptable to society. For that purpose, Building Regulations invoke engineering tools and engineered systems as well as reference to the fire brigades. The interaction between the building, the engineered systems and the fire brigades with the fire are governed by the laws of physics and in principle could be describable by means of engineered tools. Nevertheless, the complexity of some of these interactions is such that sometimes the implemented solutions have to be sufficiently over-dimensioned (or robust) to provide confidence of adequate performance without the explicit representation of the physics. Building Regulations are, in principle, meant to provide these robust solutions that meet the objectives of the fire safety strategy. Some Building Regulations approach these solutions as functional requirements others as detailed sets of rules.

An analysis of Building Regulations and their manifestation in building design is beyond the scope of this report, nevertheless, this report will include references to particular Building Regulations that aim to address each aspect of the fire safety strategy applied to Grenfell Tower. Examples of these Building Regulations will be extracted from Mr Todd's report [1] to serve as illustration of how those Building Regulations provide solutions to the requirements of the fire safety strategy.

The events of June 14th, 2017 will be discussed following the structure described below:

1. Assessment of the evolution of the fire within the room of origin. The room of origin is assumed to be the kitchen of Flat 16 based on references [2] and [3]. An analysis of the potential dynamics of the fire event will be used to provide some insight into the mechanisms by which the fire exited the compartment of origin. These mechanisms will be contrasted against the fire safety strategy and compliance failures as per reference [4].
2. Assessment of the external fire growth and its impact on tenability[11]. Details of the evolution of the external fire will be extracted from reference [5] together with video, photographs and other documentation provided by the Public Inquiry. These will be used to describe the time evolution of tenability through the building.
3. Comparison with prior events. The evolution of the Grenfell Tower fire will be contrasted with past fire events with similar characteristics and where there were similar compliance failures as per reference [4]. This information will be used to provide some insight into aspects of the fire safety strategy that were critical to the outcome.

The description of human behaviour in the event of a fire requires more than a Newtonian physics framework. A fire safety strategy is intended to provide sufficiently robust solutions that do not depend upon a detailed analysis of human behaviour. The interactions between people and the fire, human behaviour and decision making will therefore not be discussed in this report. In contrast, the evolution of the fire as it pertains to tenability of the different areas of the building will be discussed in detail. Placement and communications from individuals within the building will be contrasted with

[11] See footnote (1) for approximate times for each stage.

the evolution of the fire to draw conclusions on the impact that each element of the fire safety strategy had on the evolution of tenability.

The intervention timeline and firefighting procedures are beyond the scope of this report, but nevertheless, the evolution of firefighting activities relative to the fire growth and the attainment of untenable conditions will be discussed. The evolution of the fire will be contrasted with fire brigade related information to draw conclusions on the role of each element of the fire safety strategy.

1.4. FIELD OF EXPERTISE

1.4.1. My name is José L. Torero. I am the John L. Bryan Chair at the Department of Fire Protection Engineering and the Director of the Center for Disaster Resilience at the Department of Civil Engineering at the University of Maryland, USA. I also serve as Director of TAEC. Previously, I was Prof. of Civil Engineering and Head of the School of Civil Engineering at the University of Queensland, Australia (2012-2017). Before moving to Australia, I held the Landolt & Cia Chair for Innovation for a Sustainable Future at the Ecole Polytechnique Fédéral de Lausanne, Switzerland (2012) and the BRE Trust/RAEng Chair in Fire Safety Engineering at the University of Edinburgh (2004-2011). Between 2004 and 2011 I was also the Director of the BRE Centre for Fire Safety Engineering and in the 2008 to 2011 period I was Head of the Institute for Infrastructure and Environment, both at the University of Edinburgh. I have held other positions at CNRS (France), University of Maryland (USA), NIST (USA) and NASA (USA).

1.4.2. My field of expertise is fire safety; a field in which I have worked for more than 25 years. I was trained as a Mechanical Engineer obtaining a Bachelor of Science from the Pontificia Universidad Católica del Perú in 1989. In 1991 I obtained a Master of Science and in 1992 a PhD from the University of California, Berkeley, both in Mechanical Engineering with specialty in Fire Safety. I am a Chartered Engineer by the Engineering Council Division of the Institution of Fire Engineers (UK), a Registered Professional Engineer in Queensland and a full member of the Society of Fire Protection Engineers (USA).

1.4.3. I am a Fellow of the Royal Academy of Engineering, the Royal Society of Edinburgh, the Australian Academy of Technological Sciences and Engineering, The Institution of Civil Engineers, The Institution of Fire Engineers, the Society of Fire Protection Engineers and the Combustion Institute. In 2008 I was awarded the Arthur B. Guise Medal by the Society of Fire Protection Engineers (USA) and in 2011 the David Rasbash Medal by the Institution of Fire Engineers (UK) in recognition for eminent achievement in the education, engineering and science of fire safety. In 2016 I was awarded a Doctor of Science *Honoris Causa* from Ghent University, Belgium. I am the author of more than 500 technical documents in all aspects of fire safety of which more than 200 are peer review scientific journal publications. I have been invited to deliver more than 100 keynote lectures in conferences and professional fora worldwide of which more than 20 have been in the area of Fire Investigation.

1.4.4. I was the Editor-in-Chief of Fire Safety Journal (2010-2016), the most respected scientific publication in the field, Associate Editor of Combustion Science and Technology (1997-2008) and a member of the Editorial Board of Fire Technology, ICE Journal of Forensic Engineering, Fire Science and Technology, Case Studies in Fire Safety, Progress in Energy and Combustion Science and the

Journal of the International Council for Tall Buildings. I am one of the Editors of the 4th Edition of the Fire Protection Engineering Handbook of the Society of Fire Protection Engineers (USA) and an author of several chapters. I am regularly in the Scientific Advisory Boards of most conferences in the field and a member of the Committee of many professional organizations. I chaired the Fire Safety Working Group for the International Council for Tall Buildings and Urban Habitat and was the vice-Chair of the International Association for Fire Safety Science.

1.4.5. I have been involved in numerous fire investigations many of which have been landmark studies. Between 2001-2010 I was involved in an independent investigation of the World Trade Center buildings 1 and 2 collapses. I was involved in the fire and structural modelling of the World Trade Center building 7 collapse in support of litigation and conducted an independent investigation of the fire growth and structural failure of the Madrid Windsor Tower Fire commissioned by the British Concrete Institute. I conducted a cause and origin investigation of the Texas City explosion and subsequent fires as well as a damage correlation analysis. I conducted dispersion fire modelling supporting the litigation of the Buncefield Explosion and of the Sego mine explosion (USA). I supported the fire service investigation of the Ycua Bolanos supermarket fire in Paraguay to establish the cause of the fire and to analyse the reasons for the fatalities. I conducted the fire investigation of La Rocha prison fire in Uruguay where 12 inmates died where we developed analytical and numerical model of fire growth in support of the investigation. I conducted the fire investigation of the San Miguel prison fire in Chile where 26 inmates died where we developed analytical and numerical models of fire growth in support of the investigation. I worked with the Scottish Fire Service on the Balmoral Bar fire investigation. I conducted the post-fire structural assessment of the Abu-Dhabi Plaza fire in Kazakhstan, probably the biggest ever fire of a building under construction. Recently, I led the fire investigation of the Ayotzinapa 43 murder case driven by the Organization of American States that encouraged the Mexican government to reopen the investigation. (*Science*, 11 March 2016, vol. 351 Issue 6278, pp.1141-1143 and *Science*, 29 April 2016, vol. 352, issue 6285, p.499) and by the National Academy of Science (USA) (http://www7.nationalacademies.org/humanrights/). I served as advisor to the Attorney General of Mexico in the subsequent investigation. I have given expert testimony in several forensic fire investigations worldwide.

1.4.6. I have developed novel methodologies for forensic fire investigation that have affected the manner in which fire investigation is conducted and its legal ramifications (V. Brannigan and J. L. Torero, "The Expert's New Clothes: Arson "Science" After Kumho Tire," Fire Chief Magazine, 60-65, July 1999.). For these studies I have received the William M. Carey Award for the Best Paper Presented at the Fire Suppression and Detection Research Application Symposium (C. Worrell, G. Gaines, R. Roby, L. Streit and J.L. Torero, "Enhanced Deposition, Acoustic Agglomeration and Chladni Figures in Smoke Detectors," Fire Technology, Fourth Quarter, 37, Number 4, pages 343-363, 2001), the Harry C. Bigglestone Award for the Best Paper Published in Fire Technology (T .Ma, S.M. Olenick, M.S. Klassen, R.J. Roby and J.L. Torero, "Burning Rate of Liquid Fuel on Carpet (Porous Media)" Fire Technology, 40,3, 227-246, 2004) and the Telford Premium Best Paper Award by the Institution of Civil Engineers (J.L. Torero, "Forensic Analysis of Fire Induced Structural Failure: The World Trade Centre, New York" ICE Journal of Forensic Engineering, 164, 2, 69-77, 2011.). I was awarded the FM Global Best Paper Award for a paper on the precision of fire models and the required skills for fire modelling (G. Rein, J. L. Torero, W. Jahn, J. Stern-Gottfried, N. L. Ryder, S. Desanghere, M Lazaro, F. Mowrer, A. Coles, D. Joyeux, D. Alvear, J. A. Capote, A. Jowsey, C. Abecassis-Empis,

P. Reszka, Round-robin study of a priori modelling predictions of the Dalmarnock Fire Test One, Fire Safety Journal, 44, 590-602, 2009.).

1.4.7. For more than 20 years I have been involved in the education and training of fire engineers, fire investigators and the fire service. I have developed training programmes on fire investigation for the Bureau of Alcohol Tobacco and Fire Arms (USA), fire investigators and fire brigades in the UK (University of Edinburgh short course in Fire Science and Fire Investigation, 2001-20012), the RAIB (UK) and the Police Scientifique of Lyon (France) among others. I have taught courses at Fire Service College Gullane, for the Queensland Fire and Emergency Services and for the fire services in numerous other countries (Costa Rica, Chile, Peru, Argentina, Singapore, Malaysia, etc.). I have developed curriculum and taught the Fire Protection Engineering programme at the University of Maryland, the Structural and Fire Safety Engineering course at the University of Edinburgh, the Civil and Fire Safety Engineering course at the University of Queensland and the International Masters in Fire Safety Engineering (Ghent, Lund and Edinburgh Universities). I was external examiner to the Fire Safety programme of Glasgow Caledonian University (UK) and I am on the Advisory Board of Worcester Polytechnic Institute (USA) Fire Protection Engineering programme. I am a Distinguished Visiting Chair Prof. in Fire Safety Engineering at the Hong Kong Polytechnic University.

1.4.8. In the period 2007 to 2010 I lead the development of the FireGrid project funded by the Department of Trade and Industry and in partnership with the London, Manchester, Strathclyde and Lothian and Borders Fire Brigades where a detailed study of the role of information on fire brigade emergency response was analysed. This project was featured in the 2007 BBC Horizon Documentary "Skyscrapers Fire Fighters" that has been shown in more than 30 countries. In 2010 I was awarded a GBP 2M grant by the Engineering and Physical Sciences Research Council UK to study the Real Fires for the Safe Design of Tall Buildings.

1.4.9. I have been involved in numerous advisory roles for industry and government many of them including the fire service. I was involved in the Nuclear Regulatory Commission (USA), PRiT Committee on Fire Modelling, a member of the Expert panel of the Fire and Resilience Directorate (Communities and Local Government, UK) and of the Forum of Chief Fire Officers of Scotland (SDAF). I was advisor to the Department of Transportation and Main Roads (Queensland, Australia), special advisor to the vice- President of Peru on the Utopia Club and Mesa Redonda fire investigations and a member of the CFOA Training Needs Analysis Gateway Review Group. I am currently special advisor to the Minister of Housing (Queensland) on issues of façade fires. I am a regular participant in standards development committees worldwide.

1.4.10 A full and up to date CV (current at the time of Torero's initial instruction as Expert Witness) has previously been provided to the Inquiry's Core Participants.

1.5. STATEMENTS

I confirm that I have made clear which facts and matters referred to in this report are within my own knowledge and which are not. Those that are within my own knowledge I confirm to be true. The opinions I have expressed represent my true and complete professional opinions on the matters to which they refer.

I was assisted in the production of this report by the following individuals:

Dr Adam Cowlard - Director and senior engineer at Torero, Abecassis Empis and Cowlard Ltd. Dr Cowlard holds a PhD in Fire Safety Engineering and an MEng in Civil Engineering from the University of Edinburgh. He has undertaken a wide range of consultancy and research work encompassing development of fire safety strategies for a wide range of complex infrastructure, development of design fires and heat transfer modelling, and fire and evacuation modelling. Dr Cowlard supported my work primarily on modelling, data analysis, reporting and reviewing.

Dr Richard Krupar III – While conducting this work he was a post-doctoral research associate at the Center for Disaster resilience at the University of Maryland. Dr Krupar holds a PhD in Wind Science and Engineering and is an expert in damage assessment. He has conducted damage assessment for many major events such as Hurricane Harvey. Dr Krupar supported my work primarily on the damage analysis, video footage assessment, reporting and reviewing.

Mr Alex Duffy – Faculty Assistant at the Department of Civil Engineering (University of Maryland. Mr Duffy holds a Master in Design Studies from Harvard Graduate School of Design, and a Master in Civil Engineering from the University of Edinburgh. He has more than five years' experience in fire safety engineering design. Mr Duffy supported my work primarily through data collection, analysis, organization of information, reporting and reviewing.

I confirm that I understand my duty to assist the Inquiry on matters within my expertise, and that I have complied with that duty. I also confirm that I am aware of the requirements of Part 35 and the supporting Practice Direction and the Guidance for the Instruction of Experts in Civil Claims 2014.

I confirm that I have no conflict of interest of any kind, other than any which I have already set out in this report. I do not consider that any interest which I have disclosed affects my suitability to give expert evidence to the Inquiry on any issue on which I have given evidence and I will advise the Inquiry if, between the date of this report and the Inquiry hearings, there is any change in circumstances which affects this statement.

Signed:  Dated: 23 May, 2018

2 BACKGROUND

2.1. THE FIRE SAFETY STRATEGY FOR HIGH-RISE BUILDINGS

To guarantee the safety of people occupying a high-rise building during a fire event, it is necessary to implement a complex and precise fire safety strategy [7, 8]. The components of such a fire safety strategy can be explicitly stated or introduced in an implicit manner through prescriptive requirements. In both cases, the design of such a strategy requires careful consideration because the safe use of a high-rise building is a complex problem [7, 8].

Fire safety strategy, as referred to in this document, is the concept by which different measures are taken to guarantee a societally accepted adequate level of safety of people against fire. It is also implied that by guaranteeing the adequate safety of people, material losses will also be mitigated. In many countries, the concept of a fire safety strategy is required to be translated to documents that are part of the approvals process and might be referred by the same name or others (e.g. Fire safety brief, fire protection strategy, fire engineering brief, etc.). For the purpose of this report the term fire safety strategy is not related to any of these documents but remains purely as the concept explained above.

The fire safety strategy is linked to how the building is defined or classified. The definition of a building that is to be classified as a high-rise building is also complex. Regulations many times propose simple definitions of a high-rise building only on the basis of height, (Sections 4.1.5 and 4.1.6 [1]) nevertheless numerous assumptions hide behind the classification. These assumptions, together with the many protective measures implemented, allow these buildings to be used in a safe manner. The assumptions and protective measures will vary depending on the specific characteristics and use of a building (Section 4.1.6 [1]).

Conceptually, the fire safety strategy for a high-rise building recognises that the main characteristic that defines a high-rise building is a convergence of time scales. In a high-rise building, people will take significant time to evacuate (several minutes), therefore the time to egress is of the same order of magnitude as the time for failure or the time required for fire and rescue service intervention [8]. Time for failure could be defined in many ways, such as attainment of conditions that are untenable, structural failure, etc. In buildings that are not classified as high-rise, egress times are generally very short compared to all other characteristic times, therefore occupants are not expected to interact with firefighting operations or with the different potential modes of failure. It is clear that this will only be the case if the fire safety strategy works appropriately during the fire event.

Given this convergence of time scales, there is insufficient time to evacuate everyone and therefore a high-rise building requires the existence of safe areas within the building. These safe areas are intended to assure the wellbeing of occupants while the fire grows and while countermeasures and fire fighter operations are in progress. Furthermore, in the case of vulnerable people, these safe areas will serve to provide protection until rescue is achieved (Section 2.105 [1]).

The most common safe areas are the stairwells. Stairwells are intended to remain isolated from the event during the duration of the fire, guaranteeing the egress process. There is no limit to the time where stairwells are to remain safe. To maintain the stairs as safe areas during the fire, these have to

be constructed such that the fire is prevented from damaging the enclosure (i.e. walls and doors). Furthermore, redundancies are necessary for all safety systems; therefore, supplemental protection can be introduced to prevent smoke from entering the stairs. Typical approaches are: ventilated lobbies that create a buffer between areas with combustible materials and the stairs, or increasing the pressure within the stair thus ensuring a flow of air from the stair to the lobby (as opposed to smoke from the lobby to the stair), etc. Some of these are discussed in Section 3.2.20 of Dr. Lane's Phase One report [4].

Also, it is important for safety systems to have redundancies, therefore having more than one means of egress is highly desirable. Nevertheless, it is recognised that emergency stairs can occupy a significant fraction of the surface area of a high-rise building, challenging its functionality. Limiting the number of stairs therefore might be necessary. In this case, other forms of redundancy might be introduced. A common form of redundancy is to prevent the fire or smoke from escaping the sector of the building where the fire originated. This is achieved by means of barriers that block the progression of a fire out of a sector. Egress, in this case, can be contained to the high-risk sectors of the building and the rest of the occupants will remain in place. All other sectors of the building are deemed safe. Firefighting operations will proceed with occupants in the building, therefore, provisions have to be made to account for firefighter-occupant interactions. These provisions are in part designed into the building but also relate to firefighting operations. This strategy is generally named "stay put" or "defend-in-place.[12]"

Buildings will bound these sectors by means of barriers that are qualified as "fire resistant[13]." Typically, for residential units, each unit represents a sector, therefore the perimeter of the unit needs to meet "fire resistance" requirements. Certain boundaries of the sector can be deemed more important than

[12] The term "stay put" is common in the UK and it is directed towards the occupants and the instructions that need to be provided to them so that their actions during a fire are consistent with the fire safety strategy [1]. The term "defend in place" is more common in North America and emphasizes firefighting operations. The term "defend in place" indicates that firefighters will be aware that occupants will remain in place while firefighting operations proceed. While both terms might represent slightly different procedures, the primary intention is the same for "stay put" and "defend in place" strategies. In both cases, rescue (i.e. firefighter managed egress) and firefighting operations supersede occupant driven egress. These definitions are not identical but consistent with those presented in Dr. Lane's Phase 1 Expert Report (Sections 2.8.7 and 2.8.20 [4]).

[13] Fire resistance is a standard term used to describe the performance of structural components in a standard test. This test is recognized internationally (BS 476, ISO 834, ASTM-E 119, etc.) and it provides a standard and severe thermal exposure to the structural element by means of a furnace. The structural element is introduced in the furnace and the furnace temperature is then increased in a predefined and standard manner. The term "fire resistance" is then defined as the time (in intervals of 30 minutes) that the structural element can withstand the thermal exposure before it reaches a predefined failure criterion (normally specified as a critical temperature). It is important to clarify that the standard thermal exposure does not correspond to a typical thermal exposure during a fire and structural elements do not behave in exactly the same manner in a furnace as in a building, therefore the "fire resistance" does not represent a real time to failure. "Fire resistance" is nevertheless considered as a "worst case scenario" that provides a relative ranking between structural elements. Structural elements that are to act as barriers (floors, walls, doors, etc.) will therefore have to meet requirements of "fire resistance" before they can be used in a building. Products such as doors, fire-stop systems, etc. will be tested and listed with a "fire resistance" before they can be sold as barriers. Commonly used structural elements such as partition walls will be designed and built in a manner consistent with systems that have been tested and certified. Some variations can be permitted but, in general, given the complexity of these systems, any variation will have to be analyzed and approved by a competent professional.

others, therefore a higher "fire resistance" might be required. It is typical to recognize that global structural integrity and containment of a fire to the floor of origin are of critical importance for high-rise buildings, therefore floor slabs and main structural elements generally will have higher fire resistance requirements than doors or non-load bearing partition walls.

It is recognized that certain components of these sectors cannot behave as barriers to the same extent as walls or floor slabs. Windows are some of these necessary components. Windows will incorporate glazing and could be potentially open, nevertheless, provisions are still necessary to prevent a fire from entering the adjacent sectors. Figure 1 shows an external photograph of the recent Trump Tower fire in New York (April 8th, 2018). Figure 1(a) shows the magnitude of the fire and Figure 1(b) the external glazing after the event. The figure shows that the fires did not progress to the sectors above or adjacent to the sector of fire origin. In this case the compartmentalization[14] provisions performed adequately. Unfortunately, a detailed investigation is currently unavailable and therefore the design features that enabled the adequate behaviour of this building cannot be established.

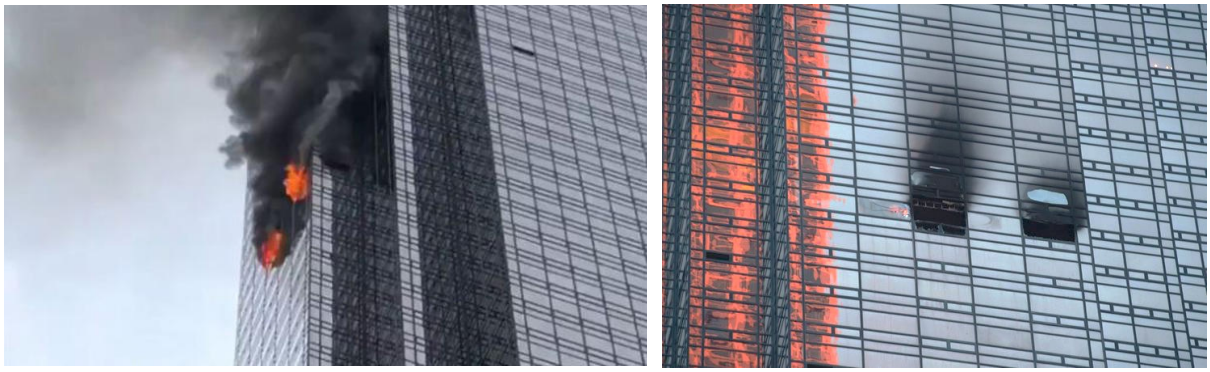


FIGURE 1: TRUMP TOWER FIRE, APRIL 8TH, 2018 (A) THE FIRE DURING BURNING SHOWING A FULLY DEVELOPED POST-FLASHOVER FIRE (B) THE AFTERMATH SHOWING THE EXTENT OF DAMAGE OF THE GLAZING.

It is important to note that robustness and redundancies are paramount for high-rise buildings because for these buildings the evolution of a fire, as it scales-up, can be extremely complex [9] and the behaviour of occupants over such long time-scales is highly uncertain. Furthermore, the performance of many of the fire safety systems and that of the fire brigades is stretched [8]. Given the characteristics of high-rise buildings, Building Regulations will therefore stipulate robust solutions and many redundancies [1].

2.2. THE GRENFELL TOWER FIRE SAFETY STRATEGY

The Grenfell Tower was classified as a high-rise residential building due to its height and occupancy. As such a fire safety strategy that is consistent with this classification would have been implemented. This section explores the different fire safety measures observed in Grenfell Tower and structures them in the context of a conceptual fire safety strategy. This section does not analyse any document on the matter of the fire safety strategy that could have been written for approvals or other purposes.

[14] Compartmentalization is the term used to describe the concept of delivering a sector that is expected to fully contain a fire. The sector is therefore generally termed a compartment. A compartment is protected by fire resistant barriers and is designed to prevent a fire from spreading to any adjacent compartment.

The building had limited means of egress (one stair) and therefore required a "stay put" strategy. In conceptual terms the safety of occupants in such a high-rise situation would be guaranteed in the following general ways:

- The objective of a fire safety strategy is to mitigate the consequences of a fire. Therefore, a fire is assumed to occur. Arson and premeditated fires are not contemplated in Building Regulations and therefore the assumption is that there will be a single event. Lobbies and stairs are required to be free of combustible materials so, in a building of this nature, fires are assumed to start and remain within a residential unit. The residential unit represents the sector to be enclosed by "fire resistant" barriers.
- Maximum allowable travel distances within the unit are restricted and smoke/heat detection and alarm is required (Section 1.5 [1]). Adequate detection and alarm will rapidly start the onset of egress, and the short travel distances will guarantee that occupants of the residential unit where the fire originates will reach a safe area before conditions within the residential unit are untenable.
- Sprinklers can be used as a means to control the rate of growth of a fire, giving the tenant more time to exit the unit. Whilst sprinklers can potentially extinguish the fire of origin, thus eliminating the problem, responsible design cannot assume that, due to the presence of sprinklers, a fire event that challenges the lives of tenants will not occur. Sprinklers will only reduce the probability of a life-threatening fire and therefore can be included as supplemental protection, but do not supersede other elements of the strategy (Section 2.30 [1]). In the case of Grenfell Tower it was not required to have sprinklers [1] as supplemental protection given the time that it was built and sprinkler protection was therefore not incorporated.
- Detection and alarm systems within a residential unit are not interconnected to the rest of the building. Interconnected detection systems are not generally desirable because otherwise a minor event can lead to the unnecessary evacuation of a building. Instead, the residential unit is the sector that is enclosed (walls, floor and ceiling) such that the fire/smoke cannot escape the unit until the full burn-out[15] of all combustible materials (fire resistant compartmentalization). A detection/alarm system that is interconnected to the rest of the building could then be placed in the lobby outside the residential unit. If the smoke has breached the barrier and compromised the lobby an alarm will occur. This signals the onset of egress for all floors at risk. It is possible to adopt an alternative approach. For example, it is possible to have a detection system in the lobby which will activate and provide a means by which egress paths can be kept clear of smoke, allowing for safe evacuation of the occupants if necessary (Section 1.5 [1]). In the Grenfell Tower the smoke detector in the lobby was not required to be interconnected (Section 1.5 [1]) but was introduced as part of the smoke control system whose objective was to maintain egress paths clear from smoke.
- To deliver the enclosure of the residential unit, walls, ceilings and floors are designed in a manner that they prevent fire and smoke from penetrating throughout the duration of burning. This applies to all penetrations (electrical, water, sewage, mechanical, gas, etc.) as well as doors. Doors designed to withstand a fire as well as self-closing systems are generally

[15] Design for burn-out is a concept implicit in the definition of required fire resistance. Structural components should be capable of withstanding the heat generated by a fire until all the fuel has been consumed. Therefore, the energy delivered by a fire until burnout should be less that the energy delivered by the fire resistance furnace until the time associated to the required fire resistance. Other factors can enhance the required fire resistance such as safety factors that serve as multipliers used to manage situations with different levels of risk.

required to prevent smoke from escaping the residential unit (Section 2.4 [1]). The requirements of all these barriers are expressed in terms of "fire resistance."

- An unavoidable penetration of the residential unit are the widows and other outward facing openings (e.g. extraction systems). These penetrations need to be designed in a manner that prevents a fire from entering any of the areas adjacent to the residential unit. It is recognized that glazing will either be open or fail in the event of a fire, therefore spreading to adjacent spaces is controlled by carefully defined strategies. Simple systems will rely on geometrical constraints that do not allow flame projections to enter adjacent spaces; more complex systems require more intricate solutions. The original design of Grenfell Tower achieved these objectives by means of simple geometrical constraints imposed on the external geometry and non-combustible fabric of the building. The refurbished building included an attached cladding system that required a more complex approach to the problem that included cavity barriers as well as detailed flammability assessment requirements for the systems used. It is important to note that the objective is to prevent a fire or smoke generated in a residential unit from penetrating any of the adjacent spaces (Section 2.24 [1]).
- In a similar manner, all vertical pathways need to be protected to prevent smoke and fire from progressing internally through the building beyond the residential unit of origin. Vertical pathways will include services, lifts, etc.
- In the event of a fire, occupants within the residential units at risk will proceed to evacuate immediately. The lobby is expected not to contain any combustible materials and to be separated from all combustibles by a barrier (Section 2.95 [1]). These barriers can be properly designed walls, enclosures or doors (Section 1.4 [1]). The units at risk could be interpreted as those in the floor of the fire or even just the unit were the fire originated (Section 2.10 [1])
- The pathway between the residential units and the safe area (i.e. the stairwell) has no redundancy, therefore a smoke management system is used in Grenfell Tower to provide a redundant system that could clear smoke in the event that any of the barriers does not fulfil its function ("smoke dispersal," Sections 2.7 and 2.8 [1]).
- The occupants might interact with the fire brigades, although such interactions are expected to be in sufficiently small numbers that they will be well structured. Fire brigade predefined procedures will enable adequate interactions (Sections 2.11 to 2.14 [1]).
- Occupants in units that are not deemed at risk will remain in their flats ("stay put") until instructions are received from the fire brigade. Fire brigade predefined procedures will enable proper management of information to all building occupants (Sections 2.11 to 2.14 [1]).
- Fire brigade operations have the potential to affect the displacement of smoke and flames, therefore, firefighting operations take priority and occupant/fire fighter interactions are expected to be minimized. Fire brigade protocols govern these interactions (Sections 2.11 to 2.14 [1]).
- The building design will consider measures for firefighters to perform their duties adequately (section 2.9 and 2.27 [1]). This includes water supplies, means of access but also all provisions necessary for fire fighters to conduct their duties in a manner that is effective and safe.
- Through the entirety of any firefighting intervention the structure should keep sufficient mechanical strength so that it can fulfil its functions. All structural elements are therefore required to withstand a fire until burn-out. This is normally expressed in terms of "fire resistance" (Section 4.1.16 [1]) and is generally specified not as withstanding burn-out but as "stability will be maintained for a reasonable period" (Section 5.1.14 [1]).

2.3. ASSUMPTIONS EMBEDDED IN THE GRENFELL TOWER FIRE SAFETY STRATEGY

A fire safety strategy relies on many assumptions. Some of these assumptions are associated with the design and implementation process, others with maintenance and many with adequate performance. Having explained the rationale behind the measures implemented or not implemented within the conceptual fire safety strategy for Grenfell Tower it is important to establish some of the key assumptions that enable the performance of these measures:

- That the means to establish performance of all fire safety systems can deliver a performance assessment that is sufficiently accurate and robust. Thus, performance is assumed to be as intended.
- That all components of the fire safety strategy are designed with the intention that they can be built such that the prescribed performance of the design is achieved. The most common means to validate this assumption is through pre-completion inspections and commissioning of the different systems. It is assumed that these occur where necessary.
- That all components of the fire safety strategy are built such that they can be appropriately maintained. Provisions for inspection and maintenance with adequate means to manage repairs and improvements are assumed. It is also assumed that these provisions and means are consistent with the complexity of the systems implemented (Section 2.32 [1]).
- That all professionals involved in the design, building, commissioning, inspection and maintenance have the competency necessary to perform their duties for the specific systems being addressed [10]. Thus, it is possible for the user to rely on the outcome of all professional assessments which have been made (Section 2.32 [1]).

A fundamental performance assumption key to all high-rise buildings is the containment of the fire within the unit of origin. Particularly important is the prevention of vertical flame spread. Horizontal spread to adjacent units is also important albeit I will focus first on vertical flame spread. It has to be noted that the LGA Guide does not envisage “no” external flame spread but states that the external facades of blocks of flats “should not provide potential for extensive fire spread” (Section 2.96 [1]). This will be addressed in detail in the next section.

It is clear that when assessing performance, it is not possible to make absolute statements. Nevertheless, in this particular case, it is important to analyse the implications of vertical flame spread by contrasting that with the scenario of “no” vertical flame spread. If it is assumed that there will be no vertical flame spread then the following performance statements are valid:

1. “Stay put” strategy: If the fire is to be contained to one floor then, in the event of a fire, only the floor of the fire (critical) and the floor above and below need to be evacuated (robustness). The rest of the occupants can remain in the building and wait until the fire service delivers evacuation instructions. Many countries assume the need for a robust approach that requires the evacuation of multiple floors. In the Building Regulations and guidelines applicable to Grenfell Tower there is no requirement for provisions that allow for occupants of more than the flat of fire origin to evacuate (Section 5.1.57 [1]). It is expected that the fire service will control the fire (which might require the use of the stairs) and then establish if there is a need to proceed to evacuate the rest of the occupants. The standard fire service instructions for all occupants away from the immediate floors of the fire will be to remain in place. These

instructions will only change as a function of a dynamic risk assessment performed by the fire fighter in command (Section 12.25 [1]). But this is only possible if no vertical flame spread occurs. As indicated in Section 5.2.94 [1], this has been acknowledged in 2011 and 2015 versions of BS 9991 where "both versions of the Standard noted that this is (vertical flame spread) particularly important where a "stay put" strategy is in place."

2. Required Safe Egress Time (RSET): The RSET will be the time for the occupants to reach the stairs if it is possible to consider the stairs as a safe area. The total time for egress of the occupants of the building is no longer a factor of consideration. This is only valid if no vertical flame spread occurs.
3. Stairs as a Safe Area: Dimensioning of the stairs is calculated to accommodate occupants from a reduced number of residential units and potential firefighting operations (critical). If many floors are evacuated congestion is possible and this has the potential to disable the orderly evacuation process necessary for an emergency. As stated by Colin Todd in his Phase 1 Report. (section 5.1.58 [1]) "…if all residents in a high-rise block chose to evacuate simultaneously, this might well place residents at risk and would create a major impediment for fire-fighting activity by the fire and rescue service." Adequate fire resistance of walls and doors (critical) and a smoke management strategy for the lobby (robustness) will guarantee the safety of the stairs. The air intake and exhaust systems will be designed on the basis of a single floor fire. But this strategy that makes the stairs a safe space is only applicable if no vertical flame spread occurs.
4. Detection and Alarm: Detection systems will provide sufficient warning by means of an alarm. Detection systems are only implemented in units and are intended to warn only the occupants of the unit where the fire originates. The fire will not be detected in any other unit. In the absence of adequate conditions for a "stay put" strategy, the detection and alarm system will not deliver adequate warning to the rest of the occupants.
5. Notification: Instructions that a "stay put" strategy is enabled are not considered necessary and notification is restricted to the unit where the fire originates. Building Regulations and guidelines require no provisions of information to the occupants (Section 9.1.24 (Fire Safety Order Article 13), Section 9.1.26, Section 12.18 [1]). It is not deemed necessary or appropriate to provide detection, alarm or notification in common parts of blocks of flats other than what is required for smoke management. In the absence of mechanisms to provide instructions, and in the event that conditions that nullify the viability of a "stay put" strategy exist (i.e. vertical flame spread), occupants will be left to their own means (and those available to the fire service), to determine that adequate conditions for a "stay put" strategy no longer exist and that an alternative approach is necessary. This is a particularly vulnerable aspect of the approach currently used and supported by Building Regulations and guidelines applicable to Grenfell Tower. If the fire remains within the unit where it originated, this approach remains viable because only those within the unit of origin are in real risk. This is, therefore, only an acceptable approach to public safety or a reasonable requirement for the fire service in the absence of vertical flame spread.
6. Sprinkler Systems: The design of a sprinkler system enables the control of fires of a magnitude and characteristics consistent with very strict operational requirements. In a residential setting, the design of a sprinkler system serves to control fires that involve furniture and other common materials such as paper, clothing, carpets, etc. The design of the water supply for sprinklers provides sufficient water to control a fire for a limited number of sprinkler heads (normally those that will activate in a one sector/floor fire). If the sprinklers operate in an adequate manner, they will control the fire and eliminate the problem. If the sprinkler is not capable of controlling the fire then the rest of the fire safety strategy has to guarantee the desirable outcome. Therefore, for high-rise buildings, sprinklers are only a supplement to the

fire safety strategy. Their primary purpose is to reduce the probability of a significant compartment fire. The performance of external sprinklers has never been studied with sufficient detail to establish what conditions will result in adequate fire control of external fires. Furthermore, multiple floor fires will exceed the water supply capacity of the sprinkler system. Therefore, a sprinkler system will not provide any protection and is not designed to operate in the event of external flame spread.

7. Structural Performance: The structural system of a high-rise building needs to provide adequate performance during the period where the building still holds occupants or fire fighters. In a "stay put" strategy, an estimation of the time required to fully evacuate the building is difficult. Statistics on the performance of fire fighters in high-rise buildings are not very extensive or quantitative. It is therefore preferable to design a high-rise building to withstand burn-out of the fuel load. The implementation of this methodology is normally done by means of fire resistance testing; single-element testing that assumes adequate load redistribution from the areas affected by the fire to areas that remain cold (and thus have their full design strength and stiffness). Horizontal and vertical compartmentalization becomes essential for the fire resistance framework to be valid. Fire resistance can only be a reasonable methodology for structural assessment if no vertical flame spread occurs. It is possible to establish the performance of a structure for different fire sizes in a quantitative manner by using complex analytical methods of structural analysis. Nevertheless, the application of these methods to conditions that involve multiple floor fires is not required or common and was therefore not applied to Grenfell Tower.
8. Firefighting operations: Firefighting protocols for response to high-rise building fires are intimately linked to a single floor fire. Furthermore, for residential buildings, the firefighters should find, upon arrival, a single unit fire. Firefighting provisions, such as water supply, are also dimensioned under the expectation of a certain magnitude event. If vertical flame spread occurs this will require the drastic modification of firefighting protocols and advance planning. These modifications rest within the remit of the command structure of the responding units. As indicated in Section 12.20 [1] of Colin Todd's Phase 1 Report, "It is the role of the fire and rescue service to make the decision as to whether…evacuation is necessary." Furthermore, the means by which the fire service can alter the strategy are very basic (by knocking on flat entrance doors, by operating sounders within residents' flats, etc. (Section 12.20 [1]) and these are all approaches that are inconsistent with a fire that has spread vertically or horizontally.

As is demonstrated from the analysis above, the occurrence of any form of vertical flame spread disables every element of the fire safety assumptions underpinning the Grenfell Tower design.

Horizontal flame spread compromises the adjacent units and has the potential to enhance vertical flame spread. The combined effects of horizontal and vertical flame spread in systems of this scale and complexity has never been studied in any detail. Acceptable rates of flame spread are defined by means of performance scenario testing. The assessment of the validity of these tests is outside the scope of this Phase One report nevertheless should be explored in Phase Two.

In the case of fires progressing inwards, there are no provisions to prevent the inward spread of fires, therefore in the event of vertical or horizontal flame spread there is no structured barrier that will prevent the involvement of further units through fires spreading inwards.

It will however be necessary to examine the active and passive fire safety systems which were in operation at Grenfell Tower at the time of the fire. The Grenfell Tower design incorporated other

layers of fire protection that, in principle, could have enhanced its robustness, even in the event of significant external flame spread. A detailed analysis of the fire performance of this specific building is necessary to establish how the fire penetrated the boundaries of the residential units, resulted in vertical and horizontal flame spread and ultimately disabled all components of the fire safety strategy.

It is important to note that current Building Regulations and firefighting practices will not touch upon a scenario where vertical and horizontal flame spread occurs [1]. Thus, from a regulatory perspective, the assumption of "no" vertical and horizontal flame spread is made. As referred to in Section 9.2.35 (v.) of Colin Todd's Phase 1 Report [1], the LGA Guide indicates that "The "stay put" principle is undoubtedly successful in an overwhelming number of fires in blocks of flats. In 2009-2010, of over 8,000 fires in blocks of flats, only 22 fires necessitated evacuation of more than five people by the fire and rescue service." While the statistics support the "stay put" approach, there is no indication of the relationship between its success and the success of compartmentalization. Furthermore, there is no indication of the conditions of the fires in the 22 cases that necessitated the evacuation of more than five people. This lack of detail further emphasizes the assumption that "no" vertical and horizontal flame spread will occur and that there is no need for further analysis of the relationship between the success of compartmentalization and success of the "stay put" strategy.

An implicit difficulty with the Building Regulations is the acceptance of some level of fire spread, by referring to the concept of "adequate" fire spread. This will be discussed in more detail in the following section.

2.4. DIFFERENTIATING "ADEQUATE" FROM "NO" FIRE SPREAD

It is clear from Section 2.3 that all Building Regulations and firefighting practices relevant to Grenfell Tower do not touch upon a scenario where vertical and horizontal flame spread occurs [1]. Thus, from a regulatory perspective, the assumption of "no" vertical and horizontal flame spread is implicitly made[16].

Section 12.5 of Approved Document B (ADB) [11] recognizes the hazard associated with external fire spread. It states: "*External Wall Construction. The external envelope of a building should <u>not</u> provide a medium for fire spread if it is likely to be a risk to health and safety. The use of combustible materials in the cladding system and extensive cavities may represent such a risk in tall buildings.*" Given the importance of this matter to the fire safety strategy, this issue is one that requires detailed consideration and section 12.5 addresses it in absolute terms.

[16] For the purposes of this report the relationship between the building and the fire will be defined as follows. An internal fire is one that originates and grows within the confines of a compartment in the building. These fires might project flames externally but the fuel is internal to the building compartment. The flame projections deliver heat to the building locally (heat fluxes as high as 120 kW/m^2 [12]) but unless they ignite materials placed on the exterior of the building or break into adjacent units, they will not spread because the fuel is all located within the building compartment. Beyond the compartment there will be no fuel to burn. Fires external to the building can be separated in two, external fires fueled by materials on the building envelope and external fires occurring in adjacent buildings. Fires fueled by materials within the building envelope can spread vertically and horizontally and provide heat fluxes similar to those of flame projections from internal fires (up to 120 kW/m^2). Fires from adjacent buildings are fueled by materials in a different building and only deliver heat. The magnitude of the heat is assumed not to exceed 12.6 kW/m^2 (ADB).

When the matter is addressed in the functional requirements, the functional requirement B4 indicates: "External fire spread: (1) The external walls of the building shall adequately resist the spread of fire over the walls and from one building to another, having regard to height, use and position of the building."

The language used in B4 introduces the ambiguity of "adequately" and it also refers to performance in terms such as "resistance." Furthermore, it requires that external walls shall "*resist the spread of fire over the walls and from one building to another.*" This leads to many potential interpretations (some of them inadequate) particularly by using the terminology "resist" which suggests that it is related to the concept of "fire resistance."

While codes commonly introduce ambiguity to allow for flexibility (which is often necessary for design purposes), in this case it hides a misunderstanding of the significance of vertical and horizontal flame spread to the fire safety strategy. Furthermore, it mixes two fundamentally different issues: fire spreading from another building, with fire initiated within the building and spreading to the external walls. While the latter is introduced in some of the relevant sections, it is clear that fire spreading from adjacent buildings is the main driver of the text.

The difference is very significant because in the case of fire spreading from one building to another, the generally accepted approach is to establish that the heat reaching the perimeter wall of an secondary building comes from a single compartment fire within the first building at a defined distance from that wall.

When the issue of fire spreading from an adjacent building is quantified, the main assumption in ADB is (Section 13.2): "*a. that the size of the fire will depend on the compartment of the building, so that a fire may involve a complete compartment, but will not spread to other compartments.*" Therefore, an explicit requirement for vertical and horizontal compartmentalization is once again introduced. Given a one compartment fire, Section 13.16 of ADB indicates that: "*The aim is to ensure that the building is separated from the boundary by at least half the distance at which the total thermal radiation intensity received from all unprotected areas in the wall would be 12.6 kW/m^2 (in still air).*" The value of 12.6 kW/m^2 therefore defines the thermal load expected on external walls (and glazing) for the scenario of fire spreading from an adjacent building. This is of fundamental importance because it defines the requirement that all external components need to meet to prevent fires igniting or entering a compartment from the outside.

In the case of a fire initiated within a building (i.e. issued from a compartment fire spill plume) and spreading on an external wall (including arson scenarios such as waste bin fires, etc.), the expected heat fluxes on the external wall can reach values in excess of 120 kW/m^2 [12]. This is not only an order of magnitude greater in intensity, but it is also a fire whose temporal evolution will be very different.

In my opinion, the two scenarios are very different and need to be addressed in an independent way. Nevertheless, ADB does not separate these scenarios. In terms of Guidance and the B4 functional requirement the following is stated:

"Performance:

In the Secretary of State's view the Requirements of B4 will be met:

a. If the external walls are constructed so that the risk of ignition from an external source and the spread of fire over their surfaces, is restricted, by making provision for them to have low rates of heat release;

b. If the amount of unprotected area in the side of the building is restricted so as to limit the amount of thermal radiation that can pass through the wall, taking the distance between the wall and the boundary into account; and

c. If the roof is constructed so that the risk of spread of flame and/or fire penetration from an external fire source is restricted.

In each case so as to limit the risk of a fire spreading from the building to a building beyond the boundary, or vice versa.

The extent to which this is necessary is dependent on the use of the building, its distance from the boundary and, in some cases, its height."

It is clear that all sections of Secretary of State's view following and including section (b) are directed at a fire spreading from an adjacent building and not for the purpose of guaranteeing adequate performance in the case were the fire initiates within the building. Furthermore, these sections are not adequate for the scenario were the fire initiates within the building.

Section (a) states "*the risk of ignition from an external source and the spread of fire over their surfaces, is restricted, by making provision for them to have low rates of heat release*". This introduces a further ambiguity through the use of the word "*restricted*." In the case of a 12.6 kW/m^2 "*external source*" many materials will not ignite or sustain spread. These include materials listed in Tables A6 (non-combustible) and A7 (limited combustibility) of ADB. Thus, in that context, the provision is logical. But, in the case of a 120 kW/m^2 "*external source*" only completely inert materials such as metals or ceramics will not ignite or sustain spread (materials classified as non-combustible – Table A6-ADB). Section (a) also indicates that the "*restriction*" is achieved "*by making provision for them to have low rates of heat release*." When addressing a thermal load of 120 kW/m^2 on an external wall to achieve the objective of "*no*" spread, the correct focus should be on the mechanisms controlling the capacity of a flame to spread. For very high heat fluxes and external walls, the rate of heat release is not the controlling variable[17] so a provision for a "*low rate of heat release*" is inappropriate.

Section 12.7 deals with "*Insulation Material Products*" and states "*In a building with a storey 18 m or more above ground level any insulation product, filler material (not including gaskets, sealants and similar) etc. used in external wall construction should be of limited combustibility (see Appendix A)*." Many materials that are classified as limited combustibility (e.g. National Class B (Table A7-ADB), National Class C (table A7-ADB), materials listed in item (5) of Class 0 (Table A8, ADB)) will ignite and spread a flame when subject to 120 kW/m^2. So, it is unclear how they will "adequately resist the spread of fire."

Furthermore, ADB indicates "*External walls should either meet the guidance given in paragraphs 12.6 to 12.9 or meet the performance criteria given in BRE Report Fire performance of external thermal insulation for walls of multi storey buildings (BR135) for cladding systems using full scale test data from BS 8414-1:2002 or BS 8414-2:2005*." But none of that testing contemplates heating from an "*external*

[17] The mechanisms controlling vertical and horizontal flame spread will be discussed in detail in Section 5.

source" of a magnitude of 120 kW/m^2 [12]. It is necessary to conduct a detailed analysis of BS 8414 aimed at establishing its true relevance and the value of information that can be extracted from the test results. This analysis is beyond the scope of this Phase One report.

Finally, Section 12.1 provides: "*for the external walls to have sufficient fire resistance to prevent fire spread across the relevant boundary*." This is followed by Section 12.2: "*Provisions are also made to restrict the combustibility of external walls of buildings that are less than 1000 mm from the relevant boundary and, irrespective of boundary distance, the external walls of high buildings and those of Assembly and Recreational Purpose Groups. This is in order to reduce the surface's susceptibility to ignition from an external source and to reduce the danger from fire spread up the external face of the building*." All these sections address solely the issue of fires spreading from an adjacent building.

While ambiguity is expected and accepted in functional requirements and guidance, any such ambiguity must nevertheless be compatible with the ability of competent professionals to understand and address any such ambiguity, in a way which means that safe and robust fire strategies can be created.

As I have illustrated above, in the case of external fire spread, the current functional requirements and guidance do not distinguish between external flame spread originating from a fire in an adjacent building from that originating in a room within the building. Given the drastically different characteristics of the thermal input for each scenario, this creates a complex ambiguity that affects classification and performance assessment procedures. The guidance adds to the confusion by not indicating which clauses apply to each scenario and by suggesting performance assessment procedures that might only be applicable to one scenario.

Given the extraordinary importance of external spread to the integrity of the fire safety strategy, I would expect that the ambiguity introduced by these functional requirements and guidance could be easily resolved by competent professional practise. But this is not the case for many materials and in particular for complex assemblies. In my opinion, functional requirements and guidance are not compatible in their current form. The ambiguity associated with performance objectives such as "restricted" and "adequate" is acceptable when addressing external fire spread but the associated performance criteria (e.g. "limited combustibility") and performance terminology (e.g. "resistance") relate to a scenario that is very different (fires providing heat from an adjacent building). In my professional opinion, it is not reasonable to expect professionals, no matter how competent they are, to correct the inconsistencies of functional requirements and guidance.

In the case of Grenfell Tower the combination of materials within the façade system was well known to catastrophically challenge the requirement for "no" external fire spread. A detailed report commissioned by the USA National Fire Protection Association and published in 2014 [13] showed statistics of significant fires with similar assemblies dating prior to 2010. Furthermore, this report explicitly presents several specific cases where similar material combinations had resulted in fires that rapidly compromised many floors and in some cases resulted in fatalities. Thus, façade systems of these nature were an accepted concern worldwide. Thus, whilst I consider the functional requirements and guidance to have been unacceptably unclear, this should not have prevented professionals with a minimum level of competence from establishing that such a system would completely undermine the integrity of the fire safety strategy and therefore provide a medium for fire spread that would definitely pose a risk to health and safety. Given the importance of "no" vertical and horizontal spread, it would have been clear that the occupants of a high-rise building cladded by

such a façade system would have been at risk and thus a detailed analysis of the impact of vertical and horizontal flame spread should have been a critical consideration in the design and implementation of the fire safety strategy.

2.5. KEY STAGES OF THE TIMELINE

The prior sections provide the general background and considerations that should govern the design of any high-rise building and the manner in which these background and considerations pertain to Grenfell Tower. If the fire safety strategy had delivered the intended outcome, an accidental fire within a residential unit of Grenfell Tower would have remained contained within the unit of fire origin. Occupants of the unit (and maybe adjacent units) would have evacuated and the fire brigade would have controlled the event within a matter of minutes. The occupants of all other units would have stayed put and the building normal operation could have resumed in a matter of hours. The event, nevertheless, followed a completely different and tragic timeline characterized by the overwhelming failure of many of the fire safety provisions. It is therefore essential, before drawing any conclusions, to first study the evolution of this timeline.

The following sections provide an assessment of the events of June 14th, 2017. The sequence of events has been broken down into key stages of the fire. The defined stages of the fire correspond to periods where distinctive interactions between the fire, the building, its occupants and the fire brigade were observed. While different ways of structuring the timeline are possible, in this case, I considered that for clarity, the stages of the fire timeline were to be separated as follows[18]:

- **Stage One:** From the initiation of the fire event to the breaching of the compartment of origin.
- **Stage Two:** From the breaching of the compartment of origin to the point when the fire reaches the top of the building.
- **Stage Three:** The internal migration of the fire until the full compromise of the interior of the building, including the stairs.
- **Stage Four:** Conditions in the building are deemed untenable.

[18] See footnote (1) for approximate times for each stage.

3 STAGE ONE: BREACHING OF THE COMPARTMENT

3.1. INTRODUCTION

All buildings are designed on the understanding that accidental fires will occur. As indicated above, the fire safety strategy is required to provide adequate management of these events in a manner that guarantees a performance acceptable to society. In the particular case of a unit in a high-rise building, the required performance is that the building will prevent propagation of a fire beyond the unit of origin. Thus, the first aspect to be analysed is how the fire escaped the unit of origin and thus was able to spread externally both vertically and horizontally. The period between the first report of a fire (00:54:29) and the first observation of smoke or debris originating from outside the compartment (01:08:06) is defined as the First Stage of the fire.

A number of potential routes for fire spread from the compartment of fire origin to the external cladding system at Grenfell Tower have been identified in the Phase One expert reports by Dr Lane [4] and Prof. Bisby [5]. The authors do not identify the exact mechanism by which the compartmentalization was breached, principally due to the scarcity of reliable data, in terms of both the exact point of origin of the fire and the contents of the kitchen.

With the objective of better identifying the exact mechanism by which the fire breached the compartment, a simple first principles elimination analysis is conducted here to try to bound the actual fire scenario within the kitchen more precisely. The nature of the analysis (i.e. simple and adopting some basic first principles) is necessitated by the constraints imposed by both the complexity of the problem and lack of reliable data with which to bound the scenario. More complex models can be used, however these models require greater inputs and a precision that is currently not consistent with the available information. Major assumptions have had to be made reducing their value to simple validation of the general physical principles.

It is especially important to note that this analysis is conducted from the basis that the origin of the fire is not established as concluded by Prof. Nic Daeid [2]. If in future more data becomes available, more complex and exact analytical and computational modelling techniques can be performed to provide a greater degree of certainty as to the likely mechanism of spread.

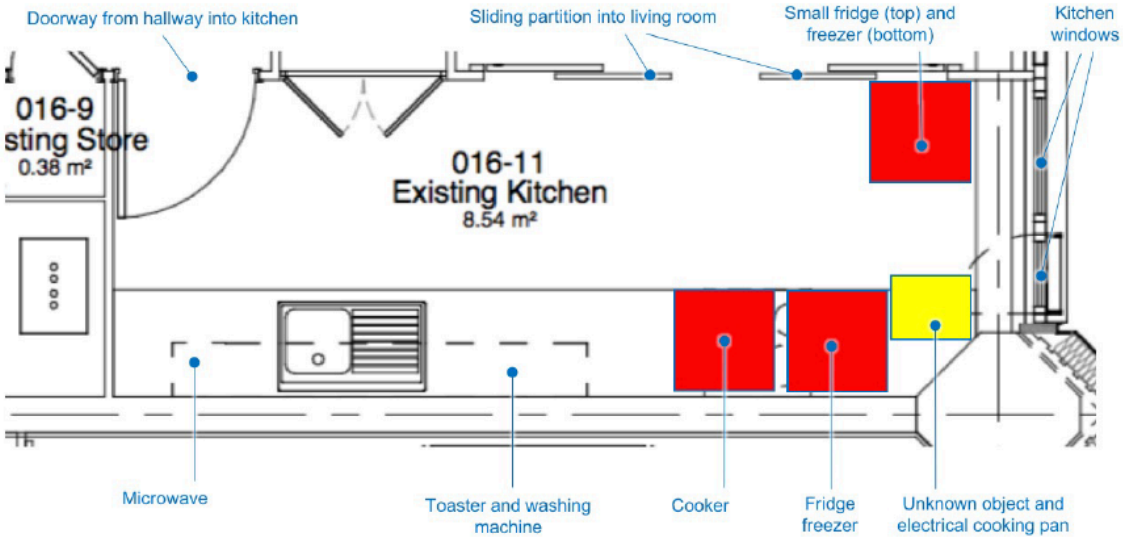
Prof. Bisby [5] identifies in detail three principle potential routes, corroborated by Dr Lane [4], for the fire inside the kitchen to ignite the cladding system components:

Mechanism 1. Fire products (flames and smoke) escaping through the open window and impinging on the cladding directly ignite the Aluminium Composite Panels (ACPs) above the window.

Mechanism 2. Secondary ignition of the kitchen fan leading to direct flame impingement on, and ignition of, the ACPs above the window.

Mechanism 3. Loss of structural integrity and / or combustion of the uPVC window surround, exposing passages by which flames and / or fire products can impinge directly on the various flammable component materials of the cladding system.

998 This section of the report describes a methodical analysis that aims to bound the fire scenario and in
999 doing so, address each of these mechanisms within the constraints of the available evidence.



(b)

Figure 12 Approximate arrangement of kitchen of Flat 16 a): Photograph 12 from [MET00007748] looking into kitchen from living room; b) annotated extract from design drawing [SEA00000199] showing assumed layout of kitchen at the time of initiation of the fire, which I have prepared based on the available evidence.

1000

1001 **FIGURE 2: DIAGRAM TAKEN FROM PROF. BISBY [5] SHOWING THE LAYOUT OF THE KITCHEN OF FLAT 16 AND ITS**
1002 **VARIOUS APPLIANCES (NOT TO SCALE).**

1003 3.2. THE FIRE COMPARTMENT

1004 The Bureau Veritas report [3], corroborated by Prof. Nic Daeid [2], identifies that two separate fire
1005 events occurred in Flat 16 of Grenfell Tower. The initial event was the fire in the kitchen, which both
1006 aforementioned authors agree did not reach flashover. This is corroborated by post-fire photographic
1007 evidence of the kitchen [MET00007448] and firefighter statements [MET00005251, MET00005214,
1008 MET00005674, MET00005701]. The second event was likely a more significant fire in the bedroom
1009 adjacent to the living room, likely a result of re-entry of the fire that had propagated externally via the
1010 cladding system.

1011 The compartment comprising the kitchen of Flat 16 is approximately 4.8m long, 1.9m wide, and 2.35m
1012 high. The diagram shown in Figure 2 taken from Prof. Bisby [5] shows the layout of the kitchen and
1013 the various appliances currently believed to have been present there. The window cavity, located on
1014 the east side of the compartment, has a sill height of approx. 1.05m and a total opening height of
1015 approx. 1.2m. These dimensions have been extracted from various drawings provided to the inquiry
1016 [SEA00000230].

3.1.1 Ventilation Sources

In total, there are three principal ventilation sources in the kitchen; the principal entry door, the window, and a sliding door connecting to the living room. Thermal imaging camera footage [MET00005816] suggests that the kitchen door is closed during the kitchen fire phase of the fire, aside from the time when the flat occupant entered the kitchen to confirm the presence of the fire prior to evacuating the flat, and during firefighter intervention itself.

The sliding doors to the living room are believed to be closed during the kitchen fire phase, at least up to the point of firefighter intervention. The flat occupant, who had been sleeping in the adjoining room, states that he entered the kitchen via the corridor [MET00006339] and Thermal Imaging Camera (TIC) footage [MET00005816] shows the doors closed at the time of the initial firefighter intervention.

The flat occupant states [MET00006339] that the window in the kitchen was open by about 10 inches. Drawings supplied to the inquiry indicate that the windows are tilt and turn windows and that in the tilt position, the upper side of the windows open approximately 100mm inwards [SEA00000230]. In the turn position, the windows open fully.

3.1.2 Fuel Sources

A number of items known to be present in the kitchen contain flammable materials. These are labelled in the diagram in Figure 2. Most items are well identified however the exact nature of any objects between the Hotpoint fridge freezer and the window have not been fully confirmed at the time this report was written[19]. Sufficient detail is not provided in the witness statement by the flat occupant [MET00006339] or included on the annotated sketch of the kitchen [MET00005190]. It is visible however in the thermal imaging camera footage [MET00005816] as identified by Prof. Bisby [5]. A report by Exponent [14] designate this as some kind of cabinet. Prof. Nic Daeid [2] also identifies that as yet unknown items were likely located there. This is deemed relevant as the occupant that discovered the fire describes smoke coming from the area between the fridge and the window [MET00006339] and identifies this area on their sketch, shown in Figure 4. The sketch does not show anything between the fridge-freezer and the window, however, to the extent of the evidence available, all other items are apparently shown.

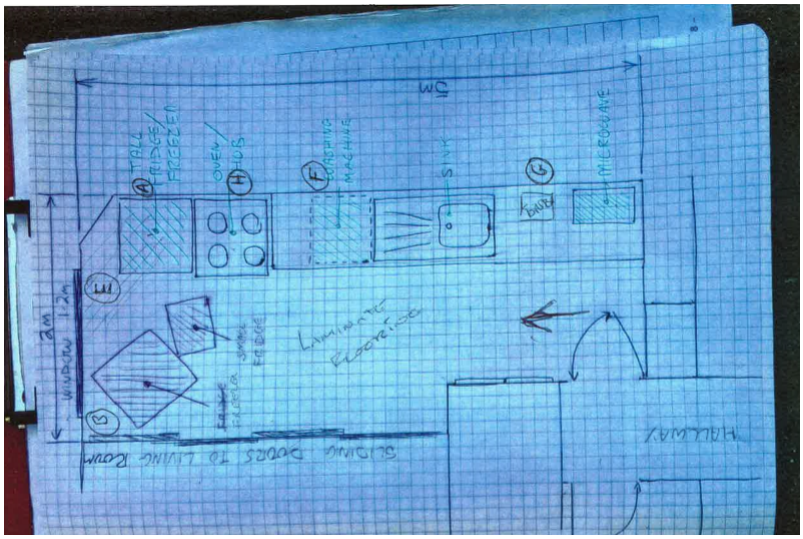
[19] New witness testimony was made available a few days before the submission of this report. This information has not been considered in this report because 1) it does not alter the analysis or conclusions presented here 2) because this information needs to be verified and analyzed by means of appropriate testing. The outcome of this verification analysis and testing might alter some of the details of this report.



1045

1046 **FIGURE 3: THE IMAGE FROM [MET00005816] SHOWS AN UNKNOWN OBJECT BETWEEN THE FRIDGE-FREEZER AND**
1047 **THE WINDOW IN FRONT OF THE CORNER COLUMN.**

1048



1049

1050 **FIGURE 4: SKETCH [MET00005190] PRODUCED ALONGSIDE STATEMENT [MET00006339] OF FLAT OCCUPANT THAT**
1051 **INITIALLY DISCOVERED THE FIRE. LOCATION MARKED E IS THAT IDENTIFIED BY OCCUPANT AS AREA WHERE THEY SAW**
1052 **SMOKE.**

1053

3.3. TIMELINE OF THE KITCHEN FIRE

For the purpose of providing a time-scale for the analysis, the following two pieces of evidence bound the timeline of the kitchen fire:

00:54:29 - The 999-call reporting the presence of fire is received [MET000080589].

01:05:57(+2mins) - The first evidence of fire having reached the cladding system is shown on a video recovered from a mobile phone [MET000083355]. A still image from this video (shown in Figure 18 in Section 4) shows molten material / debris falling from the cladding system to the left of the Flat 16 kitchen window as viewed from the outside. Prof. Bisby [5] identifies that the video appears to be two videos spliced together and thus the timestamp may not be exact. The timestamps on the filenames of these videos are likely to depend on the accuracy of the clock on the mobile phone device that was being used. A subsequent video from the same phone [MET000083356] timed at 01:08:06 filmed from approximately the same location shows the fire at a more advanced stage therefore the clip can be inferred to have been taken before this, thus between 01:05:57 and approx. 01:08:00.

An image taken by a member of the public at 01:14:53 [MET00006589] shows the fire to be well established on the outside of the cladding system, again to the left side of the Flat 16 kitchen window as viewed from the outside. This image is shown in Figure 5.



Figure 67 Image [MET00006589] (01:14:53) – annotated.

FIGURE 5: IMAGE FROM MET00006589 SHOWS A SIGNIFICANT EXTERNAL FIRE ENGULFING THE LEFT SIDE OF THE FLAT 16 KITCHEN WINDOW. EXTRACTED FROM PROF. BISBY [5]

The time of the firefighters' initial interaction with the fire and subsequent entering of the kitchen to extinguish the fire is unclear due to the discrepancy between the time-stamps on thermal imaging cameras used by the first responders. However thermal imaging camera footage of a significant quantity of burning debris / droplets falling past the window moments after the firefighters had initially entered indicates that the fire had already spread to the façade before they entered the kitchen [MET00005816].

The events stated here are also identified in the report by Prof. Nic Daeid [2]. This timeline provides an approximate bounding for any proposed mechanism for fire spread from the kitchen interior to the external façade of approximately 11.5 -13.5 minutes. It is only approximate as it does not include the time taken for activation of the alarm (assumed to be minimal given the size of the kitchen[20]) and any delay between the occupant discovering the fire and calling 999 (again assumed to be minimal given the occupants' statement [MET00006339]). The reports by Prof. Bisby [5] and Prof. Nic Daeid [4] compile the available information

3.4. BOUNDING THE COMPARTMENT FIRE

Ignition of the flammable components of the cladding system requires the fire within the kitchen to be able to provide a sufficient flux of heat to any component made of combustible materials so as to bring the component to its ignition temperature. This could either be through direct flame impingement, or as a result of sustained contact with smoke and /or heat accumulated in the kitchen at a remote location from the immediate fire plume.

It is also the case with certain polymers that loss of rigidity / stiffness and melting can occur pre- or post-ignition. It is therefore possible that polymer components of the construction can fall or flow away from their original positions when exposed to elevated temperatures, potentially exposing / uncovering other flammable materials.

The following section estimates (1) the fire sizes that might have existed in the kitchen of Flat 16, (2) determines the thermal conditions that could have resulted from them (be that in the direct path of the fire plume or in the hot gas layer that forms), and (3) compares them with the ignition temperatures of the various polymer materials in the cladding system and surrounding the window frame.

3.4.1 MATERIAL PROPERTIES

Table 1 details the relevant material properties of selected polymers applicable to this analysis. These have been taken from the report by Prof. Bisby [5] as well as work from Hidalgo [15] and Ogilvie [16]. It is also of note that uPVC begins to rapidly lose its structural integrity above 60°C, losing 80% of its stiffness by 80°C and 100% of its stiffness by 90°C [17].

[20] Smoke detectors will generally activate at the very incipient stages of a fire and therefore the time to detection is normally considered to be very small compared to typical times for fire growth. Given the type of materials present in the kitchen of Flat 16, activation would have been expected to occur when the fire was a few centimetres in diameter. This can be verified through a reconstruction of the event.

Material	Property	Value
Polyethylene (PE)	Ignition Temperature (piloted)	377°C [5], 363-415 [16]
Polyisocyanurate (PIR)	Ignition Temperature (piloted)	306-377°C [5], 377 [15]
Unplasticised Polyvinyl Chloride (uPVC)	Ignition Temperature (piloted)	318-374°C [5]
Unplasticised Polyvinyl Chloride (uPVC)	Melting Temperature	75-105°C [5]

TABLE 1: MATERIAL PROPERTIES OF VARIOUS POLYMERS RELEVANT TO THIS SECTION OF THE ANALYSIS.

3.4.2 FIRE SIZE AND COMPARTMENT TEMPERATURE

When a combustible material ignites, it starts burning and producing smoke. Smoke migrates towards the ceiling accumulating at the top of the compartment. The accumulated smoke is generally referred to as a smoke layer (see Figure 6). The height of the smoke layer ("H") will increase in time because the fire will continue to produce smoke. The faster the fire grows the faster the smoke layer height and its temperature increase. There are several possible scenarios. If there are open vents (e.g. doors, windows, etc.) a portion of the smoke will exit the compartment. The loss of smoke decelerates the descent of the smoke layer but if smoke cannot flow out faster than it is produced, the smoke layer will continue to descend until it fills the compartment. It is likely that the fire will die in this case due to lack of oxygen. If the smoke leaving the compartment is the same as the smoke produced by the fire then the smoke layer will stabilize. If all the vents are closed the smoke will fill the compartment and potentially extinguish the fire due to lack of oxygen. As the smoke layer descends the smoke temperature generally increases. The increase in temperature results in heat being transferred from the smoke to the unburnt combustibles by radiation. If sufficient heat is transferred, all combustibles within the room will ignite. This phenomenon is called "flashover." The relationship between the smoke layer height and its temperature is complex and there is no guarantee that the smoke layer will reach a temperature that will result in flashover. As indicated above, in the case of Grenfell Tower, the fire in the kitchen of Flat 16 did not reach "flashover." The fact that the smoke layer did not reach temperatures that resulted in flashover provides evidence that allows for the bounding of the temperature of the smoke layer and thus the extraction of important information.

The first step of the analysis estimates the maximum size of fire, known as the Heat Release Rate (HRR) (kW), that could exist within the kitchen and that would not bring the compartment to flashover. Next, the likely smoke layer temperature range that would result from fires within the kitchen compartment is estimated. For this purpose, a simple zone model has been developed which is valid for the time it takes to fill the compartment with smoke.

For this model, all openings (doors and windows) are taken as closed. If doors and windows are open (it is known, in this case, that the windows were partially open[21]) larger fires could have been attained

[21] Prof. Bisby [5] indicates (lines 452-457) that smoke was emerging from the window at 1:05:36 but that multiple components of the window were damaged or ignited by then. Figure 58 of the same report shows evidence of smoke at this stage. The amount of smoke is noticeable but not very significant. Given that these first images are approximately 10 minutes into the fire (towards the end of the period being studied), it is very likely that very little smoke would have escaped through the window in the first few minutes of the fire.

before the room filled with smoke. Thus, the present values of the heat release rate should be taken as a lower bound of the heat release rate that will fill the compartment with smoke. The modelling strategy conforms with well accepted practises and provides the information necessary. While very simple in nature, the model precision is consistent with the information available. Details of the model are presented in Appendix A.

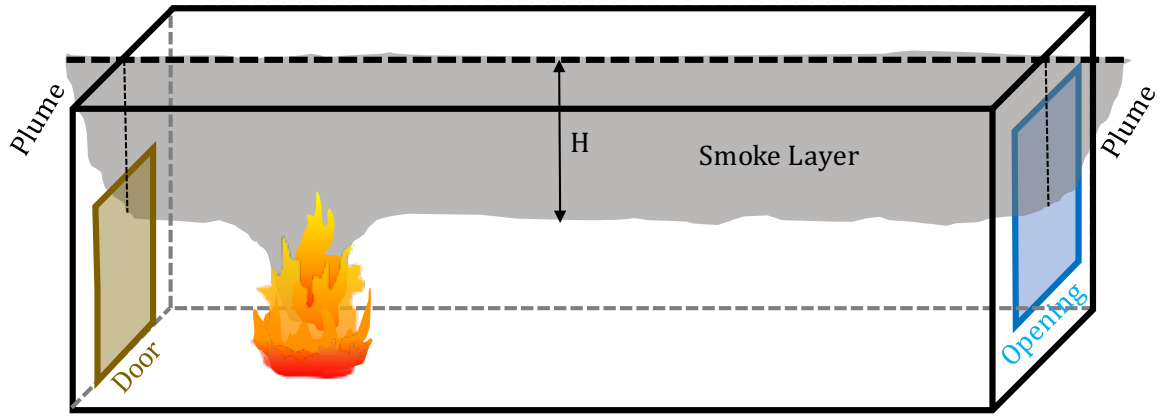


FIGURE 6: SCHEMATIC OF A COMPARTMENT FIRE, "H" IS THE HEIGHT OF THE SMOKE LAYER AND THE WINDOW AND DOOR ARE OPEN.

A simple way of characterizing the growth of the fire is by defining the growth rate of the heat release rate. Simple approaches classify fires as being of slow, medium, fast or ultra-fast growth. The slow and ultra-fast fires will be the extremes. These two extremes have been introduced in the model described in Appendix A and the evolution of the temperature of the smoke layer has been ascertained. The results presented in Figure 7 illustrate the bounding cases, i.e. the slow and ultrafast fires. The curves end when the smoke layer has reached the floor and further temperature increase (or fire growth) is not possible. The smoke layer temperature within the kitchen of Flat 16 would have been somewhere between these two values.

The results show that the compartment fills with smoke very rapidly in both cases, which is to be expected given the small volume of the kitchen.

The model reached a peak HRR before smoke filled the volume of the kitchen during the ultrafast fire growth of the order of 300kW. This corresponds to a hot layer temperature of approximately 220°C. At the lower bound, the slow fire growth results in a peak HRR of approximately 60kW and a hot-layer temperature of approximately 110°C. Limiting the HRR to a peak of 25kW resulted in a temperature slightly above 100°C thus this value is taken as the lower bound. These results are summarised in Table 2.

Given the relatively small fire sizes (i.e. 60-300kW), it is assumed that the available leakage via the open tilted window, and around the kitchen door and partition to the lounge will provide sufficient air supply to maintain the internal fire at these levels but probably no bigger.

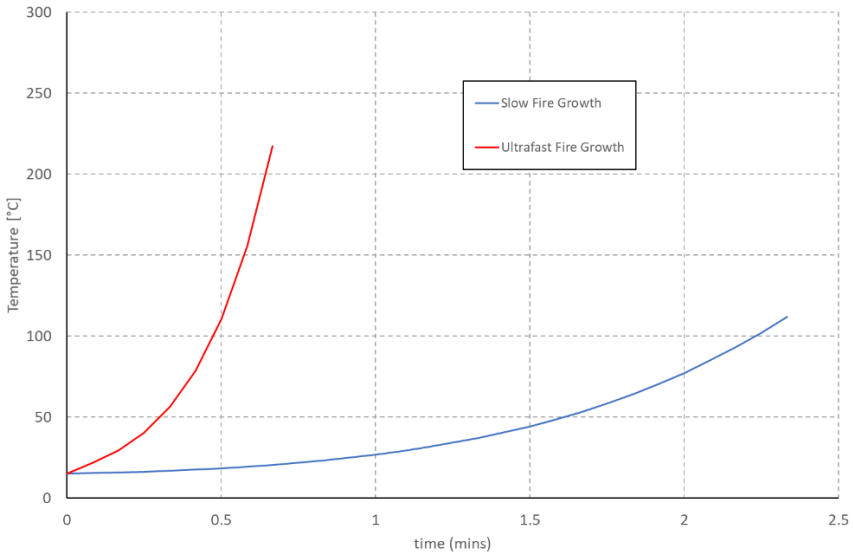


FIGURE 7: THE PLOT SHOWS THE ESTIMATED BOUNDS OF COMPARTMENT TEMPERATURE EVOLUTION DURING THE GROWTH PHASE OF THE KITCHEN FIRE. THE FIRE IN THE KITCHEN OF FLAT 16 WOULD HAVE BEEN SOMEWHERE BETWEEN THESE TWO BOUNDING GROWTH RATES.

Property	Range
Peak Heat Release Rate [Q]	60kW < Q < 300 kW
Hot-Layer Temperature [T_g]	100°C < T_g < 220°C
Fire Growth Rate [α]	0.0029 < α < 0.1876
Fire Growth Time [t_{growth}]	40s < t_{growth} < 138s

TABLE 2: BOUNDING CHARACTERISTICS OF THE KITCHEN FIRE GROWTH PHASE. THE PARAMETER "α" CHARACTERIZES THE FIRE GROWTH RATE (SEE APPENDIX A)

These values have been subsequently verified with a computation zone modelling tool CFAST[22], the output of which correlates well with the values described here. CFAST solves the same equations as those described in Appendix A, but the added functionality of this tool enabled modelling of the scenario with an open kitchen door. The model results show that flashover could be reached if the door was open. If the door is open, then smoke will exit the kitchen allowing for the fire to continue to grow without the smoke layer reaching the floor. This results in higher temperatures and the potential for flashover. The contents of the kitchen were sufficient to deliver a heat release rate greater than 1000 kW which, the model established was the heat release rate necessary to attain flashover. This appears to confirm that the kitchen door was likely closed during this phase of the fire. A description of this modelling and details of the output are described in Appendix B. A simple assessment was made of the impact of having the window partially open. This assessment shows that the area through which the smoke could vent was too small to have an impact on smoke filling. The window was not observed to break during this stage so that scenario was not evaluated.

[22] https://www.nist.gov/el/fire-research-division-73300/product-services/consolidated-fire-and-smoke-transport-model-cfast

3.4.3 Estimation of Fire Base Area

An analysis is performed to approximate the area of the base of the fire when the fire sizes identified above (60 – 300kW) are reached. This analysis is based on the assumed fire growth rates and assumed characteristic materials. Details of the calculations are presented in Appendix C.

For the slow growth rate fire, the fire area corresponding to the maximum possible heat release rates equates to a 17 – 20cm radius circular base, or a 29 – 37cm sided square base. By means of comparison, [12] reports that a 30cm x 30cm pan fire will produce a HRR in the range of approx. 47-65 kW. This matches well with the 60kW calculated HRR and thus gives confidence in the result despite the crudity of the technique. For the ultrafast fire growth rate, the fire equates to a 40 – 50cm radius circular base, or a 68 - 87cm sided square base.

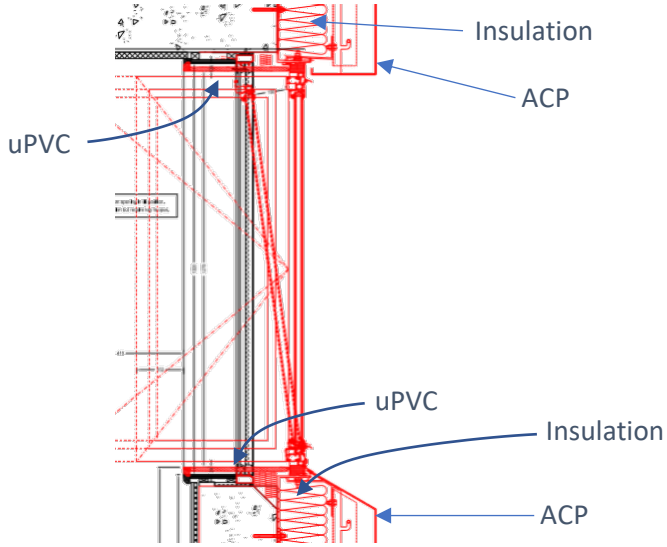
If there was sufficient ventilation to allow for a fire to grow beyond the values reported here (i.e. if there was extra supply of oxygen that would be available to the fire), the fire would have progressed to flashover. The photographic evidence shows that the fire did not progress to flashover so it can be concluded that the kitchen fire would not have been bigger than a 300 kW (40-50 cm radius) fire. The maximum distance between the fire and any combustible materials that could potentially ignite will be calculated with this value. This will establish the potential location of the initial fire.

3.4.4 Thermal Performance of the uPVC Window Surround

The uPVC window surround system is described in detail by Prof. Bisby [5]. This system covers the existing window frame and extends out to the new windows housed within the cladding system (Figure 8). As this system extends beyond the original façade to the new windows that are mounted on a system of Aluminium rails, they also span across the cavity between the window and the original façade. The uPVC components are adhered to the original window frame with adhesive [5].

Clearly, damage, removal, or poor workmanship could expose the cladding components covered by this system to a lesser or greater extent, providing a direct path for flames to impinge on the external flammable materials as highlighted by Prof. Bisby [5] and Dr Lane [4]. Thus, it is important to understand the effect that elevated temperatures resulting from the fire in the kitchen could have had on uPVC.

Section 3.3 above lists some relevant properties of uPVC. Of particular interest in this case are the melting temperature and the elastic modulus shown in Figure 9. The former, with a range of 75 – 105°C, represents the range at which the material will transition from a solid to a liquid. The latter is closely correlated to the elastic modulus and therefore is a measure of stiffness or the rigidity of the material and is thus a measure of its ability to support its own weight. The plot in Figure 9 shows that the material begins to rapidly lose stiffness around 60°C, losing 80% by 80°C and 100% by 90°C. Logically, this overlaps with the temperature range for melting. It is clear that these temperatures are well within the range expected in the compartment as per the calculations of Section 3.4.2.



(A) (B)

FIGURE 8: THE IMAGE SHOWS A CROSS-SECTION THROUGH THE WINDOW AS DESIGNED [SEA00000230] WITH THE ORIGINAL COMPONENTS SHOWN IN BLACK AND THE NEW SYSTEM IN RED.

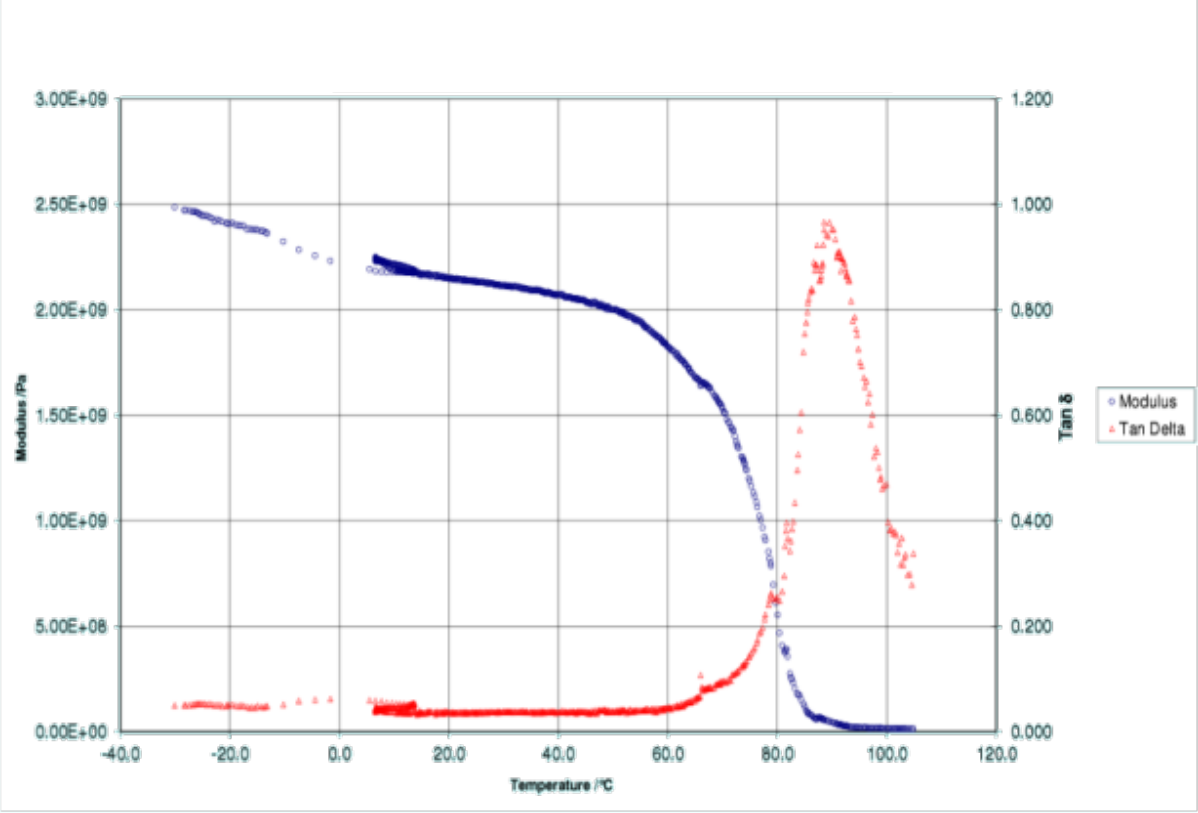


FIGURE 9: MECHANICAL PROPERTIES OF UPVC AS A FUNCTION OF TEMPERATURE [°C]. THE MODULUS (IN BLUE) IS RELATED TO THE ELASTIC MODULUS OF THE MATERIAL. THE PLOT INDICATES THAT THE MATERIAL BEGINS TO DRASTICALLY LOSE STIFFNESS AT APPROX. 60°C, LOSING 80°C BY 80°C AND 100% BY 90°C. TESTS WERE CONDUCTED AT THE UNIVERSITY OF EDINBURGH AND THE DATA WAS PROVIDED BY PROF. BISBY.

Once the material has lost the ability to support itself, it will only be held in place at the locations where the bonding adhesive is located (Figure 10). That bonding adhesive is a material which itself will be vulnerable to heating and thus is not expected to be functional in this temperature range. Given the sparse application of the adhesive, its ability to secure the uPVC at elevated temperatures is considered negligible. While demonstrating this sequence of failure is difficult, several examples of the uPVC falling due to heating can be observed in post-event inspections (some examples are presented in Figure 11) strengthening these arguments.



Figure 55 Line of adhesive used to bond uPVC refurbishment window jamb boards to the pre-existing painted (in this case) timber window jamb board. Considerable use of aluminium tape within refurbishment window frame construction [My photo, Flat 13, 09/01/2018].

FIGURE 10: IMAGE OF THE ADHESIVE TAKEN FROM PROF. BISBY [5].

Photographic evidence obtained following the fire at the Grenfell Tower has identified many instances of this type of failure as shown in Figure 11. It should be noted that these elements do not all show signs of charring implying that they did not all combust but simply lost stiffness. Typically, it is the head and jambs that exhibit de-bonding as this mechanism is gravity assisted for these elements.

1248



1249

1250 (A)

1251



1252

1253 (B)



(C)

FIGURE 11: A RANGE OF EXAMPLES OF DEBONDING OF UPVC ELEMENTS OF THE WINDOW SURROUNDS DUE TO HEAT EXPOSURE. (A) SHOWS DEBONDING OF A WINDOW JAMB THAT HIS LOST RIGIDITY DUE TO HEATING FROM THE EXTERNAL FIRE CREATING AN OPEN PASSAGE BETWEEN THE INTERIOR AND EXTERIOR. (B) SHOWS THE WINDOW UPPER PEELING AWAY (C) SHOWS THE MAIN WINDOW JAMBS DEBONDING FROM THE SIDE OF THE WINDOW CAVITY.

A simple energy storage analysis is conducted to approximate the change in temperature of the uPVC as a result of exposure to the hot-layer gases (details of the analysis are presented in Appendix D), and thus establish if any thermal degradation of the material is possible within the timeframe provided by the evidence in Section 0. The results of the model are presented in Figure 12. They illustrate the range of effects that a fire, within the ranges defined by the limited evidence, could have on the uPVC.

The lower bound, defined by a slow growing fire reaching a peak HRR of 60kW and a hot-layer temperature of 100°C, brings the uPVC to a temperature of approx. 65°C within the 11.5 minute timeframe. This, as stated earlier, is slightly above the onset temperature of rapid loss of stiffness (60°C).

The upper bound, defined by an ultrafast growing fire peaking at a HRR of 300kW and a hot-layer temperature of 220°C, brings the uPVC to 150°C within the 11.5 minute timeframe, reaching the point of loss of 100% stiffness (90°C) in less than 5.5 minutes.

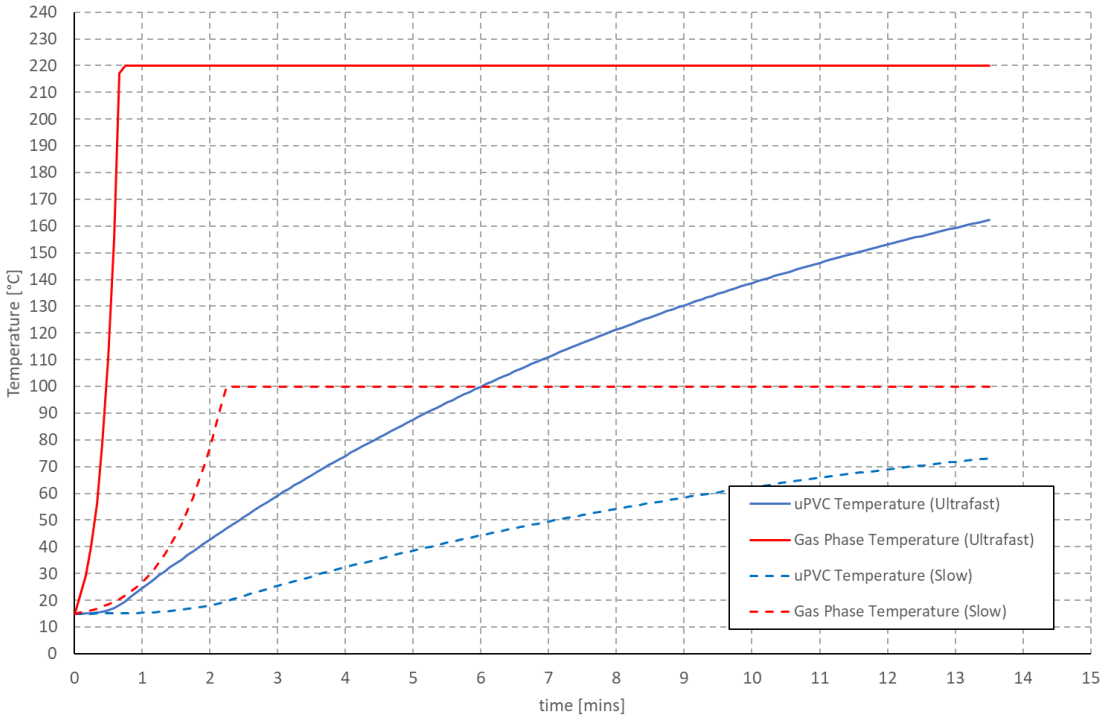


FIGURE 12: THE PLOT SHOW THE BOUNDING GAS PHASE TEMPERATURES (RED) AND RESULTANT SOLID PHASE (UPVC) TEMPERATURES (BLUE). THE LOWER LIMIT IS DEPICTED BY DASHED LINES, AND THE UPPER LIMIT BY SOLID LINES.

The minimum conditions required to bring the 9.5mm thick uPVC to a temperature of 90°C within the 11.5 minute timeframe are a fire growth rate, α, of 0.0091kW/m^2 which falls between the slow (0.0029) and medium (0.0117) fire growth rates, reaching a peak HRR of 90kW and peaking at a temperature of 140°C.

From these results, it can be concluded that most fires originating from fuels typical of a domestic kitchen will have the capacity to significantly damage the uPVC. It is very likely that the loss of stiffness will result in deformations and the generation of gaps. The adhesive, as it was applied, will have no capacity to prevent this.

3.5. MECHANISMS OF IGNITION OF AN EXTERNAL FLAME

The maximum temperature of the smoke layer cannot exceed 220°C even if an ultra-fast fire is considered (Figure 12). Ignition of the combustible materials of the façade surrounding the window requires at least 306°C (Table 1). Therefore, ignition of any of the combustible facade materials by means of the smoke layer is not possible. Ignition must occur by means of direct impingement of the flame.

Different hypotheses regarding the cause and origin of the fire have been postulated and described in detail in the Phase 1 Expert Report submitted by Prof. Nic Daeid [2]. Prof. Bisby's Phase 1 Expert Report also provides information on the different means by which the fire started [5]. This report will not expand on matters of cause and origin.

From the analysis presented so far in Sections 3.3 and 3.4 it is clear that the most significant events leading to the involvement of the façade elements in the fire would have occurred within the first 5 minutes from ignition. The reports by Prof. Nic Daeid [2] and Prof. Bisby [5] establish that with the exception of the occupant witness statement [MET00006639] there is no other information on that period. A detailed analysis of the fire scene after the event would have also been able to provide some additional information, nevertheless, this information is not presented in the available forensic reports [3]. Despite the limited information, Prof. Bisby postulates three hypotheses in his Phase 1 Expert Report [5]. These are transcribed here for clarity:

Line 575. "Hypothesis B1: The route of fire spread from inside the kitchen of Flat 16 to the external cladding was via the infill sandwich panel within which the extract fan was mounted, or via the extract fan itself, and igniting the external cladding adjacent to the kitchen window of Flat 16. This subsequently led to sustained burning of the external cladding."

Line 579. "Hypothesis B2: The route of fire spread from inside the kitchen of Flat 16 to the external cladding was due to flame impingement from the internal fire venting from the window opening. This subsequently led to sustained burning of the external cladding."

Line 582. "Hypothesis B3: The route of fire spread from inside the kitchen of Flat 16 to the external cladding was due to parts of the internal window surround and external cladding system being penetrated by the fire, thus allowing fire spread directly into the back of the cladding cavity from within the room of origin. This subsequently led to sustained burning of the cladding either within the cavity or on its external surface, or both."

Hypothesis B1, as indicated by Prof. Bisby [5], is highly unlikely and very easily disproven by means of testing. Section 6.10.2.4 in Prof. Nic Daeid's Expert Report [2] indicates that "the extractor fan associated with the kitchen window of Flat 16 can be eliminated as being within the area of origin of the fire as no physical evidence of electrical damage has been observed." The materials present in the fan and casing (type and quantity) are too small to provide a sufficient heat flux to ignite the cladding by means of external flames [16]. A simple analysis that demonstrates this will be provided in Section 3.5.3. This analysis uses a simplified geometry and cannot be conclusive because geometrical intricacies of the assembly might affect the flame geometry and subsequently the heat flux distribution. While very unlikely, the hypothesis cannot be completely discarded with the current information, nevertheless, a test can serve to exclude this hypothesis. This should be a matter for Phase 2.

Hypothesis B2 can be split into two different cases, the first case corresponds to the gases from the smoke layer venting from the window and subsequently igniting the cladding, the second is flames close enough to the window so that they can directly vent from the window opening. The first case can be discarded on the basis that the smoke layer would have never been hot enough for the smoke venting from the window to ignite the cladding. The second scenario is a subset of Hypothesis B3 given that the window surround will be much closer to the fire than the cladding, thus would have most likely ignited first by direct impingement of flames. The following analysis will address the scenario of direct impingement. This is consistent with the conclusion of Prof. Bisby [5] who states:

Line 597. "There is insufficient evidence to fully accept Hypothesis B3 at present. However, on the balance of probabilities and the evidence presented in this section, I consider Hypothesis B3 to be the most likely, by a considerable margin, of hypotheses B1, B2, and B3."

As stated by Prof. Bisby [5], the following sequence of events is necessary before the fire could spread into the cladding cavity.

> Line 585. "(1) The uPVC window boards forming the sill, jamb, or head of the internal window framing enclosure would have to be penetrated or removed;"
>
> Line 586. "(2) The thermal insulation applied to the back face of the uPVC window boards would have to be penetrated or removed; and"
>
> Line 587. "(3) The EPDM rubber membrane would have to be penetrated (or not be present in that location)."

Details of all these components are presented in Sections 4.5 to 4.9 of Prof. Bisby's Phase 1 Expert Report. Section 3.4.4 of this present report has shown that it is very likely that in the presence of the smoke layer the uPVC would have deformed establishing paths for the fire to reach any of the other components (EPDM Synthetic Rubber Membrane, PIR insulation and ACP panel). None of these components would have ignited with the temperatures attained by the smoke layer, therefore the conditions that will lead to direct impingement of flames on these materials need to be analyzed.

A series of potential scenarios for the origin of the fire were established by the Phase 1 Expert reports of Prof. Nic Daeid (Section 6.10.2) [2] and Prof. Bisby (Section 5.7.2) [5]. These scenarios require the analysis of two conditions, an open fire that could directly impinge on the materials part of the window assembly or a fire occurring behind an appliance/obstacle, where the flame will have to migrate to the ceiling before travelling towards the window assembly. Figure 13 shows a schematic of the two conditions.

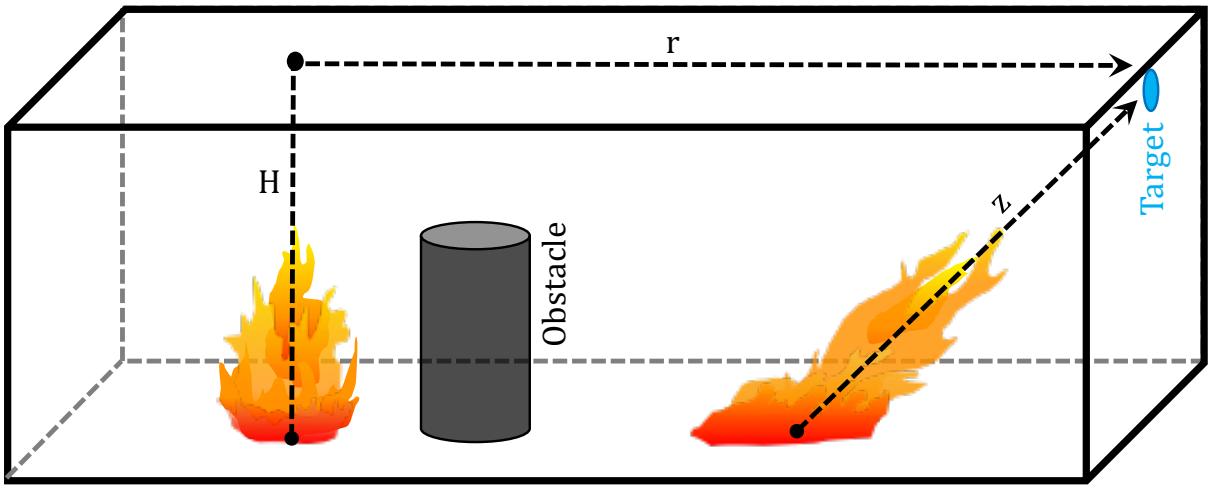


FIGURE 13: SCHEMATIC OF THE TWO CONDITIONS TO BE ANALYZED, DIRECT IMPINGEMENT OVER A DISTANCE "Z" OR FIRE BEHIND AN APPLIANCE/OBSTACLE WHERE THE FLAMES HAVE TO FIRST REACH THE CEILING AND THEN PROGRESS TOWARDS THE TARGET FOLLOWING A PATH "H + R."

The following sections will use very simple analysis methods. These methods are not necessarily very precise or strictly valid for the conditions of the Grenfell Tower fire, nevertheless the results serve to provide a clear idea of scenarios that can be discarded. If more precise methodologies become necessary, these will be used as part of subsequent reports.

3.5.1 Ignition by Direct Impingement

This part of the analysis aims to determine what are the necessary conditions where direct flame impingement could result in ignition. This is depicted by the diagram in Figure 14. A plot created by McCaffrey [18], reproduced in Figure 15, is used to establish the characteristics of the fire in the kitchen that could lead to ignition of various flammable components. The ignition temperatures of each component material are used to define the value of $\Delta T=T_{ig}-T_a$ (T_{ig} is the ignition temperature and T_a the ambient temperature). "z" is defined as the height above the base of the fire (m) at which the flame or plume comes into direct contact with the flammable material. Using these two values and the plot in Figure 15, $\dot{Q}_c$, the convective portion of the heat release rate, can be established. The total HRR, $\dot{Q}$, is then established from the following relationship [20]

$$\dot{Q}_c = \frac{\dot{Q}}{1.5}$$

Equation 1

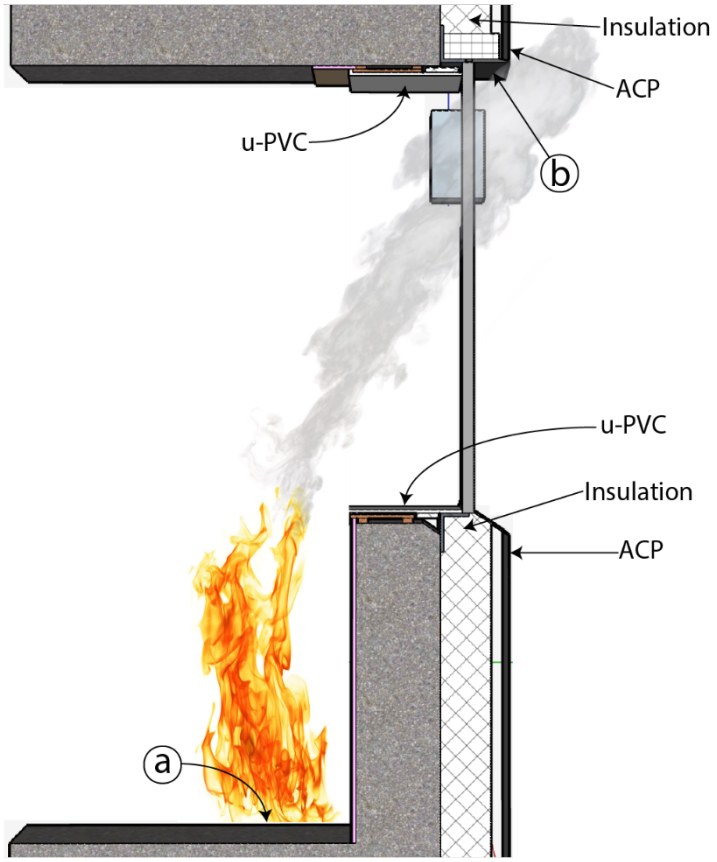


Figure 14: The diagram illustrates the window and cladding system as constructed at the time of the fire. It illustrates the concept of flame and plume impingement on the flammable materials around the window cavity.

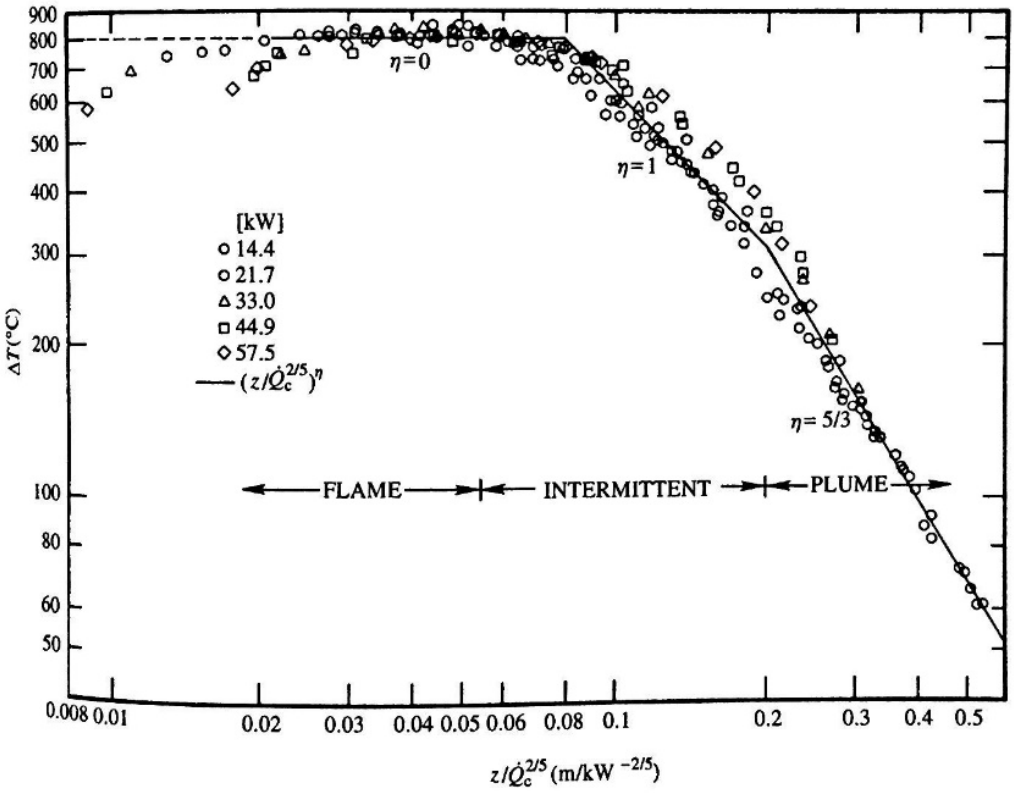


FIGURE 15: PLOT BY MCCAFFREY [18] REPRODUCED FROM DRYSDALE [21] CORRELATING THE INCREASE IN TEMPERATURE ABOVE AMBIENT WITHIN THE FIRE PLUME WITH THE HEAT RELEASE RATE AND HEIGHT ABOVE THE BASE OF THE FIRE.

Using the example of Hypothesis B3 depicted in Figure 14, the ignition temperature of the Polyethylene in the ACP panel is given in Table 1 as 377°C, thus $\Delta T = T_{ig} - T_a = 362°C$. Using the plot in Figure 15, this equates to a value of $\left(\frac{z}{\dot{Q}_c^{\frac{2}{5}}}\right)^{\eta} = 0.18$ where $\eta = 1$ and is located in the intermittent plume. The distance "z" is approx. 2.3m (point a to point b in Figure 14), thus solving for $\dot{Q}_c$, and subsequently for $\dot{Q}$, gives a required HRR of 875kW to ignite the ACP panel above the window (point b) from direct flame / plume impingement from a fire within the kitchen at floor level, immediately beneath the window (point a). This method is reproduced for the three relevant ignitable materials, for the range of relevant heights i.e. top to bottom of the window cavity. Table 3 summarises the results from this analysis.

There are two columns of results presented in Table 3. The 'Smallest Fire' column represents the smallest fire located, at floor level, necessary to cause an ignition of the given material at the given location. For example, the uPVC window surround can theoretically be ignited at the sill level by a 20kW fire, however would need a 120 kW fire to ignite it level with the top of the window. Heights in between would require a fire size, at this location, between these two bounding values. The PIR insulation shows similar requirements in terms of fire size. For means of illustration, Figure 16 shows two buoyant flames, the smaller ≈ 25 kW and the large ≈ 75 kW.

The second group of results labelled 'max distance', represents the maximum horizontal distance that the largest possible fire (300 kW) could be from the base of the wall beneath the window, in order to result in an ignition via direct impingement. This assumes a tilted plume forming a straight line between the base of the fire and the ignition location.

Material	Window Location	Smallest Fire [kW]	Max Distance [m]
uPVC	Top	120	2.4
	Bottom	20	3.1
Polyethylene (ACP)	Top	830	No Ignition
	Bottom	125	1.2
Insulation (PIR)	Top	110	2.5
	Bottom	20	3.2

TABLE 3: RESULTS FROM THE MCCAFFREY PLOT. SHOWS BOTH THE SMALLEST FIRE THAT COULD IGNITE THE MATERIAL AT A SPECIFIED LOCATION AND THE FURTHEST A FIRE COULD BE TO IGNITE A MATERIAL WITHOUT REACHING FLASHOVER



FIGURE 16: TWO BUOYANT FLAMES, THE LEFT APPROX. 25 KW AND THE RIGHT APPROX. 75 KW, FROM HTTPS://WWW.YOUTUBE.COM/WATCH?V=7B9-BZCCUXU.

Table 3 indicates that a fire located at ground level of 300 kW of less, could not provide the required ΔT to cause ignition of the ACP directly above the window. The base of a 300kW fire would have to be within 1.5 m (direct line) of the ACP outside the window to be capable of causing direct ignition via flame / plume impingement. A fire at floor level, even directly beneath the window, would need to be

of the order of 830kW to ignite the ACP through the window. A fire of this size, with the compartment ventilation as it was, would have brought the compartment to flashover, thus is not consistent with the evidence.

3.5.2 Fires Behind an Obstacle

If the plume originating from a fire at floor level is obstructed by appliances and unable to directly impinge on the flammable materials around the window (Figure 13), impingement must occur indirectly. The flames must migrate first towards the ceiling and then travel horizontally as a ceiling jet until reaching a combustible component. This scenario corresponds to the fire suggested as having its origin in the Hotpoint FF1758P.

A correlation by Alpert [22] that describes the decay in temperature of the smoke products as they travel horizontally across the ceiling is used to determine the Heat Release Rate (HRR) required from an obscured fire to ignite PIR and uPVC materials at ceiling height, as a function of distance from the window of a ground level fire. The temperature of the ceiling jet, T_{max} [°C], in the area where the plume impinges on the ceiling is given by Alpert as:

$$T_{max} = T_{\infty} + \frac{16.9\dot{Q}_c^{\frac{2}{3}}}{H^{\frac{5}{3}}}$$

Equation 2

Where T_{∞} [°C] is the ambient temperature, $\dot{Q}_c$ [kW] is the convective portion of the heat release rate, and H [m] is the height of the room. The radius of impingement r [m] is defined as 0.18H. Outside of this radius, the temperature of the ceiling jet is defined as:

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

Equation 3

The lower bound of the range of ignition temperatures of PIR (insulation) and uPVC (window surround) is approx. 305°C. The blue line in Figure 17 shows the HRR required to produce a ceiling jet temperature above 305°C at the top of the window if the fire is at floor level. The horizontal axis shows the distance between the fire and the external wall. In all cases, the required HRR is of sufficient magnitude that the fire would be expected to result in flashover. This implies that only direct, unimpeded flame / plume impingement would result in ignition of these materials at the upper window level.

A fire that starts at the floor level and finds combustible materials to spread vertically can eventually produce temperatures that could ignite ceiling covers (i.e. PURLBoard (Section 4.2.3 [5]: Line 312: “a band approximately 350 mm wide on the ceiling around the entire exterior perimeter of all intact and partially intact flats”)) or potentially find its way to the window. Proof of the viability of any scenario of this nature will require the testing of the fire source with the potential source of ignition. These tests should be carefully instrumented to quantify all relevant variables and should be undertaken as part of a Phase 2 analysis.

The orange line in Figure 17 indicates the HRR required to attain a temperature of 90°C impinging on the window. This corresponds to the temperature at which the uPVC will lose its structural integrity. The plot indicates that the initial ceiling jet of a fire less than 300kW in size, at floor level up to 1m away from the window, could result in smoke impingement on the uPVC at 90°C.

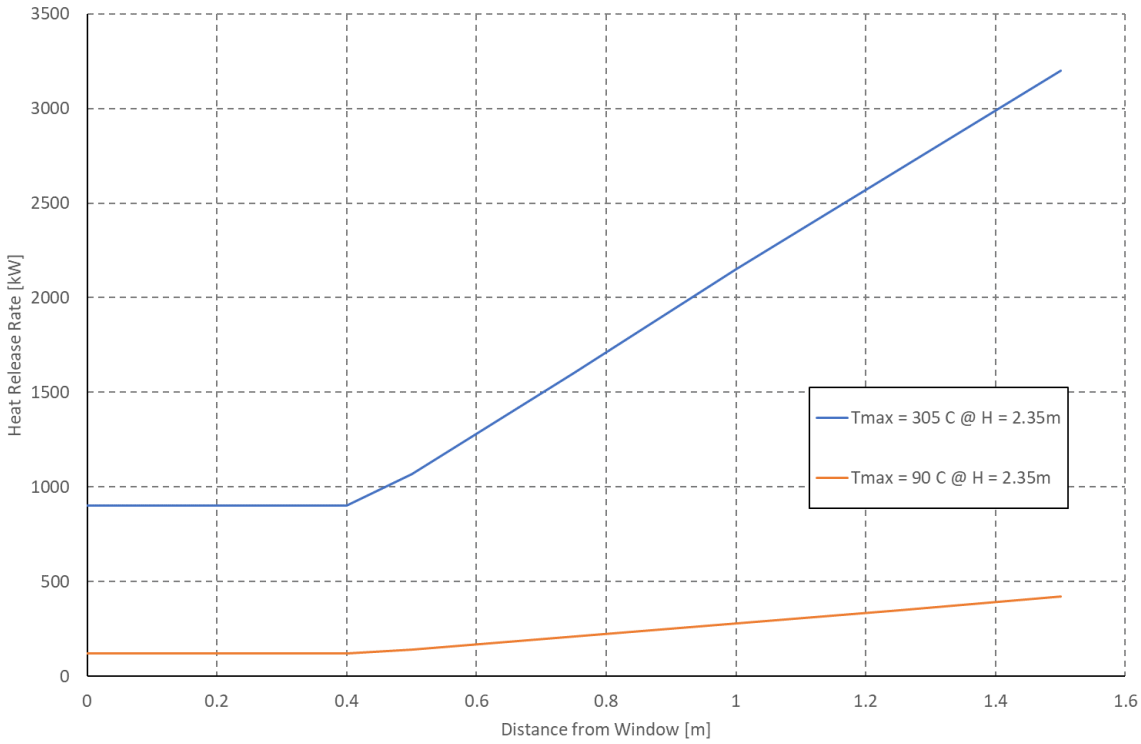


FIGURE 17: THE PLOT SHOWS: BLUE LINE - THE HRR [KW] REQUIRED TO PRODUCE A CEILING JET WITH SUFFICIENT TEMPERATURE TO IGNITE PIR AND UPVC COMPONENTS AT THE TOP OF THE WINDOW, AS A FUNCTION OF THE DISTANCE [M] OF THE ORIGINATING FIRE FROM THE WINDOW AT FLOOR LEVEL. ORANGE LINE - THE HRR [KW] REQUIRED TO PRODUCE A CEILING JET WITH SUFFICIENT TEMPERATURE TO CAUSE THE UPVC TO LOSE 100% OF ITS STRUCTURAL INTEGRITY [90°C].

3.5.3 THE FAN AND FAN MOUNTING UNIT AS AN IGNITION SOURCE OF THE ACP

In the same video that indicates the first instance of spread to the cladding [MET000083355], flames are visible in or around the location of the fan and its mounting panel. This is shown in detail by Prof. Bisby [5] and leads to Hypothesis B1. It is not clear from the video footage if it is the fan and / or the fan mounting panel that are alight, or if it is a flame emerging from the window beneath the mounting panel. Prof. Bisby indicates that the source of the flame is initially located at the base of the mounting panel, thus for this to be the ignition source of the ACP panels, the flame either had to originate in the compartment or, by some means of exposure due to failure of the window system, originate from the base of the fan mounting panel. The former has been addressed in Section 3.5 The latter is addressed here. The report by Dr Lane [4] gives dimensions of the fan mounting panel as approx. 0.5 x 0.5 m, with a 1.5 mm aluminium skin either side of a 25mm thick PIR core.

Assuming the underside of the fan mounting is burning, the methodology described in Appendix C is used to establish an upper bound heat release rate of approximately 5 kW. Using the plot by McCaffrey

in Figure 15, the flame and plume resulting from this fire would have a temperature above the ignition temperature of any of the combustible materials for less than 30cm from its base. This means that the temperature in the plume issued from a fire at the base of the mounting panel could have not ignited the ACP panel or any of the combustible materials present in the façade system.

3.6. RELEVANT ACTIVE AND PASSIVE FIRE SAFETY SYSTEMS

As indicated in Table A [4], the following items would have been relevant to preventing a typical residential kitchen fire from impacting the building beyond Flat 16:

- The loadbearing elements of structure of the building are capable of withstanding the effects of fire for an appropriate period without loss of stability; Structural Stability - Temperatures between 100 - 220^{o}C will pose no challenge to any of the structural systems. Therefore, the structure can be deemed to be sound.
- The building is sub-divided by elements of fire resisting construction into compartments; Compartmentalization – Only the south facing wall of the kitchen serves as boundary to a different unit, thus is required to provide compartmentalization. Temperatures between 100 - 220^{o}C will pose no challenge to this wall. The walls facing outwards are not required to maintain compartmentalization (Line 3.4.2 [4]), thus window system and glazing are not included in this requirement. Therefore, compartmentalization is maintained.
- Any openings in fire separating elements are suitably protected in order to maintain the integrity of the element (i.e. continuity of fire separation); Fire stopping – This requirement only pertains to the south facing wall of the kitchen and there is no evidence that there was any fire stopping on this wall.
- Any hidden voids in the construction are sealed and sub-divided to inhibit the unseen spread of fire and products of combustion, in order to reduce the risk of structural failure and the spread of fire, insofar as they pose a threat to the safety of people in and around the building; Cavity barriers – Given that the uPVC window surround acted as a barrier between the façade system cavities and the compartment, these should have inhibited the spread of fire and products of combustion. Given the low temperatures that will breach this barrier (less than 90^{o}C), any fire common to a residential kitchen would have resulted in failure of the intended barrier in a few minutes (less than 12 min for Grenfell Tower).

3.7. SUMMARY

- The photographic evidence indicates that this fire never reached flashover [2,3].
- Analysis based on the geometry of the compartment and the known ventilation conditions (door and window closed) establishes that a fire would have reached a steady temperature between 100^{o}C-220^{o}C. These temperatures are below those capable of inducing flashover. These temperatures are not capable of igniting any of the combustible components adjacent to the window.
- If the door and main window were to provide a means for smoke to exit the kitchen, a fire in excess of 300 kW would have brought the room to flashover. This indicates that it is most likely

that the door to the kitchen (as well as the partition) must have been closed for most of the initial stages of the fire.

- The fire that occurred in the kitchen of Flat 16 of the Grenfell Tower would have not exceeded 300 kW and a lower bound approximation for the temperatures of the smoke would have been between 100°C-220°C.
- Heating of the uPVC by smoke between 140°C - 220°C would have resulted in the uPVC reaching temperatures that led to total loss of its mechanical strength in a period between approx. 5 - 11.5 min.
- A fire of characteristics common to any residential kitchen fire would have therefore resulted in the loss of strength of the uPVC surrounding the window. This would have happened within a period consistent with the time gap between the first observation of the fire and the first evidence of involving external to the building (11.5 - 13.5 min) [2].
- The dimensions of the kitchen are sufficiently small that the location of the fire is irrelevant when it comes to breaching the uPVC by loss of mechanical strength. This failure can be deemed as a failure of the barrier to protect the cavity.
- The uPVC served as the single barrier between the interior of the building and the components of the cladding system. Thus, after breaching the uPVC barrier, any of those components would have been exposed.
- Given the low temperatures of the smoke, ignition of the combustible components adjacent to the window requires direct flame impingement.
- Given that flashover was not observed, the maximum fire size that will not result in flashover was used to determine how far from the window this fire could be. A fire of 300 kW will have to be at the most 3m way from the window to ignite any of the combustible materials adjacent to the window.
- Therefore, as an upper bound, a fire of characteristics common to a kitchen fire and that will not lead to flashover (less than 300 kW), if placed within 3 m of the window, is capable of triggering external flame spread.
- As a lower bound, a fire at floor level directly beneath the window, greater than 20kW, is capable of igniting exposed flammable materials (PIR, uPVC) at window sill level via flame/plume impingement, thus potentially leading to ignition of external cladding and external fire propagation.
- Flames from fires behind an obstacle will have much longer paths, therefore will require larger fires in order to cause direct ignition of combustible materials within the cladding system. Given the narrow window, it is probable that any obstructed fire capable of igniting any of the window materials will have to be of such a magnitude that it would have led to flashover.
- An obstructed fire that finds combustible materials to spread upwards cannot be discarded as a potential source of ignition of the combustible materials that make up the cladding system.
- The extent of burning as a result of secondary ignition of the fan / fan mounting unit is not sufficient to induce ignition of the ACP panels as a result of plume impingement.
- Evidence of initial dripping and external flame development point to ignition of the cladding to the left side of the kitchen window as viewed from the outside.
- Temperatures between 100°C - 220°C will pose no challenge to any components of the structure. Therefore, the structure can be deemed to be sound. Furthermore, a fire of this nature would have not been perceived by occupants or firefighters as a challenge to structural stability.

Structural stability is essential to enable egress and firefighting operations. The perception that the structure might be compromised could also affect decision making.

- The size of the fire that breaches the uPVC and the size of the fire that will ignite the exposed combustible materials of the façade system are within a range that can be considered as a feasible event within a residential kitchen. Many activities and appliances could serve as sources of ignition and can experience a fire consistent with the values reported here (less than 300 kW). The probability of such an event can therefore be considered one.
- Given that the initial fire event cannot be considered unusual in any way, determination of the cause and origin of the fire is therefore of secondary relevance to the definition of the development of the fire after ignition of the façade system.

4 STAGE TWO: VERTICAL FIRE SPREAD

4.1. VERTICAL FIRE SPREAD AT GRENFELL TOWER

Once the fire enters the façade system it initiates its spread outwards and then upwards. The first image where flaming debris and smoke is observed emerging outside the compartment is presented in [2] and timed stamped at 01:05:57 (see Figure 18 from [2]). By 01:14 the fire is visibly established on the outside the building (Figure 19) and has compromised many components of the façade system and by 01:26 it has propagated upwards past floor 18 (see Figure 20 from [4]). The fire appears to reach the architectural crown of the building before 01:30. During the process of vertical flame spread the fire does not propagate in the south direction (contained by the column) but it does spread laterally towards the North/East corner. It is evident that vertical flame spread is much faster than horizontal flame spread. Much more detailed recounts of the process are provided by Dr Lane and Prof. Bisby's Phase One expert reports [4,5].



Figure 20: Screen shot taken from the video recovered from Mr KEBEDE's mobile phone [A14] at time stamp 01:05:57. This shows some material falling from the building beneath the left hand side of the window (as viewed from outside).

FIGURE 18: FIRST EVIDENCE OF FLAMES EXITING THE COMPARTMENT OF ORIGIN [2].

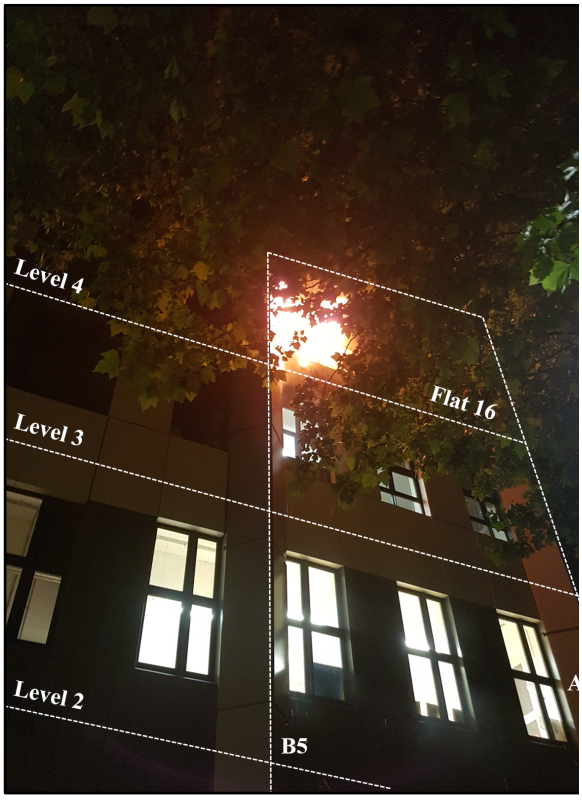


FIGURE 19: EARLIEST IMAGE OF EXTERNAL FIRE OBSERVED ON LEVEL 4, AT 01:14 ON 14 JUNE 2017 (MET00006589)

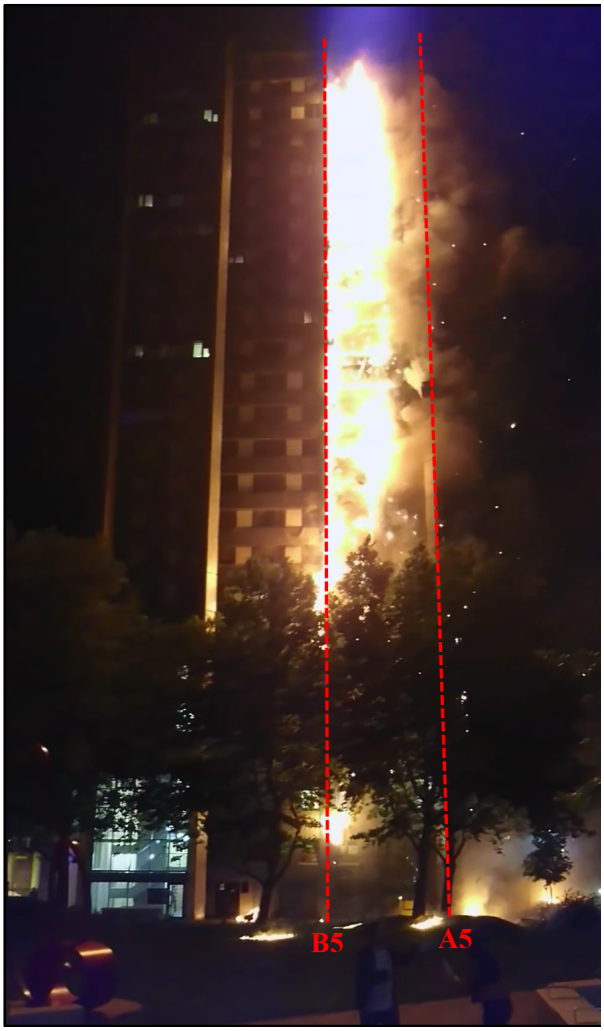


FIGURE 20: FIRE ON THE FULL HEIGHT EAST ELEVATION OF THE BUILDING ENVELOPE ON 14 JUNE 2017, ESTIMATED TIME 01:26 (COUNSEL TO CONFIRM TIME) (HTTPS://WWW.YOUTUBE.COM/WATCH?V=6AYUZ5SNXZO)

4.2. VERTICAL FIRE SPREAD OVER ACP PANELS

Flame spread is controlled by the transfer of heat from the flame to the combustible material. This is a complex process, in particular for products such as Aluminium Composite Panels where spread requires breaching non-combustible layers such as aluminium. The literature on the physics of flame spread provides extensive data characterizing vertical and lateral flame spread which shows that vertical flame spread rates are generally at least ten times faster than lateral flame spread rates [23]. Furthermore, the bigger the burning zone, the faster the rate of spread of a vertical flame i.e. upward flame spread self-accelerates. In contrast, lateral spread does not accelerate unless external heat is provided. Most data on flame spread is associated to combustible materials with not much data available on composite systems such as Aluminium Composite Panels (ACP). There are few studies on this matter, with the most specific being that of Ogilvie [16]. Ogilvie confirms that vertical flame spread rates are more than three times the rates of lateral flame spread.

The most comprehensive review of external fires was produced by the NFPA [13]. This document describes briefly a significant number of fires occurring prior to 2014 but unfortunately provides very few details of each event. An independent review of international events involving external fires was conducted for the purpose of this report. This review shows that the most common scenario is that of a flame rapidly spreading upwards with very limited lateral flame spread. Figure 21 shows three examples, the Torch Building in Dubai, the Lacrosse Building in Melbourne and the Address Building in Dubai. With the exception of the Lacrosse fire, where a report was made public, there is not much reliable data on the characteristics of these events. Nevertheless, the available footage clearly shows that once the fire has spread to the top, it proceeds to decay and eventually extinguish. There are many reasons why this could happen. The main one is that the amount of fuel per unit area is small so the local duration of the fire is limited to a few minutes.

In most of these cases lateral flame spread was limited. This is to be expected because the amount of energy necessary to spread a flame (critical heat flux for ignition) over an ACP panel is significant. Common materials will not exceed a critical heat flux for ignition of 15 kW/m^2 [24], while ACP panels can commonly reach values as high as 18 kW/m^2 [16]. Lateral spread is controlled by radiative heat transfer from the flame to the unburnt material, with convection cooling the same area of material, thus the net heat flux provided by the flame is the difference between the two. Heating areas are very small because convective flows carry heat from the material towards the flame, limiting the preheating area (Figure 22 (a)). In contrast, in vertical flame spread, convection and conduction both heat the material, so not only is the heat flux to the unburned surface greater (the sum of the two), but it also heats a larger area. The larger the flame the larger the heated area and therefore the faster the spread (Figure 22 (b)). Therefore, as time progresses, vertical flame spread accelerates while lateral flame spread tends to have a constant velocity.

Literature review on past fire events in high-rise buildings involving vertical flame spread via external cladding shows a very similar behaviour in most cases. This literature includes official reports, media, video footage, and industry and academic papers. Quantified rates of vertical flame spread based on available evidence were developed and are presented in Figure 23. As can be seen from Figure 23, vertical flame spread for Grenfell Tower is among the lowest reported. Fire spread rates range from less than 1 m/min to approximately 20 m/min.

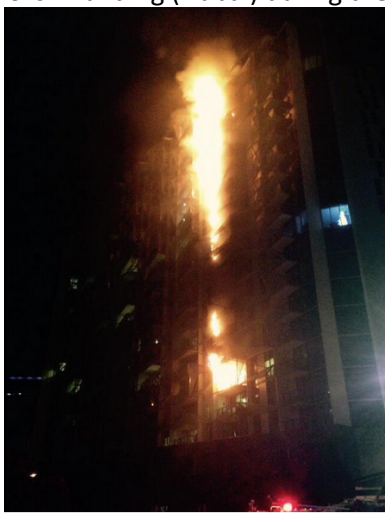
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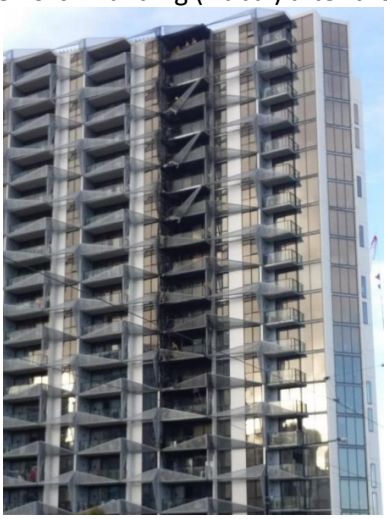
(a) The Torch Building (Dubai) during the fire



(b) The Torch Building (Dubai) after the fire



(c) The Lacrosse Building (Melbourne) during the fire



(d) The Lacrosse Building (Melbourne) after the fire



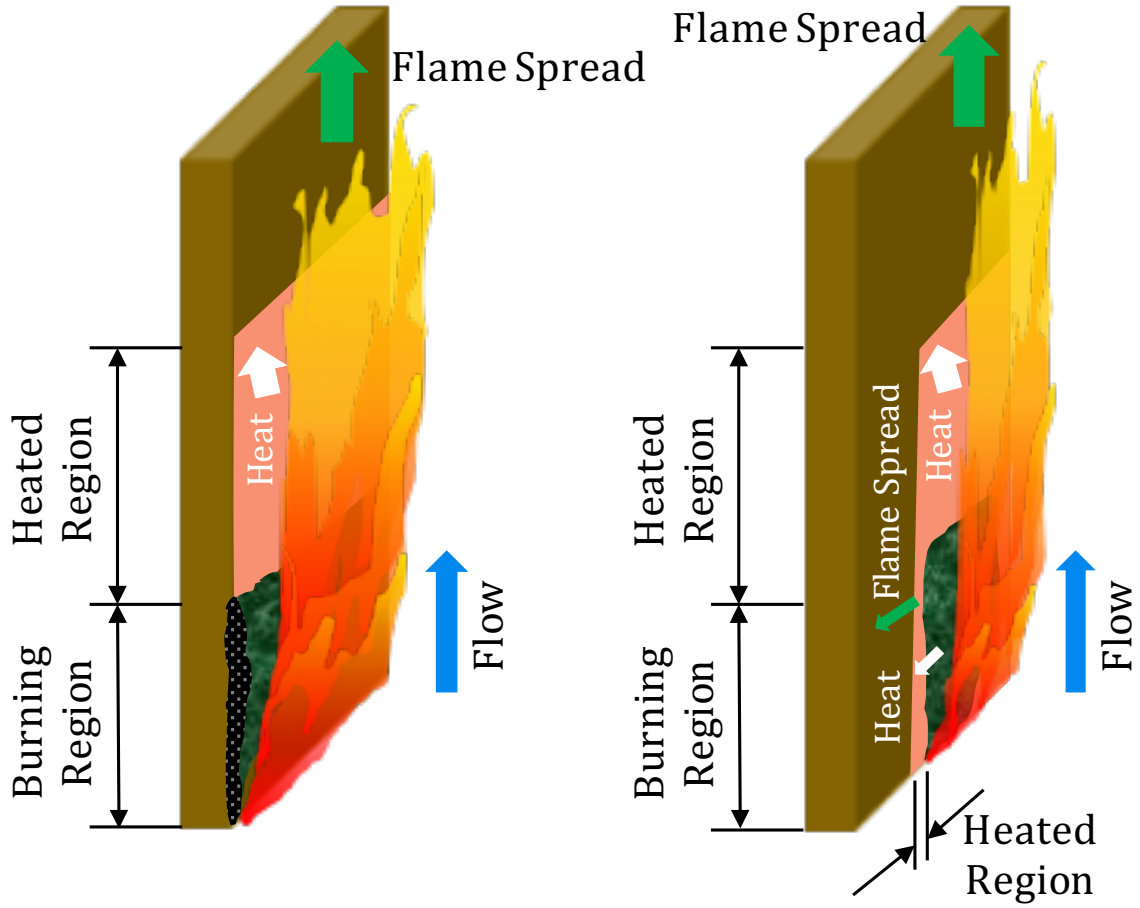
(e) The Address Building (Dubai) during the fire



(f) The Address building (Dubail) after the fire

1629

1630 **FIGURE 21: EXAMPLES OF VERTICAL FIRE PROPAGATION WHERE THERE WAS MINOR HORIZONTAL FIRE SPREAD.**



(a) (b)

FIGURE 22: SCHEMATICS OF LATERAL AND VERTICAL FLAME SPREAD. (A) SHOWS A FLAME SPREADING ONLY UPWARDS AND COVERING THE ENTIRE WIDTH OF A MATERIAL. THE AREA IN GREEN (BURNING REGION) PRODUCES FUEL AND IT DEGRADE IN-DEPTH (BLACK AREA). THE FUEL FEEDS THE FLAME THAT IS LONGER THAN THE BURNING AREA. THEREFORE, THERE IS AN AREA THAT IS TO BE HEATED (HEATED REGION). GIVEN THAT THE FLOW AND THE FLAME SPREAD ARE GOING IN THE SAME DIRECTION, THE AMOUNT OF HEAT LANDING IN THE HEATED REGION IS LARGE AND THE SIZE OF THE HEATED REGION IS LARGE. THE RESULT IS ROBUST AND FAST FLAME SPREAD VERTICALLY. (B) SHOWS THE CASE WHERE THE FLAME DOES NOT COVER THE ENTIRE WITH OF THE MATERIAL (GREEN), IN THIS CASE IT CAN CONTINUE TO SPREAD VERTICALLY AS PER FIGURE (A) NEVERTHELESS IT CAN ALSO SPREAD HORIZONTALLY. HORIZONTAL FLAME SPREAD WILL NOT BE IN THE SAME DIRECTION OF THE FLOW, SO MOST OF THE HEAT WILL BE CARRIED UPWARDS, THEREFORE THE AMOUNT OF HEAT REACHING THE HEATED REGION IS VERY SMALL. THE HORIZONTAL PROJECTION OF THE FLAME IS ALMOST OF THE SAME SIZE AS THE BURNING REGION THEREFORE THE HEATED REGION ITSELF IS VERY SMALL. THE RESULT IS THAT HORIZONTAL FLAME SPREAD WILL BE WEAK AND SLOW.

The Grenfell Tower cladding system was composed of multiple components, these are described in detail in [4] and [5] so they will not be described here. This system included multiple combustible materials (ex. Polyisocyanurate insulation (PIR), polyethylene infill for the ACP panels, EPDM Synthetic Rubber Membrane, etc.). All these materials would have sustained combustion. The polyethylene infill was placed between two aluminium plates that will melt in the range 580 - 650°C. Thus, in the presence of a significant flame the aluminium would have represented no protection to the polyethylene. Flames are typically between 600°C-800°C, thus are hotter than the melting

temperature of aluminium. Furthermore, polyethylene is a thermoplastic, thus will melt and drip. This can happen before or after ignition. In the case of polyisocyanurate, this material is low density closed pore insulation that will not melt. Instead it will char and stay in place. Polyisocyanurate has been studied in detail by Hidalgo *et al* [25]. Polyisocyanurate foams when heated and releases very little heat per unit area (less than 60 kW/m^2). In the absence of any external heating it will generally extinguish leaving approximately 60% of its mass as residue. When heated by more than 40 kW/m^2 it will generally be consumed fully [25].

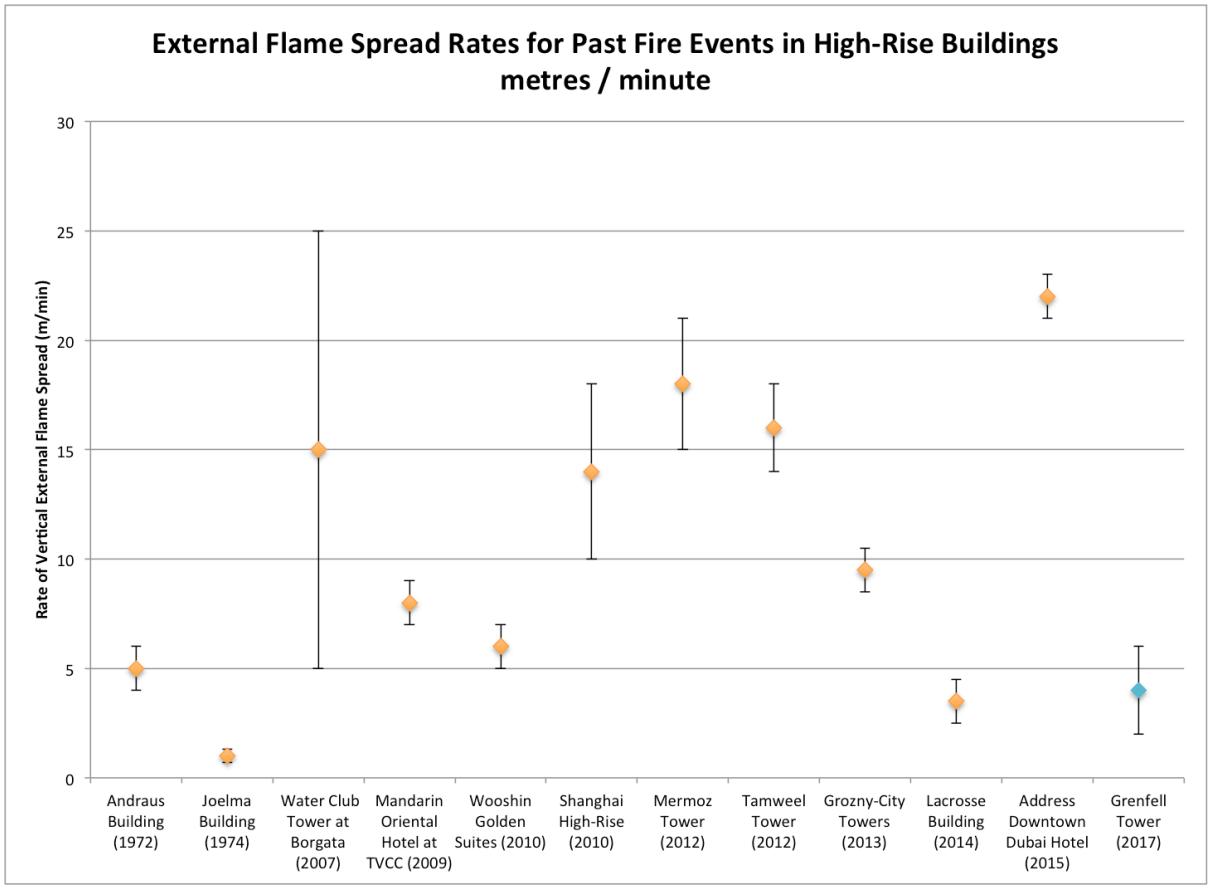


FIGURE 23: EXTERNAL FLAME SPREAD RATES FOR PAST FIRE EVENTS, COMPARED TO GRENFELL TOWER. NOT INCLUDED IN THIS PLOT IS A RESIDENTIAL BUILDING FIRE IN BAKU, AZERBAIJAN IN 2015, WHICH HAD AN UNEXPLAINED RATE OF FLAME SPREAD OF ~110 M / MIN. THIS FIGURE PRESENT AVERAGE VALUES FOR COMPARISON PURPOSES, NEVERTHELESS IT IS RECOGNIZED (AS INDICATED ABOVE) THAT THE FIRE SPREAD RATE WILL ACCELERATE. VALUES FOR GREFELL TOWER AND ADDRESS DOWNTOWN DUBAI HOTEL SHOW CONSISTENCY WITH THOSE REPORTED IN (FIGURE 97 [5]).

Figure 24 shows the different levels of damage of the cladding system. In the bottom and bottom right corner, sectors of the cladding appear undamaged, with the aluminium plates intact. Other sectors towards the middle of the photograph show the melted aluminium with the fully consumed insulation (centre of the image). Other sectors show the charred insulation which indicates that heat fluxes were not sufficiently high to consume the char. Finally, other sectors show the distinctive yellow colour of

the unburnt PIR. The infill is extracted from Hidalgo *et al* [25] for illustration. This shows a sample exposed to 25 kW/m^2 for a period of 22.5 minutes. The range of conditions observed from a single image (In Figure 24) demonstrates that the heat exposure was not homogeneous, with areas of intense local heating and areas of mild heating. These same observations can be seen in multiple locations on the building after the fire.



FIGURE 24: IMAGE OF THE GRENFELL TOWER AFTER THE FIRE SHOWING DIFFERENT LEVELS OF DAMAGE IN ONE SINGLE LOCATION. INFILL PHOTOGRAPH FROM HIDALGO ET AL [25] SHOWING THE DIFFERENT LEVELS OF DEGRADATION OF PIR.

It is less common for fires to spread laterally. In most cases, once the fire has reached the upper parts of the building, the lower areas are progressing towards extinction because most of the fuel has been either consumed or melted and dropped downwards. It is common to see burning debris descend but the debris is generally localized within the area of the fire.



FIGURE 25: SULAFA TOWER (DUBAI) DURING THE FIRE. LATERAL PROPAGATION EXTENDED TO ALMOST HALF OF THE BUILDING.

There are a few exceptions where the fire has propagated laterally fully or partially involving the building (Figure 25). There is very limited information about the construction details of any of these buildings, therefore it is not possible to establish what enabled the horizontal flame spread.

4.3. CONTROLLING MECHANISMS OF FLAME SPREAD

Vertical flame spread over combustible materials has been studied for decades [26] and the mechanisms controlling the different modes of flame spread have been described in great detail. The effect of flow velocity, external heat fluxes, material properties, etc. have been analysed extensively. Adequate models for simple scenarios such as vertical spread or lateral spread over a flat plate have also been studied. Less attention has been given to the spread of flames within cavities [12]. Nevertheless, it has been found that the width of the cavity ("W" in Figure 26) plays a fundamental role in the rate of flame spread. At the extremes, if "W" is large, radiative feedback and buoyantly driven chimney effects disappear with flames spreading at similar rates, as in the case of an exposed surface. Conversely, if "W" is very small, thermal expansion of the gases block the flow and the flames cease to spread internally remaining outside the gap. This information provides valuable insight and can potentially be used to explain some of the visual observations of the fire spread process during the Grenfell Tower fire [4, 5]. Accelerated spread can be explained by the presence of open vertical channels, inducing chimney effects associated to their width ("W") and also by preferential burning of polyethylene over PIR insulation, based on their material properties. Nevertheless, the adequacy of these interpretations is limited to very simple scenarios and requires caution.

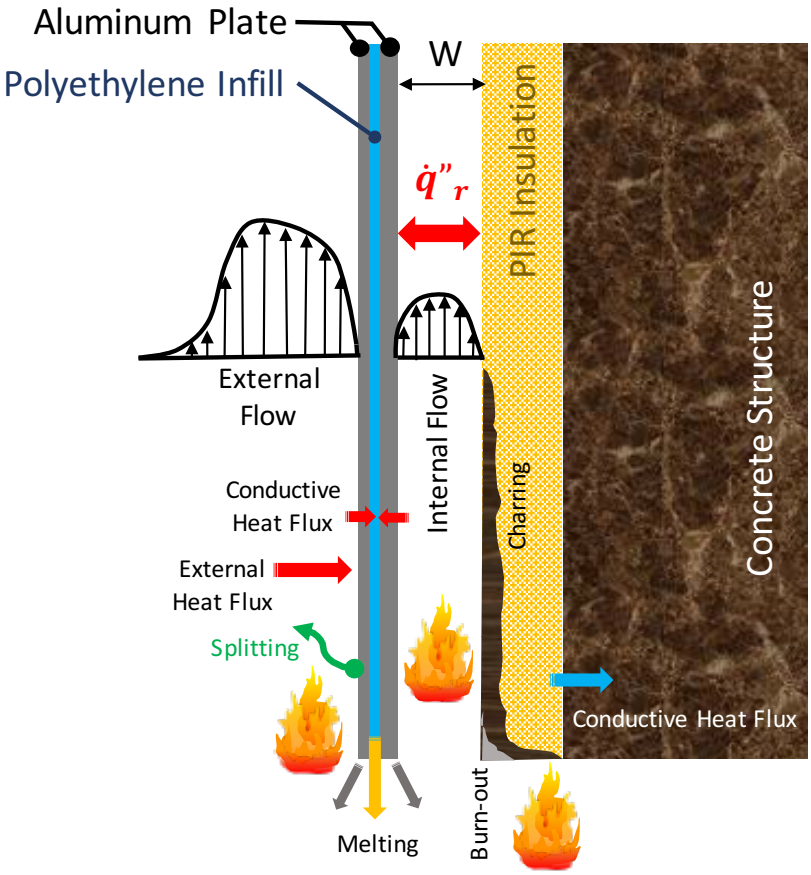


FIGURE 26: PROCESSES CONTROLLING FLAME SPREAD.

It is often the case that when construction systems are developed, little attention is given to the extreme complexity introduced. Figure 26 shows a very simplified schematic of the different processes

occurring during the spread of a flame within a simplified version of the system used in Grenfell Tower. In a system of such complexity, many other processes are introduced beyond simple effects such as the role of "W" (i.e. the cavity width). The low melting temperature and high thermal conductivity of aluminium results in complex heat transfer from external flames into the infill. Furthermore, melting of the aluminium is possible, so the loss of protection needs to be accounted for. The polyethylene infill will also melt at low temperatures, while the temperature gradients between the inside and the outside will result in differential deformations of the plates. This can lead to splitting of the plates and exposure of the polyethylene [16]. Inside the cavity, the PIR will pyrolyze, char, burn but also potentially burn-out. The PIR has a very low thermal inertia [5] which favours a fast flame spread rate, nevertheless its charring potential results in small fuel production and therefore short flame lengths. Charring, therefore, has a detrimental effect on flame spread. The outcome of these two competing effects is determined by the radiative feedback from the ACP, thus the way the ACP burns defines the way the PIR will spread a flame. Furthermore, the way the PIR burns will then affect the rate at which the ACP will degrade, melt and burn. Faster degradation induces further melting and thus might reduce spread rates but increase the rate at which molten debris falls. The interactions between the two materials are therefore difficult to uncouple.

These are only a few of the complexities introduced in these systems. When the systems are applied in construction, a multiplicity of other complexities are introduced (cavity barriers, complex geometries, other materials, intumescent sealants, etc.). The level of complexity is such that a very careful analysis is necessary to establish the fire performance of such a system. A comprehensive treatment of all complexities is beyond the objectives of this section, nevertheless, some of these complexities are introduced to highlight the need for a different form of thinking.

Tests such as BS 8414 [27] provide a single scenario deemed consistent with an external fire, a very limited number of measurements and a very simple failure criterion. The combination of these three characteristics does not provide a sufficiently comprehensive assessment of performance. Many details can be hidden within the results of the test and therefore great caution needs to be exercised when interpreting such tests. In particular, it is essential to recognize the limitations of the failure criteria and the complexities associated to its extrapolation to real systems.

Observation of the images associated with the Grenfell Tower fire can establish patterns of behaviour specific to this incident. These patterns of behaviour are a combination of multiple processes interacting with each other (Figure 26 and many more) and leading to specific observations. These observations are by no means universal, they are intimately associated with the conditions of the building and this specific event, and should only be extrapolated with great care.

A critical aspect that is missed by BS 8414 [27] and observations is the burn-out of the insulation material. As explained in previous sections, the residual PIR has different levels of degradation, thus it burns-out at different stages as a function of the heat flux that is fed back to the material. All other components of the cladding either melt or have a small mass per unit area, thus their burning time is very short. The insulation has the potential to burn for a much longer time period. The duration of localized burning will be critical when defining the capacity of these fire to break back into the building. Observations focus on visible flames, but these can over emphasize the burning of the rain-screen. The fire source, the focus on flame spread and duration of the test in BS 8414 [27] all mask the role of the insulation and over emphasize the role of the rain-screen. None address the burn-out times and their role on sustaining localized burning.

It is important to emphasize that a significant reason for the numerous external fires that have occurred in the last few years is the incapacity of these traditional approaches to establish the performance of these complex systems (assessments and/or tests). The information that can be extracted from current tests and observations of events is very limited. This information is of a quantity and quality which is inconsistent with the complexity of the systems. If these performance assessment methodologies are to be used, then the façade systems need to be drastically simplified. If systems of this complexity are to remain, so as to fulfil other functions, then a more comprehensive methodology of testing and a very different approach to performance assessment needs to be implemented.

As indicated in Dr Lane's Phase One Expert Report [4] in section 2.29.2 and 2.29.3, the introduction of these complex façade systems results in "complex and confusing" National and European reaction to fire tests. This results from the inadequate use and adaptation of tests that were never intended to define what "adequate" flame spread should be. While all these tests provide valuable information, this information requires interpretation beyond what can be issued by means of guidance. Appendix F (Section 1.1) of Dr Lane's report [4] illustrates the resulting complexity of the different accepted testing regimes. It is important to note that the testing options are so extensive that materials well known to challenge the concept of "adequate" flame spread can find a path to be routinely used in high rise buildings.

There is fear that a comprehensive testing methodology will be impractical and expensive and that simple failure criteria with standardized tests is the most practical approach to performance assessment. In my view, this is an incorrect way of thinking. A comprehensive methodology establishes the specific processes that matter, provides the information that is necessary and allows for establishing the robustness of the system. Gathering this information might only require simple and fast experimentation. What will be unavoidable is a comprehensive analysis that can only be conducted by a highly proficient professional.

No detailed differentiation of the mechanisms controlling flame spread will be proposed here. A detailed analysis of BS 8414 [27] to establish is value and limitations is proposed for Phase Two. The development of a testing protocol that will allow for comprehensively determining the influence that each material, components and geometry had on the spread of fire on the Grenfell Tower will also be a fundamental aspect of Phase Two. It is my firm view that only on the basis of this new approach can recommendations for future designs be made.

4.4. EFFECT ON TENABILITY AND STRUCTURAL STABILITY

At the time of writing, available evidence and expert reports point to at least three internal fires igniting as a result of the initial vertical propagation, within the timeframe of Stage 2. These fires occurred on the 5th, 12th and 22nd floor, in flats directly above the flat of fire origin, and were ignited at approx. 01:18, 01:24, and 01:28 respectively. This fire re-entry is discussed in detail in the following section (Section 5).

Towards the end of Stage 2, calls to emergency services rapidly began to increase reporting inability of residents to evacuate their flats due to smoke build-up in communal lobbies, both on and around

the floors with known fires. This indicates a rapid failure of horizontal and potentially also vertical compartmentalization within the tower.

While tenability was beginning to be compromised locally, this time period (01:15 – 01:30) falls within the period of peak egress rate of occupants from the tower according to Table D in Dr Lane's Phase 1 Expert Report [4], indicating that the egress stair was still passable and smoke propagation was confined to communal lobbies.

4.5. COMPLIANCE ISSUES AFFECTING THE CHARACTERISTICS OF STAGE TWO

The main issue of compliance stems from Section 12 of ADB and Appendix A of ADB (covered in Section F1.1.5 [4]) where it is stated at paragraph 1:

"In such cases the material, product or structure should:

a. Be in accordance with a specification or design which has been shown by test to be capable of meeting that performance; or
   Note: For this purpose, laboratories accredited by the United Kingdom Accreditation Service (UKAS) for conducting the relevant tests would be expected to have the necessary expertise.
b. have been assessed from test evidence against appropriate standards, or by using relevant designs guides, as meeting that performance; or
   Note: For this purpose, laboratories accredited by UKAS for conducting the relevant tests and suitably qualified fire safety engineers might be expected to have the necessary expertise.
   For materials/products where European standards or approvals are not yet available and for a transition period after they become available, British standards may continue to be used. Any body notified to the UK Government by the Government of another member state of the European Union as capable of assessing such materials/products against the relevant British standards may also be expected to have the necessary expertise. Where European material/products standards or approvals are available, any body notified to the European Commission as competent to assess such materials or products against the relevant European standards or technical approval can be considered to have the appropriate expertise.
c. where tables of notional performance are included in this document, conform with an appropriate specification given in these tables; or …"

As the above extract from Appendix A of ADB indicates, there are three clear paths towards acceptance of a material or product; in section (a) performance is established "by test," in section (b) performance is established by "test evidence" against "appropriate standards" or "design guides" and in section (c) by means of tables of notional performance.

The performance criteria specified in Section 12.5 (ADB) [11] states: "The external walls of the building shall adequately resist the spread of fire over the walls and from one building to another." As explained in Sections 2.3 and 2.4 of this report, for a building like Grenfell Tower the criteria of "adequately resist" is intimately linked to the fire safety strategy, thus a material or product to be used needs to be analysed in conjunction with the fire safety strategy and the building itself. Analysis of the material separate to the building will not guarantee the performance of the fire safety strategy. This invalidates paths (a) and (c) because both paths focus on the material/product and do not include

statements about the design. Path (b) requires performance assessment "from test evidence against appropriate standards, or by using relevant designs guides" and as such remains as the single performance assessment route. Test evidence is to be provided by "laboratories accredited by UKAS for conducting the relevant tests" and used as evidence by "suitably qualified fire safety engineers" who "might be expected to have the necessary expertise."

Path (b) is not explicit on what are the "relevant design guides," furthermore when it comes to competence the vague terms "suitably" and "might" are used. Given that this is the only path to compliance, this performance assessment is of critical importance to the integrity of the fire safety strategy, and given that the consequences of inadequate performance are enormous; it is not acceptable to treat the problem in this manner. As indicated in Section 4.3 this matter is of a level of complexity that is not suitable for design guidelines, and instead requires a competent designer. A competent designer has to be properly qualified and assessed and it is not acceptable to treat competence in such a vague manner on a matter of such importance to safety. To my knowledge, a clear definition of necessary competence is currently not available and therefore this is a matter of critical importance that needs to be explored in Phase Two.

4.6. UNDERSTANDING THE RELATIONSHIP BETWEEN COMPLIANCE, PERFORMANCE AND QUALITY

The concepts of compliance, performance and quality should be related. One potential path to guarantee adequate performance and adequate quality should be compliance with existing building regulations and guidance. Other mechanisms, such as explicit performance assessment, are not excluded in Building Regulations (Section: Use of Guidance – The Approved Documents, paragraph 3 (ADB)).

In a system where compliance is the means of establishing adequate performance and adequate quality, it is necessary to introduce a process of approval. An approvals process seeks to evaluate compliance by establishing that the performance and quality criteria defined by Building Regulations and guidance are "complied" with. Approval will therefore, indirectly, establish adequate performance and adequate quality.

It is important to note that quality is only mentioned in ADB in matters pertaining to detection systems (Section 1.23, Section 1.37 and Appendix E (ADB)). In matters pertaining to functional requirement B4, only performance is discussed and it is defined as a function of criteria specified by means of standard tests (e.g. BS 476 Parts 4, 6, 7, 11, etc.), other guidance documents (BR 135), Council Directives (e.g. Council Directive 89/106/EEC, etc.), European Standards, etc. These criteria shall be used within the context of the three possible paths defined in Section 12 of ADB which are presented in the previous section.

In the case of the Grenfell Tower façade systems, it was established that path (b), which requires performance assessment "from test evidence against appropriate standards, or by using relevant designs guides" is the single path to compliance (Section 12 of ADB). Dr Lane in her Phase One expert report [4] states that: "2.29.21 I have concluded in Appendix D that the legal requirement is to demonstrate compliance with the functional requirement of the Building regulations 2010." In the

case of the façade system this is functional requirement B4. (1) “adequately resist the spread of fire” (ADB).

Section 4.3 of this report describes the complexity of these façade systems and concludes that these systems are of such complexity that the direct results from any of the relevant tests are not sufficient. This is consistent with path (b) as specified by ADB and therefore this is the only path to compliance.

The relevant standard testing methodologies are discussed in detail in Appendix F of Dr. Lane’s Phase One expert report [4]. Those of direct relevance are BS 476 (parts 4, 6, 7 and 11). These methods address combustibility (part 4), fire propagation (part 6), surface flame of spread (part 7) and heat emission (part 11). All variables are of great relevance to the spread of a fire over a façade system of this nature even if they are not required by ADB (Table A7).

When following “path (b)” (ADB), “evidence” from these or other tests is to be used by “suitably qualified fire safety engineers” to establish if the performance of the system meets the functionality requirement B4. (1). The physical relationships that govern the spread of flame over façade systems of this nature are of extreme complexity (Section 4.3 of this report). In contrast, the tests are very simple, perform very basic measurements and none of them, by itself, incorporates all relevant features. Thus, the competency of the qualified fire safety engineer is of paramount importance. Any approval process attempting to establish “compliance” should therefore have focused on the performance analysis presented by a qualified fire safety engineer and on the qualifications of such a professional.

Instead, in Dr. Lane’s Phase One expert report (Section 2) [4] it is stated:

“2.19.2 I have found no evidence yet that any member of the design team or the construction team ascertained the fire performance of the rainscreen cladding system materials, nor understood how the assembly performed in fire. I have found no evidence that Building control were either informed or understood how the assembly would perform in a fire. Further, I have found no evidence that the TMO risk assessment recorded the performance of the rainscreen cladding system, nor have I found evidence that the LFB risk assessment recorded the fire performance of the rainscreen cladding system. I await further evidence on these matters, which I will explore in my Phase 2 report.”

Furthermore, and as an example, Appendix E of Dr. Lane’s report [4] discusses the available testing evidence on relevant Celotex products. Here, she provides assessments of non-compliance (e.g. Table E.2) and concludes:

“E2.3.4 I therefore conclude from my comparison that there are multiple significant differences between the rainscreen system tested in BS 8414-2:205 Test on Celotex RS500 insulated system with a ventilated Eternit Rainscreen produced by BRE Global on 01/08/2014, when compared with as built Grenfell Tower construction.

E2.3.5 The most significant discrepancies are: …

… E2.3.6 This test report therefore does not certify the as built Grenfell façade construction as compliant with ADB 2013, nor do I consider it to demonstrate compliance with the functional requirement B4 of the Building Regulations.”

Dr. Lane presents further examples where other discrepancies between reported tests and the as built Grenfell façade system were observed leading to the same conclusions. These are described in detail in Appendix E [4].

In my opinion, Dr. Lane's conclusions [4] are correct. In the complete absence of an analysis of the test evidence, any differences between the as built and the tested systems will result in direct failure to comply. Furthermore, any tests that are not exactly those required by ADB, cannot be used for compliance purposes.

Nevertheless, of even greater importance is the fact that, even if the tested system was identical to the as built system, the tests conducted were exactly those required by the guidance, and that all failure criteria for the tests were met, the Grenfell Tower façade system could have not been deemed compliant without a detailed performance analysis and an appropriate assessment of the qualifications of the fire safety engineer involved. These are requirements for "path (b)" (ADB).

What is evidenced in this section is a misunderstanding of the process of compliance. The evidence provided by Dr. Lane in her Phase One expert report (in particular Sections 2, Appendix E and Appendix F) [4] demonstrates a culture by which "compliance" is trivialized by assuming that being "compliant" only requires meeting the individual requirements stated in the Building Regulations and guidance. In an approvals environment dominated by this culture, compliance simply becomes the process by which approval is being sought/granted as a function of establishing that each individual criterion set by standard tests, guidance documents, Council Directives, European Standards, etc. has been met. Concepts such as adequate performance or adequate quality, which are the real objectives of Building Regulations, are not proven to be attained by "compliance." The simple fact that ADB does not introduce the term quality in section B4 is further demonstration of this culture. Finally, competency of the engineer is completely disregarded.

This section represents a brief presentation of the current culture of "compliance" and its non-existent relationship with competency, performance or quality. It is of paramount importance to give further attention to this matter in Phase Two.

4.7. SUMMARY

- Due to the comparative physical manifestations of buoyancy and air entrainment on heat feed back to the unburned fuel, flames on a vertical surface will spread far more rapidly in the upward direction than they will laterally.
- This was observed at Grenfell Tower where, in approximately the first 15 minutes following the establishment of flames on the exterior of the building, the flame spread rapidly from Level 4 to the top of the building, while in the same period only spreading laterally a matter of meters to the North.
- The rate of upward flame spread observed was not unusual when placed in the context of other historical events of this nature. In fact, at approximately 4m/minute it was one of the slowest upward propagating examples.
- The flames can be seen to take hold on the outside of the ACP panels from the very early stages of vertical flame spread. Any non-conformity of cavity barriers or other detailing would

therefore have not significantly affected the rate of vertical spread once the fire was established on the exterior of the building.

- As detailed in the following section, the initial vertical spread ignited a kitchen fire directly above Flat 16 on Level 5.
- Towards the end of this stage, a fire is ignited in Flat 196, Level 22. This fire apparently resulted in reports of smoke blocking the communal corridor on this level however this is believed to have happened later, probably in Stage Three.
- Given the continued evacuation of occupants, the stairwell is still presumed to be tenable, at least in parts, for the duration of this second stage of the fire. It is not known however which floors in the building the evacuating occupants originated from. It can therefore not be discounted that parts of the stairwell may have experienced smoke infiltration.
- The vast majority of the heat produced by the combustion of the cladding will be lost in the smoke plume or absorbed by the unburned cladding ahead of the flame front and therefore will not have reached the load bearing structure of the tower. The structure is not considered to be at any risk during this stage of the fire.
- Different details in the façade system (materials, geometry, cavity barriers, etc.) seem to impact in different ways on the rate of flame spread [4,5]. Test conducted after the Grenfell Tower fire [4,5] seem to provide further information. The complexity of this façade system is such that observations and tests such as BS8414 [27] do not provide sufficient information to be able to understand these differences. The quantity and quality of the data is inconsistent with the complexity of the problem. At Phase Two I will be suggesting a testing protocol that will provide information that is more pertinent to the complexity of these systems. At this stage, this Phase One Report will not reach any conclusions on what are the controlling mechanisms for flame spread in this stage of the fire.
- Compliance of the façade design relies on establishing if it can “adequately resist the spread of fire.” The only path to compliance is performance assessment “from test evidence” used by a competent engineer using “relevant designs guides.” The complexity and importance of the façade system requires more than guides and therefore the reliance is fully on competency. There is no clear definition of competency, therefore this is a matter that needs to be studied with great attention in Phase Two.
- The relationship between compliance, performance and quality is currently poorly established. The means by which performance, quality and compliance for the Grenfell Tower façade system were assessed are deeply flawed. The current culture of “compliance” needs to be revisited in great detail in Phase Two.

5 STAGE THREE: LATERAL FIRE SPREAD AND INTERNAL MIGRATION

5.1. LATERAL MIGRATION OF THE EXTERNAL FIRE

The Grenfell Tower fire is unusual in that horizontal flame spread enveloped the entirety of the building. The fires spread laterally around the building in less than three hours. It is clear that there are multiple pathways for the fire to spread through the façade system [4, 5], nevertheless, in my opinion, none of these explain the lateral propagation of the fire. As can be seen from the earlier footage of the fire, there is very limited lateral spread across the face of the building. Dr Lane [4] and Prof. Bisby [5] present in their Phase One expert reports, ample evidence of many pathways to lateral spread and specific photographic evidence is presented for each of these pathways ,but, nevertheless, no dominant pathway is conclusively established. Furthermore, video and photographic images do not seem to determine clear and consistent propagation characteristics.

5.1.1 MECHANISMS DRIVING LATERAL FLAME SPREAD

This section serves as a complement to Dr Lane [4] and Prof. Bisby's [5] Phase One expert reports with the objective of adding further clarity to a mechanism of fire spread that is particular to Grenfell Tower. This is not intended to diminish the importance of other hypotheses (Section 6.3.4 [5]) nor to diminish the complexities associated with external spread over these type of façade systems (as indicated in Section 4.3 of this report).

Figure 27 shows a different mechanism. The fire reaches the architectural crown of the building and this crown behaves as a preferred path for lateral propagation. Hot smoke plumes from fires lower down on the building façade will also contribute to lateral spread. The rising plume will widen with height and transfer heat over a greater width in the upper levels of the building. This hot smoke preheats upper sections of the cladding which facilitates later ignitions in these areas. Thus, the expanding smoke plumes would serve to accelerate lateral flame spread at the upper areas of the building.

While this is clearly a factor that needs to be considered [5], it seems that a different process drives horizontal spread. In particular, it can be observed that lateral fire spread is more rapid over the architectural crown structure of the building than elsewhere.

Figure 28 shows a view of the East façade where it can be clearly seen that the fire is propagating faster over the architectural crown structure. The following figure shows how debris from this fire starts to ignite the areas below. In the meantime, the fire continues to propagate through the architectural crown structure towards the South-East corner.

By 02:16:41 (Figure 29) falling debris continues to spread the fire downwards while the flames now involve several floors underneath the architectural crown structure almost to the South-East corner.

2020 The final photograph of the sequence (Figure 30, 02:30:10) shows the fire turning the South-East
2021 corner and starting its propagation over the architectural crown structure in the south face of the
2022 building.



2023

2024 **FIGURE 27: EAST FAÇADE - BURNING DEBRIS GATHERING ON LEDGES BELOW FIRE AT ~LEVEL 18 (FLAT 151, 2:09:20)**



2025

2026 **FIGURE 28: EAST FAÇADE – SIGNIFICANT DOWNWARD FIRE SPREADS IN 6 MINUTES (2:16:14)**



2027

2028 Figure 29: Flaming falling debris have ignited 3 further floors downwards (02:16:41)



2029

2030 Figure 30: Fire spreading to south façade from east façade architectural crown (2:30:10)

It is important to note that the lateral spread of the flames through the architectural crown structure is faster than the lateral propagation through the façade system in the building. The characteristics of the architectural crown structure have been described in detail by Prof. Bisby in his Phase One expert report [5]. As indicated by Prof. Bisby [5], the characteristics of the façade system in this region of the building will clearly allow for faster propagation (Hypothesis E5, lines 858-864).

Finally, simple calculations show that the average lateral fire spread in the architectural crown structure remains less than 0.5 m/min which is about one eighth of typical vertical fire spread rates.

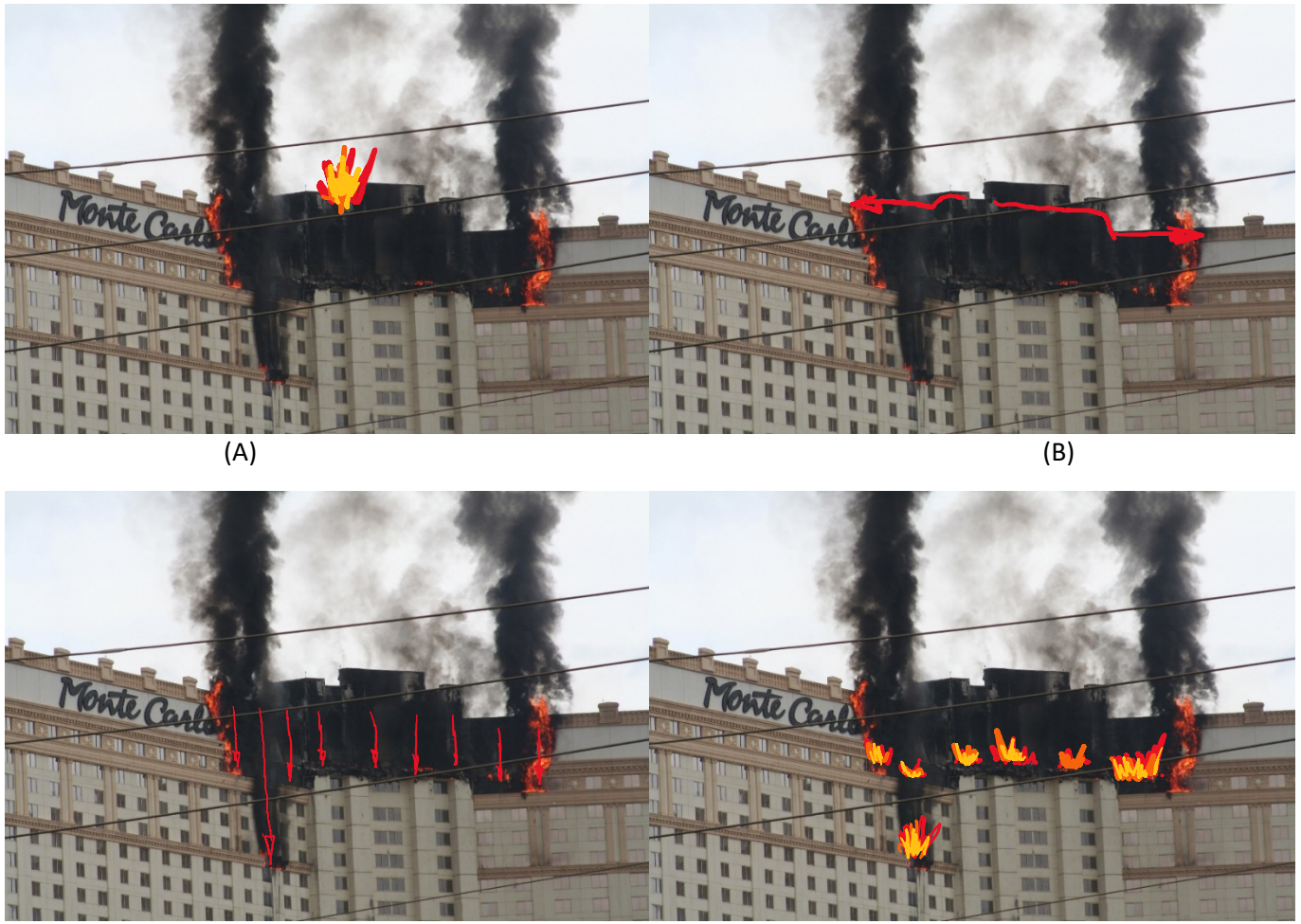
As debris falls from burning areas, they will accumulate on window ledges or indeed on any available horizontal surface, igniting new localised fires. Figure 31 shows an example of such a spread mechanism. Debris will ignite a fire which will then propagate upwards to meet with other fires thereby covering completely that sector of the building. This appears to be the governing mechanism for lateral spread observed at Grenfell Tower.



FIGURE 31: FIRE VISIBLE ON FAÇADE BELOW FIRE ON EAST ELEVATION

This mechanism (lateral flame spread over the architectural crown of a building) has been observed in previous fires, in particular in the Monte Carlo Casino & Hotel Fire in Las Vegas on January 25th, 2008 (Figure 32). At the Monte Carlo Casino & Hotel, the polystyrene and polyurethane portions of the exterior insulation and finishing panels (EIFS panels) and trim burned along the building's parapet. Molten material ran down the exterior edge of the hotel, starting fires in other EIFS panels. As the fire spread from the centre of the west and south wings of the hotel, it also began to burn downward, impinging the windows of the suites on the 32nd floor. The heat caused several windows on the 32nd floor to fail and flames spread into the building.

This mechanism was also recently observed in a fire at the Taksim Ilk Yardim Hospital in Istanbul, Turkey on April 5th, 2018 (Figure 33). Local news coverage reported the fire started on the roof of the hospital and spread downwards and laterally to incorporate the external façade of the building. The fire did not spread into the interior of the building, however there was smoke spread internally. Patients were evacuated and no casualties have been reported to date from the event.



(A) (B)

(C) (D)

FIGURE 32: MONTE CARLO CASINO & HOTEL FIRE, LAS VEGAS, JANUARY 25TH, 2008. (A) SHOWS THE EXTERNAL FIRE SPREAD FROM THE INITIAL IGNITION AT THE ROOF LEVEL OF THE BUILDING. (B) THE FIRE SPREADS LATERALLY ACROSS THE PARAPET. (C) MOLTEN BURNING MATERIAL DRIPS DOWN THE FAÇADE AND BUILDS UP ON LOWER LEVEL PARAPETS. (D) BUILD-UP OF MOLTEN MATERIAL IGNITES FRESH FIRES WHICH BREAK IN THROUGH WINDOWS AND RESULTS IN FURTHER COMPARTMENT FIRES.



FIGURE 33: STILL IMAGES FROM COGAN NEWS AGENCY COVERAGE OF THE TAKSIM ILK YARDIM HOSPITAL FIRE IN ISTANBUL, TURKEY ON APRIL 5TH, 2018, SHOWING THE PROGRESSIVE DOWNWARD AND LATERAL SPREAD OF FLAMES

5.1.2 DETAILED ANALYSIS OF THE EXTERNAL SPREAD OF THE FIRE

To understand the timeline of external fire spread it was necessary to analyse multiple images. This enabled identification of the mechanisms by which fire spread around the building and confirmed a timeline of spread. The building was divided in sectors as indicated in Figure 34 extracted from [MET00008024].

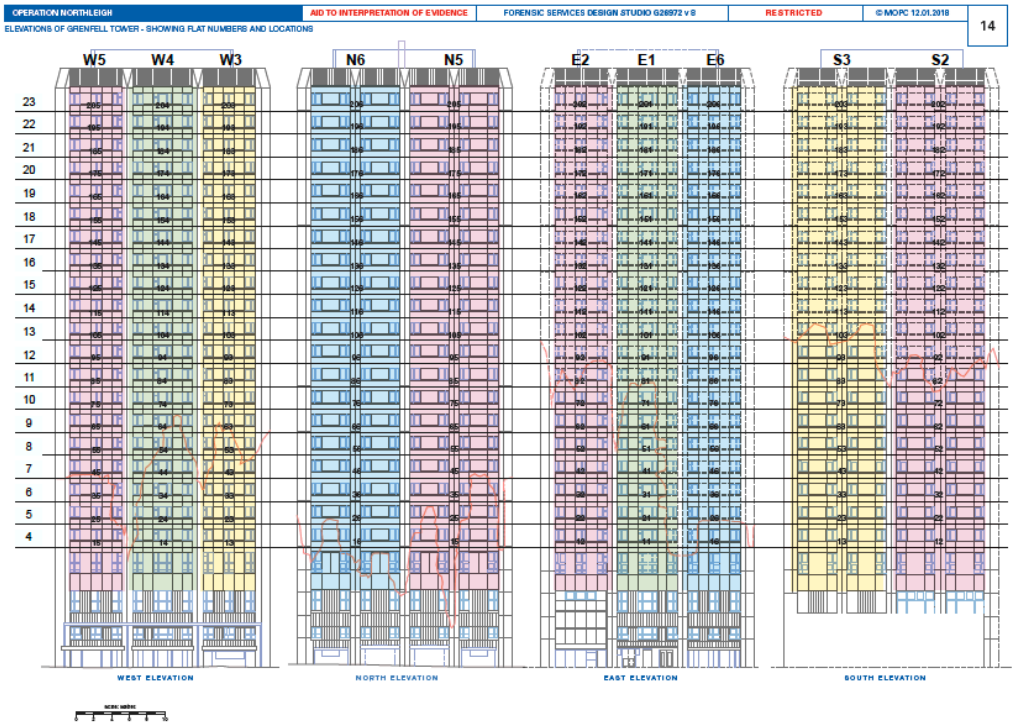


FIGURE 34: THIS FIGURE WAS EXTRACTED FROM REFERENCE [MET00008024] AND INDICATES THE COORDINATES OF EACH RESIDENTIAL UNIT. THE NOMENCLATURE STIPULATED IN THE FIGURE WILL BE USED FOR THE FIRE SPREAD ANALYSIS.

In an effort to examine, floor by floor, external flame spread (both lateral and vertical), floor versus time plots were created using time stamped facade elevation tower plan views that highlighted fire coverage, including the public footage sourced from MET00008024. A series of steps were executed to estimate and visualize the external flame spread across each facade.

The first step involved plotting approximate fire coverage (i.e. highlighted markings) from 01:14 am local time onward based on time stamped facade elevation tower plan views in MET00008024. For examples of this step, see Appendix E Figure 98 - Figure 102, Figure 105, Figure 107 - Figure 109, and Figure 111 - Figure 128.

The second step was to identify any space and time gaps (i.e. greater than 30 min) in the analysis. The north elevation was the only facade where there were any such gaps. Public footage between 1:42 am and 3:07 am on the north elevation was sourced from MET00008024 to help fill in these spatial and temporal data gaps (Appendix E Figure 103).

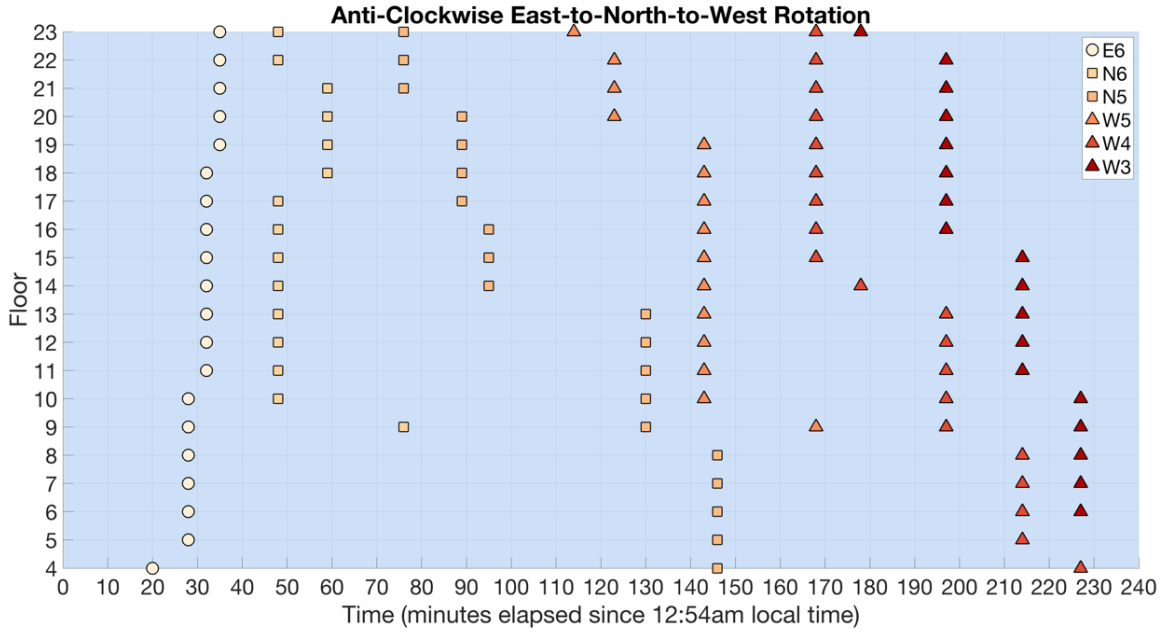
To be able to discern some of the details of the images, it is necessary to process the images. In this case the brightness of the flames hides details behind the fire and therefore it is necessary to illuminate the fire to see what is behind. Well accepted professional tools exist in specialized commercial packages such as MATLAB. For the purposes of this analysis MATLAB's image processing toolbox and a modified Spectral colorbar native to ColorBrewer[23] was used to illuminate fire coverage. This toolbox was only deployed on three public images of the north elevation (Appendix E Figure 104; Figure 106; and Figure 110).

The resultant characterisation of the external fire spread is condensed into the plots in Figure 35. The plots show spread to the north and south respectively from the initial external fire on the east façade. The key indicates which of the sectors each data point refers to as established in Figure 34. A step by step guide through the external evolution of the fire is presented in Appendix E.

The initial vertical line of markers, common to each plot, represents the initial vertical fire spread from the initial point of ignition on the external façade. By following the subsequent markers for each sector, it is clear that the initial ignition in each sector, beyond those immediately adjacent to the initial vertical spread, is at the top of the building where lateral spread happens most rapidly. Subsequent ignition of each of these sectors further down the building happens noticeably later in time.

The plot also captures how spread down the façade happens in clusters of floors. This is due to the spread mechanism identified above. The lowest marker identified represents the level at which flaming debris or molten material has collected and resulted in a remote ignition. The data points representing floors above this appear to be a result of upward flame spread from this remote ignition.

[23] https://www.mathworks.com/matlabcentral/fileexchange/45208-colorbrewer--attractive-and-distinctive-colormaps



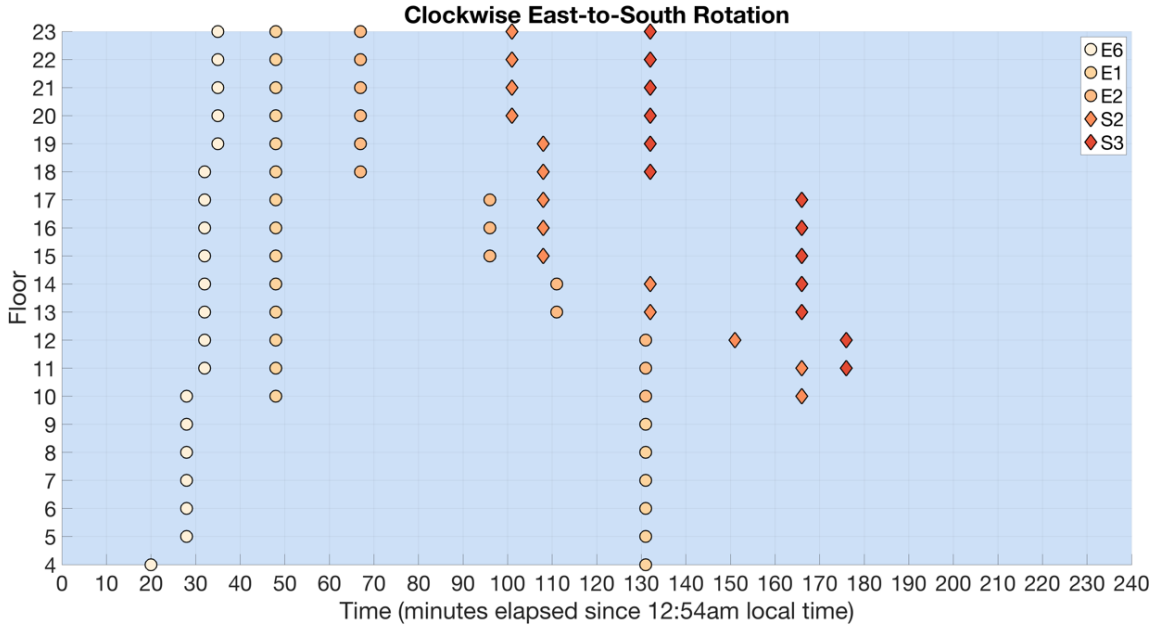


FIGURE 35: PLOTS INDICATING PROGRESSION OF LATERAL SPREAD IN TIME FROM 12:54 AM. AN EXTENSIVE DIAGRAMMATIC BREAKDOWN OF THESE CHARTS IN PROVIDED IN APPENDIX E.

5.2. INTERNAL PENETRATION

The external flames established on the façade system encounter multiple paths of entry into the building. The building envelope is designed to serve as a barrier for fires occurring in adjacent buildings (heat fluxes as high as 12.6 kW/m^2), but not to withstand an external fire generated within the building (see Section 2.4). External fires will result in very significant heat fluxes (as high as 120 kW/m^2) that will damage numerous components

of the building, in particular the window systems. Mechanisms for re-entry via the window systems principally follow three paths:

1. Failure of the window glazing
2. Failure of kitchen extraction fans
3. Failure of the uPVC window surrounds

While mechanism 3 is discussed in detail in Section 3.4.4, mechanisms 1 and 2 are discussed here. This discussion is presented here only with the objective of providing examples of paths through which the fire re-entered the building and in order to explain how none of the components of the window system were designed to serve as a barrier to prevent the fire from re-entering the building. It is not the intention of this section to describe a preferred path of re-entry.

Dr Lane's Phase One expert report (Section 9 [4]) also provides a detailed account of all the weakness of the window as designed and built. Any of these weaknesses would have accelerated the ingress of the flames back into the building (as shown by the multiple evidence and testimonies presented). While all these weaknesses are important, and in many cases, will appear to dominate the ingress process, they will not be further discussed here. Given that the windows could not have been designed to withstand the level of heating provided by an external fire, there cannot be any expectation that the performance of the window system would have prevented ingress of the fire to other units. The presentation here should be seen as complimentary to Dr Lane's descriptions [4].

Following any one of these failures, if the flames are then in contact with other combustible materials in the interior of the unit, then an internal fire will occur that could progress in a manner consistent with any compartment fire.

5.2.1 Glazing Failure

Ogilvie [16] summarizes the range of heat fluxes delivered by external flames as reported by different authors (Table 4). FM Global considers in their testing requirements that the range should be extended up to approximately 120 kW/m^2 [12]. While the range is very large, it is clear that the magnitude of potential heat fluxes is above the critical heat flux for ignition of almost all combustible materials [28]. In particular, it is above the critical heat flux for ignition of all combustible materials present in the façade of Grenfell Tower [5]. Building design guidelines suggest that the external envelope of a building shall withstand 12.6 kW/m^2 (see Section 2.4).

Glazing has been extensively studied and experimental data shows that all forms of glazing will fail between 5-10 kW/m^2 in a period of exposure between 60-300 seconds [29]. The higher the heat flux, the shorter the failure time. Given the typical heat fluxes for external fires, it will be expected that once the windows become engulfed by flames the fire will find a path inwards.

Author	Heat Flux Value (kW/m^2)
Saito et al.	25
Mowrer and Williamson	30
Delichatsios et al.	30
Delichatsios and Delichatsios	25
Delichatsios and Chen	25
Grant and Drysdale	20
Anderson et al.	35
Kokkala et al.	25
Qian and Saito	25
Quintiere and Lee	25
Lee et al.	60
Markstein and de Ris	50

TABLE 4: TYPICAL VALUES REPORTED FOR HEAT FLUXES EMERGING FROM EXTERNAL FLAMES, TAKEN FROM [16] CITING [30,31,32,33]

5.2.2 KITCHEN EXTRACTION FAN FAILURE

Based on actual photos taken after the fire, it is possible to identify different scenarios where the failure of the kitchen extraction fan occurred. An analysis of the damage patterns to different components in this part of the windows shows clearly the multiple routes for the passage of flames from the exterior of the building to the interior of the building.

Figure 36 shows a scenario where the heat fluxes available have not been able to breach any of the components of the window i.e. flames have not penetrated through any component of the window. But the detailing of the window, as described by [4,5], does not provide an adequate barrier between the interior and the exterior of the building and thus smoke is observed to have entered through any of the existing gaps.

Figure 37 shows a slightly higher level of heat insult. This time the fan, which appears to be the weakest component (to heat), has deformed and is beginning to fall from its casing. A greater amount of smoke is present in the interior of the unit but this has not resulted in the ignition of any of the combustible materials of the compartment. It is important to note that in this case, the window is open allowing for smoke to penetrate freely.

In Figure 38 it can be observed that the fan has now failed leaving a circular opening on the panel at the location of the original placement of the fan. Smoke has not only penetrated through this opening but has also entered the compartment through gaps between the window frame and the window. Flames did not propagate to the interior of the unit.

In the next sequence of images (Figure 39, Figure 40 and Figure 41) the fan has failed, the windows are open, the glazing has, in some cases, failed (in others not) and the fire has penetrated and damaged the unit. In all of these cases, the panel originally holding the fan is still in place.

A similar scenario can be seen in Figure 43 where the kitchen and adjacent room are significantly damaged, but the extractor fan panel still remains in place. The window in the room adjacent to the kitchen is severely damaged including the frame.



Figure 36: Kitchen window Level 9, Flat 62



FIGURE 37: KITCHEN WINDOW LEVEL 10, FLAT 71



Figure 38: Kitchen Window level 5, Flat 25



Figure 39: Kitchen window, level 7, Flat 44



Figure 40: Kitchen window, Level 6, flat 31



FIGURE 41: KITCHEN WINDOW, LEVEL 7, FLAT 43



Figure 42: Kitchen window, level 8, flat 54

Figure 43, Figure 44 and Figure 45 show examples where the extractor fan panel has failed and the adjacent rooms have suffered different levels of damage. In Figure 42 and Figure 43 the external flames have ignited some elements of the unit while in Figure 44 and Figure 45 the elements of the unit are intact while the linings of the unit have been damaged but with very minor signs of a fire. Different levels of damage can also be observed on the window. Different levels of charring can be observed on the uPVC covering the window side (Figure 44 and Figure 45) while in other cases the window side is undamaged.



Figure 43: Kitchen window, Level 6, Flat 36



Figure 44: Kitchen window, Level 8, flat 53



Figure 45: Kitchen window, Level 12, flat 93

An important observation from Figure 42 and Figure 43 is the tall refrigerators located close to the windows. These refrigerators have similar characteristics to that which was present in the kitchen of Flat 16. The damage patterns seem to be quite similar, therefore it is important to explore the possibility that the external cladding fire outside the kitchen of Flat 16 might have been the cause of the damage to the tall refrigerator that was witnessed after the event. Given the information available, this is currently not possible to verify.

5.2.3 Internal Penetration Summary

In summary, the analysis of these images (and others around the building (Figures 10.48, 10.49 and 10.50 [4])) shows that penetration of the fire could have happened in multiple ways. While some components, like the fan, seem to be more vulnerable than others, there is no evidence that they would have represented a preferred path for an external fire to ignite the interior of a unit.

Given the high levels of heat flux that would be incident on the external façade due to the external fire, a path for the fire to re-enter the building will inevitably be created. The controlling factor therefore for the subsequent damage in the interior of the building is the characteristics of the external fire not the characteristics of the window, or its components.

5.3. FIRE AND SMOKE MIGRATION TO THE INTERIOR

Once the external envelope of the building is breached by the external fire, the possibility of ignition of combustible materials within the units is introduced. These combustible materials will then lead to conditions which are controlled by the fire dynamics of a pre-flashover compartment fire [2,34] that could potentially lead to a post-flashover fire [35]. It is important to note that, despite major damage in many of the units, a significant number of flats only resulted in fires that did not attain flashover. This would have impacted on the temperature of the smoke and its capacity to ignite other combustible materials, although it is important to approach this issue with some caution. The presence of an external flame can result in a very hot and potentially thin ceiling layer. This ceiling layer might have a very high temperature, severely damaging the ceiling, but be too thin to be able to provide sufficient radiation to ignite materials close to the floor (these flames are commonly referred to as optically thin). It is therefore possible, in these very unique circumstances, to have very hot gases that can ignite materials when touching them but that will not lead to generalized burning or flashover. Figure 46 and Figure 47 show two examples of such cases. The damage in each case is different, more structural damage is evident in Figure 47, while more fire damage is evident in Figure 46, but neither case experienced flashover.



FIGURE 46: FLAT 9 (LEVEL 3) WHERE THE FIRE IGNITED CEILING MATERIAL LEADING TO SPALLING, BUT FAILED TO ATTAIN FLASHOVER

In other cases, the fires would have manged to ignite all the combustible materials within the compartment. These will be discussed later in more detail because they are relevant to the breach of compartmentalization of the units. Fires that did not attain flashover would have been less likely to thermally compromise the main door of the unit given the distance between the windows and the main door.



FIGURE 47: FLAT 35 (LEVEL 6) CEILING SUSTAINED SEVERE DAMAGE, NECESSITATING STRUCTURAL SUPPORT WITHOUT REACHING FLASHOVER CONDITIONS

5.3.1 Early Passage of Smoke Through the Building

Once fires have entered the building, the next level of protection are the boundaries of the units. These boundaries are fire resistant walls and doors. These fire-resistant walls and doors are intended to stop the propagation of flames and smoke into the lobbies and stairs. The requirements for these doors are described in Dr Lane's Phase One Expert report (Section 2.21 and Appendix I) [4]. These requirements pertain to fire resistance, smoke seals and self-closing mechanisms. It is clear from the earlier stages of the fire at Grenfell Tower that internal compartmentalization was breached, and smoke had migrated into the stair lobby. Smoke was observed from very early on emerging from windows in areas very far from where the external fire was progressing (Figure 48 to Figure 52). This clearly indicates that the boundaries of at least two units had been breached. These observations need to be further explored in Phase Two.



Figure 48: Night vision camera (time: 01:57:03), smoke coming from Flat 94 on Level 12



Figure 49: Night vision camera (time: 01:58:32), West façade, smoke coming from multiple windows of Flat 174 on Level 20



Figure 50: Night vision camera (time: 02:40:47), West façade, smoke coming from Flat 205 on Level 23



FIGURE 51: NIGHT VISION CAMERA (TIME: 2:03:30), WEST FAÇADE, SMOKE COMING FROM MULTIPLE WINDOWS ON LEVEL 20 (FLAT 174 AND 175).



FIGURE 52: NIGHT VISION CAMERA (TIME: 2:14:57), WEST FAÇADE, SMOKE COMING FROM FLAT 94 ON LEVEL 12.

A review of past fire events in high-rise buildings involving internal smoke spread shows that in most cases where casualties occurred, smoke had spread into vital parts of the building. Events with high casualties include:

- Andraus Fire, Sao Paulo, Brazil, 1972 – 16 fatalities, 375 injuries
  - smoke entered stairwell
- Joelma Fire, Sao Paolo, Brazil, 1974 – 179 fatalities, 300 injuries
  - smoke entered stairwell
- MGM Grand Hotel, Las Vegas, NV, 1980 – 85 fatalities, 600 injuries
  - smoke travelled through the entire building because of unprotected openings in compartmentalization walls
  - Fans drew smoke from the mechanical room, spreading into occupied spaces
  - Smoke spread in the elevator shaft due to doors remaining open on the first floor
- Dupont Plaza, San Juan Puerto Rico, 1986 – 98 fatalities
  - Smoke was coming through air conditioning system vents and was an initial warning to the fire (alarms were not functioning). Smoke entered the foyer due to a missing panel. Extensive compartmentalization breaching.

In contrast, events where compartmentalization was not breached and the stairwells remained clean of smoke resulted in none or limited casualties:

- 7 buildings that experienced large external fires had no injuries or fatalities
- 2 of the buildings had effective external compartmentalization that prevented the fire or smoke from spreading into the building until the occupants had all escaped
- 2 of the buildings did have smoke spread/fire spread in the building. One of those buildings (Wooshin Golden Suites) had fire brigade access to the roof where many occupants were saved[24]. Another building (Al Tayer tower) had an isolated staircase that held out smoke and fire until all of the occupants had left.

[24] At the moment of writing this report there is no reliable information on how this was achieved, therefore, this matter needs to be further explored.

The vital role of compartmentalization is expressed clearly in all Building Regulations and it is summarized in Dr Lane's Phase One expert report (Section 3, Section 4, Appendices I and J) [4]. At the point where the perimeter of the building is breached by the external fire, this becomes the next line of defence. It is therefore important to assess the performance of the compartmentalization to understand the role it played in allowing smoke migration through Grenfell Tower.

5.3.2 Compartmentalization Performance Following Fire Re-entry

Once the external fire has breached the boundary of a flat unit, the potential for ignition of items within the unit and a subsequent compartment fire is realised. At this stage, it is reasonable to assume that the compartmentalization separating this unit from the surrounding units and communal areas should be adequate to prevent the fire and smoke progressing in a way that compromises these areas.

The performance of these boundaries is quantified by providing a regulatory specified, required level of fire resistance. Fire resistance refers to the ability of a building element to not exceed specified failure criteria (related to its function) for a duration of exposure to a specific thermal loading in a test furnace. The length of time that an element is required to perform in the testing environment is designated according to the expected fire load of the eventual occupancy in which the building element will be deployed. The fire load is a surrogate for the expected severity of the fire that could exist in that space, i.e. a larger fire load is expected to result in a more severe fire, a more severe fire requires a more robust building element, and therefore the building element is required to endure a greater time in the furnace test to be considered robust enough to perform adequately in the real fire.

Figure 53 shows the temperature curve that a fire resistance test is required to follow. The insert shows two photographs of typical furnaces used to test elements that require fire resistance. Also indicated in the figure is a typical compartment fire temperature. As can be seen from the figure, a compartment fire temperature is very different to the temperature history followed by the regulatory test. Therefore, while fire resistance is presented in terms of time, it needs to be understood that fire resistance does not correlate to time to failure in a real event. All structural elements requiring fire resistance (i.e. doors, fire stop materials and other component parts of fire rated compartments), are required to be tested according to this specified testing regime.

For the compartmentalization to be expected to perform in the case of a re-entrant fire, the severity of the compartment fire must be assumed to be primarily a result of the consumption of the fire load within the flat unit and the external fire's contribution assumed negligible. The external fire can then be simply categorised as the source of ignition of a pre-flashover fire. This is a reasonable assumption given that the amount of fuel provided by the cladding per unit area is less significant than the fuel within the flat and also because most of the energy from the external flames will be dissipated outwards.

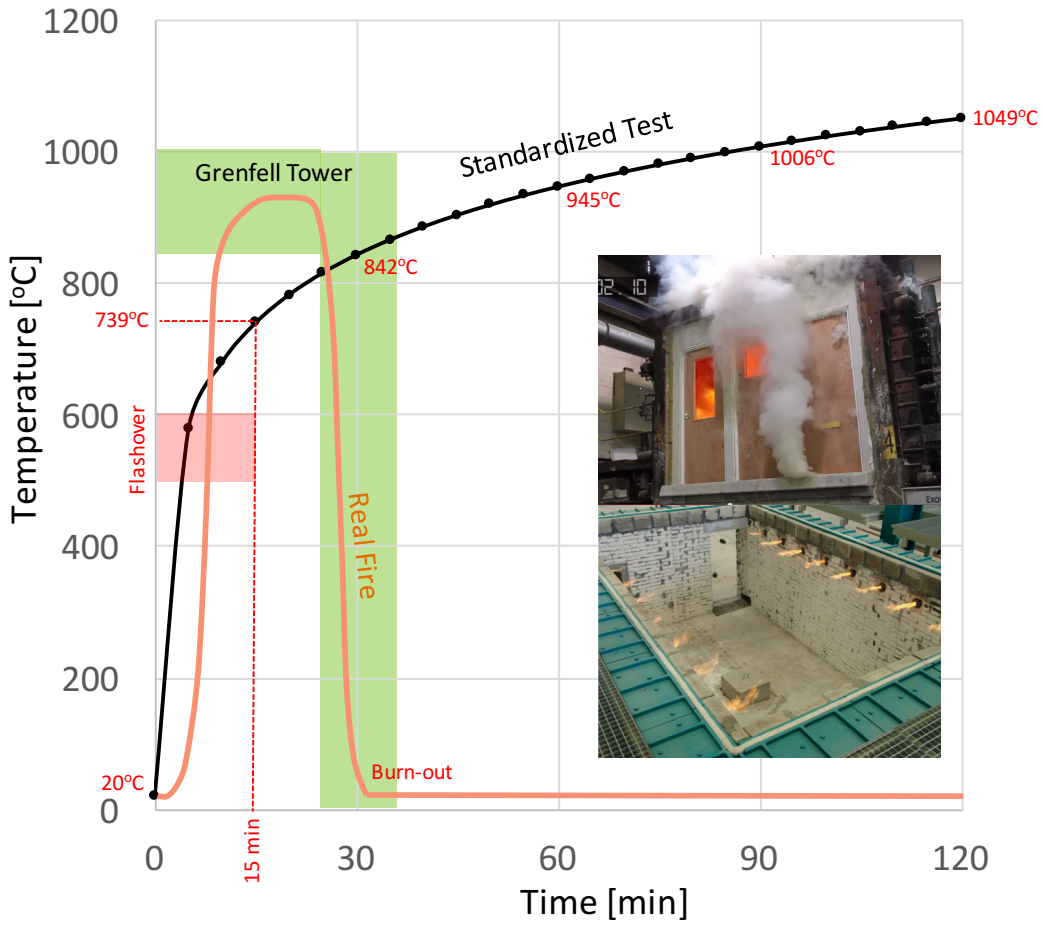


FIGURE 53: COMPARISON BETWEEN THE FIRE RESISTANCE TEST TEMPERATURE HISTORY AND THOSE OF A COMPARTMENT FIRE TYPICAL OF A RESIDENTIAL BUILDING COMPARTMENT. THE LABEL GRENFELL TOWER CORRESPONDS TO THE GREEN RANGE OF POSSIBLE VALUES. THE LABEL REAL FIRE IS AN EXAMPLE OF A POSSIBLE FIRE WITHIN THIS RANGE.

5.3.2.1 THE CONTRIBUTION OF THE RE-ENTRANT FIRE

In the case of Grenfell Tower, a forensic quantitative assessment of the external fire contribution is not viable given the availability of evidence, however the external fire contribution can be assessed qualitatively by observation of the damage in flats where the external fire breached the compartmentalization.

It is important to note that, despite major damage in many of the units, a significant number of flats never attained flashover. This impacts on the potential temperatures of the smoke and its capacity to ignite other combustible materials, although it has to be interpreted with caution. As indicated earlier in this section, the presence of an external flame can result in a very hot and potentially thin ceiling layer creating the very unique circumstances of having a layer of very hot gases that could ignite materials when touching them but that will not lead to generalized flashover. Examples of this scenario can be seen in Figure 54 and Figure 55.



FIGURE 54: FLAT 63 (LEVEL 9) SHOWING SEVERELY DAMAGED CEILING IN ROOM THAT DID NOT REACH FLASHOVER. NOTE UPHOLSTERED CHAIR IN LOWER RIGHT



FIGURE 55: FLAT 54 (LEVEL 8) SHOWS SEVERELY DAMAGED CEILING IN KITCHEN, HOWEVER FLASHOVER HAS NOT OCCURRED

An assessment of the damage in flats other than that of the fire origin (Flat 16) is described later in detail in Section 6.2. Of the 113 flats where fire or smoke breached the compartmentalization, 13 experienced minor damage, 9 experienced moderate damage, and 91 experienced major damage.

Minor damage is defined as smoke ingress, low levels of heat damage, or small localised fires around the point of entry. This may be in the form of soot deposition, localised deformation of polymer-based furniture and fittings, or evidence of localised burning. Figure 56 and Figure 57 shows typical examples of this level of damage. This is not expected to challenge the compartmentalization of the flat unit.

Moderate damage corresponds to localised damage around the point of re-entry of the fire where this has occurred in more than one location within a single flat unit. This could range from localised charred surfaces to localised fires that failed to involve other objects in the room and thus did not progress to flashover. Figure 58 and Figure 59 show typical examples of this level of damage. In certain cases, the localised fires resulted in some level of damage to components such as windows or furniture but no structural damage could be observed.

Severe damage is characterized by the presence of spalling on ceilings and compartment walls, as well as evidence of structural damage to ceilings and compartment walls. In some cases, one room may have significant structural damage (e.g. living room), while the remainder of rooms had no visible structural damage with spalling on ceilings and walls present and sometimes not present. Examples of this degree of damage are displayed in Figure 60 and Figure 61. The impact of these fires on compartmentalization is difficult to assess, nevertheless it is expected that damage to the walls and doors separating the unit from the lobby would have been minor. This is mostly because of the distance between the perimeter of the building and the boundary to the lobby.

Major damage is typified by an ignition resulting from external flaming that subsequently develops into a fully-developed compartment fire (flashover). The majority of the sources of fuel within the room or even flat would be involved in the fire and without intervention, consumed by it. This level of fire is expected to challenge the compartmentalization. Examples of this type of damage are shown in Figure 62 and Figure 63.

The presence of this entire range of behaviours indicates that the influence of the external fire alone is not sufficient to consistently result in a fully-developed fire in a flat unit. This implies that the heat introduced by the external fire is typically only significant locally to the entry point, and it is the characteristics of the fuel distribution in a flat and specifically of the first internally ignited item(s) that determines if a fire will subsequently grow to be fully-developed. The aleatory (i.e. unpredictable) distribution of combustible materials in residential units correlates well with the variability of damage in different units. It is very likely that in a residential unit there will be sufficient fuel to attain flashover and develop a fire that could lead to major damage, thus is not surprising that 91 of the 113 affected flats experienced major damage.

It should therefore be considered that, with regard to the compartmentalization of the internal boundary of a flat unit, the thermal loading imposed by the external fire is secondary in comparison with the thermal loading imposed by combustion of the furniture and fittings. Given the type of construction of Grenfell Tower and the minor compartmentalization non-compliances between flats (Section 4 [4]) it is also appropriate to assume that the compartmentalization separating each flat from neighbouring flats should be capable of restricting any significant passage of smoke, heat and fire from one unit to another.

Finally, it is expected that for the 91 units with major damage, compartmentalization of the boundary between the unit and the lobby (in particular the doors) would have been challenged.



FIGURE 56: EXAMPLE OF MINOR DAMAGE FROM FLAT 62, FLOOR 9.



FIGURE 57: EXAMPLES OF MINOR DAMAGE FROM FLAT 62, FLOOR 9.



FIGURE 58: EXAMPLES OF MODERATE DAMAGE FROM FLAT 93, FLOOR 12.



FIGURE 59: EXAMPLES OF MODERATE DAMAGE FROM FLAT 93, FLOOR 12.



FIGURE 60: EXAMPLES OF SEVERE DAMAGE FROM FLAT 45, FLOOR 7.



FIGURE 61: EXAMPLES OF SEVERE DAMAGE FROM FLAT 45, FLOOR 7.



FIGURE 62: EXAMPLES OF SEVERE DAMAGE FROM FLAT 114, FLOOR 14.



FIGURE 63: EXAMPLES OF SEVERE DAMAGE FROM FLAT 114, FLOOR 14.

5.3.2.2 FAILURE OF FLAT DOORS

Following the fire at Grenfell Tower, investigations have noted a number of flat doors that were damaged to various extents. Such damage to compartmentalization therefore represents a viable path for fire and smoke migration to the communal lobbies, egress stair, and surrounding flats. It is important therefore to establish under what conditions these doors might have failed and to ascertain how this relates to the timeline of the fire and smoke progression through Grenfell Tower, thus contextualising the impact of any door failure.

Tests conducted at BRE on flat doors [36] removed from the building demonstrated a fire resistance rating of the order of 15 minutes. As described previously in this section, this means that the doors failed defined performance criteria after 15 minutes of thermal exposure to the ISO 834 temperature-time curve (Figure 53) within a furnace. This corresponds to a failure temperature of the order of 740°C (739°C in Figure 53). Figure 53 also shows the evolution of the temperature in a typical residential compartment. In a fire that starts within the compartment, flashover will most likely occur in the first 5 minutes when temperatures reach values between 500°C and 600°C, the post-flashover fire can then reach temperatures as high as 1200°C. Eventually, all combustibles will be consumed and burn-out will occur. This will generally take no more than 40 minutes. If the fire is ignited externally, flashover can be attained very rapidly but the characteristic compartment temperatures will remain the same because a post-flashover fire is not limited by the fuel but by the available ventilation.

To establish the typical range of post-flashover compartment fire temperatures, a brief analysis is performed for a typical one-bedroom flat in Grenfell Tower. Upper and lower bound temperatures and corresponding fire durations are established for both of the principle rooms in this flat configuration.

Temperatures are assessed using the experimental data provided by Thomas [37] (Figure 64) which uses an inverse opening factor, ϕ', to establish a representative compartment temperature. The inverse opening factor represents the relationship between the size of the compartment and the size of the ventilation, assuming that the amount of combustion in a post-flashover fire is limited by the air available to it. Inverse opening factors for these spaces range from approx. 10 – 25 $m^{-½}$. This corresponds to characteristic compartment temperatures in the range of 850 – 1000°C.

To estimate the duration of burning for such a compartment, the experimental data provided by Kawagoe [38] (Figure 65) is used to determine characteristic burning rates, as a function of the typical fuel type and compartment temperature. Assuming a mixture of wood and PU foam as the principle fuel sources in a bedroom or living room, this gives burning rates in the range 0.012 – 0.018 kg/m^2.s.

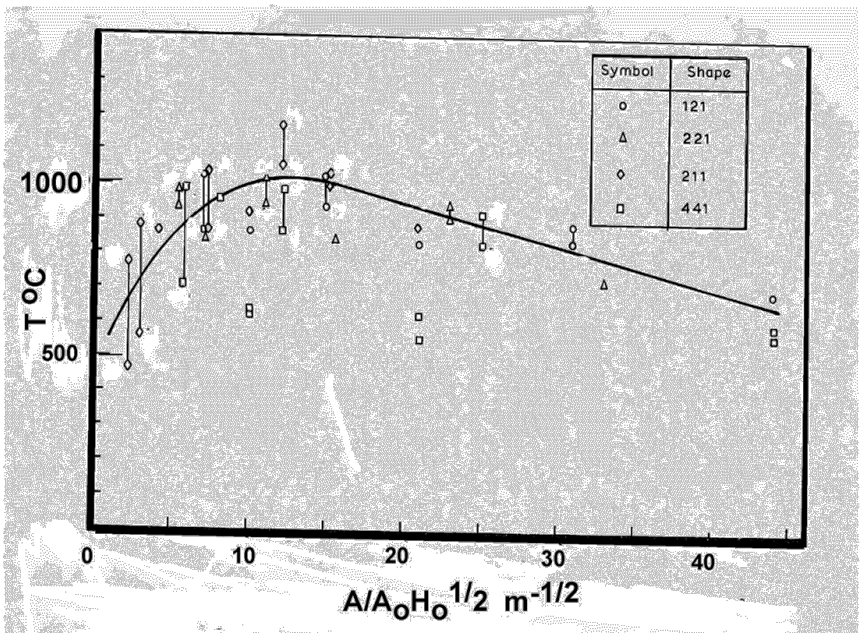
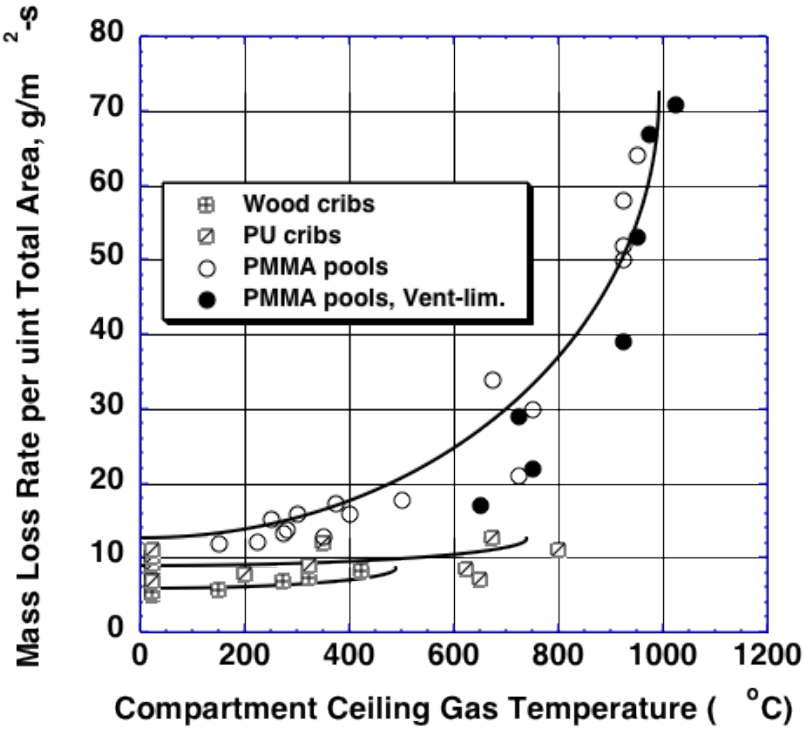


FIGURE 64: THE PLOT BY THOMAS [37] PROVIDES AN INDICATION OF THE TEMPERATURE OF A FULLY-DEVELOPED COMPARTMENT FIRE BASED ON THE INVERSE OPENING FACTOR.

2436



2437

2438 **FIGURE 65: THE PLOT BY KAWAGOE [38] DEFINES BURNING RATE [G/M^2.S] AS A FUNCTION OF COMPARTMENT TEMPERATURE**
2439 **[°C].**

2440 Eurocode 1 [39] gives an average fire load density for a dwelling of 780 MJ/m^2. For the assumed fuel sources,
2441 the typical energy content is taken as ~30 MJ/kg [40], which equates to a fuel load of approximately 26 kg/m^2.
2442 Given the estimated range of burning rates from Figure 65, this gives a fire duration of the order of 25 – 35
2443 minutes for a single compartment.

2444 It has been reported [35] that standard testing of the doors showed failure at approximately 15 min.
2445 Furthermore, it is reported that, given the composition of the doors (i.e. Section 14.5.12, Appendix I [4]),
2446 failure was characterized by flaming of the doors. If the failure times of these tests are used to indicate the
2447 conditions necessary for failure, then Figure 53 shows that the gas temperature during the test when failure
2448 occurred was of the order of 740°C. This temperature is above characteristic flashover temperatures and
2449 therefore would most likely occur in cases were the units had major damage. Furthermore, failure of the doors
2450 would have only occurred after conditions in the unit were untenable. Section 4.4 indicates that the vertically
2451 propagating fire was observed to start internal fires on the 5th, 12th and 22nd floors as early as approximately
2452 01:18, 01:24, and 01:28 respectively. Therefore, the lobbies in these floors could have been compromised
2453 prior to 02:00.

2454 In cases where moderate or severe damage was observed, smoke and flame entering the unit from external
2455 fires would not provide sufficient thermal insult for sufficient duration to affect such failures. This is evidenced
2456 by the fact that the flat doors in flats where damage was of this nature (See Section 5.3.2.2) i.e. no post-
2457 flashover fire, did not experience damage that cannot be explained by either firefighter intervention or
2458 thermal insult from the communal lobby side due to failure of all other flat doors on that floor. In the majority

of cases where flat doors were damaged (and still identifiable), this coincided with a major, post-flashover fire in the flat.

5.3.2.3 MECHANISMS FOR INTERNAL SMOKE SPREAD

As explained above, for a fire to bring smoke and heat to the stairs it is necessary to breach several barriers. For the purposes of this section, a barrier is defined simply as a physical obstruction to the smoke and heat. Some of these barriers have regulatory requirements for levels of fire resistance, however for the purpose of this section, barriers are differentiated by an expectation of their level of robustness. These are illustrated in

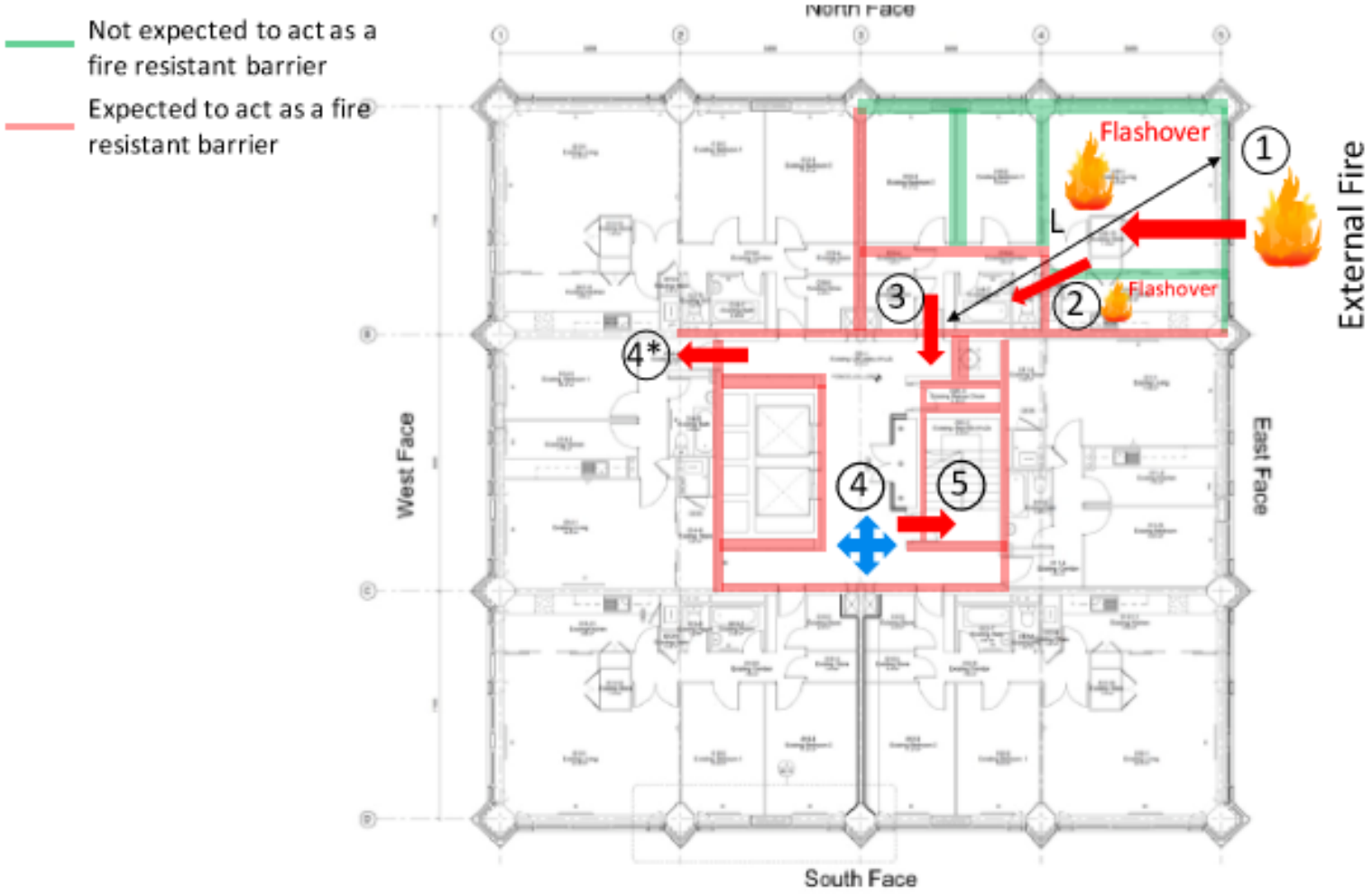
Figure 66.

Green lines indicate barriers that are not expected to afford significant robustness in respect to the resistance to the passage of heat and smoke, while pink lines represent barriers that are expected to provide a significant level of robustness. Red arrows indicate a barrier of either type that must be breached for smoke and / or heat to reach the protected stairwell. Barrier (1) is the building façade. As explained in previous sections, there are no expectations for windows on the external wall to protect the building in a manner that they will serve as a barrier to an external fire. Nevertheless, this will be deemed the first level of containment. Barrier (2) is defined as the boundary of the internal hallway within the unit (walls and doors). This hallway is defined as a protected hallway therefore, these elements are expected to represent a robust barrier. Barrier (3) is the entrance door to the unit. Again, this is expected to provide a robust barrier. Barrier (4) is defined as the lobby ventilation system which, while not a physical barrier, is expected to provide a preferential pathway for smoke in the lobby. Finally, barrier (5) is the stair door which is expected to provide a robust barrier to smoke and heat ingress into the stair.

If the breach of barrier (1) was not sufficient to ignite the combustible materials in the compartment adjacent to the external wall, then smoke from the external fire would have had to migrate through the internal doors (2), the unit entrance door (3) overwhelmed the lobby ventilation system (4) and then finally the stair door (5). The fire itself would have been too remote to thermally damage any of these layers as distance L (the distance between the point of entry of the flames and subsequent barriers) is too large. Smoke migration could have been either through poor design of walls and doors or poor installation or maintenance leading to leakages.

Another alternative is if all the doors were left open. The state of the lobby ventilation system, the doors and the walls are described in detail in Dr Lane's Phase One expert report [4]. It was established that no significant issues could be found with the walls (Section 19.7.8 [4]) but that there was no sufficient evidence to establish the state of the lobby ventilation system (Section 19.7.21 [4]). So, smoke migration had to occur through the doors.

Barrier (4*) represents doors to other units that open to the lobby. Section 5.3 of this report shows that path (4*) occurred in several places slightly after 02:00 further emphasizing that smoke migration had to occur through the doors. The issue of self-closing mechanisms for the flat and stair doors thus needs to be considered.



2495

2496 Figure 66: Mechanisms of smoke spread to the lobby, assuming fire has spread inside via the external wall assembly

If the breach of containment was sufficient to ignite combustible materials in the compartments adjacent to the external wall, then flames and smoke, hot enough to cause damage to the flat doors, would have been present. The fire would have been brought towards the entry of the unit, thus, distance L will be small enough that the unit doors (2) and entrance door (3) would have been damaged and, given their characteristics, would have ignited. There is sufficient evidence to establish that the doors ignited in many of the units with major damage. Ignition of the doors would have posed a severe challenge to the lobby. Because of its small size, the lobby would have rapidly filled with smoke but also potentially with flames. Post fire inspections by Dr Lane indicate that there is sufficient evidence of high temperatures between floors 13 and 16 (Section 19.6.7 [4]). The lobby ventilation system (4) would have been inevitably overwhelmed and stair doors (5) and other unit doors (4*) would have also been compromised. For this scenario, there is no need for the doors to be open for smoke to migrate into the stairs.

The following sections discuss in more detailed how all these levels of containment could have potentially been breached.

5.3.2.3.1 OCCUPANT EGRESS

Occupant egress necessitates the opening of fire doors; thus smoke would have been able to escape into communal lobbies during occupant movement/evacuation and, to a lesser extent, into the egress stair. CCTV video evidence from the Level 7 lift lobby corroborates this breach of compartmentalization [MetUSB:NORTHLEIGH/Op Northleigh Spread of Fire/Interactive/CCTV/7th floor.mp4]. This action is a very brief event and the impact of this action is likely to be negligible providing doors are closed promptly behind the evacuating occupants.

5.3.2.3.2 FIRE DOOR DEFICIENCY / LACK OF DOOR CLOSERS

It has not been possible to establish if apartment doors were not fitted with functioning door closers and or installed deficiently [Section 2.15.15 [4]] nor is there conclusive evidence that door closers on the stair fire doors were not working (Section 2.21.34 [4]). Nevertheless, if any of these mechanisms did not function during internal circulation and evacuation, smoke would have been able to spread from fire affected compartments into communal lobbies. This is a viable mechanism for the early passage of large quantities of smoke through the building (Section 5.3) and for the early compromise of lift lobbies in and around floors where compartment fires were ignited within Stage 2 (Section 4.4).

5.3.2.3.3 FIREFIGHTER INTERVENTION

Emergency response by firefighters frequently has an impact on compartmentalization. Typically, this is not an issue as occupants that are able to will have already evacuated. In the case of a “stay put” strategy most occupants will remain safe in their units. This leaves firefighters free to fight the fire and perform any required search and rescue activities. Firefighters have specific protocols with regards to high rise buildings, however as outlined in Mr. Todd’s Phase One expert report [1] and as is likely to be outlined in their operational procedures (information remains incomplete at the moment of writing this report), these protocols will be driven by the unique characteristics of these buildings and, by extension, the implications for firefighter safety that these characteristics bring about.

One characteristic is that fire appliances and hoses cannot always directly reach the compartment of fire origin therefore requiring responders to enter the building and connect hoses to risers. Typically, this action is performed at a bridgehead set up two floors below the floor of the fire compartment to allow responders to enter the floor on which the fire is located and be primed to immediately fight the fire, should it be necessary. This tactic of establishing a bridgehead beneath the fire floor necessitates running hoses via an emergency stair, and in doing so propping open the door to the stairwell and flat simultaneously. This will potentially result in the passage of smoke into the egress stair which will reduce the capacity of the stair itself due to the presence of the hose.

In the context of a single unit fire and a functioning “stay put” strategy, this practice is acceptable as occupant use of the stair is minimal and restrictions caused by the presence of the hose and smoke in the stair are therefore negligible. This is borne out by reports from the period of time following the initial firefighting activity in Flat 16. The fire was at a pre-flashover stage when the hoses were potentially compromising the egress stair, thus smoke production and migration into the egress stair was minimal. There is a continued, steady flow of occupants down the stair subsequent to these actions ([Section 14 [4]) and Section 5.3.4). Once the scenario escalated however, firefighting activities became required on multiple floors and smoke from increasingly developed fires was able, by some means, to reach the stairwell which also later became increasingly unnavigable due to the quantity of hoses present. These issues are discussed in great detail in Dr Lane’s Phase One expert report (Sections 14, 17 and 19) [4] and will therefore not be further discussed here.

Beyond the logistics of supplying water, gaining access to flats as part of firefighting and search and rescue activities may require forced entry. This has the potential to compromise the integrity of the door and, by extension, its ability to fulfil its role as a fire barrier. Again, in the context of a single flat fire which is controlled and extinguished by the responders, this is not a significant issue. Once multiple fires exist however, the effect of the loss of fire barriers on the single egress stair is compounded. Firefighter testimony establishes numerous occurrences of damage to flat entry fire doors by responders during both firefighting and search and rescue activities [MET00005251, MET00005700, MET000080558, MET00005429, MET00005467, MET00005413].

Statements of the initial responders [MET00005251] establishes that firefighters forced the door of Flat 16 as they initially responded to the kitchen fire. Even though the initial kitchen fire was extinguished, a later more severe fire event occurred within the flat, following re-entry of the fire into a bedroom.

[MET00005700, MET000080558] reports response to a fire that developed in Flat 26 on Level 5, immediately above Flat 16, following re-entry of the fire from the cladding. In this case the firefighters “kicked the door in”. Unable to extinguish the fire due to the hose being snagged elsewhere, the firefighters retreated to the lobby where they noted that conditions in the lobby were “almost as bad as in the flat”. In this case, a flashover event occurred later in time potentially without the benefit of a fully functioning fire door at the flat entrance to protect the lobby.

Seemingly later in the fire, at an undetermined time, [MET00005429] describes firefighting activities on the 12th floor where numerous fire doors were forced open. “…we think entered the twelfth floor [sic]. The door was opened by WM McKay and I pulsed some water into the floor. We then moved into the floor and started fire-fighting. First, I fired water into the flat down the left-hand end which knocked the remainder of the door off its hinges and created a lot of helpful light and cooler air. We then tried to get into the flat next to it. Fired the jet into the flat after forcing our way in as there was bedding behind the door. After more water was fired into the flat we then searched it and found nothing. Moved onto the next flat, number 82. Same scenario with bedding behind the door. " This evidence may correspond to the early passage of smoke (Section 5.3.1) seen

emerging from the west face of Flat 94 on Level 12 at the end of Stage 3, and significantly earlier than the arrival of fire on that side of the building.

[MET00005467] reports using an enforcer to smash through a door panel, "cow kicking", and "smashing" doors open in order to search 4th and 5th floor flats. Re-entering the building later to resume search and rescue activities on the 11th floor, the same statement describes taking sledgehammers and axes, presumably to gain access to individual flats. [MET00005413] describes braking a hole in the door (9th floor) beneath the door handle in order to reach through to open it.

These tactics, though likely inconsequential under a controlled "stay put" strategy, have a strong impact on the protection of egress paths and thus may disable any strategy change, later in time, when occupant evacuation becomes more critical.

Further investigation is required to understand if continued following of the "stay put" protocol and corresponding firefighting, search and rescue activities, contributed to the rapid decline of general tenability in the egress passages. It is important to understand what the implications were for the egress routes given how early on in the incident the framework for a "stay put" strategy was undermined This need is highlighted further when considering other fires of a similar nature, described in Section 4.2, where maintained tenability of the egress stair was key to ensuring the safe evacuation of building occupants once extensive external fire spread had occurred. This matter will require significant attention in Phase Two.

5.3.2.3.4 LARGE SCALE EFFECTS

For completeness, other mechanisms of smoke migration have been evaluated. Large-scale buoyancy (stack effect) and lift shafts provide mechanisms for vertical smoke movement. Two mechanisms, described briefly here, are associated with such vertical smoke movement.

Stack Effect:

The stack effect is the process through which air flows through a building due to temperature differential between the inside and outside of the building. When the outside air is below room temperature, this cold air enters the building and heats up to room temperature and flows upwards. At Grenfell Tower on the day / night of the fire, outdoor temperatures ranged from around 18.3°C (12:00 PM)-15.5°C (5:00 AM), or slightly below room temperature. Some qualitative conclusions can be drawn from this:

- The stack effect will be fairly negligible in driving smoke up the building.
- The stack effect may draw smoke into the elevator shaft, which could potentially rise up under its own buoyancy.

It is also possible that, later in the fire, this effect may begin to happen in reverse due to the outside air being heated by an exterior fire as well as many windows being breached. This effect could have led to significant motion of smoke around the building. Currently research into this scenario is limited and therefore the stack effects on Grenfell Tower are difficult to assess.

While the influence of the stack effect might be relevant, its effects would have been very unique to the Grenfell Tower fire scenario. It is not clear if any lessons might be learnt from a detailed analysis of the stack effect, thus I consider studying this phenomenon of lesser priority.

Piston effect in lift lobby:

The piston effect is the process where a vertically-moving lift creates suction pressure in its wake, which pulls air from in front of it to the area behind it. This mass flow can then pull air through the openings and leakage areas between the elevator shaft and the wall, creating a vertical flow between floors above an elevator and below an elevator.

The number of necessary assumptions regarding the air flow and exact conditions of the building preclude the undertaking of a detailed analysis of the impact of this effect. However, the NFPA reference "Smoke Movement and Control in High Rise Buildings" chapter 4.5 [42] provides a comprehensive background to this issue. In a multiple-car elevator shaft, the adverse effects of a single elevator moving are typically negligible. From video evidence [MetUSB:NORTHLEIGH/Op Northleigh Spread of Fire/Interactive/CCTV/Southlift.mp4] of the south lift it can be inferred that this lift remained at the 2nd floor between approximately 01:03 and 01:37, thus it can be assumed that these early stages of a fire can be treated as a single car in a double car shaft. The chart Figure 67 shows the upper limit pressure difference between the elevator shaft and the lobby and it has been calculated that the elevator car in Grenfell Tower moved at between approximately 1.5 m/s. Thus, the max pressure difference is around 3 Pa, which is negligible. This effect can therefore be discounted and should be given no further attention.

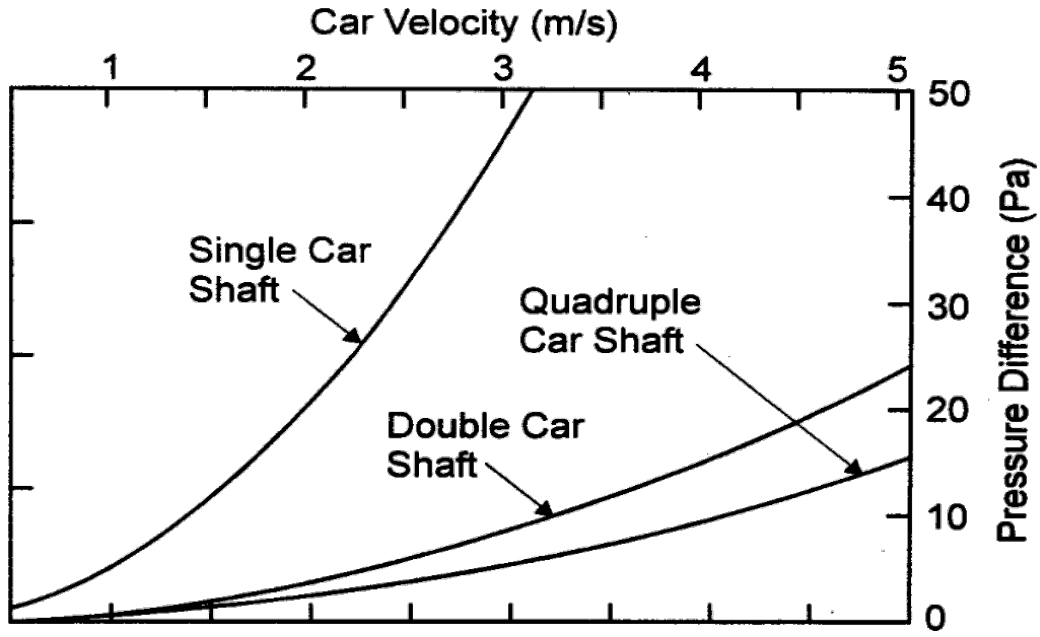


FIGURE 67: PRESSURE DIFFERENCES AS A FUNCTION OF CAR VELOCITY FOR LIFT SHAFTS.

5.3.2.3.5 MISSING OR DAMAGED FIRE STOPPING

The state of the fire barriers leading to the lobby (Section 19.7.8 [4]) and in particular the stair enclosure shows only minor weaknesses in regard to its capacity to deliver adequate compartmentalization (Section 19.6.2 [4]). These often provide small leakage paths for smoke to pass, nevertheless do not seem to have had a major impact on what should be smoke proof compartmentalization.

5.3.2.3.6 VIA THE SMOKE CONTROL SYSTEM

It is unclear if the smoke management system, designed to vent smoke from communal lobbies, performed as specified or was indeed even compliant (Section 19.7.21 [4]). A correctly designed and specified system would be sized to perform within the framework of a contained single compartment fire, with the intention of maintaining a single lobby as passable. Given the scale of the event and the number of lobbies that were simultaneously compromised by smoke ingress, a fully functioning, compliant system would have provided negligible benefits to egressing occupants, thus any discussion of its compliance or functionality is secondary in the context of the Grenfell Tower fire.

5.3.3 INTERNAL SMOKE SPREAD

The following section provides an approximate overview of the spread of fire and smoke, from the exterior façade, via individual flats, to the interior common elements of the tower. An approximate timeline is constructed from 999 calls, firefighter statements and videos and images to reconstruct as accurately as possible the time period until general conditions within the building could be deemed as untenable.

The previous sections have analysed the potential for smoke migration on the basis of physical variables and fire dynamics. This section takes information from the event with the purpose of contrasting this information with the physical arguments made in previous sections. This analysis is not intended to be comprehensive, but is presented to demonstrate the importance of contrasting different forms of information. Dr Lane's Phase One expert report [4] provides a complementary, and in many cases more detailed analysis of this information. Correlation of all this information, and any new information made available, should be conducted as part of Phase Two.

Despite the many photos and videos available for review, limited time-stamped photographs and videos exist from which to build an internal smoke spread timeline. Exterior photographs taken during the fire event were analysed to help infer smoke/fire spread within compartments, however, the quality of available images limited the effectiveness of this approach.

The most reliable videos from of the interior of the building during the event were CCTV footage provided by the Metropolitan Police. These CCTV cameras were located at:

- Inside the South Lift
- Ground floor Lift Lobby
- Level 7 Lift Lobby

Furthermore, the following sources were used to provide temporal information:

- Transcripts of 999 calls handled by the LFB and other fire authorities.
- CCTV exit times (MET000080493)
- Facebook Live video from Rania Ibrahim

The data recorded in Table 5 is used to establish a smoke movement timeline for the first hour of the fire (00:54 to 02:00). When residents from the same apartment make multiple calls, additional calls are listed under the time of the first call. While this list is not complete, it is indicative of rates of internal smoke spread.

Time	*Action*	*Evidence*
00:54	LFB 999 call**:** Resident of Flat 16 (Level 4) indicates fire in the flat kitchen: Caller reports a fire in Flat 16 on the 4th floor. Refers to the "fridge". Caller is outside and says "...quick, quick, quick ... It's burning".	LFB00000301
00:56	Four people enter the south lift. Lift rises to Level 4, doors open and smoke spills into lift from lift lobby.	NORTHLEIGH/Op Northleigh Spread of Fire/Interactive/CCTV/Southlift.mp4
	One of the lift occupants, Miguel Alves: "I just arrived when the fire started…I was in the lift, I pressed 13, and somebody pressed four." When the doors opened at the fourth floor, where the fire had started, smoke billowed into the lift, Miguel said. "I just came out of the lift because I didn't know what was going on, and I went up by the staircase to wake up my son and daughter."	IWS00000537
01:02	Fire Brigade enter south lift at ground level, rise to Level 2. Lift door held open by fire hoses.	NORTHLEIGH/Op Northleigh Spread of Fire/Interactive/CCTV/Southlift.mp4
01:04	Tiago Alves: "Me and my sisters ran down the stairs. My dad stayed upstairs and he was knocking on the neighbours' doors."	IWS00000123
	CCTV shows Ines and Tiago Alves exiting the building	MET000080463
01:08	CCTV shows Miguel Alves exiting building with others – possibly Level 13 occupants	MET000080463
01:14	Fire spreads from Flat 16 window to external cladding	MET00006589
01:21	LFB 999 call: Flat 195 (Level 22): Caller is Naomi Li. She describes smelling smoke "from the lift side". Advised to "stay inside and keep your door and windows shut."	LFB00000303; IWS00000515; LFB4828_0038
01:22	Occupants seen moving (presumably evacuating) from 7th floor. No smoke visible in lift lobby.	NORTHLEIGH/Op Northleigh Spread of Fire/Interactive/CCTV/7th floor.mp4
01:24	LFB 999 call: Occupant in Flat 96 (Level 12) indicates that fire has spread internally through the kitchen window: Says "I can't breathe'	LFB00000304; LFB00000309; IWS00000771
01:25	LFB 999 call: Occupant in Flat 111 (Level 14) unable to egress due to smoke in lift lobby: Caller says 'it's [the fire] coming right past my window from next door." There is fire "all on my side" but it is not inside the flat. The caller can smell smoke. There is smoke coming into the flat from the landing. Caller says that he has "tried to open the door and there's a lot of smoke".	LFB00000308
01:26	LFB 999 call: Neighbour from Flat 95 (Level 12) confirms fire in Flat 96, with smoke outside. The caller states her neighbour has had a fire in the kitchen already and says	LFB00000309

Time	*Action*	*Evidence*
	smoke is "coming through the floor - from our main door because it's outside."	
01:27	CCTV footage shows two occupants arriving at Ground Level using the north lift (the south lift at this time is being held at Level 2). Smoke spills into the lobby as occupants exit. As the occupants open the door to the lift lobby, rush of make-up air causes smoke to be drawn back in to the lift shaft. This occurs again when a firefighter opens the same door to enter the lift lobby.	NORTHLEIGH/Op Northleigh Spread of Fire/Interactive/CCTV/Lift lobby.mp4
01:28	Caller in Flat 73 (Level 10) Grenfell Tower. Reports smoke 'coming onto my floor' and 'seeping into my house'. Also reports 'smoke outside the flat'.	INQ00000282
01:28	LFB 999 call: 3 Occupants from Flat 82 (Level 11) unable to egress due to smoke in lift lobby: Caller states she is stuck on the 11th floor and does not know how to get out. Asked if there is any smoke coming into the property, the caller responds, "Not at the moment but if I open the door there's smoke on the landing." There are further 999 calls from Flat 82 at 01:33 (states no smoke in flat but it is getting worse outside, asks for assistance in evacuating), 02:02, 02:18, 02:32 (no smoke coming in), 02:37 (flames on landing), 02:44 (smoke coming through windows and fire coming through kitchen window), 03:00, 03:03, 03:04, 03:13 & 03:32 (fire in flat, egress not possible due to smoke).	LFB00000307 LFB00000313 LFB00000338 LFB00000347 LFB00000360 LFB00000367 LFB00000377 LFB00000393 LFB00000394 LFB00000401 LFB00000410 LFB00000425
01:29	Caller in Flat 142 (Level 17), reports that there is smoke 'on our floor' and 'in our house'. Caller also explains the fire is 'right next door'. They can see flames from the window.	INQ00000264
01:29	LFB Call: Caller in Flat 201 (Level 23). Confirmed as Jessica Urbano Ramirez. The call lasts 55 minutes. Jessica states that she came out of her house because of the fire. She is now in a group of 10 in a bedroom in a flat on the top floor. The fire is in the living room. Jessica describes smoke coming from "everywhere" including the floor. People have tried to go outside but there was a lot of smoke. The operator refers to a smoke alarm making it difficult to hear. Jessica says more than once that she and others 'can't breathe". She confirms seeing "flames coming up through the window". Later she says that fire is "coming through the window" and that the window is on fire..	LFB00000507
01:30	LFB 999 Call: Caller is Mariem Elghwary (from Flat 196 on Level 22) who is calling from Level 23 (she is in a neighbour's flat – Flat 205 on level 23): states "we are all stuck on the top floor and the doors [presumably to the roof] won't open". Caller continues that there is smoke everywhere and the fire is in our house on the 22nd floor. Everyone is now on the 23rd floor. Caller states the fire had "broken into the kitchen of our flat" and she had run into the neighbour's flat.	LFB00000310

Time	*Action*	*Evidence*
01:30	LFB 999 Call: Caller ion Level 22. States it is "terrible up here" and "you can't see your hand in front of you." Caller advised to put towels down to stop smoke coming in.	LFB00000459
	LFB 999 Call: Caller is Naomi LI on Level 22. She states she is in a neighbour's house and There is smoke now everywhere.	LFB00000311; IWS00000515
01:30	LFB 999 Call. Caller is in Flat 175 (Level 20) with her husband and 3 children. The caller indicates that the fire is "in my neighbour's." She reports that smoke is coming into her flat. Her husband has blocked the doors and the family is now in the living room. Caller states she is "really scared" and "panicking." She has seen the flames and can smell smoke.	LFB00000314
01:32	Caller lives in Flat 155 but has moved to Flat 201 on Level 23. Smoke is coming into the flat and the "windows already burning up'. Another person in the flat reports that fire and smoke is coming through the window.	LFB00000667
01:33	LFB 999 Call: Caller from Level 11 says "Please, please, the fire is inside of my flat." He continues that "it's inside of the room."	LFB00000312
01:33	Caller in Flat 152 on Level 18. No smoke 'in my house yet' and 'tried to go out through the fire escape and there's just thick black smoke'.	LFB00000662
01:34	LFB 999 Call: Occupant in Flat 192 (Level 22) states "we are trapped in 192 …" and continues "We couldn't get down the stairs, because the stairs is full of smoke." Operator advises the caller to close doors and windows to keep the smoke out of the flat.	LFB00000315
01:36	NWFC 999 Call; Occupant in Flat 9 (Level 3). The caller is identified as Mariko Toyoshima-Lewis. She explains that as a wheelchair user she is unable to self-evacuate. Mrs Toyoshima-Lewis reports that she can see smoke coming into the flat. Operator confirms that information has been passed to the fire crews. The call ends with the arrival of fire fighters to assist evacuation (exit building at 2:10 am).	LFB00000506
01:37	Caller from Flat 133 on Level 16. Reports that the fire is underneath, they tried to get out to the stairs, but it was dark and there was so much smoke they 'ran back inside our flat'. Smoke coming underneath flat door.	INQ00000280
01:37	Caller in Flat 113 on Level 14. Smoke is coming in to the flat from the corridor. Tried to escape but had to come back.	LFB00000678
01:38	MPS calling LFB to say they have had a call from Flat 142 on Level 17. Caller apparently said, 'they say there's smoke coming into the….'. No further audio.	LFB00000668
01:38	LFB 999 Call: Caller is in Flat 205 (Level 23). 7 persons in the flat altogether. The caller confirms that no smoke is coming into the property but adds "but our flat was underneath, and that -- there was no smoke in there. It was absolutely	LFB00000317

Time	*Action*	*Evidence*
	fine, but then all of a sudden the flames just blew into our kitchen --". [See call from Level 23 timed at 01:30 above].	
01:38	LFB 999 Call: Occupant in Flat 95 (Level 12), reiterates fire is in neighbour's flat (Flat 96), implies that smoke is in lift lobby. Additional calls are made from the same flat at 01:44 (embers have come through window and started fire in kitchen of Flat 96), 01:54 (caller reports that surrounded by fire - next door, on the "landing" and near the lift, below and on the flat windows. Describes the smoke in the flat as "terrible". At the end of the call the flat occupants are advised to leave and appear to encounter fire fighters on doing so).	LFB00000318 LFB00000324 LFB00000332
01:37-01:38	Fire brigade re-enter south lift, rise to smoke effected floor at Level 11 or Level 12, discharge onto smoke-filled lobby.	NORTHLEIGH/Op Northleigh Spread of Fire/Interactive/CCTV/Southlift.mp4
01:38	Caller in Flat 182 on Level 21. Caller reports 'not from outside but the smoke is coming from… the front of the flat.' And 'It's very smoky in the landing.'. Occupants had tried to leave but was too smoky. Caller states that, 'Something is right next door to us, it's burning, it's really burning.'. Further transcript seems to imply that the fire has reached the adjacent flat (presumably Flat 181) and begins to threaten their kitchen window.	LFB00000677
01:38	Rania Ibrahim (Flat 203, Level 23) starts Facebook Live videos which shows the corridor filled with black smoke with very limited visibility.	Facebook Live: https://www.facebook.com/ribrham/videos/1499323993475925/ (NB. Accuracy of timing is not confirmed)
01:40	An increase of smoke is observed on CCTV footage on the 7th floor lobby. CCTV footage jumps from 01:25 to 01:40 between which there has been a significant build-up of smoke.	Op Northleigh Spread of Fire/Interactive/CCTV/7th floor.mp4
01:38	LFB 999 Call. Caller is in Flat 115 (Level 14). She is alone with her baby. Reports smoke is coming in under the front door and through the windows. Advised to block the door and close windows. Caller cries, "there is fire coming from the door". The call appears to end abruptly. Occupant calls back at 01:48. Asked if there is a room without smoke, caller replies, "All of them have smoke…" The smoke is coming in through the door the windows. She confirms she has already blocked the door and closed the windows.	LFB00000321 LFB00000331

Time	*Action*	*Evidence*
01:39	Caller from Flat 204 on Level 23. His flat is not yet compromised but for a little smoke, but he cannot escape through the lobby as, 'I can't see at all'. 'I can't see to get out, that is the problem.'.	LFB00000329
01:40	Reduced visibility in Level 7 lift lobby. Occupants evacuated with assistance from firefighters.	NORTHLEIGH/Op Northleigh Spread of Fire/Interactive/CCTV/Lift lobby.mp4
01:40	LFB Call. Occupant in Flat 111 (Level 14). Caller states he is on his own and his "whole flat is full of smoke." The smoke is coming in through the windows and the door. Caller has locked himself in the bathroom. The operator advises him to put towels around the door to stop smoke coming in.	LFB00000322
01:41	Call from Flat 201, Level 23. Smoke in flat is getting thicker and occupants are getting sick. Fire subsequently breaches into flat.	LFB00000486
01:41	LFB 999 Call. Occupant in Flat 73 (Level 10): asked if there is smoke in the flat**,** the caller says "…there's smoke coming up and the door [to lift lobby] is completely hot. Advised to stay in flat and block the door to stop any smoke coming in.	LFB00000319
01:43	Caller from Flat 175 on Level 20. Smoke is entering flat but not certain where from, however caller states that 'It's really smoky in the hallway now' suggesting it is from the lobby. Unable to leave due to black smoke in the hallway.	LFB00000444
01:43	Caller from Flat 82 on Level 11. Caller asked if they can leave, states 'The stairs will be completely full of smoke now'. Firefighter arrives at the flat.	LFB00000323
01:43	Caller in Flat 41 on Level 7. States smoke is coming into flat but no indication of where from. Firefighter arrives at the flat.	INQ00000373
01:44	LFB 999 Call. Occupant of Flat 95 (Level 12) states that, "fire embers have started a fire in the flat next door … it's come up through the windows, it's gone into number 96". The kitchen of 96 is on fire. The caller states that smoke is coming in to his flat and that it is "really smoky in here" and "someone's trapped on 11th floor".	LFB00000324
01:46	MPS conference call with LFB CRO and Occupant of Flat 133 on Level 16. Smoke is coming in through the front door.	LFB00000326
01:47	LFB 999 Call**.** Two callers from Flat 74 (Level 10): Caller 1 says they are still "inside", asks how they are going to get outs and then says that they are going outside. Caller 2 then comes on the line. She confirms to the operator that they "can't leave because there is smoke in the corridor, but people are leaving." Call again at 02:00 (asking for further advice - smoke still coming in - and told to put sheets and towels down). Follow up calls from relative outside the building at 3:53 (reporting	LFB00000330 LFB00000336 LFB00000592 LFB00000600

Time	*Action*	*Evidence*
	that there are two adults in the flat, the flat door is jammed and so they can't get out) & 4:10 (caller reporting that the occupants of Flat 74 are now in the staircase)	
01:48	Caller in Flat 193 on Level 22. Caller says, 'it's getting smoky in the house', and 'a lot on the 22nd floor'.	LFB00000325
01:48	Caller from Flat 115 on Level 14. Smoke is coming from the front door and the window.	LFB00000331
01:50	LFB 999 Call. Caller from Flat 194 (Level 22). Occupant says smoke is coming into the flat and he can't see anything. The operator advises that he close any windows, block doors and and stay low. **02:00:** a further call from Flat 194. Caller says he has been waiting for 15 minutes. He says the flat is "worse. It's black in here. I can't see a thing". He is a pensioner and "can't get about." He mentions that his letterbox won't close and is advised to block it with a towel. **2:24:** Call from Flat 194. Caller says "I'm so fucking frightened up here! ... 45 minutes I've been in my flat ... I'm jumping out the window..." **3:01:** Call from Flat 194. Male says, "Please come and get me". Says he is not able to get out of the property. "It's too dark, it's too hot." He confirms that the fire is "next door" and says, "it's on the other side as well." Advised by operator to wrap himself in sheets and towels and get out. The caller asks for someone to come up and get him but then the call is cut off. **3:10:** Surrey Fire & Rescue call LFB. Surrey have just spoken to the family of the occupant of Flat 194. Surrey reports that there is so much smoke and flame that he cannot get out of the flat - "He is literally going to be running through flame – ". LFB advises Surrey to tell people to just get out.	LFB00000328 LFB00000337 LFB00000695 LFB00000352 LFB00000395 LFB00000407
01:54	Caller in Flat 95 on Level 12. Caller reports that fire is in the kitchen of Flat 96. Smoke is coming into the flat through the windows and front door. Reports that fire is outside his front door and has reached his landing. Looking out of the door he can see 'dark and yellow'. Fire is burning the windows and later 'coming in the window now'. Firefighters eventually arrive at the flat.	LFB00000332
01:56	Caller from Flat 165 on Level 19. Cannot leave as there is too much smoke outside.	LFB00000334
01:57	Caller in Flat 92 on Level 12. They could not get out because there was too much smoke and 'we couldn't breathe'. Smoke coming in from the door.	LFB00000335
02:00	Caller in Flat 74 on Level 10. Smoke is coming into the property, unclear exactly where from.	LFB00000336

TABLE 5: BASIS FOR THE FIRST HOUR OF THE INTERNAL SMOKE SPREAD TIMELINE

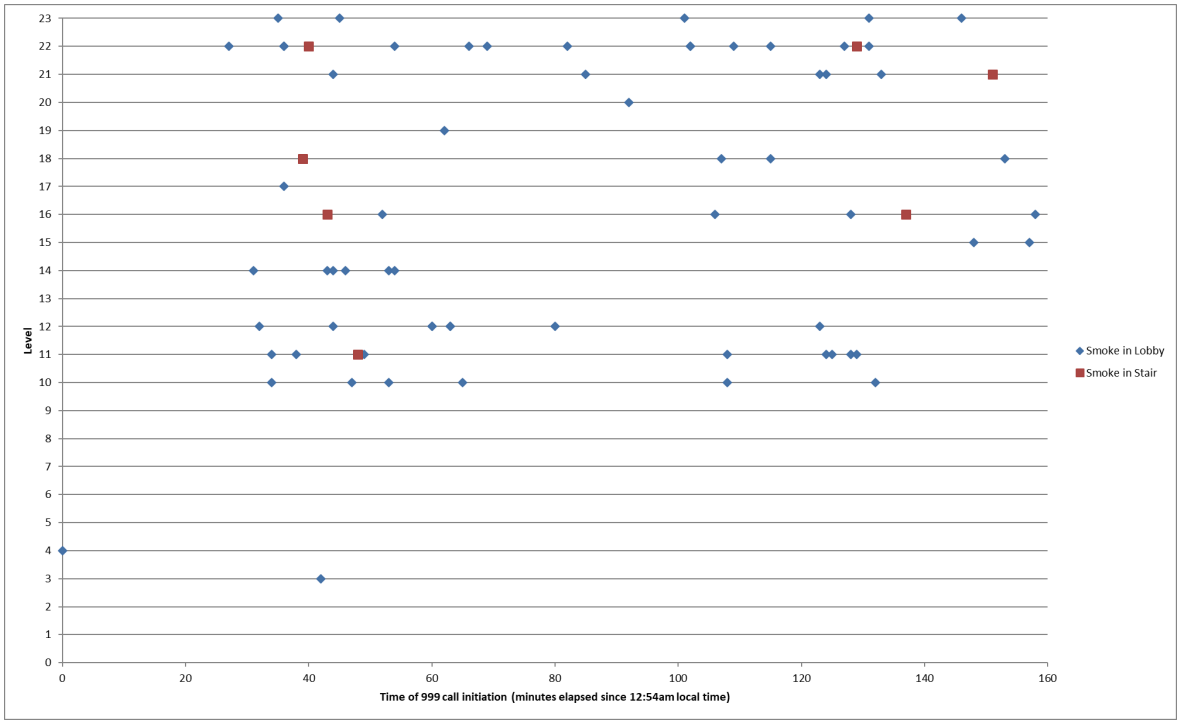
The compilation of 999 calls, including those presented in Table 5, is summarised in Figure 68 and Figure 69. There is still a large amount of data in the form of firefighter statements and testimony to the inquiry, surviving residents' statements, and (albeit coarse) camera footage that could, when combined, allow for a more complete picture of internal fire spread and smoke migration.

Figure 68 shows that smoke was reported for the first time in the lobby area in 10th to 14th and 22nd and 23rd floors approximately 30-35 minutes after the first 999 call. Figure 70 shows that at approximately the same time, internal fires were reported on the 12th and 22nd floors. The fire on the 12th floor is in Flat 96, directly above the flat of fire origin. This flat was first reported on fire at 01:24.

At same time as the report of fire on 12th floor (01:24), a 14th floor occupant reports lobby as impassable due to smoke. Within two minutes of call from occupant of 12th floor fire flat (01:26), 12th floor neighbour reports smoke coming from outside the main door of Flat 96. This implies that the 12th floor lobby has smoke but not flames. Four minutes after report of fire on 12th floor (01:28), smoke is reported on the 11th floor landing that is preventing occupants from leaving.

The location of the flat on the 22nd floor is not identified in the 999-call transcript however calls suggest that occupants evacuated up to the 23rd floor. They then quickly became trapped in that flat due to smoke in the lobby on that level. Other calls at 01:30 from the occupants on Level 22 state that the visibility is "terrible" on the 22nd Floor.

Given the timelines and fire characteristics required for door damage, it is clear that early smoke migration (01:24 to 01:28) between floors 11th and 14th would have to be through open doors. Figure 70 shows the consequent damage of the area associated to Flat 96. Ultimately, Flat 96 suffered severe damage and the door was found half broken in the doorway. However, smoke is clearly spreading very rapidly in this area and at a rate that is not compatible with the fire induced failure of the entrance door of Flat 96. Therefore, other mechanisms must be responsible for the rapid ingress and spread of smoke. These mechanisms are not immediately clear but appear to have led to a single flat fire compromising the stairwell and lobbies of floors 10 – 14. It is important for Phase Two that, once all evidence is collected, the correlation between physical variables and evidence is considered in more detail.



2704

2705

2706 **FIGURE 68: LOCATIONS OF 999 CALLERS DESCRIBING SMOKE IN LIFT LOBBIES & SMOKE IN STAIRS. NOTE THAT THE LOCATIONS**
2707 **SHOWN HERE ARE NOT NECESSARILY ON THE SAME FLOOR AS THE FIRE OR SMOKE BEING DESCRIBED BY THE CALLER, BUT INSTEAD**
2708 **THE LOCATION OF THE CALLER AT THE TIME. NO CALLS RECORDED FROM LEVEL 13 CAN BE ATTRIBUTED TO THE EARLY EVACUATION**
2709 **OF LEVEL 13 OCCUPANTS IN THE FIRST 30 MINUTES OF THE FIRE EVENT. ADDITIONAL CALL RECEIVED AT T=251 FROM CALLER ON**
2710 **10TH FLOOR, DESCRIBING SMOKE IN LOBBY.**

2711

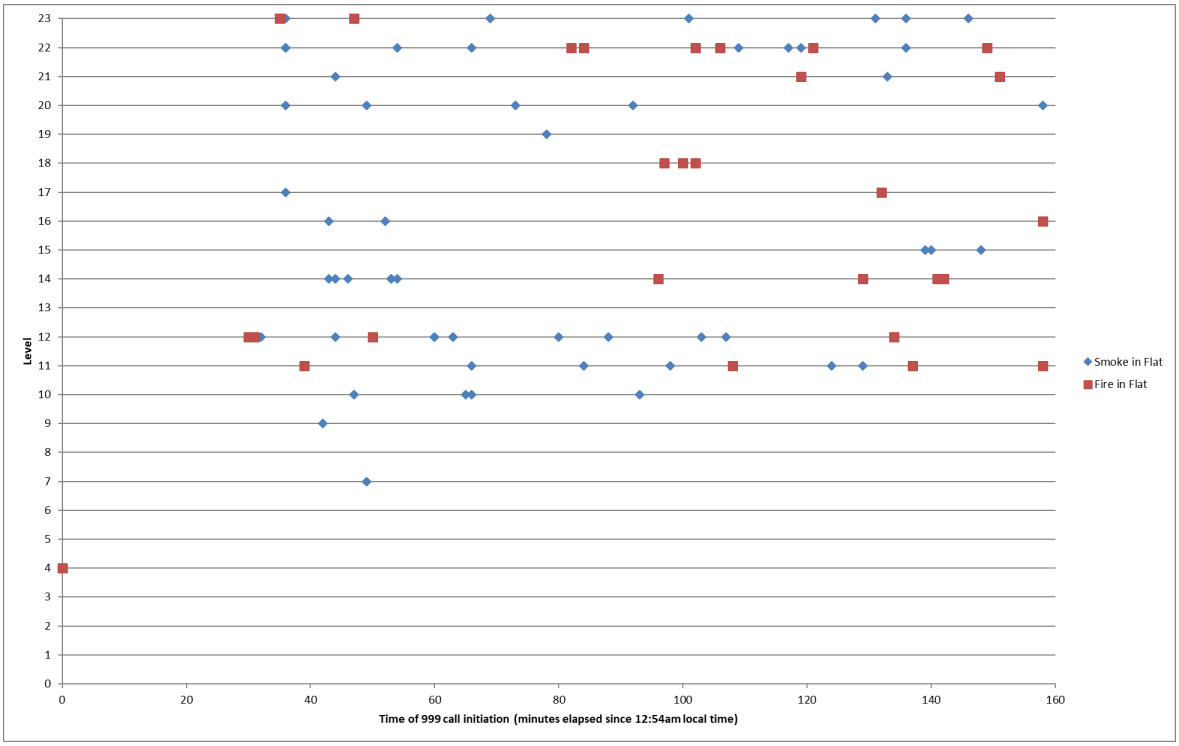


FIGURE 69: LOCATIONS FROM WHICH 999 CALLS WERE MADE DESCRIBING SMOKE AND FIRE IN FLATS. NOTE THAT THE LOCATIONS SHOWN HERE ARE NOT NECESSARILY ON THE SAME FLOOR AS THE FIRE OR SMOKE BEING DESCRIBED BY THE CALLER. PLOT DOES NOT CAPTURE CALL DURATIONS; FOR EXAMPLE, CALL FROM LEVEL 23 AT T=35 LASTS FOR 55 MINUTES, NOT KNOWN AT WHAT TIME DURING CALLER DESCRIBES FIRE IN FLAT. NO CALLS RECORDED FROM LEVEL 13 CAN BE ATTRIBUTED TO THE EARLY EVACUATION OF LEVEL 13 OCCUPANTS WITHIN THE FIRST 30 MINUTES OF THE FIRE EVENT. ADDITIONAL CALL RECEIVED AT T=251 FROM CALLER ON 10TH FLOOR, DESCRIBING SMOKE IN FLAT.



FIGURE 70: FLAT 96 AS VIEWED FROM THE LEVEL 12 LOBBY, WITH BROKEN FRONT DOOR VISIBLE IN DOORWAY

5.3.4 Onset of General Untenable Conditions

At some point during this third stage of the fire, as more and more compartment fires were ignited, and smoke migrated into the egress paths and unaffected flats, general conditions within the building can be deemed to have become untenable[25]. Figure 68 and Figure 69 show the increase in calls reporting smoke and fires in units as well as smoke in the lift lobbies and stairs.

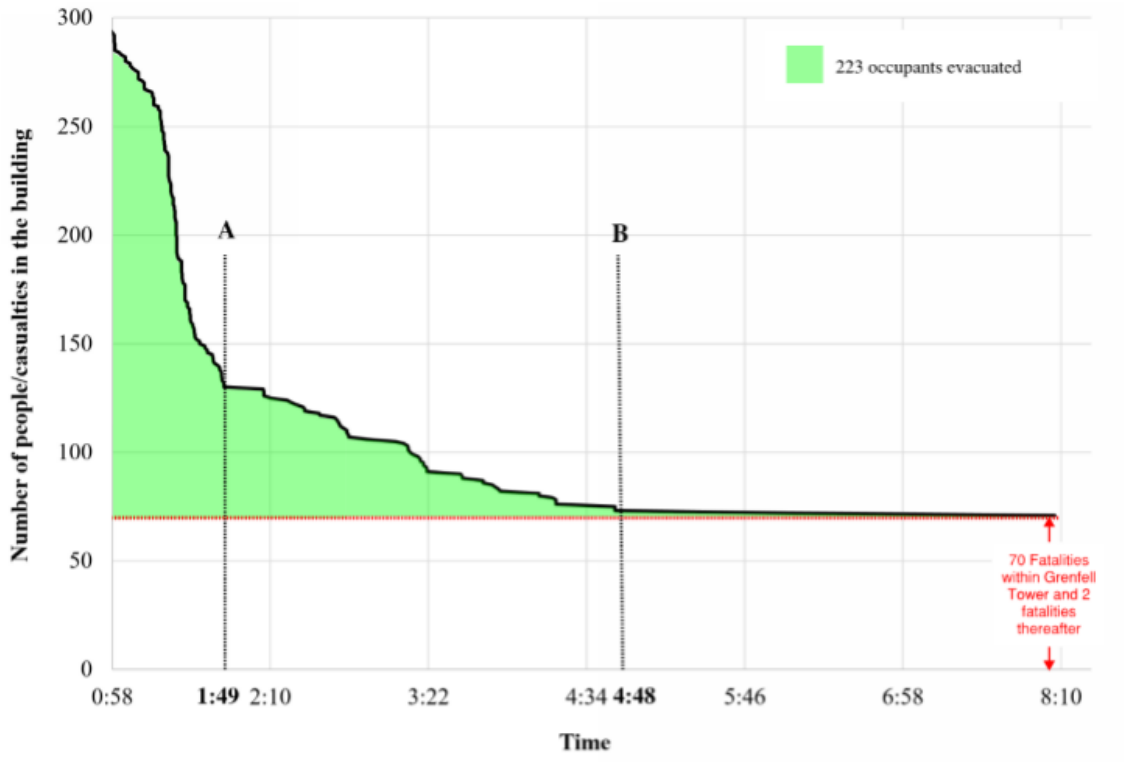


Figure 71: Number of occupants in Grenfell Tower during the fire event from [4].

Dr Lane's Phase One expert report [4] shows an overview of the number of people remaining in the building over time from the onset of the fire (Figure 71). The rate of evacuation slowed significantly at 01:50. At this point the fire has reached the East elevation windows of approximately 25 separate flats, and the North elevation windows of approximately 9 of those same flats (Figure 72). In this first hour of the fire most of the calls reporting smoke are localized in areas where the fires have been observed to breach the external envelope of the building (Floors 11th to 16th and 22nd and above). Given the significance of the external spread on all subsequent events potentially leading to the involvement of the compartment and then the breaching of the unit, the consistency of all this information is as expected.

[25] See footnote (1) for approximate times for each stage.

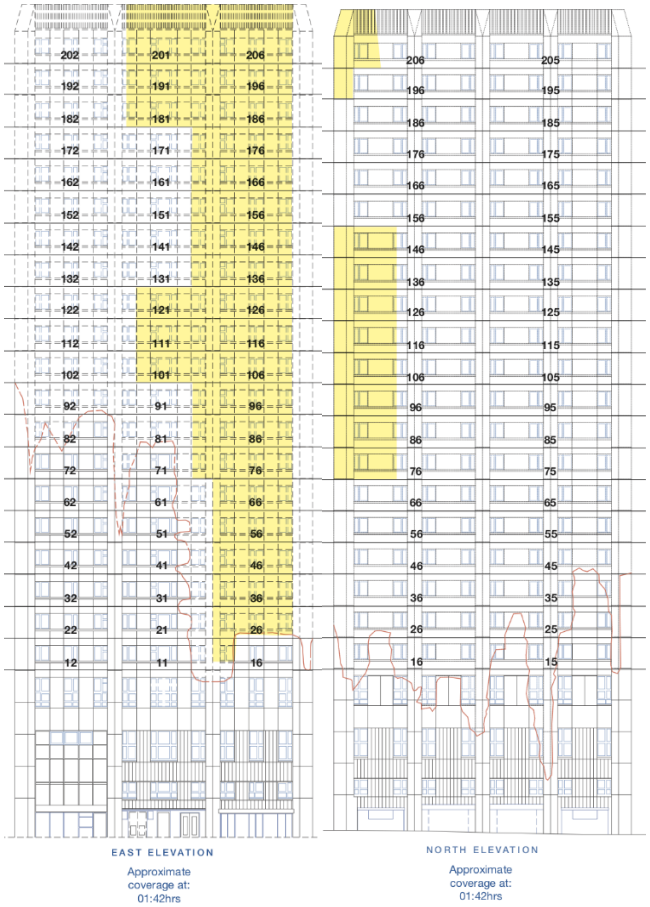


FIGURE 72: APPROXIMATE EXTENT OF EXTERNAL FLAME SPREAD AT 01:42 AM, THE TIME OF THE INITIAL SIGNIFICANT DECREASE IN THE RATE OF PEOPLE EGRESSING THE BUILDING NOTICEABLY DECREASED.

5.3.4.1 INTERPRETATION

During this stage of the fire, the smoke was passable by firefighters with Breathing Apparatus (BA), and as shown in Figure 71 (adapted from Figure 14.17[4]), during this period at approx. 01:50, occupants stop evacuating the building. At this point, there was a period of approximately 20 minutes where no egress took place. At 02:06 the fire was declared a major incident and from this point, egress appears to have resumed however at a much lesser rate than before. The reasons for this are unclear.

Up to 02:45, 1/3rd of the 80+ calls had come from Levels 22 and 23 and another 1/3rd had come from Floors 10 – 12 suggesting these areas in particular were unpassable. Firefighters issued an official end to the "stay put" guidance and initiation of evacuation of remaining residents at 02:47, however they had been in a search and rescue mode prior to that.

The rapid decrease in egress of occupants at approximately 01:50 corresponded with the fire spreading laterally to the central panel of the east elevation and to the North elevation. Egress paths from the floors around Level 12 and above Level 20 had become unpassable, evolving from sporadic, localised unpassable areas at the start of Stage 3 to blocks of unpassable levels by this time. Therefore, the time range 01:50 – 02:00 is considered to mark the onset of generalised untenable conditions and the beginning of Stage 4.

5.4. ASSESSMENT OF CHARACTERISTIC STRUCTURAL HEATING DURING STAGE THREE

Heating of the structure is briefly assessed here to provide an indication of the likely impact of a typical compartment fire on the Grenfell Tower structure. The intent is not to provide an assessment of structural stability, but to give a baseline assessment purely based on a thermal analysis. This assessment utilises the temperature of the reinforcing steel (rebar) in the slab to make a crude assessment of any impact compartment fires might have had on load bearing capacity. Details of the analysis are provided in Appendix F. Two scenarios are evaluated, the presence of a post flashover compartment fire and heating via the external fire.

Information available at present is limited to the depth of the slab, indicated as 200mm in [SEA00000271] and [43] with a 50mm screed on the top side. The rebar depth is not known exactly at the present time. Coring results reported in [43] imply that the rebar could be located between 25 – 35mm from the slab underside, and a minimum concrete cover of 25mm is typically required in order for rebar to act effectively [44]. A 1D heat transfer model of a typical roof slab is developed. From this model, the temperature of the rebar in the slab can be evaluated and the time to reach onset of loss of strength is established.

The model assumes that the rebar temperature can be conservatively approximated as the temperature of the concrete between 25mm and 35mm depth in to the concrete slab [44]. The gas phase temperature was taken as having a lower bounding value of 850^{o}C and an upper value of 1000^{o}C as estimated in Section 5.4. A conservative estimate for the onset of the rebar degradation is 300^{o}C so this will be taken as a lower bound failure criterion, while 550°C is more commonly taken as a failure condition for the rebar, this will be used as the upper bound failure criterion. The plot in Figure 73 presents the results of the two heating regimes implemented. The results are summarised in Table 6.

Bound	25mm - 300°C	25mm – 550°C	35mm - 300°C	35mm – 550°C
Upper	28 mins	120 mins	40 mins	161 mins
Lower	40 mins	220 mins	54 mins	286 mins

TABLE 6: THE TABLE GIVES CHARACTERISTIC TIMES TO HEAT THE REBAR AT 25MM AND 35MM DEPTH, TO TEMPERATURES OF 300°C AND 500°C, UNDER UPPER BOUND (1000°C) AND LOWER BOUND (850°C) GAS PHASE EXPOSURES. TIMES TO REACH THE ONSET OF LOSS OF STRENGTH ARE IN THE RANGE OF 30 – 60 MINUTES. TIMES TO REACH THE TYPICAL CONSERVATIVE DESIGN FAILURE CRITERIA OF 550°C ARE IN THE RANGE OF 2 – 5 HOURS.

The first flat unit fires ignited due to re-entry of the fire from external flame spread are reported as beginning at approx. 01:20-01:30. This stage of the fire lasts until approx. 02:00, a maximum of 40 minutes after these fires ignited. Given the structural heating timescales calculated above, it is estimated that the structure is not at risk during this stage of the fire as the rebar in the concrete slabs of the first flats to catch fire will at most only be beginning to approach temperatures at which its strength is affected. This also does not account for the time associated with the fire growing to this fully-developed phase.

This conclusion is further endorsed by Buchanan [44] who states that, “Catastrophic failures of reinforced concrete structures are rare, but some occasionally occur. Observations have shown that when concrete

buildings fail in real fires, it is seldom because of the loss of strength of materials." Thus, the approach used here can be considered as being very conservative.

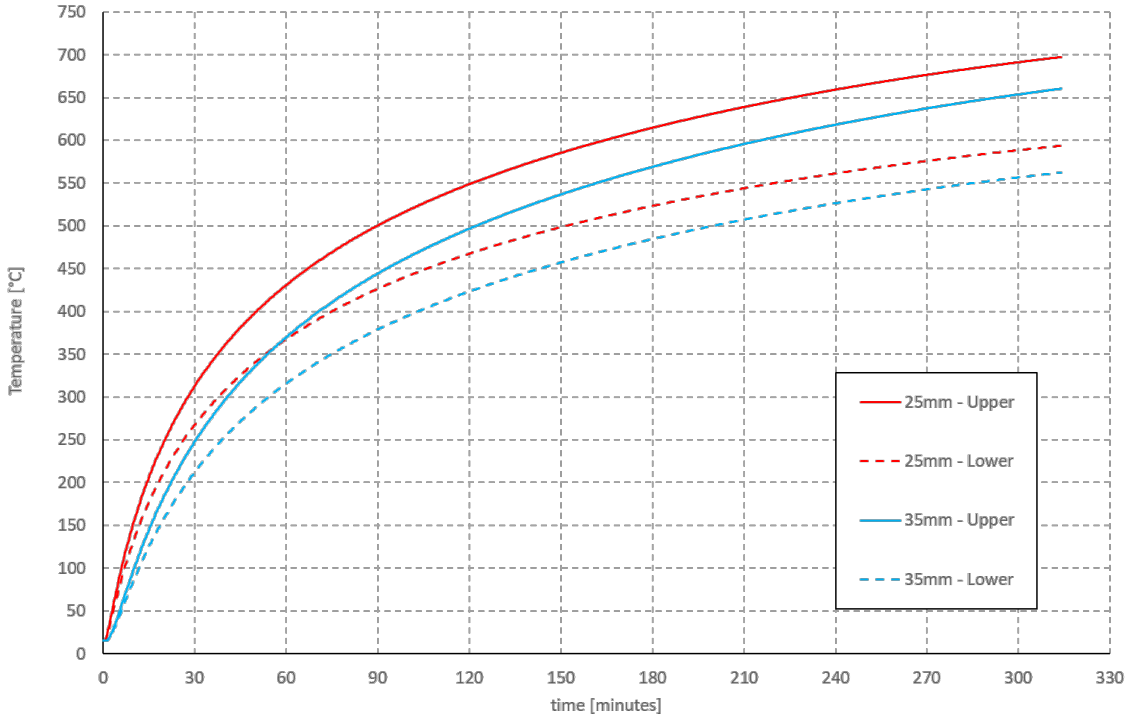


FIGURE 73: HEATING CURVES FOR SLAB REBAR LOCATED AT 25MM AND 35MM ABOVE THE BASE OF THE CONCRETE SLAB FOR UPPER BOUND (1000°C) AND LOWER BOUND (850°C) GAS PHASE TEMPERATURE EXPOSURES.

Given that the characteristic times of impingement of external flames on the interior slabs will be less than 25 minutes at this stage, it is clear that this mechanism of heating would also not impact the global stability of the structure. This is due to the short exposure time, the expectation that the temperature of the impinging flames will be no greater than the values assessed above, and the fact that the heat application is typically only localised around the window (see Section 5.3.2.1).

5.5. COMPLIANCE ISSUES AFFECTING THE CHARACTERISTICS OF STAGE THREE

At this stage, the building is experiencing a fire for which it was not designed. The building envelope was not designed to withstand an external fire emerging from the building itself, thus the failure of the different components of the window system that allow for penetration of the fire into the building cannot be explained solely by compliance issues. There are clearly stronger and weaker elements and many of the weaknesses are associated with poor quality design and/or construction; issues which are important when considering recommendations for improvements in construction practice. Nevertheless, in the case of the Grenfell Tower fire, the failure of the window system will have happened by one path or another. It is not possible to establish a detailed sequence of failure (it will vary from unit to unit) but what is clear is that, given the high heat fluxes, all failure paths would have manifested within a very narrow period of time.

Once the fire has re-entered the building, compartmentalization is the main line of defence. Compliant systems would have helped to protect egress paths and deliver safe paths for the occupants to evacuate. While the external fire contributes to ignition of the unit furnishings, the energy contribution to the unit is limited and localized to the areas around the window. Thus, there is no reason for compartmentalization requirements designed to withstand a post-flashover fire, not to be capable of withstanding a fire of the nature of that in Grenfell Tower.

Occupant behaviour (leaving doors open) or firefighting operations most likely had an impact on the capability of smoke and flames to migrate from the units towards the lobby and stairs. Nevertheless, this possibility cannot exonerate the need for compliant compartmentalization features (walls, fire doors, fire stop, etc.).

The design of the lobby and single stair egress called for greater redundancy by means of a smoke management system. The system was not designed to manage the smoke generated by fires in multiple units, therefore the performance of this system could have not been guaranteed given the nature of the Grenfell Tower fire. Independent of the conditions of the smoke management system for Grenfell Tower, it is important to revisit the compliance requirements for ventilated lobbies if the scenario of external fires is to be considered.

5.6. SUMMARY

- The third stage of the fire begins at approximately 01:30 when the external fire propagation reaches the top of the building and begins to spread laterally.
- The principle mechanism for lateral spread of fire around the external cladding of Grenfell Tower was via the architectural crown.
- Burning molten materials and debris fell from the top down, collecting on horizontal shelves and initiating new fires which then spread back up the building. These fires will progress upwards towards the fire that originated them, further up the building.
- This was more prominent higher up the building as lateral expansion of the smoke plume from fires lower down the adjacent façade resulted in more generalised pre-heating of the upper parts of the façade, aiding their subsequent ignition and downward spread.
- A fire that is capable of spreading over the surface of the façade system will impose sufficient fluxes of heat, that breaching of the façade at window locations is inevitable, regardless of the detailing of the window and its surroundings.
- Once fire has re-entered it may act as an ignition source resulting in a fire that may or may not result in flashover.
- Adequate compartmentalization would be expected to restrict any resulting fire to that unit. This is valid for a single unit fire and there is no reason why it should not be valid for a fire that spreads externally.
- Early internal spread of smoke on and around floors, where early ingress of the external fire led to compartment fires, implies compromised performance of internal compartmentalization.
- Fire induced compromise of the integrity of the flat doors would have required a post-flashover fire based on the subsequent testing of doors by the BRE. The brief period of time until loss of compartmentalization in Stage 2 and Stage 3 (as evidenced by smoke appearing in west and south facades) is not consistent with the longer timescales associated with the fire induced failure of the

doors. It is therefore very likely that doors were left open allowing free migration of some through undamaged doors.

- Analysis of emergency calls and firefighter statements indicate that communal lobbies and stairwells in the middle of the building (Levels 10-14) and at the top of the building (Level 20 and above) rapidly became either actually, if not seemingly, impassable to occupants on and around those levels by approximately 01:50.
- This rapid spread of smoke points to human factors (actions on the day, or in the design and maintenance) hindering the performance of the compartmentalization. The exact form of this involvement is unclear based on the available evidence however possibilities include:
    - Doors to flats with compartment fires being left open / door closers removed.
    - Firefighter intervention damaging flat doors through forced entry / holding flat and stair doors open to enable passage of hoses for direct intervention.
    - Poor design of compartmentalization, primarily doors, since no evidence has been found of inadequate walls.
    - Poor implementation of fire stopping during construction and subsequent renovations / works. Nevertheless, no significant evidence of poor practise has been found
    - Any use of the lift.
    - Smoke ventilation shaft.
- In general, the timeline of egress of occupants, reports of smoke and fire locations, and the actions and locations of firefighters are not well understood at this stage, based on the available evidence. This information is crucial to identifying the mechanisms by which smoke was able to migrate to, and through, the core of the structure so rapidly. Work on correlating physical evidence with testimony should continue in Phase Two.
- An analysis of the effect of compartment fires on the structural stability of the floor slabs indicates that the floors would have maintained structural integrity during this Stage.
- The third stage ends at approximately 01:50 – 02:00 when general conditions throughout the building can be considered untenable.

6 STAGE FOUR: UNTENABLE CONDITIONS IN THE BUILDING

There is not much that can be said about this stage of the fire beyond what has been described in detail in Dr Lane's Phase One expert report [4]. This section will therefore focus simply on establishing any indication of tenability and a post event final damage assessment. At this stage, the fire has involved a very large number of units, compartmentalization has been breached at multiple levels and firefighting capabilities have been significantly exceeded by the event. Conditions in the building are difficult to establish but it is clear that a significant part of the building is untenable. Egress potential has diminished dramatically, as clearly indicated by the slow rate of evacuation of building occupants. The following provides an indication of overall tenability based on the location and movement therein of casualties from the fire. Post fire damage assessment provides further information on the conditions within the building at this later stage of the fire.

6.1. LOCATION OF CASUALTIES

Based on the DVI Reconciliation Unit final floor plan of recoveries from Grenfell Tower [MET00008018], the location and movement of casualties based on their apartment of origin and their end location was tabulated. Figure 74 shows a visualisation of casualties found on the same level on which they were known to have lived.

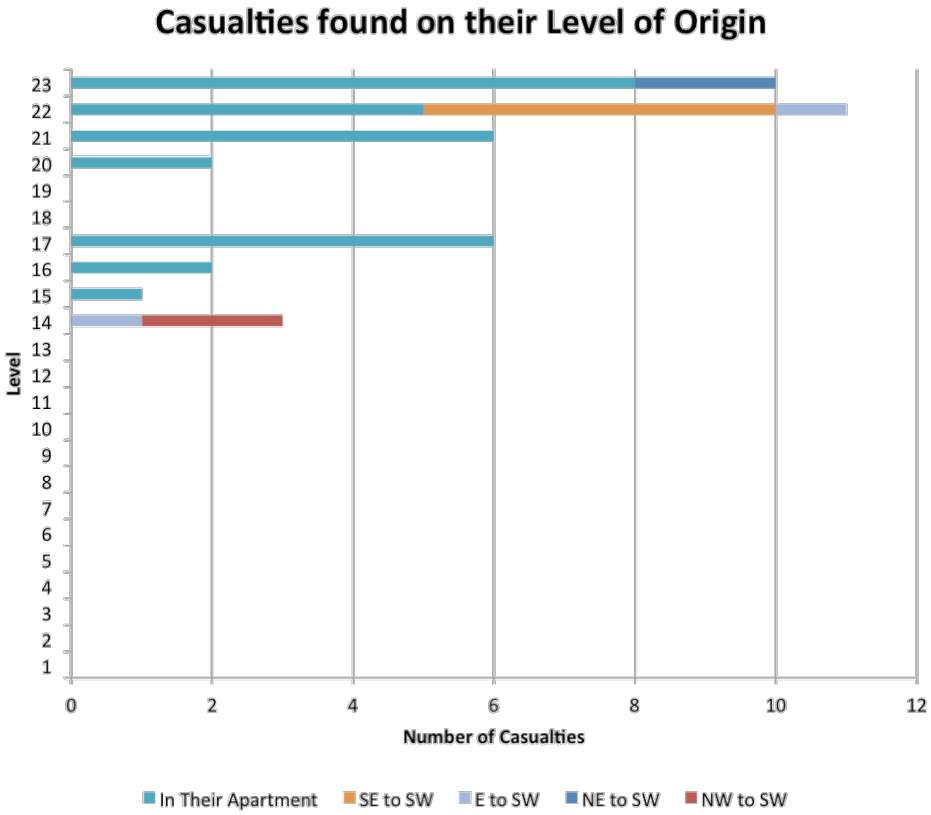


FIGURE 74: VISUAL REPRESENTATION OF CASUALTIES FOUND ON THE SAME LEVEL AS THEIR APARTMENT OF ORIGIN. IN SOME INSTANCES, CASUALTIES MOVED LATERALLY FROM THEIR OWN APARTMENT TO APARTMENTS IN THE SOUTHWEST CORNER OF

THE BUILDING (APARTMENTS '3'). THE SOUTHWEST CORNER OF THE BUILDING WAS THE LAST CORNER TO BE DIRECTLY EXPOSED TO EXTERNAL FLAME SPREAD ON THE BUILDING FAÇADE.

While most casualties were found within their apartment of origin, twenty-nine (29) casualties were found in other locations. Their movement is visually represented in Figure 75.

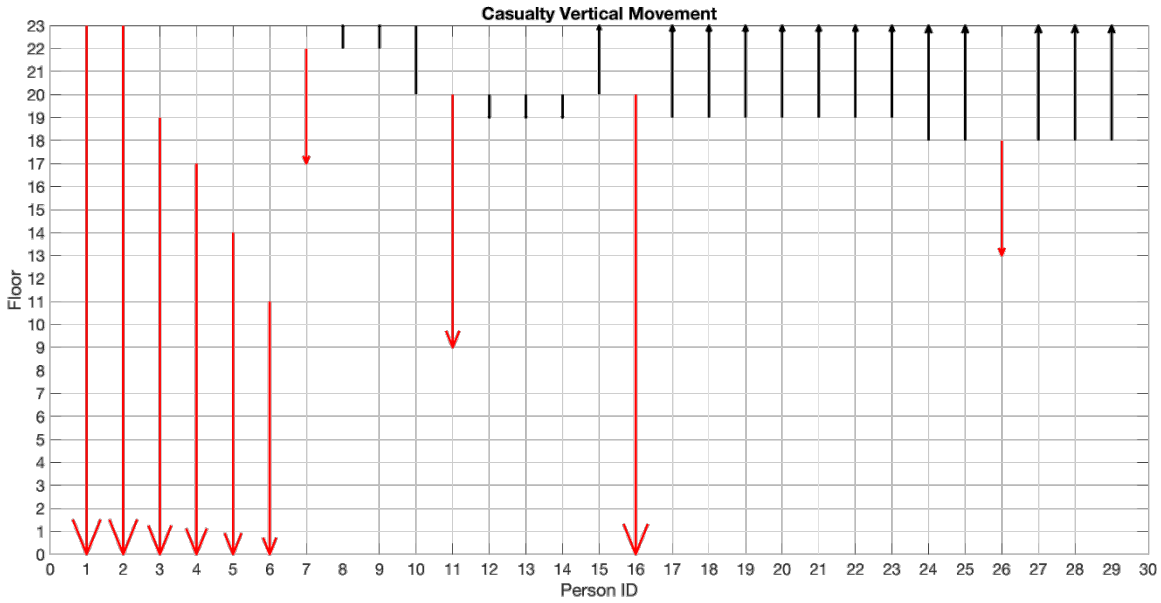


FIGURE 75: VISUAL REPRESENTATION OF CASUALTIES FOUND ON A FLOOR OTHER THAN THE ONE OF THEIR OWN FLAT. DATA SOURCED FROM MET00008018. 19 CASUALTIES WERE ABLE TO REACH THE EXIT STAIR BUT PROCEEDED UPWARDS RATHER THAN DOWN THE STAIR. 3 CASUALTIES WERE FOUND EITHER IN THE STAIR OR IN ADJACENT LOBBIES, SUGGESTING THEY ATTEMPTED TO TRAVEL DOWN THE EGRESS STAIR.

There is a clear cut off above Levels 12 – 13 where the vast majority of occupants living on or below these floors survived. Above these levels fatalities are grouped into two distinct bands.

The number of casualties immediately above Levels 12-13 corresponds to these levels being unpassable relatively early on in the event. Below these levels, all people escaped or were rescued. Immediately above these levels (14 – 17), occupants/casualties don't appear to have been able to move up or down. This is evidenced in the statements of firefighters which describe a sustained effort from the onset of Stage Four onwards, to extinguish and climb beyond Levels 12 and 13. There are limited reports of firefighters accessing the upper floors prior to this [MET00005348, MET00005590, MET00005350, MET00005384] however these appear to be isolated incidents during earlier stages of the fire.

By 02:05 [MET000080602] it is already documented that getting beyond these floors is presenting a significant difficulty. Numerous accounts of the building being clear up to the 12th floor and firefighting teams being sent to the 12th floor to extinguish fires are available [MET00007520, MET00005357, LFB00000007] spanning times estimated to be as late as 08:30. Typically, firefighters report a lack of water pressure when trying to extinguish fires on this floor. Numerous other statements [MET00005437, MET00005299, MET00005478] with unclear

timings report attempts to firefight and search and rescue on these floors that were impeded by consistent high levels of dense smoke and heat.

At some stage (unclear) Levels 18 – 19 also appear to have been untenable to the point that occupants from these levels attempted to move up or down the building. This would also explain why occupants/casualties were found in Levels 14 – 17, located between regions of untenability.

Above Level 20, occupants/casualties were prevented from moving downwards early on and either remained in their flats, moved to the SW corner flats, and / or moved to the 23rd floor (potentially to try and access the roof of the building) where they remained trapped.

While rescue operations continued throughout the first hours of this stage, it is unclear from exactly where these rescues took place. The dynamic location of the bridgehead does however provide some indication as to the levels which firefighters were able to reach. The following diagram (Figure 76) adapted from [4] can be used to illustrate this movement.

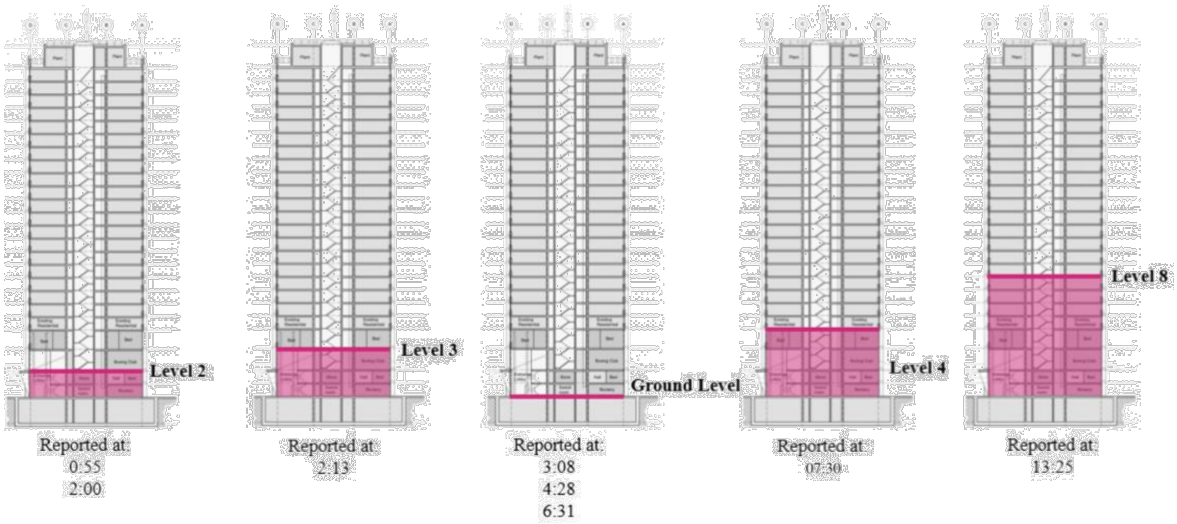


FIGURE 76: LOCATION OF THE BRIDGEHEAD THROUGHOUT FIREFIGHTING ACTIVITIES AT GRENFELL TOWER [4].

The diagram shows that, following the onset of generalised untenable conditions, firefighters were attempting to move up the building however were soon forced back down due to smoke concentrations as far down the building as Level 3. The implications of the extent of usable duration of breathing apparatus would mean that the firefighters were generally operating at lower levels over this period of time, therefore rescue operations would likely have been concentrated beneath Levels 10-12.

6.2. POST-FIRE STRUCTURAL ASSESSMENT

An assessment of images taken of all flats within the tower post fire have been assessed and categorised according to the level of damage. A summary table of this assessment is provided in Appendix G. Damage is grouped in to five categories:

- No damage
- Minor: Smoke damage only i.e. soot ingress through windows / doors

- Moderate: Smoke and partial fire damage
- Severe: Significant structural damage and spalling
- Major: Post-flashover fire conditions

All 10 instances of no damage occur from the 8th floor down with 6 of those on the lowest 2 levels. There are 15 instances of minor damage from the 10th floor down. Other than 1 flat on each of the 11th and 12th floors which have moderate damage, and 2 flats on the 11th and 1 on the 12 that have severe damage, all other flats from Level 11 upwards experienced major damage. All flats above the flat of fire origin experience severe (2) or major (16) damage. Ignition of these flats is likely to have been in the time window represented by Stages 2 and 3, and the early stages of Stage 4.

From Level 10 upwards, the vast majority of lift lobbies experienced either severe (5) or major (9) damage. There is a strong correlation with the number of flats experiencing severe damage and similar damage occurring in the lift lobbies. This implies systematic failure of fire doors following post-flashover fires. In most cases, fire doors are not visible in the images provided, indicating that they have subsequently been removed or were consumed in the fire.

From the 8th floor down, stair doors showed no signs of damage. From the 9th floor upwards, the degree of damage to the stair doors ranges from soot on the door (e.g. Level 11) to moderate fire damage on the lobby side of the door (e.g. Level 19). The variability in the degree of damage is believed to be a function of smoke ingress in the lobby, firefighter interaction with the doors, and internal penetration of flames into the lobby area. Unfortunately, not all of the stair doors could be evaluated from evidence provided because they were removed from hinges on floors where it is critical to evaluate their performance. It is not clear if the cause of this is due to the fire itself, firefighting and search and rescue activities, or subsequent removal of doors for forensic testing.

A post-fire structural assessment has been conducted by DeconstructUK [43] followed by shoring up of the structure to enable safe inspection of the site. In general, aside from sporadic inconstancies, the authors note that the worst effects of the fire, in terms of structural damage, are found between the 10th to 14th floor. Above this, fire damage is extensive but not as serious in structural terms. Below this, damage to the structure is typically negligible.

The authors state that, in all but a few locations, the effect of the fire is on the cover (the outer layer). Internally, the concrete appears unaffected. This is indicated by assessment of sample cores taken from the building. Spalling of concrete columns at 14th, 16th, 20th, and 21st floor levels has left rebar exposed, with spalling depths ranging from 35 to 100 mm. In two locations, this reinforcement has yielded. However, the authors do not believe this to be a concern in terms of the stability of the structure.

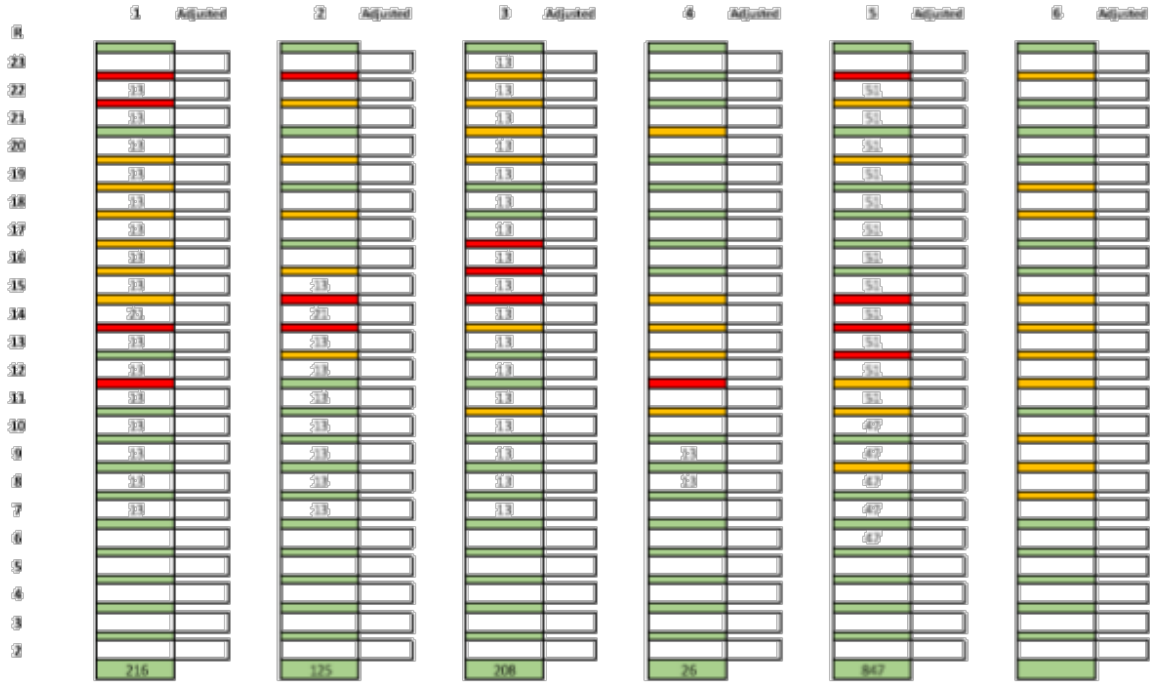


FIGURE 77: THIS FIGURE TAKEN FROM [43] INDICATES DEGREES OF STRUCTURAL DAMAGE THROUGHOUT THE GRENFELL TOWER. GREEN REPRESENTS FLATS WITH LITTLE OR NO DAMAGE AND IMPERCEPTIBLE DEFLECTION. AMBER REPRESENTS FLATS WHERE SPALLING HAS OCCURRED, REINFORCEMENT IS PARTIALLY VISIBLE, AND / OR VISIBLE DEFLECTIONS ARE LESS THAN 100MM. RED REPRESENTS SPALLING HAS OCCURRED, REINFORCEMENT IS VISIBLE AND DETACHED FROM THE SLAB OR THE SLAB IS IN A DEGRADED STATE, AND / OR DEFLECTIONS ARE LARGER THAN 100MM. NO EXPLANATION OF THE NUMBERING SYSTEM SHOWN IN THE GRAPHIC IS PROVIDED.

Figure 77 provides an overview of the structural damage by floor and by flat extracted from the DeconstructUK report [43]. Where slabs are coloured green, this represents flats with little or no damage and imperceptible deflection. Amber represents flats where spalling has occurred, reinforcement is partially visible, and / or visible deflections are less than 100mm. Red represents spalling has occurred, reinforcement is visible and detached from the slab or the slab is in a degraded state, and / or deflections are larger than 100mm. No explanation of the numbering system shown in the graphic is provided.

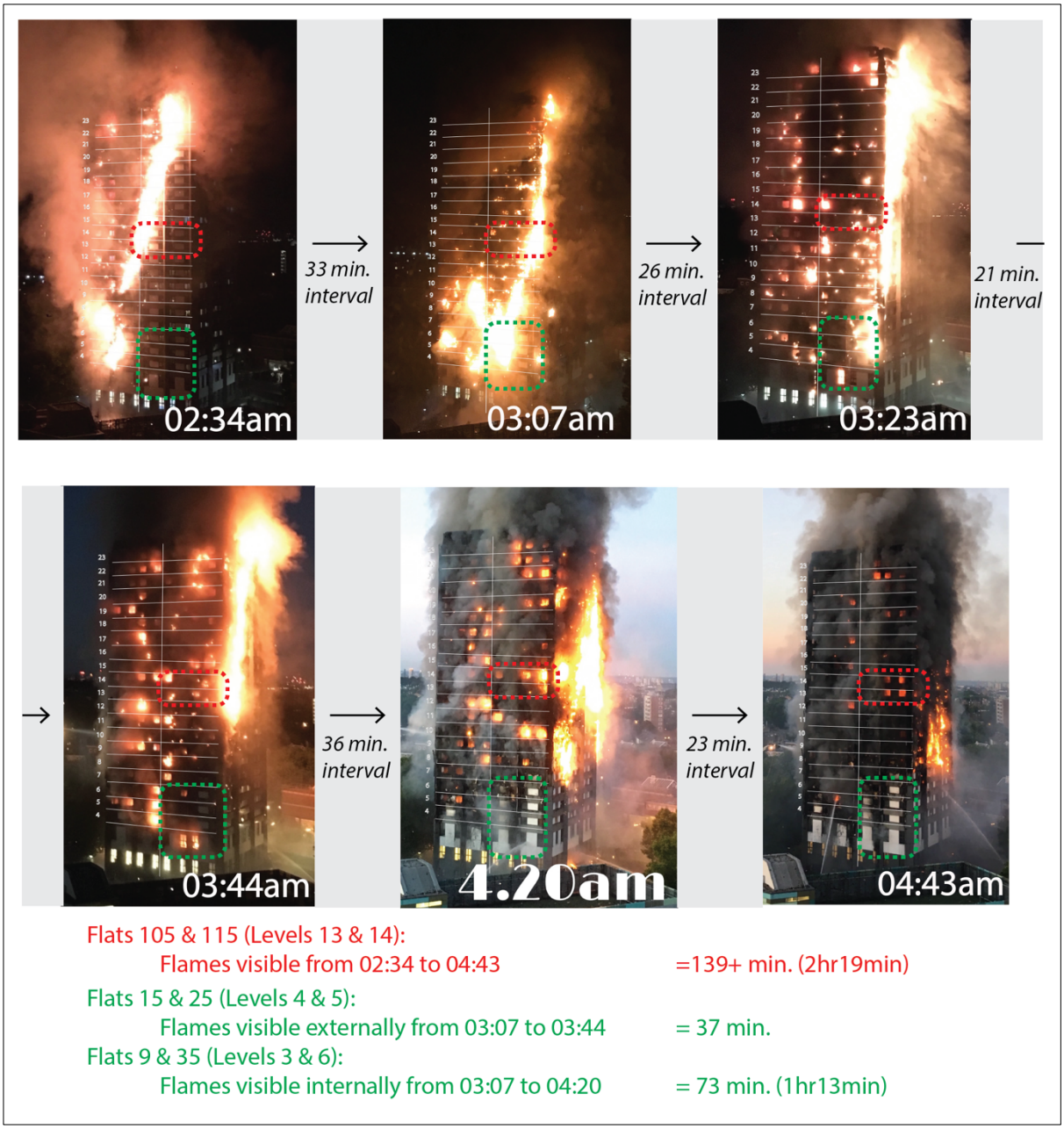
This correlation is assessed in conjunction with observed durations of fires to ascertain if the observed damage corresponds to the duration of fire exposure. Select photographs of Grenfell Tower during the fire event were sequenced and analysed to identify bounding fire durations internally i.e. the shortest and longest times for burning within flats. Figure 78 presents a sequence of photographs of the north elevation from 02:34 am to 04:43 am. Flats in the northwest corner (numbered “5”, right of centre in photos below) were the subject of focus as all northeast corner flats (numbered “6”, on the left of centre) were classified as either “severe” or “major” in the post-fire damage assessment, and thus would not have provided a clear delineation between short and long duration fires.

Flats 105 and 115, on Levels 13 and 14 respectively, are highlighted in red. These were identified in the DeconstructUK post-damage assessment as flats where spalling occurred, reinforcement was visible and detached from the slab and the slab was found in a degraded state and/or deflections were larger than 100mm. These flats are shown to be initially exposed to external flames at 02:34. Flames are visible inside these flats through to 04:43. In photos beyond 04:43, these flats were obscured by smoke, making it difficult

to determine the end of burning within these flats. In any case, the available evidence shows that fires burned internally within Flats 95 and 105 for at least 139 minutes i.e. over 2 hours and 19 minutes. This corresponds to the analysis in Section 5.4 as falling within the period of time associated with steel reaching a design failure criteria temperature.

Flats 9, 15, 25 & 35 are highlighted in green. These flats were determined by DeconstructUK to have suffered little to no damage and imperceptible deflection. As seen in Figure 78, all four flats are shown to be exposed to external flames at 03:07. Flames are no longer visible in Flats 15 and 25 at 03:44. However, at this time, flames remain visible in Flats 9 and 35, and are not seen to be extinguished until 04:20. Thus, the available evidence shows that fires burned internally within Flats 15 & 25 for less than 37 minutes, and within Flats 9 and 35 for less than 73 minutes. This again is in agreement with the results of the heat transfer analysis shown in Section 5.4, where rebar steel is expected to have reached the range in which its strength is beginning to degrade, however the slab as a whole still retains sufficient load carrying capacity hence little to no visible damage and imperceptible deflections.

The appended post-damage assessment, based on the 360 degree photographs, is visually summarized in Figure 79 below. The flats analysed above are highlighted in red and green below. As can be seen, Flats 95 and 105 suffered severe damage i.e. post-flashover conditions. Flats 15 and 25 suffered minor damage i.e. from smoke only. Flats 9 and 35 suffered moderate damage i.e. smoke and partial fire damage. Thus, the available evidence suggests that the duration of fire exposure corresponds with the severity of structural damage experienced within the impacted compartment.



3033

3034 **FIGURE 78: A SEQUENCE OF PHOTOGRAPHS OF GRENFELL TOWER NORTH ELEVATION DURING FIRE EVENT. FLATS SHOWING**
3035 **INDICATIVE LONG AND SHORT DURATION FIRES ARE HIGHLIGHTED IN RED AND GREEN, RESPECTIVELY.**

3036

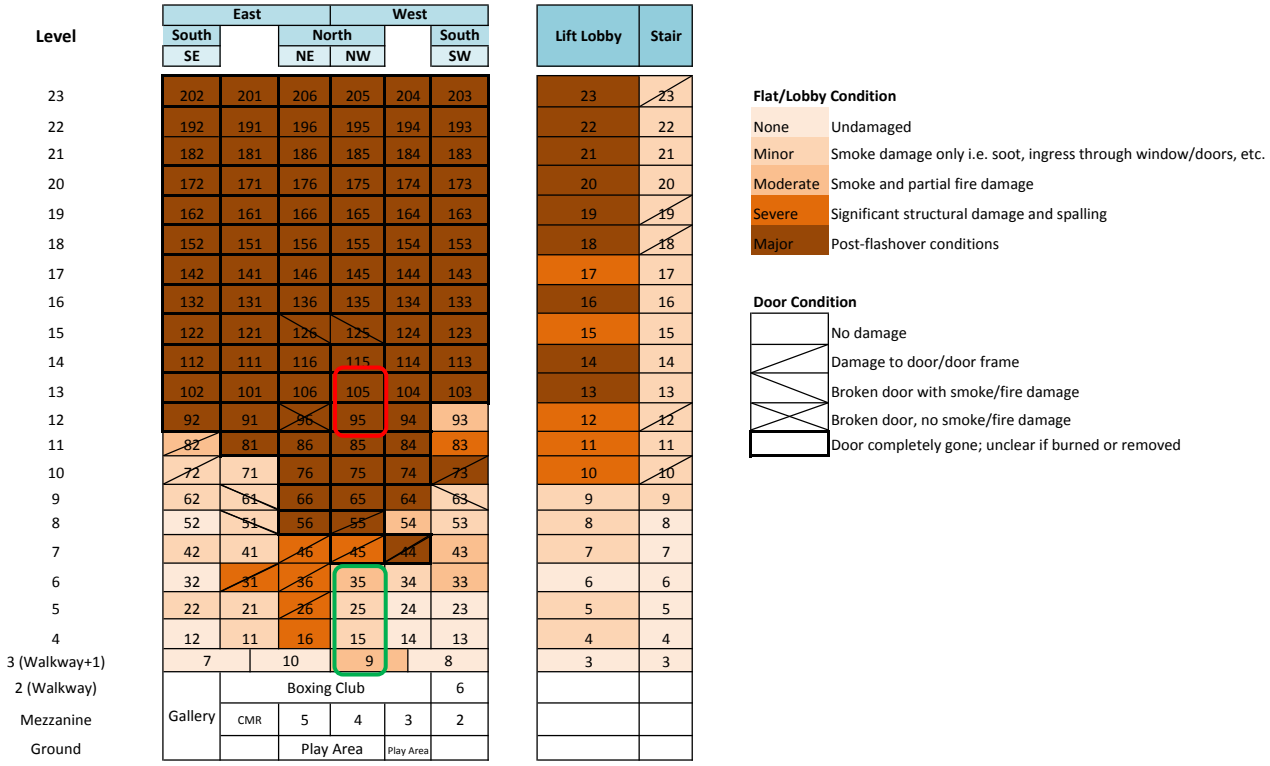


FIGURE 79: GRAPHIC SUMMARY OF POST-FIRE DAMAGE ASSESSMENT INCLUDED IN APPENDIX. FLATS HIGHLIGHTED IN FIGURE 78 ARE HIGHLIGHTED IN RED AND GREEN. NOTE THAT TWO FLATS 9 AND 35 CORRESPOND WITH MODERATE DAMAGE CONDITIONS, WHEREAS FLATS 15 & 25 CORRESPOND WITH MINOR DAMAGE CONDITIONS

6.3. SUMMARY

- This stage represents the period of the fire, after 02:00, where conditions within the wider building of Grenfell Tower could be considered as untenable.
- Egress / rescue of occupants from the tower during this stage was considerably slower than in previous stages providing an indication of increasingly challenging conditions within the building.
- Firefighter operations within this stage would likely have been confined to the lower levels due to the deteriorating conditions within the building, especially above floor 12.
- With multiple compartment fires already occurring and more igniting as the external fire continued to spread around the building, any firefighter operations or egress actions are far outside the intended strategy for the building and implied by regulatory compliance.
- Locations of fatalities are consistent with records from emergency calls and firefighter statements regarding locations where egress was compromised.
- Most fatalities occurred on the 14th to 17th and 20th to 23rd floors which corresponds to early reports of lobbies made impassable by smoke and heat.
- Flats on Level 12 and upwards almost exclusively experienced post-flashover fires. This corresponds well to observed visible structural damage.

- There is a direct correlation between number of severe fires and severely damaged lift lobbies indicating that fire doors separating individual flats from the lobbies were not sufficient for the thermal load experienced.
- In general, the structure remains stable, however most instances of spalling and structural damage are reported in the middle floors. The reasons for this distribution are not immediately clear. While a post-fire analysis enables this conclusion, there are no realistic means by which anyone could establish during the event that the structure remained sound at this stage of the fire.

7 CONCLUSIONS

Analysis indicates that a relatively minor, localised fire, compromised the uPVC window fittings and ignited one of the flammable components of the cladding by direct flame/plume impingement. This likely occurred before 01:05, and before first responders entered Flat 16. This marked the end of the first stage of the fire. From this point forward, the "stay put" strategy was compromised and evacuation of occupants was an option to consider. Firefighters would have been operating outside of their prescribed operating procedures. The building performance implied by the design approach followed was also breached.

Fire spread up the façade was inevitable once the fire was established on the outside of the façade system. Based on similar international events, the rate of spread was not unusual. Breaching of the window assemblies of flats higher up the building was also inevitable given the comparative levels of heat flux delivered by external fires to those required to break the window assemblies or induce glazing failure. Performance of external detailing such as fire-stopping or window units had no bearing on this outcome due to fire spreading over the exterior of the façade system. Fire reached the top of the building at approximately 01:30 which marks the end of the second stage of the fire. Throughout this stage, notwithstanding the fact that tenability levels in some lift lobbies is questionable, egress or rescue is the preferred option. The structural integrity of the building is not in question.

An important conclusion that cannot be overlooked is the complexity associated with predicting the rate of spread of a fire over a system as complex as these façade systems. Current performance criteria do not give justice to the complexity of the systems and observation of past fires does not provide sufficient information. While significant non-compliances have been established, the compliance approach used to determine "adequate" fire spread needs to be revisited and should be studied in much greater detail in Phase Two. This analysis should address not only technical issues pertaining to the fire dynamics associated with these complex systems, but should also focus on the implied competence introduced by Building Regulations. It is clear that currently there is an inconsistency between the necessary competency to address such complex systems, the levels of competency interpreted as required by Building Regulations and the mechanisms that serve to enforce competency. This applies to all aspects of the design, build, approvals and maintenance processes.

One key distinction between the fire at Grenfell Tower and other fires that have seen extensive vertical fire spread was the performance of the architectural crown, in particular its propensity to support lateral flame propagation, drip molten material and drop burning debris. This architectural crown was a key component that enabled the extensive lateral spread of fire around the entirety of Grenfell Tower.

Despite having several levels of containment, smoke and heat reached the stairwell early on in the fire. A variety of potential mechanisms, most likely linked to human action, error occurring either during the fire event or during design, construction and ongoing maintenance of the building, are most likely associated with the rapid internal spread of heat and smoke within the building. This rapidly impeded egress of occupants in the region around Floor 12 and above Floor 20. While human factors are relevant, the failure of compartmentalization needs to be treated as a compliance issue. The severity of interior fires generated by external fires is most likely very similar to that of a conventional compartment fire. Thus, fire resistance requirements, if valid for a conventional compartment fire should be valid for internal fires initiated by external fires. This aspect needs to be explored in Phase Two because compliance in matters of compartmentalization should be much less complex, and thus robust improvements should be easy to implement.

A combination of these mechanisms and also potentially fire door failure as a result of multiple severe compartment fires led to generalised untenable conditions throughout the Tower by approximately 01:50 – 02:30. This marks the end of the third stage of the fire.

Beyond this point, in the fourth stage, firefighting activities are governed by conditions in the building and are performed in an ad-hoc manner. There is considerable risk to those rescuing and being rescued, however egress remains the preferred option. Prior to widespread untenable conditions throughout the building, the structural integrity is not considered to have been compromised to an extent that put occupants and rescuers lives at risk. Only beyond the point at which general conditions in the building were untenable would the structure could be deemed at risk. Post-fire analysis indicates that this risk is generally localised and in the middle region of the building but this could have not been assessed during the event. The reasons for this are as yet undetermined. Structural assessment methods that could enable firefighters to establish the risk of structural failure appear as a potential improvement to operations and should be explored in Phase Two.

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APPENDIX A. SMOKE FILLING MODEL

The description of the fire growth in the early stages of the fire depends on the surface area of combustible materials burning, as well as on the type of fuels burning. In most cases it is very difficult to establish precisely what is burning, the relevant properties of the materials and also the area burning. A simple and common way of characterizing a wide range of growing fires is the "αt^2" fire [20]. The value of "α" represents all the properties of the burning materials while the "t^2" the growth of the area in time (t is time in seconds). Many tests have been done in the past for various materials and data sets are available that serve to characterize the corresponding value of "α" for numerous combustible materials. These classify fires in four categories: slow, medium, fast and ultra-fast fire growth. The value of "α [kW/s^2]" covers the range of α=0.0029 for a slow fire to α=0.1876 for an ultra-fast fire. To represent a broad spectrum of fire growth behaviour the whole range of fire growth rates will be used here. This is necessary given the lack of clarity regarding the exact point of origin and thus type, orientation and position of the fuel exposed. The range covers all possible fires according to the available literature data. The range is not established to attempt to define the actual rate of growth of the fire, but to cover all possible conditions.

The model, described below, solves a simple set of equations over sequential, small time, increments to describe the amount of smoke produced by a fire and the subsequent contribution that it makes to the hot-layer of smoke that builds beneath the compartment ceiling, and gradually descends towards the floor. Where terms in these expressions span across time-steps, superscripts t and t+1 have been used to differentiate between terms that refer to the previous and new time-step respectively. Where no guidance is given, all terms refer to the same time-step.

The size of the fire, $\dot{Q}$ (kW) at any point in time, t (s), post-ignition, is characterised as:

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

EQUATION 4

It is only the convective portion of this total energy release that contributes to the fire plume, and this portion, $\dot{Q}_c$ (kW), is defined as:

$$\dot{Q}_c = \frac{\dot{Q}}{1.5}$$

EQUATION 5

As the plume rises due to buoyancy created by this heat, $\dot{Q}_c$, air is entrained into the plume causing it to increase in mass the higher it rises. The mass flow rate of smoke in the plume, $\dot{M}_a$ (kg/s), as a function of the height above the base of the fire, z (m), is given as:

$$\dot{M}_a = E\left(\frac{g.\rho_a^2}{c_p.T_a}\right)^{\frac{1}{3}}.\dot{Q}_c^{\frac{1}{3}}.z^{\frac{5}{3}}$$

EQUATION 6

Where E is a dimensionless constant (0.21), g is the acceleration due to gravity (9.81 m/s^2), ρ_a is the density of air (1.2 kg/m^3), c_p is the specific heat capacity of air (1.0 J/kg.K), and T_a is the temperature of the ambient air (288 K).

This entrained air is orders of magnitude larger than the other components of the smoke, therefore the mass flow of air is assumed to be equivalent to the mass flow of smoke in the plume, $\dot{M}_s$ (kg/s), therefore:

$$\dot{M}_a \approx \dot{M}_s$$

EQUATION 7

It is this mass flow that creates and subsequently continually feeds the smoke layer. Thus, it is necessary to determine the temperature of the smoke plume, T_s (K), to subsequently establish the temperature of the hot upper layer, T_u (K). The smoke plume is given as:

$$T_s = T_a + \frac{\dot{Q}_c}{\dot{M}_s . c_p}$$

EQUATION 8

Having established the characteristics (mass and temperature) of the smoke entering the upper layer, the mass of the upper layer, m_u (kg), can be established at each time-step as:

$$m_u^{t+1} = m_u^t + \dot{M}_s^{t+1} . \Delta t$$

EQUATION 9

Where Δt is the length of the timestep (s). This mass can be equated to a height of the smoke layer, H (m), using the temperature, T_u (K), and subsequently density, ρ_u (kg/m^3), of the upper layer. The temperature of the upper layer, T_u (K), is established as:

$$T_u^{t+1} = \frac{m_u^t T_u^t + \dot{M}_s^{t+1} T_s^{t+1} \Delta t}{m_u^t + \dot{M}_s^{t+1} \Delta t}$$

EQUATION 10

The density of the upper layer, ρ_u (kg/m^3), is established as:

$$\rho_u = \rho_\infty \left(\frac{T_a}{T_u} \right)$$

EQUATION 11

These parameters are then equated to the height of the smoke layer, H (m), as:

$$H = \frac{m_u}{A . \rho_u}$$

EQUATION 12

Where A (m) is the area of the footprint of the compartment. Combined, these expressions can be used to depict the evolution of the smoke layer height and temperature.

APPENDIX B. Verification of Bounding Fire Sizes

An analysis conducted with the aim of providing coarse bounds to the fire scenarios that could potentially have occurred in the kitchen of Flat 16 was presented in the body of the report. The simplest possible approach was followed to keep the precision of the analysis consistent with the range of accuracy and detail provided by evidence. Given the limited information available on the earlier stages of the fire, it is important that the calculations do not provide an unrealistic expectation of precision that then cannot be validated by evidence. Better analysis tools exist that could provide more accurate characterization of the fire, nevertheless, these tools will only be used to establish if the bounds provided by the simple model are appropriate and to explore the influence of variables omitted by the simplicity of the model. Therefore, the modelling results produced here do not attempt to match the exact timeline of the fire. Rather they intend to provide an indication of the impact of a variety of fire sizes and orientations on compartment temperatures and thus inform the reliability of the analysis presented in the body of the report.

Zone modelling of the kitchen fire in Flat 16 has been performed using the Consolidated Model of Smoke and Heat Transport (CFAST)[26] tool developed at the National Institute of Standards and Technology (NIST), USA. This tool is used to assess temperatures and HRRs at the point in time when the smoke layer interface reaches its lowest point. Computational Fluid Dynamics (CFD) modelling using The Fire dynamics Simulator[27] also developed by NIST was undertaken to confirm the accuracy of the range of HRRs and compartment temperatures. While use of these models is not intended to serve as a full sensitivity analysis, they do serve the purpose of testing model assumptions and several different scenarios, providing confidence in the results presented in the main body of the report.

ZONE MODELLING

CFAST MODEL SCENARIOS

Two model variations of the Flat 16 fire scenario have been constructed. Scenario 1 represents the assumed ventilation conditions during the kitchen fire event based on the available evidence. The kitchen door is closed and the main kitchen window is only partially open (tilted position). An example of this scenario is shown in Figure 80. The purpose of this model is to provide verification of the range of compartment temperatures and HRRs estimated by the analytical approach described in the main body of this report.

Scenario 2 takes advantage of the extra functionality of the model to explore the potential conditions that could result from different ventilation configurations, namely if the kitchen door was open or closed for the duration of the fire, to try to provide confirmation of this potential variable. Thermal imaging camera footage [MET00005810-17] also show the door and window to Bedroom 1 open as the firefighters enter and search the flat for the first time. The Scenario 2 model replicated this as shown in Figure 81.

[26] https://www.nist.gov/el/fire-research-division-73300/product-services/consolidated-fire-and-smoke-transport-model-cfast

[27] K. McGrattan, S. Hostikka, R. McDermott, J. Floyd and M. Vanella, Fire Dynamics Simulator Technical Reference Guide, NIST Special Publication 1018-1, National Institute of Standards and Technology, Sixth Edition, June 2018.

CHARACTERISTIC FIRE SCENARIOS

Four characteristic fire growth rates are simulated to establish bounding values for the compartment temperature and HRR at the point when the kitchen compartment has filled with smoke. Growth rates represent the range explored in the main body of the report i.e. slow, medium, fast and ultra-fast. The HRR is allowed to grow and the value at the time corresponding to the smoke layer interface reaching the compartment floor is recorded. The model also provides some measure of physical cap on the magnitude of the HRR and the model is allowed to run in order to see what this value is. The other results recorded are the time at which the smoke layer interface reaches the floor and the temperature of the smoke layer at this time. Results are presented in Table 7 and discussed below.

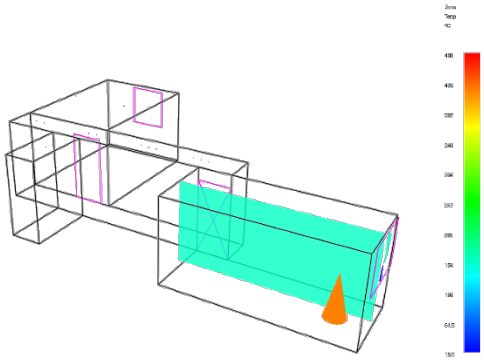


FIGURE 80: SCENARIO 1: KITCHEN FIRE SCENARIO WITH VENTILATION CONDITIONS BASED ON OBSERVED EVIDENCE. THE KITCHEN DOOR IS CLOSED, AND KITCHEN WINDOW IS PARTIALLY OPEN.

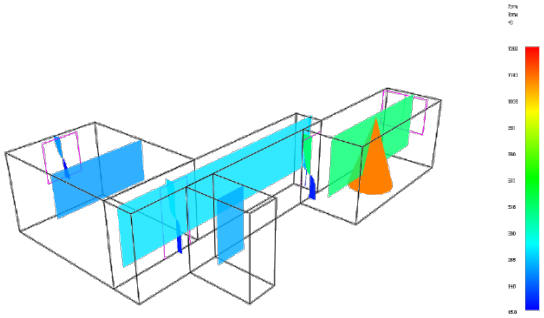


FIGURE 81: SCENARIO 2: KITCHEN FIRE SCENARIO WITH WINDOW PARTIALLY OPEN AND KITCHEN DOOR FULLY OPEN. THE DOOR FROM THE CORRIDOR TO BEDROOM 1 AND WINDOW IN BEDROOM 1 ARE ALSO OPEN AS OBSERVED IN THERMAL IMAGING CAMERA FOOTAGE [MET00005810-17].

RESULTS

Results from Scenario 1 modelling correlate well with the results from the analytical model described in the main body of the report. The results show the range of time for the smoke layer to descend as 50 – 200s (40 – 140s in empirical model), the upper layer temperature range at this point as 125 – 250°C (100 – 220°C in empirical model), the range of HRR at this time as 110 – 360kW (60 – 300kW in empirical model) and the limiting peak HRR imposed by the model as ~360kW.

Results from Scenario 2 demonstrate that the extra ventilation provided by the open door would likely lead to a flashover scenario. The smoke layer takes longer to reach its lowest point due to the extra leakage to the rest of Flat 16 (115 – 850s). The upper layer temperature at the point at which the smoke layer interface reaches its lowest point is in the range of 750 – 900°C, with temperatures beyond the 500 – 600°C range associated to flashover conditions[28]. The corresponding peak HRR which is the limiting value imposed by the model is of the order of 1.5MW.

[28] Drysdale, D., "Introduction to Fire Dynamics," Third Edition, Chapter 4 – Diffusion Flames and Fire Plumes, John Wiley and Sons, 2011.

Scenario	Growth Rate	Spread Rate [mm/s]	Ventilation	Time for Smoke Layer to Reach Floor [s]	Corresponding Temperature of Hot Layer [°C]	Corresponding HRR [kW]	Peak HRR [kW]
1	Slow	1.2	Kitchen Window 10%	200	125	110	350
1	Medium	4	Kitchen Window 10%	125	160	160	355
1	Fast	6.7	Kitchen Window 10%	75	175	250	360
1	Ultra-Fast	9.5	Kitchen Window 10%	50	250	360	360
2	Slow	1.2	Kitchen Window 10%, Kitchen Door 95%	850	900	1550	1550
2	Medium	4	Kitchen Window 10%, Kitchen Door 95%	500	875	1550	1550
2	Fast	6.7	Kitchen Window 10%, Kitchen Door 95%	220	850	1550	1550
2	Ultra-Fast	9.5	Kitchen Window 10%, Kitchen Door 95%	115	750	1550	1550

3247

3248 Table 7: Results from the 8 CFAST model configurations run.

CFD MODELLING

An overview of the CFD model is shown in Figure 82. The modelled grid resolution is 5cm x 5cm x 5cm as recommended by the FDS user manual[2]. A grid independence study was not conducted given that the intention was not to attain a high-fidelity model. The recommended grid resolution was therefore deemed sufficient.

It is assumed that doors to the living room and 2nd bedroom are closed thus they will not participate in the simulation. These areas have therefore been excluded from the model to save on computational load. A comparison simulation with the entire flat modelled has been run and the exclusion of these areas does not change the modelling results for the kitchen compartment.

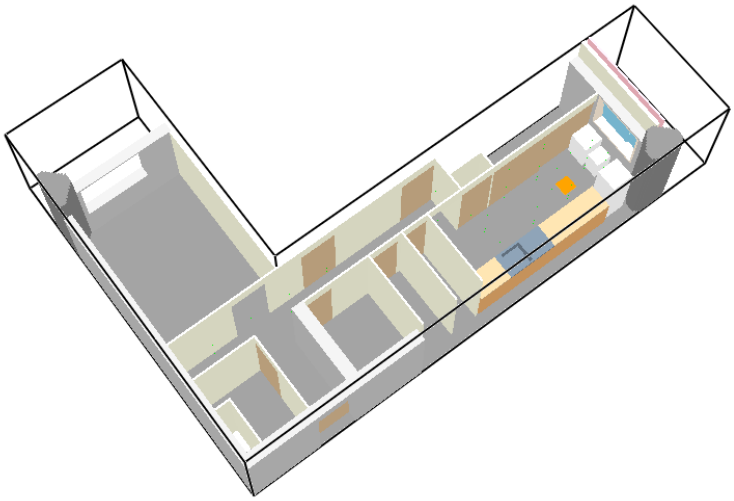


FIGURE 82: OVERVIEW OF THE CFD MODEL USED FOR THE ANALYSIS DESCRIBED WITHIN THIS DOCUMENT.

The fire is defined as a mass loss rate from a surface with properties of polystyrene. The soot yield is set at 0.2, and CO yield at 0.02. The fire locations are defined as either:

- Floor -> fire is located at floor level as per Figure 82.
- Fridge -> the fire is located on the back of the fridge as per the image in Figure 83.

When the fridge is the fire location, the entire fridge back is defined as the burning area. When the fire is at floor level, the fire area is sized to maintain a heat release rate per unit area (HRRPUA) as 0.55MW/m^2. These two fires represent two extreme conditions. Fires burning on horizontal surfaces but elevated from the floor will lead to results somewhere in between these conditions. Given that the purpose of this analysis is only to bound the potential temperatures within the compartment it was not deemed essential to run these scenarios.

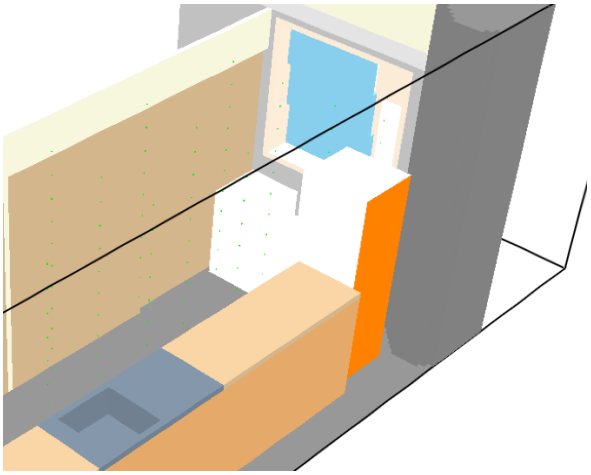


FIGURE 83: IMAGE OF THE MODEL SHOWING THE FIRE LOCATED ON THE BACK OF THE FRIDGE, WITH VENTILATION SET AS A TILTED LARGE WINDOW AND OPEN SMALL WINDOW. THIS CORRESPONDS TO THE BRE RECONSTRUCTION SETUP.

Several ventilation conditions were studied to assess the role of ventilation on the evolution of the compartment. Ventilation variations for the kitchen are as follows:

- Case I: Large window tilted inwards only, all other openings closed, as per the original assumption in the Phase One report (see Figure 84)
- Case II: Large window tilted inwards, small window open, all other openings closed (see Figure 83)
- Case III: Large window tilted inwards, door open, all other openings closed (see Figure 84).

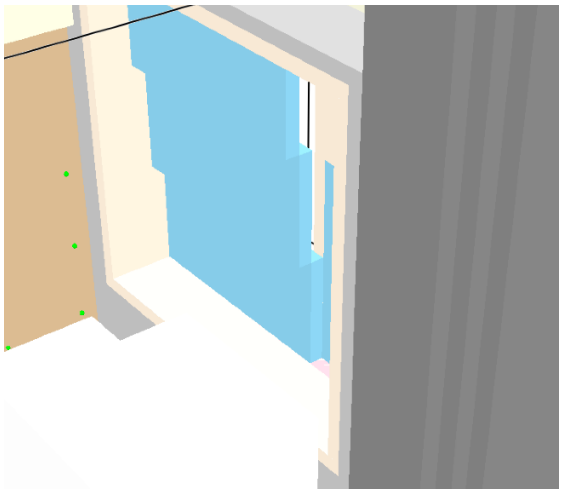


FIGURE 84: IMAGE SHOWS THE MODELLING OF THE TILTED LARGE WINDOW. THE RESTRICTIONS OF THE MODEL LIMIT OBJECTS TO A RECTILINEAR GRID.

Within these ranges for fire location and ventilation, modelling of the fire was executed for a range of fire sizes. The matrix of models run as part of this analysis is presented in Table 8. While all model results have been produced, not all are discussed in this report.

3289 **TABLE 8: ALL MODELS RUN TO SUPPORT THE ANALYSIS DESCRIBED IN THIS REPORT. NOT ALL RESULTS ARE PRESENTED HEREIN.**

Ventilation	Fire Location	Maximum Fire Size [kW]
Original	Floor	60
Original	Floor	300
Original	Floor	1000
Original + Door	Floor	60
Original + Door	Floor	300
Original + Door	Floor	1000
BRE	Floor	60
BRE	Fridge	60
BRE	Floor	100
BRE	Fridge	100
BRE	Floor	200
BRE	Fridge	200
BRE	Floor	300
BRE	Fridge	300
BRE	Floor	400
BRE	Fridge	400
BRE	Floor	500
BRE	Fridge	500

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3292 BENCHMARKING OF THE CFD MODEL

3293 Results from a standalone test carried out at BRE on a fridge under a hood are used to estimate a potential
3294 the range of Heat Release Rates (HRR). The standalone fridge test conducted in the BRE Burnhall is described
3295 by Nic Daeid[29]. HRR data from this test is shown in Figure 85. This data displays two distinct periods of burning,
3296 the first from approximately 7 – 30 minutes, and the second from approximately 30 – 54 minutes.

3297 The initial peak of approx. 400 kW, 7 minutes from the start of the experiment, followed by a significantly
3298 reduced rate of approx. 75 - 100kW, corresponds to burning on the rear of the fridge which then gradually
3299 spreads to the material on the inside. This range of values is relatively consistent with 60 – 300kW range
3300 estimated in the main body of this report.

3301 The later peak in Figure 85, in the range of 1.0 – 1.6MW, at approximately 32 minutes corresponds to the fire
3302 breaking out of the fridge. The analysis provided here and in the body of this report suggests that combustion
3303 during the period of the fire following the involvement of the interior of the upper portion of the fridge will
3304 be limited by available ventilation. It is therefore likely that the values of HRR recorded in the standalone fridge
3305 test will be greater than those in the compartment.

[29] Nic Daeid, N., Grenfell Tower Public Inquiry, Provisional Report, GTPI/NND/2017, 12th February, 2018.

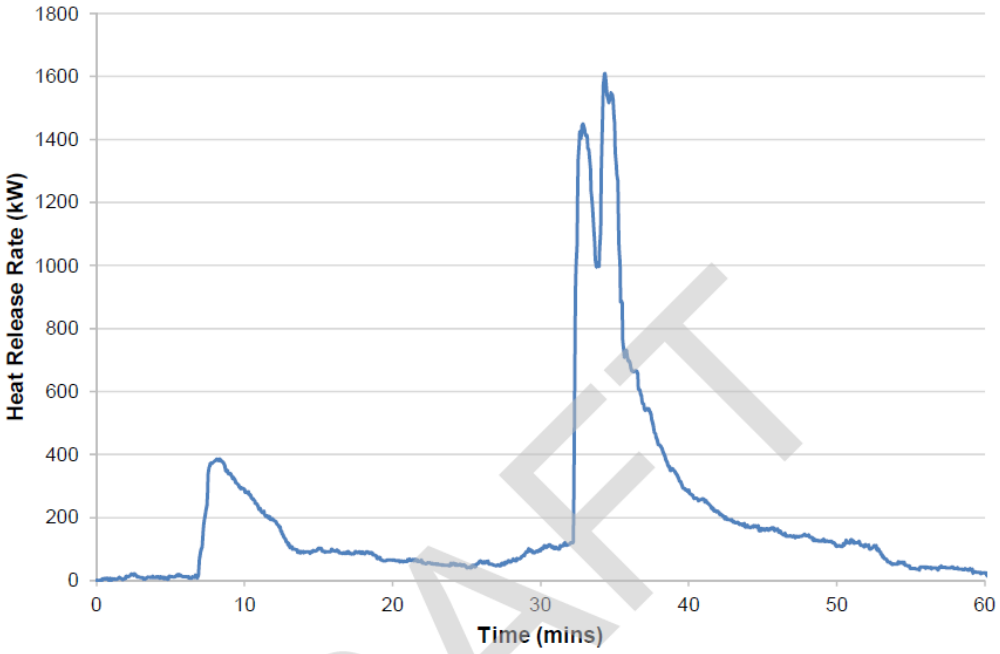


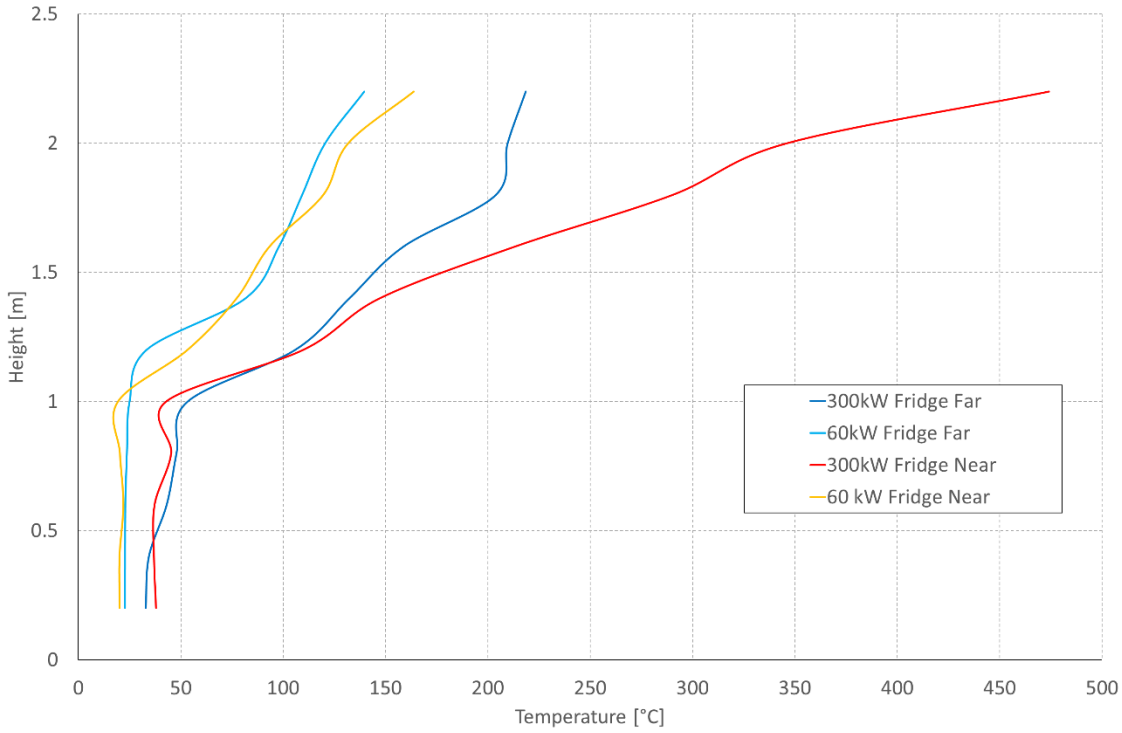
Figure 57 – Heat release rate curve for single free burning fridge freezer

FIGURE 85: HRR VS. TIME CURVE FOR THE STANDALONE FRIDGE BURN CARRIED OUT BY BRE.

Results from CFD models of the fire located on the back of the fridge with Case II ventilation are presented for the range of HRRs estimated in the Section 3.4.2. Figure 86 compares CFD output vertical temperature profiles for 60 and 300kW fires. The results show that temperature magnitudes, both by the window and by the door, fall within the bounds of the 60 and 300kW predictions of the simple model. Furthermore, it shows that the smoke layer interface temperatures are very similar through the compartment but that, as expected, ceiling jet temperatures near to the door are lower than above the seat of the fire near the window.

HRR output from these models, shown in Figure 87, indicates that the models have no issue maintaining the requested energy output and therefore there is sufficient ventilation capacity to support these fire sizes in the window and door configuration of Case II.

DRAFT

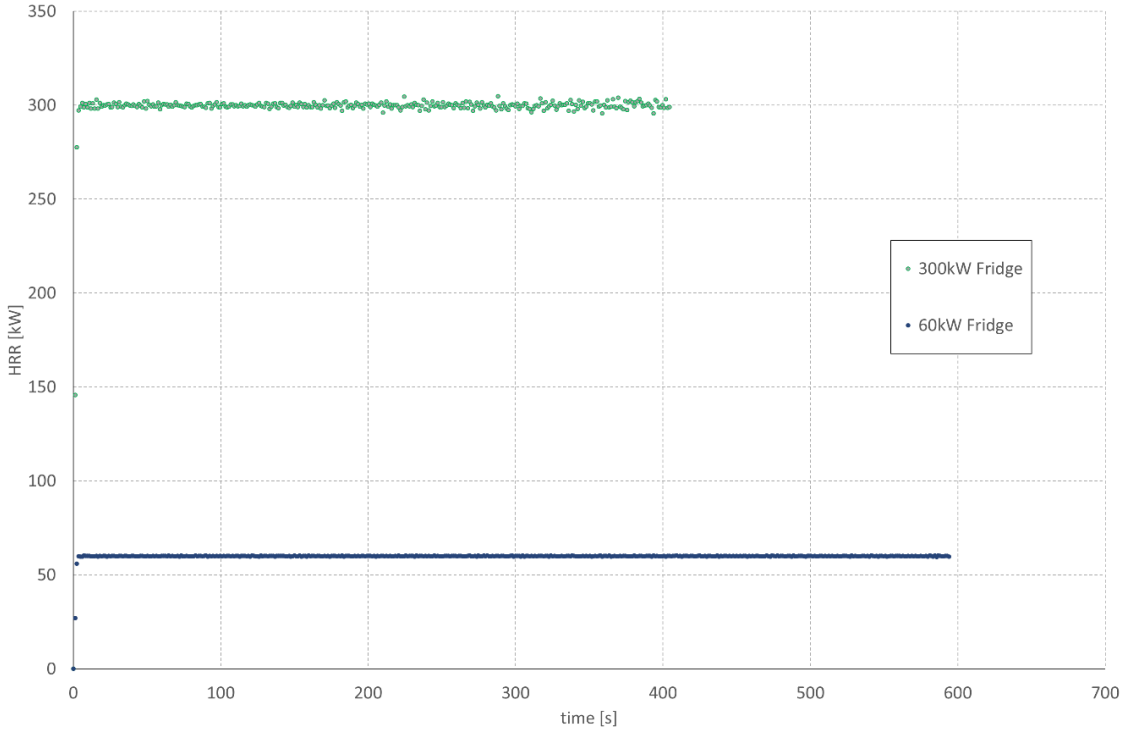


3319

3320 **FIGURE 86: TEMPERATURE PROFILES FOR 60KW AND 300KW FRIDGE FIRE MODELS WITH CASE II OPENINGS.**

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3322



3323

3324 **FIGURE 87: HRR VS TIME PLOTS FOR THE 60KW AND 300KW FRIDGE FIRE CFD SIMULATIONS.**

The HRR in the model is increased to determine the limitation imposed by the ventilation and establish the resulting temperatures. This should serve to confirm the temperatures under ventilation limited conditions. The heat release rate for a fire on the back of the fridge is set at 400kW and 500kW. The plot in Figure 88 shows the actual HRRs that the model achieved. The model manages to maintain the 400kW level, although resulting in a more scattered set of data than that shown for lower HRR (Figure 87). This suggests that this is the limit of the available ventilation. The model does not manage to maintain the 500kW HRR converging on a maximum value around 400kW. This suggests that this value is the limit imposed by the ventilation configuration in Case II. This is consistent with the simple model and with the assessment that under these ventilation conditions flashover will not be attained.

Figure 89 presents vertical temperature profiles for both models. The results seem to confirm that the fire was limited to this range of temperatures and HRR by the ventilation and did not achieve the 1.5MW (approximately) that the standalone fridge test achieved (Figure 85). In terms of temperature profiles, the CFD model profiles show a layer interface at a height of 0.8 - 1.0m in the 400kW model across the compartment. The 500kW model seems to show smoke almost reaching the floor which is consistent with a single layer dynamic which matches the predictions of the simple model.

These results give sufficient confidence however that the model is capable of representing the compartment dynamics of the kitchen while the fire is not limited by ventilation. The results are sufficiently comparable for the purposes of this part of the study therefore further refinement is not undertaken at this time. Case II provides a higher level of ventilation than the original analysis therefore delivers an upper bound to the conditions modelled in the body of the report.

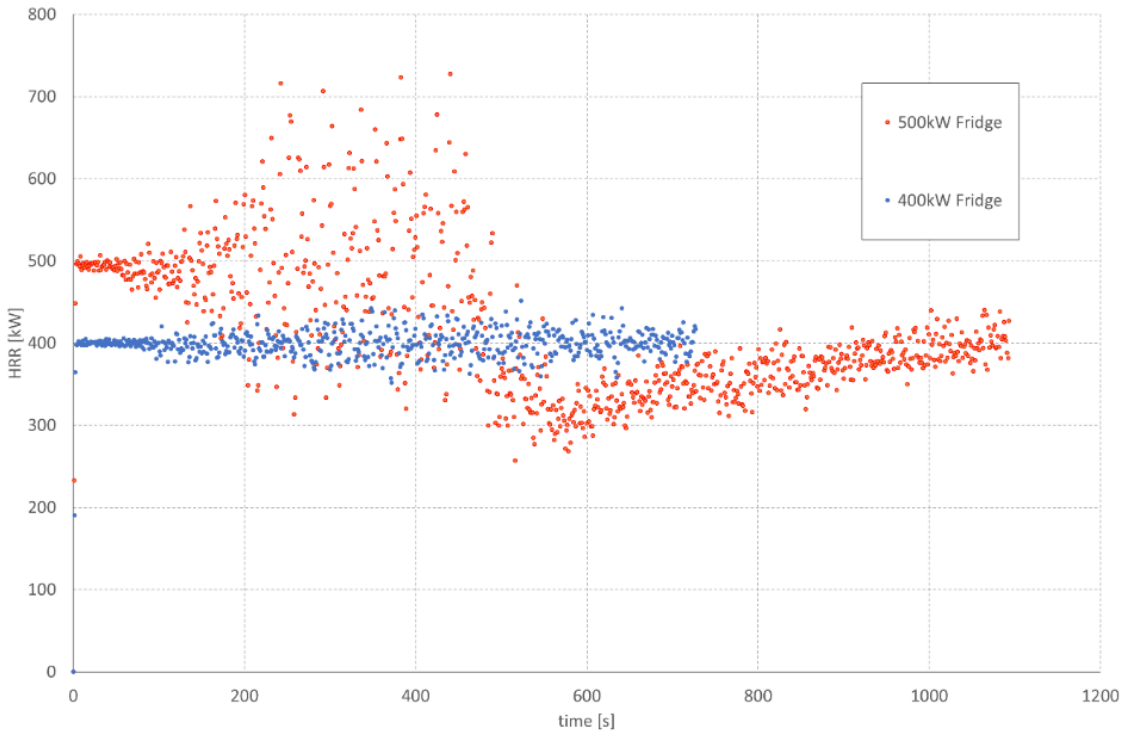


FIGURE 88: ACTUAL HRRS FOR 400KW AND 500KW FRIDGE FIRE MODELS.

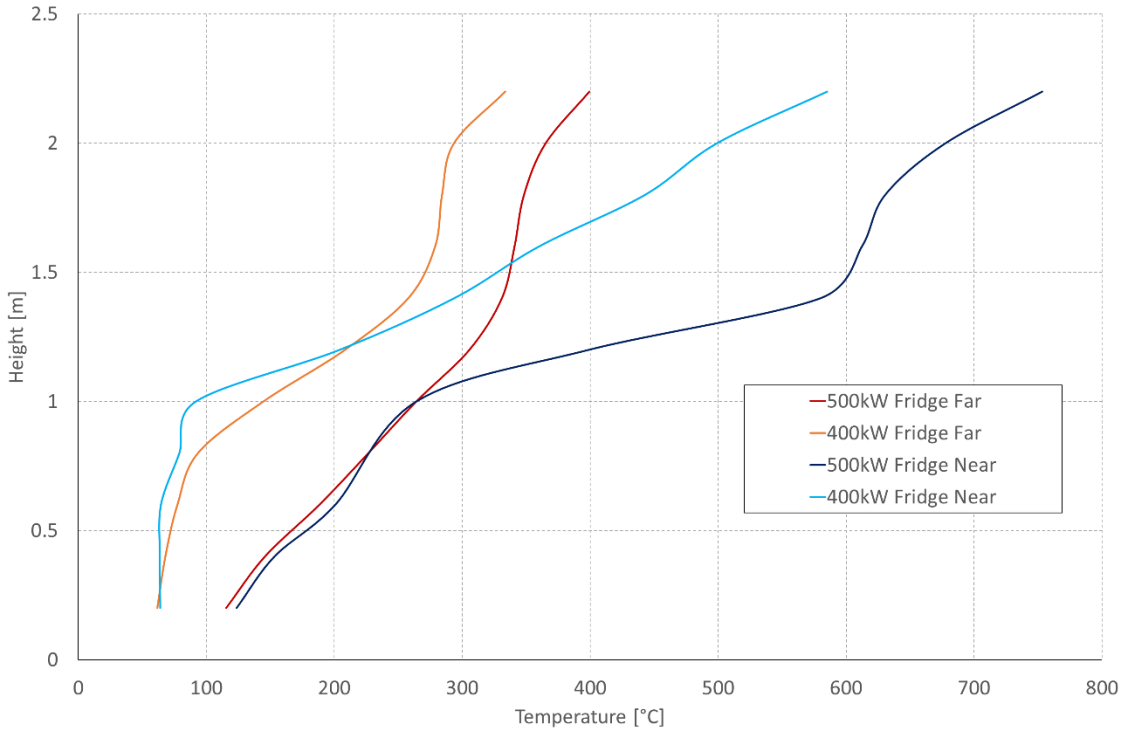


FIGURE 89: TEMPERATURE PROFILES FOR 400KW AND 500KW FRIDGE FIRE MODELS WITH CASE II VENTILATION. LOCATION "FAR" IS BY THE KITCHEN DOOR AND LOCATION "NEAR" IS BY THE KITCHEN WINDOW.

CFD – EMPIRICAL MODEL COMPARISON

CFD modelling is compared to the initial empirical modelling that was presented in the body of the report to provide an indication of its degree of accuracy. In this model, the ventilation available is restricted to the tilted window as this minimal ventilation is what was estimated at the time (Case I). The fire is also located at floor level of the kitchen towards the window end.

The model shows that under these ventilation conditions the fire becomes under-ventilated and cannot sustain 300 kW (Figure 90). These results are consistent with the simple model. The results indicate that the assumed ventilation conditions can only support heat release rates of the magnitude of 300kW for a short period of time until the room fills (see Figure 90). The model indicates that HRR's fall away after approximately 2.5 minutes. This is believed to result from descent of the smoke layer limiting the ventilation available to sustain the fire. More in-depth analysis to investigate the limitations imposed by available ventilation on fire size (HRR) is presented later.

The CFD model shows that the time taken for the hot upper layer to fill the compartment is consistent with that estimated by the simple model. These results, along with those from the CFAST model, are shown in Table 9.

The temperature distributions also indicate that the empirical model gave representative results for the boundary conditions that were assumed. The results for the lower bound (60kW) in particular showed a very good match to the temperature calculated by the empirical model as shown in Figure 91. The upper bound (300kW) empirical model gave a good estimate of the average compartment temperature but only the CFD model can establish the spatial distribution. Therefore, Figure 91 shows that the CFD model delivers a more accentuated temperature gradient over the height of the compartment.

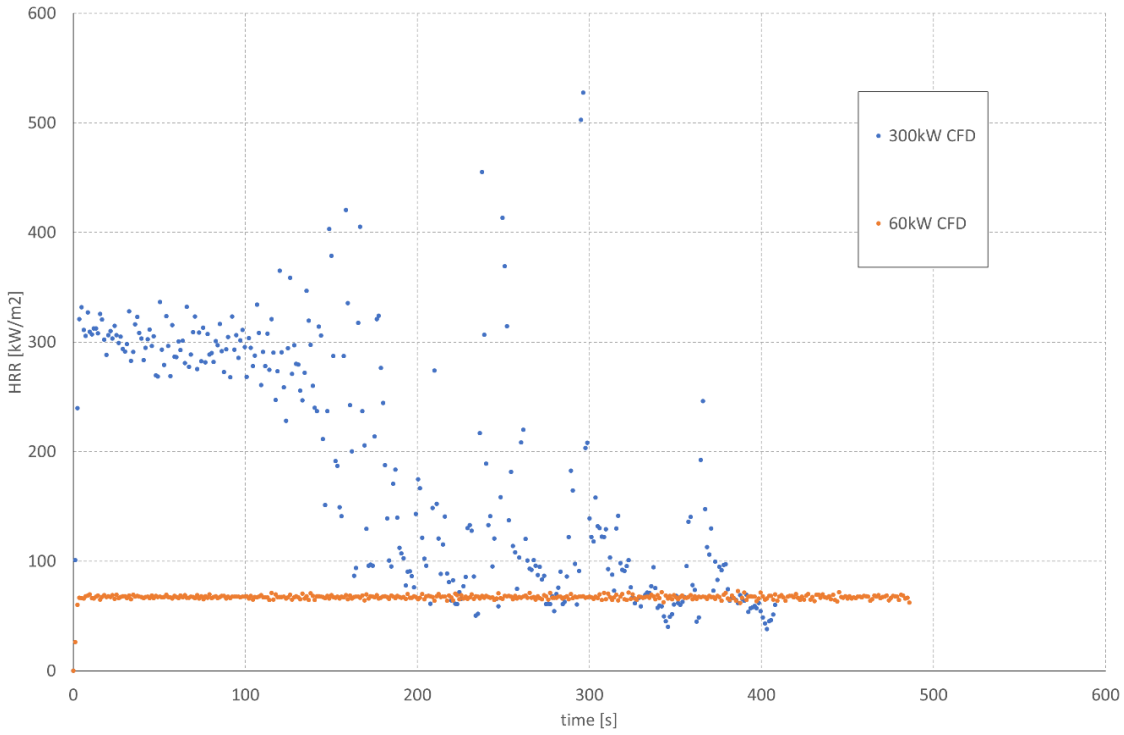


FIGURE 90: HRR VS. TIME DATA FROM THE 60KW AND 300KW FLOOR FIRE CFD MODELS WITH VENTILATION SUPPLIED BY THE TILTED WINDOW.

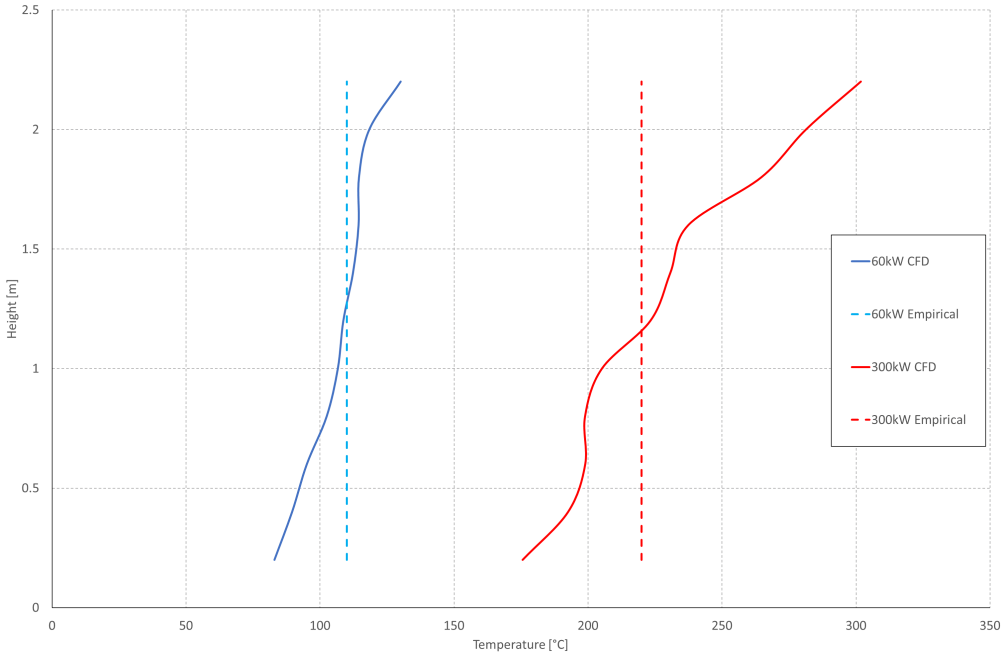


FIGURE 91: COMPARISON OF RESULTS BETWEEN CFD AND EMPIRICAL MODELLING FOR 60KW AND 300KW FLOOR LEVEL FIRE SOURCE WITH MINIMAL VENTILATION.

TABLE 9: RATES FOR SMOKE LAYER TO DESCEND TO KITCHEN FLOOR FOR ALL MODEL TYPES.

Model Type	Fire Size	
	60kW	300kW
CFD	110s	50s
Zone	200s	50s
Empirical	138s	40s

VARIABILITY INTRODUCED BY FIRE LOCATION

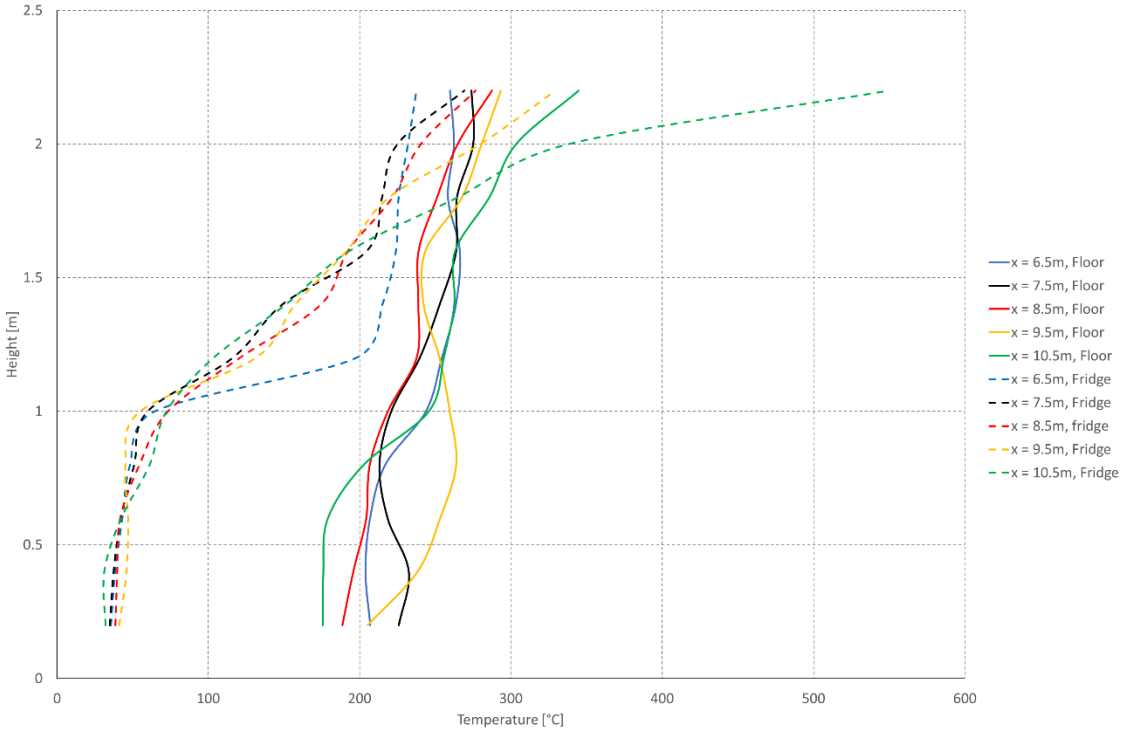
The location and orientation of the fire results in different temperature profiles. Figure 92 shows temperature profiles for a 300kW fire, located both at floor level and on the back of the large fridge-freezer. Ventilation corresponds to Case II.

Magnitudes of peak temperatures do not differ significantly, only the distribution in height. The floor level model results in a more even temperature distribution over the entire room whereas the fridge back fire results in the two-layer profile observed previously.

Figure 93 shows the HRR calculated by the model indicating that both fires release similar HRR but that the fire placed at the floor will produce more scatter of the data. This is a well-known phenomenon associated to

3400 the fluctuating flow created by a pool fire, as opposed to the strong boundary layer flow created by a vertical
3401 fire.

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3405 **FIGURE 92: TEMPERATURE PROFILES FROM THE ENTIRE LENGTH OF THE KITCHEN FOR A 300KW FLOOR LEVEL FIRE AND**
3406 **VENTILATION VIA TILTED LARGE WINDOW AND OPEN SMALL WINDOW. X = 10.5M IS CLOSEST TO THE WINDOW.**

3407

3408 The plots show temperature profiles for both cases along the length of the kitchen with x = 10.5 m being
3409 closest to the window and x = 6.5m being close to the kitchen door. The clustering of these profiles suggests
3410 that there is little variance in depth along the compartment. These relationships are replicated for the smaller
3411 60kW fire as shown in Figure 94.

3412



FIGURE 93: MODEL CALCULATED HRRS FOR A 300KW FIRE LOCATED ON THE BACK OF THE FRIDGE (GREEN DOTS) AND AT FLOOR LEVEL (RED DOTS).

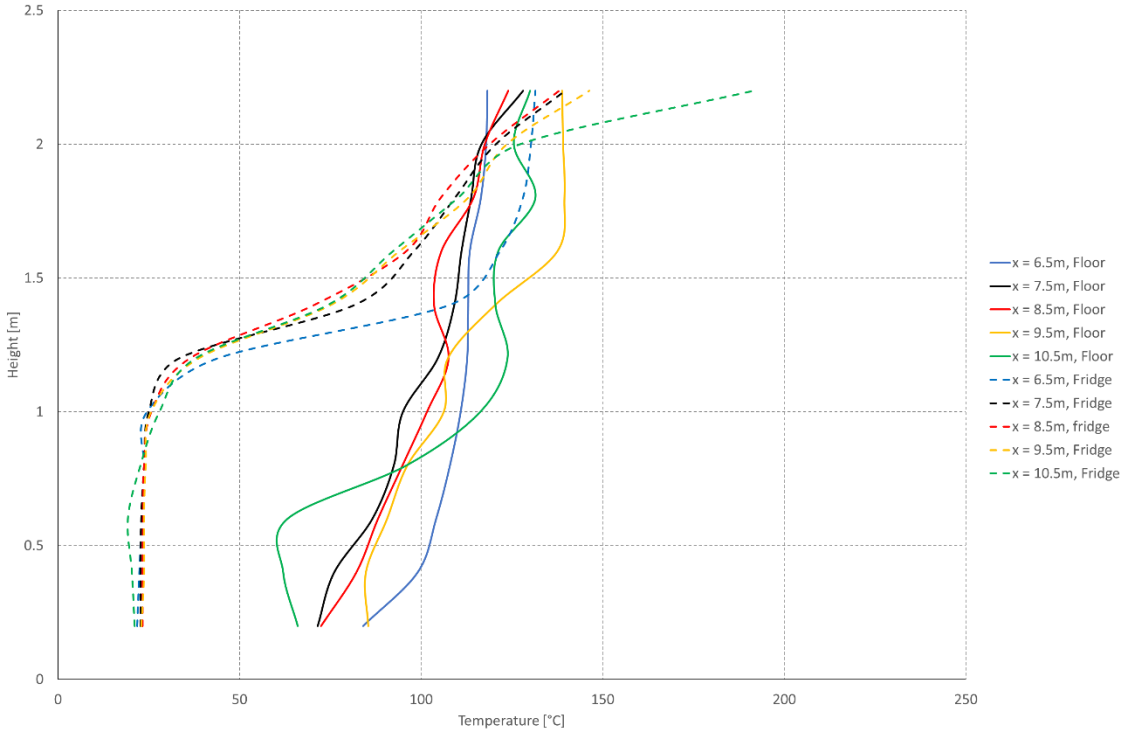


FIGURE 94: TEMPERATURE PROFILES FROM THE ENTIRE LENGTH OF THE KITCHEN FOR A 60KW FLOOR LEVEL FIRE AND VENTILATION VIA TILTED LARGE WINDOW AND OPEN SMALL WINDOW. X = 10.5M IS CLOSEST TO THE WINDOW.

VARIABILITY INTRODUCED BY VENTILATION

A range of models have been run to demonstrate the variability introduced by the assumed ventilation boundary condition. The principal objective of these models is to confirm that the door to the kitchen was closed and that ventilation to the kitchen fire came from the window only.

Results above in Figure 90 indicate that for the initial ventilation assumption for the kitchen of just the large window opened in the tilted position and all other sources closed (Case I), the HRR is limited to approximately 100kW. Larger rates can only be sustained for a small period of time before the compartment fills with smoke products and the combustion becomes limited by available oxygen. This is to be expected for a small compartment like the kitchen for a scenario with limited ventilation so there is reasonable confidence in the validity of the results.

Results presented in Figure 88 indicate that for the large window in the tilted position and small window fully open (Case II), a peak HRR of approximately 400kW can be sustained. This means that a larger fire will result in higher overall compartment temperatures as shown in Figure 89 as there is more air available to support combustion.

Models were run to analyse the difference in thermal profiles created by the opening of the small kitchen window in addition to the tilted kitchen window (Case II) for a small (60kW) fire. The results, shown in Figure 95, indicate that there is little difference between the two, with the lower ventilation resulting in only slightly higher temperatures, attributable the lower heat losses from the compartment.

In order to verify the position of the kitchen door, models were run with a HRR of 1MW. The large window is open in the tilted position and the model is run with the door open and closed (Case III and Case I). Temperature profile results are presented in Figure 96. They show that for an open door, the temperature is of the order of 400-500°C hotter nearer the compartment ceiling than for the door in the closed position. Temperatures in the upper 1m of the compartment are in the range of 500-800°C which would be expected to bring all other fuel sources in the compartment to ignition i.e. cause a flashover event. This is once again consistent with the results of the simple model.

Actual HRR values for the two models are shown in Figure 97. They confirm that the increased ventilation supports more burning and thus higher temperatures for the Case III ventilation model maintaining a 1MW output. The door closed (case I) model quickly consumes the available oxygen and the HRR rapidly falls away to the limits observed preciously for a minimal ventilation scenario. These results, combined with the observation at Grenfell Tower Flat 16 that the kitchen did not experience a flashover event, support the belief that the kitchen door remained closed for the fire event prior to firefighter intervention.

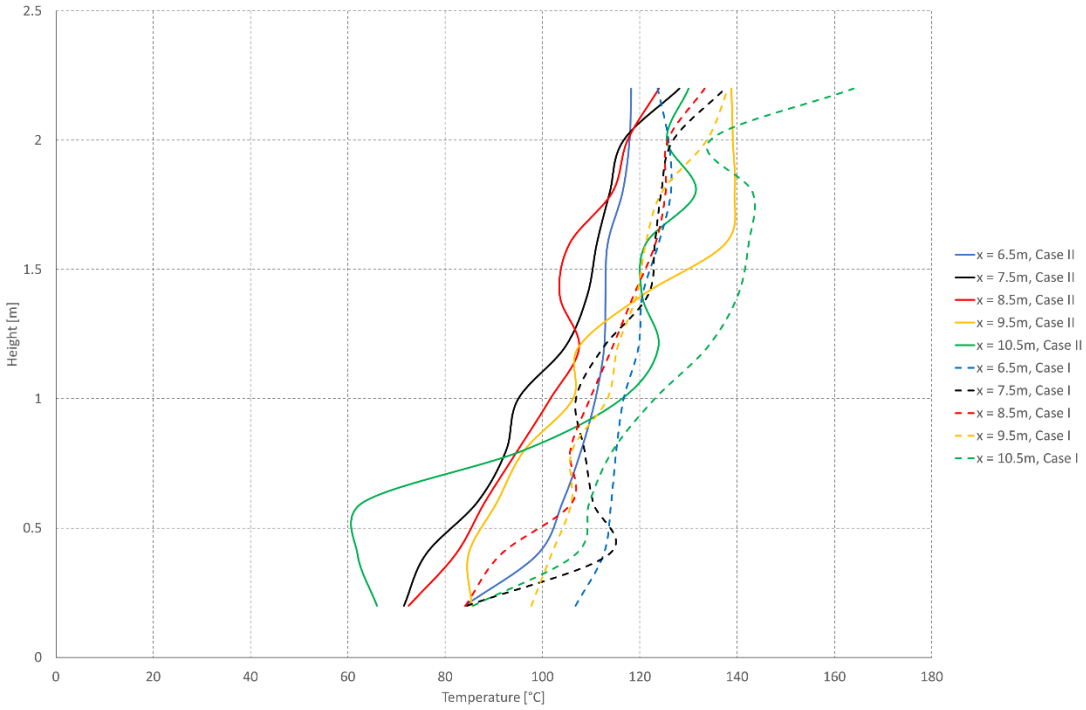


FIGURE 95: VERTICAL TEMPERATURE PROFILES FOR 60KW FIRES. DASHED LINES REPRESENT CASE I VENTILATION. FULL LINES REPRESENT CASE II VENTILATION. LOCATION X = 6.5M IS CLOSET TO THE KITCHEN DOOR, WHILE LOCATION X = 10.5M IS CLOSEST TO THE KITCHEN WINDOW.

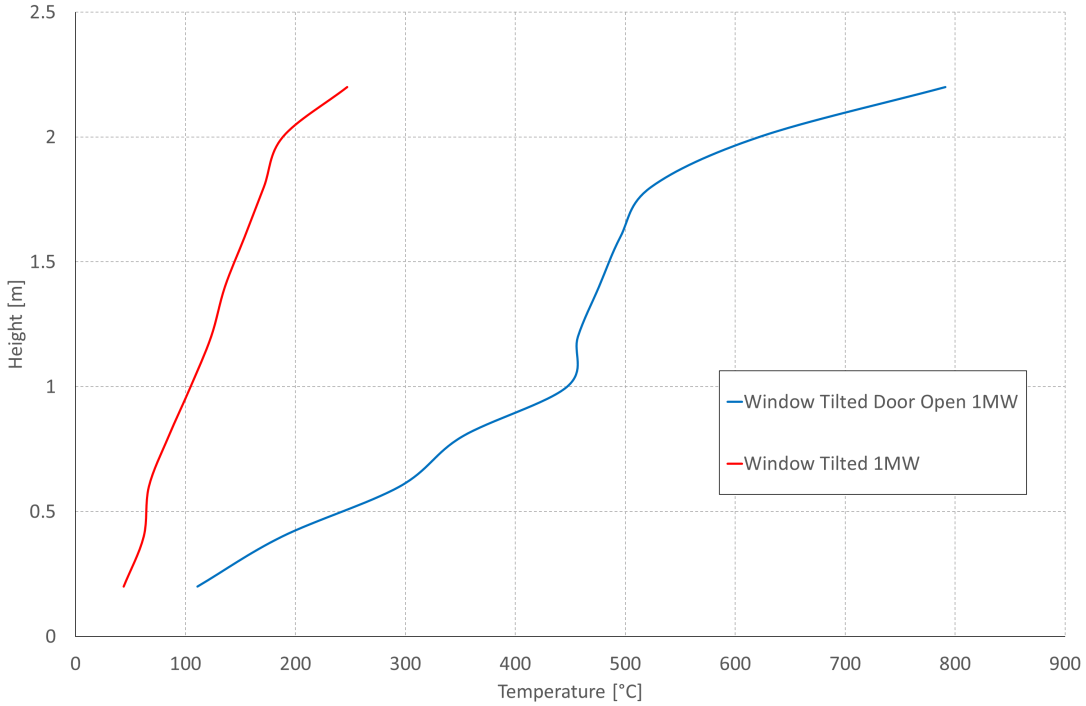
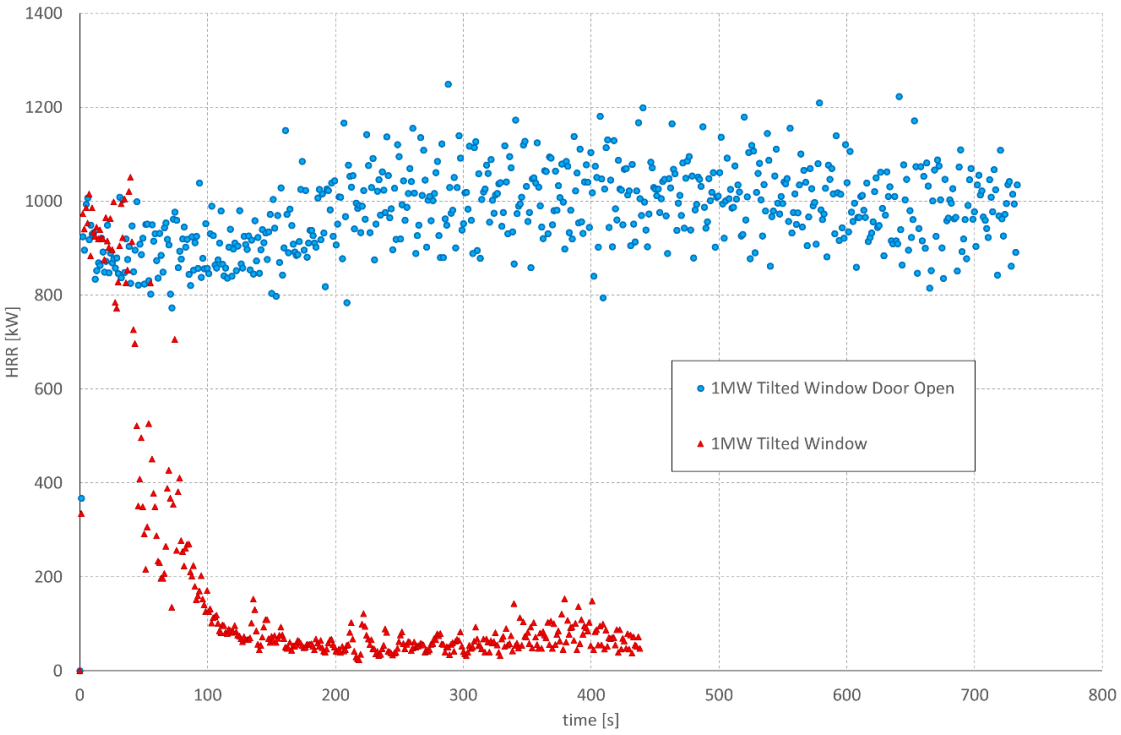


FIGURE 96: TEMPERATURE PROFILES FOR 1MW EQUIVALENT MASS LOSS RATE FOR KITCHEN DOOR OPEN (BLUE) AND CLOSED (RED).



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3462

3463 **FIGURE 97: ACTUAL HRR FOR 1MW EQUIVALENT MASS LOSS RATE FOR TWO VENTILATION CONFIGURATIONS. BLUE MARKERS**
3464 **REPRESENT KITCHEN DOOR IN OPEN POSITION, RED MARKERS REPRESENT THE KITCHEN DOOR IN THE CLOSED POSITION. IN BOTH**
3465 **CASES, THE LARGE WINDOW IS IN THE TILTED POSITION.**

3466

3467

3468 # EXTERNAL SPILL PLUME TEMPERATURES

3469 Temperatures immediately outside the kitchen window, in a location corresponding to directly beneath the
3470 ACP cladding above the window are presented in Table 10. The table presents a range of ventilation setups,
3471 fire locations, and fire size inputs i.e. not necessarily the achieved HRR in the calculation. The table implies
3472 that the smoke temperature only reaches temperatures capable of igniting the ACP cladding for large fire
3473 sizes with ventilation available to support them and thus under conditions where post-flashover fires would
3474 exist. In contrast, for fires as low as 60 kW, smoke temperatures reach vales that can compromise the
3475 mechanical integrity of the uPVC. As established by the simple model in the body of the report, for smaller
3476 fires, ignition can only be achieved with impinging flames but the smoke can compromise the mechanical
3477 integrity of the uPVC.

3478

3479

3480 **TABLE 10: SPILL PLUME TEMPERATURES IMMEDIATELY OUTSIDE AND ABOVE THE WINDOW FOR A RANGE OF VENTILATION**
3481 **CONDITIONS, FIRE LOCATIONS AND INPUT HEAT RELEASE RATES.**

3482

Ventilation	Fire Location	Input Fire Size (Achieved Fire Size) [kW]	Characteristic Outflow Temperature [°C]
Big Window Tilted	Floor	60 (60)	95
Big Window Tilted, Little Window Open	Floor	60 (60)	120
Big Window Tilted, Little Window Open	Fridge	60 (60)	140
Big Window Tilted, Door Open	Floor	60 (60)	95
Big Window Tilted	Floor	300 (70)	120
Big Window Tilted, Little Window Open	Floor	300 (300)	310
Big Window Tilted, Little Window Open	Fridge	300 (300)	300
Big Window Tilted, Door Open	Floor	300 (300)	220
Big Window Tilted, Little Window Open	Floor	500 (400)	450
Big Window Tilted, Door Open	Floor	1000 (1000)	450

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3485 SUMMARY

3486 Extensive modelling using simple tools, CFAST and FDS show consistent results that confirm the information
3487 and conclusions provided in the body of this report. The detail and precision of the available evidence is only
3488 consistent with the simple model, thus only these results are presented in the body of the report. The more
3489 complex models (CFAST, FDS) presented in this appendix only serve to provide confidence to these results.

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APPENDIX C. ESTIMATION OF FIRE BASE AREA

From the perspective of design, fires growth rates (α values) are grouped into categories according to how quickly a fire is expected to grow in a particular occupancy, based on the typical materials found in that occupancy. For example, a fire in an occupancy with strict controls on flammable materials would be expected to experience a slow fire growth rate.

These values are essentially representative of material properties, as will be demonstrated subsequently. The slow fire represents materials that would typically propagate fire slowly, and vice-versa for ultrafast.

Given the unknowns associated to the exact fire origin in the case of Grenfell Tower, it is difficult to isolate a representative alpha, hence the inability to bound the value of alpha used in the previous section of this analysis more precisely than the two extremes used.

As stated above, alpha, α (kW/s^2), is representative of the typical materials expected to be present in the occupancy under consideration, and thus can be broken down into a number of parameters that are time independent, material properties. α is related to the HRR, $\dot{Q}$ (kW), according to the following relationship:

$$\dot{Q} = \alpha t^2 = \dot{m}_f \Delta H_c$$

EQUATION 13

Where t (s) is the time from the ignition of the fire, $\dot{m}_f$ (kg/s), is the mass loss rate of the burning fuel i.e. it's rate of decomposition from solid to gaseous fuel, and ΔH_c (J/kg), is the heat of combustion of the fuel i.e. the energy produced by burning each kg of fuel that is gasified.

The mass loss rate can be made time independent by a simple augmentation of the equation where multiplying by the area of the fire, A (m^2) at any time t, it can be replaced as a characteristic mass loss rate per unit area, $\dot{m}_f''$ (kg/s.m^2), as follows:

$$\dot{m}_f \Delta H_c = A \dot{m}_f'' \Delta H_c$$

EQUATION 14

The αt^2 correlation represents a radially growing fire, therefore the area, A, at any point is a circle, and thus can be expressed as:

$$A = \pi r^2$$

EQUATION 15

Where r (m) is the radius of the circle and in real terms, the distance travelled by the fire in any direction from the point of origin at any time t (s). This enables the expression of the characteristic lateral spread rate of the fire, V_s (m/s) as:

$$V_s = \frac{r}{t}$$

EQUATION 16

Rearranging as:

$$r^2 = V_s^2 t^2$$

EQUATION 17

And substituting **EQUATION 17** into **EQUATION 15**, and the result into **EQUATION 14**, the result is as follows:

$$\alpha t^2 = \left(\pi V_s^2 \dot{m}_f^{"} \Delta H_c\right) t^2$$

EQUATION 18

Thus α is expressed as a function of a mathematical constant and time independent, characteristic material properties.

According to the report by Prof. Bisby [5], most of the combustible elements in the area of the kitchen identified are polymers, therefore characteristic polymer values are assumed and taken from Drysdale [45] as:

- $\dot{m}_f^{"}$ = 0.01 - 0.014 kg/s.m^2
- ΔH_c = 40 - 46 MJ/kg

Other bounding values are:

- α = 0.0029 – 0.1876 kW/s^2
- t_{growth} = 40 s (ultrafast) and 138 s (slow)
- π = 3.14

Using these parameters, it is possible to establish a range of values for the spread rate of the fire, V_s (m/s) as:

$$V_s = \left(\frac{\alpha}{\pi \dot{m}_f^{"} \Delta H_c}\right)^{\frac{1}{2}}$$

EQUATION 19

And thus the area of the fire as:

$$A = \pi\left(V_s t_{growth}\right)^2$$

EQUATION 20

The heat release rate, $\dot{Q}$ (kW), can then be verified against the earlier results using **EQUATION 14**. The results of this stage of the analysis are presented in Table 11 below.

α [kW/m^2]	$\dot{m}_f^{"}$ [kg/s.m^2]	ΔH_c [MJ/kg]	V_s [mm/s]	A [m^2]	r [m]	$\dot{Q}$ [kW]
0.0029 (S)	0.01	40	1.5	0.14	0.2	55
0.0029 (S)	0.014	46	1.2	0.085	0.17	55
0.1876 (UF)	0.01	40	12.2	0.75	0.5	300
0.1876 (UF)	0.014	46	9.5	0.46	0.4	300

TABLE 11: RESULTS OF THE ASSESSMENT TO BOUND THE FIRE AREA BY MEANS OF CHARACTERISTIC MATERIAL PROPERTIES.

APPENDIX D. ESTIMATION OF THE uPVC TEMPERATURE

A simple heat storage analysis is conducted to approximate the change in temperature of the uPVC as a result of exposure to the hot-layer gases, and thus establish if any thermal degradation of the material is possible within the timeframe provided by the evidence in section 0. The analysis equates the energy stored in the uPVC (E_{STO}, J) to the energy provided by the fire environment (E_{IN}, J) as:

$$E_{IN} = E_{STO}$$

EQUATION 21

The calculation is deliberately kept to a crude approximation, thus no losses have been assumed, as the intention is simply to provide a bounding heating time. Each term can be expanded as:

$$h_T(T_g - T_s)A = \rho . c_p . V . \frac{\Delta T_s}{\Delta t}$$

EQUATION 22

Where h_T is the total heat transfer coefficient (25 W/m^2.K), T_g is the gas phase (hot layer) temperature (K), T_s is the solid (uPVC) temperature (K), A is the exposed surface area (m^2), ρ is the density of the solid (1390 kg/m2), c_p is the specific heat capacity of the solid (1170 J/kg.K), V is the volume of the solid (m^3), and ΔT_s is the change in temperature of the solid, and Δt is the time-step (s). This expression can be rearranged in terms of ΔT_s as:

$$\Delta T_s = \frac{h_T(T_g - T_s)\Delta t}{\rho . c_p . \delta}$$

EQUATION 23

Where δ is the thickness of the uPVC (9.5mm) derived from the ratio of volume (V) and surface area (A).

APPENDIX E. STEP BY STEP LATERAL FLAME SPREAD

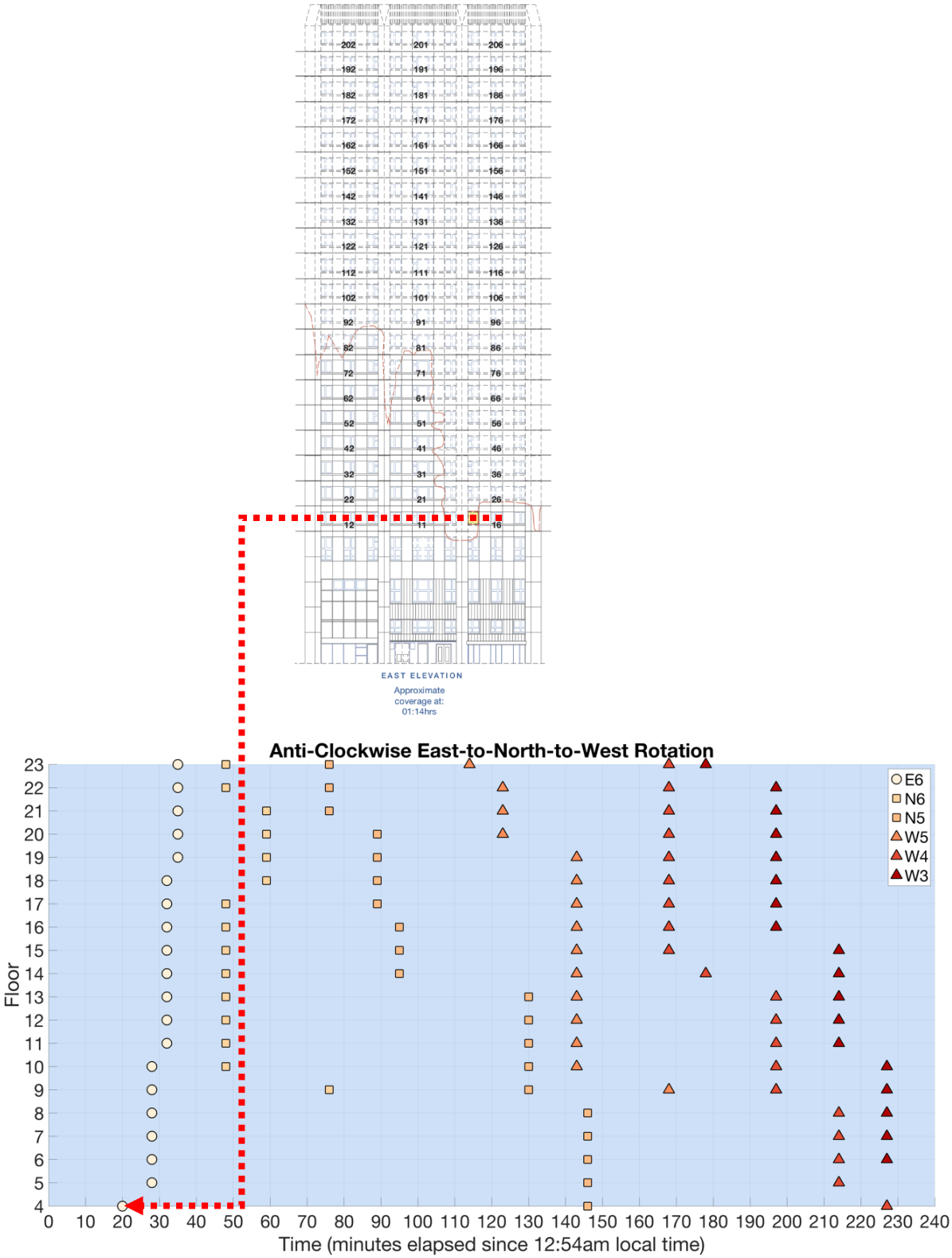


FIGURE 98: TIME HISTORY OF EXTERNAL FLAME SPREAD ON THE EASTERN (E), NORTHERN (N) AND WESTERN (W) FACADES. THE STACK OF FLATS IMPACTED BY THE EXTERNAL FLAME SPREAD ARE INDICATED USING NUMBERS 1-6 APPENDED TO THE FACADE DESCRIPTOR IN THE LEGEND. THE RED ARROW INDICATES THE ESTIMATED POSITION OF EXTERNAL FLAMES AT 01:14 AM ON THE EAST ELEVATION TOWER PLAN VIEW.

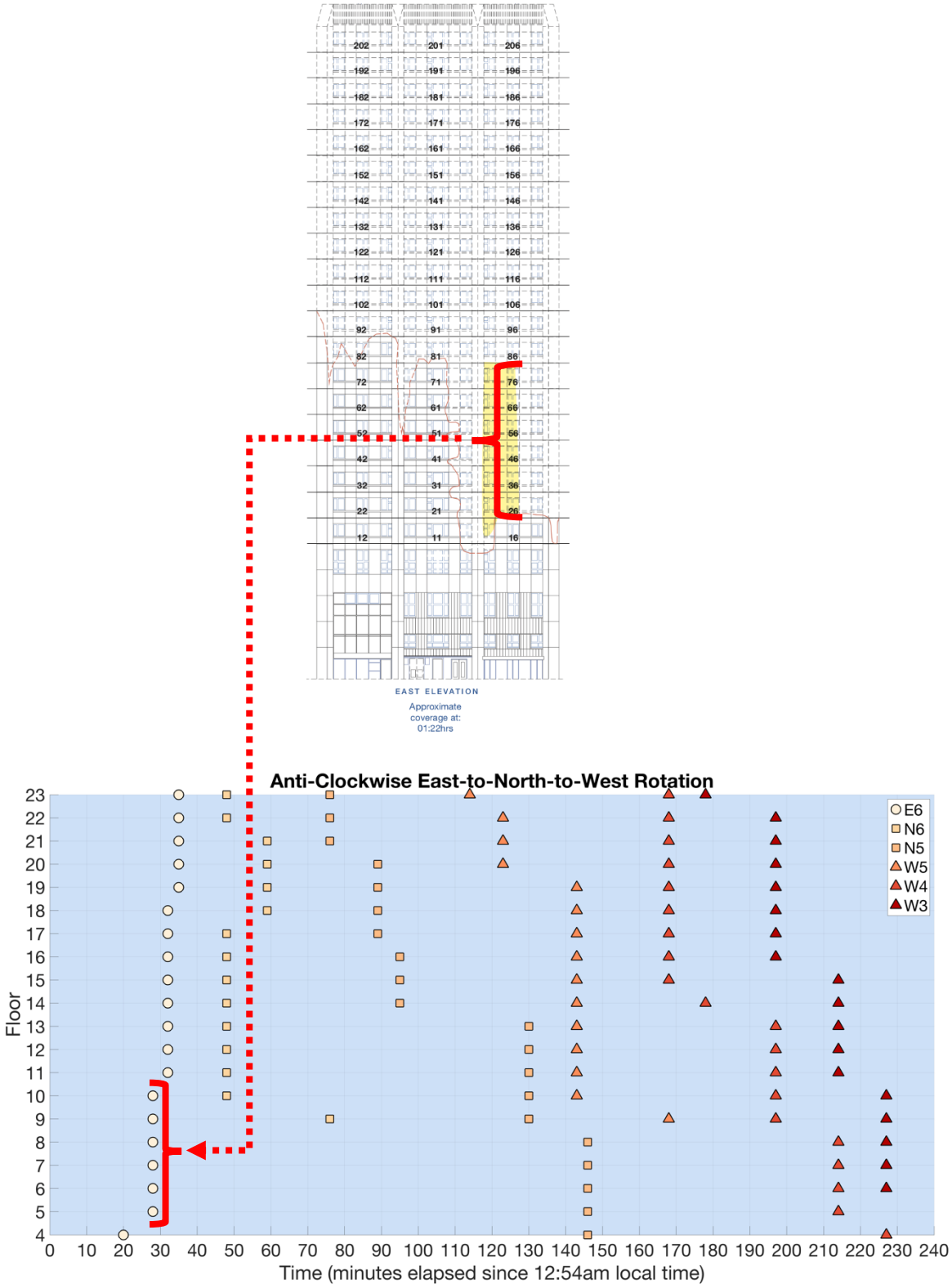


FIGURE 99: TIME HISTORY OF EXTERNAL FLAME SPREAD ON THE EASTERN (E), NORTHERN (N) AND WESTERN (W) FACADES. THE STACK OF FLATS IMPACTED BY THE EXTERNAL FLAME SPREAD ARE INDICATED USING NUMBERS 1-6 APPENDED TO THE FACADE DESCRIPTOR IN THE LEGEND. THE RED ARROW INDICATES THE ESTIMATED POSITION OF EXTERNAL FLAMES AT 01:22 AM ON THE EAST ELEVATION TOWER PLAN VIEW.

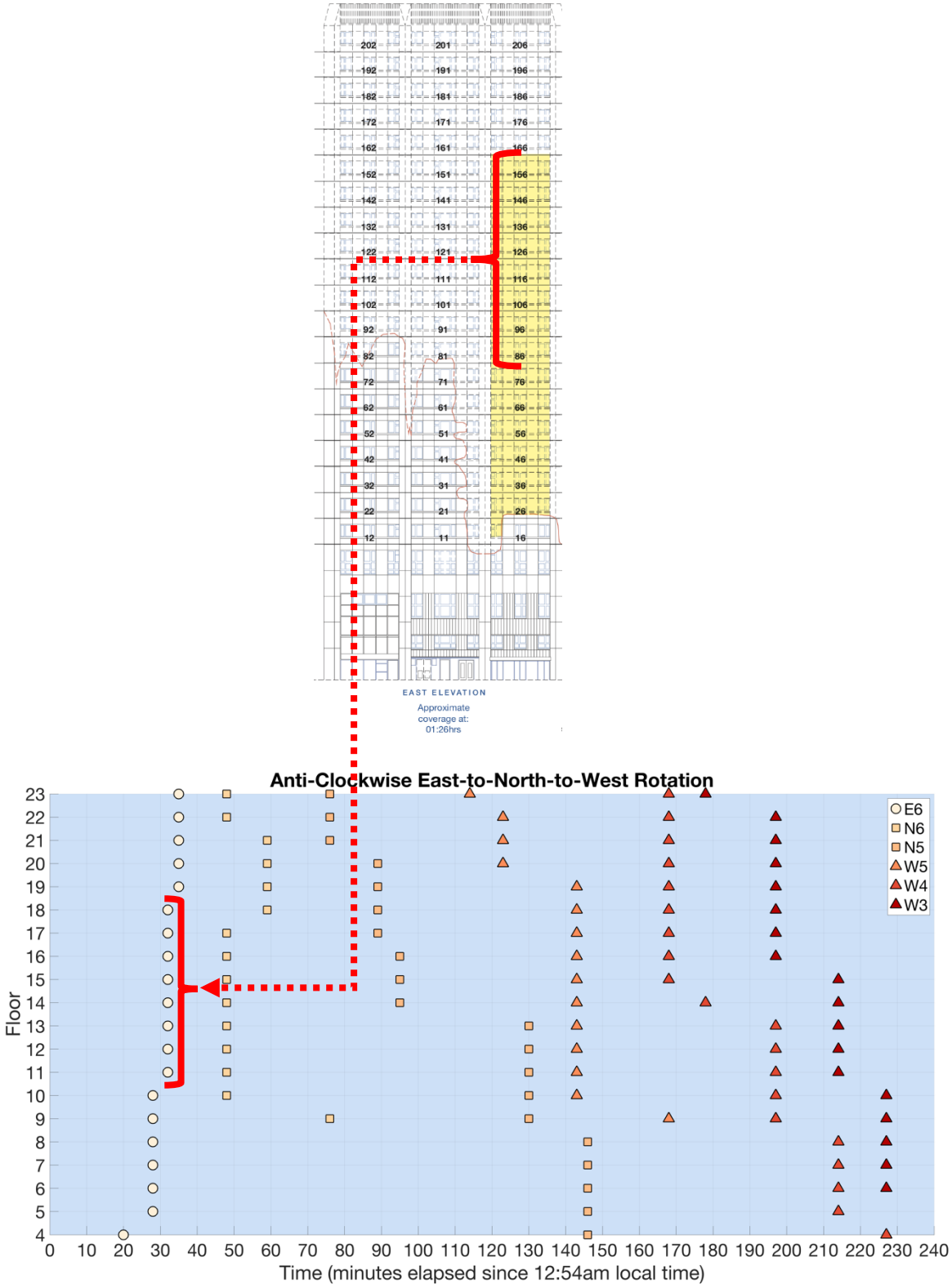


FIGURE 100: TIME HISTORY OF EXTERNAL FLAME SPREAD ON THE EASTERN (E), NORTHERN (N) AND WESTERN (W) FACADES. THE STACK OF FLATS IMPACTED BY THE EXTERNAL FLAME SPREAD ARE INDICATED USING NUMBERS 1-6 APPENDED TO THE FACADE DESCRIPTOR IN THE LEGEND. THE RED ARROW INDICATES THE ESTIMATED POSITION OF EXTERNAL FLAMES AT 01:26 AM ON THE EAST ELEVATION TOWER PLAN VIEW.

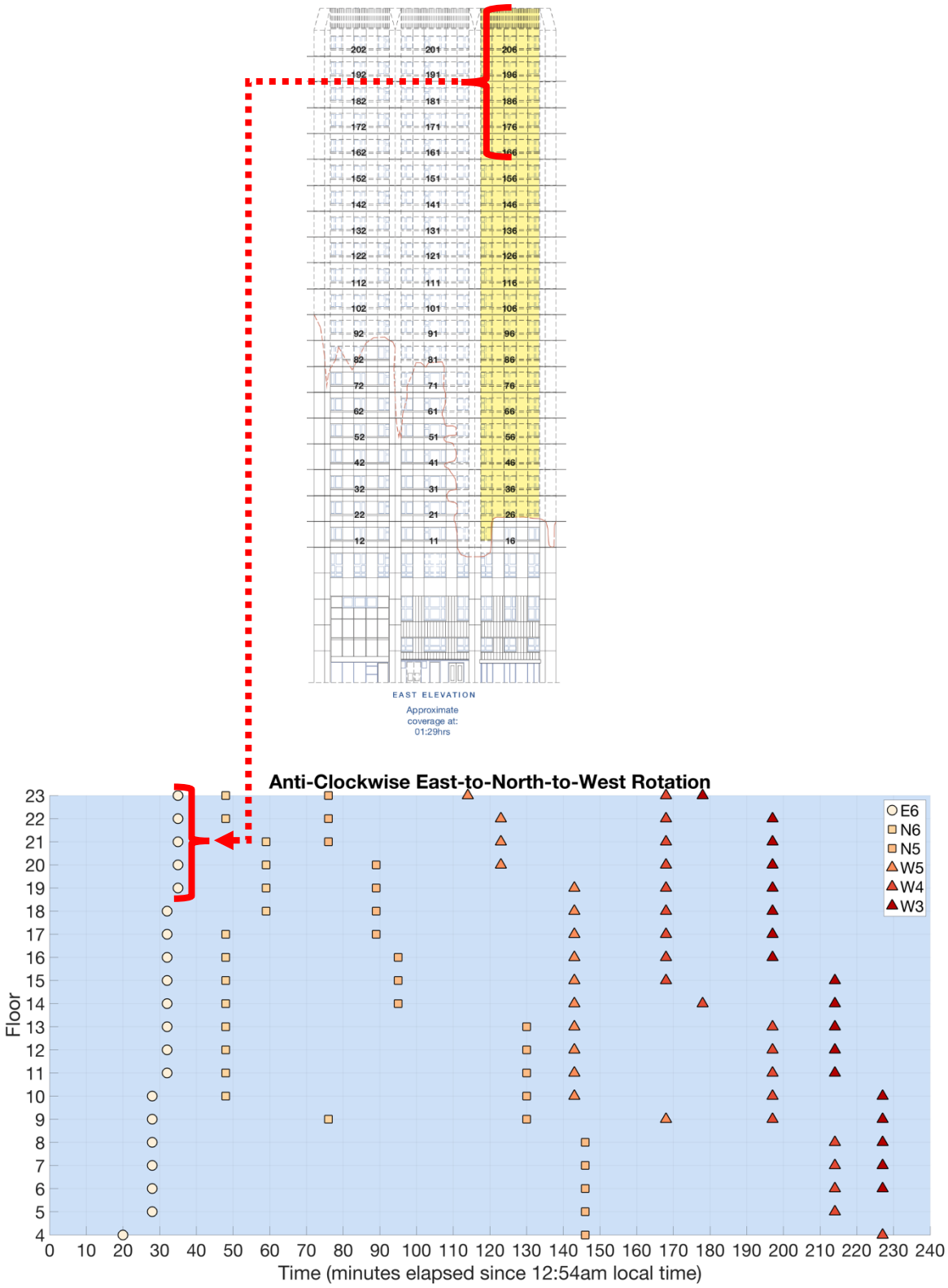


FIGURE 101: TIME HISTORY OF EXTERNAL FLAME SPREAD ON THE EASTERN (E), NORTHERN (N) AND WESTERN (W) FACADES. THE STACK OF FLATS IMPACTED BY THE EXTERNAL FLAME SPREAD ARE INDICATED USING NUMBERS 1-6 APPENDED TO THE FACADE DESCRIPTOR IN THE LEGEND. THE RED ARROW INDICATES THE ESTIMATED POSITION OF EXTERNAL FLAMES AT 01:29 AM ON THE EAST ELEVATION TOWER PLAN VIEW.

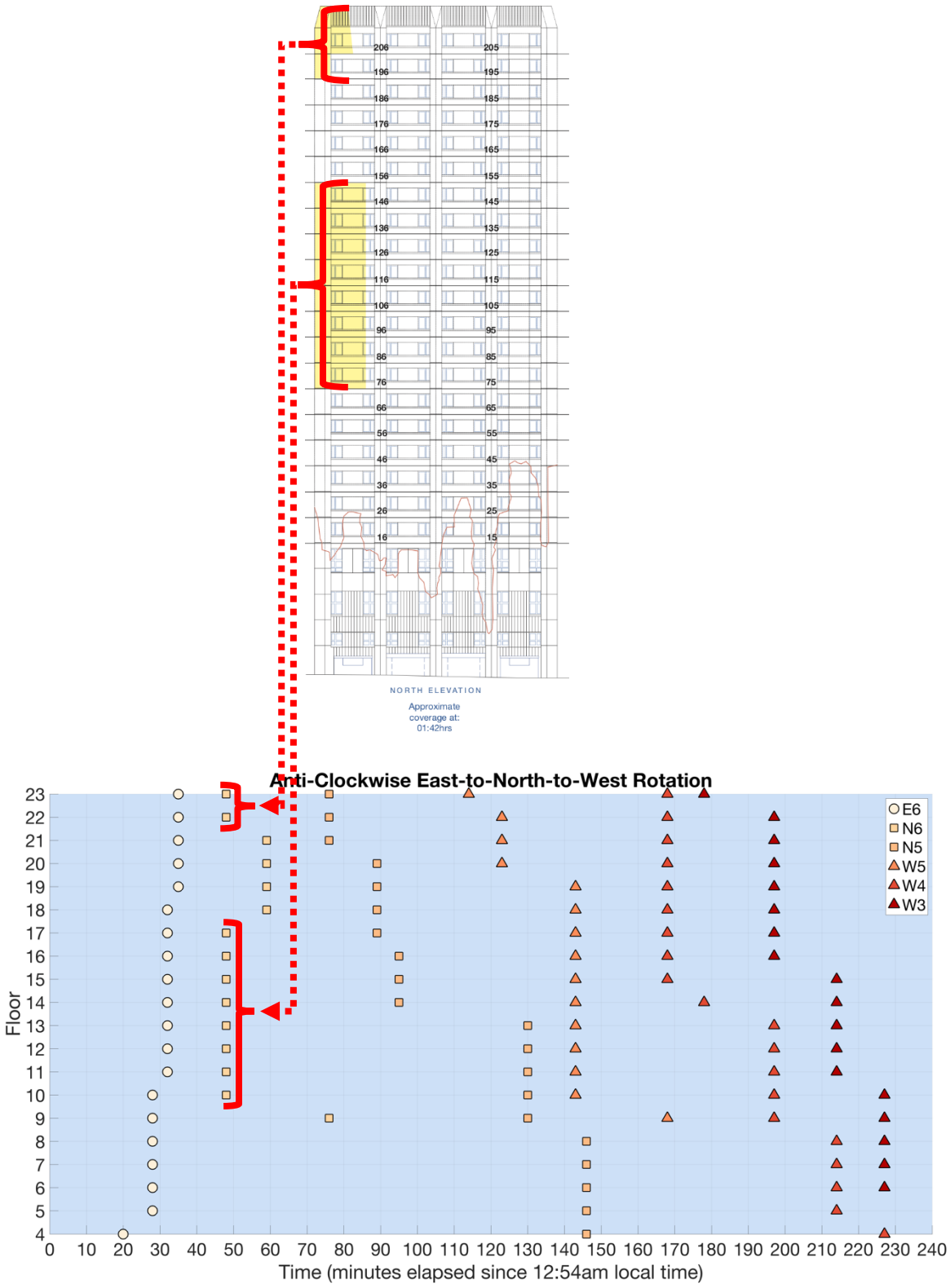


FIGURE 102: TIME HISTORY OF EXTERNAL FLAME SPREAD ON THE EASTERN (E), NORTHERN (N) AND WESTERN (W) FACADES. THE STACK OF FLATS IMPACTED BY THE EXTERNAL FLAME SPREAD ARE INDICATED USING NUMBERS 1-6 APPENDED TO THE FACADE DESCRIPTOR IN THE LEGEND. THE RED ARROWS INDICATE THE ESTIMATED POSITION OF EXTERNAL FLAMES AT 01:42 AM ON THE NORTH ELEVATION TOWER PLAN VIEW.

(a)  (b) 

(c)  (d) 

(e)  (f) 

(g)  (h) 

FIGURE 103: ORIGINAL PUBLIC FOOTAGE OF LATERAL AND VERTICAL (DOWNWARD) FLAME SPREAD ON THE NORTH FACADE OF GRENFELL TOWER AT (A) 01:42 AM; (B) 01:53 AM; (C) 02:23 AM; (D) 02:32 AM; (E) 02:49 AM; (F) 02:55 AM; (G) 03:04 AM; AND (H) 03:07 AM RESPECTIVELY. PHOTOS WERE SOURCED FROM MET00008024, PAGE 36.

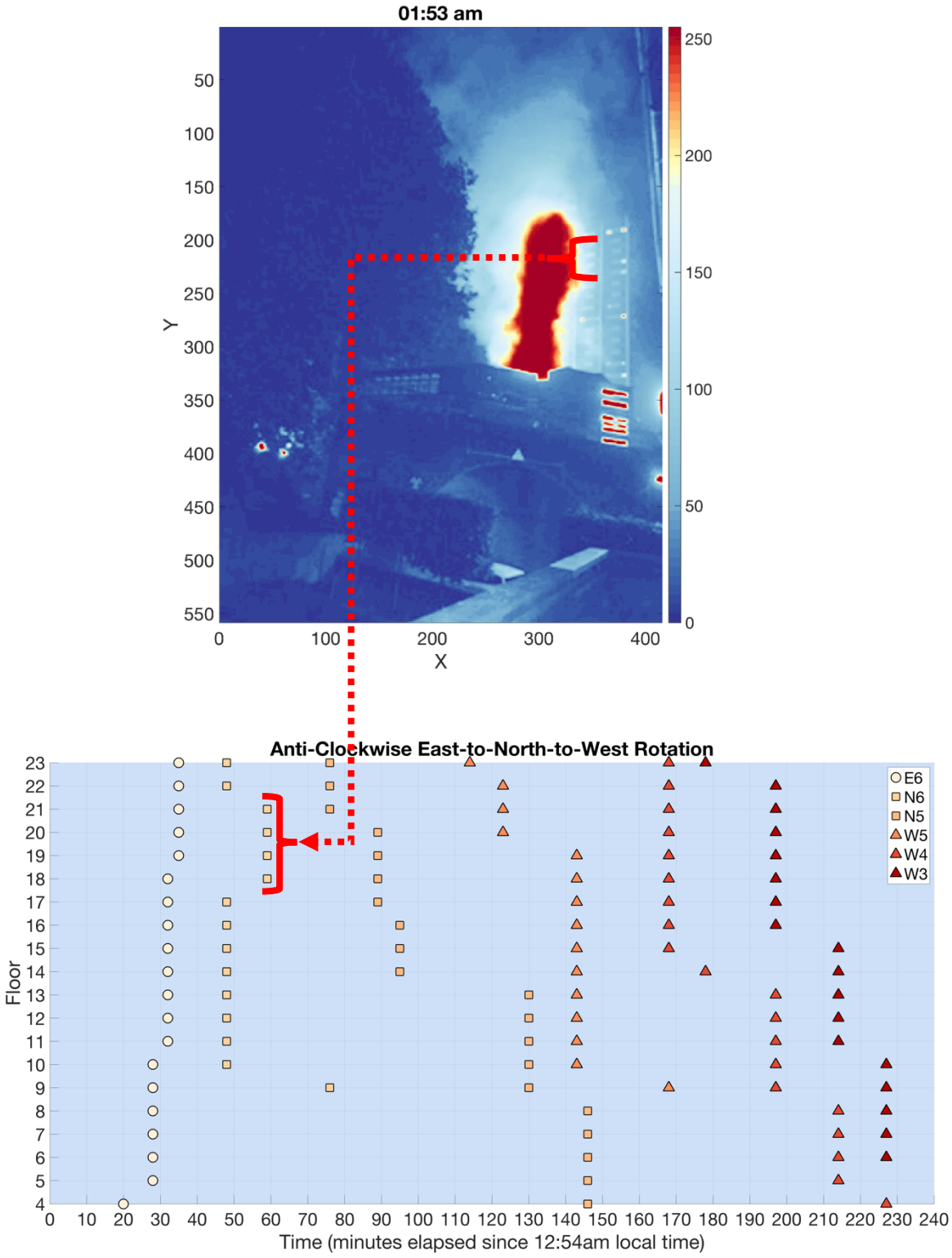


FIGURE 104: TIME HISTORY OF EXTERNAL FLAME SPREAD ON THE EASTERN (E), NORTHERN (N) AND WESTERN (W) FACADES. THE STACK OF FLATS IMPACTED BY THE EXTERNAL FLAME SPREAD ARE INDICATED USING NUMBERS 1-6 APPENDED TO THE FACADE DESCRIPTOR IN THE LEGEND. THE RED ARROW INDICATES THE ESTIMATED POSITION OF EXTERNAL FLAMES AT 01:53 AM ON THE NORTH ELEVATION PROCESSED IMAGE (FIGURE 5B).

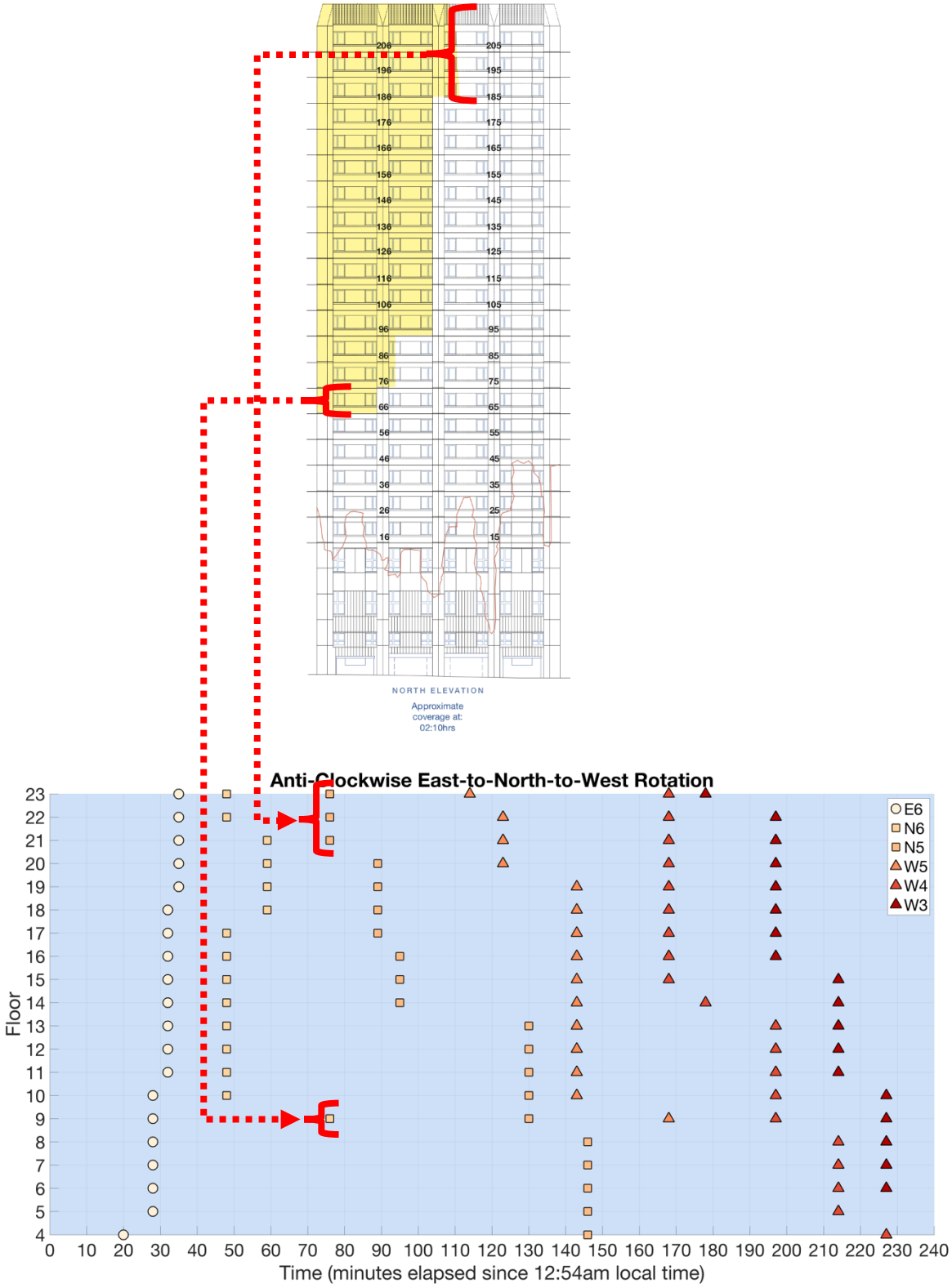


FIGURE 105: TIME HISTORY OF EXTERNAL FLAME SPREAD ON THE EASTERN (E), NORTHERN (N) AND WESTERN (W) FACADES. THE STACK OF FLATS IMPACTED BY THE EXTERNAL FLAME SPREAD ARE INDICATED USING NUMBERS 1-6 APPENDED TO THE FACADE DESCRIPTOR IN THE LEGEND. THE RED ARROWS INDICATE THE ESTIMATED POSITION OF EXTERNAL FLAMES AT 02:10 AM ON THE NORTH ELEVATION TOWER PLAN VIEW.

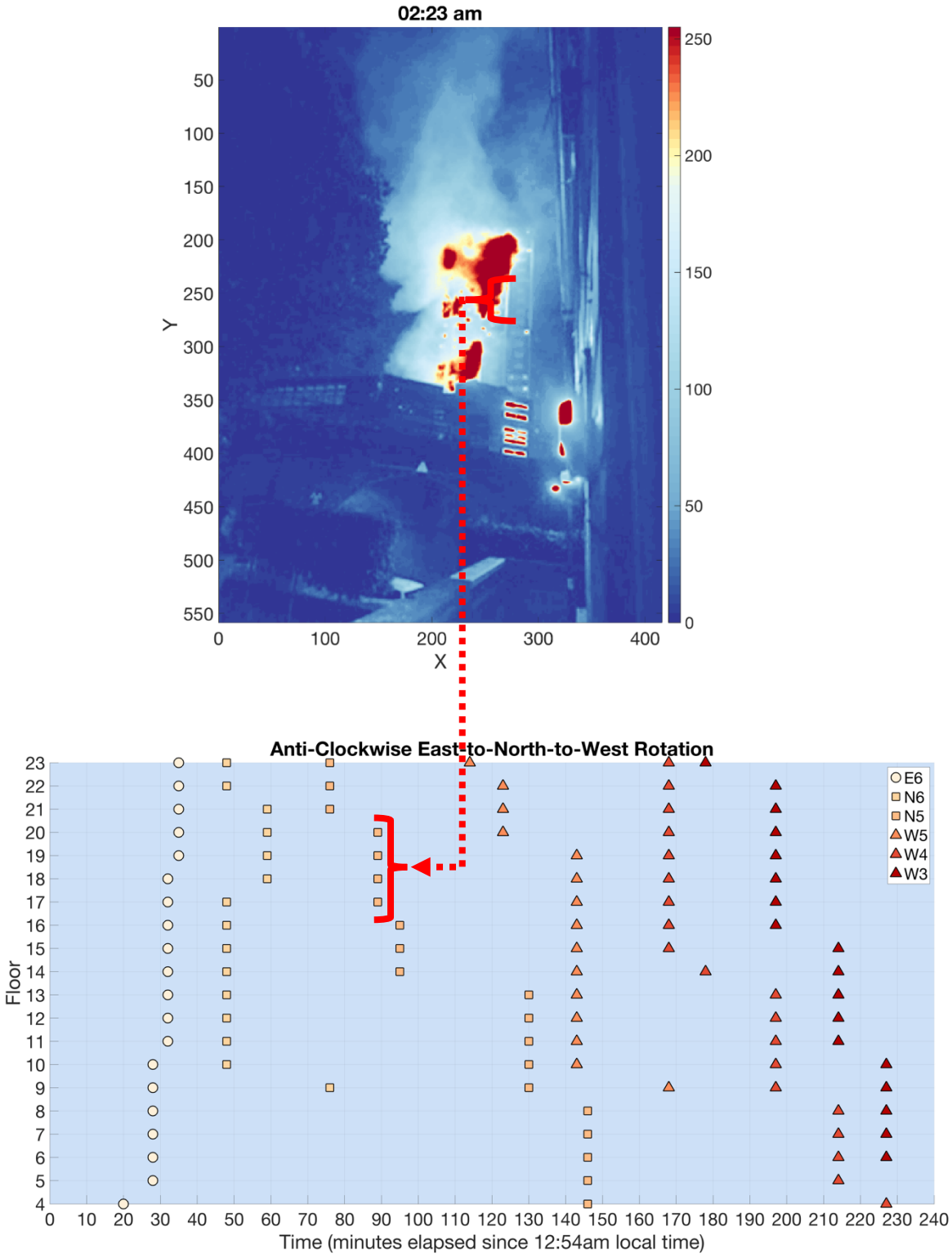
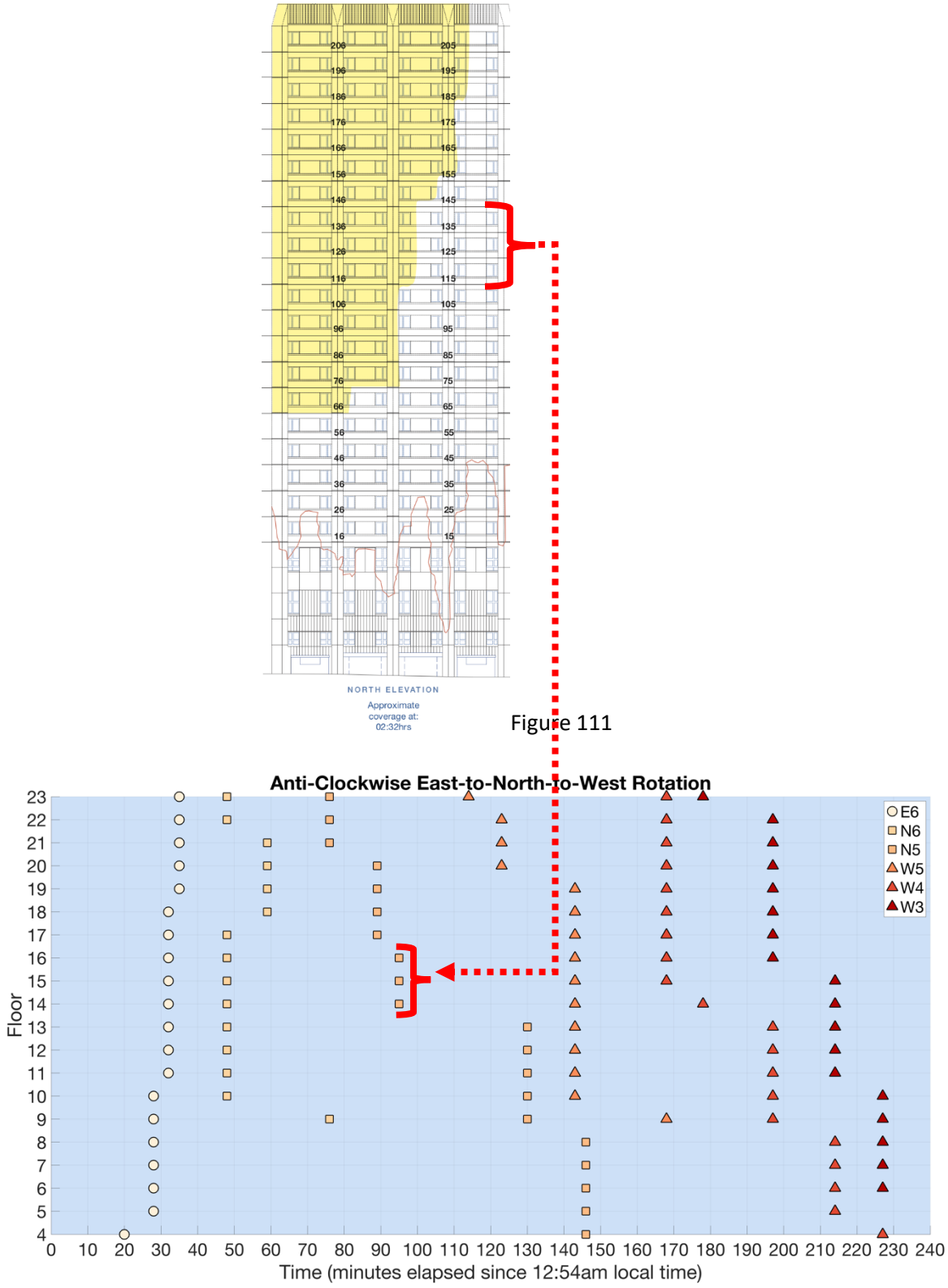


FIGURE 106: TIME HISTORY OF EXTERNAL FLAME SPREAD ON THE EASTERN (E), NORTHERN (N) AND WESTERN (W) FACADES. THE STACK OF FLATS IMPACTED BY THE EXTERNAL FLAME SPREAD ARE INDICATED USING NUMBERS 1-6 APPENDED TO THE FACADE DESCRIPTOR IN THE LEGEND. THE RED ARROW INDICATES THE ESTIMATED POSITION OF EXTERNAL FLAMES AT 02:23 AM ON THE NORTH ELEVATION PROCESSED IMAGE (FIGURE 5C).

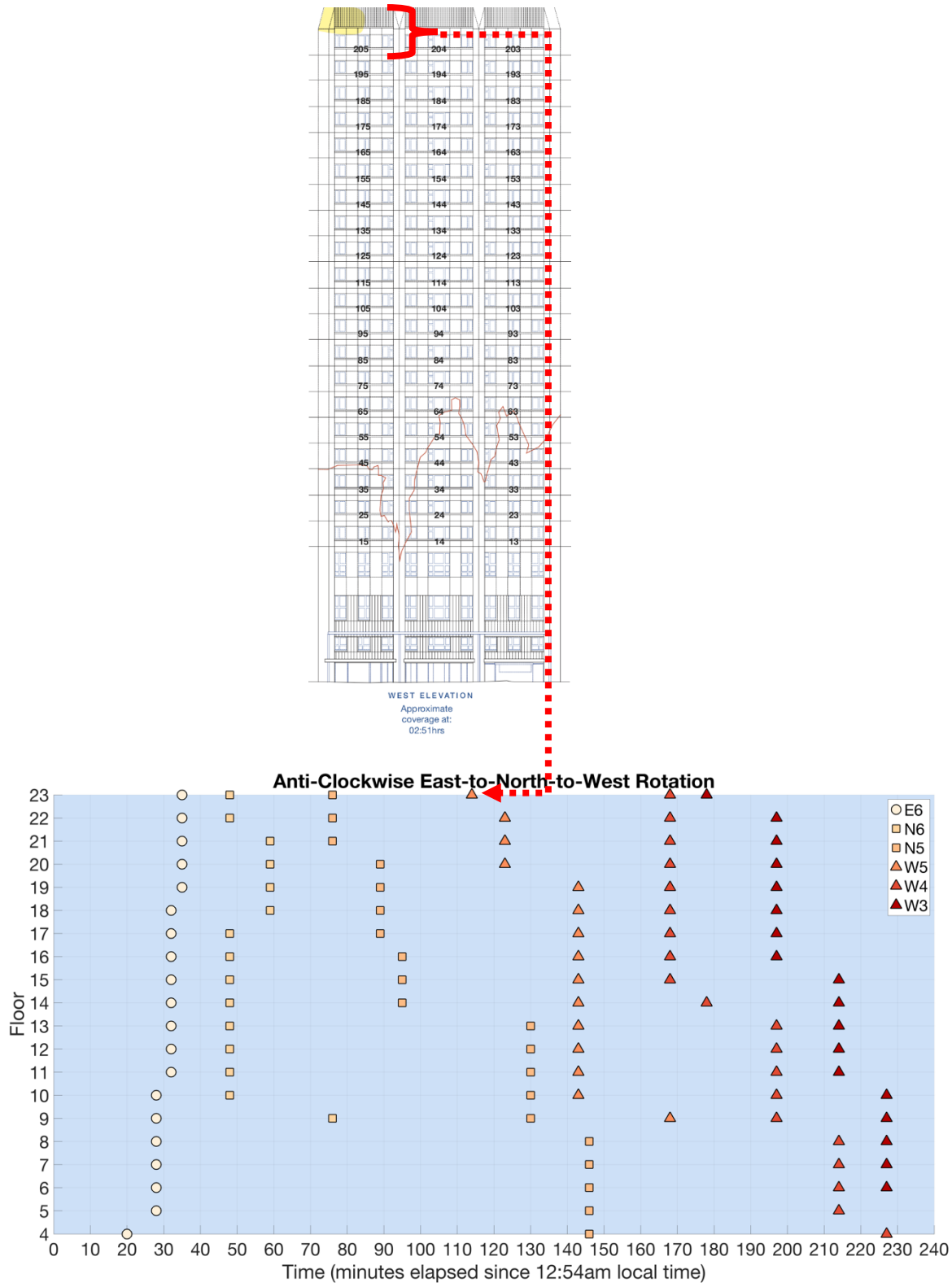


3632 Figure 111

3633

3634 **FIGURE 107: TIME HISTORY OF EXTERNAL FLAME SPREAD ON THE EASTERN (E), NORTHERN (N) AND WESTERN (W) FACADES. THE STACK OF**
3635 **FLATS IMPACTED BY THE EXTERNAL FLAME SPREAD ARE INDICATED USING NUMBERS 1-6 APPENDED TO THE FACADE DESCRIPTOR IN THE LEGEND.**
3636 **THE RED ARROW INDICATES THE ESTIMATED POSITION OF EXTERNAL FLAMES AT 02:32 AM ON THE NORTH ELEVATION TOWER PLAN VIEW.**

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3639 **FIGURE 108: TIME HISTORY OF EXTERNAL FLAME SPREAD ON THE EASTERN (E), NORTHERN (N) AND WESTERN (W) FACADES. THE STACK OF**
3640 **FLATS IMPACTED BY THE EXTERNAL FLAME SPREAD ARE INDICATED USING NUMBERS 1-6 APPENDED TO THE FACADE DESCRIPTOR IN THE LEGEND.**
3641 **THE RED ARROW INDICATES THE ESTIMATED POSITION OF EXTERNAL FLAMES AT 02:51 AM ON THE WEST ELEVATION TOWER PLAN VIEW.**

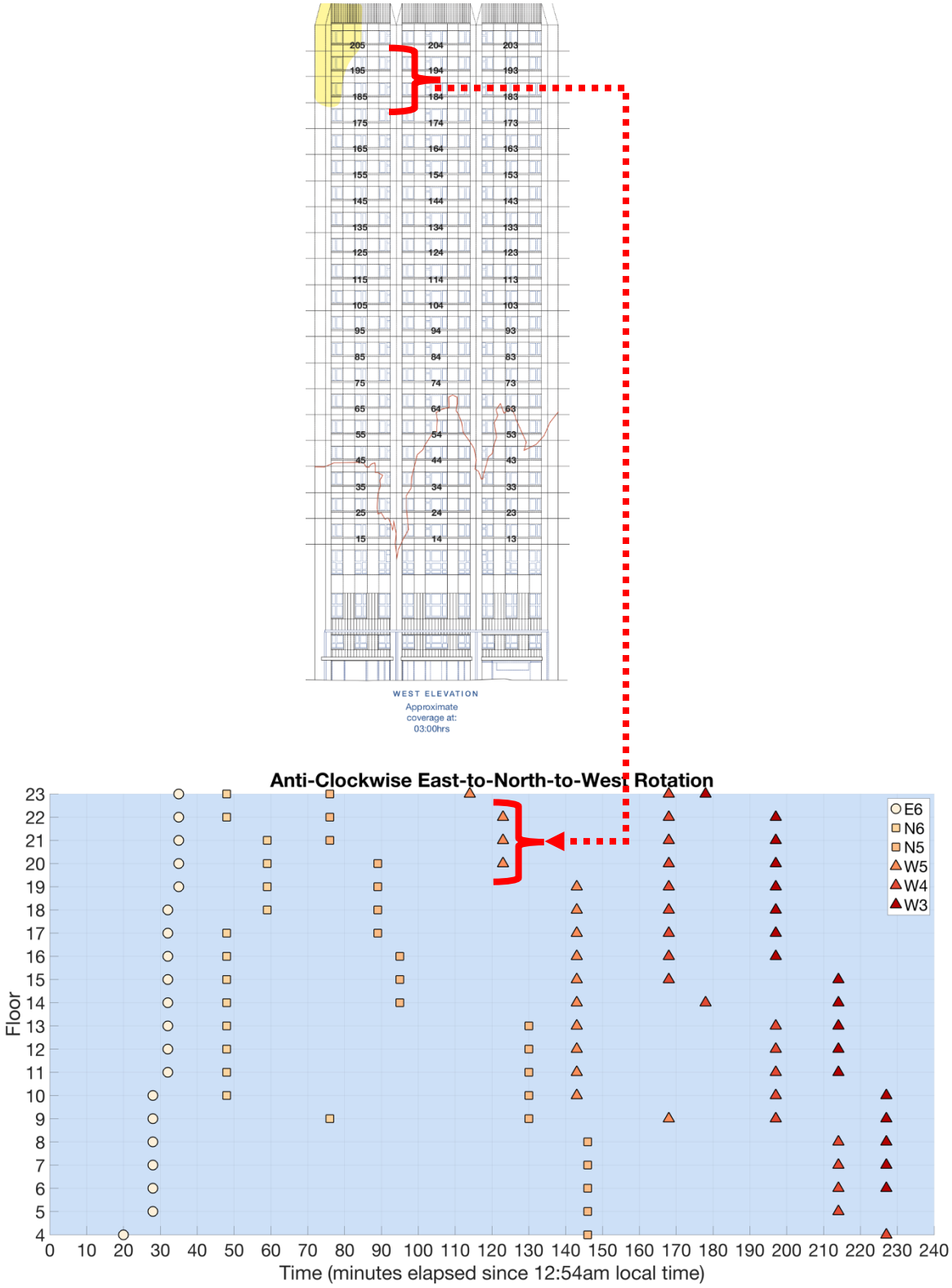


FIGURE 109: TIME HISTORY OF EXTERNAL FLAME SPREAD ON THE EASTERN (E), NORTHERN (N) AND WESTERN (W) FACADES. THE STACK OF FLATS IMPACTED BY THE EXTERNAL FLAME SPREAD ARE INDICATED USING NUMBERS 1-6 APPENDED TO THE FACADE DESCRIPTOR IN THE LEGEND. THE RED ARROW INDICATES THE ESTIMATED POSITION OF EXTERNAL FLAMES AT 02:51 AM ON THE WEST ELEVATION TOWER PLAN VIEW.

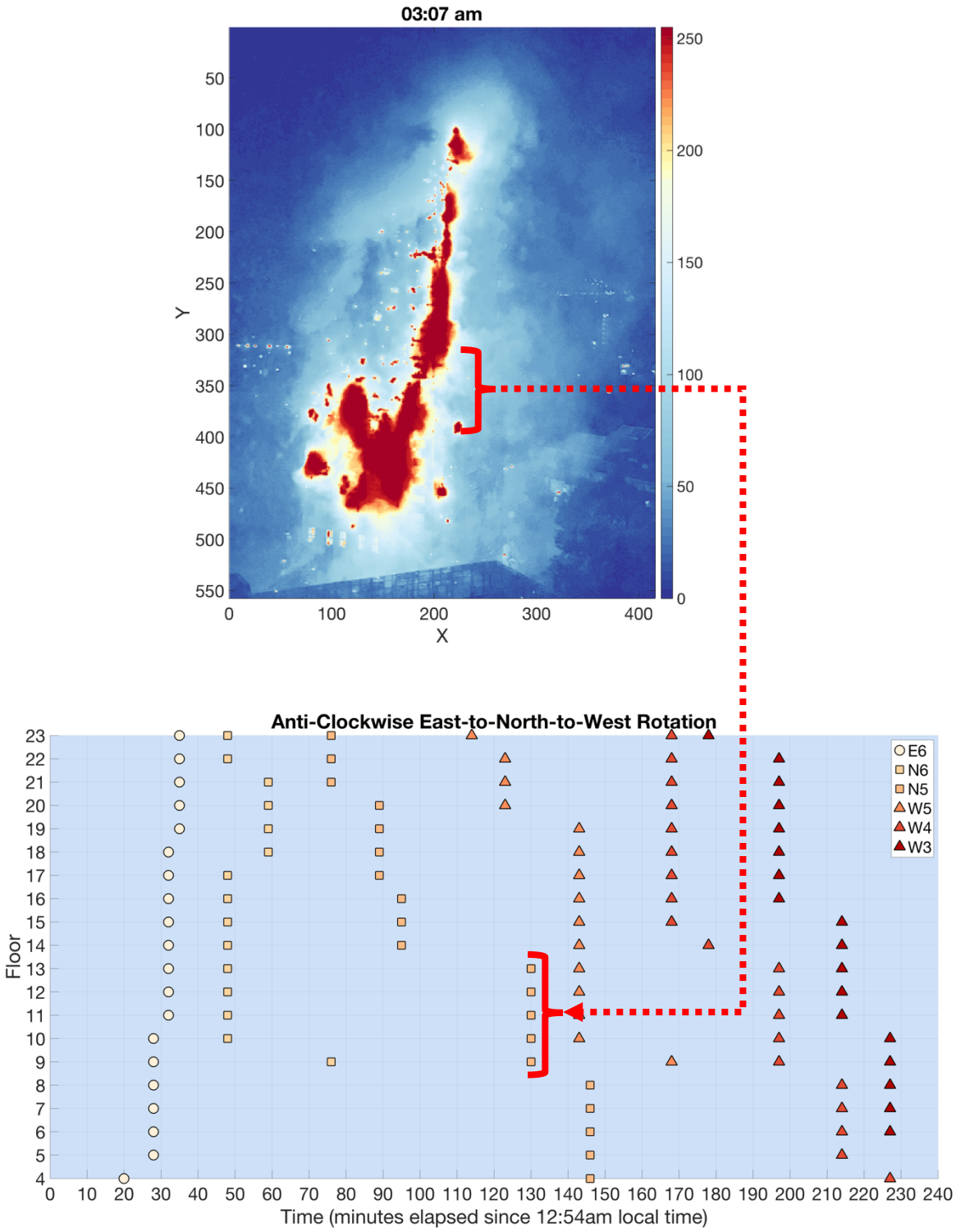


FIGURE 110: TIME HISTORY OF EXTERNAL FLAME SPREAD ON THE EASTERN (E), NORTHERN (N) AND WESTERN (W) FACADES. THE STACK OF FLATS IMPACTED BY THE EXTERNAL FLAME SPREAD ARE INDICATED USING NUMBERS 1-6 APPENDED TO THE FACADE DESCRIPTOR IN THE LEGEND. THE RED ARROW INDICATES THE ESTIMATED POSITION OF EXTERNAL FLAMES AT 03:07 AM ON THE NORTH ELEVATION PROCESSED IMAGE (FIGURE 5H).

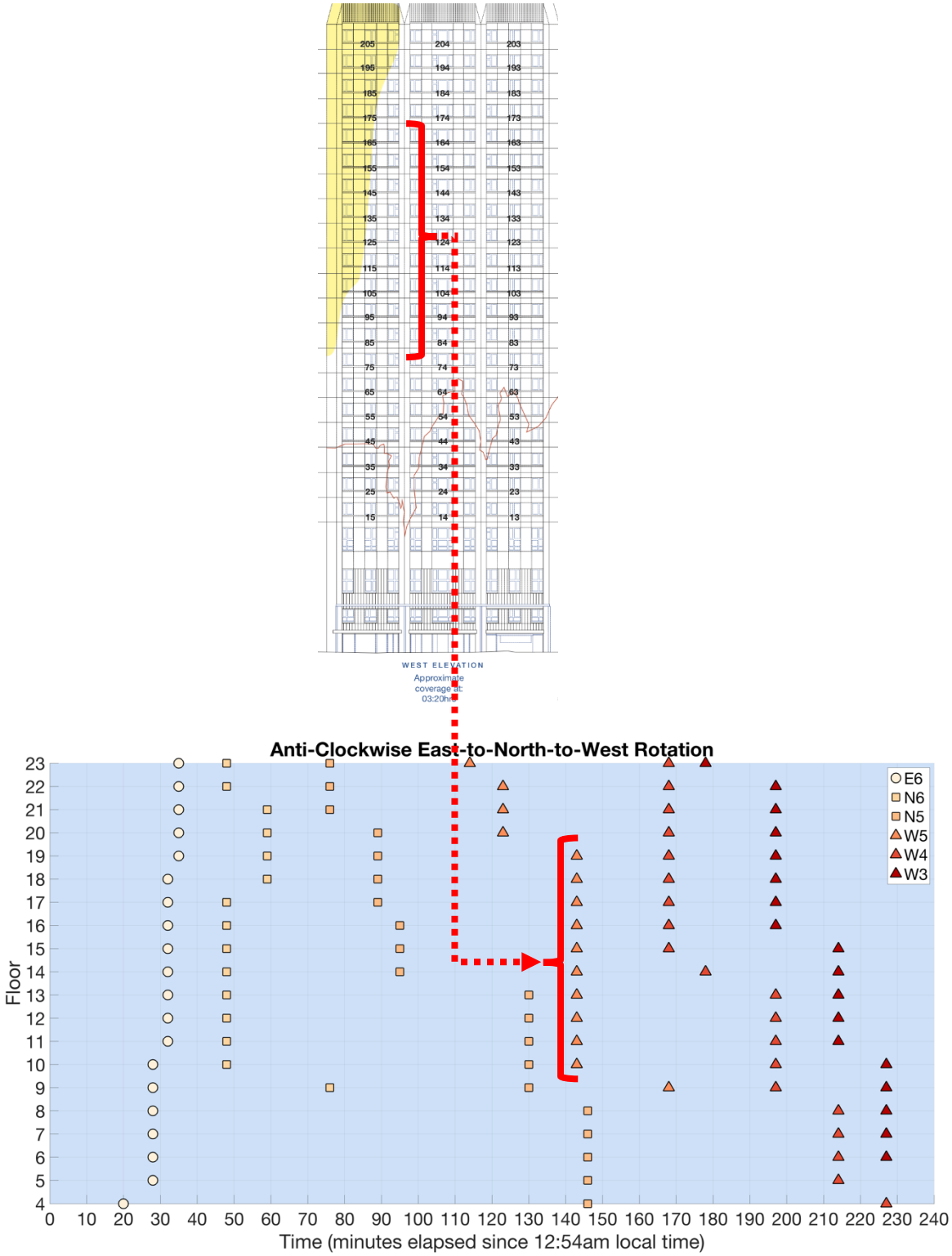


FIGURE 111: TIME HISTORY OF EXTERNAL FLAME SPREAD ON THE EASTERN (E), NORTHERN (N) AND WESTERN (W) FACADES. THE STACK OF FLATS IMPACTED BY THE EXTERNAL FLAME SPREAD ARE INDICATED USING NUMBERS 1-6 APPENDED TO THE FACADE DESCRIPTOR IN THE LEGEND. THE RED ARROW INDICATES THE ESTIMATED POSITION OF EXTERNAL FLAMES AT 03:20 AM ON THE WEST ELEVATION TOWER PLAN VIEW.

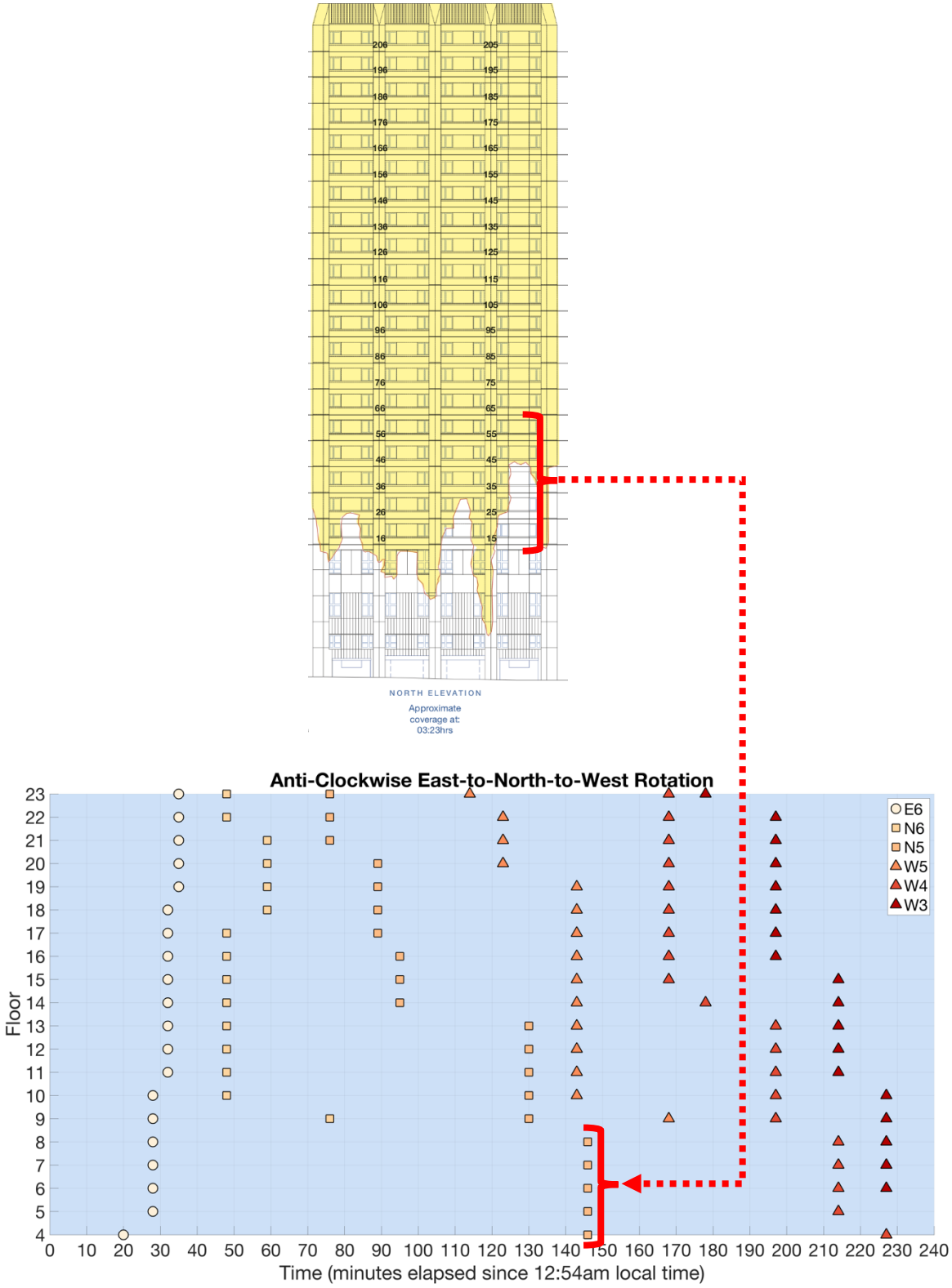


FIGURE 112: TIME HISTORY OF EXTERNAL FLAME SPREAD ON THE EASTERN (E), NORTHERN (N) AND WESTERN (W) FACADES. THE STACK OF FLATS IMPACTED BY THE EXTERNAL FLAME SPREAD ARE INDICATED USING NUMBERS 1-6 APPENDED TO THE FACADE DESCRIPTOR IN THE LEGEND. THE RED ARROW INDICATES THE ESTIMATED POSITION OF EXTERNAL FLAMES AT 03:23 AM ON THE NORTH ELEVATION TOWER PLAN VIEW.

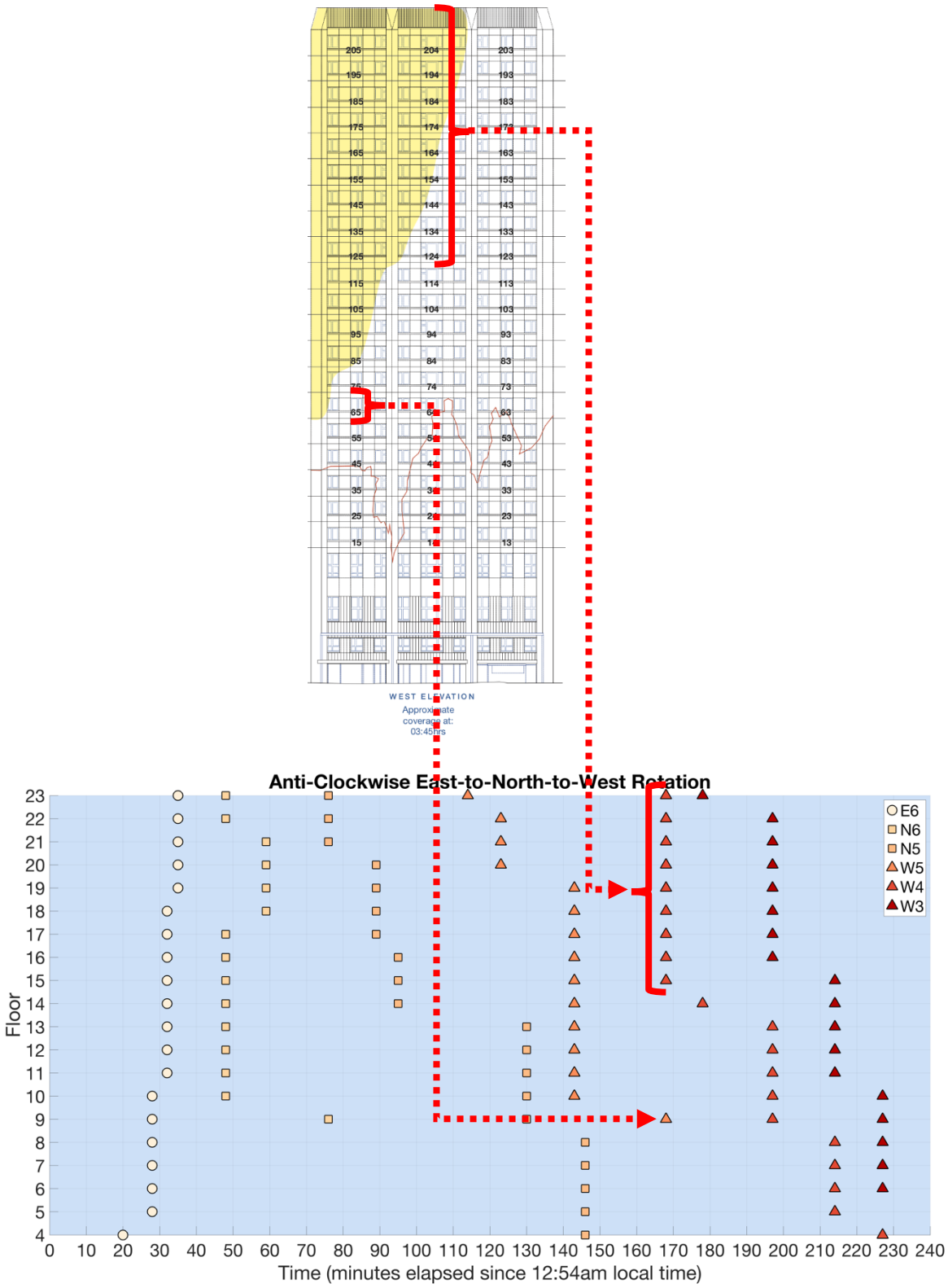
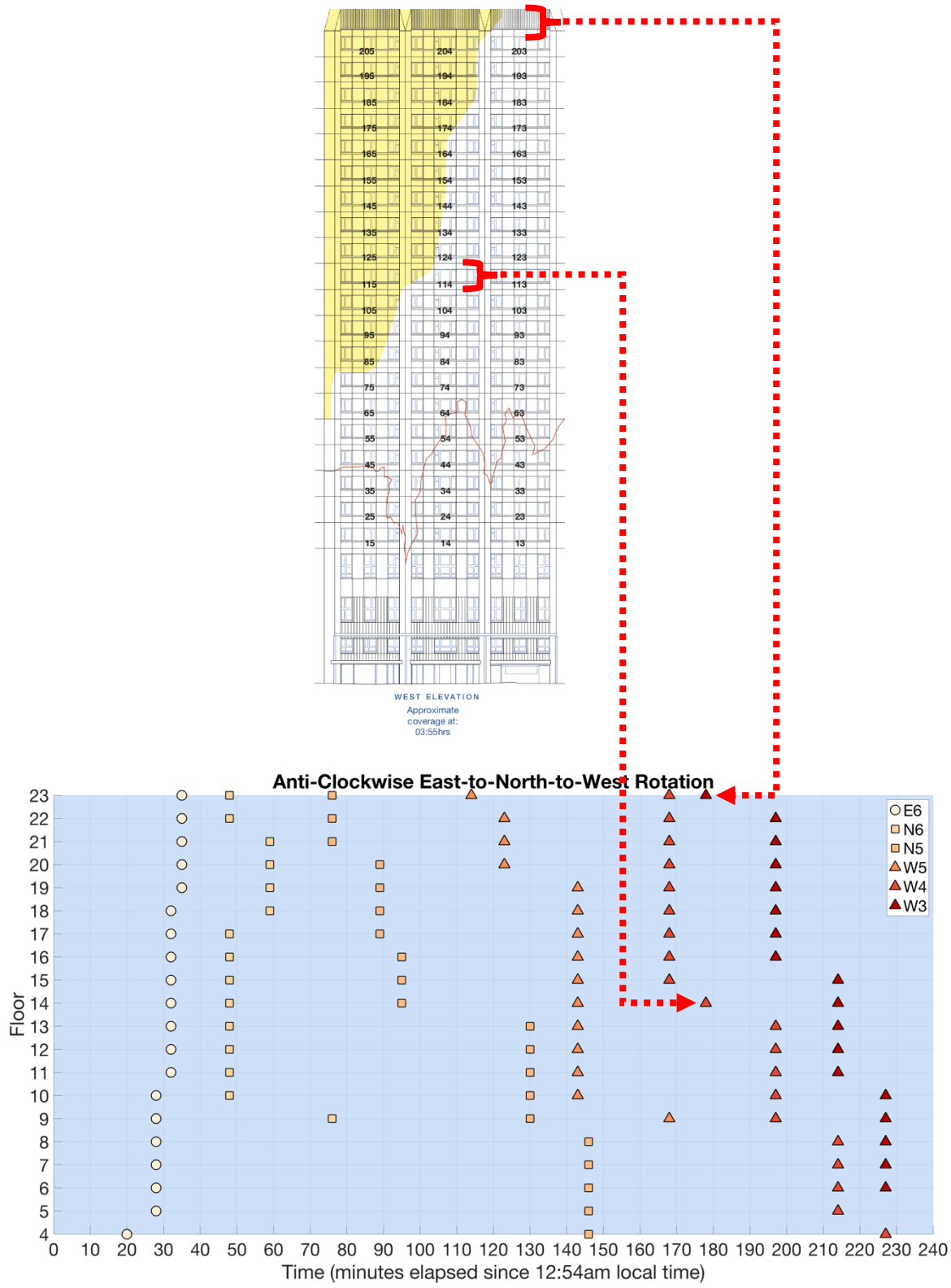


FIGURE 113: TIME HISTORY OF EXTERNAL FLAME SPREAD ON THE EASTERN (E), NORTHERN (N) AND WESTERN (W) FACADES. THE STACK OF FLATS IMPACTED BY THE EXTERNAL FLAME SPREAD ARE INDICATED USING NUMBERS 1-6 APPENDED TO THE FACADE DESCRIPTOR IN THE LEGEND. THE RED ARROWS INDICATE THE ESTIMATED POSITION OF EXTERNAL FLAMES AT 03:45 AM ON THE WEST ELEVATION TOWER PLAN VIEW.

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3671 **FIGURE 114: TIME HISTORY OF EXTERNAL FLAME SPREAD ON THE EASTERN (E), NORTHERN (N) AND WESTERN (W) FACADES. THE STACK OF**
3672 **FLATS IMPACTED BY THE EXTERNAL FLAME SPREAD ARE INDICATED USING NUMBERS 1-6 APPENDED TO THE FACADE DESCRIPTOR IN THE LEGEND.**
3673 **THE RED ARROWS INDICATE THE ESTIMATED POSITION OF EXTERNAL FLAMES AT 03:55 AM ON THE WEST ELEVATION TOWER PLAN VIEW.**

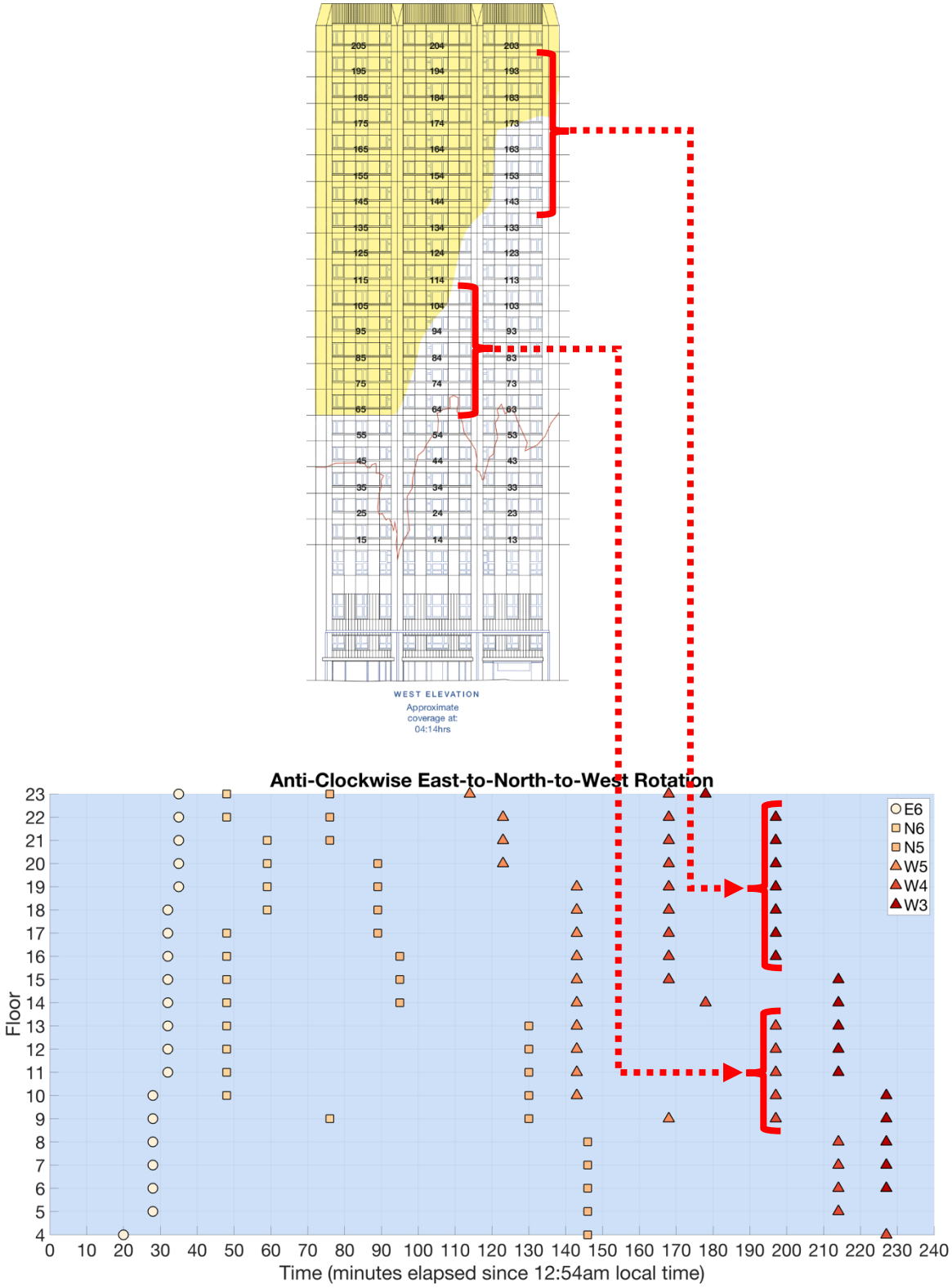


FIGURE 115: TIME HISTORY OF EXTERNAL FLAME SPREAD ON THE EASTERN (E), NORTHERN (N) AND WESTERN (W) FACADES. THE STACK OF FLATS IMPACTED BY THE EXTERNAL FLAME SPREAD ARE INDICATED USING NUMBERS 1-6 APPENDED TO THE FACADE DESCRIPTOR IN THE LEGEND. THE RED ARROWS INDICATE THE ESTIMATED POSITION OF EXTERNAL FLAMES AT 04:14 AM ON THE WEST ELEVATION TOWER PLAN VIEW.

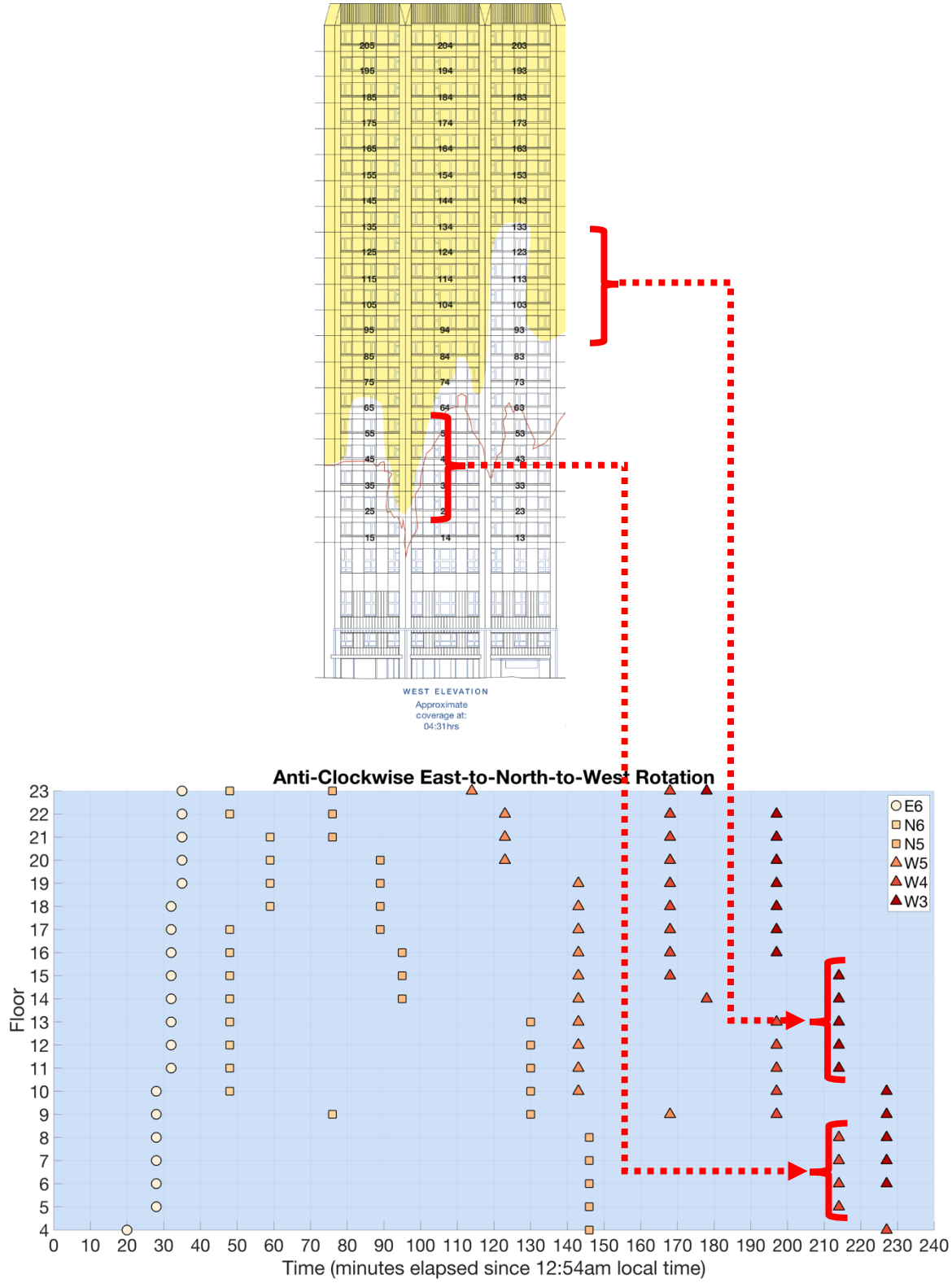


FIGURE 116: TIME HISTORY OF EXTERNAL FLAME SPREAD ON THE EASTERN (E), NORTHERN (N) AND WESTERN (W) FACADES. THE STACK OF FLATS IMPACTED BY THE EXTERNAL FLAME SPREAD ARE INDICATED USING NUMBERS 1-6 APPENDED TO THE FACADE DESCRIPTOR IN THE LEGEND. THE RED ARROWS INDICATE THE ESTIMATED POSITION OF EXTERNAL FLAMES AT 04:31 AM ON THE WEST ELEVATION TOWER PLAN VIEW.

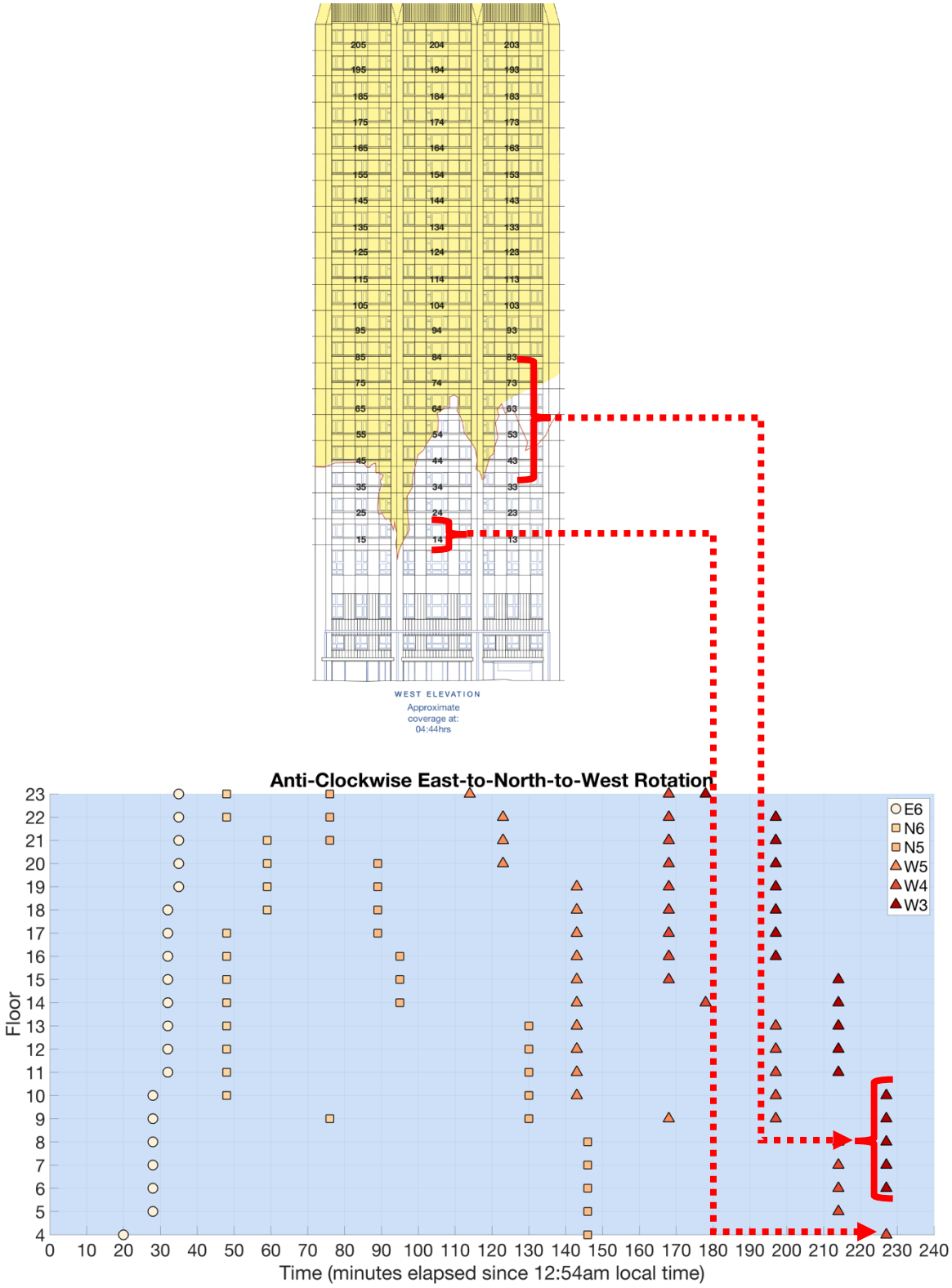


FIGURE 117: TIME HISTORY OF EXTERNAL FLAME SPREAD ON THE EASTERN (E), NORTHERN (N) AND WESTERN (W) FACADES. THE STACK OF FLATS IMPACTED BY THE EXTERNAL FLAME SPREAD ARE INDICATED USING NUMBERS 1-6 APPENDED TO THE FACADE DESCRIPTOR IN THE LEGEND. THE RED ARROWS INDICATE THE ESTIMATED POSITION OF EXTERNAL FLAMES AT 04:44 AM ON THE WEST ELEVATION TOWER PLAN VIEW.

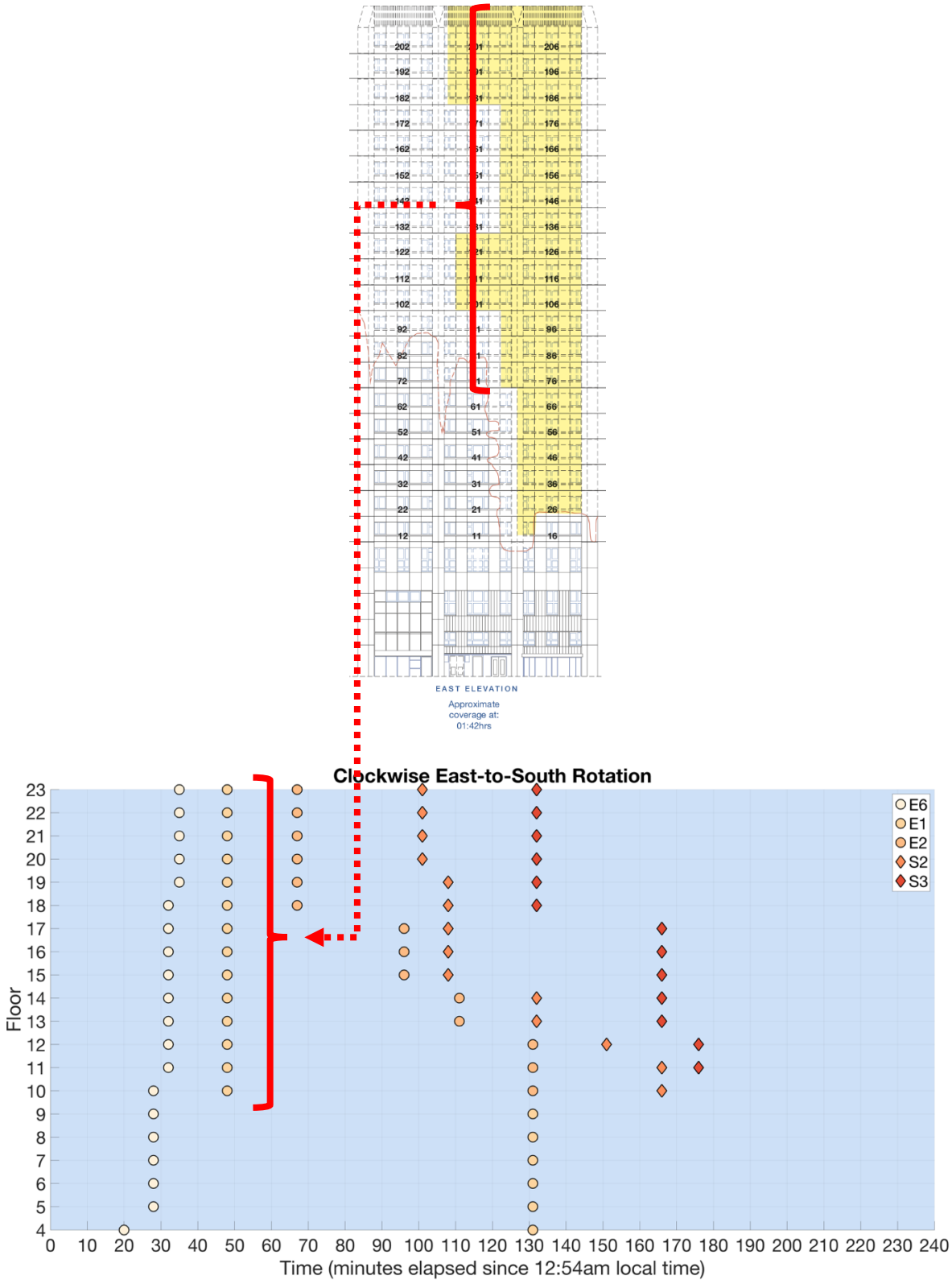


FIGURE 118: TIME HISTORY OF EXTERNAL FLAME SPREAD ON THE EASTERN (E) AND SOUTHERN (S) FACADES. THE STACK OF FLATS IMPACTED BY THE EXTERNAL FLAME SPREAD ARE INDICATED USING NUMBERS 1-6 APPENDED TO THE FACADE DESCRIPTOR IN THE LEGEND. THE RED ARROW INDICATES THE ESTIMATED POSITION OF EXTERNAL FLAMES AT 01:42 AM ON THE EAST ELEVATION TOWER PLAN VIEW.

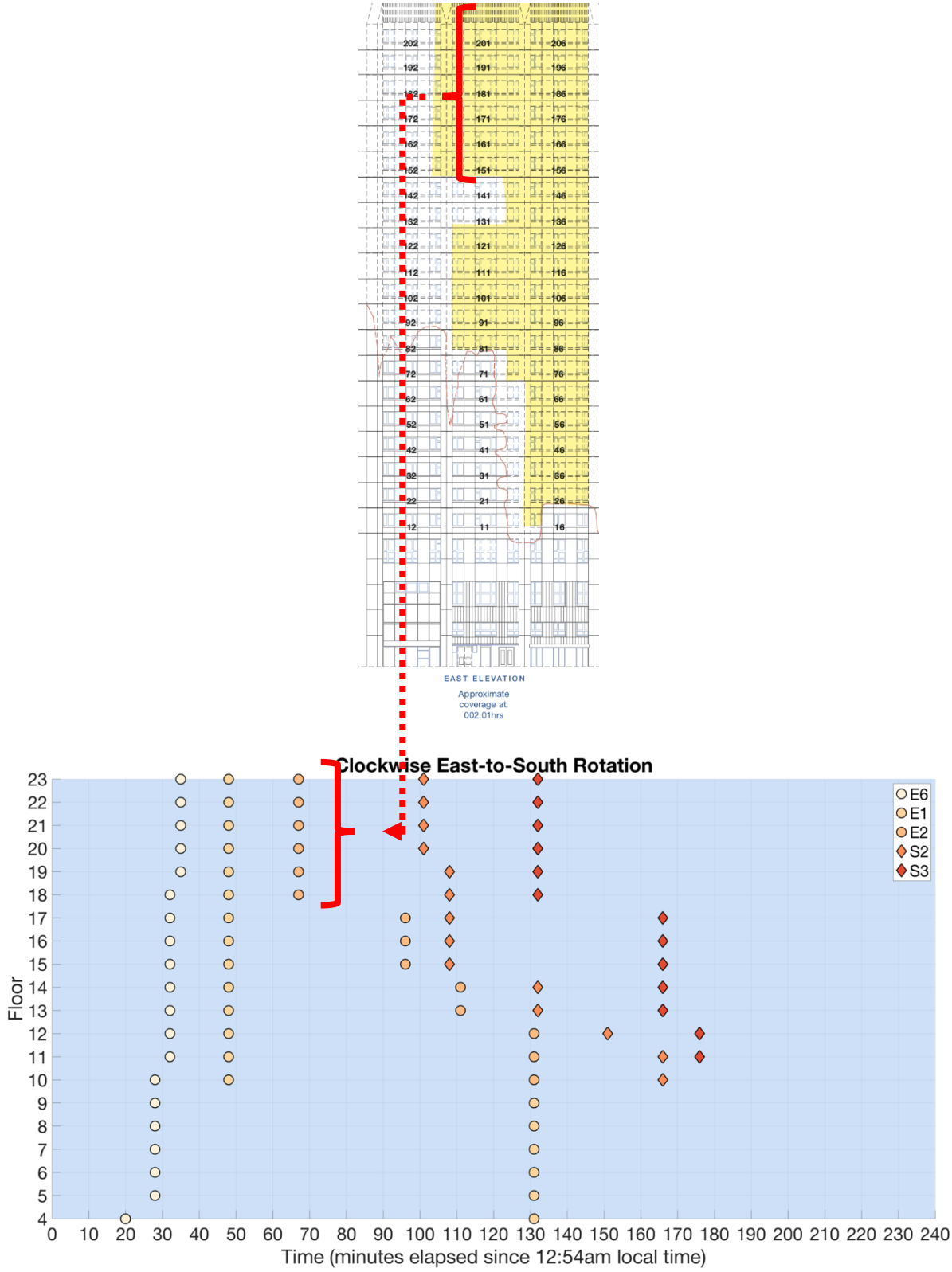


FIGURE 119: TIME HISTORY OF EXTERNAL FLAME SPREAD ON THE EASTERN (E) AND SOUTHERN (S) FACADES. THE STACK OF FLATS IMPACTED BY THE EXTERNAL FLAME SPREAD ARE INDICATED USING NUMBERS 1-6 APPENDED TO THE FACADE DESCRIPTOR IN THE LEGEND. THE RED ARROW INDICATES THE ESTIMATED POSITION OF EXTERNAL FLAMES AT 02:01 AM ON THE EAST ELEVATION TOWER PLAN VIEW.

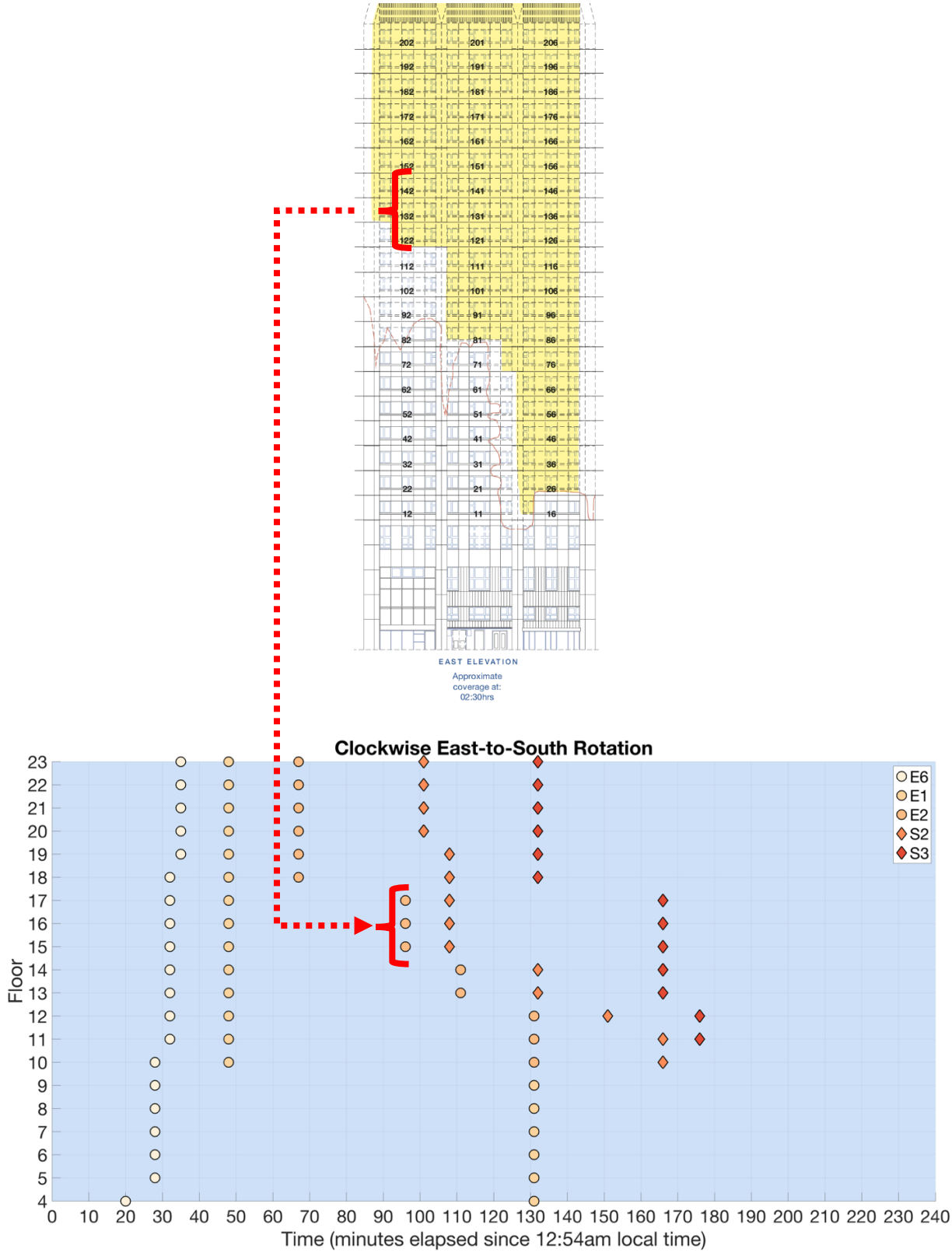


FIGURE 120: TIME HISTORY OF EXTERNAL FLAME SPREAD ON THE EASTERN (E) AND SOUTHERN (S) FACADES. THE STACK OF FLATS IMPACTED BY THE EXTERNAL FLAME SPREAD ARE INDICATED USING NUMBERS 1-6 APPENDED TO THE FACADE DESCRIPTOR IN THE LEGEND. THE RED ARROW INDICATES THE ESTIMATED POSITION OF EXTERNAL FLAMES AT 02:30 AM ON THE EAST ELEVATION TOWER PLAN VIEW.

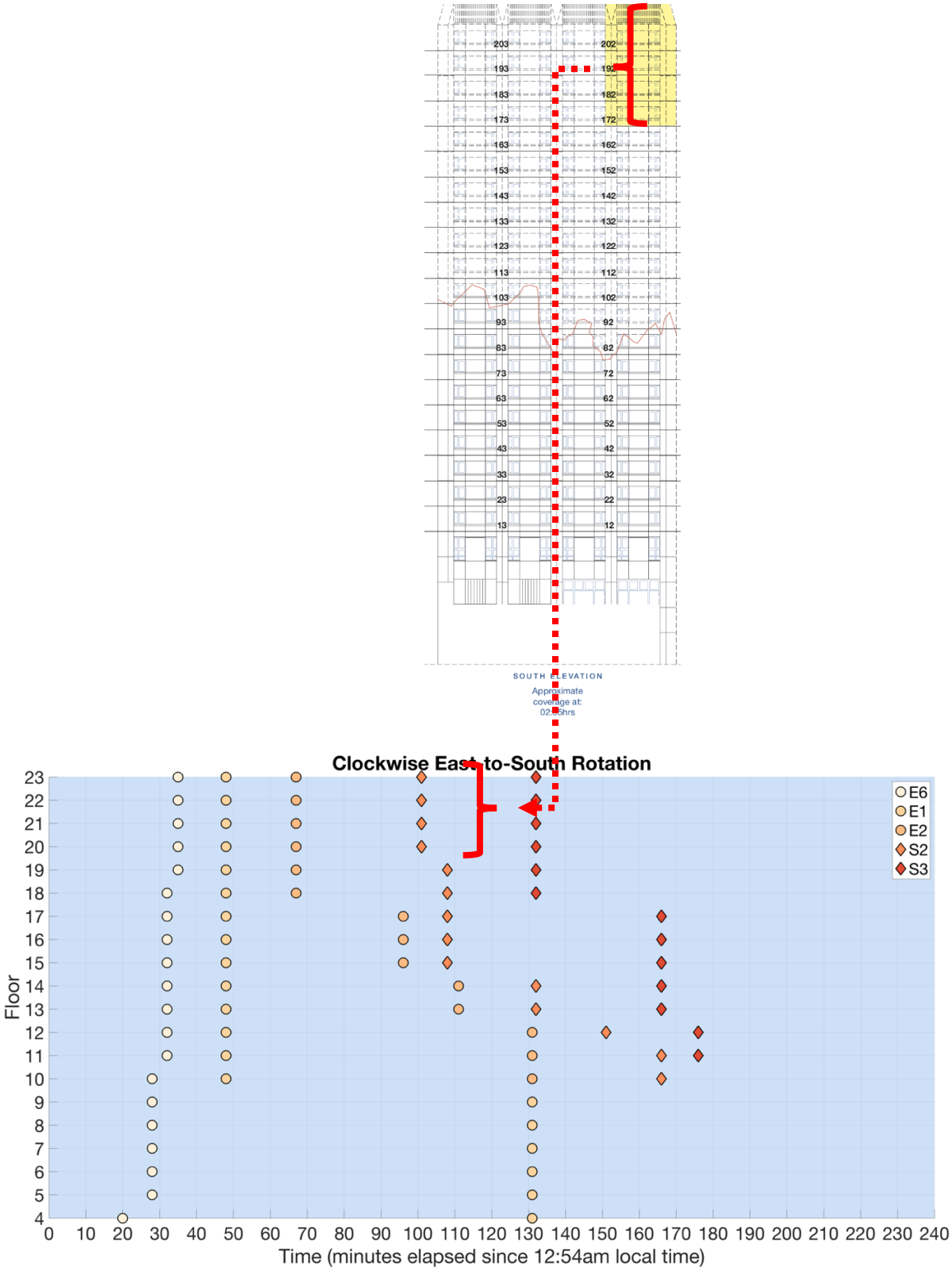


FIGURE 121: TIME HISTORY OF EXTERNAL FLAME SPREAD ON THE EASTERN (E) AND SOUTHERN (S) FACADES. THE STACK OF FLATS IMPACTED BY THE EXTERNAL FLAME SPREAD ARE INDICATED USING NUMBERS 1-6 APPENDED TO THE FACADE DESCRIPTOR IN THE LEGEND. THE RED ARROW INDICATES THE ESTIMATED POSITION OF EXTERNAL FLAMES AT 02:35 AM ON THE SOUTH ELEVATION TOWER PLAN VIEW.

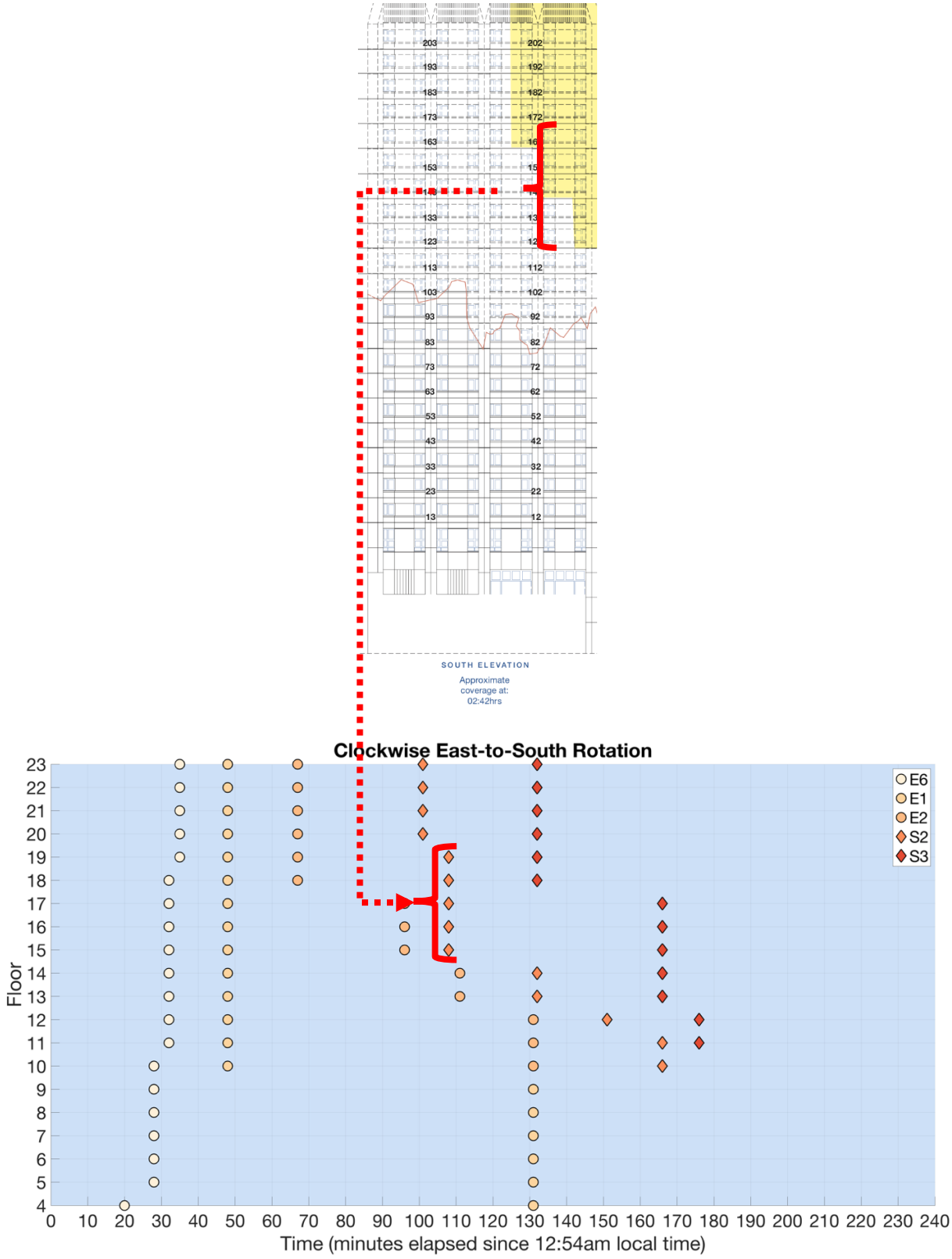


FIGURE 122: TIME HISTORY OF EXTERNAL FLAME SPREAD ON THE EASTERN (E) AND SOUTHERN (S) FACADES. THE STACK OF FLATS IMPACTED BY THE EXTERNAL FLAME SPREAD ARE INDICATED USING NUMBERS 1-6 APPENDED TO THE FACADE DESCRIPTOR IN THE LEGEND. THE RED ARROW INDICATES THE ESTIMATED POSITION OF EXTERNAL FLAMES AT 02:42 AM ON THE SOUTH ELEVATION TOWER PLAN VIEW.

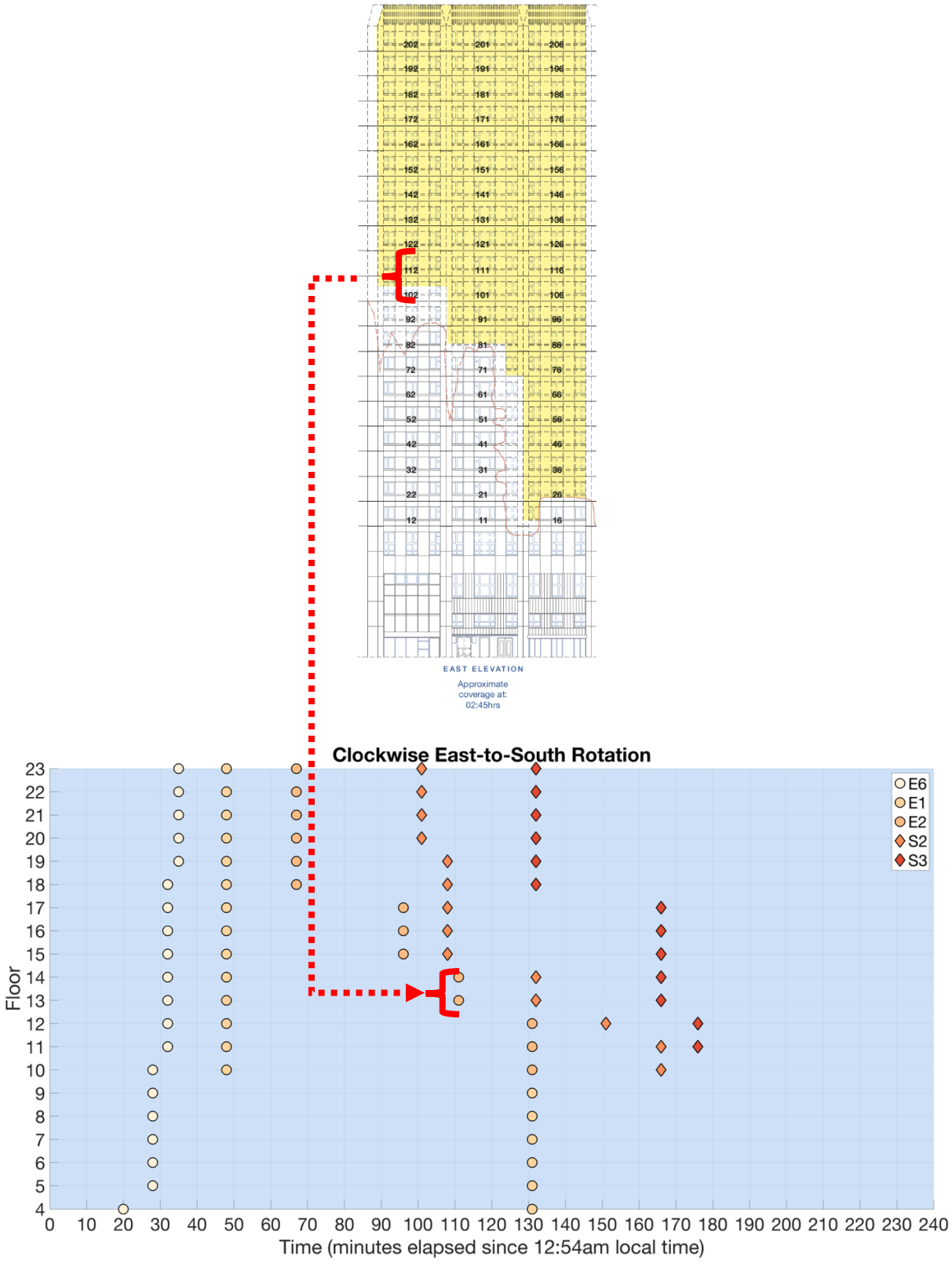


FIGURE 123: TIME HISTORY OF EXTERNAL FLAME SPREAD ON THE EASTERN (E) AND SOUTHERN (S) FACADES. THE STACK OF FLATS IMPACTED BY THE EXTERNAL FLAME SPREAD ARE INDICATED USING NUMBERS 1-6 APPENDED TO THE FACADE DESCRIPTOR IN THE LEGEND. THE RED ARROW INDICATES THE ESTIMATED POSITION OF EXTERNAL FLAMES AT 02:45 AM ON THE EAST ELEVATION TOWER PLAN VIEW.

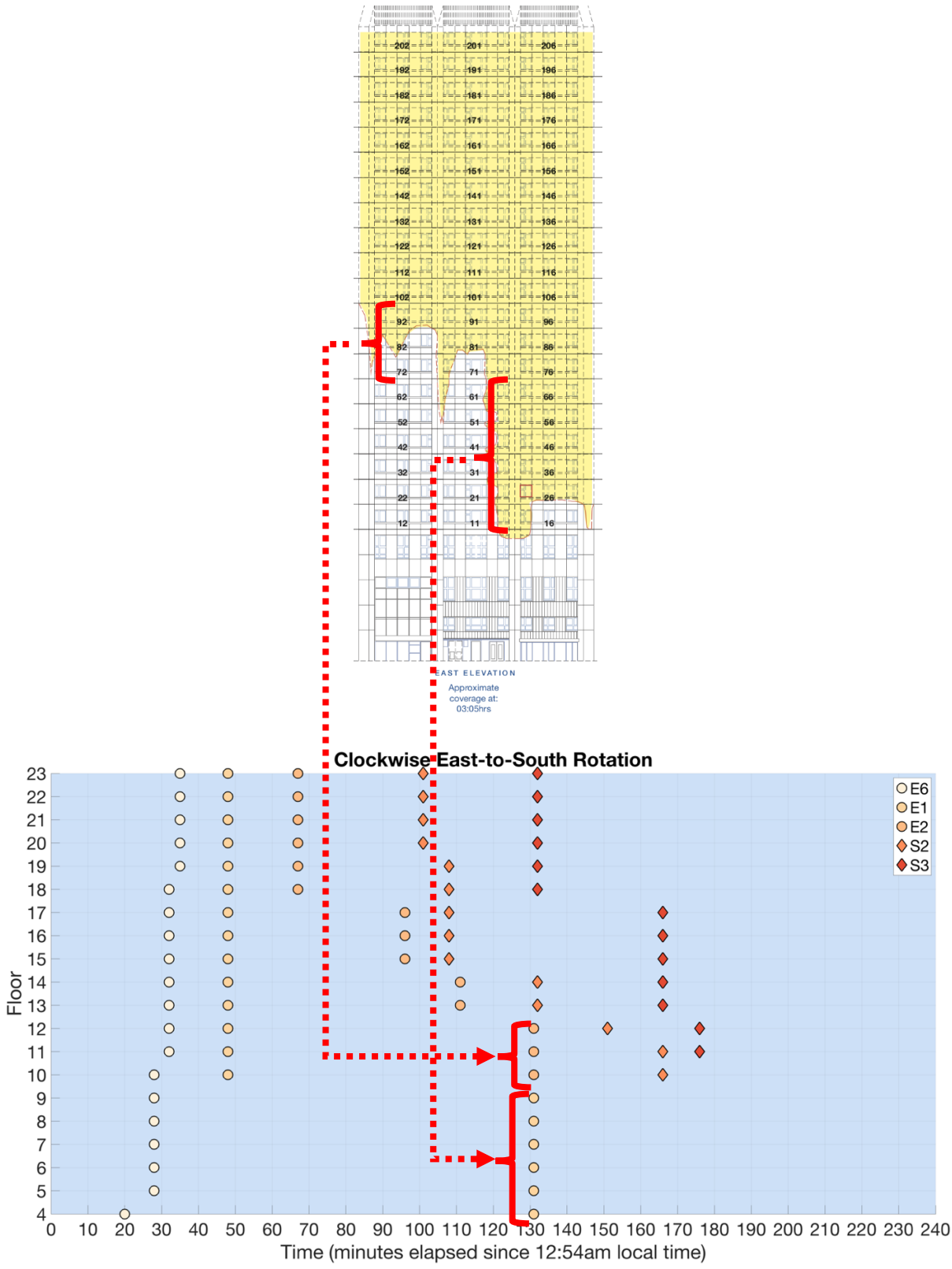


FIGURE 124: TIME HISTORY OF EXTERNAL FLAME SPREAD ON THE EASTERN (E) AND SOUTHERN (S) FACADES. THE STACK OF FLATS IMPACTED BY THE EXTERNAL FLAME SPREAD ARE INDICATED USING NUMBERS 1-6 APPENDED TO THE FACADE DESCRIPTOR IN THE LEGEND. THE RED ARROWS INDICATE THE ESTIMATED POSITION OF EXTERNAL FLAMES AT 03:05 AM ON THE EAST ELEVATION TOWER PLAN VIEW.

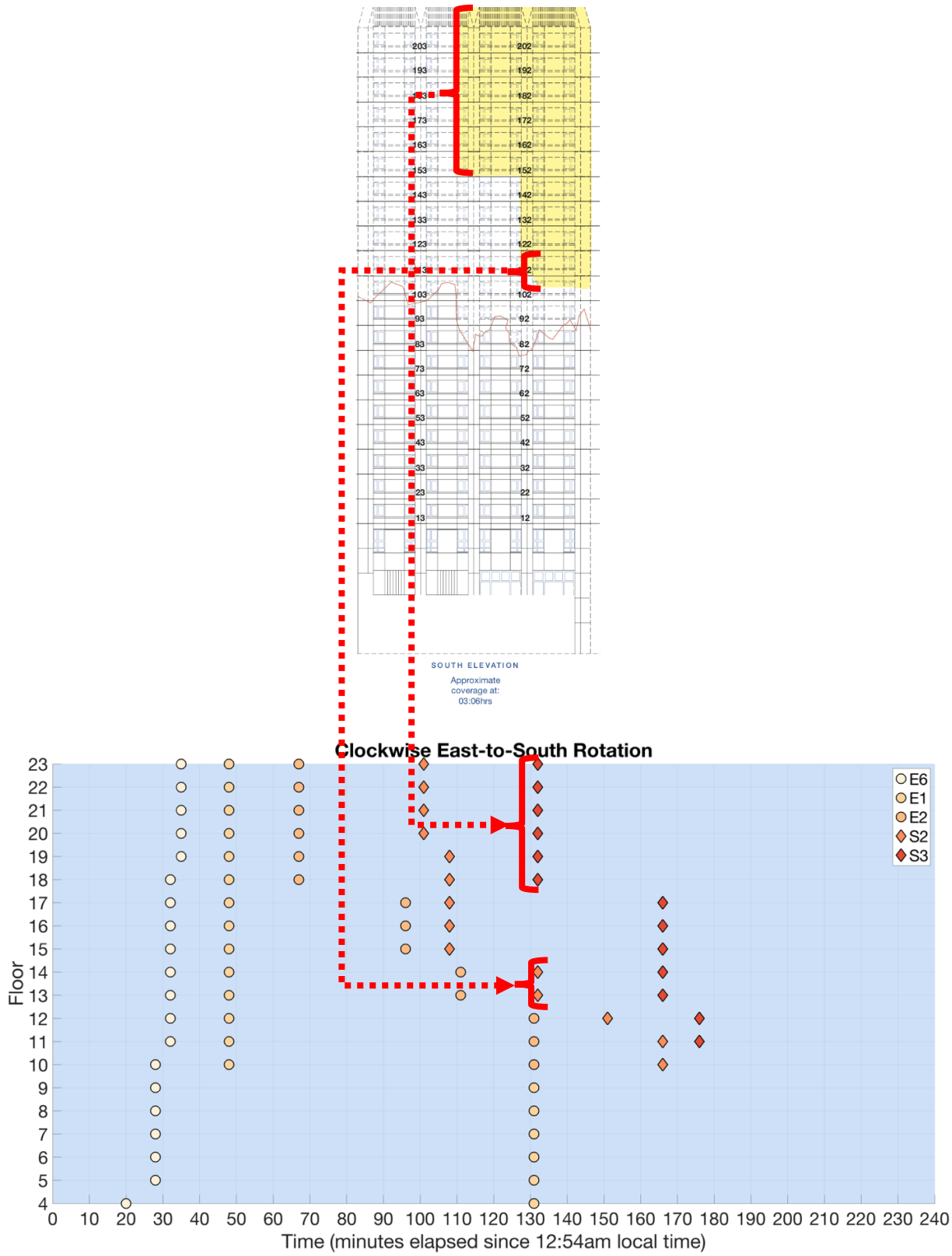


FIGURE 125: TIME HISTORY OF EXTERNAL FLAME SPREAD ON THE EASTERN (E) AND SOUTHERN (S) FACADES. THE STACK OF FLATS IMPACTED BY THE EXTERNAL FLAME SPREAD ARE INDICATED USING NUMBERS 1-6 APPENDED TO THE FACADE DESCRIPTOR IN THE LEGEND. THE RED ARROWS INDICATE THE ESTIMATED POSITION OF EXTERNAL FLAMES AT 03:06 AM ON THE SOUTH ELEVATION TOWER PLAN VIEW.

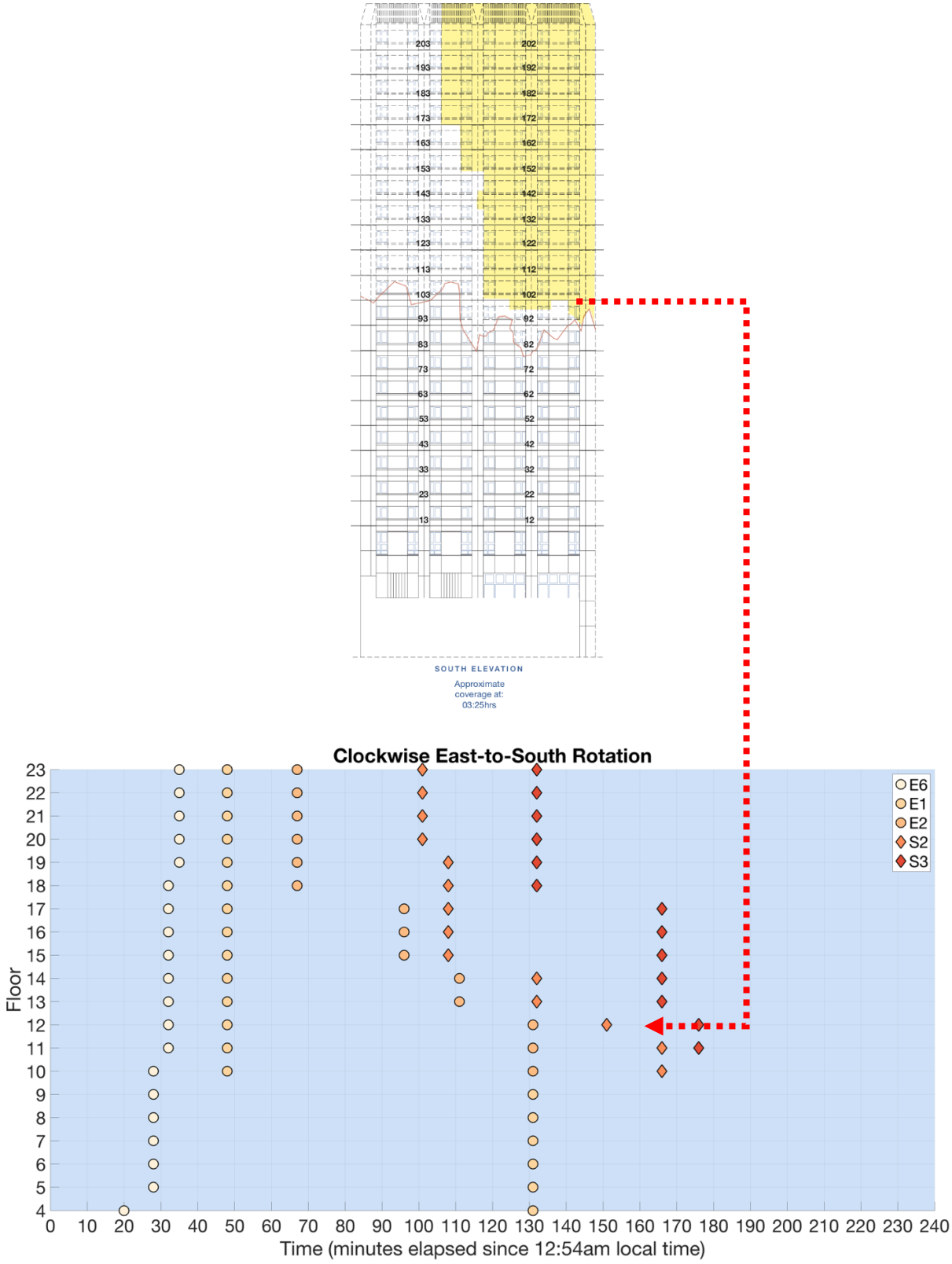


FIGURE 126: TIME HISTORY OF EXTERNAL FLAME SPREAD ON THE EASTERN (E) AND SOUTHERN (S) FACADES. THE STACK OF FLATS IMPACTED BY THE EXTERNAL FLAME SPREAD ARE INDICATED USING NUMBERS 1-6 APPENDED TO THE FACADE DESCRIPTOR IN THE LEGEND. THE RED ARROW INDICATES THE ESTIMATED POSITION OF EXTERNAL FLAMES AT 03:25 AM ON THE SOUTH ELEVATION TOWER PLAN VIEW.

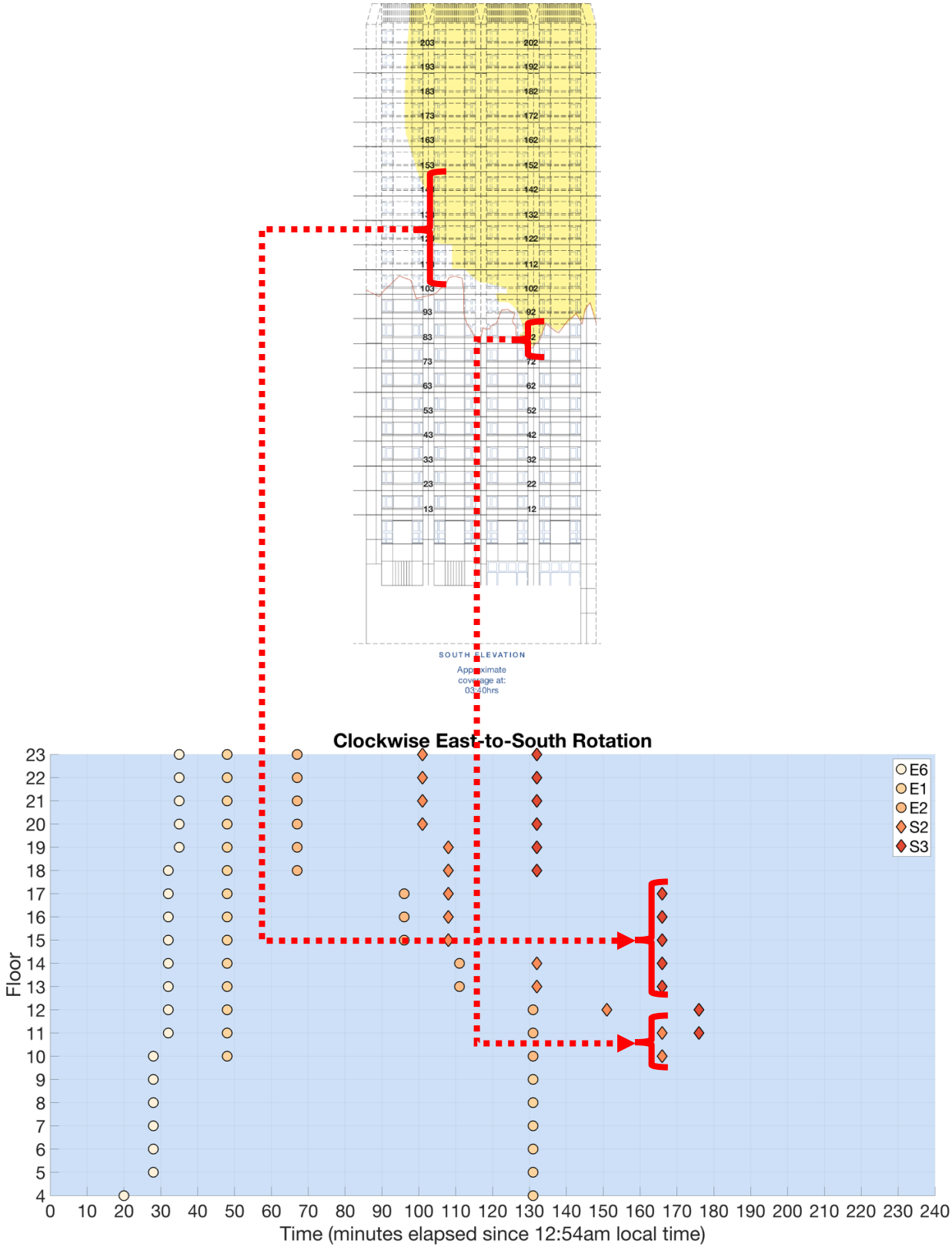


FIGURE 127: TIME HISTORY OF EXTERNAL FLAME SPREAD ON THE EASTERN (E) AND SOUTHERN (S) FACADES. THE STACK OF FLATS IMPACTED BY THE EXTERNAL FLAME SPREAD ARE INDICATED USING NUMBERS 1-6 APPENDED TO THE FACADE DESCRIPTOR IN THE

LEGEND. THE RED ARROWS INDICATE THE ESTIMATED POSITION OF EXTERNAL FLAMES AT 03:40 AM ON THE SOUTH ELEVATION TOWER PLAN VIEW.

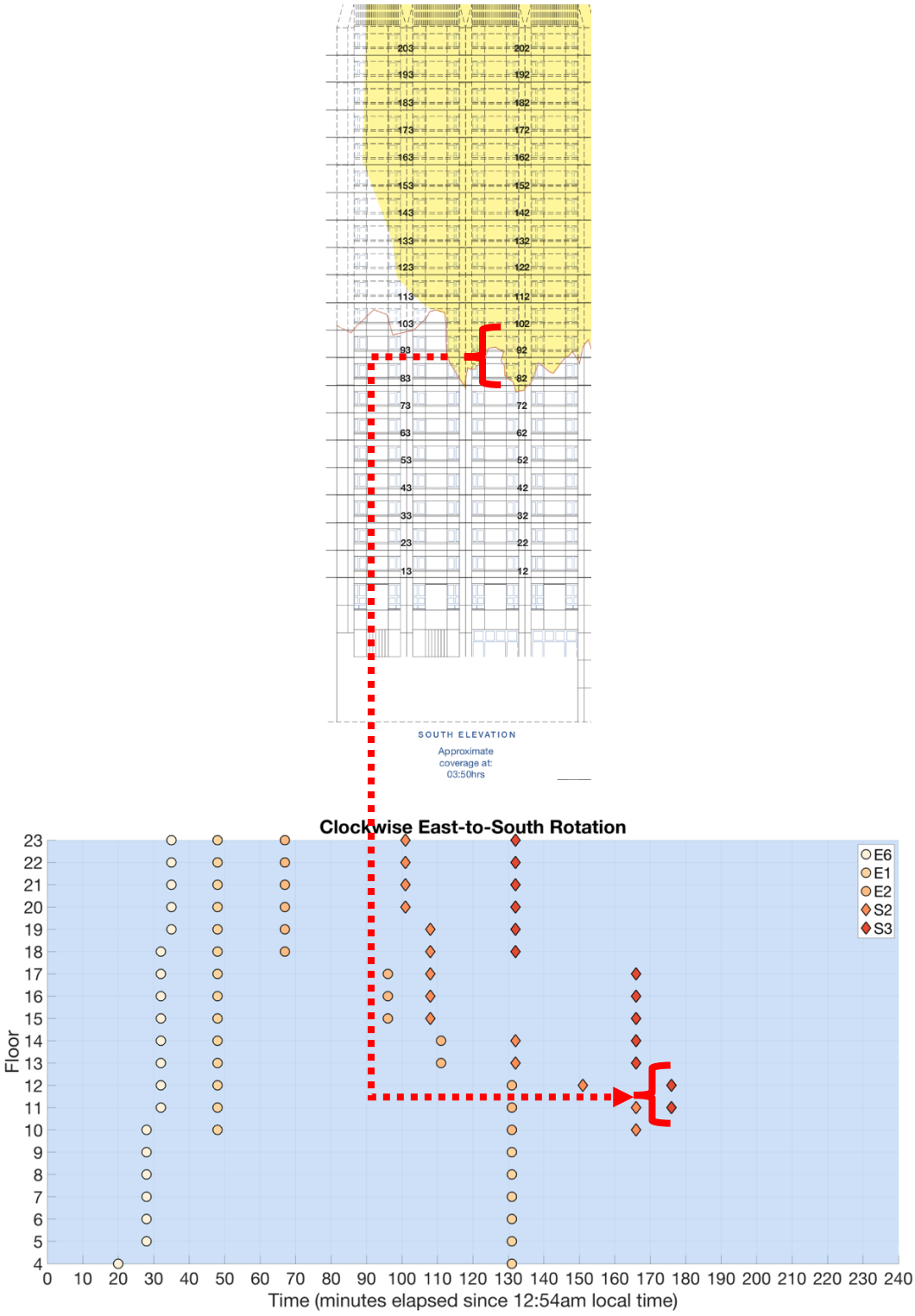


FIGURE 128: TIME HISTORY OF EXTERNAL FLAME SPREAD ON THE EASTERN (E) AND SOUTHERN (S) FACADES. THE STACK OF FLATS IMPACTED BY THE EXTERNAL FLAME SPREAD ARE INDICATED USING NUMBERS 1-6 APPENDED TO THE FACADE DESCRIPTOR IN THE LEGEND. THE RED ARROW INDICATES THE ESTIMATED POSITION OF EXTERNAL FLAMES AT 03:50 AM ON THE SOUTH ELEVATION TOWER PLAN VIEW.

Additional photos showing lateral and vertical flame spread

East Facade

(a)



(b)



(c)



(d)



(e)  (f) 

FIGURE 129: ORIGINAL PUBLIC FOOTAGE OF LATERAL AND VERTICAL (UPWARD AND DOWNWARD) FLAME SPREAD ON THE EAST FACADE OF GRENFELL TOWER AT (A) 01:22 AM; (B) 01:36 AM; (C) 01:52 AM; (D) 02:08 AM; (E) 02:22 AM; AND (F) 02:53 AM RESPECTIVELY. PHOTOS WERE SOURCED FROM MET00008024, PAGES 28-29.

West Facade

(a)  (b) 

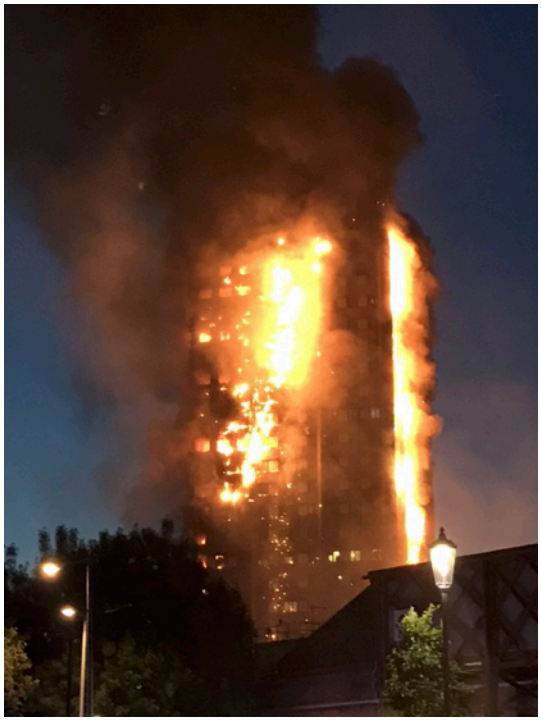
(c)  (d) 

FIGURE 130: ORIGINAL PUBLIC FOOTAGE OF LATERAL AND VERTICAL (DOWNWARD) FLAME SPREAD ON THE WEST FACADE OF GRENFELL TOWER AT (A) 02:50 AM; (B) 03:15 AM; (C) 03:20 AM; AND (D) 03:48 AM RESPECTIVELY. PHOTOS WERE SOURCED FROM MET00008024, PAGE 59.

(b)  (b) 

FIGURE 131: IMAGES FROM THE WEST FAÇADE CORRESPONDING TO (A) 03:20 AM; AND (B) 03:48 AM RESPECTIVELY.

APPENDIX F. STRUCTURAL ANALYSIS

The properties defining loss of strength in rebar are given in Euro Code 2 [46] and shown in the plot in Figure 132. The plot indicates that typical rebar begins to lose strength at 300°C, losing 50% of its strength by 550°C, this latter threshold typically taken as a conservative failure criterion. Eurocode 2 also gives the reduction in concrete strength as a function of temperature, shown in Figure 133.

The range of thermal loading applied in the model is taken from Section 5.4 of this report, which represents estimated characteristic, upper and lower bound, compartment temperatures in a typical one-bedroom flat in the Grenfell Tower. The growth phase of the fires is ignored and gas phase temperature boundary conditions between 850°C and 1000°C are applied.

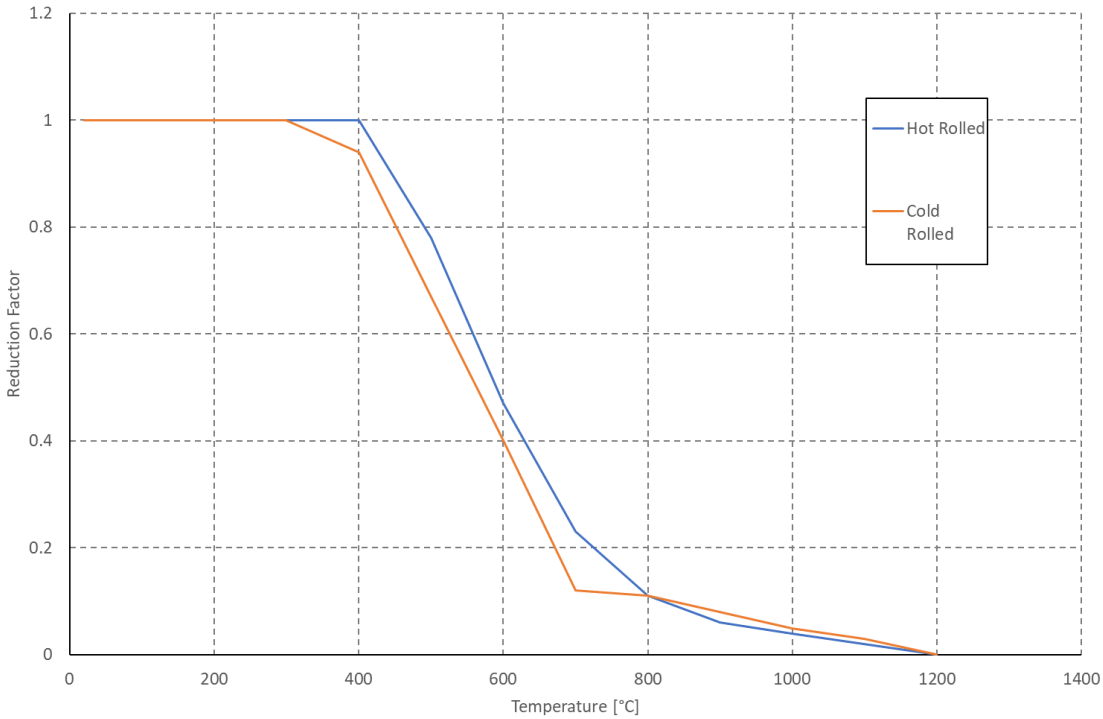


FIGURE 132: Strength reduction factor of typical rebar steels as a function of temperature according to [46].

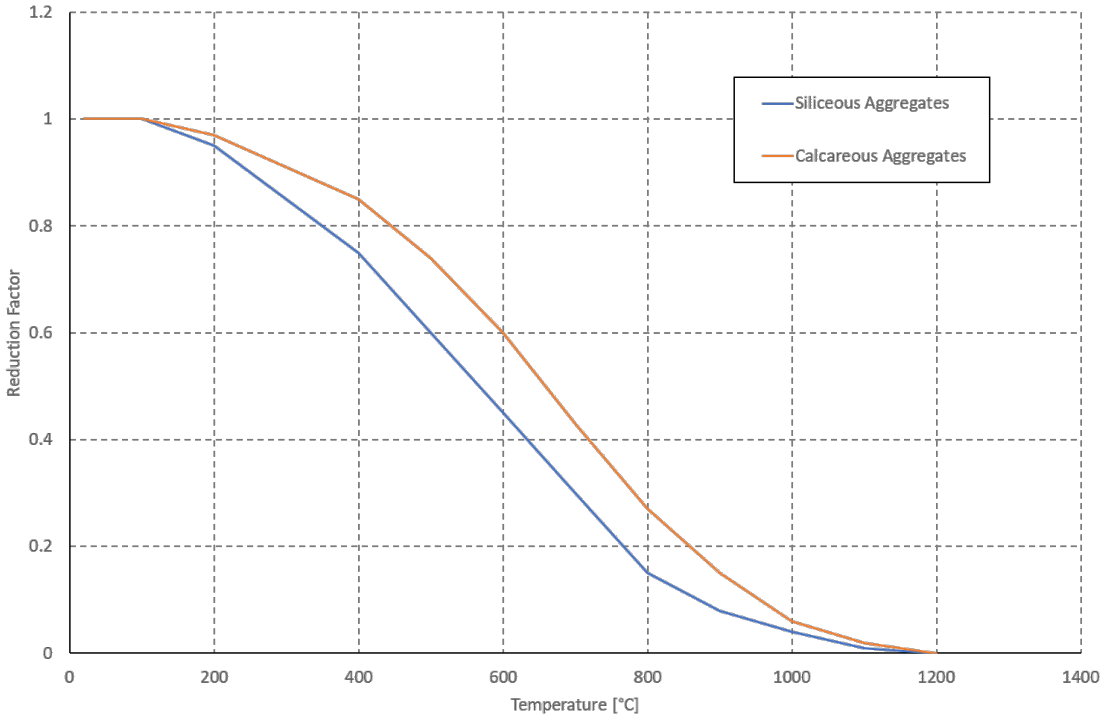


FIGURE 133: Strength reduction factors of normal weight concretes as a function of temperature according to [46].

ONE-DIMENSIONAL FINITE DIFFERENCE MODEL

The finite difference heat transfer model by Emmons [47] and Dusinberre [48] is described by Maluk [49]. It breaks the concrete into finite thicknesses for which the energy entering and leaving each thickness over a fixed period of time is resolved to define the resultant temperature of that thickness.

Notation is such that the subscript represents the element number (1 for the surface, 2 for the next layer and so on) and the superscript represents the timestep. The temperature of each node at the next timestep, (i+1), is defined as a function of the conditions at the current timestep, i. At the exposed surface, Node J=1, the Temperature at the following timestep i+1 is defined as:

$$T_1^{i+1} = T_1^i + \frac{2.\Delta t}{(\rho.c)_1^i \Delta x}.\left[\dot{q}''^i_{abs} - \left(\frac{\lambda_1^i + \lambda_2^i}{2}\right).\left(\frac{T_1^i - T_2^i}{\Delta x}\right)\right]$$

EQUATION 24

Where λ_j^i is the thermal conductivity of the material of element j at time step i. T_j^i is the temperature of element j at timestep i, ρ is the density of the material that forms the element, c is the specific heat capacity of the material that forms the element, Δx is the thickness of the element, and Δt is the timestep. $\dot{q}''^i_{abs}$ is the flux of heat from the fire environment to the exposed concrete surface and is defined as:

$$\dot{q}''^{i}_{abs} = h_T\left(T_g^i - T_1^i\right)$$

EQUATION 25

Where h_t is the total heat transfer coefficient (45 W/m^2.K), T_g is the exposure temperature (K), and T_1 is the temperature of the surface element (K). The temperature of any interior node j, at the next timestep i+1, is defined as:

$$T_j^{i+1} = T_j^i + \frac{\Delta t}{(\rho.c)_j^i \Delta x^2}.\left[\left(\frac{\lambda_{j-1}^i + \lambda_j^i}{2}\right)\left(T_{j-1}^i - T_j^i\right) - \left(\frac{\lambda_j^i + \lambda_{j+1}^i}{2}\right)\left(T_j^i - T_{j+1}^i\right)\right]$$

EQUATION 26

And the temperature at the unexposed face is defined as:

$$T_N^{i+1} = T_N^i + \frac{2.\Delta t}{(\rho c)_N^i}.\left[\left(\frac{\lambda_{N-1}^i + \lambda_N^i}{2}\right).\left(\frac{T_{N-1}^i - T_N^i}{\Delta x}\right) - \sigma\varepsilon\left({T_N^i}^4 - {T_{amb}}^4\right) - h_c\left(T_N^i - T_{amb}\right)\right]$$

EQUATION 27

Where σ is the Steffen-Boltzmann constant (5.67 x 10^{-8}W/m^2.K^4), ε is the emissivity of concrete, T_{amb} is the ambient temperature on the unexposed side (K), and h_c is the convective heat transfer coefficient (15 W/m^2.K).

APPENDIX G. DAMAGE ASSESSMENT FROM PHOTOGRAPHS

		Damage						
Level	Flat	None	Minor	Moderate	Severe	Major	Lobby Door Damage (All, Some, None)	Notes
3	7							
	8							
	9							Good example of high end Moderate damage, which contains some structural damage.
	10							
	Lift Lobby							
	Stair							
4	11							
	12							
	13							
	14							
	15							
	16							Spalling on most ceilings and walls in this flat; damage to bedroom compartment wall.
	Lift Lobby							
	Stair							
5	21							
	22							
	23							
	24							
	25							
	26							Spalling on most ceilings and walls in this flat; damage to compartment walls evident, but they are not completely gone.
	Lift Lobby							
	Stair							
6	31							Spalling on most ceilings and walls in this flat; no spalling on bedroom walls; damage to compartment walls evident, but they are not completely gone.
	32							
	33							
	34							Bedroom has partial fire-induced window damage but not enough to classify entire flat at moderate damage.
	35							
	36							Spalling on livingroom ceiling (not the walls) and on the ceilings and walls in the remainder of the flat; it should be noted that the compartment walls are not as damaged/burned as much as flats 31, 26, and 16, which have been rated as Severe.
	Lift Lobby							
	Stair							
7	41							Living room has minor fire-induced window damage but not enough to classify as moderate for entire flat.
	42							
	43							
	44							Lobby door completely gone and hard to say for sure whether it burned completely or not; I would consider this low end Major damage.
	45							Lobby door completely gone and hard to say for sure whether it burned completely or not; Spalling on all ceilings and walls in this flat; damage to compartment walls compared to flat 44.
	46							I would consider this middle-to-high end Severe damage based on the spalling on most ceilings and walls coupled with a compartment bedroom wall missing either from burning or post-fire teardown (hard to say for sure).
	Lift Lobby							
	Stair							
8	51							Firefighter damage to lobby door; Living room has partial fire-induced window, wall and floor damage but not enough to classify as moderate for entire flat.
	52							
	53							Partial fire-induced window damage in the living room, but not enough to classify as moderate for entire flat.
	54							
	55							Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.
	56							Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.
	Lift Lobby							Some partial fire damage coming from Flats 55 and 56, but not enough to classify as moderate for entire lobby.
	Stair							
9	61							Firefighter damage to lobby door.
	62							
	63							Firefighter damage to lobby door; Living room has fire-induced window, wall and floor damage but not enough to classify as moderate for entire flat.
	64							I would consider this low end Major damage based on the spalling on most ceilings and walls coupled with major interior compartment wall damage; lobby door completely gone; It is unclear if it burned or was simply removed.
	65							Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.
	66							Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.
	Lift Lobby							
	Stair							
10	71							Living room and a bedroom both have fire-induced window damage but not enough to classify as moderate for entire flat.
	72							Lobby door frame burned.
	73							I would consider this low end Major damage based on the spalling on most ceilings and walls coupled with major interior compartment wall damage; lobby door completely gone; It is unclear if it burned or was simply removed.
	74							Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.
	75							Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.
	76							Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions with major compartment wall damage.
	Lift Lobby							Spalling on ceiling and walls.
	Stair							Firefighter damage to lobby door.
11	81							Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.
	82							Light spalling on ceiling in entry way ceiling and peeling ceiling in the living room lead me to rate this as Moderate.
	83							I would consider this middle-to-high end Severe damage based on the spalling on most ceilings and walls with a clean bedroom; lobby door completely gone; It is unclear if it burned or was simply removed.
	84							Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.
	85							Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.
	86							Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.
	Lift Lobby							Spalling on ceiling and walls.
	Stair							Soot on the door but no damage visible.

12	91							Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.
	92							Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.
	93							Partial fire damage entering from living room windows with mainly soot evident throughout the flat; soot on the lobby door but no damage visible.
	94							Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.
	95							Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.
	96							Half broken lobby door found in doorway of Flat 96; post-flashover conditions.
	Lift Lobby							Spalling on the ceiling and walls with structural damage to the ceiling noted in entry ways to each flat.
	Stair							Some minor splittng at the top of the door.
13	101							Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.
	102							Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.
	103							Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.
	104							Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.
	105							Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.
	106							Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.
	Lift Lobby							Low-end Major damage; post-flashover conditions.
	Stair							Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.
14	111							Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.
	112							Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.
	113							Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.
	114							Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.
	115							Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.
	116							Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.
	Lift Lobby							Low-end Major damage; post-flashover conditions.
	Stair							Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.
15	121							Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.
	122							Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.
	123							Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.
	124							Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.
	125							Broken lobby door found in doorway of Flat 125.
	126							Broken lobby door found in doorway of Flat 126.
	Lift Lobby							High-end Severe damage; spalling noted on ceilings and walls, with more significant damage to ceilings and walls observed in the entry ways to each flat.
	Stair							Soot on the door but no damage visible.
16	131							
	132							Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.
	133							Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.
	134							Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.
	135							Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.
	136							Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.
	Lift Lobby							Post-flashover conditions.
	Stair							Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.
17	141							Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.
	142							Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.
	143							Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.
	144							Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.
	145							Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.
	146							Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.
	Lift Lobby							Middle-to-gigh end Severe damage; spalling noted on ceilings and walls primarily in entry walls to flats, where the most significant damage to ceilings and walls was observed.
	Stair							Soot on the door but no damage visible.
18	151							Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.
	152							Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.
	153							Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.
	154							Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.
	155							Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.
	156							Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.
	Lift Lobby							Post-flashover conditions.
	Stair							Door removed from hinge and appears to have some damage
19	161							Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.
	162							Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.
	163							Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.
	164							Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.
	165							Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.
	166							Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.
	Lift Lobby							Post-flashover conditions.
	Stair							Door has visible soot and fire damage.
20	171							Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.
	172							Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.
	173							Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.
	174							Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.
	175							Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.
	176							Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.
	Lift Lobby							Low-end Major damage; spalling noted on ceiling and most walls and some evidence of post-flashover conditions in the entry way to most flats.
	Stair							Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.
21	181							Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.
	182							Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.
	183							Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.
	184							Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.
	185							Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.
	186							Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.
	Lift Lobby							Post-flashover conditions.
	Stair							Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.
22	191							Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.
	192							Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.
	193							Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.
	194							Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.
	195							Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.
	196							Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.
	Lift Lobby							Post-flashover conditions.
	Stair							Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.
23	201							Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.
	202							Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.
	203							Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.
	204							Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.
	205							Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.
	206							Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.
	Lift Lobby							Post-flashover conditions.
	Stair							Damaged door found in hallway.

Flaming Ignition of Solid Fuels

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1. Introduction

This Chapter will describe how heating of a solid fuel leads to flaming ignition. The discussion will be centred on flaming ignition of solid fuels but will not address smouldering or spontaneous ignition since these subjects will be covered in Chapters 2.09 and 2.10 respectively. Thus, the presence of a source of heat decoupled from the solid and fuel gasification will be assumed throughout the Chapter.

The main focus of this Chapter is to assist the reader in understanding the phenomena, assumptions and simplifications embedded in different models and tests that attempt to predict ignition phenomena or to extract the parameters controlling it. The methodology to be followed goes from the general to the specific. Therefore, the problem will be initially formulated in as general a manner as possible. A series of common simplifications will then be made leading to reduced formulations. These simplifications are introduced for many reasons that include:

- Simplifications where the nature of the material studied allows the exclusion of some specific phenomena
- Simplifications where some processes disappear due to the characteristics of the test used to assess the material
- Simplifications where the required precision does not warrant the inclusion of higher levels of complexity
- etc.

To highlight the impact of simplifications, whenever possible, a comparison between the comprehensive description and the reduced formulation will be made to allow the reader to assess potential errors. As this Chapter progresses the resulting formulations become simpler and of greater practical use, nevertheless the impact of the assumptions strengthens increasing the potential for error or misuse of the information. The Chapter closes with a presentation of the simplest methodologies that correspond to classic treatments and are mainly associated to standard tests.

Most of the existing data on ignition is intimately related to the methodology used to extract it. Therefore, it is always conditioned by the nature of the test procedures, the hardware used and by the data analysis method. Given that the objective of this Chapter is to provide a phenomenological description of flaming ignition of solid fuels emphasis will be given to the different processes and not to reviewing available data. Throughout this Chapter the reader will be directed to other chapters and references where data will be presented in the context of the testing protocols used to

obtain it. As an example, some of the most comprehensive compilations of ignition data can be found in Chapter 3.04, in textbooks such as reference [1] or professional guidelines [2].

2. The Process of Ignition

When a solid material, initially at ambient temperature, is subject to an external source of energy the temperature of the exposed surface starts to increase. This moment will be defined as the onset of the ignition process, t=0. A series of physical and chemical phenomena are initiated as the energy reaches the surface of the material. This Chapter will attempt to describe these phenomena.

Without loss of generality and for simplicity, the ignition process will be described in a one-dimensional frame of reference with a single coordinate, x. Only one surface of the material will be heated and the origin of the coordinate system, x=0, will be placed at the exposed surface of the material. This frame of reference will move with a velocity V_R as the fuel consumes and the surface regresses. For some materials regression rates are very small and can be neglected, but this will not be assumed at this stage. A schematic of a generic solid material undergoing heating is presented in Figure 1. Figure 1 also shows all the different variables that evolve through the heating process. These variables will be described in detail later.

For simplicity, all processes involved will be divided in two groups, those associated with the solid phase and those with the gas phase. The solid phase treatment will lead to a description of the production of gas phase fuel ($\dot{m}''_p$) and the gas phase analysis will focus on how the ensemble of gaseous fuel and oxidizer lead to a flame. The solid phase will be treated first (Section 3), then the boundary conditions between both phases will be established, to finalize with a description of what happens in the gas phase (Section 4).

3. The Solid Phase

The temperature of the solid, initially at ambient (T_o), increases as the heat reaches the surface of the material. Highest temperatures will be achieved close to the surface, but energy transfer in-depth will result in an increase in temperature of a significant part of the solid. Therefore, the temperature will vary in-depth and in time, thus temperature needs to be represented as a function of both variables, T(x,t). Figure 1 shows a generic representation of the temperature distribution at a particular instant in time, t. The evolution of the temperature is defined by an energy balance in control volumes between both surfaces of the solid (x=0 and x=L). The surfaces will define the heat transfer in/out of the solid fuel or mathematically, the boundary conditions. It is important to note, that if other dimensions were to be considered, similar boundary conditions will have to be established at each surface of the material.

3.1 Pyrolysis Process

The process by which the solid transforms into gas phase fuel is called pyrolysis and generally implies the breakdown of the molecules into different, most of the time smaller, molecules. This is an important difference between solid and liquid

gasification. In the case of liquids a change of phase is not necessarily accompanied by a chemical change (see Chapter 2.08 for details on ignition of liquids). Pyrolysis tends to be an endothermic process generally controlled by many chemical reactions (some time hundreds) which are a strong function of the temperature. Most pyrolysis reaction rates tend to be described by Arrhenius type functions of the temperature

$$\dot{\omega} = A Y_O{}^m Y_S{}^n e^{-E/RT} \tag{1}$$

But could also be described by other simple expressions like polynomials such as

$$\dot{\omega} = C Y_O{}^m Y_S{}^n (T/T_o)^b \tag{2}$$

The reaction rate is generally defined in units of inverse seconds ($\dot{\omega}\,[1/s]$) and only when multiplied by the fuel density gives a gasification rate per unit volume ($\dot{\omega}'''$, kg/s.m^3). The constant "A" is also given in inverse seconds (1/s) and generally named the pre-exponential constant. In the case of a polynomial description, "A" will be replaced by another constant that is here defined as "C." These constants are a characteristic of each specific chemical reaction. "E" is the activation energy whose magnitude is also specific to each reaction and "R" has the value of 8.314 x 10^{-3} kJ mol^{-1}K^{-1}.

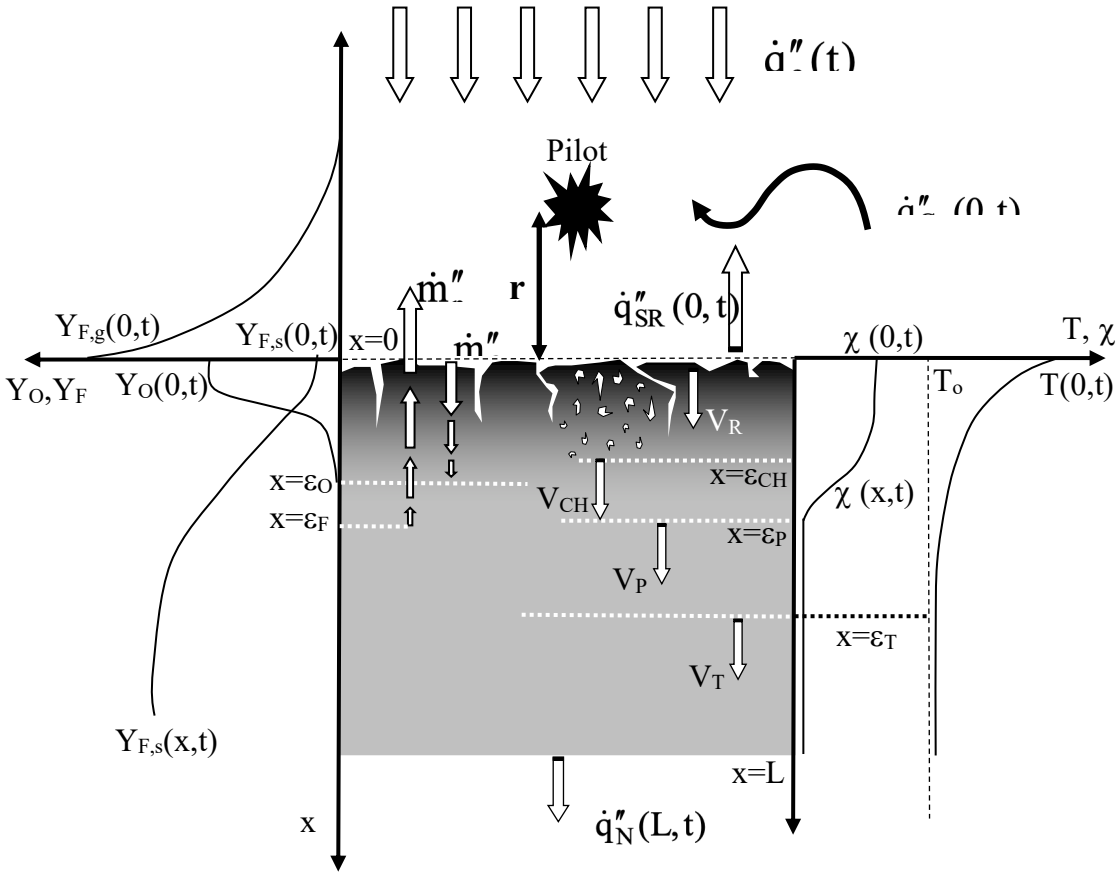


Figure 1 Schematic of the different processes occurring as a material undergoes degradation prior to ignition induced by an external source of heat.

The process of pyrolysis can be extremely complex and depending on the fuel and heating characteristics can follow distinctively different paths. These paths can be a compendium of numerous reactions that could be sequential or compete against each other. Furthermore, the chemical pathways followed can be strongly influenced by the presence of oxygen as indicated in equations (1) and (2). In both equations Y_O and Y_S are intended to be generic representations of oxygen and solid fuel mass fractions participating in the solid degradation and "m" and "n" are constants.

It is important to note that while degradation of some fuels will show dependency on the oxygen concentration many others will not [3, 4]. In those cases "m" is assumed to be zero.

The chemical pathways leading to the pyrolysis of most solid fuels of interest in fire are fundamentally incomplete as much as the constants associated to the equations that will serve to quantify the rate of each reaction step. Many studies have evaluated reduced chemical mechanisms for the pyrolysis of different solids [5,6,7] but there is still great uncertainty on the chemical pathways, the number of steps required and the constants associated to them [8,9]. Figure 2 shows an example of chemical kinetic compiled obtained for PMMA by using an expression similar to Equation (1).

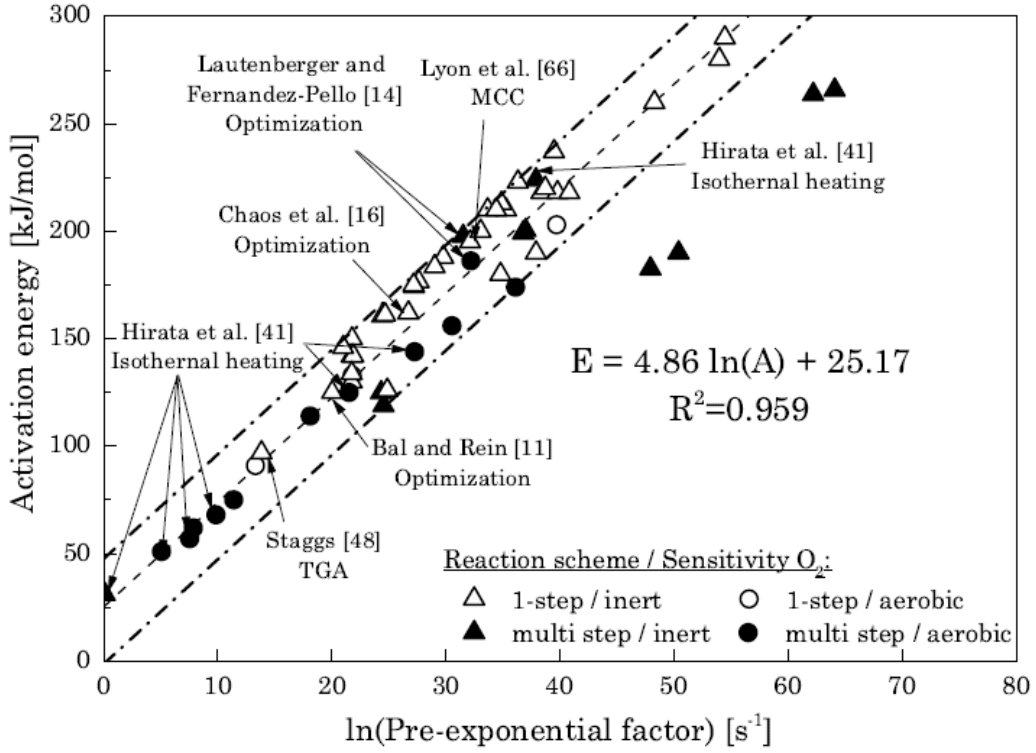


Figure 2 Kinetic parameters of the pyrolysis decomposition of PMMA as reported in the literature [8]

Thermo-Gravimetric Analysis (TGA) has been used in the past to establish reduced chemical reaction mechanisms as well as the associated constants. The principles behind TGA studies and some applications to materials relevant to fire are presented

in Chapter 1.07. As an example, a reduced kinetic mechanism for polyurethane (PU) can be found in reference [6]. The authors propose a four step mechanism of the form:

Step i=1 $$\mathrm{PU} \rightarrow \nu_{\beta,p}\ \beta\text{-PU} + \nu_{g,p}\ \mathrm{Gas}$$

Step i=2 $$\beta\text{-PU} \rightarrow \nu_{c,p\beta}\ \mathrm{Char} + \nu_{g,p\beta}\ \mathrm{Gas}$$

Step i=3 $$\begin{cases} \mathrm{PU} + \nu_{O2,o}\ \mathrm{O_2} \rightarrow \nu_{c,o}\ \mathrm{Char} + \nu_{g,o}\ \mathrm{Gas} \\ \beta\text{-PU} + \nu_{O2,o}\ \mathrm{O_2} \rightarrow \nu_{c,o}\ \mathrm{Char} + \nu_{g,o}\ \mathrm{Gas} \end{cases}$$

Step i=4 $$\mathrm{Char} + \nu_{O2,c}\ \mathrm{O_2} \rightarrow \nu_{r,c}\ \mathrm{Residue} + \nu_{g,c}\ \mathrm{Gas}$$

where the reaction rate for each step ($\dot{\omega}$) is presented by an expression of the form of Equation (1). The first two steps encompass purely thermal degradation, while the last two steps include oxidation. Two intermediate products are formed from the initial degradation of the polyurethane, β-PU and Char. While the terms Gas and Residue represent the gaseous and solid products of the degradation. It is important to note that there are sequential and competing reactions; while steps 1 and 2 are sequential, step 3 competes with both previous steps. The authors use independent TGA data [10] to obtain all twelve constants thus establishing a complete model for the degradation of polyurethane.

Figure 3 shows two curves extracted from reference [6] where the model is compared to experimental data for inert and air atmospheres. The figures show the sample mass loss rate as a function of time. The effect of oxygen and the impact of the heating rate are evident from the data. The results show very good agreement with the four step model for all conditions studied.

Despite the generalized use of TGA data, there is increasing recognition that pyrolysis reaction pathways are sensitive to the heating rate. The basic nature of TGA studies requires heating rates of the order of 1 to 20 ºC /minute which is generally an order of magnitude slower that heating rates typical of fires. Recent studies have established methodologies that use standard test methods and advanced optimization techniques to establish reduced reaction schemes and their associated constants [7,11-14]. Although, these procedures allow exposing the materials to heating rates typical of fires and obtaining comprehensive sets of constants they have only been applied to a reduced number of materials. Currently, these methodologies remain fundamentally research tools.

It is important to note that the qualitative and quantitative agreement described in the above example is not usual for materials commonly present in fire and the problem of establishing the chemistry of pyrolysis is far from being solved. Therefore, when studying flaming ignition of solids it is common to make strong simplifications to handle chemical degradation as the solid fuel is heated. Such simplifications will be made later and their impact will be assessed.

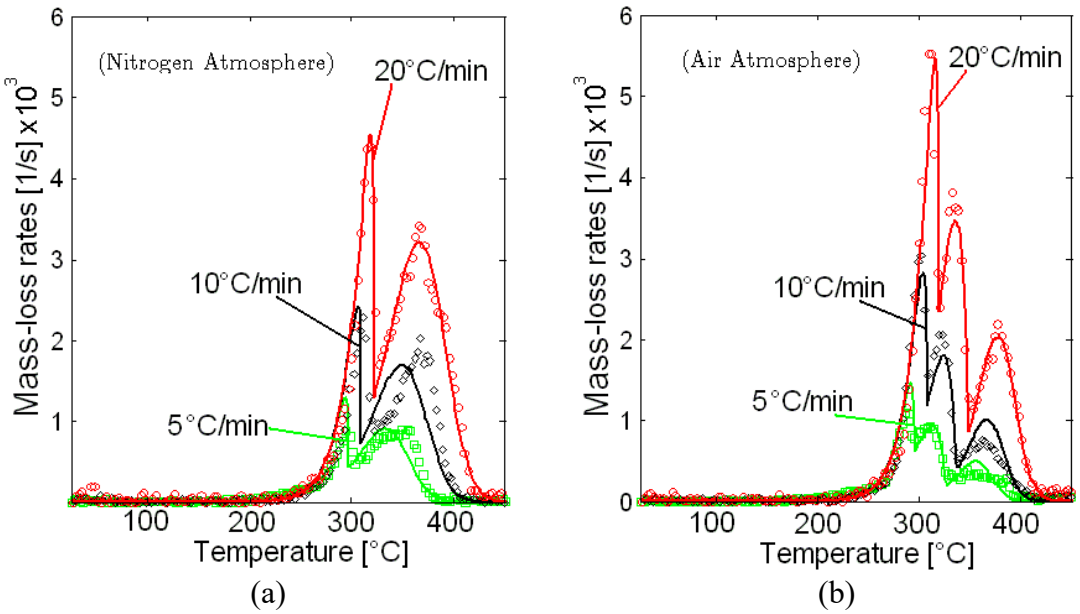


Figure 3 TGA data for polyurethane extracted from reference [10] (symbols) superposed to the reduced kinetic model from reference [7] (lines) for inert atmosphere (a) and air (b).

3.2 The Production of Gaseous Fuel

Before flaming ignition can occur, fuel in the gas phase needs to be produced. Solid materials that are not susceptible to spontaneous ignition will show very little evidence of chemical reactions at ambient temperatures, thus can be deemed as inert. The reaction rates associated to pyrolysis can be considered negligible and therefore the material will not follow any transformation. As the temperature increases the reaction rates increase and the solid fuel starts changing. Given the temperature distribution within the material, the rates of decomposition are a function of "x," with larger production of pyrolyzates close to the surface and lower production in-depth.

Local production of fuel is not the only important variable. The gas phase fuel produced might be the result of a combination of pyrolysis and oxidation reactions, thus its composition might include large quantities of fully oxidized compounds such as carbon dioxide (CO_2), partially oxidized gases such as carbon monoxide (CO) and other molecules that can have all levels of partial oxidation. Therefore, together with the reaction rates, the mass fraction of inert gases needs to be subtracted leaving the remaining reactive gases. As an example, Kashiwagi and Nambu [15] studied the degradation products of cellulosic paper showing that there is a significant presence of inert gases like water vapour, fully oxidized gases like CO_2, partially oxidized products like CO and fuel like CH_4 and H_2.

There is very little data available on the degradation products of most materials relevant to fire, therefore, the mass fraction of flammable gases present in the local products of degradation will be described here by means of a single variable, $Y_{F,s}(x,t)$, which represents a global contribution of all compounds that can be further oxidized. Figure 1 represents $Y_{F,s}(x,t)$ as an increasing function with a minimum at the surface ($Y_{F,s}(0,t)$). This is based on the assumption that where there is a higher presence of oxygen there is higher levels of oxidation.

Oxygen can migrate inside a fuel resulting also in an in-depth distribution ($Y_O(x,t)$) that reaches ambient values at the surface ($Y_O(0,t)$). In-depth oxygen and fuel diffusion is controlled by the structure of the solid. Some materials are highly permeable and allow unrestricted transport of species in and out of the solid. For other materials oxidation will occur only very close to the surface and could be potentially neglected. The permeability of the fuel can be a function of many variables including the degradation and consumption of the material and has deserved very little attention in the fire literature. In the absence of a well defined permeability function, here, a simple variable associated to the fuel permeability ($\chi(x,t)$) will be introduced and assumed to describe in a generic manner the fraction of the fuel produced that can flow through the solid material. It has to be noted that $\chi(x,t)$ is not strictly a permeability function (as per Darcy's law) but a combination of permeability, porosity and any fractures within the material.

Oxygen and fuel concentrations will be controlled by the local permeability and by production/consumption rates, thus indirectly by the temperature distribution ($T(x,t)$). This makes necessary to treat them independently, therefore two independent variables emerge, $\varepsilon_F(t)$ and $\varepsilon_O(t)$. The former represent the region where fuel is being produced while the latter represents the region where oxygen is present in relevant quantities.

If all the reactions occurring can be represented in an Arrhenius form (equation (1)) then the local mass production ($\dot{m}'''_P(x,t)$) can be the summarized into a function of the form:

$$\dot{m}'''_P(x,t) = Y_{F,s}(x,t)\sum_{i=1}^{i=N}\left[A_i Y_O^{m_i}(x,t) Y_S^{n_i}(x,t) e^{-E_{ii}/RT(x,t)}\right] \tag{3}$$

where the summation is not truly a sum of all the different "N" reaction steps but just some global combination of them that includes sequential and competitive reactions.

To obtain the total fuel production at the surface per unit area ($\dot{m}''_P(0,t)$) it is necessary to integrate equation (3) across the entire depth including the permeability function described above. It is important to note that fuel produced in-depth does not have to come out, and in many cases pressure increases within the fuel structure can be observed. The effects of permeability and pressure are combined in a complex manner to define the flow within the porous medium. This remains an unresolved problem, thus the use of a simple variable such as $\chi(x,t)$ is justified. Integrating equation (3) we obtain the following expression

$$\dot{m}''_P(0,t) = \int_0^L \chi(x,t)\left(Y_{F,s}(x,t)\sum_{i=1}^{i=N}\left[A_i Y_O^{m_i}(x,t) Y_S^{n_i}(x,t) e^{-E_{ii}/RT(x,t)}\right]\right) dx$$

Assuming that any production of fuel is negligible for $x>\varepsilon_F$ then the boundaries of integration can be changed to

$$\dot{m}''_P(0,t) = \int_0^{\varepsilon_F} \chi(x,t)\left(Y_{F,s}(x,t)\sum_{i=1}^{i=N} \left[A_i Y_O^{m_i}(x,t) Y_S^{n_i}(x,t) e^{-E_{ii}/RT(x,t)}\right]\right) dx \quad (4)$$

Where the chemical reactions are left in a generic form while recognizing that, due to the absence of oxygen, the reactions occurring between $\varepsilon_O<x<\varepsilon_F$ might differ significantly from those occurring between $0<x<\varepsilon_F$.

To summarize, the production of fuel is controlled by the following variables:

Temperature	T(x,t)
Local fuel concentration	$Y_S(x,t)$
Local oxygen concentration	$Y_O(x,t)$
Residual fuel fraction	$Y_{F,s}(x,t)$
Permeability function	$\chi(x,t)$
Oxygen penetration depth	$\varepsilon_O(t)$
Reactive depth	$\varepsilon_F(t)$
Kinetic constants	A_i, m_i, n_i, E_i

3.3 Charring

For the purpose of ignition of a solid fuel the process of charring has an impact on both heat and mass transport therefore needs to be briefly addressed. A general summary of the chemical processes leading to charring can be obtained in Chapter 1.07, and more details form Cullis and Hirschler [16] for polymers and in the case of wood from Drysdale [17], thus will not be described here. Instead an attempt will be made to explain the role of charring in ignition.

For charring materials pyrolysis leads to the production of gaseous fuel (pyrolyzate) and a residual solid phase char. The char is mainly a carbonaceous solid that could be further decomposed. The secondary decomposition could be complete, leading to an inert ash or to a secondary char that can be further decomposed in a single or multiple steps. Non-charring materials decompose leaving no residue behind.

From the perspective of ignition, the exposed surface represents the boundary between the gas and the solid. This boundary moves as the material is completely removed. The rate at which the surface moves is the regression rate (V_R). For charring and non-charring materials, this will be the boundary where complete consumption of the fuel is achieved. Although, regression rates can be very different between charring and non-charring materials, at the surface, the main difference between the two material types is the temperatures that can be achieved. Carbonaceous chars can reach much higher temperatures, leading in many cases to vigorous oxidation (surface glowing) that can be the catalyser for gas phase ignition. This will be part of the gas phase discussion. In what concerns the production of fuel, the differences appear mostly in-depth where temperature is controlled by heat transfer through the char and fuel production is affected by an overall permeability function. The effects of permeability were described above and temperature effects on fuel production will be discussed in the context of the calculation of the temperature distributions.

3.5 The Thermal Depth (ε_T)

When a heat flux is applied to one of the solid surfaces, the heat travels across the solid fuel. Initially only a very small area is affected, but as the thermal wave travels through material a larger and larger fraction of the solid is heated. The velocity of the thermal wave is represented in Figure 1 by $V_T(t)$. $V_T(t)$ is a function of time because it will decrease as the thermal wave moves away from the heating source and towards the cold back surface. The region that has been heated is quantified by the characteristic length $\varepsilon_T(t)$. It is important to note that, given that temperature is a continuous function, $\varepsilon_T(t)$ has to be arbitrarily defined simply as the end of the heated region. There is no exact mathematical definition for this length but physically it means that the temperature is approaching ambient temperature ($T \approx T_0$) or the gradient of the temperature is approaching zero ($dT/dx \approx 0$). The proximity that temperature or the gradient have to achieve when approaching these targets is only a matter of what precision is required by those making the analysis.

The length scale $\varepsilon_T(t)$ is extremely important because it characterizes solids into different groups. This breakdown enables the simplification of the energy equation and the generation of simple analytical expressions for the temperature distribution. For the purpose of ignition, solid fuels are classified in:

Semi-Infinite Solid ($L > \varepsilon_T$): If the thermal wave is far from the end of the sample, the heat coming from the exposed surface has still not migrated to the back end. The temperature at the back end is ambient (T_0) and there are no heat losses through this surface. The thickness of the sample is no longer a relevant quantity and therefore the fuel can be treated as a semi-infinite solid ($L \rightarrow \infty$). Materials do not show semi-infinite solid behaviour for ever, as time progresses the thermal wave will eventually reach the end of the sample. In many cases materials will behave as semi-infinite solids for the period of interest, in which case the assumption of $L \rightarrow \infty$ is valid. The boundary condition for the energy equation becomes:

$$x = L \rightarrow \infty \qquad \dot{q}''_N(\infty, t) = 0 \qquad T = T_0 \tag{5}$$

Thermally-Thick and Thermally-Thin Solid ($\varepsilon_T \geq L$): The thermal wave has reached the end of the sample and therefore heat losses at the back end need to be quantified. The thickness of the sample, L, becomes a relevant dimension of the problem and a boundary condition for x=L needs to be defined. This group can be sub-divided into two different cases, thermally thick and thermally thin. A solid can be defined as thermally thick if a significant thermal gradient exists within the solid through the period of ignition. In contrast, in a thermally thin solid the gradient is negligible for most of the time before ignition. A simple criterion based on the Biot number (Bi) is generally used for the purpose of establishing if a material is thermally thin or thick. The Biot number is defined as Bi=hL/k, where "h" is a global heat transfer coefficient (W/m^2K) and "k" is the thermal conductivity (W/mK). If $Bi \ll 1$ then temperature gradients inside the solid are negligible, while if the Biot number is not much smaller than unity then temperature gradients need to be considered. While this is an

important distinction for the energy equation, it does not have an effect on the boundary condition at x=L, so if $\varepsilon_T \geq L$ then the boundary condition is defined as:

$$x=L \qquad -k\left.\frac{dT}{dx}\right|_{x=L} = \dot{q}''_N(L,t) \tag{6}$$

where $\dot{q}''_N(L,t)$ will be left as a generic heat loss term at the back end of the solid fuel.

3.6 The Pyrolysis (ε_P) and Charring Depths (ε_{CH})

Within the region where the temperature has increased above ambient significant chemical activity can occur. The chemical activity leads to the production of fuel at a rate specified by equations of the type of (1) or (2). The depth at which the chemistry can be assumed to be significant is commonly defined as a pyrolysis depth (ε_P) which propagates at a velocity V_P. As with the thermal depth, there is no mathematical function that describes the location of the pyrolysis front, $x=\varepsilon_P$ because the reaction equations are also continuous functions. Nevertheless, if the assumption is made that pyrolysis reactions have high activation energy then the transition between the zones of significant and negligible reactivity can be considered as being abrupt [18]. This permits the definition of critical parameters that can be considered to define the onset of pyrolysis. The most common parameter is a pyrolysis temperature, T_P, below which the solid fuel can be considered inert. It is important to note that the pyrolysis temperature is not a true physical parameter but a simple way to track the onset of high activation chemical reactions.

As described above, for $x>\varepsilon_P$ the solid can be considered inert, thus thermal properties can be defined as those of the original solid fuel. The thermal properties relevant to ignition are

Density	$\rho(x,t)$	Kg/m^3
Thermal conductivity	$k(x,t)$	W/m.K
Specific heat	$C(x,t)$	J/kg.K

which are all functions of temperature. Since the temperature varies in-depth they are also functions of "x." The evolution of these properties with temperature for common materials can be found in most heat transfer book [19], nevertheless, for materials typically present in fires (wood, complex plastics, composites, etc.) these properties are in many cases unknown [20,21].

For $x>\varepsilon_P$ the chemical reactions have initiated the decomposition of the material. The relevant properties remain the same, nevertheless pyrolysis introduces further changes to the properties. The gasification of the fuel and its transport towards the surface will strongly affect the density, while any potential voids will force to redefine thermal conductivity and specific heat to account for the existence of at least two phases.

The process of pyrolysis can lead directly to gasification with no residue (non-charring) or to a carbonaceous residue (charring). Figure 1 shows the case of a

charring material where a second front for charring ($x=\varepsilon_{CH}$) is formed behind the pyrolysis front. The charring front will propagate at a velocity V_{CH} and will leave behind a residue that will have a new set of properties that are potentially very different to those of the fuel. The properties are still the permeability, the density, thermal conductivity and specific heat but precise values are mostly unknown for most chars issued of materials relevant to fires.

It is common to see in the char region large voids and cracks that compromise the one-dimensional treatment provided here. These have been considered when addressing materials such as wood but will not be described here.

3.7 Melting and the Evaporation of Water

Melting or water evaporation have not been considered in the description of the ignition until this point. These two processes are endothermic phase changes that can have a significant effect on the temperature distribution in the solid. Numerous models have been built in the past to describe the heat sinks associated to melting and several studies have attempted to quantify the impact of melting on practical situations such as dripping.

Phase changes are generally incorporated to the energy equation as heat sinks where some rate function is created to describe the conversion from one phase to the other. The simplest procedure is to assign a critical temperature to the phase change (i.e. 100^{o}C for water) and a heat of melting or evaporation (ΔH_M). Once the fuel or water reaches this temperature it is converted to the high temperature phase. The phase change process is assumed to be infinitely fast and therefore the rate is defined by the available energy reaching the location where the phase change is occurring. All the energy is then used for the phase change and the thermal wave can only proceed once the transition has been completed. This approach is inappropriate if the available energy is very low, in this case thermodynamic equilibrium equations will define the rate of vaporization or melting. Other more complex models that include processes such as re-condensation can be found in the literature but will not be discussed here.

The consequences of melting or water evaporation are various. Phase changes can affect the thermal properties of the fuel significantly and can result in motion of the molten fuel or water vapour. This leads to convective flow of energy or mass transfer.

Understanding the physical processes behind phase change does not represent a great challenge. Furthermore, the potential impact of phase change on ignition is clear. Thus it is evident that any predictive tool for ignition should attempt to quantify the impact of phase change on ignition. Nevertheless, the formulation of a model that can describe these processes in a comprehensive manner is extremely complex and the measurements that could serve for its validation are mostly non-existent.

Given that, phase change is fundamentally an additional heat sink that will have to be incorporated to the energy equation in an arbitrary manner, it is justifiable to exclude the treatment of this subject from the present analysis. Nevertheless, this is done with the clear warning that its exclusion will have a significant impact on any quantitative assessment of the ignition process.

Other processes that deserve to be addressed are softening or glass transition. Many materials such as thermoplastics will undergo gradual or drastic property changes with temperature. These property changes are not endothermic but will affect the progression of heat through the sample and could lead to dripping. Softening or glass transition will be directly incorporated in the analysis through the variable properties described in Section 3.6. An example of how these properties change with temperature is shown in Figure 4. Figure 4 presents the evolution of the product of all three thermal properties (kρC) for PMMA as a function of temperature, indicating the abrupt change occurring at the glass transition temperature.

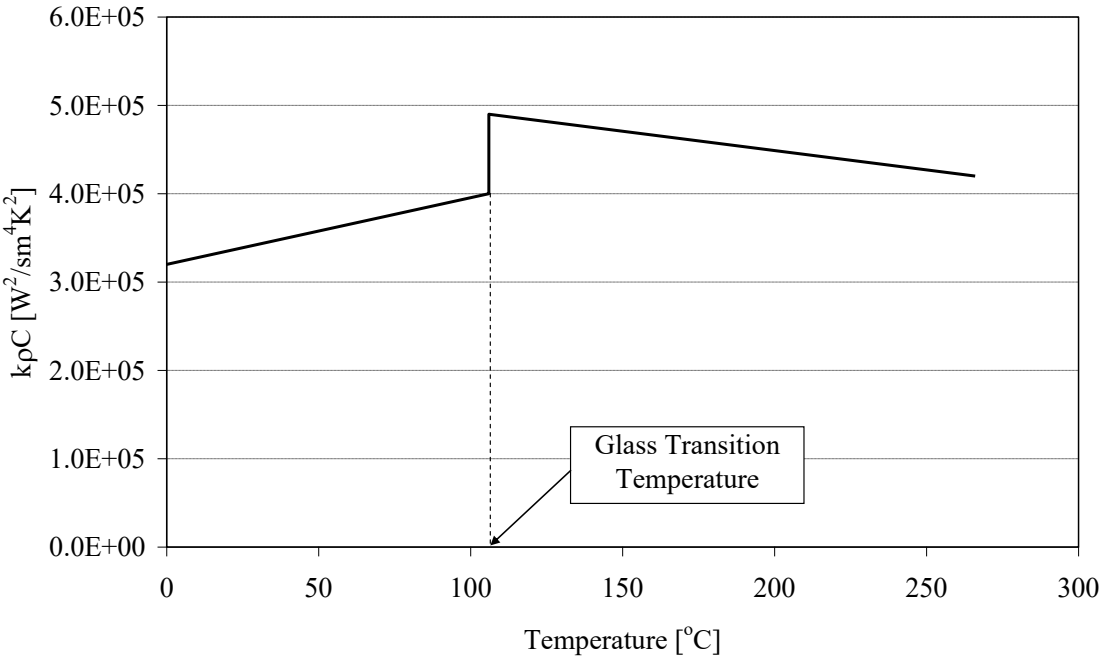


Figure 4 Evolution of the product of the thermal conductivity, density and specific heat (kρC) for PMMA as a function of temperature.

3.8 The Temperature Distribution

As explained in Section 3.2, to determine the fuel production it is necessary to define the evolution of the temperature inside the solid fuel. This can be achieved by defining a comprehensive energy equation. Figure 4 represents a typical control volume for $x<\varepsilon_P$ where all the main heat transfer mechanisms are incorporated.

For the purposes of this description the coordinate system will be anchored to the regressing surface, thus "x" will move with a velocity V_R. A mass flow of fuel will therefore cross the control volume presented in Figure 5 carrying energy in and out ($\dot{q}''_S$). The gaseous products of pyrolysis and oxygen diffusion will also carry energy in and out of the control volume ($\dot{q}''_P, \dot{q}''_O$ respectively) and the generic expression for the mass flow of these gases ($\dot{m}''_P, \dot{m}''_O$) incorporates the regression rate. Heat is conducted in and out of the control volume ($\dot{q}''_{CND}$) and for generality in-depth radiative absorption is allowed ($\dot{q}'''_{RAD}$). Since for $x<\varepsilon_P$ the temperature is sufficiently

high to allow for chemical reactions all heat sources and sinks associated to all chemistry need to be included. Table 1 summarizes all terms incorporated in Figure 5.

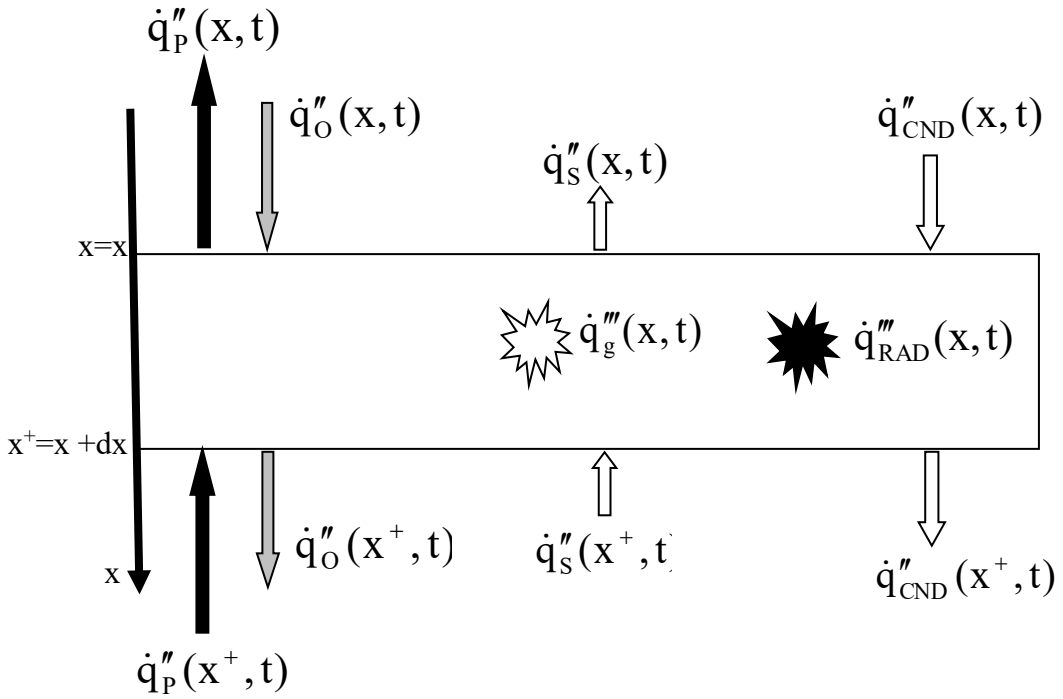


Figure 5 Typical control volume for $x<\varepsilon_P$ showing the main heat transfer mechanisms.

Estimation of the net heat transfer will lead to a change in the energy accumulated within the control volume. The following expression summarizes the energy balance:

$$\frac{\partial E_{CV}}{\partial t} = \left[\dot{q}''_S(x^+,t) + \dot{q}''_P(x^+,t) + \dot{q}''_0(x,t) + \dot{q}''_{CND}(x,t)\right] - \left[\dot{q}''_O(x+,t) + \dot{q}''_{CND}(x+,t) + \dot{q}''_S(x,t) + \dot{q}''_P(x,t)\right] + \dot{q}'''_{RAD}(x,t)\,dx + \dot{q}'''_g(x,t)\,dx$$

where $E_{CV} = \rho_S(x,t)C_S(x,t)T(x,t)\,dx$, which after appropriate substitutions results in the general energy equation for the control volume.

$$\frac{\partial[\rho_S C_S T]}{\partial t} = \frac{\partial}{\partial x}\left[k_S \frac{\partial T}{\partial x}\right] + \frac{\partial[\dot{m}''_P C_{P,P} T_P]}{\partial x} - \frac{\partial[\dot{m}''_O C_{P,O} T_O]}{\partial x} + \frac{\partial[\rho_S V_R C_S T]}{\partial x} + \dot{q}'''_{RAD} + \sum_{i=1}^{i=N} \Delta H_{P,i}\rho_S\left[A_i Y_O^{m_i} Y_S^{n_i} e^{-E_i/RT}\right] \quad (7)$$

Description	In	Out	Formulation
Energy transported by gaseous fuel traversing the control volume	$\dot{q}''_P(x^+,t)$		$\dot{m}''_p(x^+,t)C_{P,P}(x^+,t)T_P(x^+,t)$
		$\dot{q}''_P(x,t)$	$\dot{m}''_p(x,t)C_{P,P}(x,t)T_P(x,t)$
Energy transported by oxygen traversing the control volume		$\dot{q}''_O(x^+,t)$	$\dot{m}''_O(x^+,t)C_{P,O}(x^+,t)T_O(x^+,t)$
	$\dot{q}''_O(x,t)$		$\dot{m}''_O(x,t)C_{P,O}(x,t)T_O(x,t)$
Energy transported by solid fuel traversing the control volume	$\dot{q}''_S(x^+,t)$		$\rho_S(x^+,t)V_R(t)C_S(x^+,t)T(x^+,t)$
		$\dot{q}''_S(x,t)$	$\rho_S(x,t)V_R(t)C_S(x,t)T(x,t)$
Heat conduction	$\dot{q}''_{CND}(x,t)$		$-k_S\left.\frac{dT}{dx}\right\|_{x=x}$
		$\dot{q}''_{CND}(x^+,t)$	$-k_S\left.\frac{dT}{dx}\right\|_{x=x^+}$
Radiative absorption	$\dot{q}'''_{RAD}(x,t).dx$		$\dot{q}'''_{RAD}(x,t).dx$
Chemical energy (generation/sink)	$\dot{q}'''_g(x,t).dx$		$\sum_{i=1}^{i=N}\Delta H_{P,i}\rho_S(x,t)\left[A_i Y_O^{m_i}(x,t)Y_F^{n_i}(x,t)e^{-E_i/RT(x,t)}\right]$

Table 1 Summary of all energy transport within a generic control volume for $x<\varepsilon_P$. $\Delta H_{P,i}$ is the net heat resulting from each individual chemical reaction. The net heat will be endothermic for most pyrolysis processes and exothermic for oxidative reactions. The summation is not truly a summation, but as explained earlier, is the overall set of chemical reactions where some could be sequential and others competing.

Given the differential nature of the equation all variables are assumed to be functions of "x" and "t" so these dependencies are no longer indicated. Many of the terms are left in a generic form and not quantified. Their quantification is complex, thus a more detailed discussion will be provided later in those cases where it is necessary.

The solution to equation (7) will provide the evolution of the temperature distribution along the sample and as a function of time (T(x,t)). This solution can then be incorporated in Equation (4) to establish the fuel production rate. It is important to note that thermal equilibrium between phases has not been assumed, thus there are three different temperatures in equation (7), T, T_P and T_O. Expressions similar to Equation (7) can be defined for each phase and will have to be solved in a simultaneous manner. The boundary condition will be the exchange of heat between phases, this is generally done using empirical correlations for heat transfer in porous media [22]. The alternative approach is to demonstrate thermal equilibrium between the phases (heat transfer is much faster than mass transfer within the pores), in which case all temperatures will be the same and only Equation (7) will have to be solved.

To summarize, and in addition to the variables established in Sections 3.2 and 3.6, the temperature distribution is controlled by the following variables:

Thermal conductivity	$k_S(x,t)$
Specific heat	$C_S(x,t)$
	$C_{P,P}(x,t)$
	$C_{P,O}(x,t)$
Density of the solid	$\rho(x,t)$
Regression rate	$V_R(t)$
Mass flow	$\dot{m}''_P$
	$\dot{m}''_O$
Temperature of the gas phase	T_P
	T_O
Radiative properties of the solid (absorptivity, $\alpha_S(x,t)$)	$\alpha_S(x,t)$
Heat of reaction	$\Delta H_{P,i}$

3.9 The Surface Boundary Conditions (x=0 and x=L)

Figure 1 shows all the different modes of heat transfer through the surface control volumes. In theory, control volumes at x=0 and x=L could be represented in a generic manner that makes them identical. In practise this is generally not the case because materials tend to have an exposed face and one that is in contact with some backing. The backing will define a conductive boundary condition while the open face a convective/radiative one. For illustration purposes, this distinction will be made here and the exposed face will be defined as an open boundary, thus $\dot{q}''_N(0,t)$ will include convection and radiation, while the back-face, $\dot{q}''_N(L,t)$, will be attached to a substrate, thus will be defined as an impermeable conductive boundary condition. It needs to be emphasized that this is an arbitrary simplification that is only done to illustrate two different types of boundary conditions because they are mutually exclusive. In many cases a material might be sandwiched between two solids or exposed at both ends. The appropriate choice of boundary conditions needs to be made but the processes to be described will not be different.

Figure 6 shows the open boundary condition (x=0) at a specific point in time. The different components are mainly those described in Table 1 leading to a very similar expression for the energy balance as that presented in Section 3.8. So at the x=0 surface

$$\frac{\partial E_{CV}(0,t)}{\partial t} = \left[\dot{q}''_S(\varepsilon,t) + \dot{q}''_P(\varepsilon,t) + \dot{q}''_0(0,t)\right] - \left[\dot{q}''_O(\varepsilon,t) + \dot{q}''_{CND}(\varepsilon,t) + \dot{q}''_S(0,t) + \dot{q}''_P(0,t) + \dot{q}''_{SR}(0,t) + \dot{q}''_{Cv}(0,t)\right] + \dot{q}'''_{RAD}(x,t)\varepsilon + \dot{q}'''_g(x,t)\varepsilon$$

where the terms that remain undefined are described in Table 2. Radiation absorption within the surface control volume is represented as $\dot{q}''_{RAD}(0,t)\varepsilon = \dot{q}''_e(0,t) - \dot{q}''_e(\varepsilon,t)$ to remain consistent with the notation of the previous section.

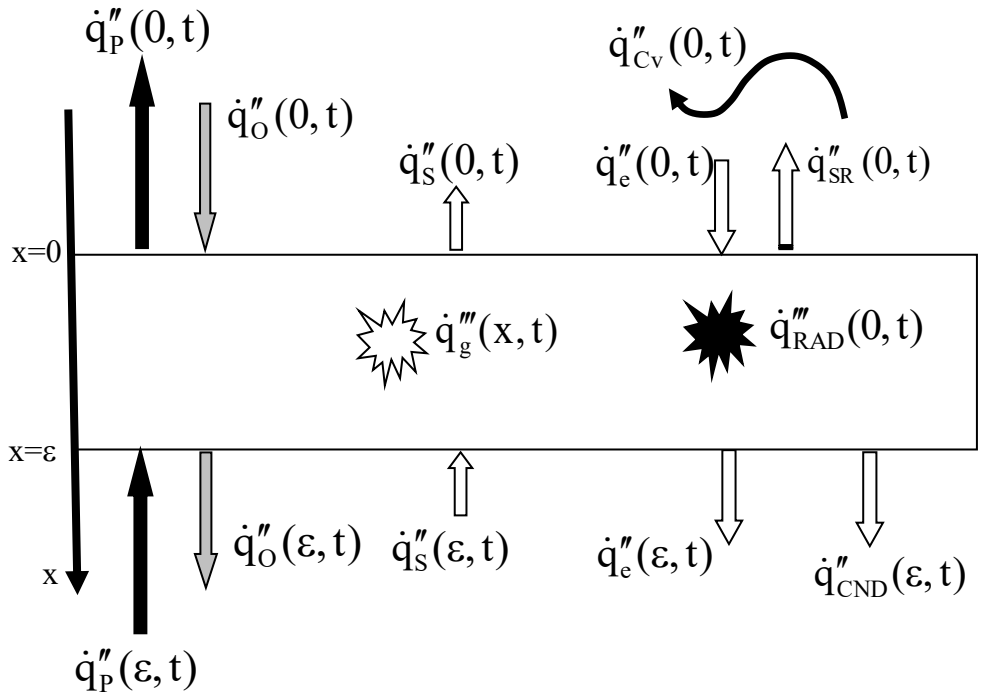


Figure 6 Boundary control volume for x=0 showing the main heat transfer mechanisms.

For the boundary control volume the characteristic thickness ε→0, which eliminates all energy transported by mass flow, radiation absorption and energy generation. The final expression for the exposed boundary condition is then:

$$0 = k_S \left.\frac{\partial T}{\partial x}\right|_{x=0^+} - \varepsilon_S(0,t)\sigma(T^4(0,t) - T_0^4) - h_{Cv}(t)(T(0,t) - T_0) \tag{8}$$

A similar treatment can be followed with the back end boundary condition (x=L). In this case the back surface is assumed to be in direct contact with another solid. Mass transfer, convection and radiative losses to the environment are therefore precluded. The boundary condition will only include conductive terms and can be described as:

$$0 = -k_S \left.\frac{\partial T}{\partial x}\right|_{x=L^-} + k_B \left.\frac{\partial T_B}{\partial x}\right|_{x=L^+} \tag{9}$$

where k_B is a global thermal conductivity of the backing material that could include the thermal resistance between the two solids. In most cases the contact between both solids is not perfect, leaving air gaps or requiring adhesives, in these cases it is important to define the thermal conductivity in a manner that includes the contact resistance. The variable T_B is the temperature of the backing solid, these temperature will come out of a solution to an additional energy balance of the form of Equation

(7). Note that if k_B is very small the backing can be assumed as an insulator and the boundary condition can be summarized to no losses at the back. This eliminates the need to solve a second energy equation for T_B.

Description	In	Out	Formulation
Radiation from the exposed surface to the environment		$\dot{q}''_{SR}(0,t)$	$\varepsilon_S(0,t)\sigma(T^4(0,t)-T_0^4)$
Convective losses from the surface		$\dot{q}''_{Cv}(0,t)$	$h_{Cv}(T(0,t)-T_0)$
External radiative heat-flux	$\dot{q}''_e(0,t)$		$\dot{q}''_e(0,t)$

Table 2 Summary of all energy transport within the surface control volume. Only terms not presented in Table 1 are described here. The Stefan-Boltzmann Constant is: σ=5.670 x 10^{-8} W/m^{2}K^4, $\varepsilon_S(0,t)$ is the surface emissivity and h_{Cv} is the convective heat transfer coefficient. Only for illustration purposes two different approaches are used to describe radiation, absorption is allowed to happen in-depth while emission is treated as a surface process. The spectral emissivity and absorptivity of the material will define the most appropriate treatment for each specific case.

To summarize, and in addition to the variables established in Sections 3.2, 3.6 and 3.8, the temperature distribution is controlled by the following variables:

Global thermal conductivity of the backing material	$k_B(x,t)$
Temperature of the backing material	$T_B(x,t)$
Emissivity of the solid	$\varepsilon_S(x,t)$
Convective heat transfer coefficient	$h_{Cv}(t)$
Ambient temperature	T_0

4. The Gas Phase

The sequence of events leading to the ignition of a gas phase flame will be described in this section. It will be assumed that gaseous fuel emerges from the solid following the description provided in Section 3.

After the onset of pyrolysis gas begins to emerge from the fuel surface, initially in very small quantities, but as ε_F and T(x,t) increase equation (4) shows that the fuel mass flux will increase. The emerging fuel will encounter the ambient oxidizer and eventually produce a flammable mixture. Given that fuel is migrating into the oxidizer flow, the definition of a flammable mixture is not a simple one. In standard test methods the ambient flow is well defined, mixed convection generated by a horizontal heated surface and the extraction system in the cone calorimeter [23], natural

convection resulting from a vertical heated surface in the LIFT apparatus [24] and forced convection over the fuel surface (horizontal or vertical) in the FM Global Fire Propagation Apparatus [25]. In real fires, flow fields are defined by the flames themselves and by the geometry of the environment (obstacles, fuel geometry, etc.) with the possibility of complex flow patterns. The only mechanisms to establish the fuel distribution within the gas phase are detailed measurements or modelling [26-28]. Nevertheless, from a phenomenological perspective, to achieve ignition, what is required is to achieve a flammable condition in at least one location in the gas phase.

The definition of a flammable mixture is for the fuel concentration to be found between the Lower or Lean Flammability Limit (LFL) and the Upper or Rich Flammability Limit (UFL). Although the LFL and UFL are apparatus dependent measurements, it is clear that the precision required for flaming ignition of solids does not require a more universal description of flammability. For a more detailed discussion on flammability limits and their limitations the reader is referred to Chapter 1.09.

4.1. Auto-Ignition

Once a flammable mixture has been attained, this mixture needs to increase in temperature until a combustion reaction can occur. This process is described in great detail by Torero [29] and by Fernandez-Pello [30, 31], who cites a series of experiments by Niioka [32] where ignition is studied using a stagnation point flow over a solid fuel surface. In these experiments the heat to initiate the combustion reaction is provided by a hot flow impinging on a fuel surface that acts as a heat sink. Niioka [32] identifies an induction time and a pyrolysis time. The pyrolysis time corresponds to the time required to attain a flammable mixture while the induction time is the time for the mixture to reach a temperature at which ignition can occur. Given the specific configuration, the pyrolysis time decreases with the flow velocity (enhanced heat transfer to the fuel surface) while the induction time increases (reduced residence time in the gas phase). Although these observations are not universally applicable, they serve to illustrate the process of auto-ignition. Fernandez-Pello [30, 31] describes Niioka's conclusions graphically by means of the schematic, this schematic is simplified and presented in Figure 7. Figure 7 shows how the summation of the pyrolysis and induction times leads to an ignition time.

In auto-ignition there is no hot spot that will serve as an initiation point for the reaction, thus the mixture has to absorb enough energy to reach ignition. The exact amount of energy required for ignition can be associated to a Damköhler number [18]. The Damköhler number corresponds to the ratio between a local residence and chemical time. The chemical time represents the necessary time for the reaction chemistry to occur and is expressed as the inverse of the reaction rate. Combustion reactions can be described by expressions like that presented in Equation (1) thus the chemical time is directly affected by the temperature of the reactants. The higher the temperature, the greater the reaction rates and the shorter the chemical time. The residence time is a measure of the strain (or dissipation rates) or the time the reactants remain together at a specific location thus it is directly related to the velocity field. The faster the flow or the velocity gradients, the shorter the residence time. If the chemical times are shorter than the residence times the reaction has enough time to proceed and a flame can exist. A critical Damköhler number for ignition can then be

established, above which a combustion reaction can proceed [18]. In the schematic presented in Figure 7, critical Damköhler numbers will be attained at both sides of the ignition curve preventing ignition. This is probably the most precise way to describe ignition but it requires the full resolution of the flow and temperature fields as well as comprehensive knowledge of the kinetic constants associated to the combustion reaction. While the flow field can be resolved by means of Computational Fluid Dynamics (CFD) the chemistry of most fire related fuels still remains uncertain. Qualitative assessment of the Damköhler number for ignition has only been achieved for a few very well defined experimental conditions such as stagnation flows [6, 32, 33] or boundary layers [34]. Other alternative representations of the ignition conditions that rest on the same fundamental approach have been discussed by Quintiere [35] and by Gray and Lee [36].

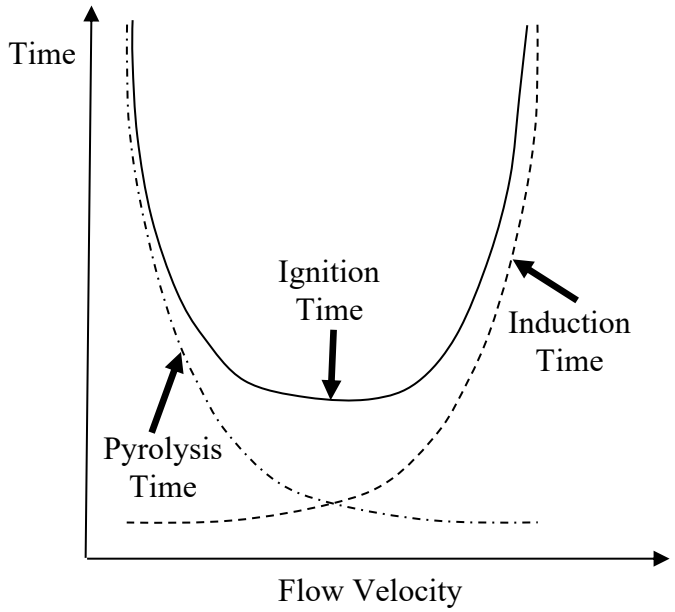


Figure 7 Schematic of the characteristic times involved in the ignition of a flat plate subject to a hot stagnation point flow. This schematic is based on the work by Niioka [32] and adapted from Fernandez-Pello [30, 31].

An important aspect of the ignition process that remains to some extent unresolved is the origin of the heat that is necessary for the gaseous fuel to reach the critical Damköhler number. If the air flow is hot, like in Niioka's experiments [32], then the energy will come from the oxidizer and the problem is immensely simplified. If the oxidizer is cold and there is an external radiative heat source, then solid and gas will heat at different rates. The solid will absorb heat and its surface temperature will change following Equation (7) while the gas will absorb heat based on its absorptivity and dissipate it in a manner governed by the flow field. The absorptivity of the gas is a strong function of the fuel type and concentration, thus also requires detailed knowledge of the flow field. The two possible outcomes are that the gas phase heats faster than the solid phase or the opposite. In the former case ignition will occur away from the fuel surface, since the fuel will act as a heat sink for the gas. In the latter case, ignition will occur closer to the fuel surface since the fuel acts as a heat source.

This latter scenario is common with charring materials where oxidation of the char contributes to increase the surface temperature [37].

It is clear that auto-ignition is a complex process that fully involves interactions of the solid and gas phases. Therefore, to characterize auto-ignition of solid fuels it is necessary to established well defined experimental conditions and simplifications to the analysis. Data obtained from different experimental conditions and with a specific analysis will generally not be compatible with other data that was obtained from a different experiment or deduced by means of an alternative analysis. Thus, scatter in the reported data is common for auto ignition.

Data on auto-ignition is generally reported as Auto-Ignition Temperatures (AIT) which corresponds to a recorded temperature at the moment where ignition of a flame is first observed. A summary of much of the data available is presented in Chapter 14 of reference [1] together with a series of references to relevant papers and textbooks [38, 39]. Given the complexity of the processes leading to auto-ignition, these values can only be taken as reference values that are a direct function of the specific test conditions. Generally, significant discrepancy is found in the literature where reported Auto-Ignition Temperatures can vary in more than 150^{o}C for the same material. The greatest discrepancies tend to be found when the orientation of the solid fuel is varied and the fluid mechanics and heat transfer are significantly altered [1]. Auto-Ignition Temperatures are most consistent for gaseous mixtures (Chapter 1.09*) and liquid fuels (Chapter 2.08) where tests are conducted in enclosed vessels where the fuel has been fully evaporated.

4.2. Piloted Ignition

As discussed in the previous section, the process of auto-ignition is extremely difficult to describe in a quantitative manner, even under simple experimental configurations. Therefore, as an example, it is not practical to rely on auto-ignition to describe the susceptibility of solid materials to ignite. A mechanism to simplify the process is to include a pilot flame or a hot spot. This is a practical experimental simplification that has a basis on reality, since in most ignition scenarios there will be a region of high temperature. The presence of a pilot strongly simplifies the gas phase processes and reduces the influence of environmental variables. While characterization of the flow field is still required to establish the presence of a flammable mixture, it is no longer necessary to resolve heat transfer between phases or to define the absorption of energy by the gas. In the presence of a pilot, ignition can be assumed at the moment where a flammable mixture (LFL) is attained at the location of the pilot.

Currently, all standard test methods that attempt the description of the ignitability of solids use some form of a pilot. In some cases, the pilot is a large flame [24] while in others is either a small pilot flame [25] or a high energy spark [23]. Both methods have their advantages and disadvantages, sparks produce only local heating thus have a weaker tendency to influence the solid phase by acting as a heat source. Nevertheless, given their small volume, ignition is strongly influenced by the spark location. The flow field has to establish a flammable mixture at exactly the location of the pilot. In contrast, large pilot flames have a tendency to supply heat to the fuel surface, but cover a large volume, therefore are less sensitive to the flow field.

Because of its practical relevance, all subsequent discussion will concern piloted ignition.

To attain the LFL at the pilot location it is necessary to resolve the momentum and mass transport equations simultaneously with the surface boundary conditions explained above. Figure 1 shows an arbitrary distribution of the fuel concentration external to the sample, $Y_{F,g}$. A similar representation could be made for the oxygen concentration ($Y_{O,g}$). The characteristic equation that describes the flow field is as follows:

$$\rho_0 \frac{D\vec{u}}{Dt} = -\nabla P + \rho_0 \vec{g} + \mu_0 \nabla^2 \vec{u} \tag{10}$$

Where $\vec{u}$ is the velocity field, ρ_0 the density of the air, P the pressure field, $\vec{g}$ the gravity vector and μ_0 the viscosity of the air. Temperature dependencies of the properties have been omitted for simplification assuming that air is the main constituent and it will remain close to ambient temperature. Conservation of fuel and oxygen concentrations can then be defined by:

$$\rho_0 \frac{DY_{F,g}}{Dt} = \rho_0 D_{F,O} \nabla^2 Y_{F,g} \tag{11}$$

$$\rho_0 \frac{DY_{O,g}}{Dt} = \rho_0 D_{F,O} \nabla^2 Y_{O,g} \tag{12}$$

where species transport is assumed to be non-reactive, thus the source/sink has been omitted. This is an adequate assumption for pure mixing. To obtain the solution of Equations (10), (11) and (12) it is necessary to add the following variables to those established in Sections 3.2, 3.6, 3.8 and 3.9:

Density of air	ρ_0
Velocity field	$\vec{u}$
Pressure field	P
Viscosity of air	μ_0
Diffusivity of fuel in air	$D_{F,0}$
Pilot location	$\vec{r}$

At this point, there is no need to specify a critical Damköhler number for ignition because of the presence of the pilot, although in absolute rigour, this assumes that the flow conditions are such that blow-off of the flame kernel does not occur, thus the pilot will allow the establishment of a flame across the flammable mixture.

4.3. “Flash Point” and “Fire Point”

Once ignition has been achieved a flame can propagate through the regions where a flammable mixture is present consuming the reactants. Independent of the flow field, it is most likely that a flammable mixture will be established close to the solid fuel surface. The pyrolysis rates at the moment when the flame is established will determine if a flame can continue to exist or if the combustion reaction will cease after the gas phase mixture is consumed. The feedback from the flame will enhance

pyrolysis, but usually, the relatively large thermal inertia of the solid will result in a slow response, therefore it will be necessary for pyrolysis rates to be sufficient even in the absence of the flame heat feedback. If pyrolysis rates are not sufficient, the flame will extinguish and continuous pyrolysis will lead once again to the formation of a flammable mixture and subsequent ignition. This manifests itself as a sequence of flashes that precede the establishment of a flame over the combustible solid. This process is identical to the "flash point" generally associated to liquid fuels (Chapter 2.08) and for solid fuels has been described in detail by Atreya [37].

The transition between the "flash point" ignition and the established flame, which could also be named the "fire point" in an analogy with liquid fuels, deserves especial attention. The characteristics of the diffusion flame established on a solid fuel surface are defined by the flow field and the supply of fuel. The rate at which both reactants reach the flame zone defines the flame temperature and thus the characteristic chemical time. If the amount of fuel reaching the flame is small, then the flame temperature will be low and the chemical time will be long. As described above, the flow field defines the residence time. A second critical Damköhler number appears, but this time is one of extinction. This concept has been described many times explicitly in the combustion literature [18] but only implicitly in the fire literature. There are only few studies where a critical extinction Damköhler number has been presented to describe the "fire point" but in all cases they concern idealized flow fields that allow establishing a direct correlation between fuel production and flame temperature [33, 34]. In most discussions simplifications have been assumed leading to simpler parameters that can serve as surrogates for the Damköhler number. Williams [40] discusses a critical gas phase temperature below which extinction will occur. If the residence time remains unchanged, then extinction is only associated to the chemical time, thus can be directly linked to a critical gas phase temperature. It can be further argued that extinction is much more sensitive to temperature than to flow, thus only radical changes in the residence time need to be addressed making this criterion a robust one. A more practical surrogate to the Damköhler number is a critical fuel mass flux criterion. Under specific testing conditions the flow field will remain invariable. In this case the attainment of a critical mass flux of fuel will be the single parameter defining the flame temperature and thus the Damköhler number [41, 42]. Furthermore, under more restrictive conditions the critical mass flux can be associated to a critical solid phase temperature [43]. Drysdale [17] and Beyler [44] provide a detail description of the classic approaches to this subject while Quintiere and Rangwala address some of the more current studies [45].

The sequence of events relating "flash" and "fire" points is not trivial because they represent distinctively different processes. For piloted ignition, the "flash point" only requires a flammable mixture while for the "fire point" the rate of fuel supply has to be enough to achieve a chemical time shorter than the residence time. Thus a number of different scenarios can be observed that in many cases can affect the consistency of different ignition studies. A simple example will be used to illustrate this. For example; if the pilot is very close to the fuel surface then a flammable mixture will be achieved at the pilot location soon after the onset of pyrolysis. In this case fuel supply will be far from that required to sustain a flame. A significant delay will exist between flash and fire points where several flashes will be observed. If the pilot is distanced from the fuel surface it will take longer to attain a flammable mixture and therefore at the moment of the first flash the fuel supply would have increased and a smaller

number of flashes will be observed before the flame is fully established. Greater separation of the pilot from the fuel surface might result in the flammable mixture being attained at the pilot location at the same time as the fuel supply is sufficient to sustain a flame. In this case the fire point will correspond with the first flash. A further increase in the distance between pilot and fuel will not change the physical manifestation but will continue to delay ignition. In this case ignition will occur when a flammable mixture is attained at the pilot but will not be related to the flash or fire points. This example has been presented to illustrate the sensitivity of ignition studies to different variables and the importance of detailed observations to the validity of conclusions and comparisons. In this case pilot location was used as the example, but a similar analysis could be made with the heat flux, the oxygen concentration, the flow field [31, 46] or the ambient pressure [47].

The only added variable required to model the "fire point" will be the critical Damköhler number for extinction ($Da_{e,cr}$) or any equivalent way to represent the extinction condition. As mentioned above, other criteria can be used to establish the extinction condition and that are partially equivalent to the critical Damköhler number. Such criteria are a critical mass transfer numbers (B_{cr}) [34, 48], critical mass fluxes [11, 28, 30, 42] or critical temperatures (T_{cr}) [17, 35, 40, 43, 45].

5. Simplifications and Standardization

To predict flaming ignition of a solid fuel is necessary to solve Equations (1) to (12). A number of authors have attempted the solution to these equations for a number of materials. Furthermore, they have in some cases added further complexity by including phenomena such as intumescent behaviour [49] or bubbling [50]. Extensive reviews of these modelling efforts can be found in references [4, 51-54] and some of the more recent modelling exercises have achieved significant success [55-59]. In most cases some simplifications have been necessary and in general the critical limitation of these models is associated to the inadequate definition of many of the relevant variables and parameters listed in the previous sections. As mentioned before, the current trend is to optimise parameters by fitting complex models to specific experimental results by means of sophisticated optimization techniques. The optimization process results in ranges of possible values for all parameters stipulated. The results have then been extrapolated to other experimental conditions. While success has been reported [6, 7], these optimization processes are only as good as the models whose parameters they optimize. It is therefore important to note that even in the most complex models some simplifying assumptions have been made. Currently, the use of such models remains a research subject with increasing applicability to the modelling of flaming ignition of solid fuels.

This section will take the equations presented in previous sections and suggest simplifications that will lead to models commonly used in the analysis of standard test methods evaluating the flaming ignition of solid fuels.

5.1. The Inert Solid Assumption

The assumption that the solid remain inert until ignition is probably the most far reaching of all proposed simplifications. As a result of this assumption the energy

equation is dramatically simplified. Despite the far reaching implications of assuming that the solid remains inert until ignition there is very limited work that assesses the validity of this assumption.

To the knowledge of the author, the only explicit studies that discuss the importance of assuming that the material is inert are those by Cordova et al. [42], Dakka et al. [60] and Beaulieu and Dembsey [61]. In the first two studies transparent Poly(methyl methacrylate) (PMMA) was used while on the latter work the detailed analysis is done with black PMMA but a number of other materials serve to confirm the conclusions. Despite the bias towards PMMA, the discussion is appropriate here to illustrate the potential errors associated to this simplification.

Figure 8 presents characteristic ignition delay times (t_{ig}) and pyrolysis dely times (t_P) for PMMA. The ignition delay time was recorded as the first flash while the pyrolysis delay time as the moment when the fuel initiates its endothermic degradation. The onset of pyrolysis was characterized by means of mass loss measurements, flow visualization and IR-Thermography. These results show that for these particular experiments there is a significant difference between the "flash point" and the onset of pyrolysis (could be up to 100%) therefore the assumption that the fuel remains inert until ignition might not be justified.

The breakdown of the inert solid heating assumption is further discussed by Beaulieu and Dembsey [61] who show that an analysis following this approximation will lead to shorter ignition delay times for realistic heat fluxes. The biggest errors were observed at the higher heat fluxes. Their tests were done for a comprehensive array of materials and with heat fluxes up to 200 kW/m^2.

Despite these experimental results, this assumption still remains the backbone of all standard test method analyses for ignition [23-25]. If this approach is followed and the regression rate is assumed to be negligible, $V_R \approx 0$, Equation (7) is reduced to

$$\frac{\partial[\rho_S C_S T]}{\partial t} = -\frac{\partial}{\partial x}\left[-k_S \frac{\partial T}{\partial x}\right] + \dot{q}'''_{RAD} \tag{13}$$

And the boundary conditions to

$$x=0 \qquad 0 = k_S \left.\frac{\partial T}{\partial x}\right|_{x=0^+} - \varepsilon_S(0,t)\sigma(T^4(0,t) - T_0^4) - h_{Cv}(t)(T(0,t) - T_0) \tag{14}$$

$$x=L \qquad 0 = -k_S \left.\frac{\partial T}{\partial x}\right|_{x=L^-} + k_B \left.\frac{\partial T_B}{\partial x}\right|_{x=L^+} \tag{15}$$

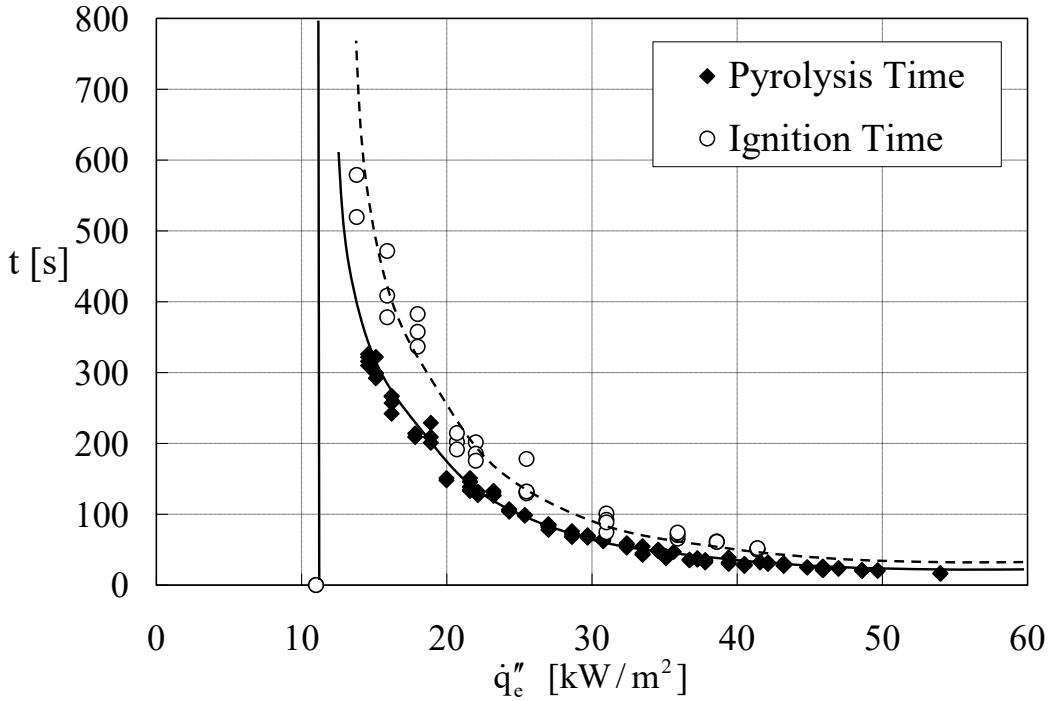


Figure 8 Characteristic ignition delay times (t_{ig}) and times to the onset of pyrolysis (t_P) for PMMA and a wide range of external heat fluxes extracted from reference [60]. Onset of pyrolysis or ignition did not occur below 11 kW/m^2.

5.2. Absorption of Radiation and Global Properties

The next major simplifications that are commonly accepted are to assume that most of the incident heat flux is absorbed at the surface ($\alpha(t)\approx 1$) and that the thermal properties of the solid can be considered invariant ($\rho_S(x,t)\approx\overline{\rho}_S$, $C_S(x,t)\approx\overline{C}_S$, and $k_S(x,t)\approx\overline{k}_S$). These assumptions further simplify Equation (13) because it allows neglecting in-depth radiative absorption. The thermal properties can then be extracted from the differential terms and external radiation now appears in the exposed boundary condition:

$$\overline{\rho}_S\overline{C}_S\frac{\partial[T]}{\partial t}=\overline{k}_S\left[\frac{\partial^2 T}{\partial x^2}\right] \tag{16}$$

$$x=0 \qquad 0=\overline{k}_S\left.\frac{\partial T}{\partial x}\right|_{x=0^+}+\dot{q}''_e-\sigma(T^4(0,t)-T_0^4)-h_{Cv}(t)(T(0,t)-T_0) \tag{17}$$

$$x=L \qquad 0=-\overline{k}_S\left.\frac{\partial T}{\partial x}\right|_{x=L^-}+\overline{k}_B\left.\frac{\partial T_B}{\partial x}\right|_{x=L^+} \tag{18}$$

There is little true justification in the literature to support these assumptions, nevertheless they are of practical use since for many fire related materials the

absorptivity (or emissivity) will approach unity [62], or in the case of testing the material surface can be treated with a coating that has these properties [25].

A series of recent studies have explored the absorptivity [63] of PMMA and the interaction between the heat source and PMMA [64, 65]. Figure 9 shows that when using an electrical resistance (cone heater [23]) the transmissivity of PMMA can be neglected and the absorption can be assumed to occur at the surface. Instead, when using tungsten lamps (from the Fire Propagation Apparatus [25]) in-depth absorption cannot be neglected. This information allowed explaining significant differences in the piloted ignition delay times obtained with both tests but mostly emphasize the potential importance of assuming an absorptivity of unity.

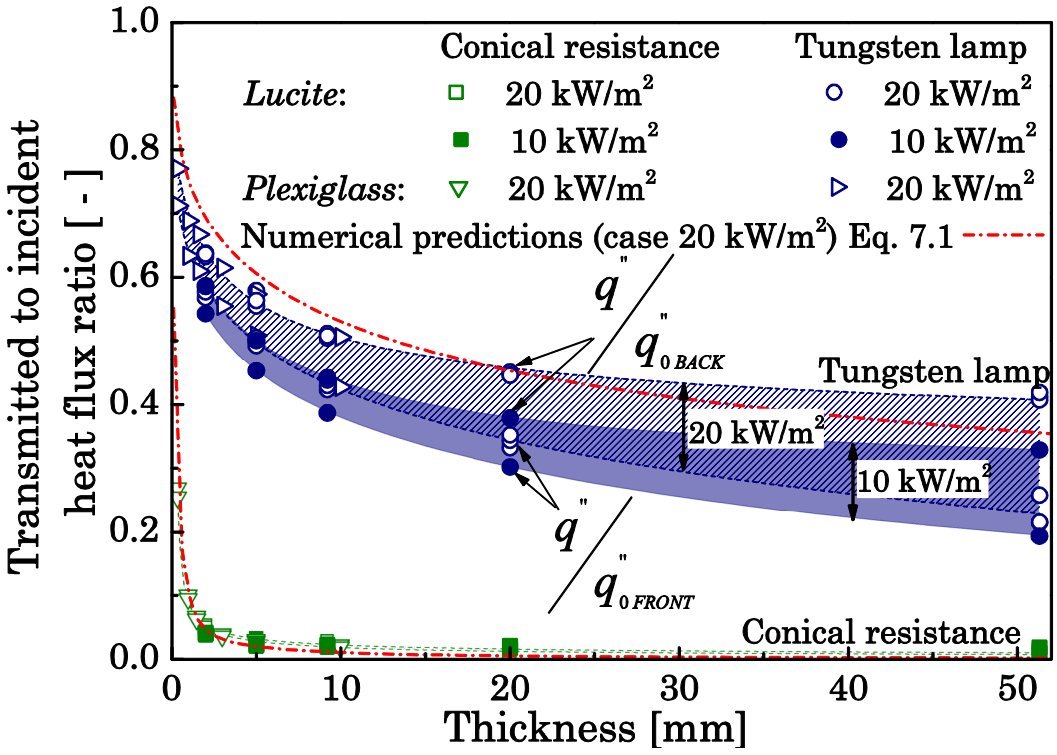


Figure 9 Transmitted to incident heat flux ratio for clear PMMA samples (*Lucite* and *Plexiglass*) exposed to a radiative source (conical resistance and tungsten lamp) providing 10 and 20 kW/m^2 for thicknesses ranging between 0.375 and 51 mm [65].

Furthermore, thermal properties vary with temperature, but a global set of properties can be established to provide a good fit to ignition data. An example of a comprehensive assessment of the impact of variable thermal properties is provided by Steinhaus [66].

5.2. The Boundary Conditions

To standardize the ignition process it is important to provide a controlled environment, so that test results can be consistent between laboratories and different users of the standard. Therefore, standard test methods provide clear definition of the environmental conditions, thermal characteristics of the backing material and pilot

location [23-25]. Equations (10), (11) and (12) do not have to be solved to obtain the fuel concentration at the pilot location. Instead the impact of the gas phase on the results is ignored. This is done on the basis that flow conditions are the same between tests thus their impact on the transport of fuel and oxidizer to the pilot is the same.

Standardization of the flow conditions has a deep effect on the meaning of the results. The thermal properties associated to the analysis are no longer true thermal properties of the material but global properties that are a combination of the solid and the standardized gas phase conditions. This is of critical importance, because, as a product of standardization, test results can be compared among themselves (if the same method is used), nevertheless can not be extrapolated to conditions different to those of the test. This applies to other standard tests or to real fire conditions. Cordova et al. [46] provides a graphical assessment of the effect of varying the flow conditions on the resulting thermal properties showing that small variations in the flow field can result in drastic variations of the resultant thermal properties.

It is common to apply ignition data from standard tests to fire models and is only recently that CFD models such as the Fire Dynamics Simulator (Version 5 and above) allow realistic representations of the solid phase that include true thermal properties [67]. It is important to note that extrapolation is not necessarily incorrect. Nevertheless, it has to be done with great care to guarantee that the effect of the environment on the thermal properties can either be neglected or an appropriate correction is provided.

Different test methods will use different flow fields therefore values for the convective heat transfer coefficient vary with the authors. A commonly cited value is 15 W/m^2K. Furthermore, it is common to linearize surface radiation to define a single total heat transfer coefficient ($h_T \approx$ 45 W/m^2K). More precise values and models are present in the literature [26-28, 31] but they correspond to very specific scenarios and therefore are hard to generalize.

Most test methods define the backing material as a good insulator ($\bar{k}_B \to 0$) neglecting heat losses through the back end of the sample. Finally, characteristic ignition delay times can be considered much shorter than the time required for the thermal wave to travel through the sample therefore $L > \varepsilon_T$ and the solid is generally assumed as semi-infinite.

These last set of simplifications are truly not necessary because a simple numerical solution can be obtained without linearizing surface radiation or assuming a semi-infinite solid. Many studies have attempted to establish the impact of these simplifications by means of numerical solutions that relax these assumptions, the most recent of these papers is by Mowrer [68]. If surface radiation is described by means of constant heat transfer coefficient, then a correction is necessary to account for the growth of this coefficient as the surface temperature increases. Mowrer [68] showed that a correction to the global thermal properties could be made to account for this effect. The back end boundary condition is a more difficult problem. For low heat fluxes the thermal wave reaches the end of the sample, $L < \varepsilon_T$, before ignition occurs and heat is exchanged between the sample and the insulating material. Quantification of this heat exchange can be done numerically, as indicated in Section 3.9, but this is not a simple process because it needs to properly describe the different components

associated to the way the sample is arranged during tests. The alternative solution of providing a well defined insulating boundary and neglecting back end losses has been preferred and detailed analyses have been conducted to characterize the physical arrangements of sample and insulating material. Among the most comprehensive of these studies is presented in reference [69].

If all these assumptions are made, Equations (16), (17) and (18) can be reduced to:

$$\bar{\rho}_S \bar{C}_S \frac{\partial T}{\partial t} = \bar{k}_S \left[\frac{\partial^2 T}{\partial x^2} \right] \tag{19}$$

$$x=0 \qquad 0 = \bar{k}_S \left. \frac{\partial T}{\partial x} \right|_{x=0^+} + \dot{q}''_e - h_T (T(0,t) - T_0) \tag{20}$$

$$x \to \infty \qquad 0 = -\bar{k}_S \left. \frac{\partial T}{\partial x} \right|_{x=L^-} \tag{21}$$

5.3. The Ignition Condition

If the solid is assumed to be inert until ignition and the gas phase can be summarized into a single total heat transfer coefficient (h_T) this amounts to the assumption that ignition will occur at the onset of pyrolysis and that these process can be simply characterized by the attainment of a characteristic surface temperature that is commonly labelled the ignition temperature, T_{ig}. If the sample is suddenly exposed to an external heat flux, then the time delay between exposure and ignition is named the ignition delay time, t_{ig}. These two parameters represent then the entire process of ignition.

A final link can be made to establish a critical ignition condition. If the ignition delay time is infinitely long, then there will be no gradients of temperature within the solid and surface heat losses will be equivalent to the heat input. This represents the minimum heat flux required to achieve T_{ig}, and thus flaming ignition of the solid fuel. This heat flux is named the minimum heat flux for ignition, $\dot{q}''_{0,ig}$. Since surface temperatures are more difficult to measure than heat fluxes, the minimum heat flux for ignition can be used to establish the ignition temperature. Equation (20) can then be re-written to

$$T_{ig} = T_0 + \frac{\dot{q}''_{0,ig}}{h_T} \tag{22}$$

Equation (22) is an idealized expression that assumes that no temperature gradients exist in the solid, this can lead to errors in the calculation of T_{ig}. To establish a relationship between external heat fluxes and surface temperature that includes in-depth heat transfer a sample can be allowed to reach thermal equilibrium and the surface temperature recorded. The obtained relationship represents a more accurate representation of equation (22) and can be used to extract ignition temperatures from

measured heat fluxes. A graphic representation of this relationship can be found in reference [34].

Again, both minimum heat flux for ignition and ignition temperature are not material properties but a combination of the material and the specific environmental conditions associated to the test [46]. Extrapolation to realistic scenarios and fire models has to be done with significant care.

5.3. The Solution

Imposing a constant external heat flux ($\dot{q}''_e$=constant) and using all the above assumptions allows for an analytical solution to equation (19). This solution establishes the evolution of the solid temperature as a function of time. This solution can be found in any heat transfer book [19] but was first postulated for the flaming ignition of a solid fuel by Quintiere [70] and incorporated in ASTM E-1321 [24]. Alternate solutions have been postulated for other test methods and will be briefly discussed in Chapters 3.03 and 3.04. More detailed discussion of methodologies and nomenclature can be found in the description of the standard tests [23, 25].

The solution for T(x,t) is given by

$$T(x,t) - T_0 = \frac{\dot{q}''_e}{(h_T)} \left[\operatorname{erfc}\left(\frac{x}{\sqrt{4\overline{\alpha}_D t}} \right) - e^{\frac{(h_T)}{\sqrt{\alpha_D}\sqrt{\overline{k}_S\overline{\rho}_S\overline{C}_S}}x + \frac{(h_T)^2}{\overline{k}_S\overline{\rho}_S\overline{C}_S}t} \operatorname{erfc}\left(\frac{(h_T)}{\sqrt{\overline{k}_S\overline{\rho}_S\overline{C}_S}} t^{\frac{1}{2}} + \frac{x}{\sqrt{4\overline{\alpha}_D t}} \right) \right] \quad (23)$$

Where $\overline{\alpha}_D = k_S/\rho_S C_S$ is the global thermal diffusivity and "erfc" is the complement to the error function. To obtain the surface temperature (T_s), x is set equal to 0 and T = T(0,t) = T_s. Therefore equation (23) simplifies to:

$$T_s = T_0 + \frac{\dot{q}''_e}{(h_T)} \left[1 - e^{\left(\frac{(h_T)^2}{\overline{k}_S\overline{\rho}_S\overline{C}_S} \right) t} \operatorname{erfc}\left(\frac{(h_T)}{\sqrt{\overline{k}_S\overline{\rho}_S\overline{C}_S}} t^{\frac{1}{2}} \right) \right] \quad (24)$$

from equation (24),

$$\overline{T} = \frac{\dot{q}''_e}{(h_T)} \quad (25)$$

can be defined as a characteristic temperature and,

$$t_c = \frac{\overline{k}_S\overline{\rho}_S\overline{C}_S}{(h_T)^2} \quad (26)$$

is defined as a characteristic time. Equation (24) is the general solution to the surface temperature at all levels of incident heat flux. To obtain the ignition delay time (t_{ig}) the surface temperature (T_s) is substituted by T_{ig} and equation (24) can be rewritten as:

$$T_{ig} = T_0 + \overline{T}\left[1 - e^{\frac{t_{ig}}{t_c}} \operatorname{erfc}\left(\left(\frac{t_{ig}}{t_c}\right)^{\frac{1}{2}}\right)\right] \tag{27}$$

To avoid the complex form of the error function simplified solutions have been proposed in the literature [70, 71]. In order to solve for the ignition delay time (t_{ig}) a first order Taylor series expansion of equation (27) is conducted. The range of validity of this expansion is limited, thus cannot be used over a large range of incident heat fluxes. Thus, the domain has to be divided at least in two.

The first domain corresponds to high incident heat fluxes where the ignition temperature (T_{ig}) is attained very fast, thus $t_{ig} << t_c$. Application of the first order Taylor Series Expansion to equation (27) around $t_{ig}/t_c \to 0$ yields the following formulation for the ignition delay time (t_{ig}):

$$\frac{1}{\sqrt{t_{ig}}} = \frac{2}{\sqrt{\pi}\sqrt{\overline{k}_S \overline{\rho}_S \overline{C}_S}} \frac{\dot{q}''_e}{\left(T_{ig} - T_0\right)} \tag{28}$$

As can be seen from equation (28), the short time solution for the ignition delay time (t_{ig}) is independent of the total heat transfer coefficient term (h_T). Thus the ignition delay time (t_{ig}) is only a function of the external heat flux ($\dot{q}''_e$) and the global properties ($\overline{k}_S$, $\overline{\rho}_S$, $\overline{C}_S$) of the solid fuel and the ignition temperature (T_{ig}).

For low incident heat fluxes $t_{ig} \geq t_c$, the Taylor series expansion is made around $t_{ig}/t_c \to \infty$, where the first order approximation yields:

$$\frac{1}{\sqrt{t_{ig}}} = \frac{\sqrt{\pi} h_T}{\sqrt{\overline{k}_S \overline{\rho}_S \overline{C}_S}} \left[1 - \frac{h_T\left(T_{ig} - T_\infty\right)}{\dot{q}''_e}\right] \tag{29}$$

Equations (28) and (29) establish the relationship between ignition delay time and external heat flux. It is convenient to express the ignition delay time data presented in Figure 7 as $1/\sqrt{t_{ig}}$ where T_{ig} is obtained from the experimental minimum heat flux for ignition and Equation (22). Such a plot is presented in Figure 8. Substituting T_{ig} in Equation (28) allows extracting the product of the three thermal properties ($\overline{k_S \rho_S C_S}$) as a single experimental parameter representing the global material properties controlling flaming ignition of solid fuels that can be considered semi-infinite. Quintiere terms this product the thermal inertia [70].

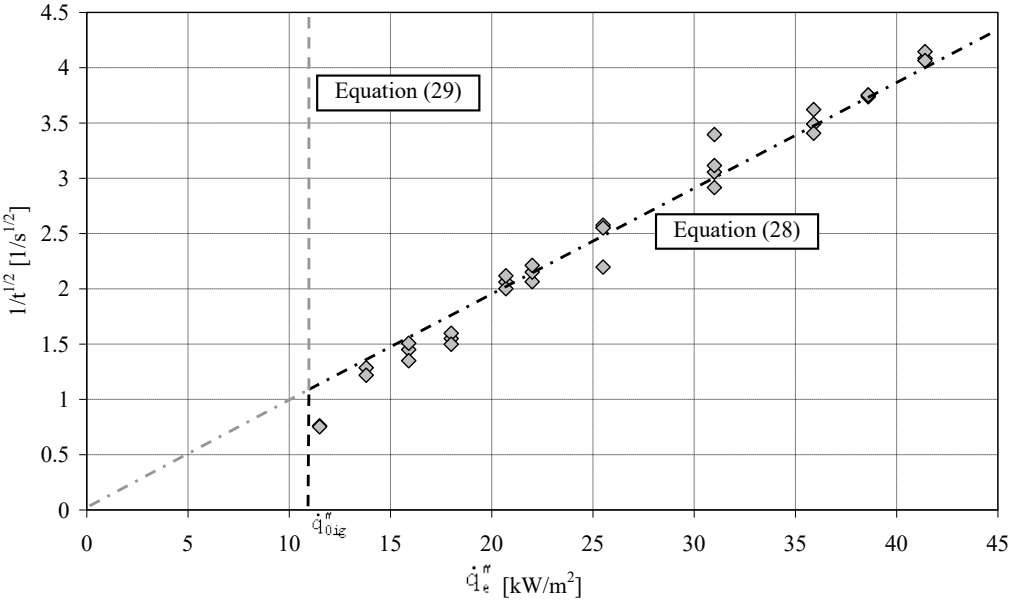


Figure 10 Ignition delay time ($1/t_{ig}^{-0.5}$) for different external heat fluxes using PMMA as a solid fuel. Data extracted from reference [60].

When describing ignition propensity of solid fuels is customary to summarize the description of the materials on the basis of only two parameters, the ignition temperature, T_{ig}, and the thermal inertia, $\overline{k_s \rho_s C_s}$. Several tables have been produced in the past with comprehensive lists of materials typical of fires. As an example, Table 3 presents the data as compiled by Quintiere [70]. A comprehensive list is not presented here because a comprehensive compilation of data is provided in Chapter 3.04 or in references [1] and [2].

Material	T_{ig} [^oC]	$\overline{k_s \rho_s C_s}$ [$(kW/m^2K)^2.s$]
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

Table 3 Ignition Data from ASTM E-1321 per Quintiere [72].

5.3. Thermally Thin Materials

A very similar analysis can be conducted for thermally thin materials where in the absence of thermal gradients and after all relevant simplifications Equation (19), (20) and (21) can be combined into a single energy equation and a boundary condition

$$\overline{\rho}_S \overline{C}_S L \frac{\partial T}{\partial t} = \dot{q}''_e - h_T (T(t) - T_0) \tag{30}$$

$$x=L \qquad \dot{q}''_N (L,t) = 0 \tag{31}$$

when the external heat flux is much larger than the losses this equation can be integrated to deliver equation (32) [73].

$$t_{ig} = \frac{\overline{\rho}_S \overline{C}_S L (T_{ig} - T_0)}{\dot{q}''_e} \tag{32}$$

This is once again not a necessary assumption but has the practical advantage of leaving the product $\overline{\rho_S C_S}$ as a single experimental parameter that can be extracted from the slope of a simple plot presenting $1/t_{ig}$ vs $\dot{q}''_e$. $\overline{\rho_S C_S}$ represents then the global material properties controlling flaming ignition of thermally thin solid fuels. A comprehensive data review of this product is provided in references [1] and [2].

6. Summary

A review of flaming ignition of solid fuels has been presented. Emphasis has been given to a comprehensive description of all processes involved. Some minor simplifications have been made to the original formulation leading to approximately thirty variables and parameters controlling flaming ignition of a solid fuel.

A section follows where the common simplifications associated to the methodologies of interpretation of standard test methods are applied. Analytical solutions are obtained showing that the description of the ignition process can be summarized to two material related parameters and two specified environmental conditions (T_0, $\dot{q}''_e$). The material related parameters are as follows:

Thermally thin materials	T_{ig}	$\overline{\rho_S C_S}$
Thermally thick materials	T_{ig}	$\overline{k_S \rho_S C_S}$

It is important to insist that these parameters are a function of the material and the environmental conditions at which they were obtained. They can be directly applied for comparison between materials (flammability assessment) but extrapolation to conditions beyond the tests where they were obtained is not always possible and if performed, has to be done with great care.

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