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# “Simulation of fire spread in large compartments under different ventilation conditions”

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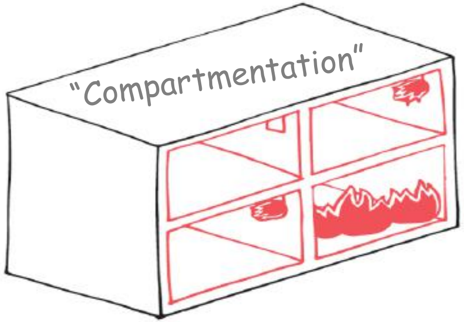
Edinburgh Fire Research Centre

# Context – "compartmentation" vs. "Open-plan"

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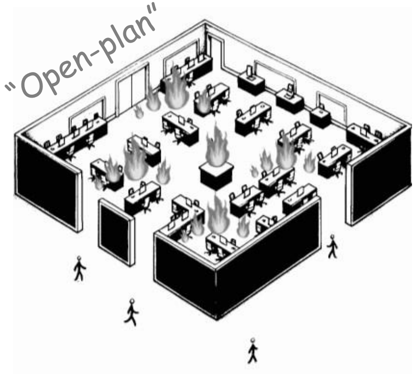


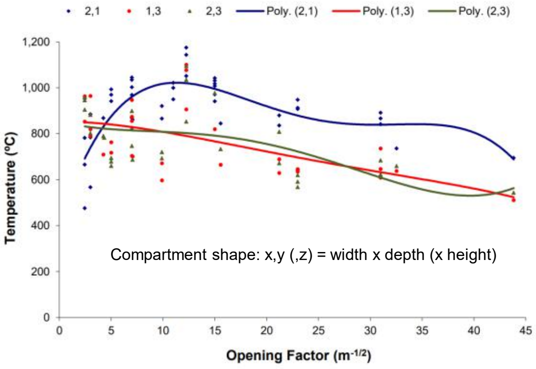
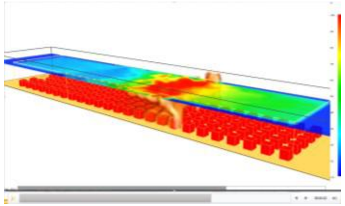



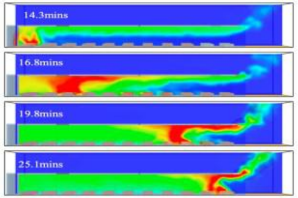

**Figure 3-2: Average compartment ceiling temperature for the CIB Tests for crib configurations 2,1 - 1,3 and 2,3, together with their correspondent best-fit lines drawn as 4th grade polynomials.**

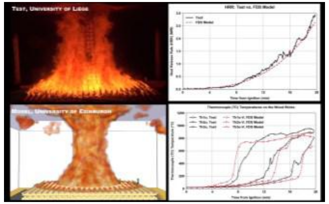
Majdalani, A. (2015) Compartment fire analysis for contemporary architecture PhD thesis, School of Engineering, Uni Edinburgh era.ed.ac.uk/handle/1842/9969

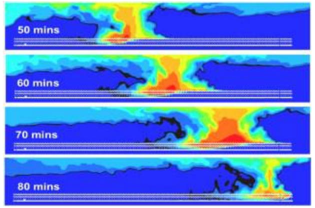
> Modern buildings **favour "open-plan" design**
> Classic compartment fire framework from fire tests in **small, near cubic** compartments
> Fires in open-plan settings tend to **"travel"** across compartments
> Characteristic **spatially and temporally** varying boundary condition
> Fire dynamics **strongly influenced by ventilation**, spanning fuel-controlled & ventilation-controlled fires
> Complex momentum/fuel bed control in former => **no simple theoretical treatments**

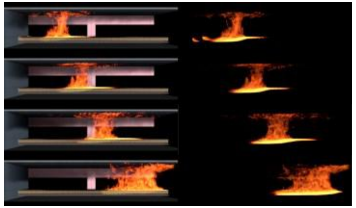
# Numerical Simulators for Travelling Fires – Road Map







2018 · 2019 · 2022 · 2023 · 2024

### Charlier *et al.*, 2018

- > Hypothetical scenarios
- > No airflow through crib
- > Discrete boxes
- > Simple pyrolysis model
- > Ignition temperature
- > Prescribed HRRPUA

### Dai *et al.*, 2019

- > BST/FRS 1993 Test
- > **Under-ventilated fires**
- > Discrete boxes
- > Simple pyrolysis model
- > Ignition temperature
- > Prescribed HRRPUA

### Dai *et al.*, 2022

- > TRAFIR-Liège Test
- > Well-ventilated fires
- > **Stick-by-stick**
- > Simple pyrolysis model
- > Ignition temperature
- > Prescribed HRRPUA

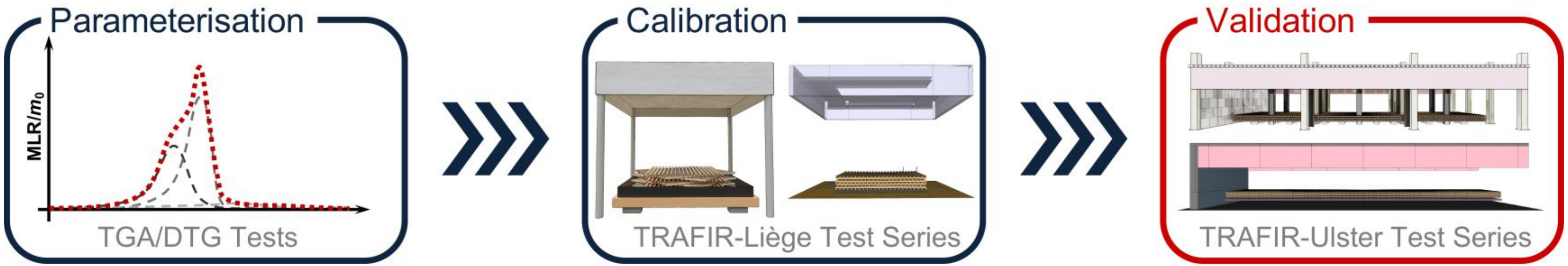
### Dai *et al.*, 2023

- > TRAFIR-Ulster Test
- > Well-ventilated fires
- > Stick-by-stick
- > Simple pyrolysis model
- > Ignition temperature
- > Prescribed HRRPUA

### Liu *et al.*, 2024

- > TRAFIR-Ulster Test
- > Well-ventilated fires
- > Stick-by-stick
- > **Detailed pyrolysis model**
- > Arrhenius equations
- > Linked with exposure

# Numerical Simulators for Travelling Fires – Workflow and Strategy




**Fuel bed representation and fire growth modelling**

> Discrete boxes ❯ Stick-by-stick

> Simple pyrolysis ❯ Detailed (or complex) pyrolysis

**Detailed pyrolysis**

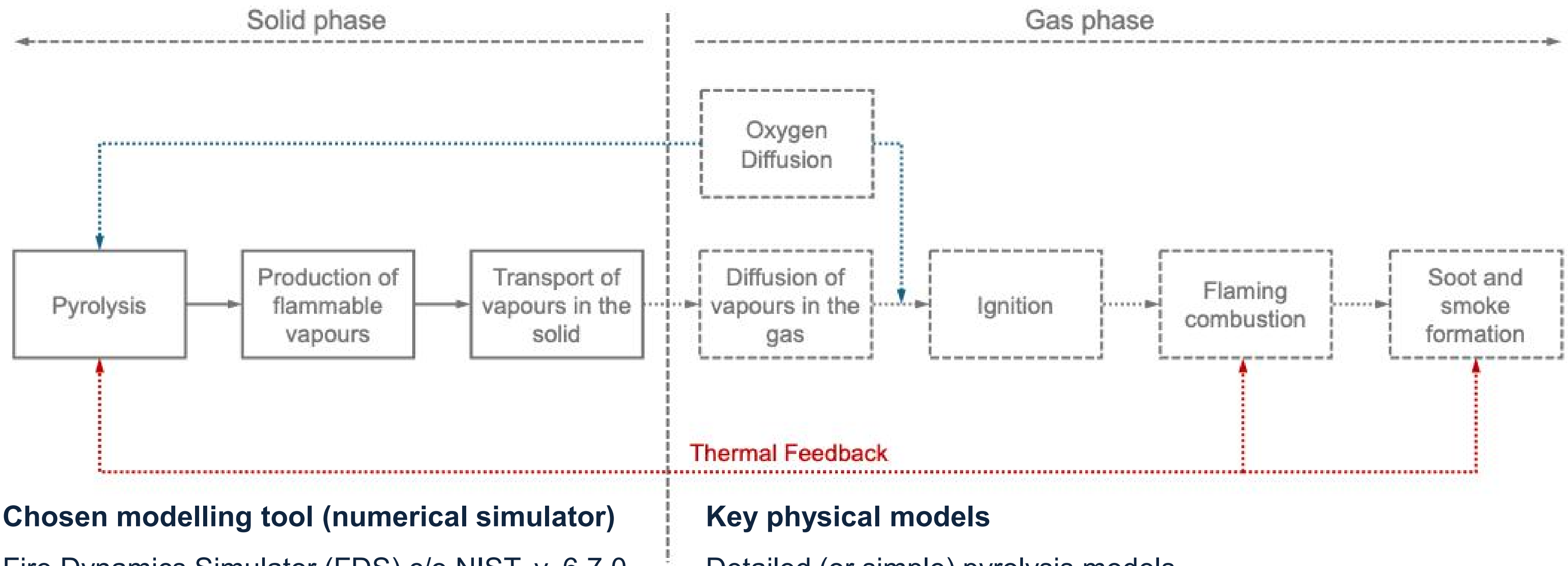
> Fire spread post-ignition **burning rates are now linked to thermal environments**

> Enhanced burning rates due to higher **thermal feedback**

> Repeated Scaling Up exercise, starting with calibration for isolated crib,

**>> then translated *predictively* for large compartments**

# Complex overlapping fire phenomena spanning gas/solid + coupling




**Chosen modelling tool (numerical simulator)**

Fire Dynamics Simulator (FDS) c/o NIST, v. 6.7.0

https://pages.nist.gov/fds-smv/

**Key physical models**

Detailed (or simple) pyrolysis models

Fixed radiative loss (0.35)

# Model parameters determination

## Parallel Reaction Schemes

$$\text{Wood Component } i \longrightarrow v_{\text{char},i}\text{Char} + (1 - v_{\text{char},i})\text{Volatiles}$$

where:

Wood Component *i* refers to cellulose and hemicellulose and lignin

$v_{\text{char},i}$ is the mass fraction of char produced by component *i*

## Reaction rates:

Each Component *i* has Arrhenius dependence on temperature, proportional to normalised mass fractions of solid-phase reactants ($Y_{s,i}$):

$$R_i = Y_{s,i} A_i \exp\left(-\frac{E_i}{RT_s}\right) X_{O_2}^{n_{O_2,i}} \; ; \; Y_{s,i} = \left(\frac{m_{s,i}}{m_s(0)}\right)$$

where:

$A_i$ is the pre-exponential factor [$s^{-1}$]

$E_i$ is the activation energy of solid-phase reactant [kJ $mol^{-1}$]

$T_s$ is the solid temperature of reactant [K]

$X_{O_2}$ is oxygen volume fraction [-]

$m_{s,i}$ is the mass of the reactant *j* [kg]

$m_{s(0)}$ is the initial mass of wood aggregate [kg]

**Table 1.** Kinetic parameters for thermal decomposition of spruce used in the model.

| | Parameter values (data bounds[a]) for first order reactions | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | $Y_{s,i}(0)$ (-) | Ref. | $A_i$[b] ($s^{-1}$) | Ref. | $E_i$[b] (kJ·$mol^{-1}$) | Ref. | $v_{char}$ (-) | Ref. |
| Cell.[c] | 0.422 (0.38-0.44) | [14-18] | $8.18 \times 10^{15}$ ($10^{13}$-$10^{15}$)/$N_2$ ($10^{16}$-$10^{17}$)/Air | [14-17] | 170 (186-236)/$N_2$ (213-221)/Air | [14-17] | 0.02 (0.06-0.13) | [18] |
| Hemi.[c] | 0.230 (0.18-0.30) | [14-18] | $2.51 \times 10^{6}$ ($10^{6}$)/$N_2$ ($10^{7}$)/Air | [14-17] | 88.5 (80-100)/$N_2$ (100-105)/Air | [14-18] | 0.15 (0.19-0.30 | [18] |
| Lign.[c] | 0.180 (0.08-0.23) | [14-18] | $4.50 \times 10^{1}$ ($10^{0}$-$10^{1}$)/$N_2$ ($10^{3}$-$10^{7}$)/Air | [14-17] | 55.0 (38-46)/$N_2$ (66-121)/Air | [14-17] | 0.37 (0.38-0.44) | [18] |

[a] Values in bracket are extracted from literature using identical reaction schemes with reaction orders set to unity for Norway spruce.
[b] Kinetic constants ($A_i$ and $E_i$) were carefully tuned within the pre-defined boundaries until all the key features associated fire spread at the crib scale has been successfully reproduced.
[c] "Cell.", "Hemi.", and "Lign." abbreviate cellulose, hemicellulose and lignin, respectively.

**Table 2.** Thermo-physical properties for spruce and char used in the model.

| | $\rho_{s,i}$ (kg·$m^{-3}$) | $k_{s,i}$ (W·$m^{-1}$·$K^{-1}$) | $c_{s,i}$ (kJ·$kg^{-1}$·$K^{-1}$) | $\varepsilon_{s,i}$ (-) | $H_{r,i}$[c] (kJ·$kg^{-1}$) | $H_{c,i}$[c] (MJ·$kg^{-1}$) |
|---|---|---|---|---|---|---|
| Virgin Wood[a] (Cell./Hemi./Lign.) | 468 | 0.13 | 1.30 | 0.9 | 600/900/-1200 | 12/17/10 |
| Char[b] | 300 | 0.05 (20°C) 0.07 (380°C) 0.10 (800°C) 0.35 (1200°C) | 0.66 (20°C) 1.05 (100°C) 1.25 (200°C) 1.45 (380°C) 1.70 (800°C) | 0.95 | n/a | n/a |

[a] Thermal properties for virgin spruce wood at ambient are kept the same with our previous publication [7].
[b] Temperature-dependent specific heat and conductivities for spruce-derived char are extracted from [20,21,23] and emissivity from [22], density from [23].
[c] Heat of Reaction $H_{r,i}$ and Heat of Combustion $H_{c,i}$ are extracted and adapted from [24] on the same wood species, to ensure that the weighted average values are in line with the literature.

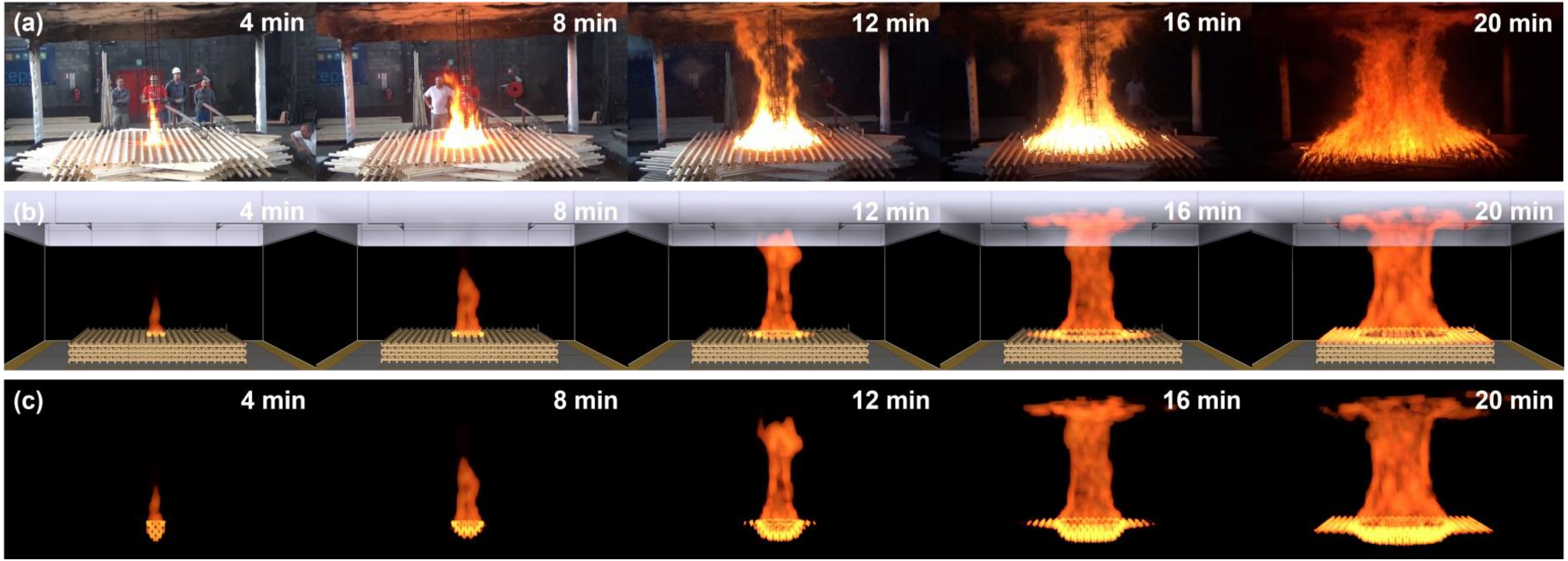



Fig 1 Comparisons of fire spread evolution between LB7 experiment and FDS model for a full-scale isolated wood crib fire test (Gamba *et al.*, 2020) at 4 min time intervals (test images provided by Uni Liège, model images rendered by PyroSim with 200 kW/m$^3$ as HRRPUV cut-off for colouring fires): a) test; b) model; c) model without obstructions

# TRAFIR Ulster tests – test 1 “open ventilation conditions”*


TRAFIR Ulster Travelling Fire Test 1, (a) Skewed view, (b) Front view, figures adapted from Nadjai et al. [11].

* Nadjai, A., Alam, N., Charlier, M., Vassart, O., Dai, X., Franssen, J.-M. & Sjöström, J. (2020) “Travelling fire in full scale experimental building subjected to open ventilation conditions”, SiF 2020 – 11th Int. Conf. Structures in Fire , University of Queensland, Brisbane, Australia, 30 Nov – 2 Dec 2020 doi:10.14264/987a305

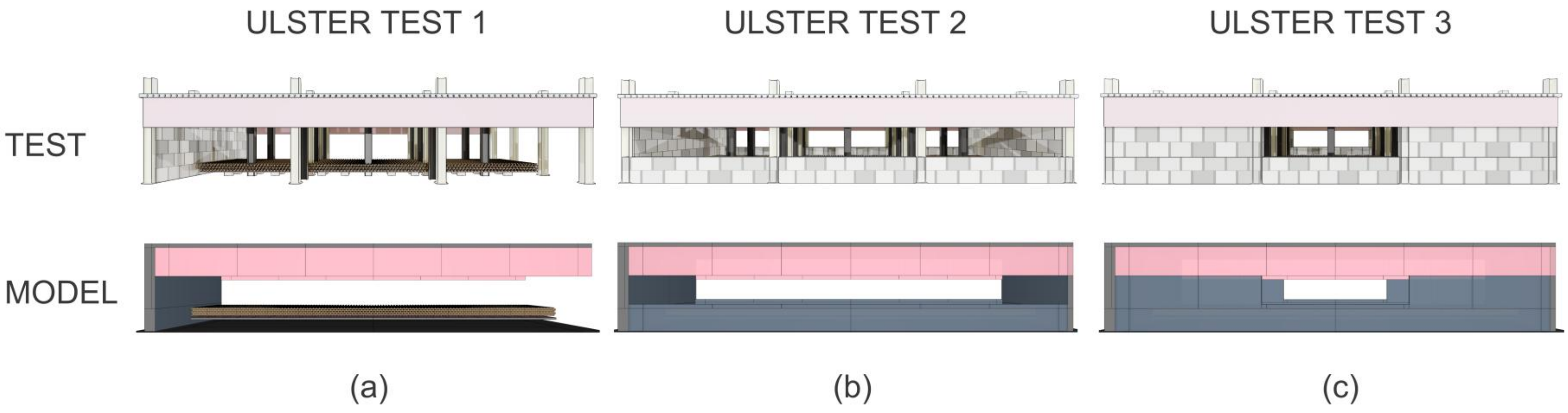



Fig 2 Comparisons of test and model set-up for TRAFIR Ulster Travelling Fire Test Series (Nadjai *et al*., 2022):
a) test 1 (inverse opening factor: 1.6); b) test 2 (inverse opening factor: 8.1); c) test 3 (inverse opening factor: 26.4)

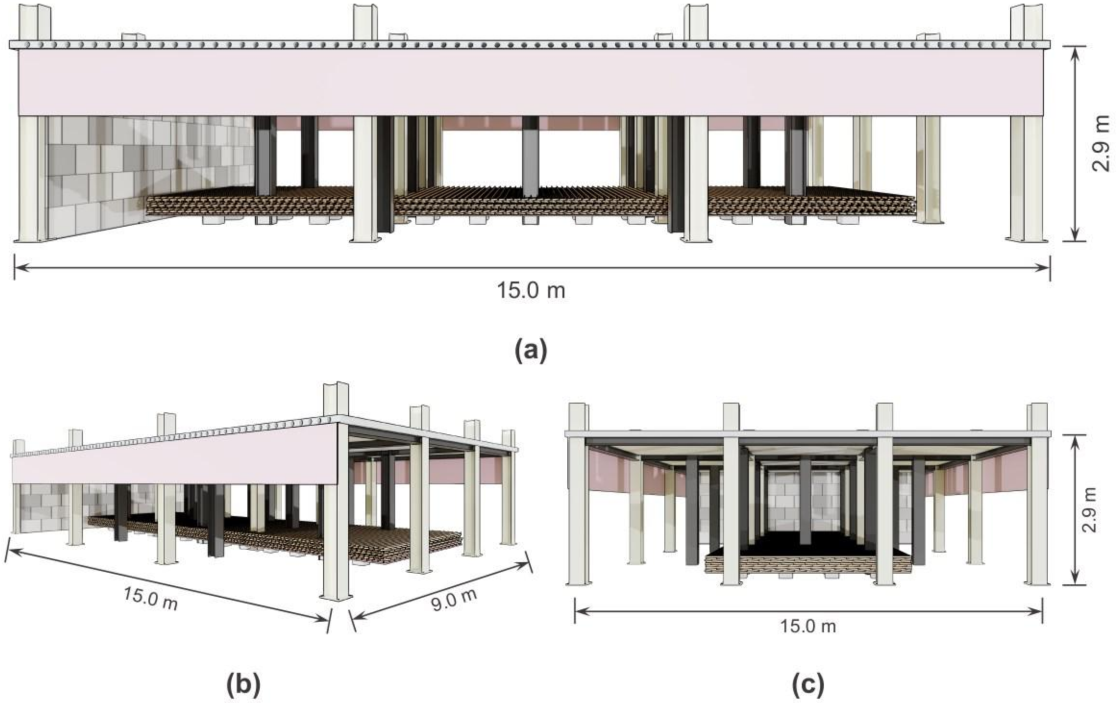



Fig 3 TRAFIR Ulster Travelling Fire Test 1 compartment with dimensions: a) front view; b) skewed view; c) side view.

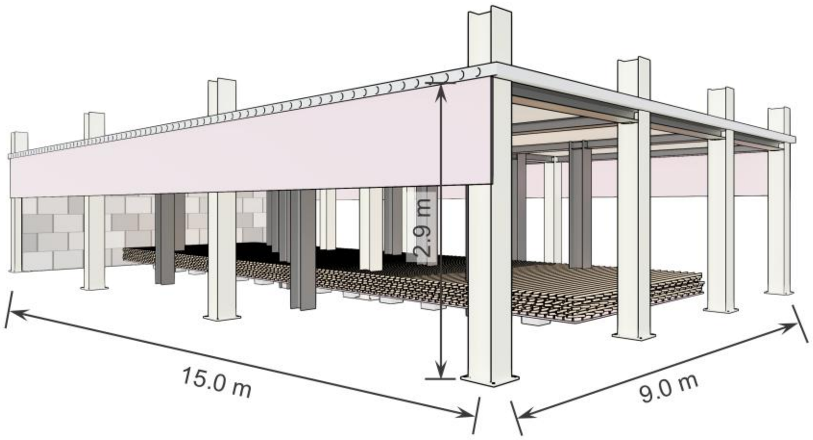



Fig 4 Comparisons of model set-up for TRAFIR Ulster Travelling Fire Test Series (Nadjai *et al*., 2022):
a) test 1 (inverse opening factor: 1.6 – well ventilated); b) test 2 (inverse opening factor: 8.1 - transitional)

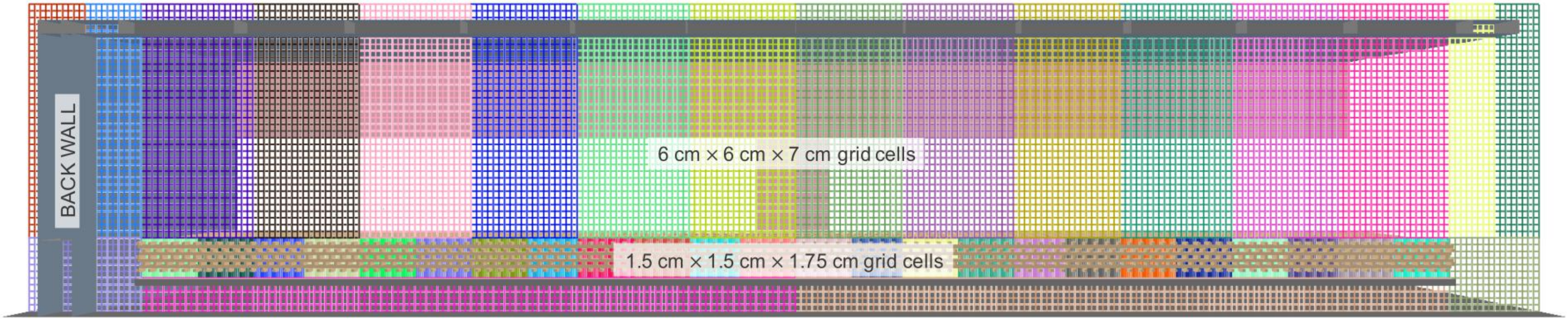



Fig 5 Grid resolution of the scaled-up model: 1.5 cm × 1.5 cm × 1.75 cm per cell inside the crib, 6.0 cm × 6.0 cm × 7.0 cm above the crib, 8.3M cells in total running on 248 cores; mesh boundary positioned 4 cells above the crib surface.

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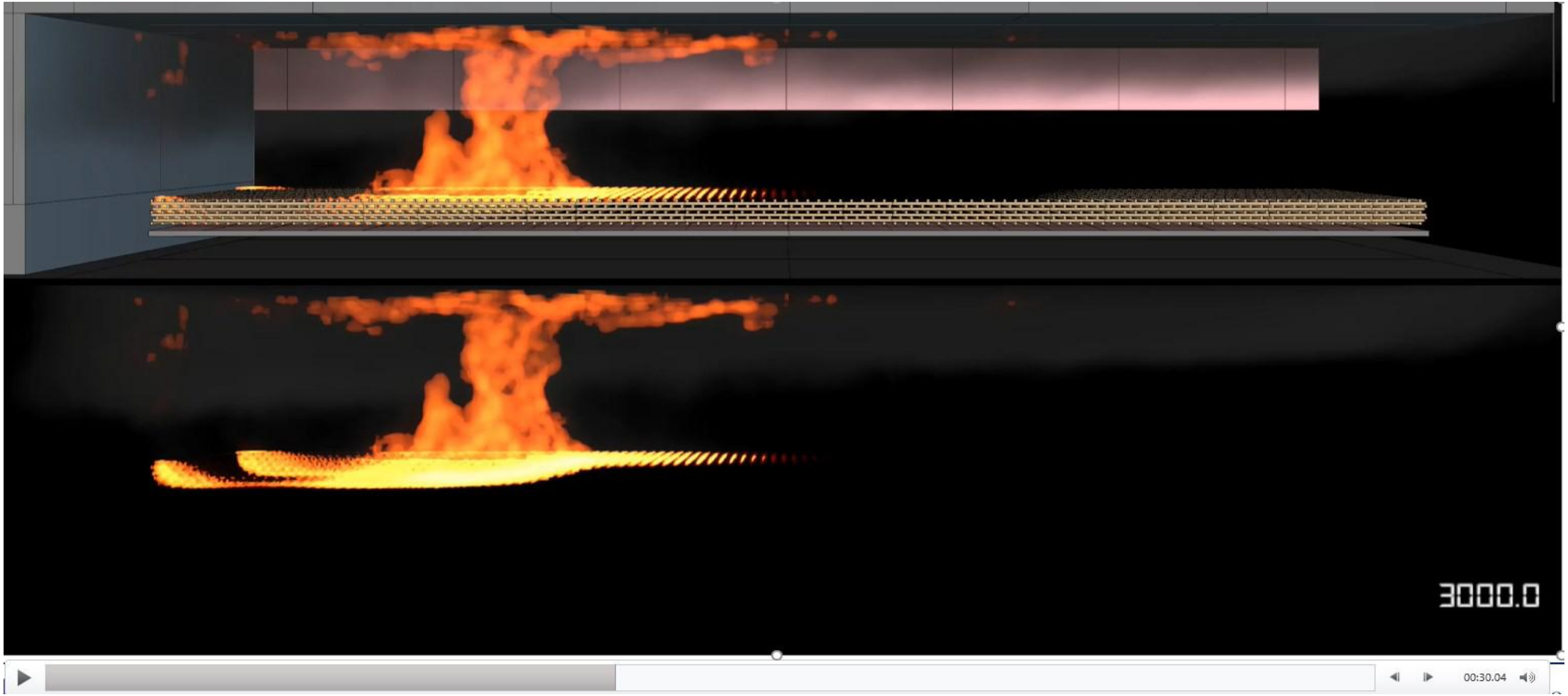
STRUCTURES IN FIRE FORUM

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(a) (b) (c)

Fig 6 Comparisons of fire spread evolutions between test and model for Ulster Travelling Fire Test 1 at 10 min time intervals (test videos c/o Ulster University, model images rendered by PyroSim with 200 kW/m$^3$ as HRRPUV cut-off for colouring fires):

a) test footage;
b) FDS model prediction;
c) model without obstructions (obstructions hidden to show fire spread on and inside wood cribs).

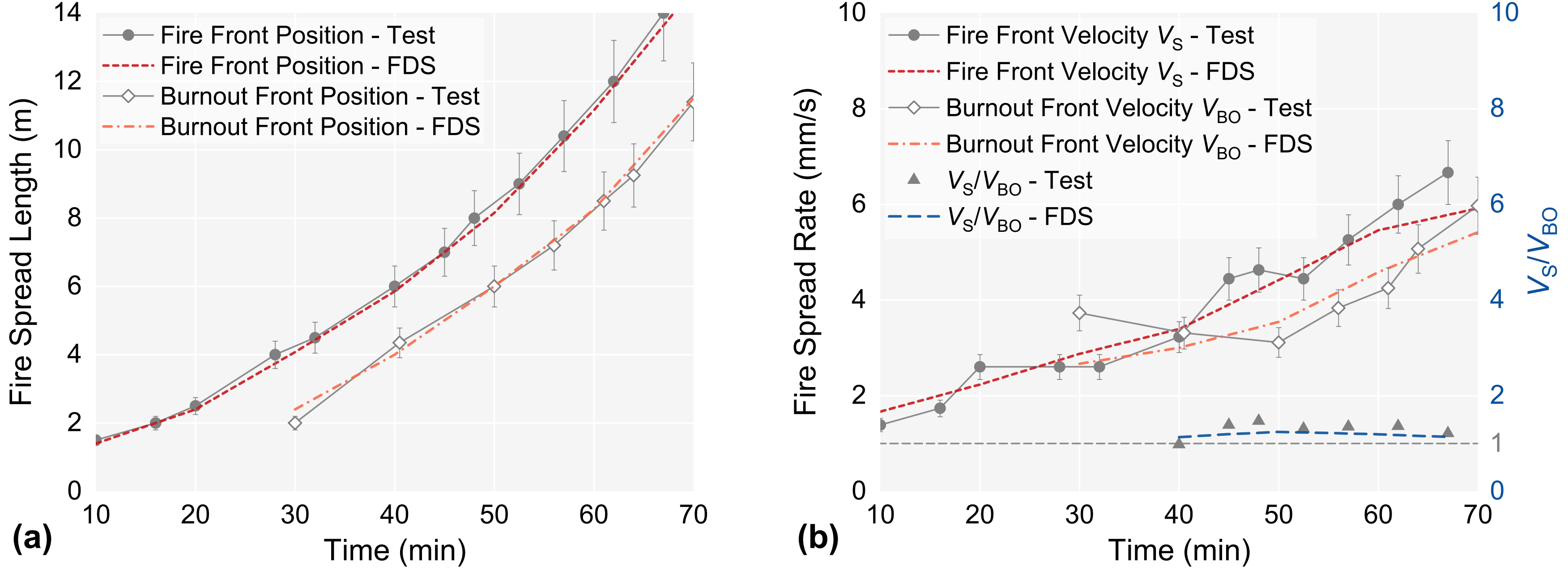



Fig 7 Comparisons of fire spread between test and model at compartment centreline along fire trajectory: a) fire spread length b) fire spread rates and ratio of fire spread rates at fire front to burnout front ($V_S/V_{BO}$).

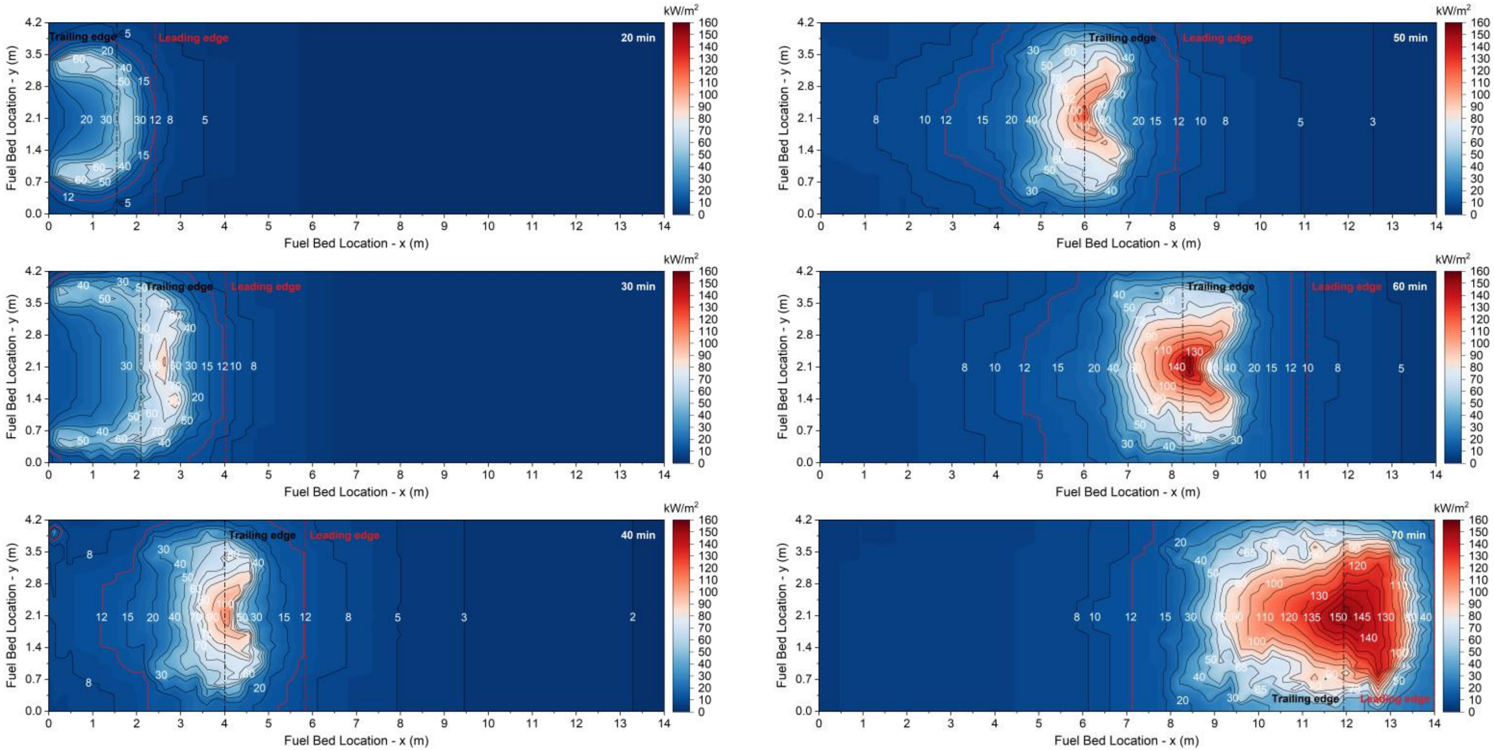



Fig 8 Evolution of **incident heat fluxes** on fuel bed top layer at 10 min time intervals (heat fluxes in kW/m$^2$)

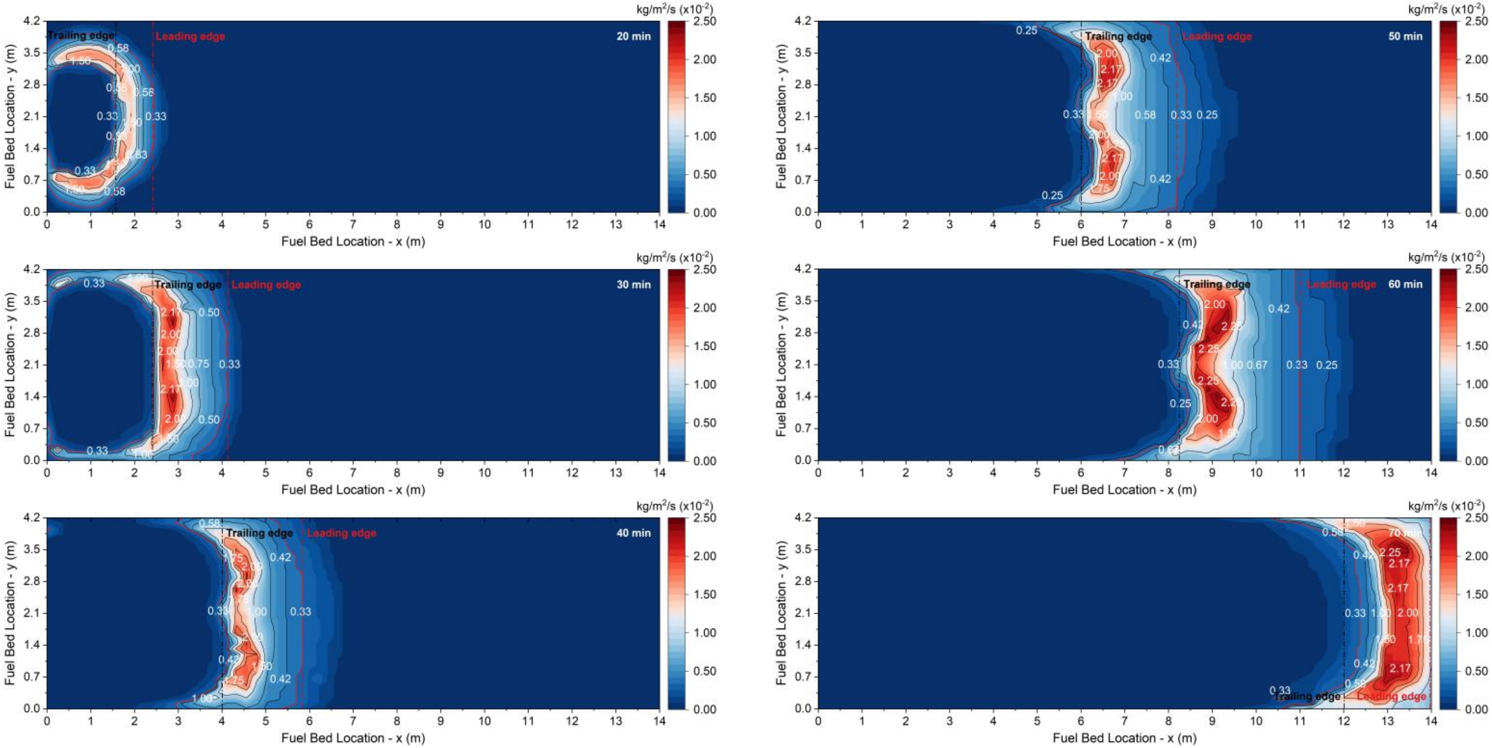



Fig 9 Evolution of instantaneous **fuel burning rates** of top layer at 10 min time intervals (burning rates in kg/m$^2$/s)

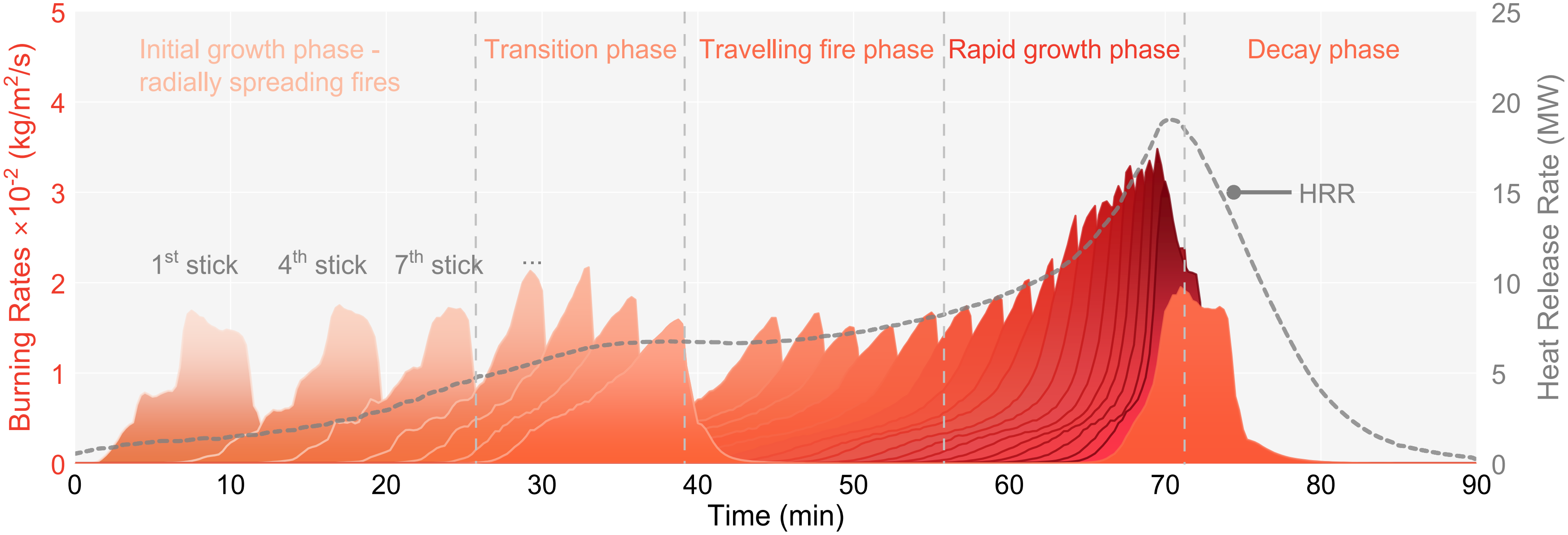



Fig 10 HRR evolution and instantaneous burning rates every 4 sticks along compartment centreline on fuel bed top layer

# Some Aspects of the Growth and Spread of Fire in the Open

P. H. THOMAS

*Ministry of Technology and Fire Offices' Committee Joint Fire Research Organization*

FIRE SPREAD IN EXPERIMENTAL FUEL BEDS, SPREAD IN STILL AIR

It is comparatively recently that attempts have been made to study the spread of fire in laboratory conditions. A large number of experiments in which fire spread through a crib of wood have been conducted by Fons *et al.* (1962) and after his death by Byram *et al.* (1964) in 'Project Fire Model'. They burnt cribs constructed of layers of wood sticks parallel to each other, spaced horizontally a fixed distance apart, each alternate layer having the sticks running at right angles to the layer beneath. Thomas and Simms (1964) and Thomas, Simms, and Wraight (1964) have briefly reported a correlation of such data, with parameters which can be used for other types of fuel beds:

$\sigma$ is the surface per unit of fuel bed volume

$\lambda$ is the volume of voids/surface of solid.

From these definitions it follows that the porosity (the volume of voids per unit of volume) is given by

$$\epsilon = \frac{\sigma\lambda}{1+\sigma\lambda}$$

and for a crib of sticks of size $a$ separated horizontally by a distance $s$ (i.e. $s+a$ between centres).

$$\sigma = 4/a \quad \text{and} \quad \lambda = s/4.$$

Equation (13) gives the rate of spread for thin fuels while equations (13) and (15) to (17) give that for thick fuels namely:

$$R \doteqdot \left(\frac{\dot{Q}_n''}{2\theta_i}\right)^2 \frac{(1+\sigma\lambda)}{K\rho_s c_w \sigma}.$$

where $\dot{Q}_n''$ is the net forward flux allowing for cooling losses

$c_w$ is the effective specific heat of the moist wood

$\theta_i$ is the temperature rise causing ignition in the presence of flame, taken here as 300° C (Simms, 1963),

and $\rho_b$ is the mass of wood heated to ignition per unit volume of fuel bed.

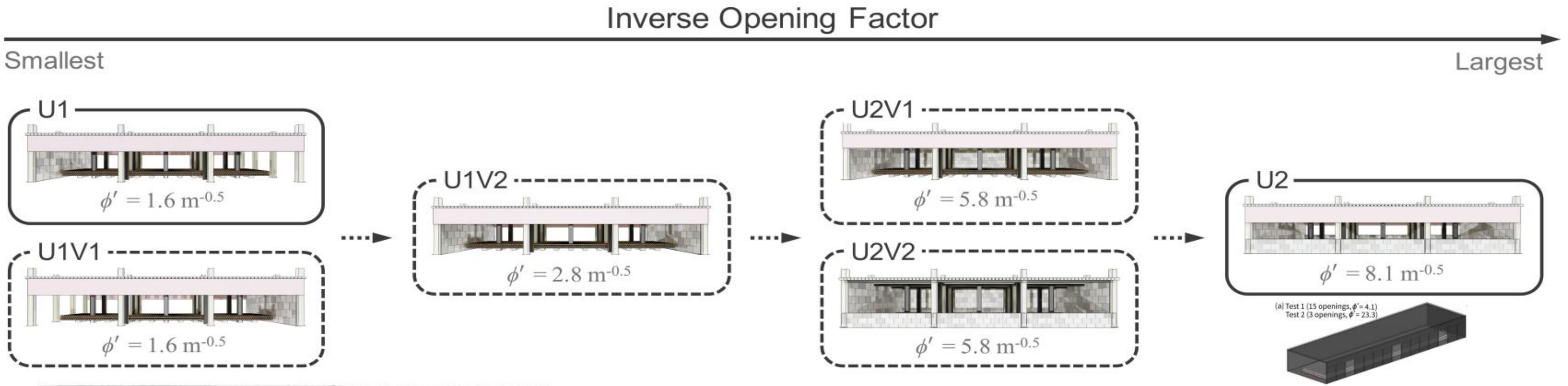
$K$ is the thermal conductivity

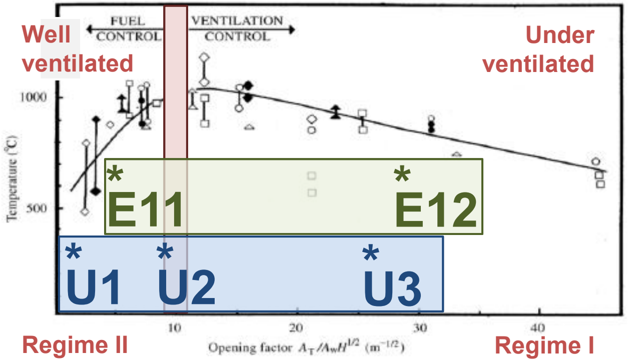
The more detailed theory (Thomas and Simms, 1964) allowing for cooling within the fuel bed gives this as the correct result with

$$\dot{Q}_n'' = \dot{Q}'' - 2{\cdot}67\, H\theta_i,$$

where $\dot{Q}''$ is the gross heat transfer flux and $H$ the cooling coefficient. Moreover, the fuller treatment can be used to calculate the theoretical value of $R$ over the range of stick sizes between thick and thin fuels. The calculations express $R\rho_b c_w/H$ as a function of $H/K\sigma$ and $\dot{Q}''/H\theta_i$ or any combination of these. Byram *et al.*'s experimental data (excluding those for which $\lambda < 0{\cdot}8$ cm, which are referred to below), and those of Fons *et al.* are shown in Fig. 7. Both sets are for white fir (*Abies concolor*). The best value of $\dot{Q}''/H\theta_i$ found by fitting a theoretical line through the data gives a value for $\dot{Q}''$ of about 6–8 W/cm² according to the choice of $H$. This value for the gross heat transfer is typical of radiation from a highly emissive burning zone at about 800° C.

* Thomas, P.H. (1965) "Some aspects of the growth and spread of fire in the open", Fire Research Note No. 552 https://publications.iafss.org/publications/frn/552/-1




| ULSTER (TRAFIR) | IOF ($m^{-0.5}$) | ETFT (RFSDTB) | IOF ($m^{-0.5}$) |
|---|---|---|---|
| Well ventilated (U1) | 1.6 | | |
| Transitional (U2) | 8.1 | ETFT unrestricted (E11) | 5.0 |
| Under ventilated (U3) | 26.4 | ETFT restricted (E12) | 28.5 |

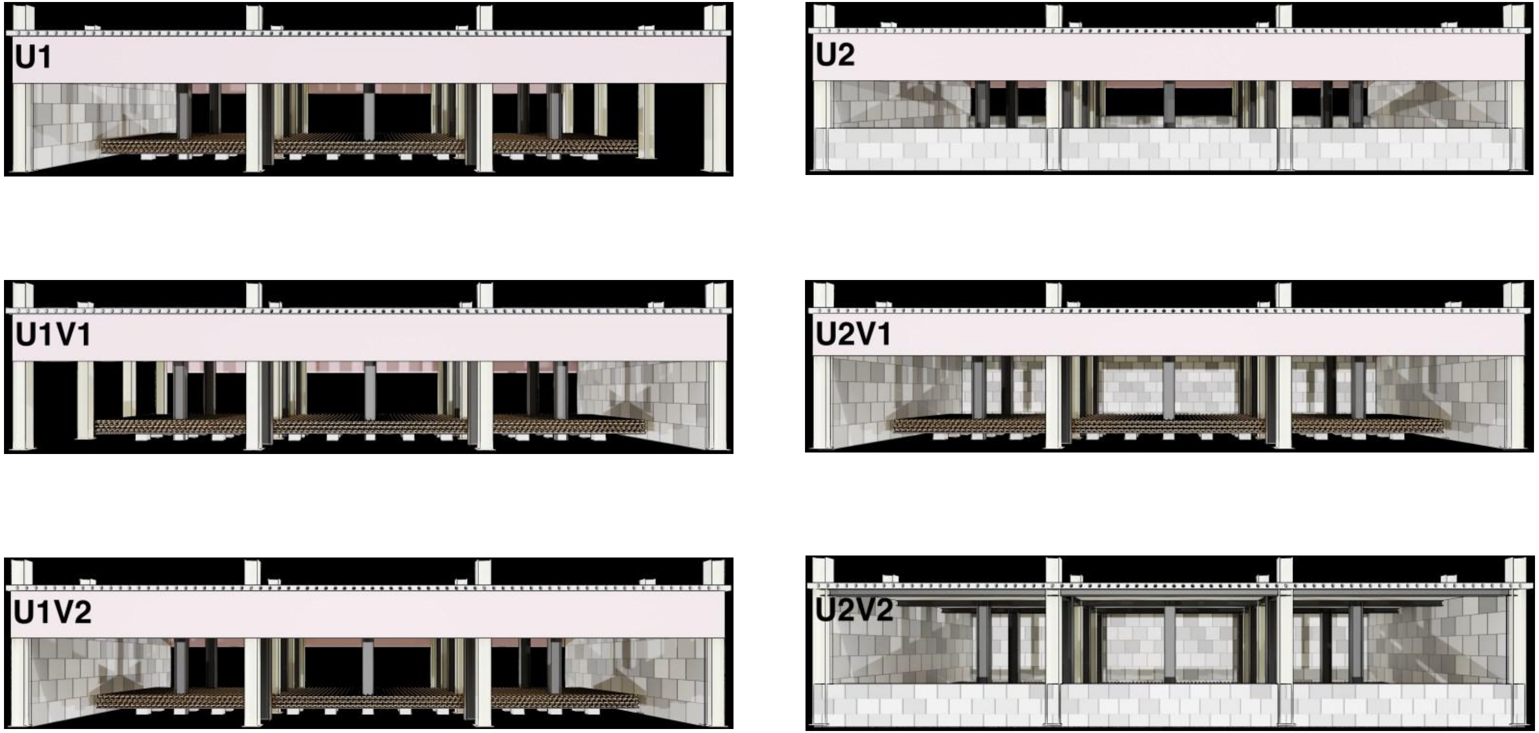
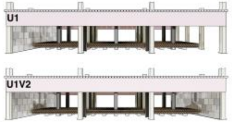
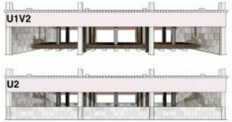



Fig 11 Parametric study on opening factors and areas extended from Ulster TRAFIR Tests 1 and 2 (U1, U2)

| Variant | Opening area ($m^2$) | IOF ($m^{-0.5}$) | Parameter studied |
|---|---|---|---|
| U1 | 15x2x2 + 9x3 = 82.2 | **1.6** | Baseline **well ventilated** |
| U1V1 | 82.2 | 1.6 | End wall by fire/distant |
| U1V2 | 57.2 | 2.8 | Two end walls |
| U2 | 15x1x2 = 30.0 | **8.1** | Baseline **transitional** |
| U2V1 | 30.0 | 5.8 | Full side wall/open wall |
| U2V2 | 30.0 | 5.8 | Downstand v upstand |
| ETFT 11 | 17.8x1.5 = 24.8 | 5.0 | Baseline well ventilated |
| ETFT 12 | (3x1.1)x1.5 = 5.0 | 28.5 | Baseline underventilated |

**Table 1.** Summary of compartment configurations used for parametric studies.

| Candidates for comparisons | Opening Area ($A_w$) [$m^2$] | Opening Factor ($\phi'$) [$m^{-0.5}$] | Main Variables | Objectives |
|---|---|---|---|---|
|  | 82.2 | 1.6 | Opening locations | The role of end walls |
|  | 82.2 (U1)<br>57.0 (U1V2) | 1.6 (U1)<br>2.8 (U1V2) | Opening areas | The role of opening areas under well-ventilated conditions |
|  | 57.0 (U1V2)<br>30.0 (U2) | 2.8 (U1V2)<br>8.1 (U2) | Opening areas | The role of opening areas |
|  | 30.0 | 8.1 (U2)<br>5.8 (U2V1) | Opening factors | The role of opening factors |
|  | 30.0 | 5.8 | Downstand /upstand | The role of downstand and upstand |

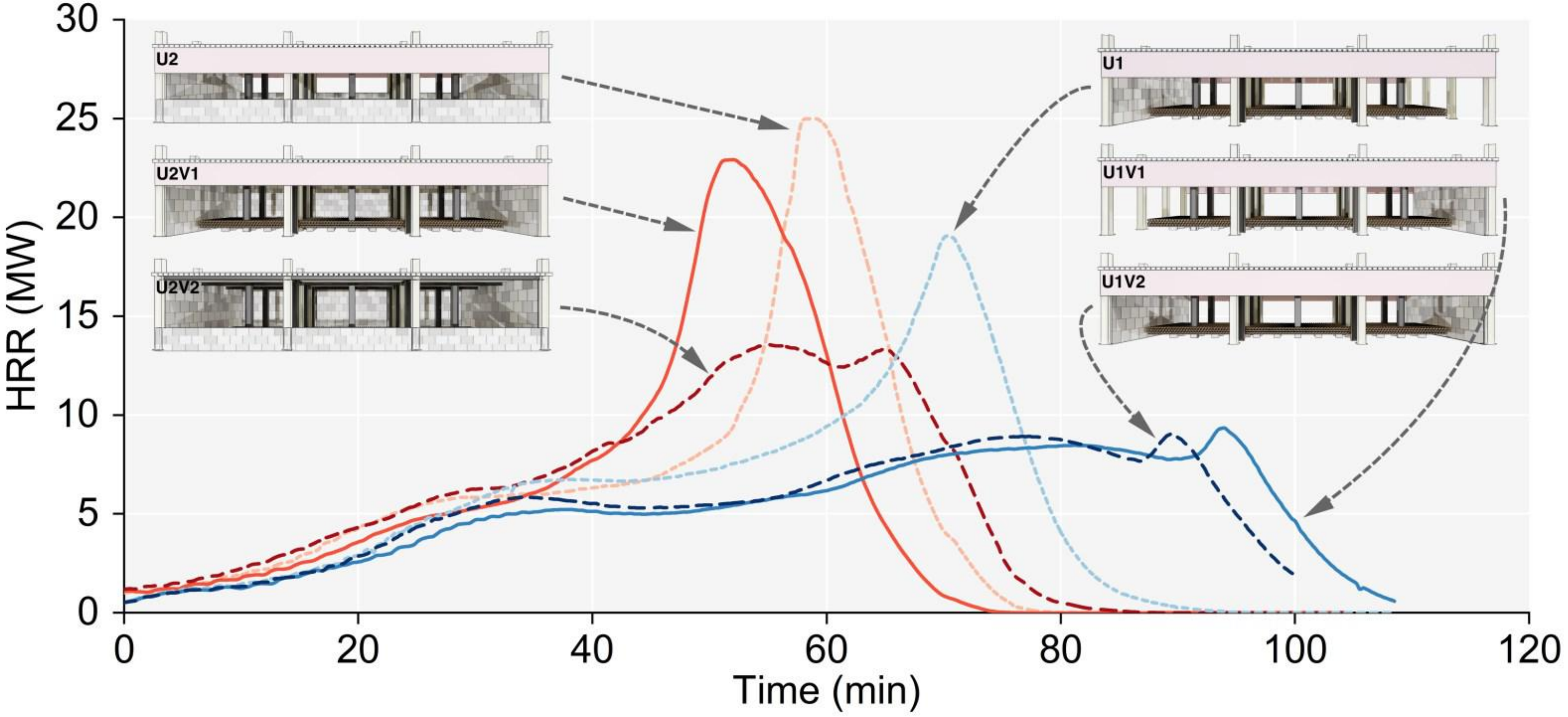



Fig 12 Comparison of heat release rate evolutions for 6 parametric study scenarios

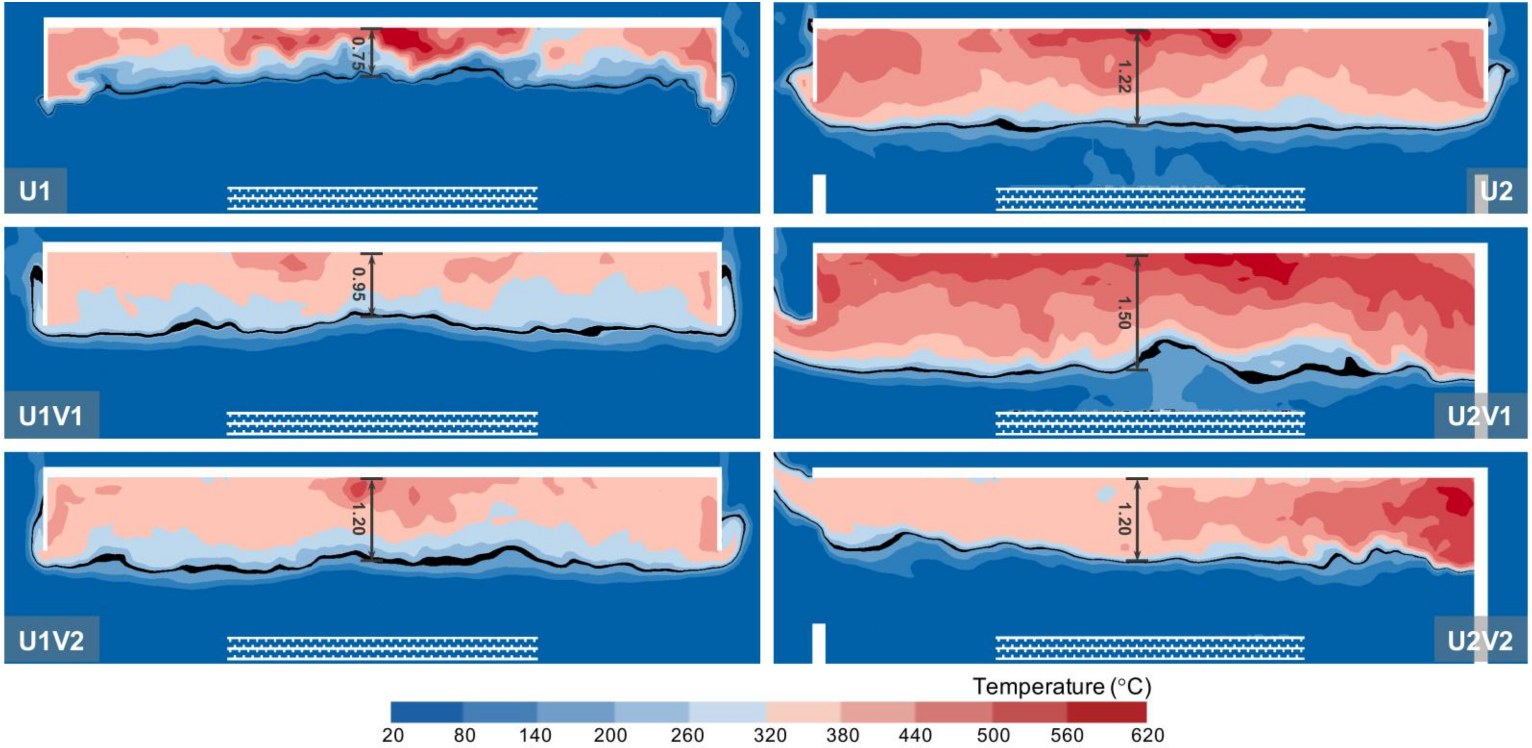



Fig 13 Comparison of “far field” smoke layer development (demarcated by 200ºC contour) for 6 parametric study scenarios

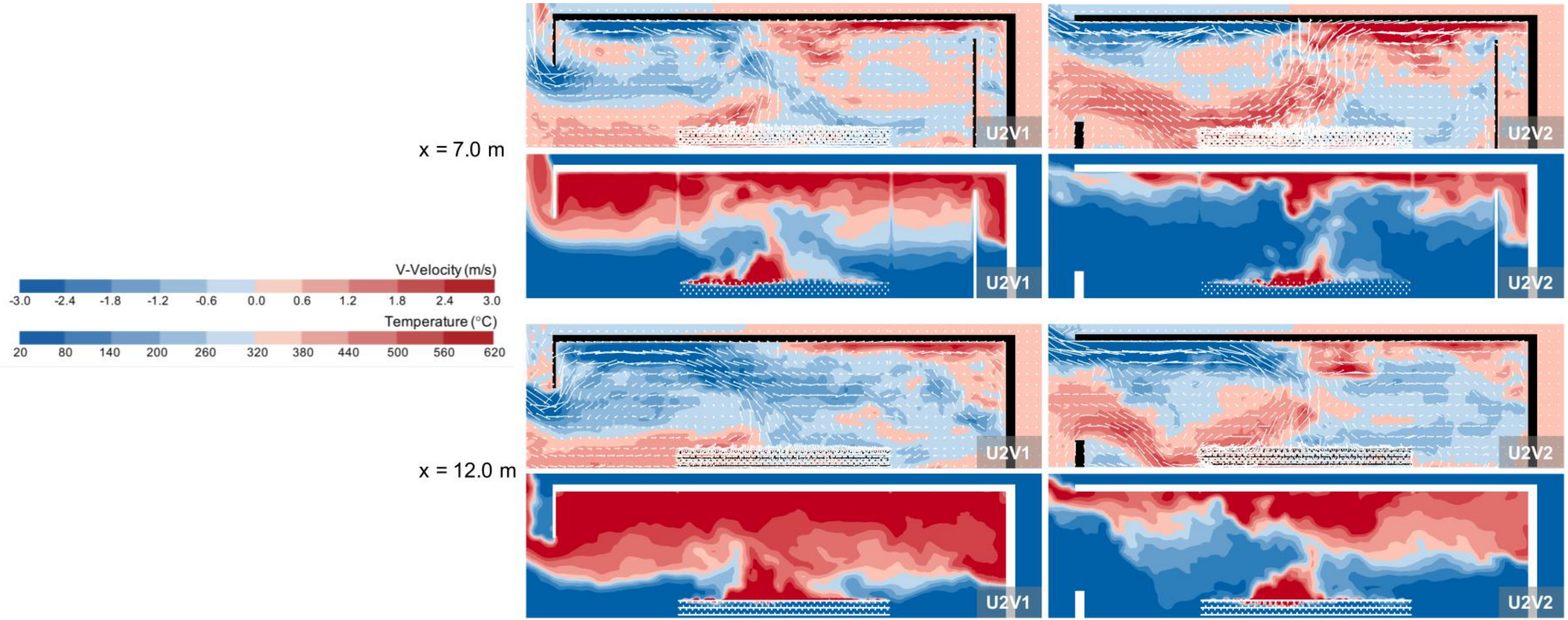



Fig 14 Comparison of “far field” smoke layer temperature and flow development for the U2 variants (downstand/upstand)

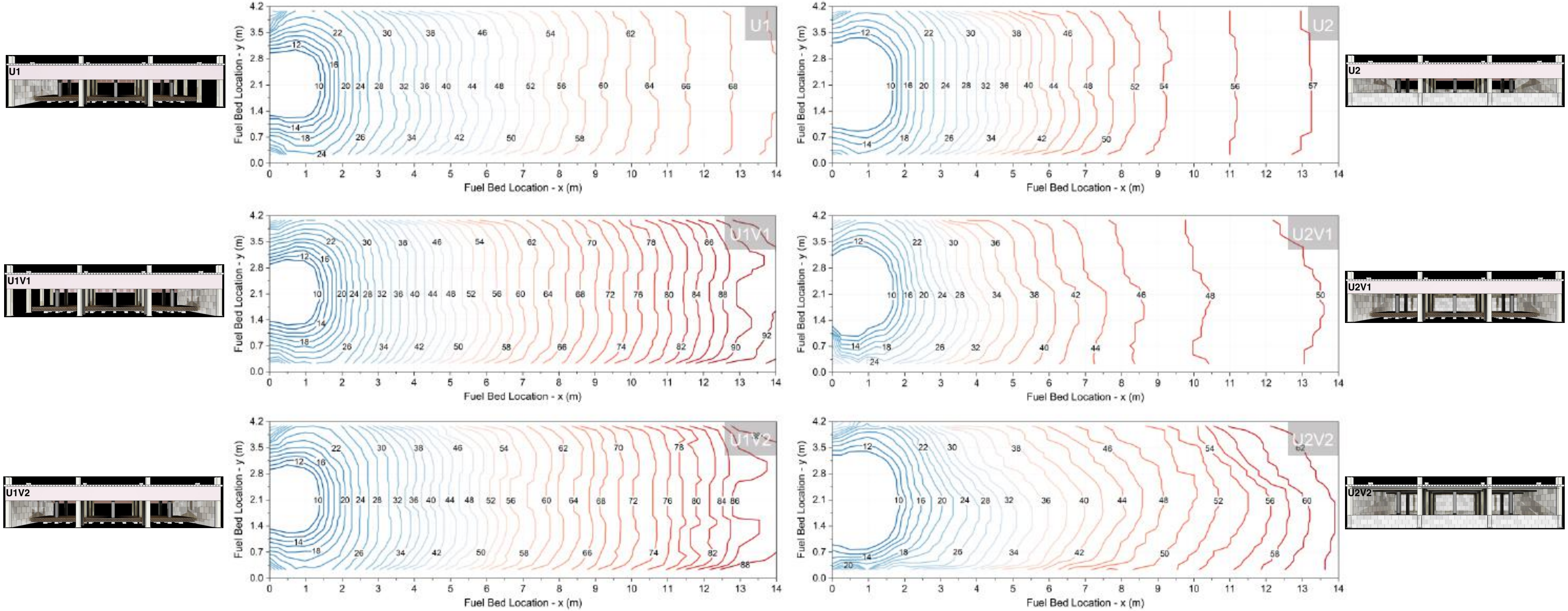



Fig 15 Comparison of fire progression (fire front contours) in plan for 6 parametric study scenarios

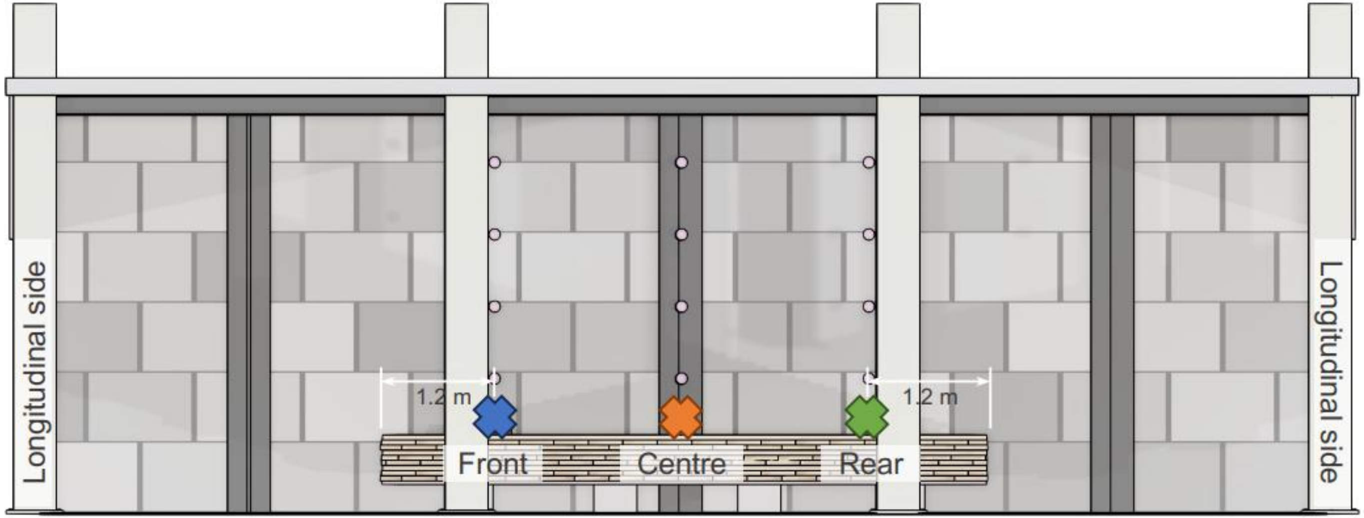



Fig 16 Locations of “front”, “centre” & “rear” longitudinal lines on fuel bed surface in right-side view of U1 compartment

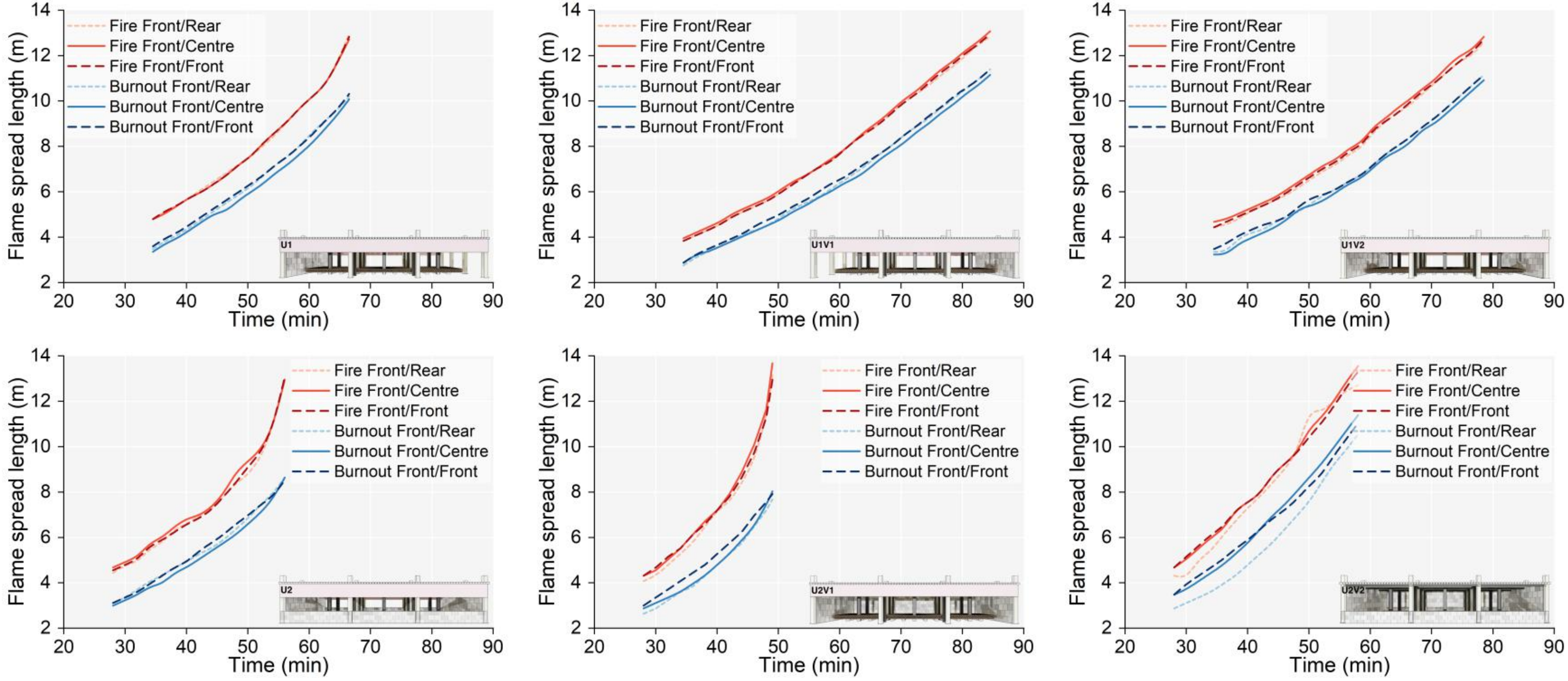



Fig 17 Comparison of fire progression (fire front/burnout front locations across depth) for 6 parametric study scenarios

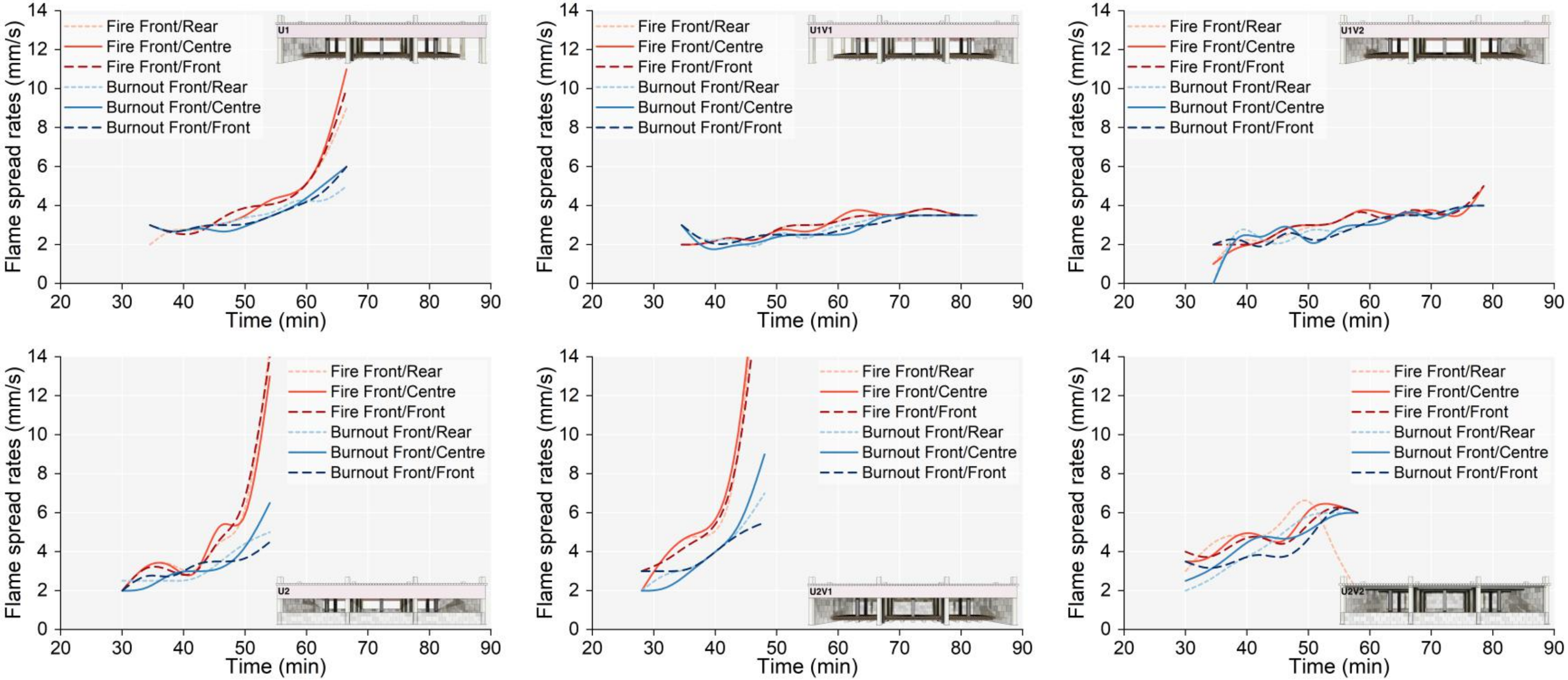



Fig 18 Comparison of fire progression rates (fire front/burnout front locations across depth) for 6 parametric study scenarios

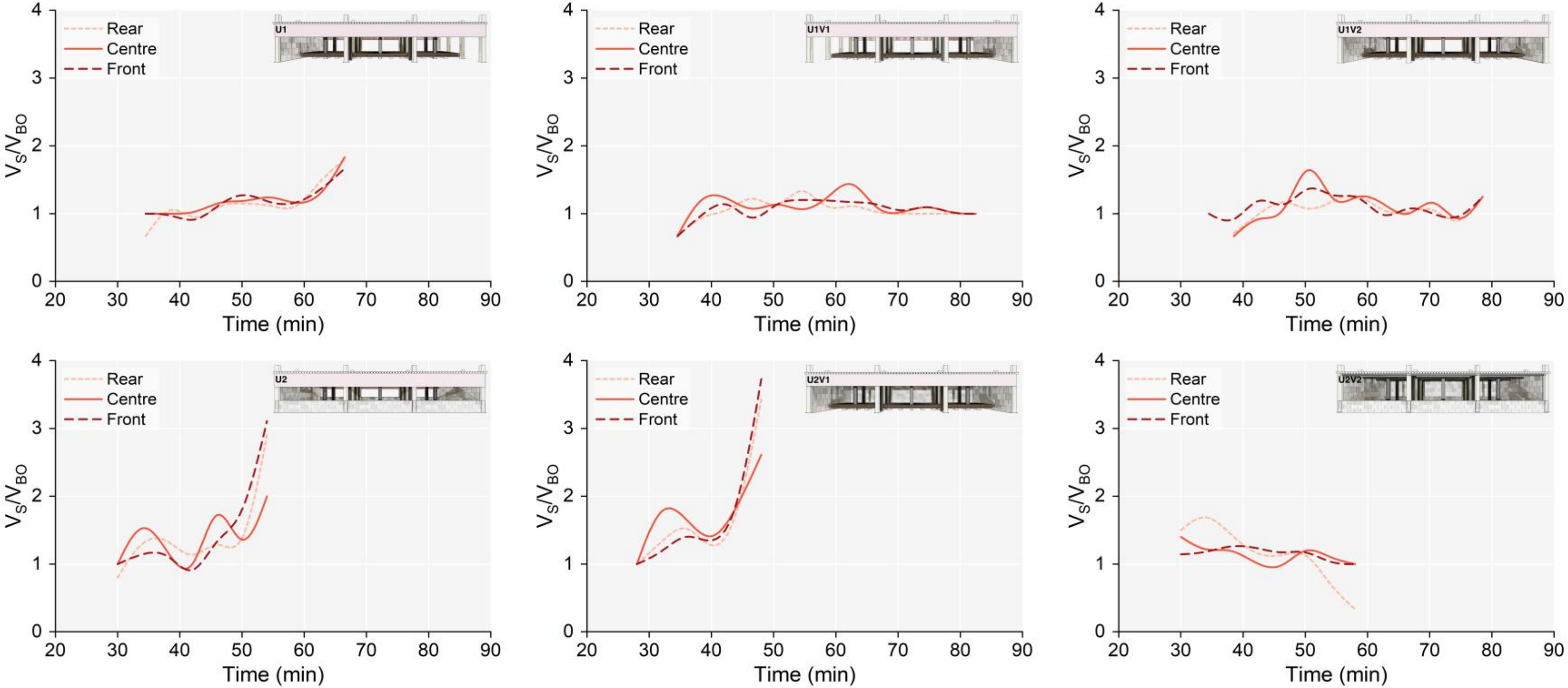



Fig 19 Comparison of fire spread velocity ratios fire ($V_s$ front/$V_{bo}$ burnout front) for 6 parametric study scenarios

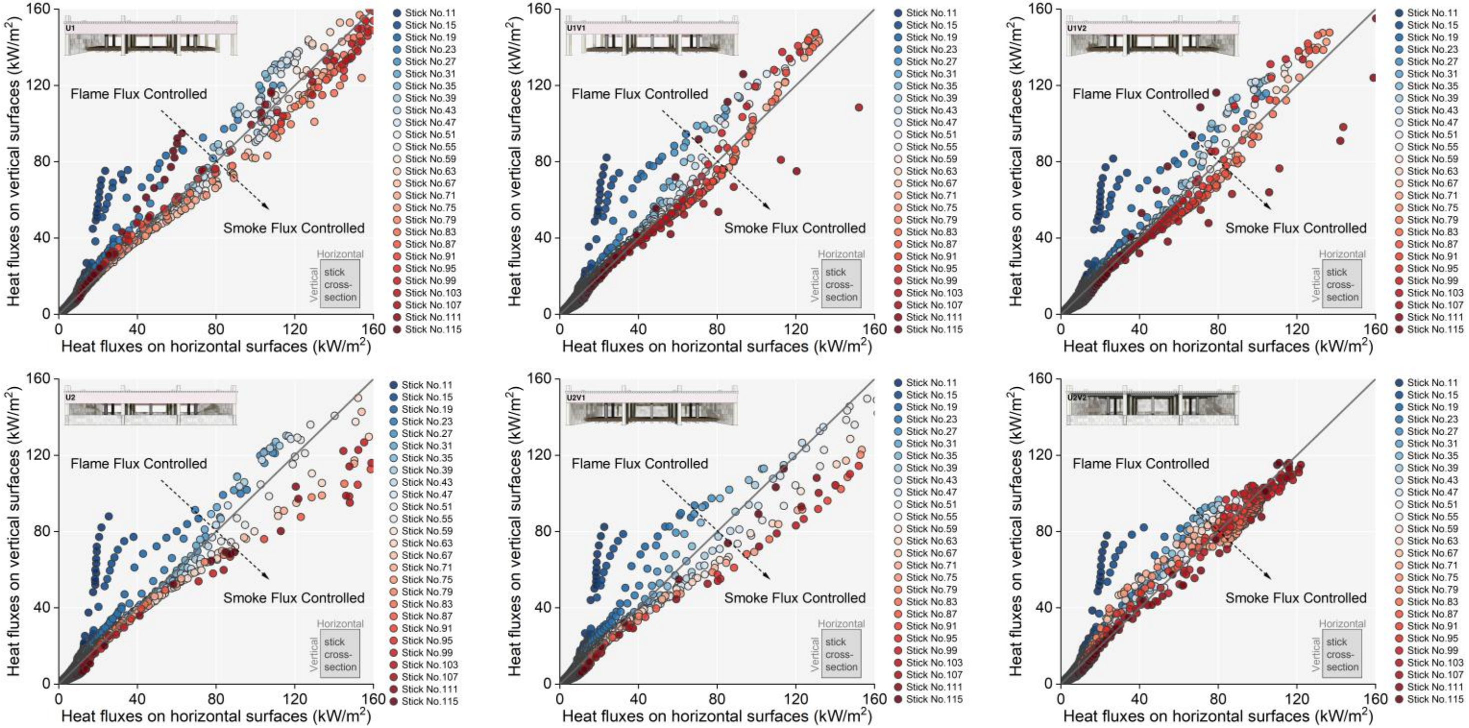



Fig 20 Comparison of heat flux ratios (vertical v horizontal) for 6 parametric study scenarios


(a) Fig 21 Comparisons of fire spread between test and model at compartment centreline along fire trajectory every 10 mins: a) Ulster TRAFIR test 1 (well ventilated IOF=1.6 $m^{-0.5}$) b) Ulster TRAFIR test 2 (transitional IOF=8.1 $m^{-0.5}$) (b)


Fig 22 Comparisons of fire spread between test and model at Ulster compartment centreline at 50 mins: a) test 1 b) test 2

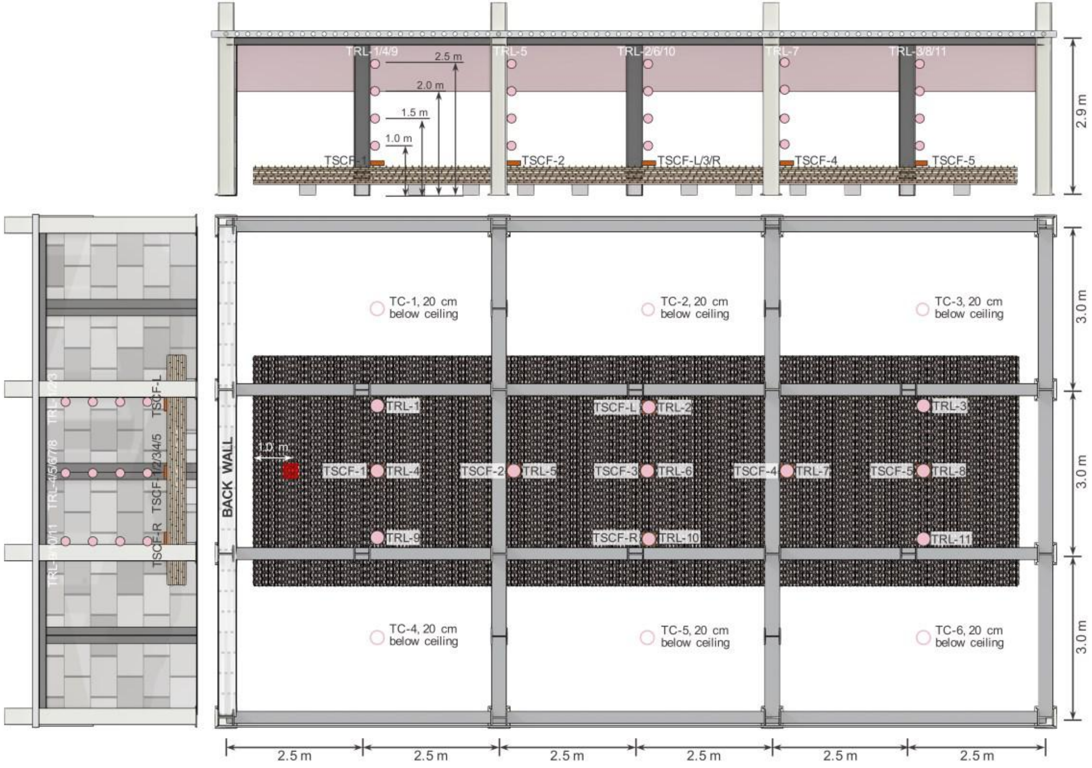



Fig 23 Instrumentation positions implemented in Ulster test and model:

a) position of thermocouple trees (TRLs) in elevation view;

b) position of thermocouples (TCs and TRLs) and Thin-Skin Calorimeters (TSCs) in plan view (TSCs were all placed on top of fuel bed level, TC 1-6 were placed 20 cm below ceiling, TRL 1-11 are thermocouple trees placed directly above the wood cribs, igniter is shown as red square 1 m away from back wall)

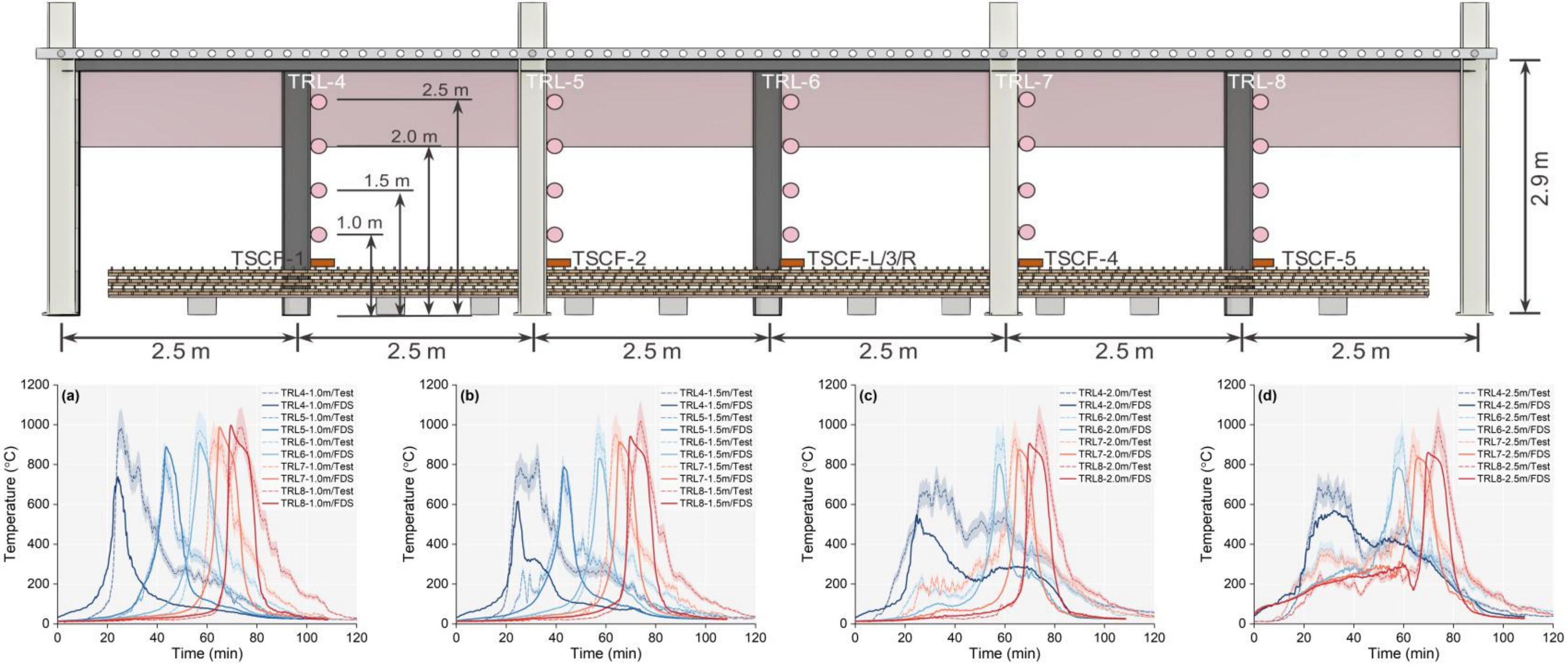



Fig 24 Ulster **Test 1**: Comparison of thermocouple temperatures at compartment centreline along fire trajectory, TRL 4-8 (NB TRL5-2.0 m and 2.5 m malfunctioned due to overheating during data acquisition)

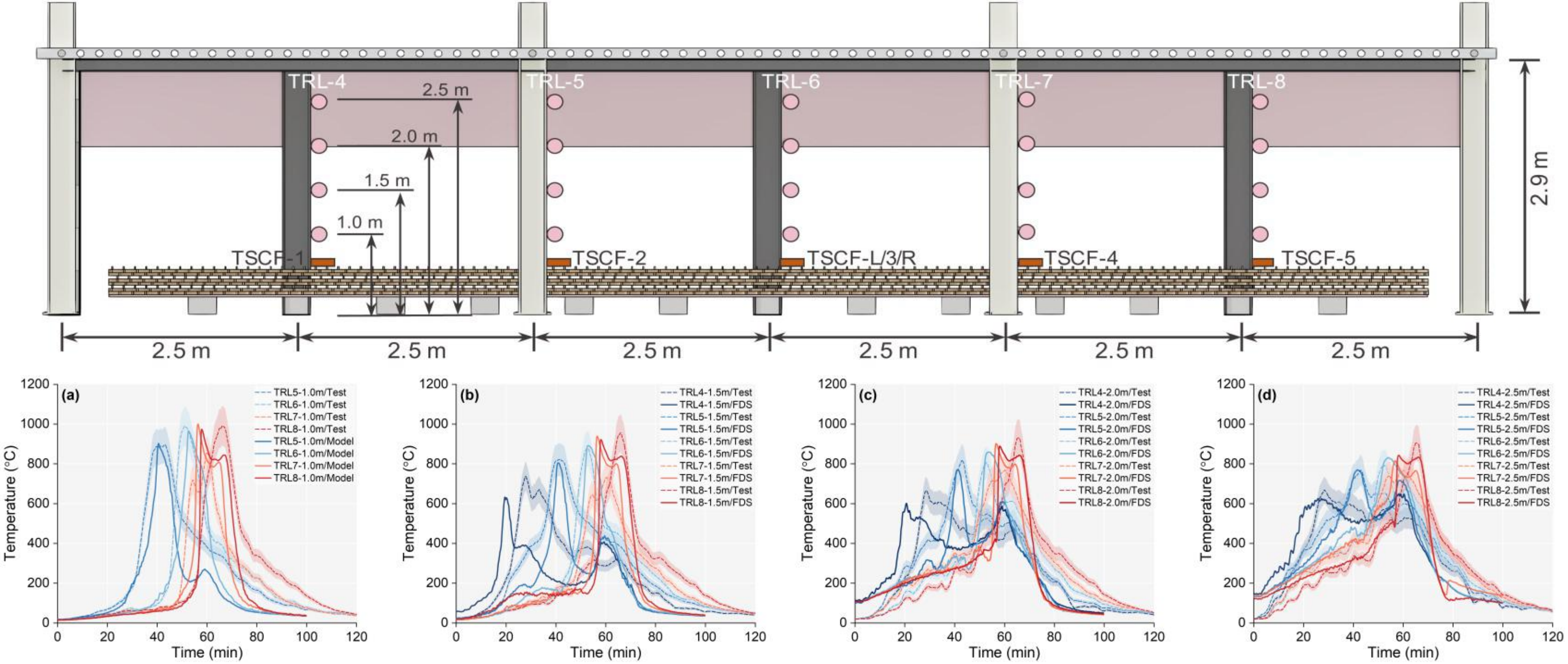



Fig 25 Ulster **Test 2**: Comparison of thermocouple temperatures at compartment centreline along fire trajectory, TRL 4-8

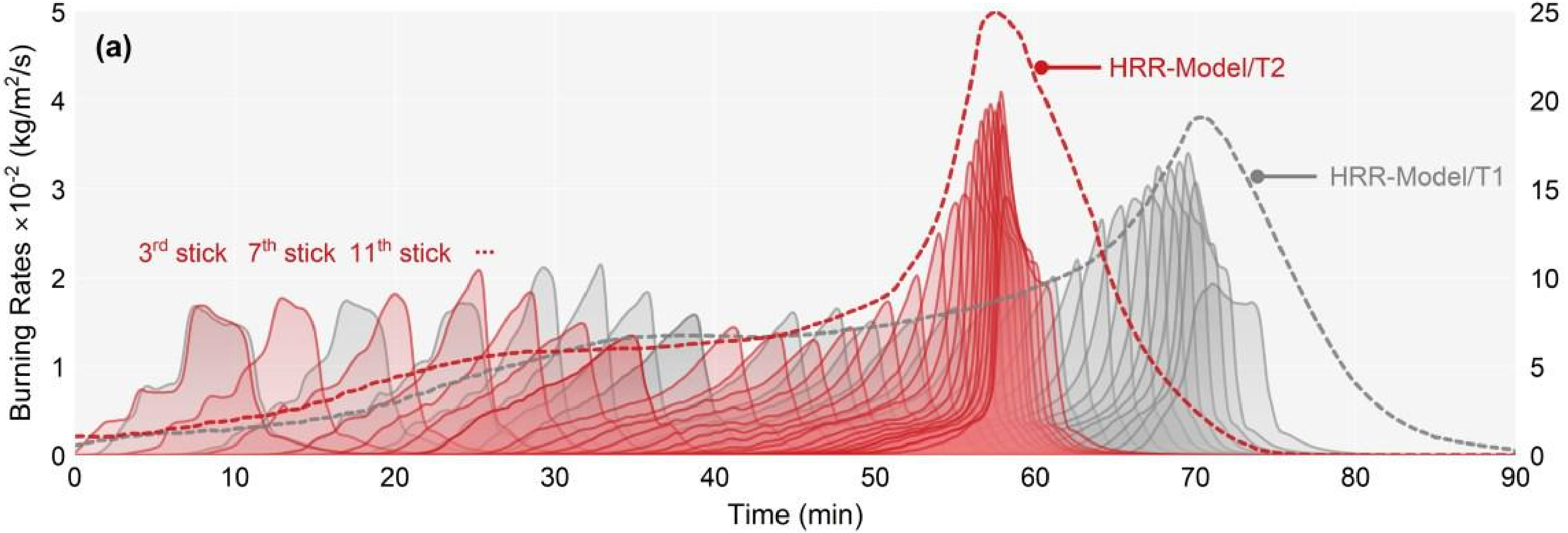



Fig 26 HRR evolution and instantaneous burning rates every 4 sticks along compartment centreline on fuel bed top layer

# Conclusions (1)

> Building on previous work which has demonstrated the possibility of **applying a detailed pyrolysis model** to predict fire spread at both lab- and compartment-scales, via a numerical simulator that provides enhanced representations of wood cribs fuel bed geometry on a detailed "**stick-by-stick**" basis and integrates **condensed-phase pyrolysis processes via multiple parallel reaction pathways**.

> Compared to approaches which consider fire spread primarily in terms of ignition to a new fuel surface, results **relate burning rates to the local fire environment** to gain better understanding of the drivers of fire spread.

> "Numerical simulator" **gives insights into fire science phenomena**:

a) Captures **progression of ignition and burning rates** on each surface of each wood stick

b) Demonstrates evolving fuel surface boundary condition arising from **fire plume and hot smoke layer** above it

c) Demonstrates evolution of **surface and in-depth burning** within crib as fire progresses in different regimes

> Validation extends to inversion opening factor range 1.6 to 8.1 $m^{-0.5}$, within the fuel-controlled regime; this opens up new avenues for **performing experiments virtually** within a similar range, enabling the exploration of fire dynamics in ways that would be **impossible or impractical to address through physical tests alone**.

# Conclusions (2)

> Parametric studies in the well-ventilated regime clarifies factors influencing **fire spread and thermal severities**:

**a)** **restriction of ventilation tends to supports heat retention** and enhances fire spread via pre-heating, resulting in more rapid transition to growing and greater thermal severities;

**b)** **proximity of initial fire to solid boundaries supports more rapid spread** away from igniter;

c) by contrast, **burning in vicinity of solid boundaries tends to be suppressed** due to lack of oxygen;

**d)** **arrangement of openings can have a big impact on fire development** due to differences in smoke layer evolution;

e) an extreme example is replacing a downstand with an upstand, and consequent reduced thermal severities;

**f)** **complex trade offs between layer depth and energy release rates** via local limits on oxygen

Hence an overall recognition that:

- **opening factors and/or areas on their own are poor determinants** of fire spread drivers (Thomas said!)
- **a clear gain associated with CFD-based numerical simulators**
  - detailed exploration of fire behaviours, potential for **unravelling fire spread mechanisms**
  - see our Interflam and forthcoming IAFSS papers…

# Limitations and further work

> Further study needed of model predictions for **more enclosed scenarios** (higher inverse opening factors):

a) higher sensitivity to uncertain thermal properties of compartment linings;

**b) extinction models are required for underventilated conditions** and remain highly uncertain;

**c) soot yields rise strongly when underventilated** and FDS uses a conserved scalar which will be unrepresentative.

> All of the same considerations apply for applications with **timber-lined compartments**:

a) prediction of time to ignition might be possible using the same detailed pyrolysis model, and variants for other woods;

b) the subsequent enhanced heat release rates typically lead directly to the conditions mentioned above;

**c) great care needed in exercising such models, and challenges in "validation" given the complexities**;

d) moreover, the inability to represent the heat transfer from glowing embers becomes a more dominant issue.

**> Ultimately provide input to analytical models for structural fire engineering:**

a) parallel research stream on sensitivities of structural performance;

b) significance of concrete/composite slab on structural fire performance

(Dr Xu Dai @Uni Liverpool, Dr Zhuojun Nan @TU Delft, etc.)

# Acknowledgements:

## ARCHER2

**This work used ARCHER2 via EPSRC Access to HPC**

**> Earlier work UKCTRF [https://www.ukctrf.com/](https://www.ukctrf.com/)**

**> UK National Supercomputing Service**

> UK's **most powerful** supercomputer

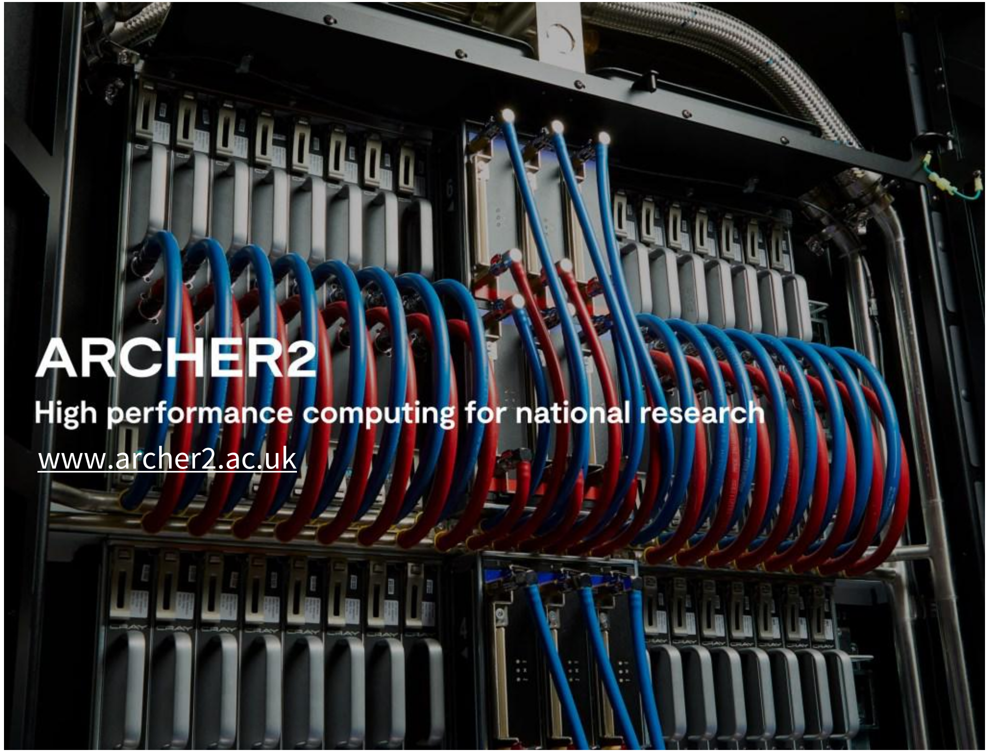
> Peak performance **28 PFLOP/s**

> Equalling **250,000** modern laptops

> **5,860** compute nodes

> **748,544** CPU cores (128 cores per node)

> Housed @ **EPCC**



# Acknowledgements:

## Cirrus

**This work used Cirrus UK National Tier-2 HPC Service via**

**Scottish Academics Access scheme**

> UKRI's **EPSRC Tier-2 HPC**

> **368** high-mem compute nodes

> **13,250** CPU cores (36 cores per node)

> **4** Nvidia Tesla V100-SXM2-16GB GPUs

> Housed @ **EPCC**

> Funded by UKRI's **EPSRC**

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15/16 Pei Ying (Penny) Yang (IMFSE)
17/18 Zhuojun Nan (SAFE MSc), Haimin Chen (SAFE MSc)
18/19 Siqi Du (SAFE MSc)
19/20 Chang Liu (SAFE MSc), Yang Xu (SAFE MSc)
20/21 Peter Charley (MEng); **Chang A. Liu (SAFE MSc => PhD 22-25)**
21/22 Weitian Lu (SAFE MSc), Yanchi Mo (SAFE MSc)
22/23 Bo Gunnarsson (MEng); Qianzhuo Zhou (SAFE MSc)
24/25 **Xiyue Ming Ming (MEng)**
24/25 Desmond Lou (IMFSE)

+ Research project courses:

- Undergraduate MEng thesis (50 credits)
- IMFSE dissertation (60 credits);
- Structural and Fire Safety Engineering (SAFE) MSc dissertation (90 credits)

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## EU RFCS TRAFIR project

Characterisation of TRAvelling FIRes in large compartments

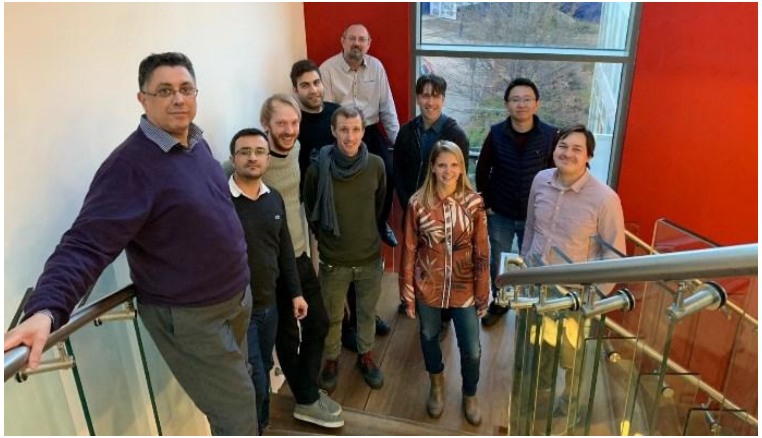
Industrial led – ArcelorMittal, Luxembourg
(1/07/2017 → 31/12/2020)

> Testing
Isolated elements & simplified fire progression, full-scale large compartment
> Modelling
Simplified analytical/phenomenological models and CFD

https://www.researchgate.net/project/TRAFIR-Characterization-of-TRAvelling-FIRes-in-large-compartments

Project partners:

ArcelorMittal, LIÈGE université, RI. SE, Ulster University, The University of Edinburgh

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# Q&A


FireSERT
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10 min
20 min
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70 min