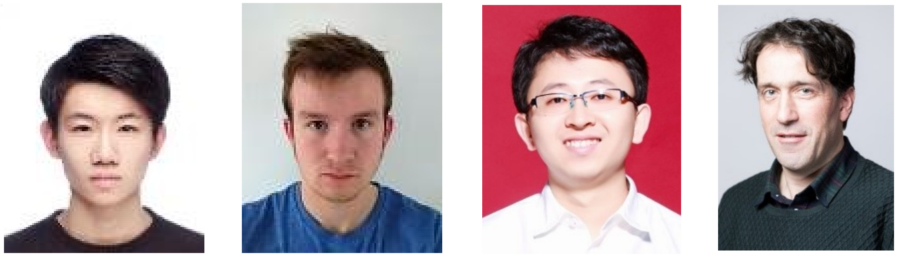
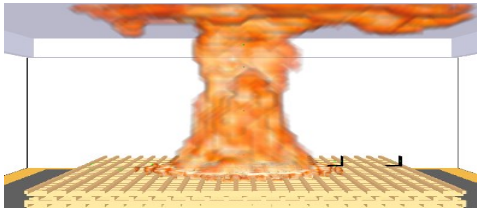
Numerical Modelling of Fire Spread on Wood Cribs: the Role of the Char and Enhanced Grid Sensitivity Studies

UKCTRF Annual conference
2 December 2021



Chang Liu, Peter Charley, Xu Dai, **Stephen Welch**



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United Kingdom

Travelling fires for structures

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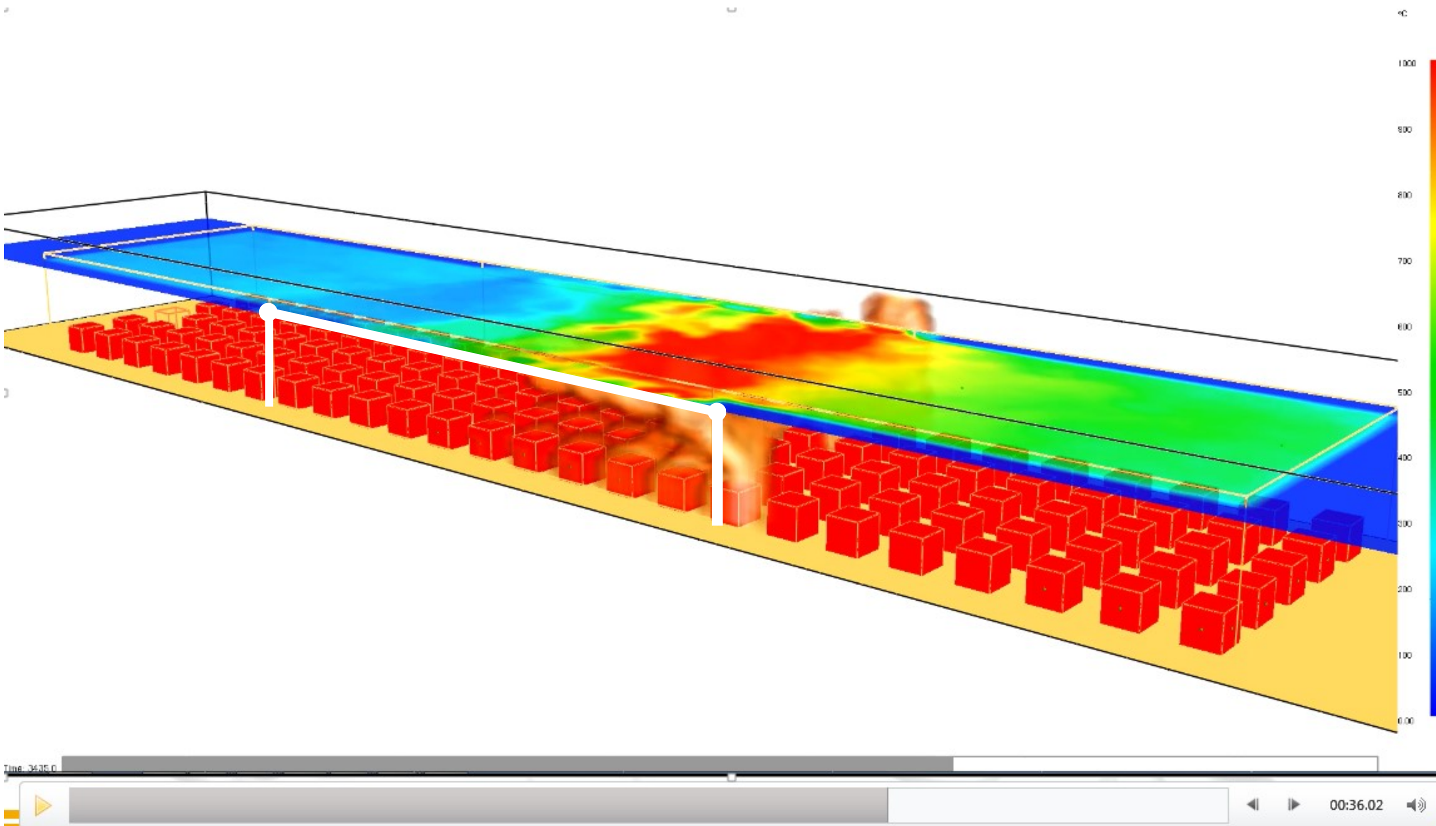

Charlier, M., Vassart, O., Gamba, A., Dai, X., Welch, S. & Franssen, J.-M. (2018) “CFD Analyses Used to Evaluate the Influence of Compartment Geometry on the Possibility of Development of a Travelling Fire”, SiF 2018, University of Ulster, 6-8 June 2018

Burning rates

* Drysdale (2011) *An introduction to fire dynamics*, Wiley, 3rd ed.

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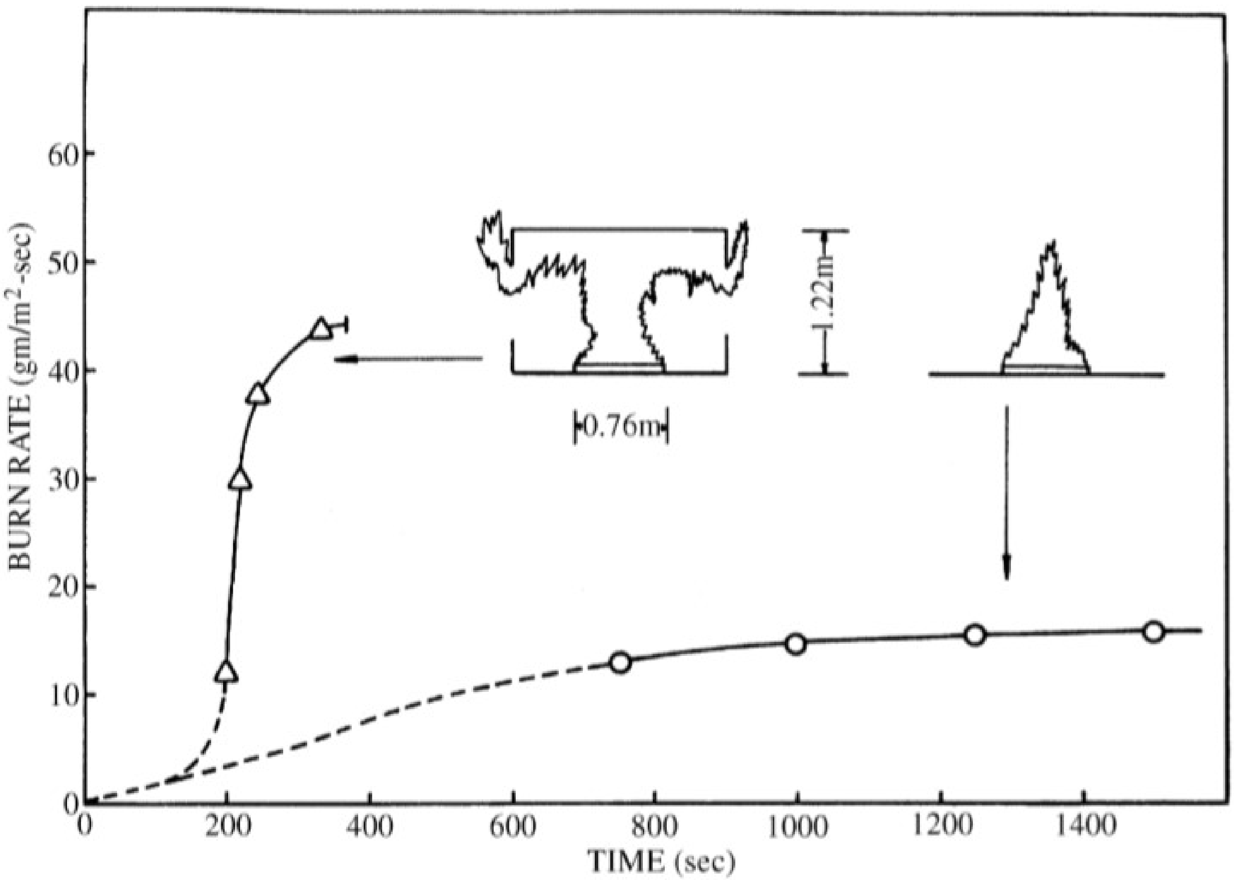


Figure 9.2 The effect of enclosure on the rate of burning of a slab of polymethylmethacrylate (0.76 m × 0.76 m) (Friedman, 1975)

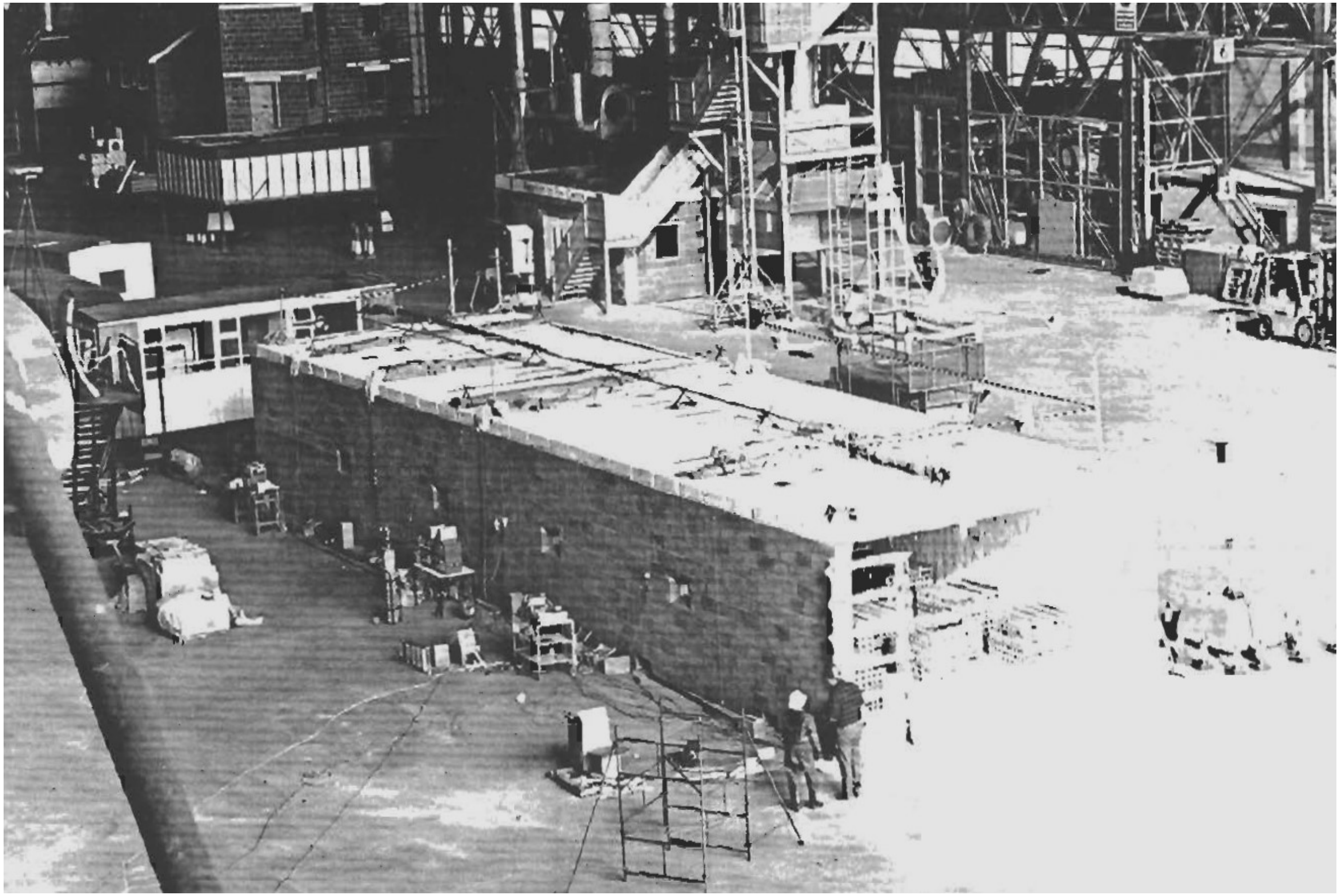
Jose Torero*, Scaling-Up Fire:

"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**.

Torero, J.L. (2013) "Scaling-Up Fire",
Proc. Comb. Inst. 34: 99-124

Cooling phase problem

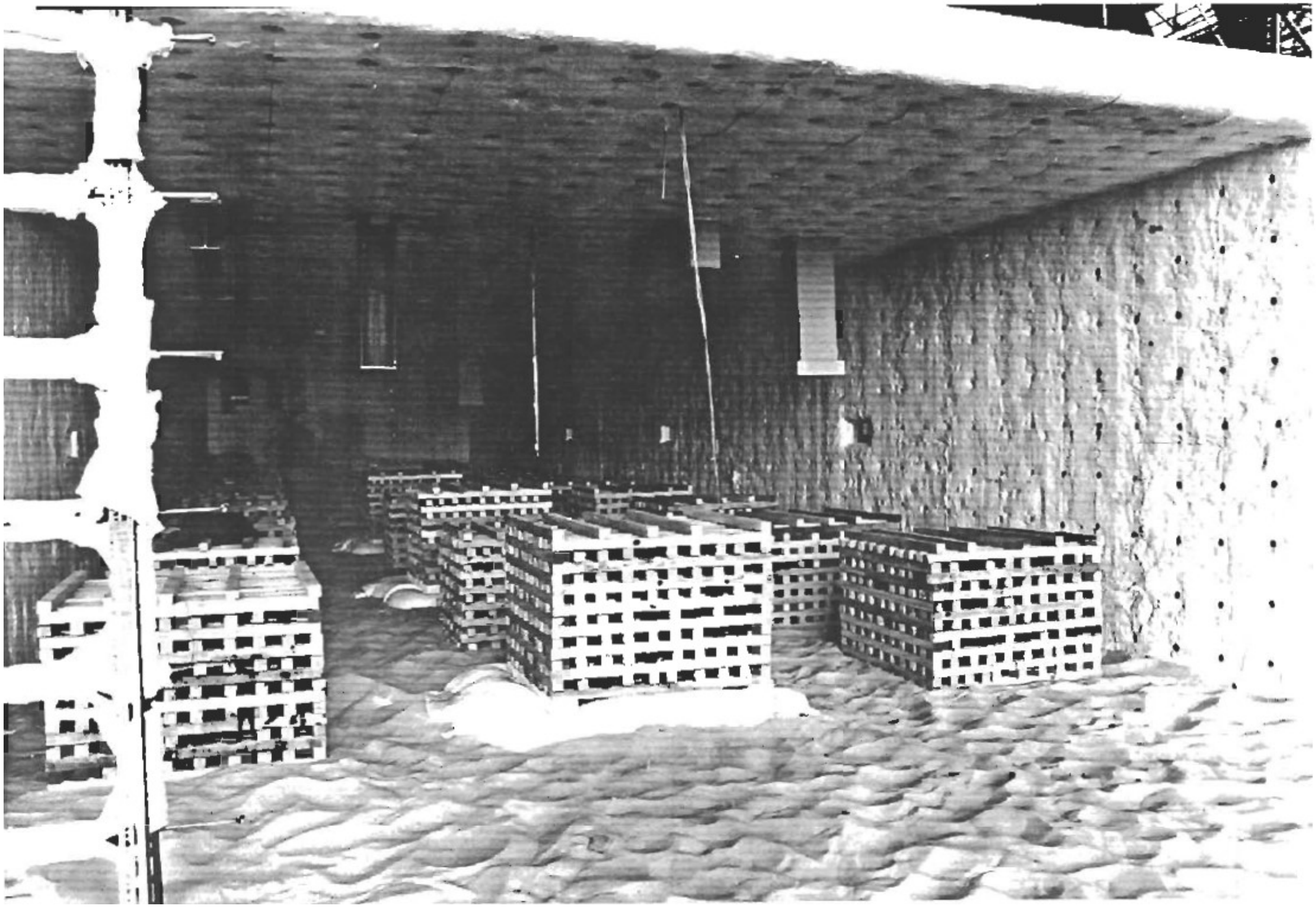
BST/FRS 1993 Fire Tests



Kirby BR, Wainman DE, Tomlinson LN, Kay TR, Peacock BN. (1994) Natural Fires in Large Scale Compartments. British Steel Technical, Fire Research Station Collaborative Project Report, UK

Cooke G (1998) Tests to Determine the Behaviour of Fully Developed Natural Fires in a Large Compartment. Fire Note 4, Fire Research Station, Building Research Establishment

BST/FRS 1993 Fire Tests



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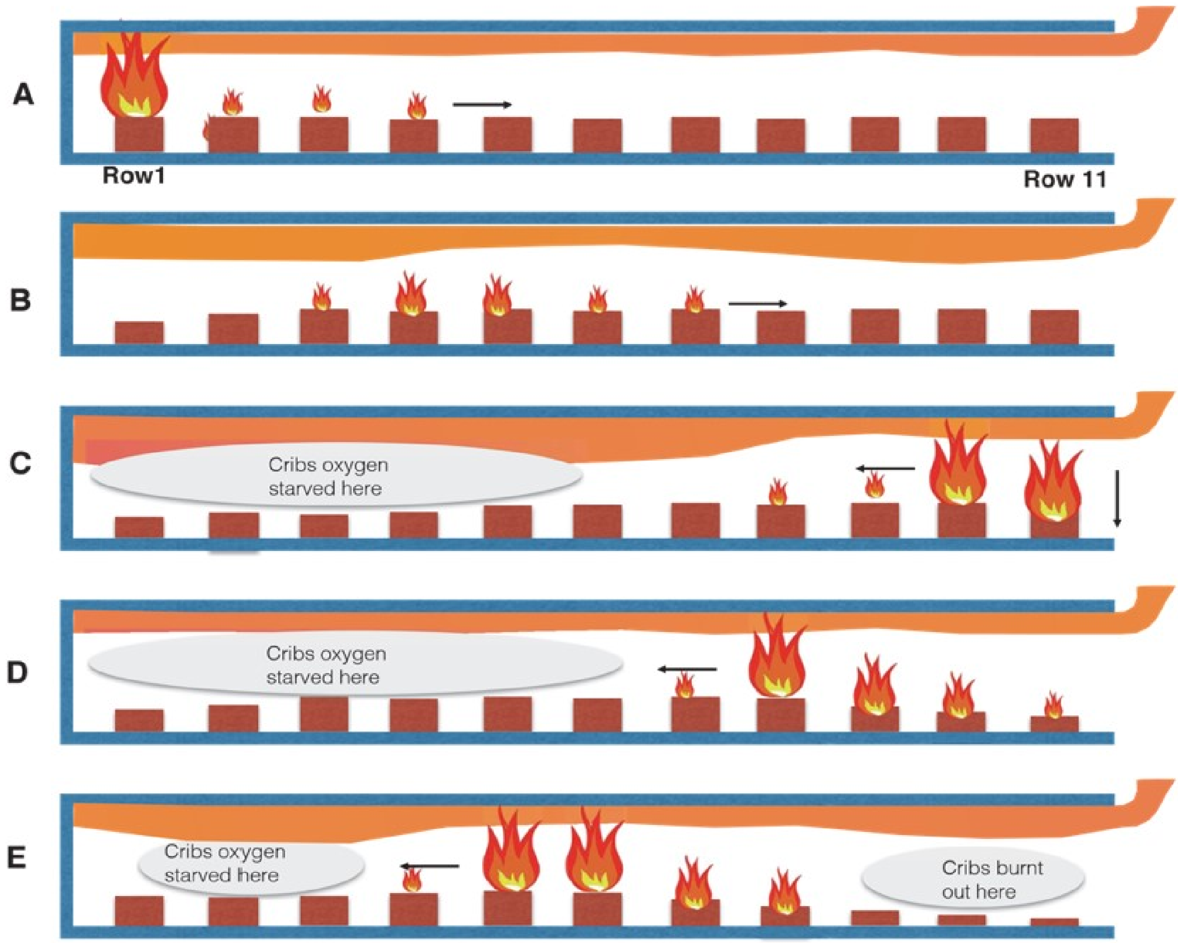
Cooling phase – BST/FRS



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Cooling phase – BST/FRS

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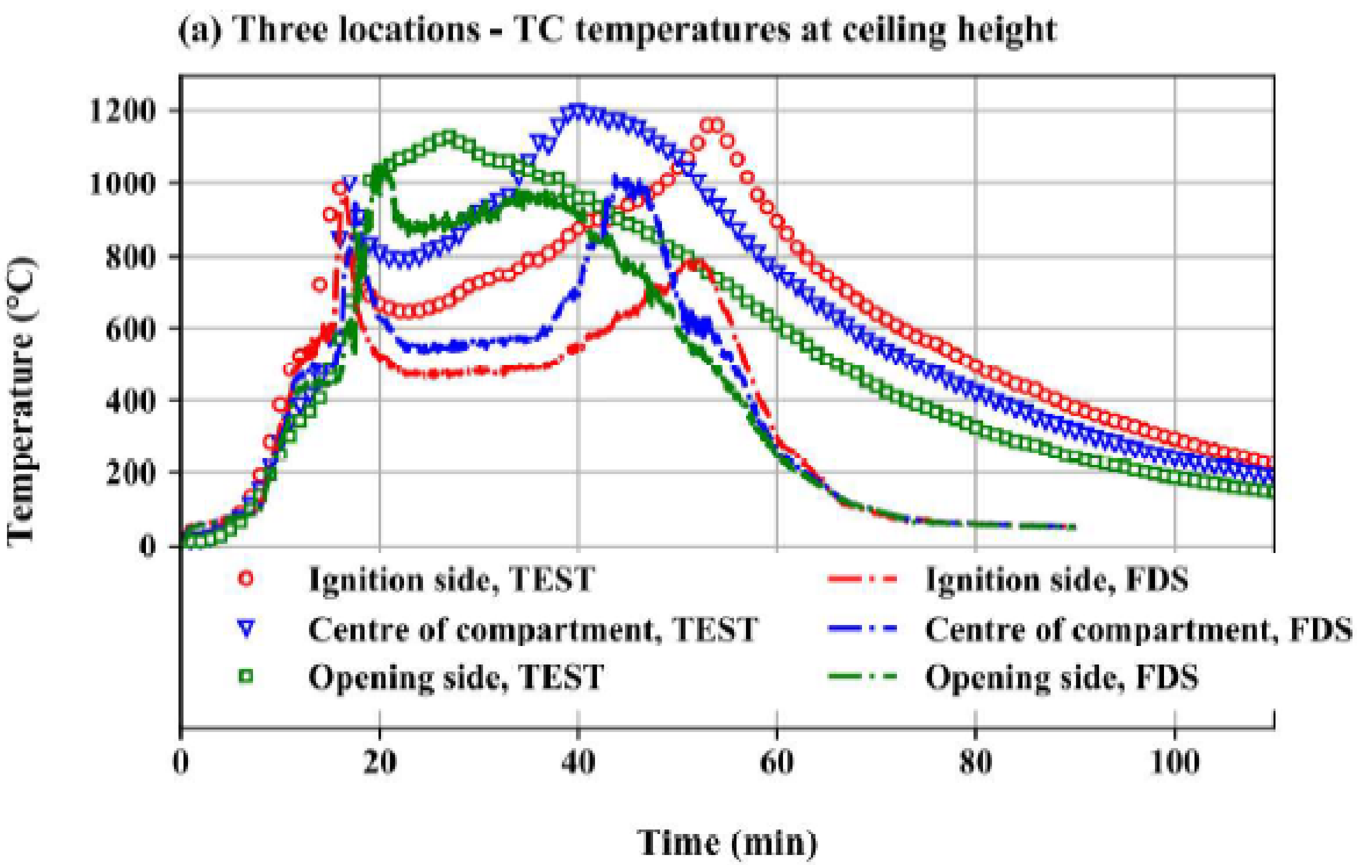

Dai, X., Welch, S., Rush, D., Charlier, M. & Anderson, J. (2019) "Characterising natural fires in large compartments – revisiting an early travelling fire test (BST/FRS 1993) with CFD", Proc. 15th Int. Conf. & Exhibition on Fire Science & Engineering (Interflam 2019), Royal Holloway College, Nr Windsor, UK, 1-3 July 2019.

Cooling phase – BST/FRS

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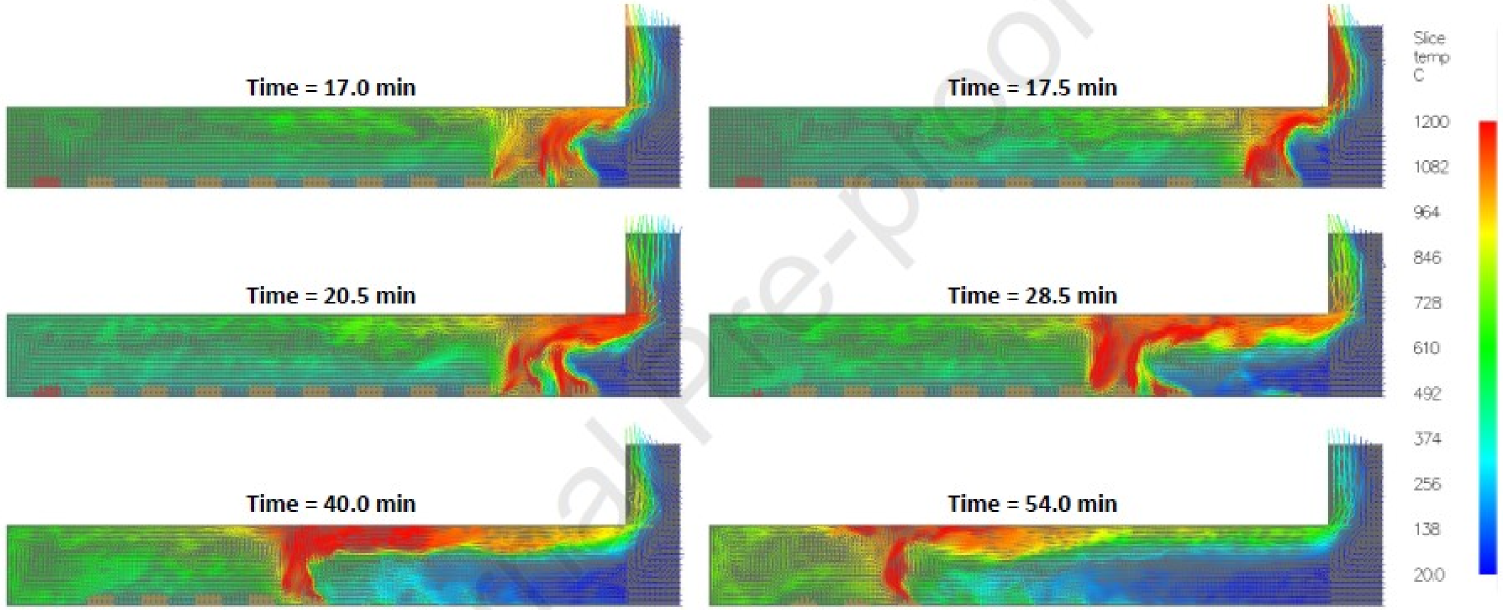

Figure 6: Predicted temperatures along the compartment midline from the 10 cm mesh simulation of BST/FRS large-scale fire test no. 2 [25].

Janardhan, R.K. & Hostikka, S. (2021) “When is the fire spreading and when it travels? – Numerical simulations of compartments with wood crib fire loads”, Fire Safety Journal (2021), doi: https://doi.org/10.1016/j.firesaf.2021.103485.

Cooling phase – BST/FRS

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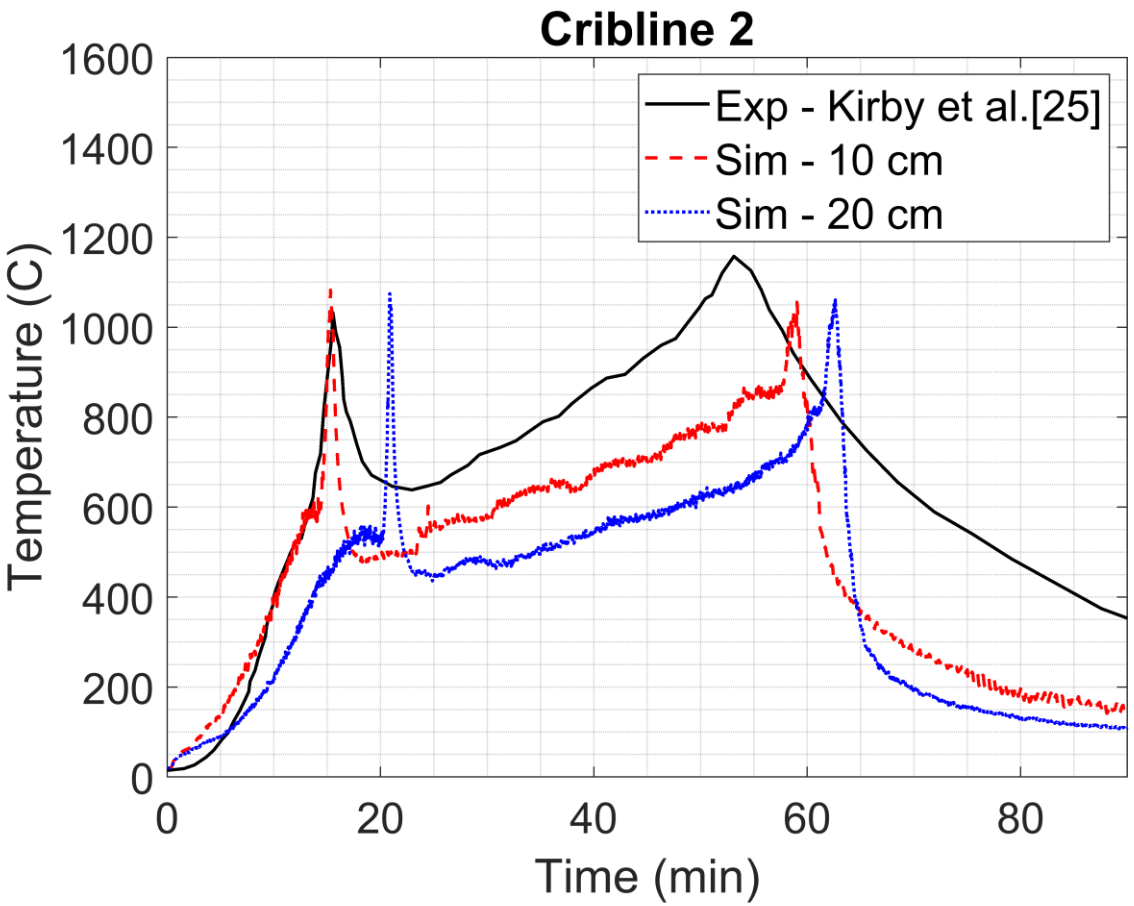

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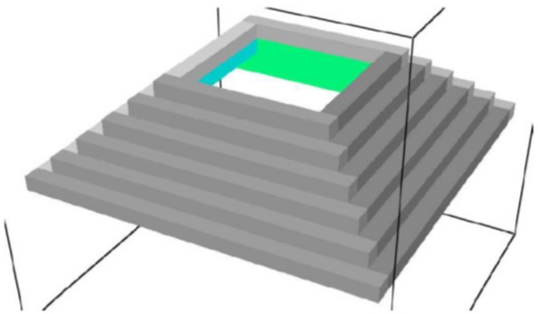
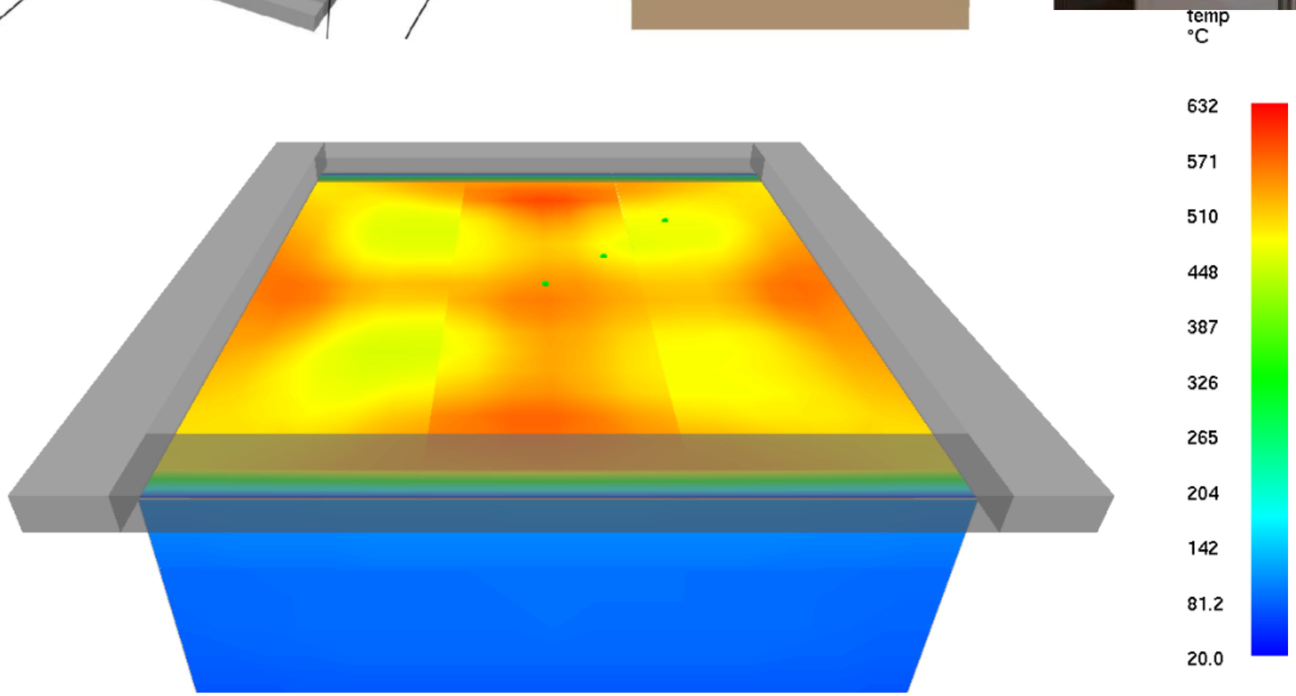
Cone calorimeter





Charley, P (2021) “Characterization of Role of Smouldering Char via Fire Simulation”, MEng thesis, School of Engineering, University of Edinburgh [unpublished]

Thermal conductivities

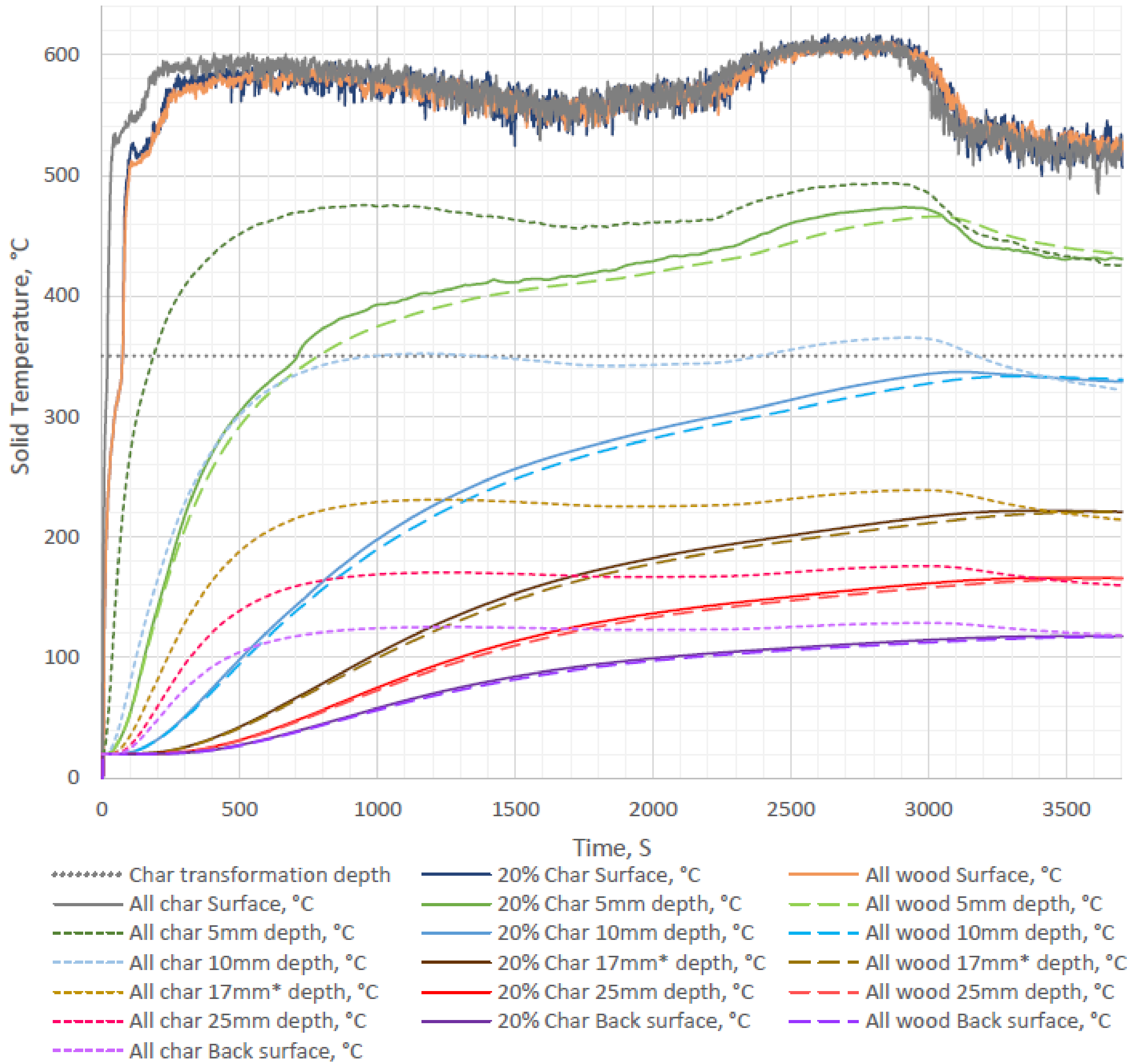
Table 4 A comparative review of the temperature dependence of thermal conductivity of wood† and char

Materials	Density (kg/m^3)	Temperature (°C)	Thermal Conductivity (W/m/K)	Rate (/°C)	References
Wood					
Wood*	N/A	>20	0.129 (20 °C)	0.2%/°C	Ragland et al., 1991
Wood	N/A	>20	N/A	0.2~0.3%/°C	Glass & Zelinka, 2011
Pine	590	35 – 118	0.166	Constant	Alves & Figueiredo, 1989
Pine	455	35 – 95	0.168 – 0.177	0.08%/°C	Hankalin et al., 2009
Birch	443	20 – 100	0.177 – 0.207	0.26%/°C	Suleiman et al., 1999
Beech	640	10 – 30	0.120 – 0.126	0.25%/°C	Sonderegger et al., 2011
Balsam fir/spruce	360	37 – 67	0.0986 – 0.1114	0.32%/°C	Gupta et al., 2003
Pine/spruce	N/A	20 – 200	0.122 – 0.139	0.08%/°C	Fredlund, 1993
Norway spruce	600	20 – 110	0.110 – 0.140	0.27%/°C	Janssen, 2004
Norway spruce	400	20 – 110	0.111 – 0.120	0.08%/°C	Janssen, 2004
Norway spruce	446	10 – 30	0.086 – 0.090	0.22%/°C	Sonderegger et al., 2011
Char					
Maple char	200	90	0.071	N/A	Grønli, 1996
Maple/beech/birch char	N/A	>20	0.052 (20 °C)	0.2~0.7%/°C	Ragland et al., 1991
Pine/spruce char	N/A	>20	0.051 (20 °C)	0.11%/°C	Fredlund, 1993
Balsam fir/spruce char	299	37 – 67	0.0946 – 0.1156	0.73%/°C	Gupta et al., 2003
Pine char	240	35 – 95	0.098 – 0.107	0.17%/°C	Hankalin et al., 2009
Pine char	N/A	30 – 220	0.091 – 0.109	0.104%/°C	Alves & Figueiredo, 1989

†Only conductivity values in transverse directions presented here;

*Wood species not specified.

Liu, C (2021) "Characterisation of Travelling Fires – The Cooling Phase", SAFE MSc dissertation, School of Engineering, University of Edinburgh [unpublished]



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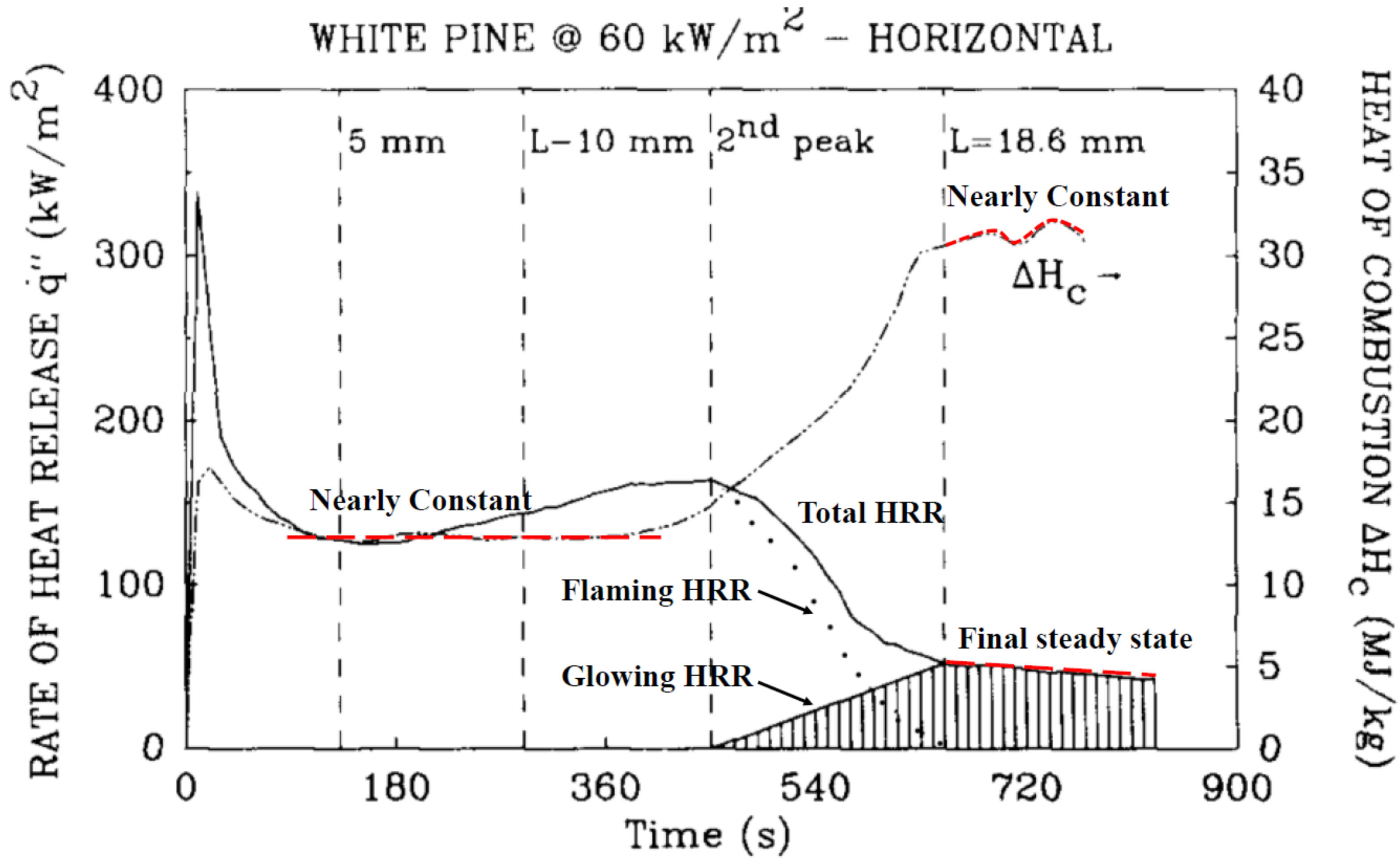
Wood charring



Janssens, M. 1991b. Rate of Heat Release of Wood Products.
Fire Safety Journal, 17(181): 217-238.
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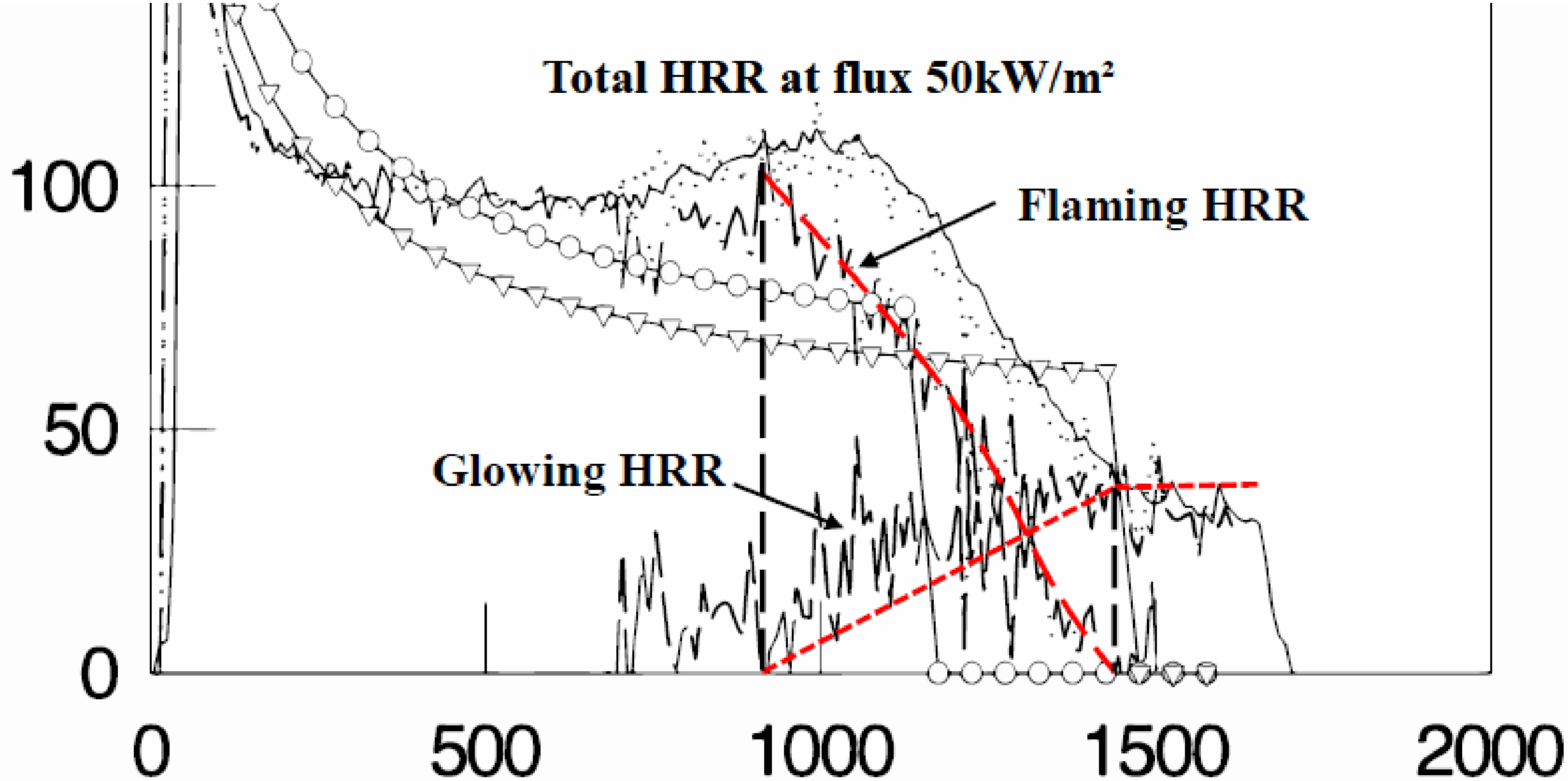
Wood charring



Janssens, M. 1991b. Rate of Heat Release of Wood Products.
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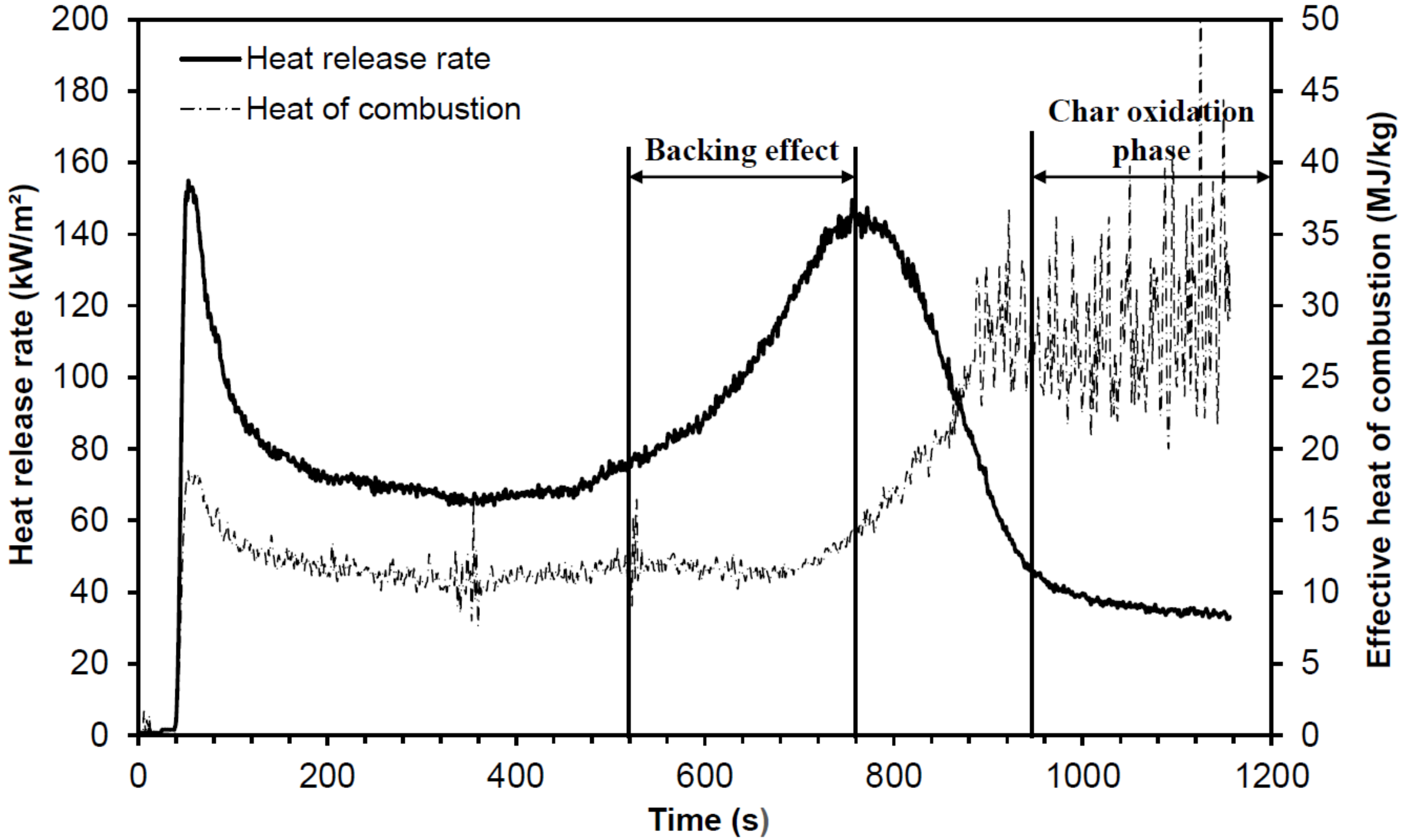
Wood charring



Forest Products Laboratory. 2010. Wood handbook, Wood as an engineering material. General Technical Report FPL-GTR-190. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

Wood charring

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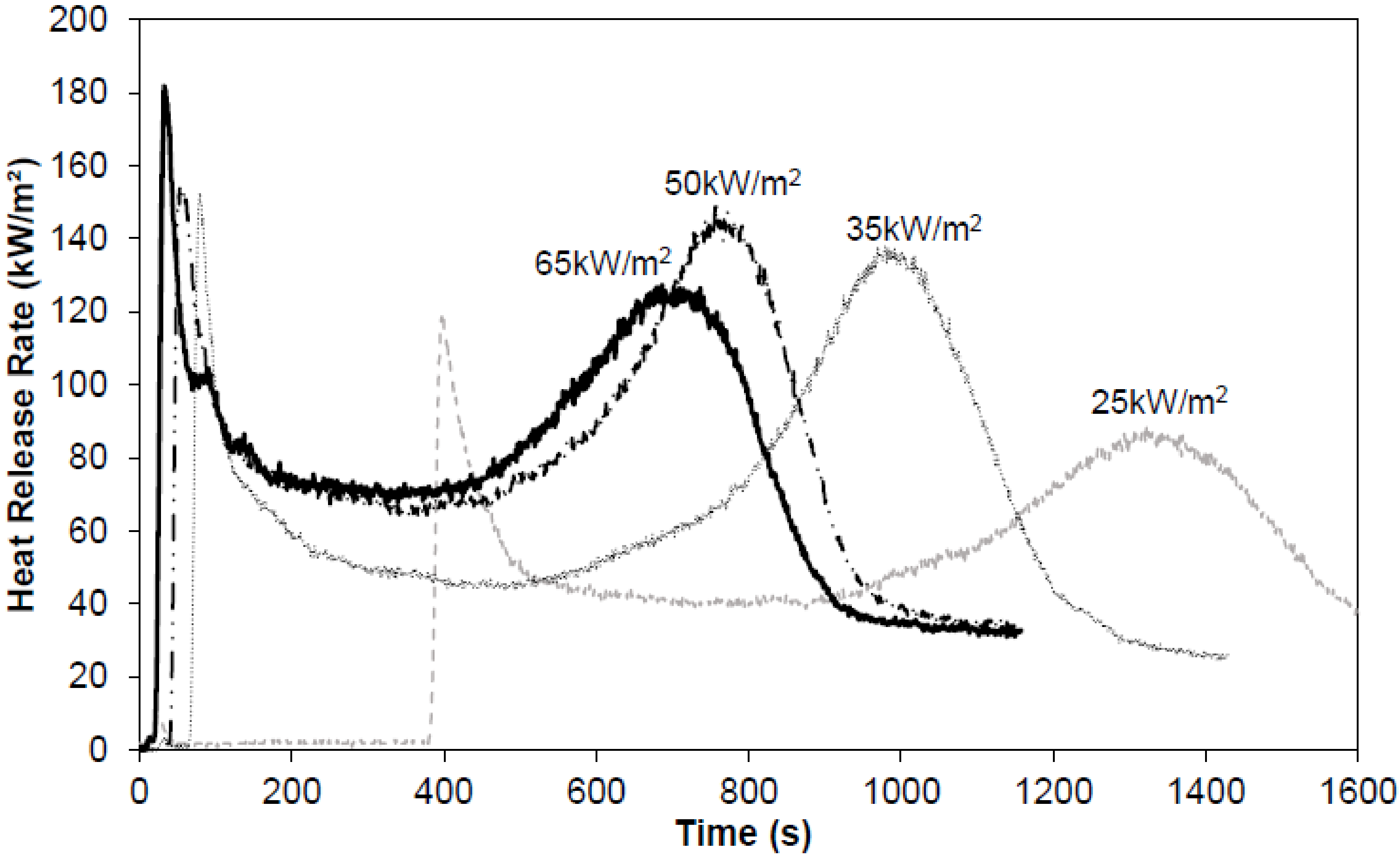


Forest Products Laboratory. 2010. Wood handbook, Wood as an engineering material. General Technical Report FPL-GTR-190. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

Heat of combustion

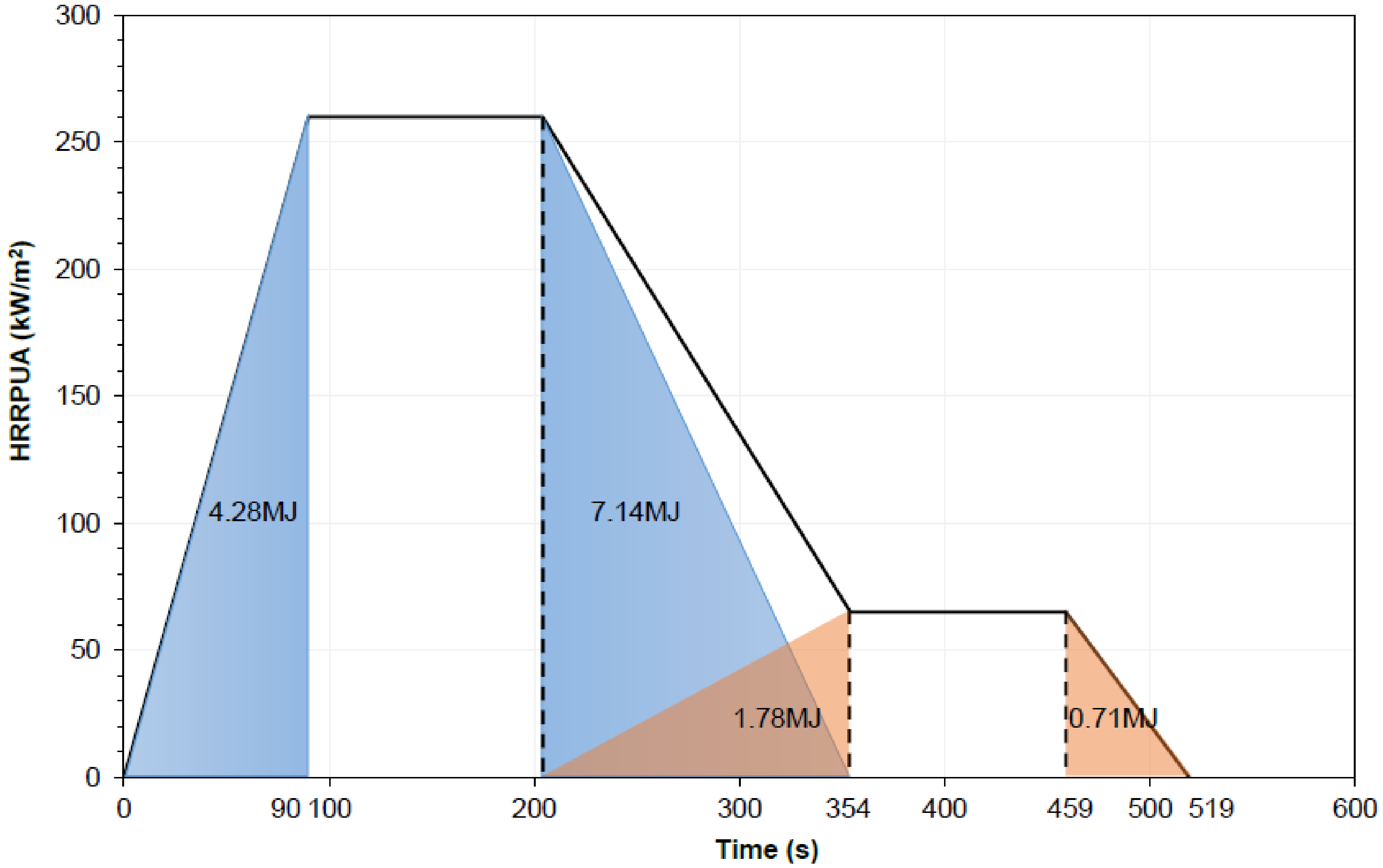
Table 8 Heat of combustion for natural fuels and their pyrolysis products as charcoal and volatiles

Wood	Source	Apparatus	Char yield (%)	Heat of combustion (MJ/kg)			Energy distribution	
				Volatile	Char	Wood	Volatile (%)	Char (%)
Douglas fir	Susott, 1982	TGA+EGA	20.1%	17.5	31.90	20.25	68%	32%
Douglas fir	Susott, 1982	TGA+EGA	22.2%	16.7	31.94	20.09	64.7%	35.2%
Douglas fir	Janssens, 1991a	Cone (50)[1]	13%	10.9	N/A	N/A	N/A	N/A
Douglas fir	Janssens, 1991a	Cone (65)	13%	11.3	N/A	N/A	N/A	N/A
Douglas fir	Spearpoint & Quintiere, 2000	Cone (75)	N/A	9.2	35.5	N/A	N/A	N/A
European beech	Roberts, 1964a	Bomb	16-17%	16.6	34.3	19.5	~70%	~30%
Ponderosa pine	Susott, 1982	TGA+EGA	19.5%	17.90	32.85	20.82	69.2%	30.8%
Ponderosa pine	Susott, 1982	TGA+EGA	20.3%	17.95	32.82	20.97	68.2%	31.8%
Larch wood	Susott, 1982	TGA+EGA	20.7%	16.6	32.29	19.83	66.3%	33.7%
Larch wood	Susott, 1982	TGA+EGA	23.7%	16.5	32.15	20.22	62.4%	37.6%
Larch wood	Shafizadeh, 1984	Bomb	26.7%	15.6	30.01	19.47	58.8%	41.2%
Poplar wood	Shafizadeh, 1984	Bomb	21.7%	16.4	29.8	19.3	66%	34%
White fir	Susott, 1982	TGA+EGA	22.1%	16.99	33.18	20.57	65%	35%
Grand fir	Susott, 1982	TGA+EGA	20.7%	17.19	32.00	20.25	71%	29%
Spruce wood	Our lab	Cone (20)	23.6%	10.8	~27	14.4	54.1%	45.9%
Spruce wood	Hagen et al., 2009	Cone (40)	11.5%	~9.8	N/A	N/A	N/A	N/A
Spruce wood	Hagen et al., 2009	Cone (50)	9%	~10.2	N/A	N/A	N/A	N/A
Spruce wood	Hagen et al., 2009	Cone (65)	~7.5%	~10.5	N/A	N/A	N/A	N/A
Spruce wood	Dietenberger et al., 2012	Cone (35)	~19.4%	10.5	26.3	13.6	62.2%	37.8%
Spruce wood	Dietenberger et al., 2012	Cone (50)	~18.2%	11.6	28.8	14.7	64.5%	35.5%
Spruce wood	Dietenberger et al., 2012	Cone (65)	~16.7%	10.98	30.95	14.3	63.9%	36.1%

[1]the value in bracket stands for the imposed heat flux in Cone Calorimeter

Liu, C (2021) “Characterisation of Travelling Fires – The Cooling Phase”, SAFE MSc dissertation, School of Engineering, University of Edinburgh [unpublished]

Model representations



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Crib fire experiments

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Gamba, Charlier & Franssen (2020) Propagation tests with uniformly distributed cellulosic fire load FSJ 103213 .pdf - Adobe Acrobat Reader DC

Fire Safety Journal 117 (2020) 103213

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Propagation tests with uniformly distributed cellulosic fire load

Antonio Gamba [a,*], Marion Charlier [b], Jean-Marc Franssen [a]

[a] Liege University, UEE Department, Belgium
[b] ArcelorMittal Global R&D, Luxembourg

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Fire spread
Fuel arrangement

ABSTRACT

In the recent past, the necessity to have a better understanding of fire dynamics and of the full structural response under real fires was the motivation for several large-scale non-standard fire tests. Nowadays, the novel need to better comprehend the fire dynamics behind the so called "travelling fires" underlined the limitations of those non-standard fire tests. The lack of standardised procedures does not allow making effective comparisons and drawing scientific conclusion from these tests. The fire group of Liege University performed eleven non-standard or "natural fire" tests within the context of the RFCS research project TRAFIR sponsored by the E.U. Commission (grant N°754,198). The aim of this experimental campaign was to determine a uniformly distributed fuel arrangement that would lead to a medium fire growth as recommended for office buildings in Eurocode 1. This

* Gamba, A., Charlier, M. & Franssen, J.-M. (2020) "Propagation tests with uniformly distributed cellulosic fire load", Fire Safety Journal 117, 103213 doi:10.1016/j.firesaf.2020.103213

"Liege test series", LB7 Test, Marchienne, Belgium, 2018

- **Photos regarding the experiment:**

Figure 1. (a) Skewed view of test rig without wood sticks, and (b) Side view of test setup.

“Liege test series”, LB7 Test, Marchienne, Belgium, 2018

- **Wood sticks layout in elevation view:**

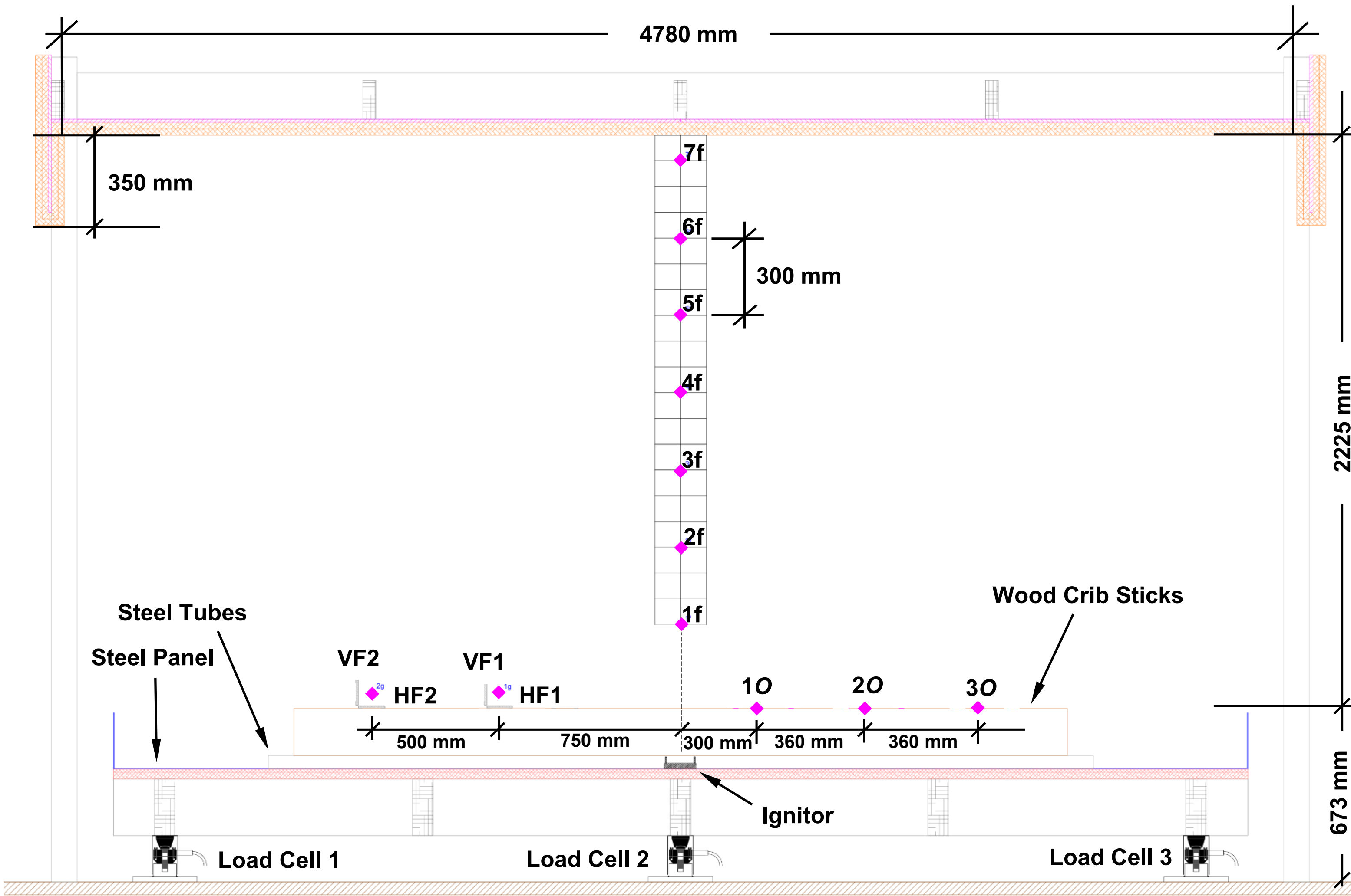

Figure 2. Overview of test setup in elevation: compartment structure, plate thermometer and thermocouple instrumentations (marked with pink square dot), and location of sticks.

FDS modelling for calibration, “Liege test series”, LB7

- Grid cell resolution in elevation view

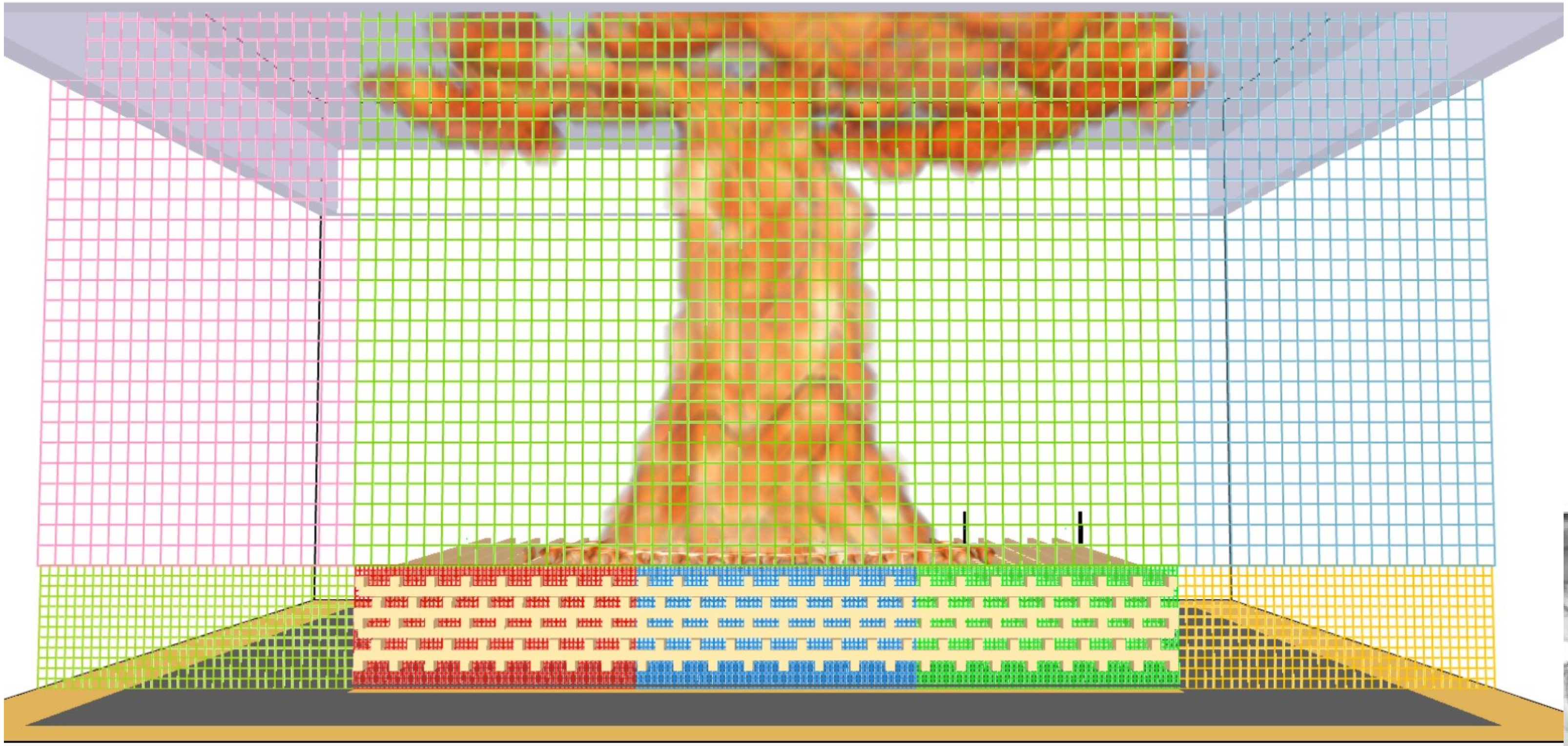

Figure 5. Grid cell resolution of the model: 1.5 cm × 1.5 cm × 1.75 cm per cell for wood sticks in porous crib structure, 6 cm × 6 cm × 7cm and 3 cm × 3 cm × 3.5 cm cell size in gas phase, total number of cells ~1.3 million.

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- Fire development within the wood crib
- Temperature development within the wood crib

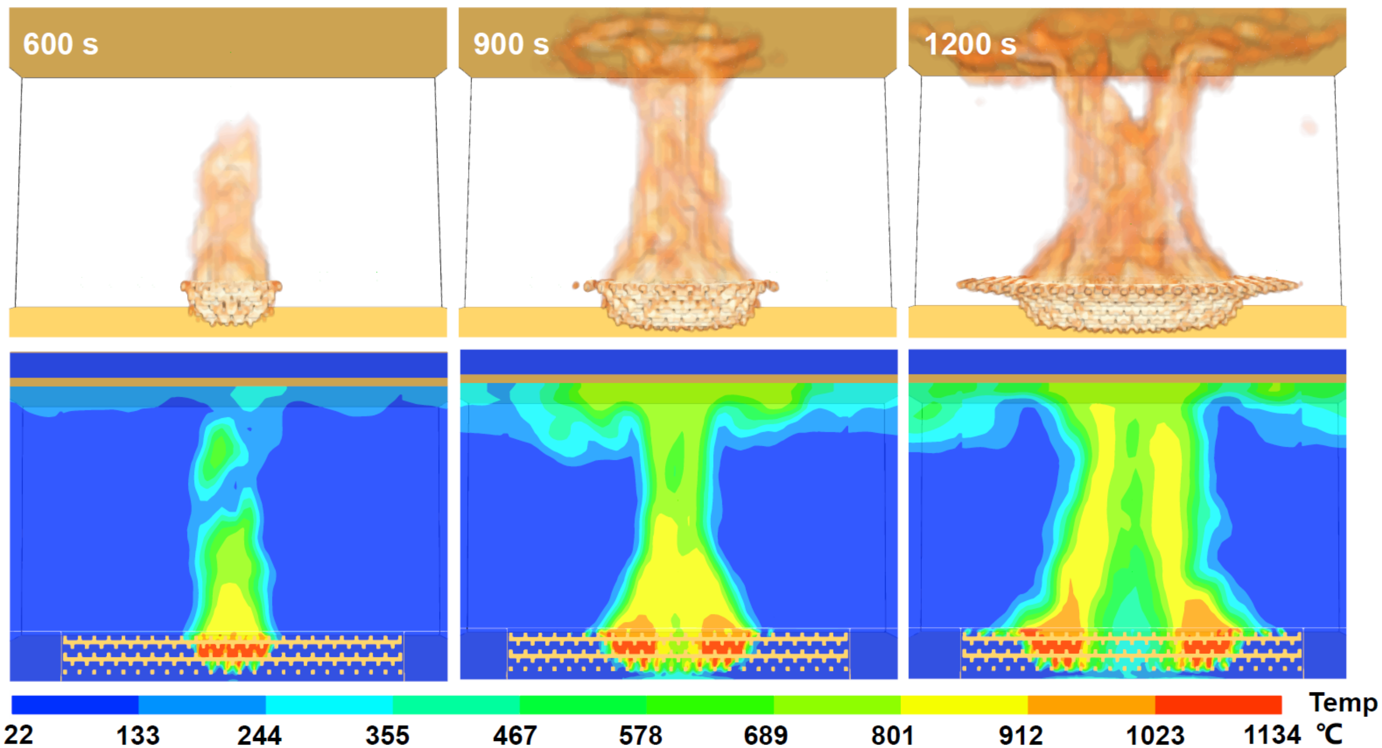


Figure 11. (a) Flame development within wood cribs (wood sticks “obstruction” removed in Smokeview for clearer flame demonstration), and (b) Temperature development at the compartment central ‘slice’.

FDS modelling for calibration, “Liege test series”, LB7

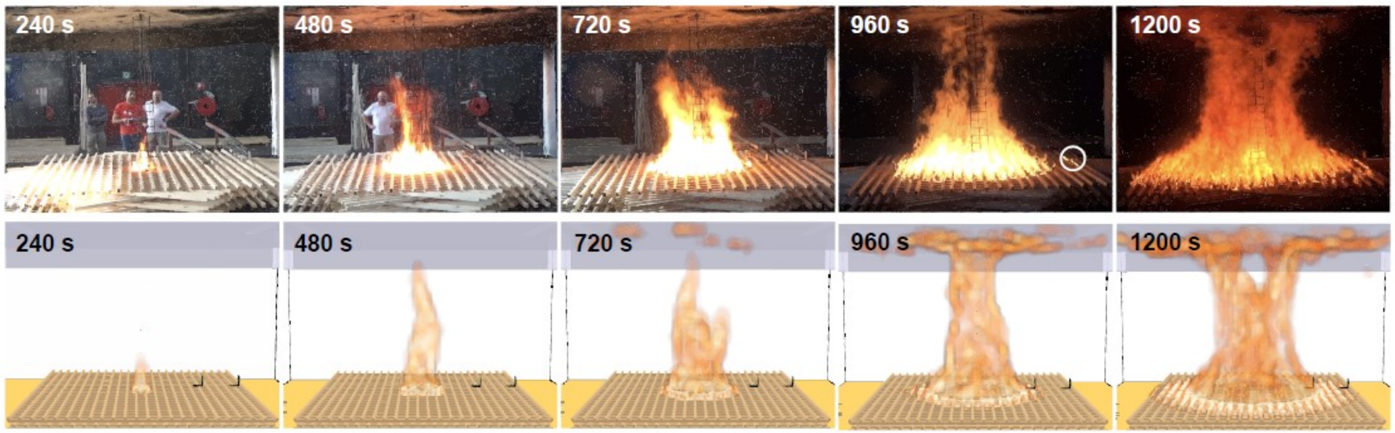
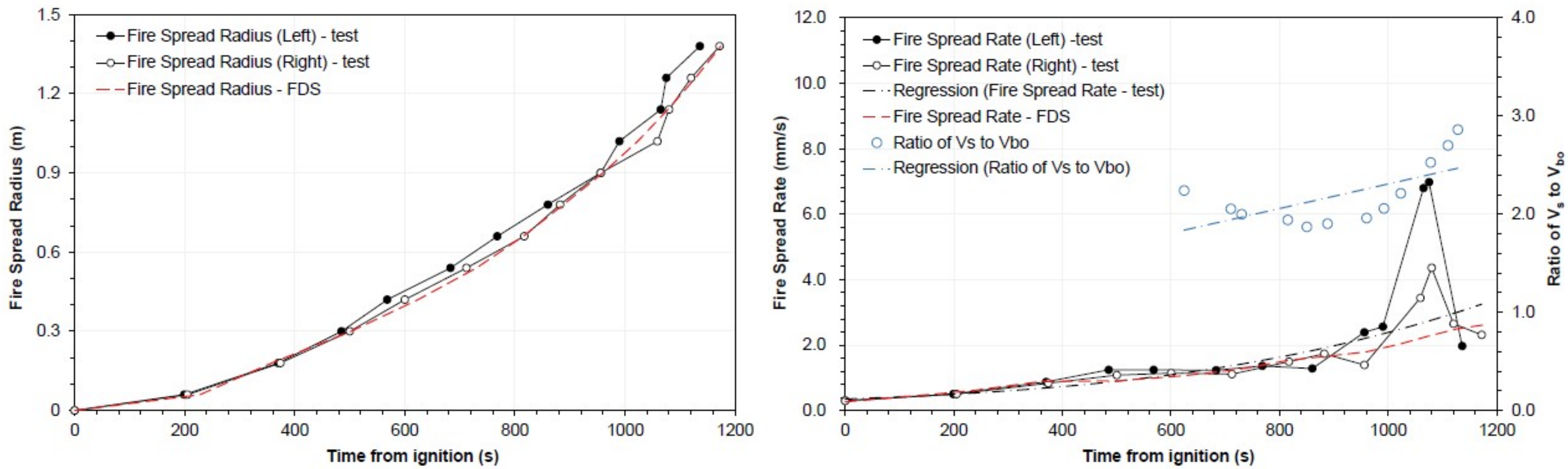


Fig.43 Comparisons of the fire spread on top layer of wood cribs in FDS and LB7 test

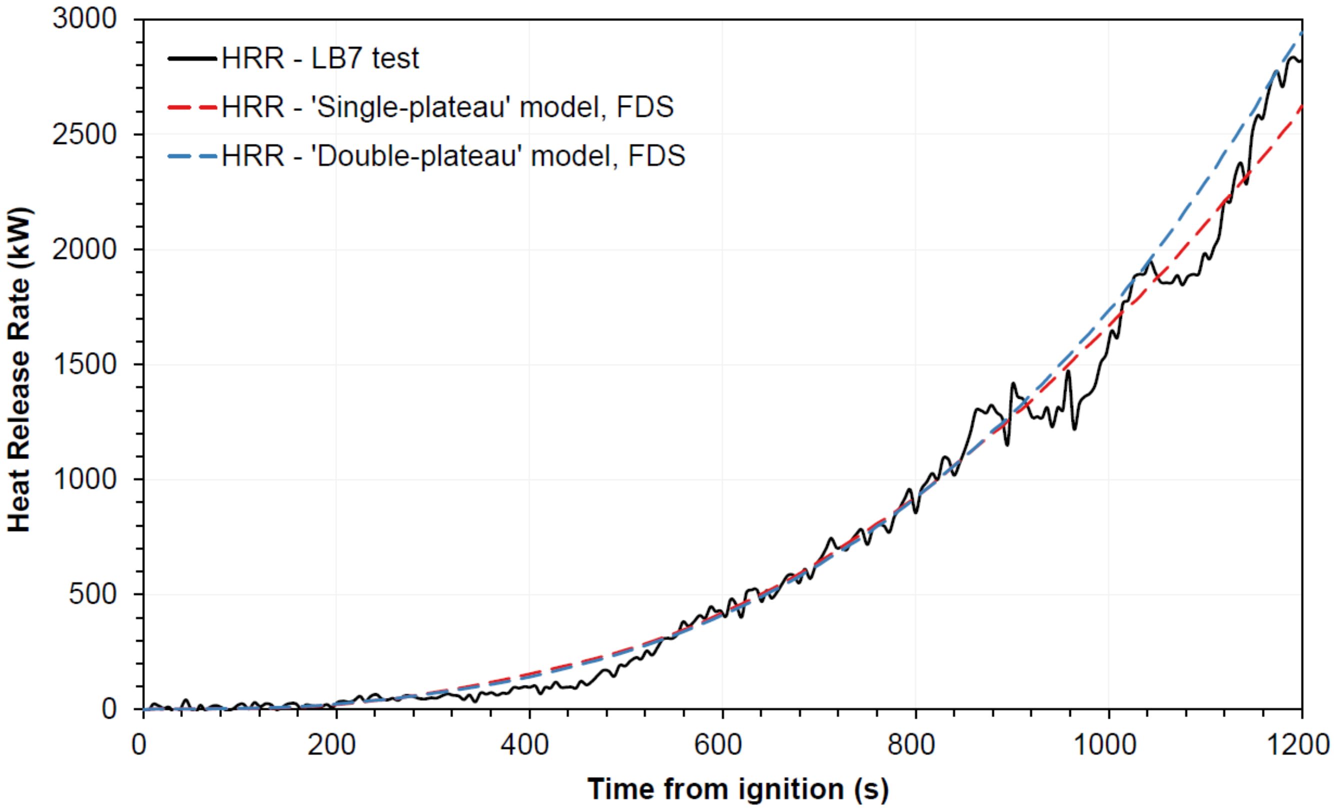


(a) (b)

Fig.44 Comparisons between the FDS model and test: (a) evolution of the fire spread radius for the top layer of cribs; (b) calculated fire spread rate for the top layer of cribs

FDS modelling for calibration, “Liege test series”, LB7

- **Fire spread rate vs. HRR (decoupling time dependency)**
- **Fire height comparison**



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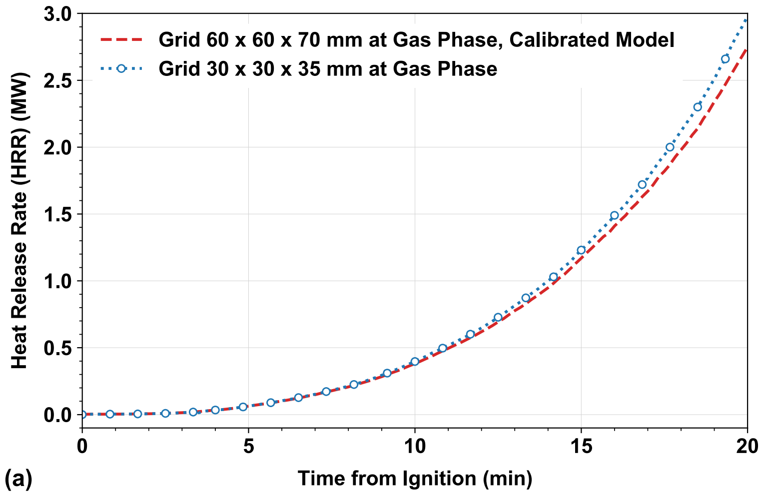
Grid Sensitivity Studies

FDS grid sensitivity studies, “Liege test series”, LB7

Cell size sensitivity in gas phase



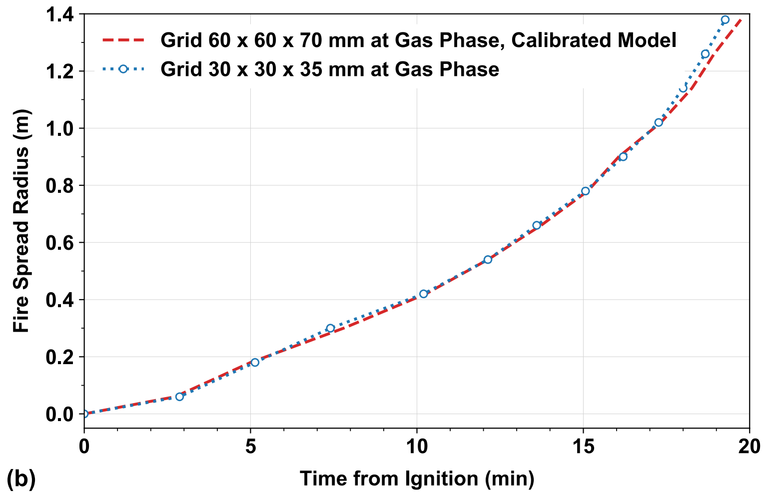


Figure 12. Cell size sensitivity at gas phase on (a) HRR, and (b) Fire spread radius.

FDS grid sensitivity studies, “Liege test series”, LB7

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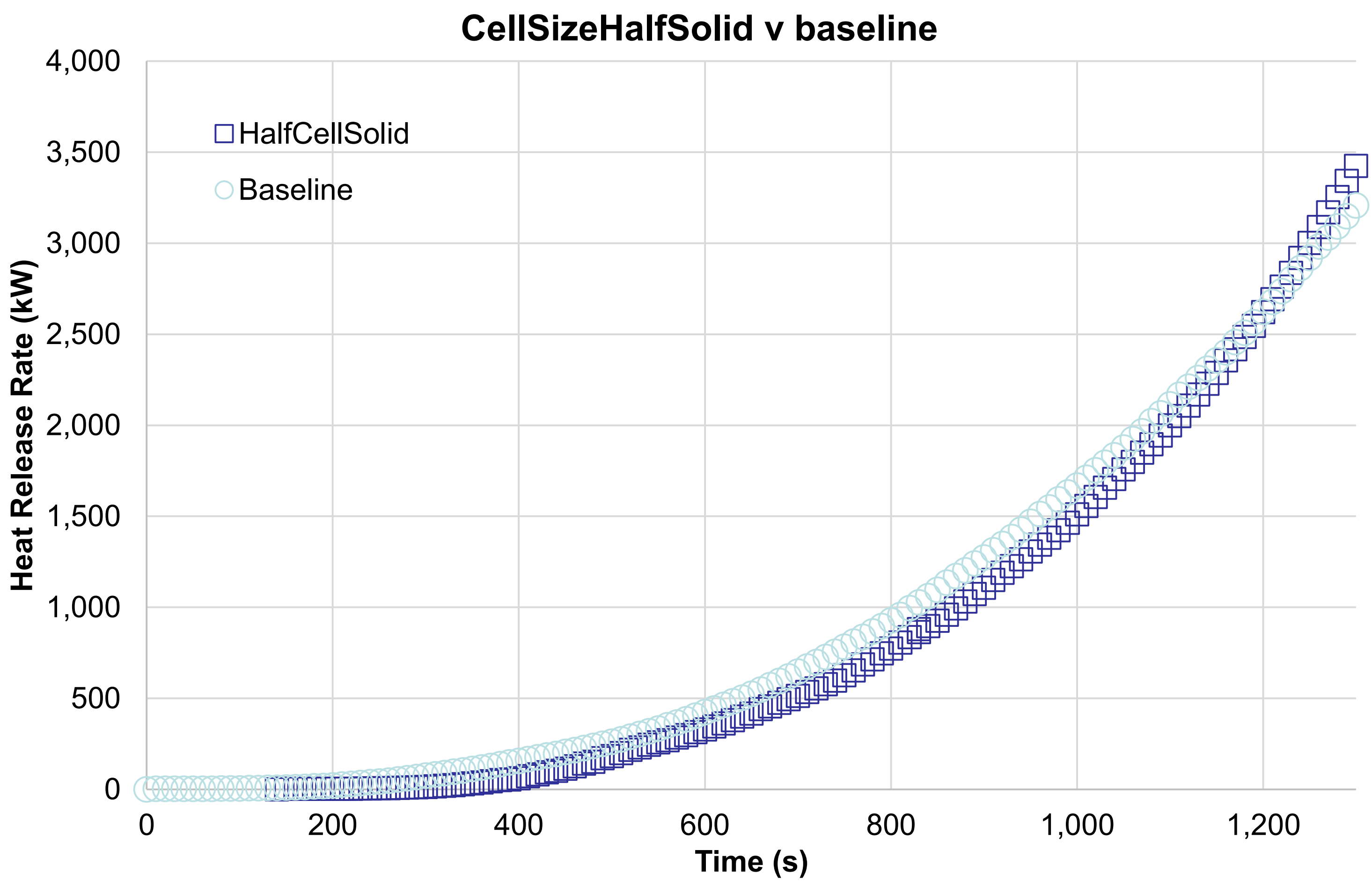
- Cell size sensitivity in gas and solid phases

Case	Fuel bed	Gas phase	Horizontal pitch	Vertical pitch	Cells
Baseline	1.5 x 1.5 x 1.75	6 x 6 x 7	9 (6 cells between)	3 (2 cells between)	1 045 787
Half gas	1.5 x 1.5 x 1.75	3 x 3 x 3.5	9 (6 cells between)	3 (2 cells between)	2 201 472
Half solid	0.75 x 0.75 x 0.875	3 x 3 x 3.5	18 (12 cells between)	6 (4 cells between)	7 237 989

FDS grid sensitivity studies, “Liege test series”, LB7

- **Cell size sensitivity in solid phase**



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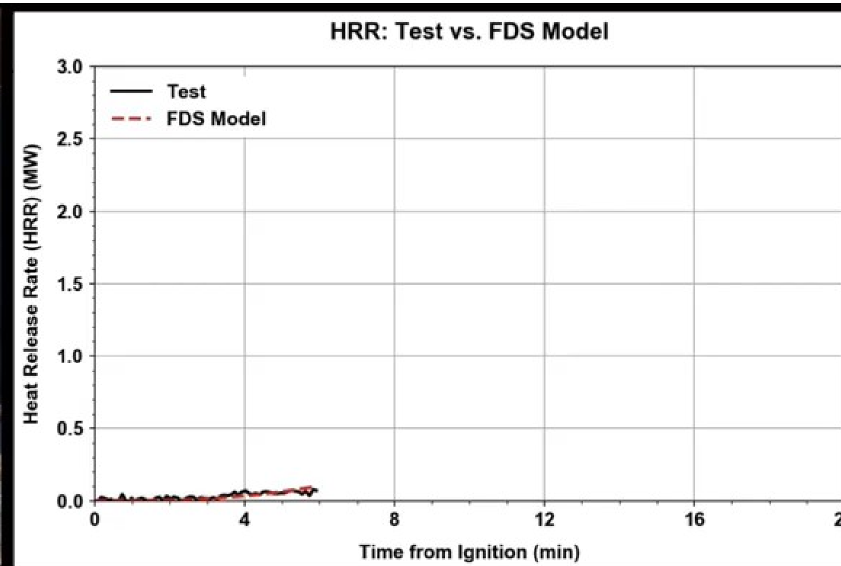
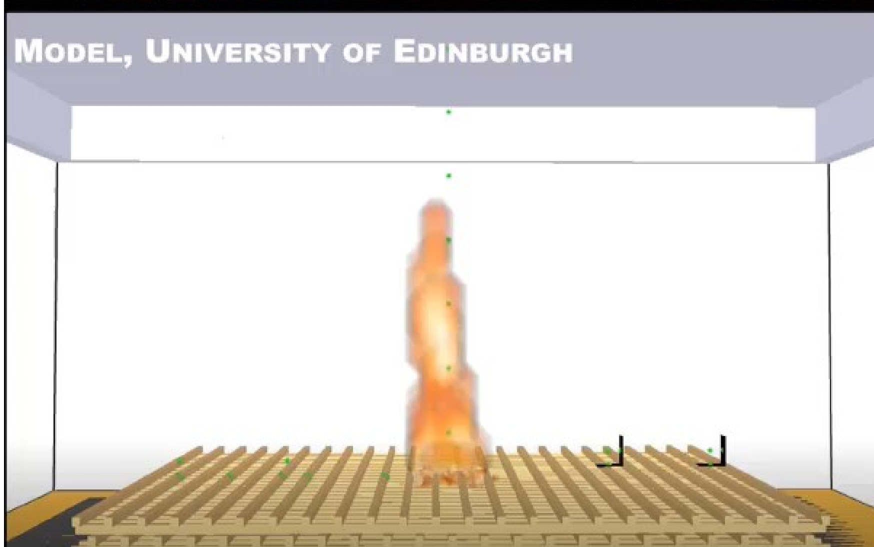
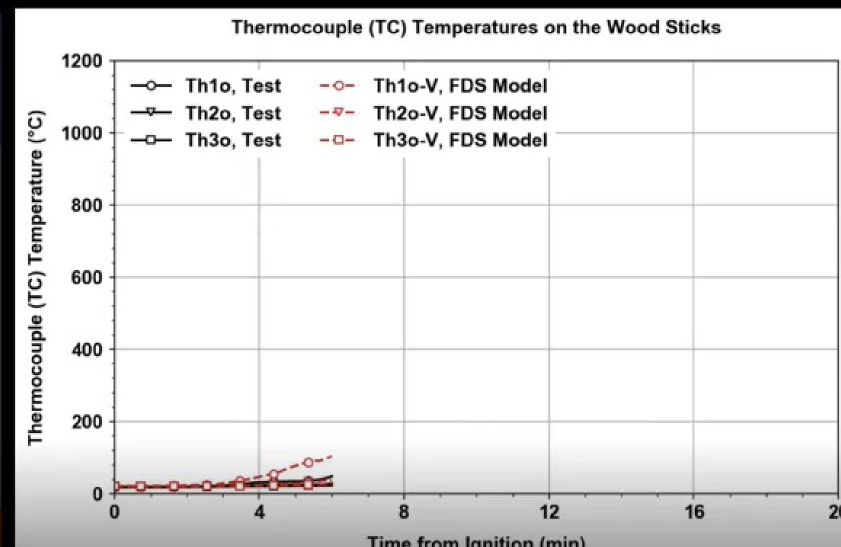
FDS grid sensitivity studies, “Liege test series”, LB7







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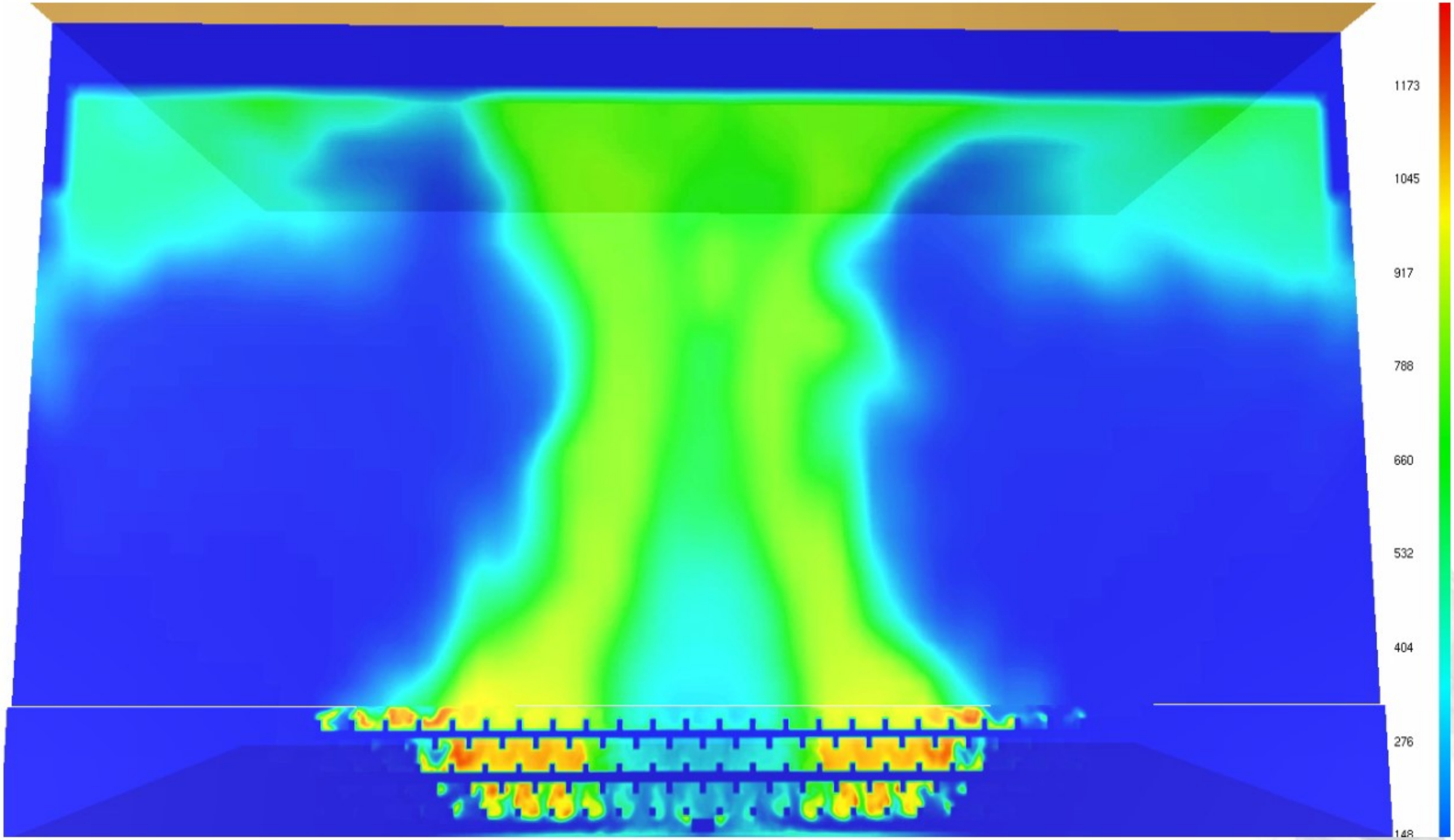
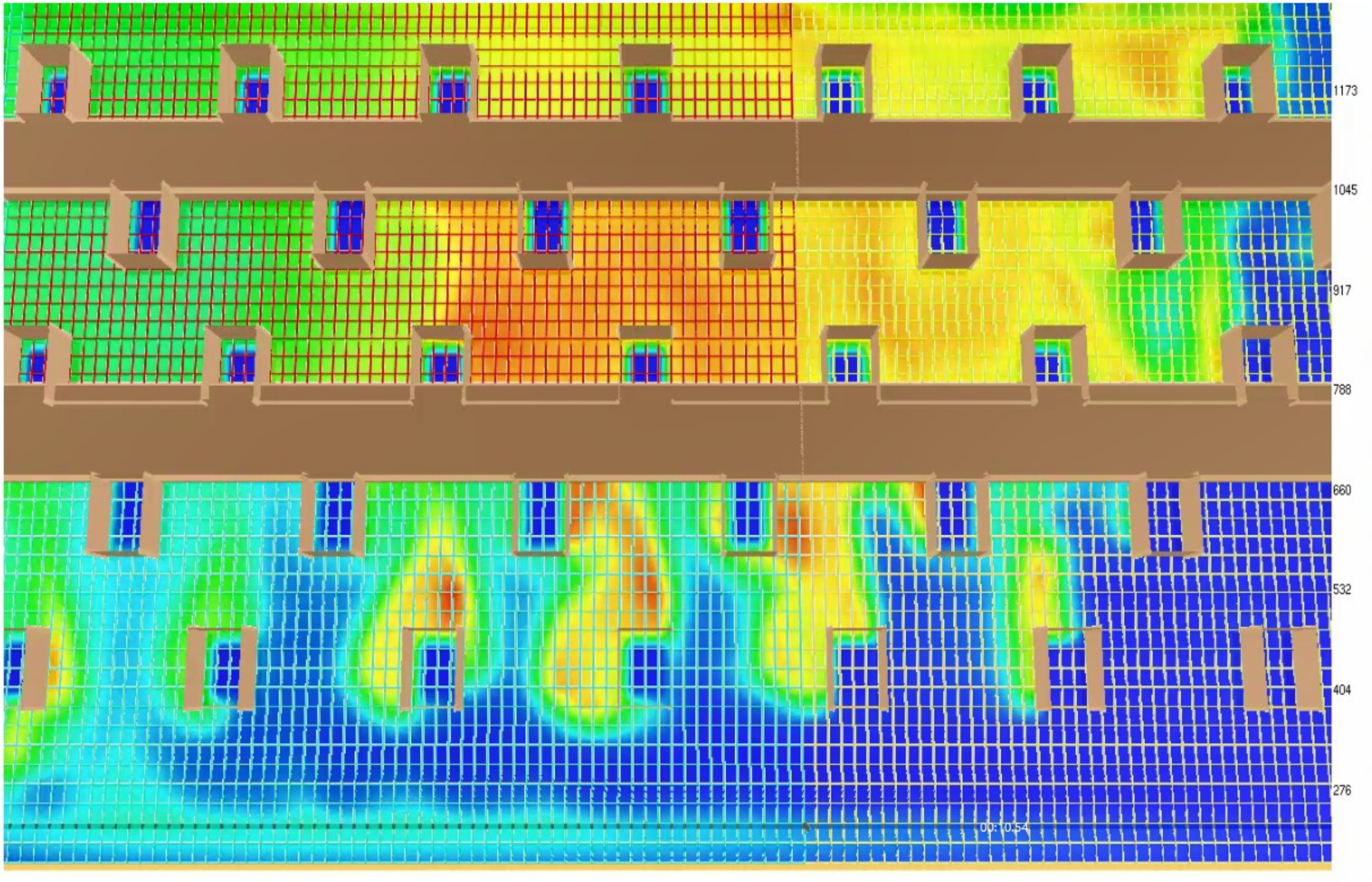
FDS grid sensitivity studies, "Liege test series", LB7



FDS grid sensitivity studies, “Liege test series”, LB7



Full scale experiments

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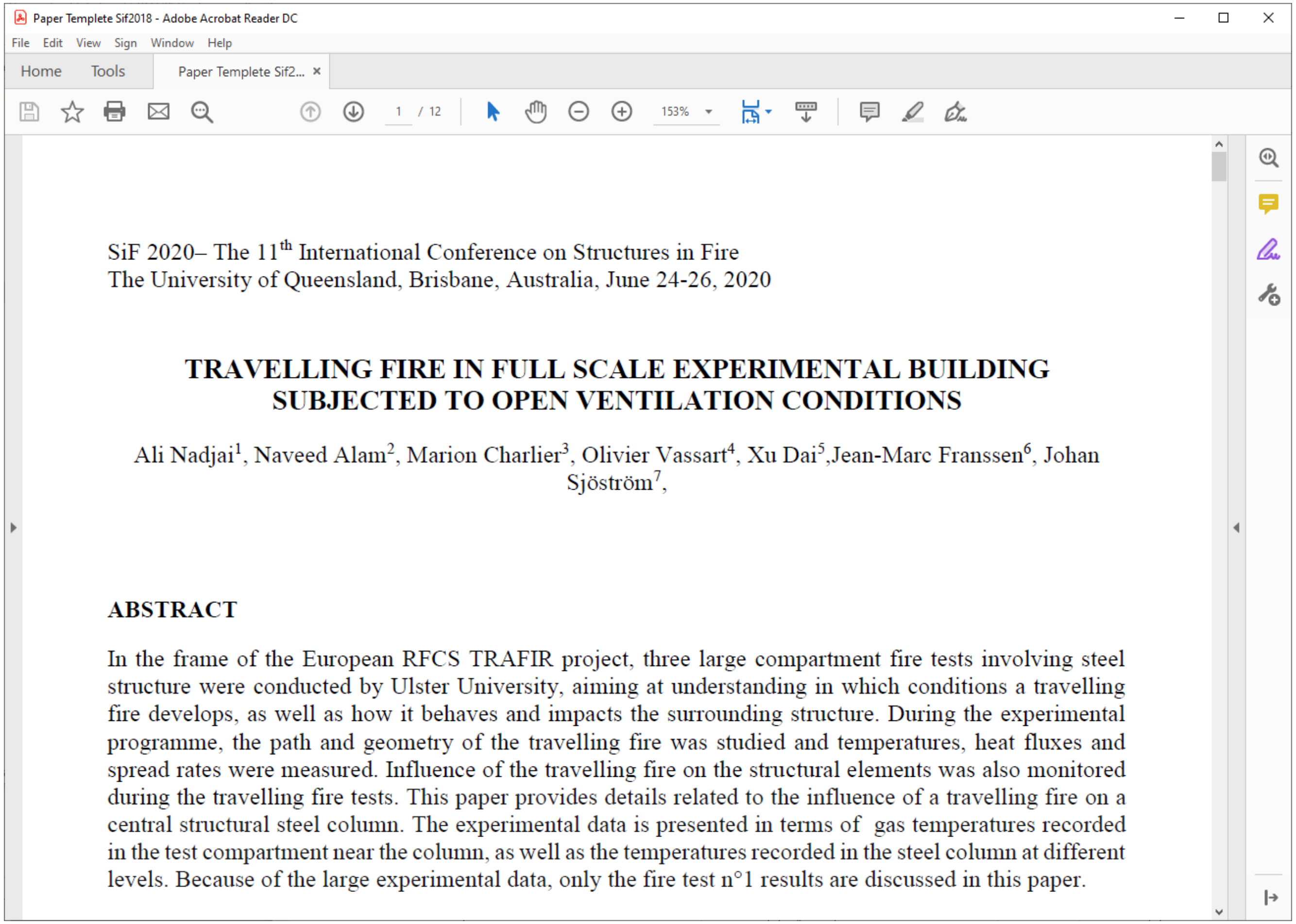

SiF 2020– The 11th International Conference on Structures in Fire
The University of Queensland, Brisbane, Australia, June 24-26, 2020

TRAVELLING FIRE IN FULL SCALE EXPERIMENTAL BUILDING SUBJECTED TO OPEN VENTILATION CONDITIONS

Ali Nadjai[1], Naveed Alam[2], Marion Charlier[3], Olivier Vassart[4], Xu Dai[5],Jean-Marc Franssen[6], Johan Sjöström[7],

ABSTRACT

In the frame of the European RFCS TRAFIR project, three large compartment fire tests involving steel structure were conducted by Ulster University, aiming at understanding in which conditions a travelling fire develops, as well as how it behaves and impacts the surrounding structure. During the experimental programme, the path and geometry of the travelling fire was studied and temperatures, heat fluxes and spread rates were measured. Influence of the travelling fire on the structural elements was also monitored during the travelling fire tests. This paper provides details related to the influence of a travelling fire on a central structural steel column. The experimental data is presented in terms of gas temperatures recorded in the test compartment near the column, as well as the temperatures recorded in the steel column at different levels. Because of the large experimental data, only the fire test n°1 results are discussed in this paper.

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”, Structures in Fire 2020, University of Queensland, Brisbane, Australia, 30 November – 2 December 2020 doi:10.14264/987a305

Full scale experiments

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”, Structures in Fire 2020, University of Queensland, Brisbane, Australia, 30 November – 2 December 2020 doi:10.14264/987a305

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Conclusions (1)

- Reconstruction of a uniform wood fuel bed for fire spread, is achieved through using a stick-to-stick model with simple pyrolysis and an ignition temperature setup. Compared with previous research the results show more parameters being comparable to the full suite of test data, suggesting potential credibility of the model for predicting fire spread rate, flame temperature, incidental radiant heat flux, burn away, and most importantly, the total HRR evolution.
- Generalisation of a simplistic single plateau representation of wood combustion to a two plateau model, accommodating charring, has been successfully demonstrated with reproduction of crib fire results. Extension to compartment scale underway with current simulations.
- The thermal properties of the char vary significantly but impact on surface temperatures, hence reradiation to gas phase, found to be negligible at relevant timescales.
- Hence previously observed discrepancies in the cooling phase temperatures are predominantly associated with limitations in representation of heat transfer processes associated with the glowing char; explicit treatment not currentl included in FDS.

Conclusions (2)

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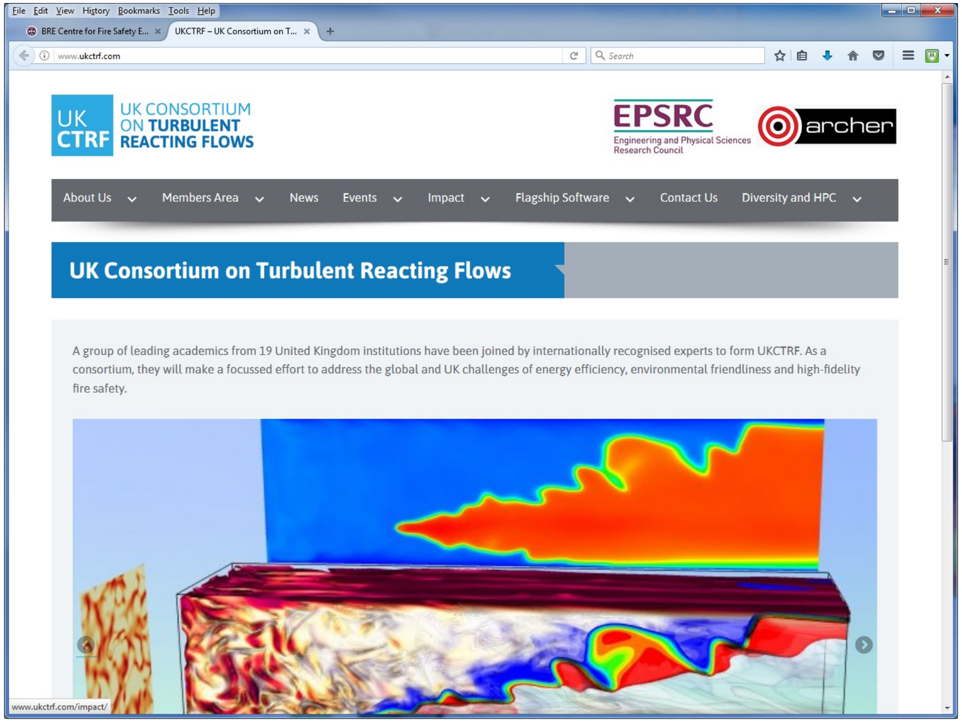
- The mesh scheme which adopts a finer mesh within the crib structure and relatively coarse mesh in the gas phase, provides an viable practical solution for modelling such crib fires, with potential for scaling up to compartment level. Some differences are found but they may be expected to be small when spread on upper surface of crib driven mainly by remote heating, not local flame front.
- New results with a very fine mesh inside the crib structure (now 7.5/8.75mm cells, giving 12x4 cells between sticks in elevation) have confirmed the plausibility of the original results with a coarser mesh (15/17.5mm cells with 6x2 cells between sticks).
- The fine grid model has a total of 7.2M cells, simulation of 20 minutes test using 78 processors requires ~12 x 48hr jobs; the coarser mesh models run ~14 times as far and hence can be used for parametric studies (~10 parameters, x3 cases each = 30 simulations, as reported previously).

Acknowledgements (1)

UK CTRF UK CONSORTIUM ON TURBULENT REACTING FLOWS

EPSRC Engineering and Physical Sciences Research Council

archer



EPSRC EP/R029369/1: Addressing Challenges Through Effective Utilisation of High Performance Computing – a case for the UK Consortium on Turbulent Reacting Flows (UKCTRF)

https://gow.epsrc.ukri.org/NGBOViewGrant.aspx?GrantRef=EP/R029369/1

Acknowledgements (2)

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Fire degree project students

Structural and Fire Safety Engineering Dissertation (90 credits)
MEng thesis (50 credits)

European Commission

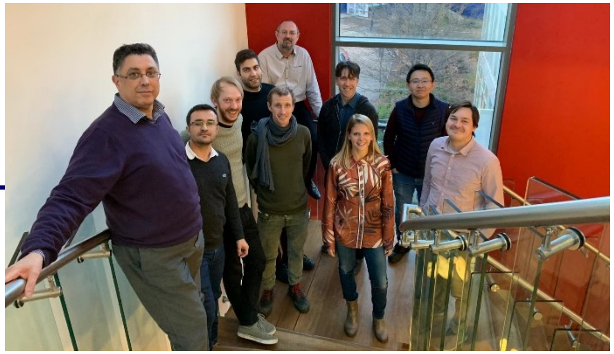
19/20 students

- **Miss Chang Liu (SAFE), Yang Xu (SAFE)**

20/21 students

- **Peter Charley (MEng), Mr Chang A. Liu (SAFE)**

Acknowledgments (3)



TRAFIR Project

Characterization of TRAvelling FIRes in large compartments

Funding from the Research Fund for Coal and Steel (RFCS) - European Commission

European Commission

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

- **testing** (isolated elements and simplified fire progression, as well as a full-scale large compartment)
- **modelling** (both simplified analytical/phenomenological models and CFD).

Project partners:

ArcelorMittal · Université de Liège (ULg) · RISE · Ulster University · The University of Edinburgh

Edinburgh fire

BRE Centre *for* Fire Safety Engineering

- Colleagues and students:
  - 7 Academic Staff (+1 retired)
  - 5 Research staff
  - c. 20 PhD Students
  - 25+ MSc students
  - ~10 pa UG students
  - Visiting researchers
- External Relationships:
  - EPSRC
  - ArcelorMittal (RFCS TRAFIR project)
  - BRE Trust (FireGrid, PhD Intelligent Egress)
  - Fire & Rescue Services
  - International academic/research partn
    - UQ (Hidalgo, Maluk, Lange, Gupta…)
    - CVUT Prague (Wald, Horová…)
    - RISE (Sjöström, …)
    - Liège (Franssen, Gamba…)
    - Ulster (Nadjai, Alam…)

Questions?