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Ministry of Housing, Communities and Local Government Final Research Report

Fire Performance of Cladding Materials Research – Appendix D Construction and design of experimental rig and calibration exercise

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D1 Introduction

The authors of this report are employed by BRE Global. The work reported herein was carried out under a Contract placed by the Ministry of Housing, Communities and Local Government. Any views expressed are not necessarily those of the Ministry of Housing, Communities and Local Government.

This Appendix is part of a Main report and Appendices and should be read in conjunction with these.

This Appendix contains a description of the construction and design of the experimental rig and the calibration exercise.

The experimental methodology and conceptual design for the experimental rig was set out in Appendix C.

D2 Numerical design of the experimental rig and performance

This section considers the preliminary analysis and pre-design of the fire source to be used in the subsequent experimental programme. Based on numerical modelling and a consideration of the information in Annex B of BS 8414 [1], [2], modelling has been used to provide input into the definition of a reliable and representative fire source for use in the experimental programme.

Both the numerical modelling and the subsequent calibrations (described in section D3) were carried out using a propane burner as the heat source to achieve a representative incident heat flux to the sample. The results from the modelling of the burner were then used to assist in the design of an appropriate timber crib fire source that provided equivalent levels of thermal exposure which was then used for the ACM calibrations and the subsequent experimental programme. For this part of the project, it is important to understand that the focus is on the characterisation of the fire dynamics of the fire source and as such, the specimen was replaced by a non combustible wall so that there was no contribution to the total heat release rate from the wall of the experimental rig itself.

It is important to establish the context for the use of the modelling for which the primary purpose was to provide estimates of the characteristics of the fire source for application in the experimental calibration stage. The procedure is summarised below:

- Initial modelling of propane burner source based on physical dimensions of the burner and mass flow rate of fuel was undertaken.
- Subsequently, modelling of crib burner source to investigate optimum size and geometric configuration and to investigate the influence of a gap between the source and the sample was undertaken.

The fire source design was based on the calibration/characterisation requirements for alternative heat sources as set out in Annex B of BS 8414 parts 1 and 2 (*Fire performance of external cladding systems – Part 1: Test method for non-loadbearing external cladding systems applied to the masonry face of a building and Part 2: Test method for non-loadbearing external cladding systems fixed to and supported by a structural steel frame*) [1], [2], which specifies the incident heat flux 1 m above the crib shall be within the range 45 to 75 kW/m^2. The fire source has been designed in such a way as to produce an incident heat flux of 45 (±5) to 75 (±5) kW/m^2 at a height of 1.5 m above the ground (approximately 1 m above crib source), see Figure D1.

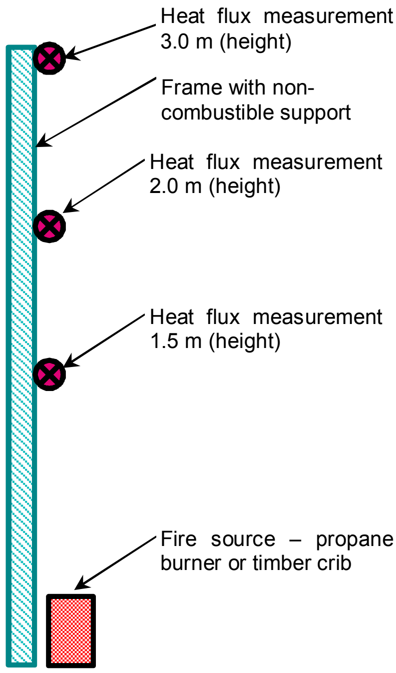


Figure D1 – Cross section sketch of the calibration rig

D2.1 Numerical modelling of the experimental rig and the gas burner fire source

A propane gas burner was selected as the fire source in the numerical model. The propane gas burner was 0.3 m by 0.3 m in plan with a height of 0.4 m identical to the dimensions of the burner to be used in the experimental calibrations. The maximum heat release rate from the burner was 400 kW. For the purpose of the numerical modelling, three different steady state heat release rates (100 kW, 300 kW and 400 kW) were used to provide the data to support the identification of the appropriate heat release rate which would provide the representative incident heat flux to the specimen at the specified location.

The numerical model used in this project was FDS (Fire Dynamic Simulator, 6.60), an open source Computational Fluid Dynamics (CFD) software for fire modelling [3], [4], [5]. In FDS, the Navier-Stokes equations are used to model the low-speed thermally driven fluid flow and the turbulent characteristics of the fluid flow are modelled using Large Eddy Simulation (LES). These equations are solved for each time step. LES describes the turbulent mixing of gaseous fuel and air within the local simulated atmosphere. The accuracy of the fire model predictions depend on the number and size of cells (the mesh) assigned to the physical space being modelled. In each cell, gas velocity and mass, gas temperature and gas concentration are evenly distributed and vary with time.

The mesh describes how many cubic cells are used within the volume and therefore the resolution of the model. The computational time is directly proportional to the mesh size i.e. for a fine mesh the model will be solved in a longer time and for a coarser mesh the computational time will be less.

In order to get an approximate value of the mesh size, the non-dimensional equation (D^*/dx), where D^* is shown in Equation 1 can be used.

$$D^* = \left(\frac{\dot{Q}}{\rho_\infty c_p T_\infty \sqrt{g}}\right)^{2/5} \qquad \text{(Equation 1)}$$

Where

D^* is the characteristic fire diameter

$\dot{Q}$ is the heat release rate of the fire source (kW)

ρ_∞ is the air density (kg/m^3)

c_p is the specific heat of the air (kJ/kg K)

T_∞ is the ambient gas temperature (K)

dx is the nominal size of the mesh cell

The impact of the mesh was analysed and reported in the NUREG-1824 validation study [6]. This analysis covered values for D*/dx between 4 and 16 and showed that the greater the ratio D*/dx, the better the resolution of the fire dynamics characteristics and therefore, the more accurate the simulation. Other work by McGrattan et al [4] has shown that a value of dx between 5 and 10 produces favourable results at a moderate computational cost. Based on this information, for this project, the preliminary calculation value of D*/dx=12 was chosen.

The geometry incorporating the non-combustible material (calcium silicate board) as the wall of the experimental rig and the propane gas burner is shown in Figure D2.

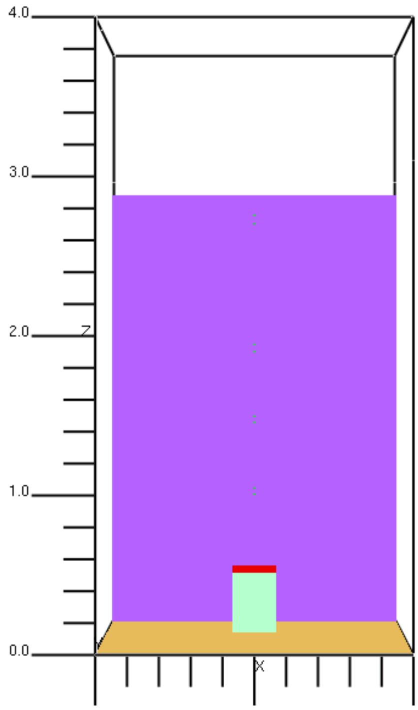


Figure D2 – Geometry of the preliminary model for the propane gas burner fire source

The input parameters used for the propane gas model are presented in Table D1.

Table D1 – Basic input parameters for the propane gas model

Parameter	Value [7]		
Calcium silicate board	ρ (kg/m³)	c_p (kJ/kg.K)	λ (W/m.K)
	720	1.25	0.12
Propane gas	Chemical formula	Heat of combustion (kJ/kg)	
	C_3H_8	46,460	
Mesh size	0.05 m		

For the preliminary modelling of the propane gas burner, the heat release rate (HRR) was varied with time. The fire size was started at 100 kW (step 1) and was ramped up in time to 300 kW (step 2) and 400 kW (final step). Each step was maintained for a period of three minutes of steady state heat release rate. The heat release rate of the burner as a function of time as used in the model is shown in Figure D3.

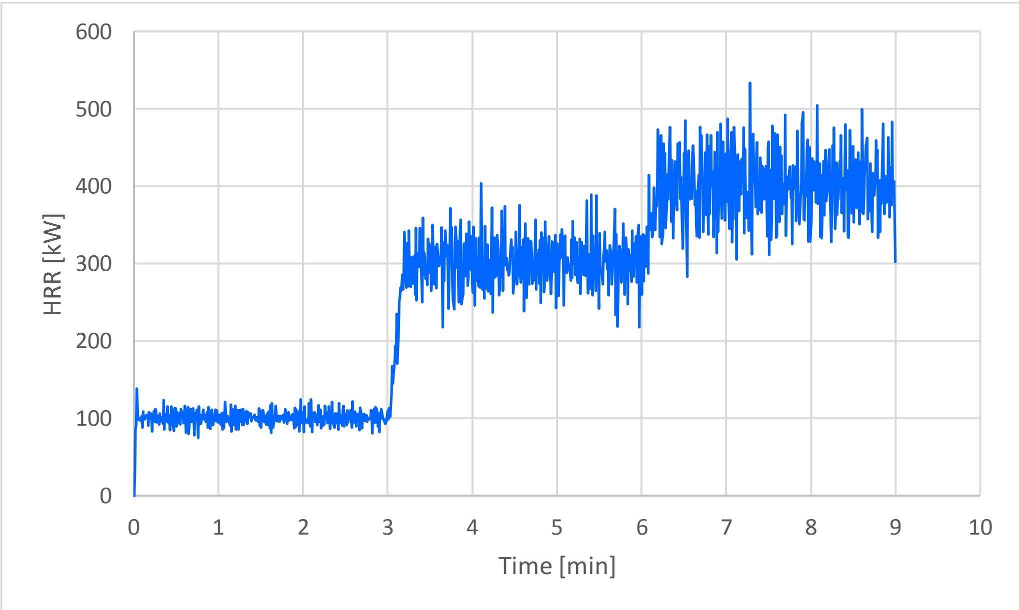


Figure D3 – Heat release rate values for the propane gas burner as used in the model

Based on discussion with the project partners, two specific scenarios were considered for the position of the fire source in relation to the non-combustible wall of the experimental rig, to establish the influence of a gap between the fire source and the rig. The first burner position was with the burner flush against the face or wall of the rig (no air gap) and the second position was with the burner horizontally offset 100 mm from the face of the rig, as shown in Figure D4.

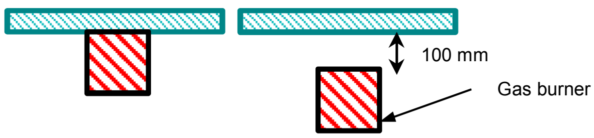


Figure D4 – Plan view sketch showing gas burner positions in the model

D2.1.1 Findings for the gas burner located against the experimental rig

Based on the preliminary modelling using the propane gas burner, average incident heat fluxes were predicted as shown in Table D2.

Table D2 – Predicted incident heat fluxes

Height/ Distance from rig	Heat flux at 1.5 m (kW/m^2)			Heat flux at 2.0 m (kW/m^2)			Heat flux at 3.0 m (kW/m^2)		
	100 kW	300 kW	400 kW	100 kW	300 kW	400 kW	100 kW	300 kW	400 kW
0 mm away	25	60	70	5	40	55	2.5	10	15
100 mm away	10	55	65	3	30	45	1.5	8	12

D2.2 Numerical modelling of the experimental rig and the wood crib fire source

The geometry incorporating the non-combustible material (calcium silicate) and the wood crib fire source is presented in Figure D5.

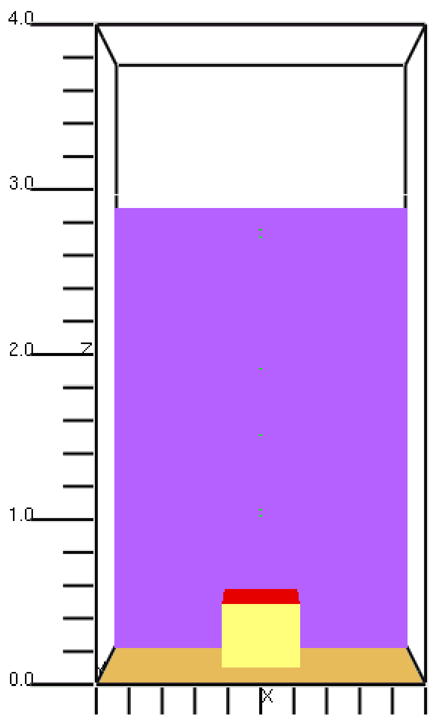


Figure D5 – Geometry of the preliminary model for the wood crib fire source

The input parameters used for the wood crib model are presented in Table D3.

Table D3 – Basic parameters used for the wood crib model

<table>
<tr><th>Parameter</th><th colspan="6">Value [7]</th></tr>
<tr><td rowspan="2">Calcium silicate board</td><td colspan="2">ρ (kg/m³)</td><td colspan="2">c_p (kJ/kg.K)</td><td colspan="2">λ (W/m.K)</td></tr>
<tr><td colspan="2">720</td><td colspan="2">1.25</td><td colspan="2">0.12</td></tr>
<tr><td rowspan="2">Wood crib</td><td colspan="3">Chemical formula</td><td colspan="3">Heat of combustion (kJ/kg)</td></tr>
<tr><td colspan="3">C=3.4; H=6.2; O=2.5</td><td colspan="3">17,700</td></tr>
<tr><td>Mesh size</td><td colspan="6">0.05 m</td></tr>
</table>

For the preliminary modelling, the fire size was approximated based on a flame height calculation given by equation 2 [8]:

$$z_{fl} = 0.2Q^{2/5} \qquad \text{(Equation 2)}$$

Where

z_{fl} represents the mean height of the flame above the fuel source (m)

Q is the total rate of heat release (kW)

The fire source was chosen in such way that the flame length does not exceed the height of the rig. Figure D6 shows the heat input of the modelled wood crib as a function of time.

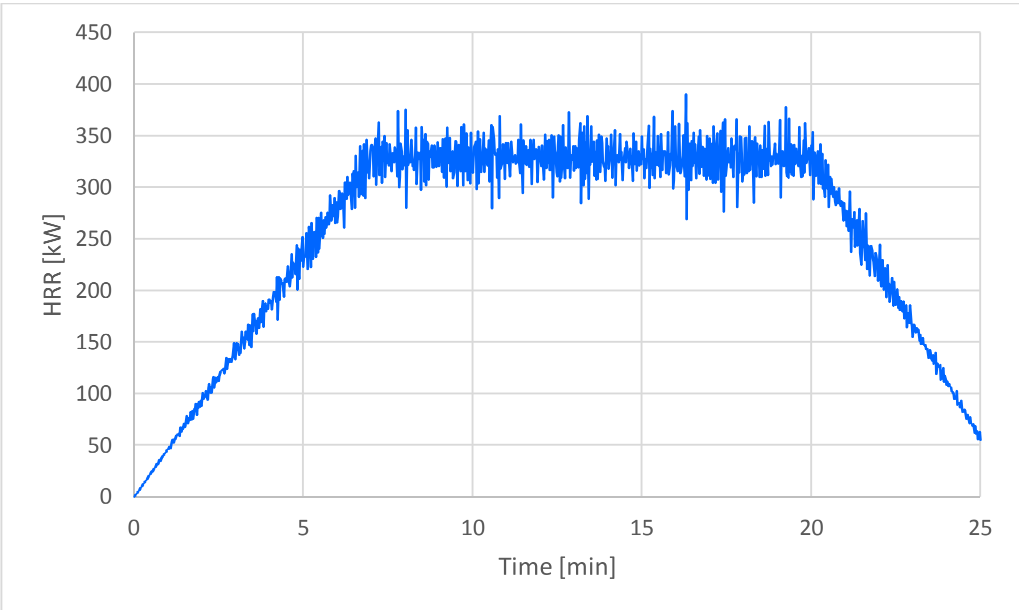


Figure D6 – Heat release rate for the wood crib used in the model

Two specific scenarios for the fire position in relation to the non-combustible face or wall of the experimental rig were considered to analyse the influence of a gap between the fire source and the experimental rig. The first position is with the wood crib located flush with the wall of the experimental rig and the second position is with the wood crib located 100 mm offset from the experimental rig as shown in Figure D7.

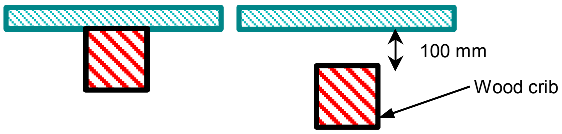


Figure D7 – Plan view sketch showing the wood crib arrangements in the model

D2.2.1 Findings for the wood crib located against the experimental rig

Based on the preliminary modelling of the wood crib, the average incident heat fluxes were predicted as shown in Table D4.

Table D4 – Predicted incident heat fluxes

Height/Distance from rig	Heat flux at 1.5 m (kW/m^2)	Heat flux at 2.0 m (kW/m^2)	Heat flux at 3.0 m (kW/m^2)
0 mm away	60	30	8
100 mm away	50	25	5

D2.3 Results

As can be seen by reference to Tables D2 and D4, the location of the fire source in relation to the non-combustible wall of the experimental rig impacts upon the predicted average incident heat fluxes. Where the fire source is flush with the non-combustible wall, the predicted average incident heat fluxes are higher than the case where there is a gap between the fire source and the non-combustible wall.

D3 Construction of experimental rig and calibration

D3.1 Construction of experimental rig

The main frame was constructed from hot rolled steel hollow section, see Figure D8. The experimental rig was used as the support frame for a range of different materials/products which required different means of fixing. In order to make the frame as versatile as possible and allow for the fixing of panels of different sizes, mild steel angles were welded to the frame and aluminium T rails mechanically fixed back to the angles as shown in Figure D9.

Figure D8 – Steel frame used to construct experimental rig

Figure D9 – Mild steel angles and aluminium T rails

The first step in undertaking the calibration of the fire source was to install a non-combustible panel as the wall that could be used to mount the instrumentation required to quantify the incident heat flux to the samples but would not provide a contribution to the heat release rate or in itself support fire growth or flame spread. The non-combustible panel was a calcium silicate board with a thickness of 20 mm which was cut and installed on the front face of the experimental rig, fixed directly to the aluminium T rails using M8 × 50 mm set screws as shown in Figure D10.

Figure D10 – Calcium silicate board during installation to the aluminium T rails

D3.2 Propane gas burner calibrations

The average incident heat flux to the non combustible board was measured on exposure to a propane fire source for which the heat release rate could be varied. The frame with the board and the instrumentation in place is shown in Figure D11 and Figure D12.

Figure D11 – Front face of experimental frame showing calcium silicate board

Figure D12 – Rear face of experimental rig showing instrumentation in place

A propane gas burner was used to control the heat input for the initial commissioning. The propane gas burner with a mass flow controller was set up in the BRE Burn Hall Laboratory. The basic layout is illustrated in Figure D13 and Figure D14.

Figure D13 – Propane gas rig showing mass flow controller

Figure D14 – Propane gas burner

The aim was to provide an incident heat flux on the surface of the calcium silicate board in the centre of the specimen at a height of 1.5 m from the floor in the range 45 to 75 kW/m² to be consistent with the typical thermal exposure on external walls from post flashover fires. Once the required level of the fire source had been established, the proposed timber crib size was modified to provide a repeatable source within the required range.

The burner was run at a constant heat release rates of 100 kW, 300 kW and 400 kW (maximum capacity of the burner) for a period of approximately 4 minutes each. The impact on the heat fluxes measured was characterised with the burner placed in two locations: tight up against the face of the calcium silicate board (Figure D15) and 100 mm from the face of the calcium silicate board (Figure D16). The results are summarised in Table D5.

Figure D15 – Burner tight up against calcium silicate board

Figure D16 – Burner 100 mm from face of the calcium silicate board

Table D5 – Results from propane burner calibrations

Run No.	Heat release rate (kW)	Distance from calcium silicate board (mm)	Average heat flux 1.5 m, 2 m and 3 m from floor (kW/m²)		
			1.5 m	2.0 m	3.0 m
1	100	0	76	11	3
2	100	100	39	9	3
3	300	0	100*	49	11
4	300	100	100*	34	8
5	400	0	100*	58	17
6	400	100	100*	43	11

**maximum output for instrument*

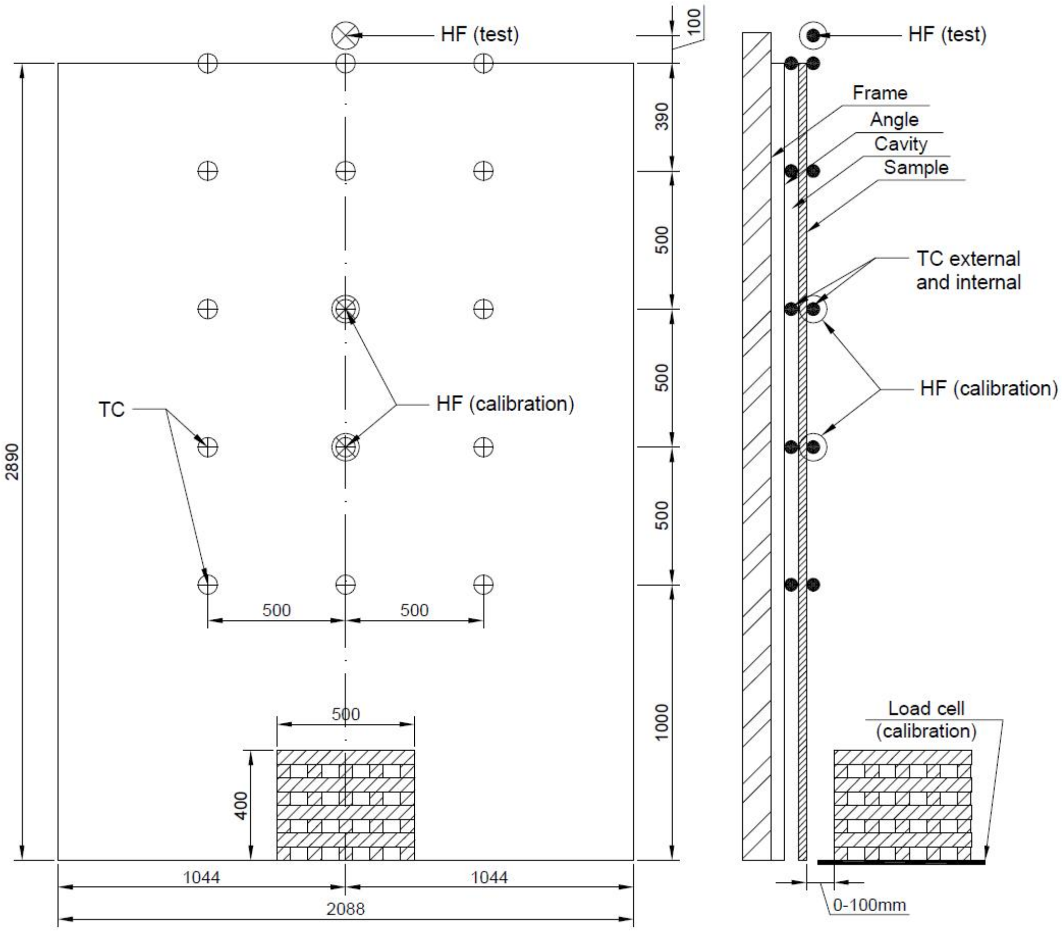
D3.2.1 Conclusions from propane gas burner calibrations

From the results from the propane gas burner calibrations the following can be concluded:

- The target heat flux at 1.5 m from the floor is achieved at a heat release rate of approximately 100 kW when the burner is flush with the board.
- In order to achieve the required heat flux, as can be seen from the results in Table D5, it is essential that the fire load is placed flush against the panel.
- Where the ignition source is placed flush against the panel, the flames adhere to the surface of the panel.
- The impact of inertia and buoyancy needs to be taken into consideration when analysing the results.
- Based on the results from the propane burner calibrations and the numerical modelling work described in section D2, the initial proposal was to investigate the use of a timber crib with a calculated (on the basis of mass burning rate and calorific value) notional heat output of between 300 kW and 500 kW.

D3.3 Timber crib calibrations

The layout of the timber crib and the location of the instrumentation on the experimental rig is shown in Figure D17.



Key

HF = water cooled heat flux sensor (measures radiative and convective heat transfer)

TC = thermocouple

Figure D17 – Layout of the crib and location of instrumentation for calibration and main experiments

The results from the trials using timber cribs are summarised in Table D6.

Table D6 – Results from timber crib calibrations

Trial No.	Crib layout	Average burning rate (10 - 20 min) (kg/s)	Average heat flux 1.5 m, 2 m and 3 m from floor (kW/m²)		
1	8 layers of 5 sticks 500 mm x 50 mm x 50 mm offset 100 mm from experimental rig	0.017	28	9	4
2	10 layers of 5 sticks 500 mm x 50 mm x 50 mm flush to experimental rig	0.02	88	27	7
3	10 layers of 5 sticks 500 mm x 50 mm x 50 mm offset 100 mm from experimental rig	0.02	26	7	3
4	8 layers of 5 sticks 500 mm x 50 mm x 50 mm tight to experimental rig*	0.017	35	8	3
5	8 layers of 5 sticks 500 mm x 50 mm x 50 mm flush to experimental rig	0.015	59	11	4
6	8 layers of 5 sticks 500 mm x 50 mm x 50 mm tight to experimental rig	0.017	63	12	4
7	8 layers of 5 sticks 500 mm x 50 mm x 50 mm flush to experimental rig	0.011	52	12	5

** = small unintentional gap present*

Figure D18 is an example of the timber crib just prior to ignition. Figure D19 is an example of a crib during the steady burning phase.

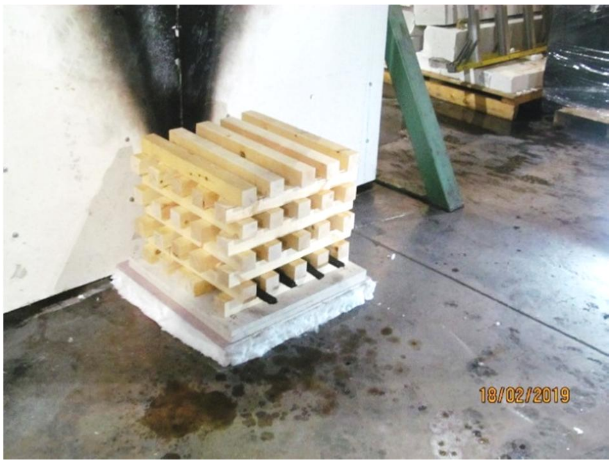


Figure D18 – Timber crib for Trial 1

Figure D19 – Steady burning phase for Trial 1

The heat flux measurements at the specified location for crib trials 5, 6 and 7 are presented in Figure D20, Figure D21 and Figure D22 respectively. The results during the steady burning phase correlate well with the target incident heat flux of between 45 and 75 kW/m^2. It should be noted that the fluctuations that can be seen in the measurements are typical of turbulent flames characteristic of real fires.

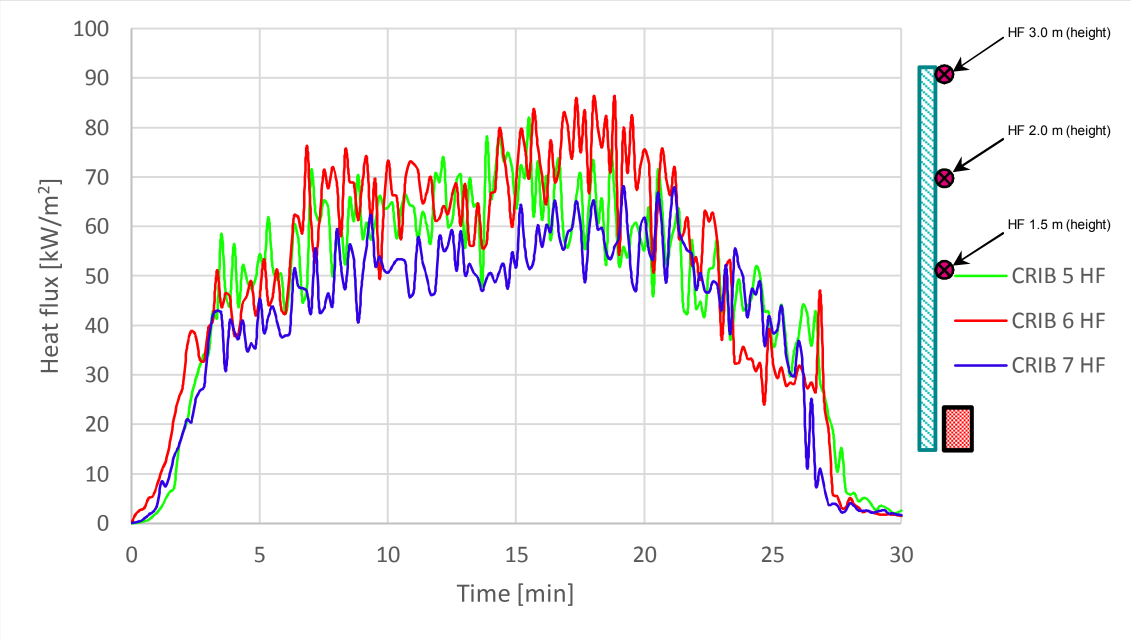


Figure D20 – Heat flux measurements at 1.5 m above the ground for Trials 5, 6 and 7

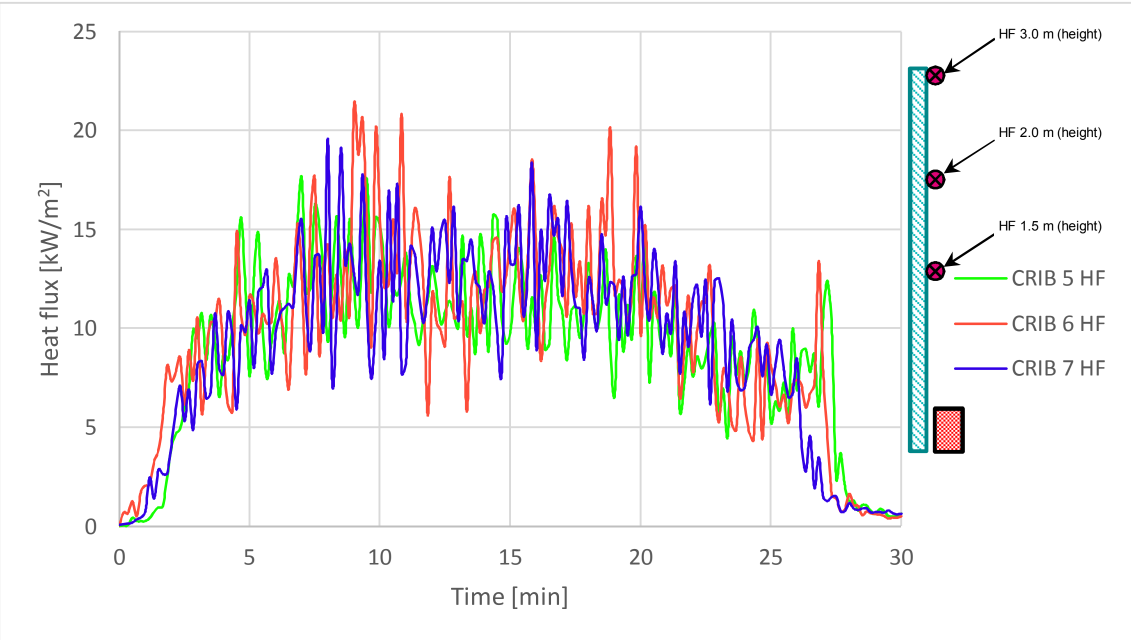


Figure D21 – Heat flux measurement at 2.0 m above the ground for Trials 5, 6 and 7

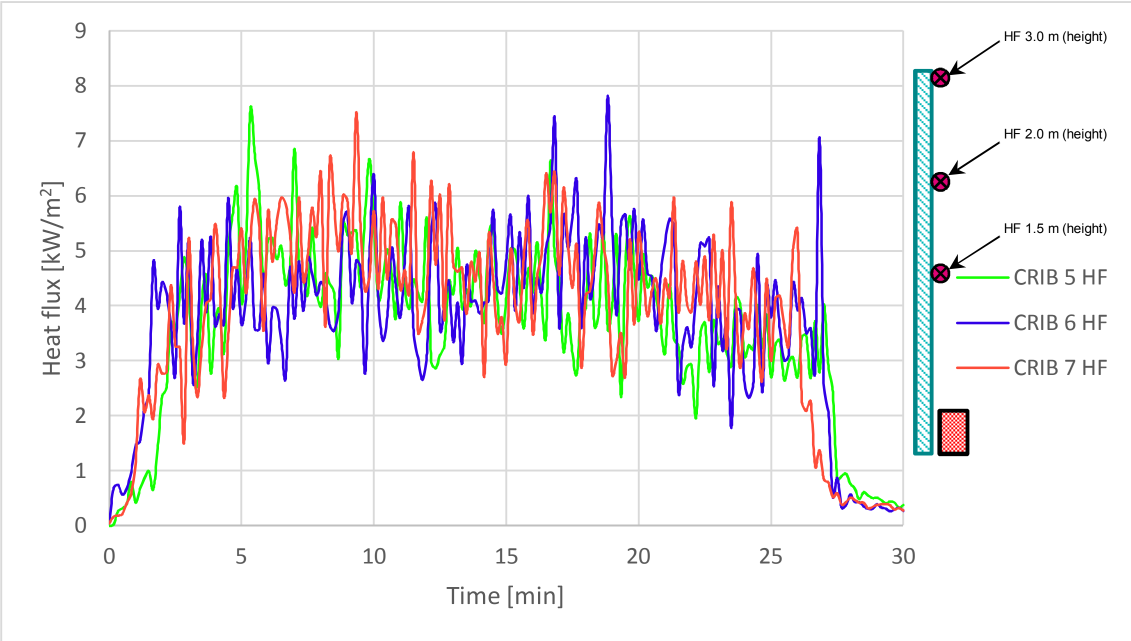


Figure D22 – Heat flux measurement at 3.0 m above the ground for Trials 5, 6 and 7

D3.3.1 Conclusions of the timber crib calibrations

The following conclusions can be drawn from the timber crib calibrations:

- A crib consisting of 40 sticks of 500 mm by 50 mm by 50 mm softwood in eight layers with a moisture content between 9% and 13% is capable of imposing an incident heat flux at a central location 1.5 m above ground level in the range 45 to 75 kW/m².

- In order to achieve the target incident heat flux on the surface of the specimen, it is essential that the fire load is placed in direct contact with the specimen to ensure that the flame adheres to the surface.

- The results clearly show, as expected, that the heat flux measured decreases with height above the crib fire source. This is due to the change in flame characteristics as a function of height which is well documented and typical of turbulent diffusion flames.

D3.4 Characterisation of the fire source by oxygen consumption calorimetry

In order to characterise the fire source in terms of heat release rate, the eight-layer timber crib selected from results of the timber crib calibrations was characterised using oxygen consumption calorimetry.

The wood crib was built as per the design specification using 40 sticks of 50 mm by 50 mm by 500 mm softwood arranged in eight rows and conditioned for one week at constant temperature and humidity. The moisture content was measured with a timber moisture meter giving an average value of 10.5%.

The wood crib was installed inside an oxygen consumption calorimeter (the Single Burning Item test apparatus [9]) to measure the heat release as shown in Figure D23. The fire was extinguished after approximately 9 minutes from ignition.

Figure D23 – Ignition of timber crib inside oxygen consumption calorimeter (Single Burning Item test apparatus [8])

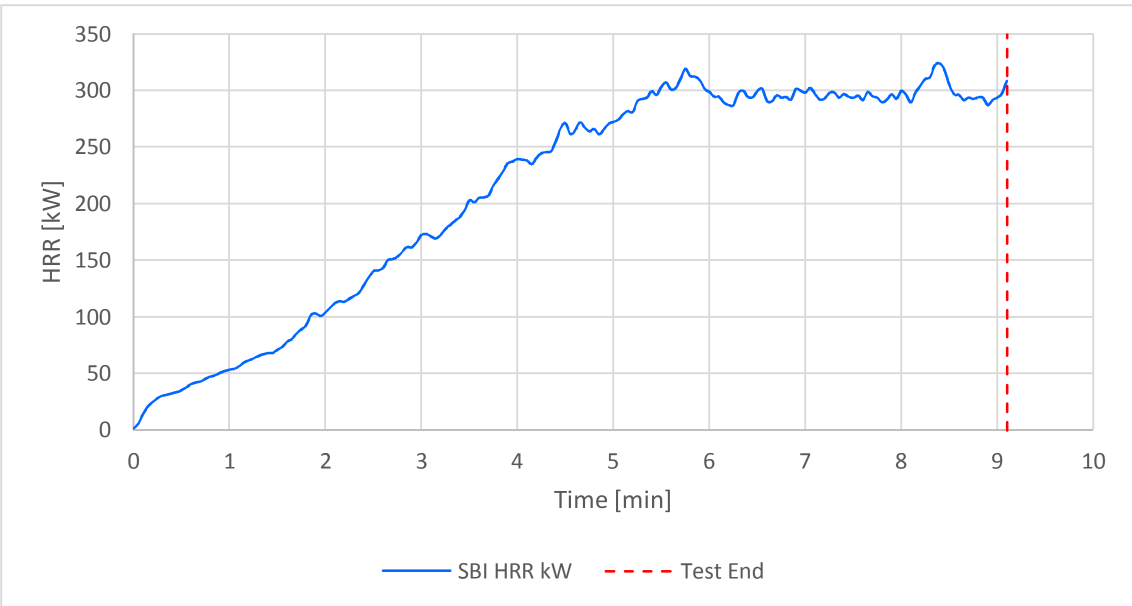


Figure D24 – Heat release rate measured in the Single Burning Item test apparatus (red dotted line indicates when the fire was extinguished at approximately 9 minutes from ignition)

During the wood crib burn, a peak value of 323 kW was measured and recorded, see Figure D24. The wood crib reached a steady state burning condition after approximately 6 minutes. These measurements are consistent with the initial predictions based on mass loss.

In addition, the heat release rate up to extinction of the wood crib was also measured under the 9 m hood apparatus, as shown in Figure D25, based on open calorimetry methodology [10].

Figure D25 – Timber crib alight under 9 m by 9 m calorimeter hood (open calorimetry)

From the oxygen consumption calorimetry results, the average baseline for the crib heat output can be considered as approximately 300 (± 20) kW during the steady burning period, see Figure D26. The difference in the initial rate of increase in the heat release rate of the crib is due to the difference in the two fire scenarios (open burning compared with closed corner arrangement in the Single Burning Item test apparatus).

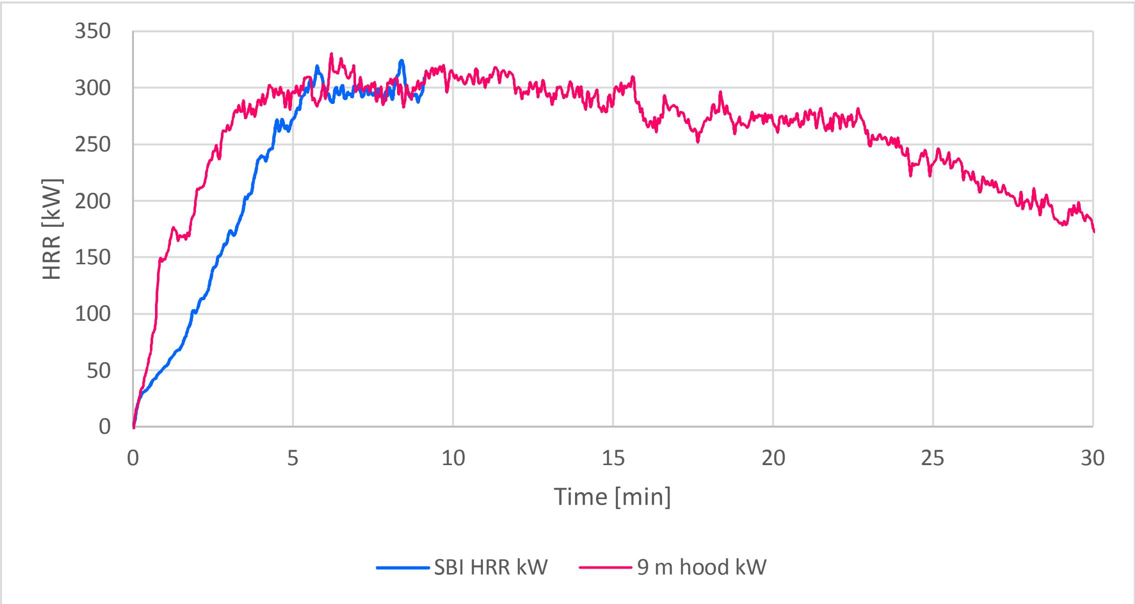


Figure D26 – Comparison of the heat release rates measured for the timber crib for the two different oxygen consumption calorimeters (Single Burning Item test apparatus and 9 m by 9 m hood apparatus)

D3.5 ACM material calibration fires

As a part of the material calibration procedure and to establish a system for ranking different materials, it was necessary to assess performance in relation to a material with a known level of performance in terms of gross heat of combustion. For this reason, aluminium composite material (ACM) was chosen to provide the likely range of expected outcomes. The thickness of the ACM material was 4.0 mm, consisting of 0.5 mm aluminium faces on both sides and a 3.0 mm solid core. Three different types of ACM were used, incorporating polyethylene core (PE), fire retardant core (FR) and limited combustibility core (A2).

D3.5.1 Indicative gross heat of combustion of ACM samples

Prior to the ACM calibration fires, a set of indicative gross heat of combustion (bomb calorimeter[12]) tests were carried out on all the cores of the ACM material samples. A summary of the gross heat of combustion results (MJ/kg) is presented in Table D7.

Table D7 – Gross heat of combustion for the specified samples in MJ/kg

Sample	Test 1	Test 2	Test 3	Mean
ACM PE	46.3	46.4	46.4	46.4
ACM FR	12.9	12.9	12.9	12.9
ACM A2	3.5	3.5	3.4	3.5

The results show a clear differentiation between the different classes of ACM material. Although the results for the ACM A2 lie slightly outside the limits used for A2 material classification this was not a standard reaction to fire classification but an indicative test.

D3.5.1 Experimental matrix for the ACM material calibration fires

The experimental matrix for the ACM calibration fires is summarised in Table D8. Six material calibration fires were carried out, two of each type of PE, FR and A2.

Table D8 – Experimental matrix

Experiment No.	Sample description	Thickness (mm)	Vertical joint (offset from central axis) (m)	Horizontal joint (m)	Cavity (mm)	Fixings spacing (mm)
1	ACM FR	4 mm (0.5 mm aluminium faces and 3 mm core)	0.5	2.0 2.9	50	300 (vertical) 400 (horizontal)
2	ACM PE		0	2.0		
3	ACM A2		0.5	2.0		
4	ACM FR		0.25	2.0		
5	ACM A2		0.5	2.0		
6	ACM PE		0	2.0		

D3.5.2 Results of the ACM material calibration fires

In each case the results are presented in terms of measured values and visual observations. It is important to view the results and observations together. A focus on a single peak value may not be representative of the performance of the sample. The time to burn through is assessed based on observed behaviour and the results from the thermocouples within the cavity and the heat flux meter at the top of the rig.

The crib source was placed tight up against the rig on the centre line in each case. Each experiment incorporated a single vertical joint (approximately 10 mm) offset from the centre and at least one horizontal joint (approximately 10 mm) at approximately 2 m from the ground. The general arrangement is illustrated in Figure D27. The precise location of the vertical joint was dependent on the panel width. The vertical joint for the ACM PE panels coincided with the centre of the rig as the panel width supplied was 1 m. In this case, the joint location is probably the most onerous as the core of the ACM is exposed to the highest heat fluxes which are along the vertical centreline from the crib from the start of the experiment. For the other types of ACM, the core was not directly exposed to the crib flames from the start of the experiments.

In each case, the panels were fixed to 100 mm wide aluminium T rails fixed back to mild steel angles at 400 mm centres. The ACM panels were fixed to the rails using 4.8 × 25 mm long self-drill screws at 300 mm vertical centres. A cavity of approximately 50 mm was provided between the ACM panels and the non-combustible support (calcium silicate board) of the experimental rig.

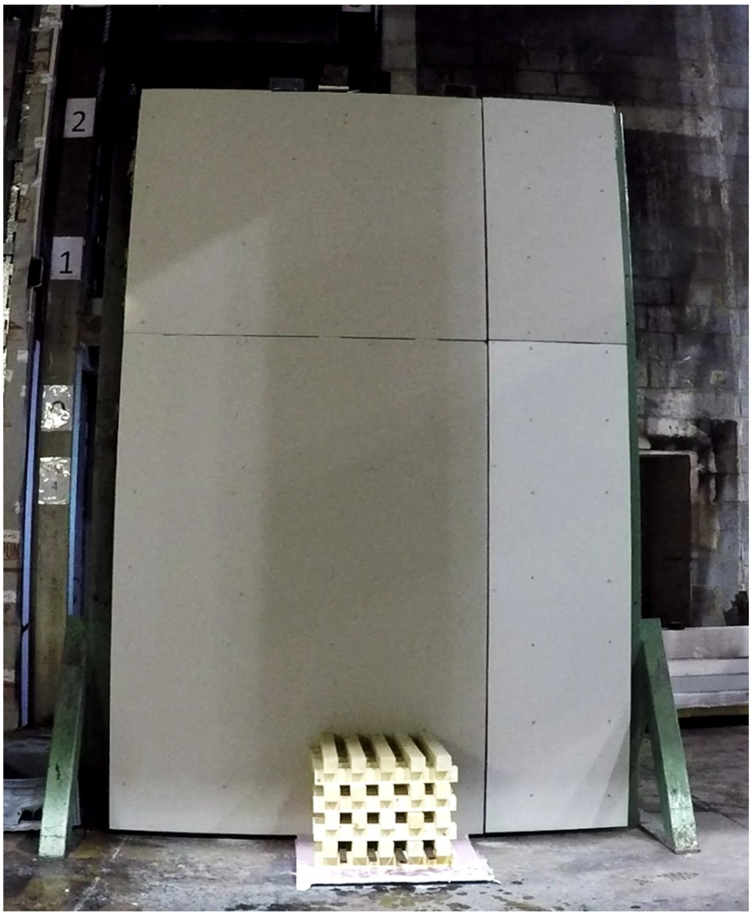


Figure D27 – General arrangement of the sample and the fire load

D3.5.2.1 ACM calibration fire 1 with ACM FR

The first ACM calibration fire was carried out using aluminium composite material with fire retardant core (ACM FR). Figure D28 shows the material installed on the experimental rig prior to the experimental fire. One vertical joint and two horizontal joints of approximately 10 mm were provided within the installation as shown in Figure D28.

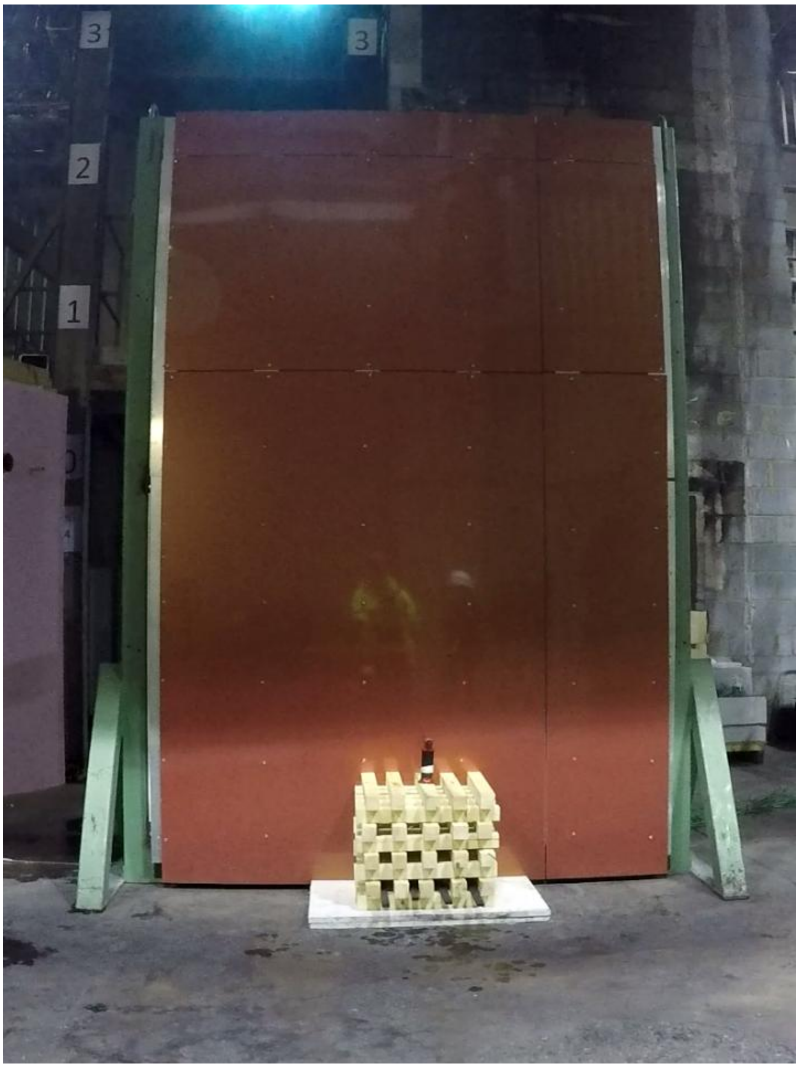
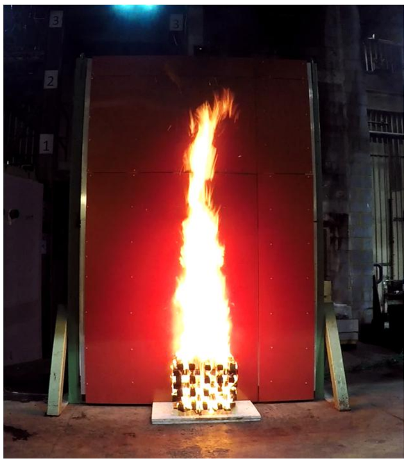


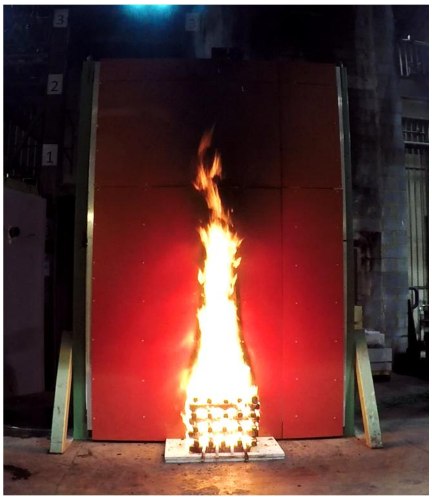
Figure D28 – ACM FR material installed on the experimental rig for ACM fire 1

Figure D29 shows photograph during the fire exposure at specified times.



5 minutes from ignition

10 minutes from ignition



20 minutes from ignition

25 minutes from ignition

Figure D29 – Photographs during the fire at 5, 10, 20 and 25 minutes from ignition

No significant falling debris or burning droplets were observed during the experimental fire. A discoloration of the panels was observed in the area of direct flame exposure.

After approximately 21 minutes, the fire consumed the aluminium panel and breached inside the cavity. No significant changes to the burning behaviour were recorded.

No significant vertical or horizontal flame spread on the surface of the ACM FR panels was recorded.

Figure D30 shows the heat release rate as a function of time during the fire exposure, including the contribution of the fire source. Based on the original crib calibrations and the measured values from the calorimeter, it is assumed that the peak heat release rate for the crib alone is approximately 300 (±20) kW. It can therefore be concluded that the ACM FR had a limited contribution to the heat release rate.

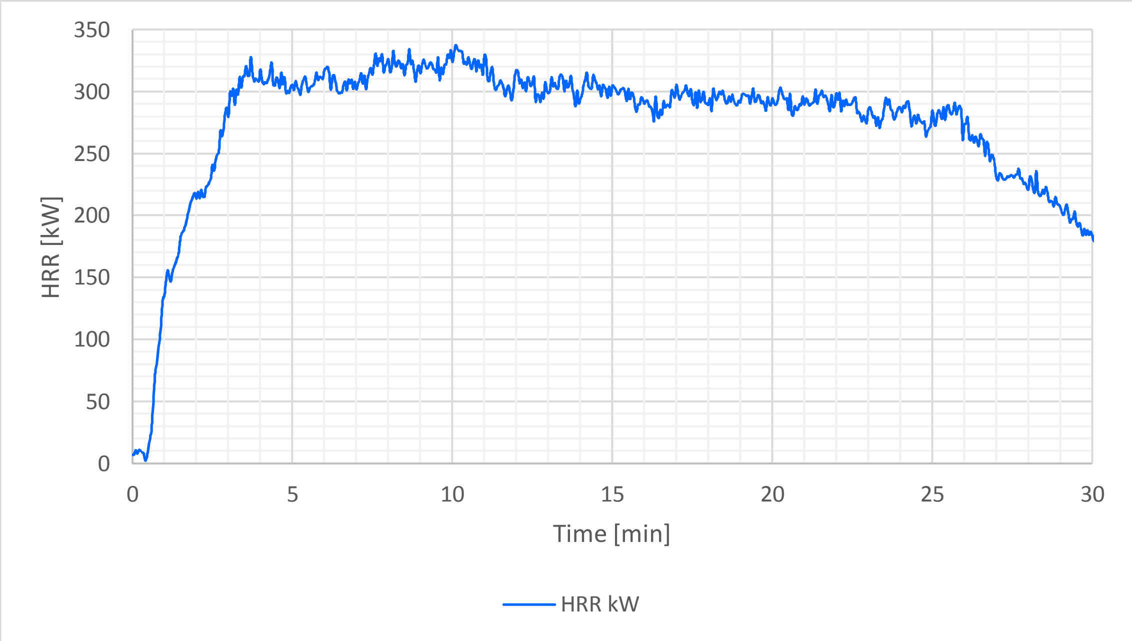


Figure D30 – Heat release measured during the fire for ACM FR material including the fire source

Figure D31 shows the heat flux recorded during the fire at a height of 3.0 m from the ground.

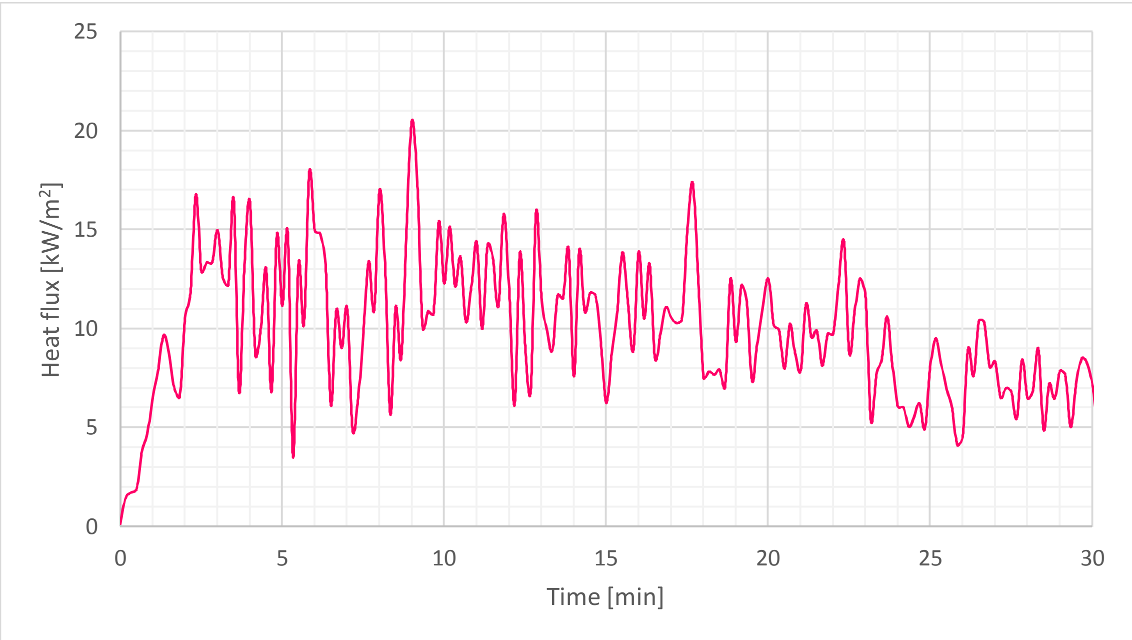


Figure D31 – Heat flux recorded during the fire at 3.0 m height

Table D9 shows the maximum external temperature, the maximum cavity temperature, the maximum temperature at 3.0 m, the time to peak heat release rate (HRR), the peak HRR, the maximum heat flux (HF) at 3.0 m and the total heat release (THR) over a period of 30 minutes.

Table D9 – Summary of different measured parameters during the experiment

Maximum external temp. [°C]	Maximum cavity temp. [°C]	Maximum H=3.0m Temp. [°C]	Time to peak HRR [min]	Peak HRR [kW]	Maximum H=3.0m Heat flux [kW/m^2]	THR [MJ]
975	1017	198	10.1	338	20.5	497

A summary of the visual observations is presented in Table D10.

Table D10 – Visual observations during the experiment

Burning droplets	Burn through (30 min)	Time to burn through [min]	Area consumed [m^2]	Vertical flame spread	Horizontal flame spread
Not significant	Yes	22	≈0.5	No	No

Figure D32 shows the sample after the fire. The ACM FR panels were consumed locally in the zone of direct flame impingement. Discoloration and distortion could be observed on the surface of the panels. On the horizontal joint above the fire source, the core had melted, filling up a small portion of the joint.

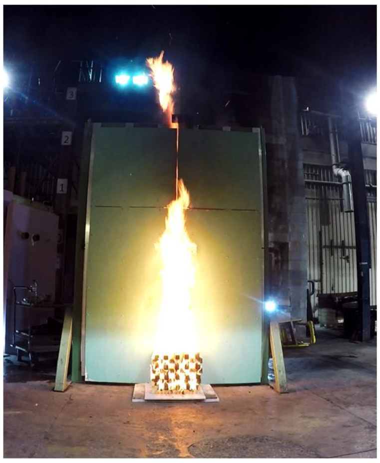
Figure D32 – Post fire observations

D3.5.2.2 ACM calibration fire 2 with ACM PE

The second ACM calibration fire was carried out with aluminium composite material with polyethylene core (ACM PE). Figure D33 shows the material installed on the experimental rig prior to the fire. One vertical joint and one horizontal joint of approximately 10 mm were provided within the installation process as shown in Figure D33.

Figure D33 – ACM PE material installed on the experimental rig

Figure D34 shows photographs during the fire exposure at specified times.



5 minutes from ignition

10 minutes from ignition

20 minutes from ignition

25 minutes from ignition

Figure D34 – Photographs during the fire at 5, 10, 20 and 25 minutes from ignition

The fire development was very rapid. After approximately 5 minutes, the fire breached the cavity. Flames could be observed coming out from the cavity at the top of the rig. A molten plastic pool fire started at the bottom of the experimental rig.

After approximately 7 minutes, the flame height above the rig was more than 2 m. Sustained flaming could be observed inside the cavity and on the outer surface of the panels.

After 10 minutes, the fire started to spread laterally, involving more material. The ACM PE panels were consumed in the central flame axis from bottom to the top of the experimental rig. The non-combustible support of the experimental rig could be seen through the flames.

In the central area, all the T-shaped aluminium rails were consumed due to the high temperatures recorded.

Falling debris and burning droplets were observed during the fire. At the end of the fire, most of the ACM PE panels were consumed.

Figure D35 shows the heat release rate as a function of time during the fire exposure, including the contribution of the fire source. Given the nominal peak heat release rate for the crib of 300 (±20) kW, then the peak contribution of the panel is approximately four to five times that of the fire source.

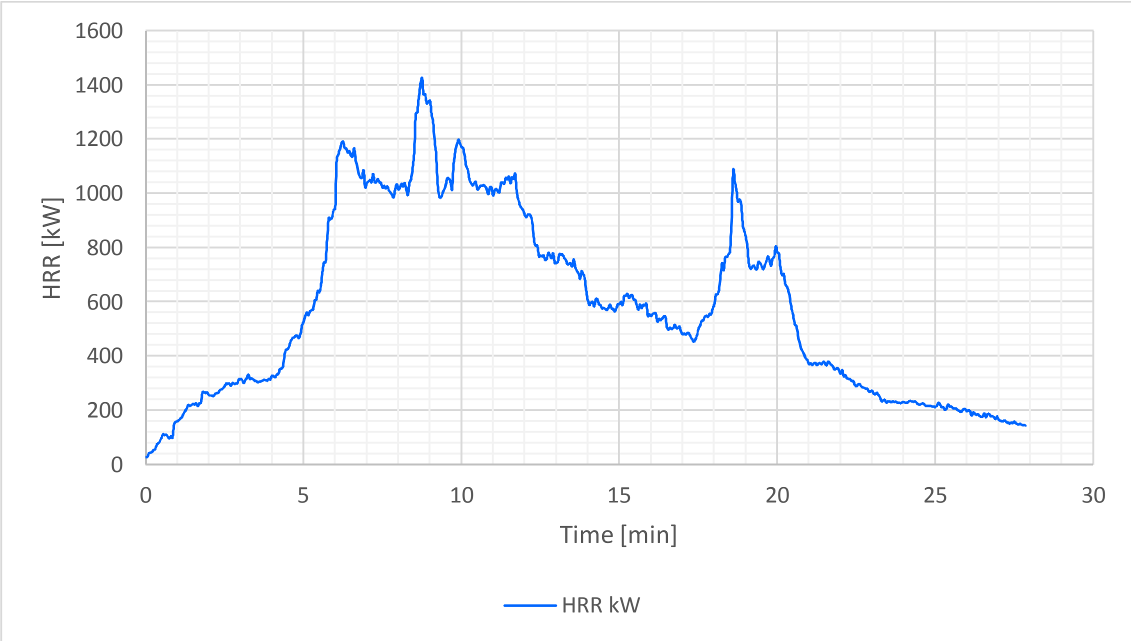


Figure D35 – Heat release measured during the experimental fire for ACM PE material including the fire source

Figure D36 shows the heat flux recorded during the fire at a height of 3.0 m from the ground. The maximum range of the heat flux meter of 100 kW/m^2 was reached 5 minutes after ignition.

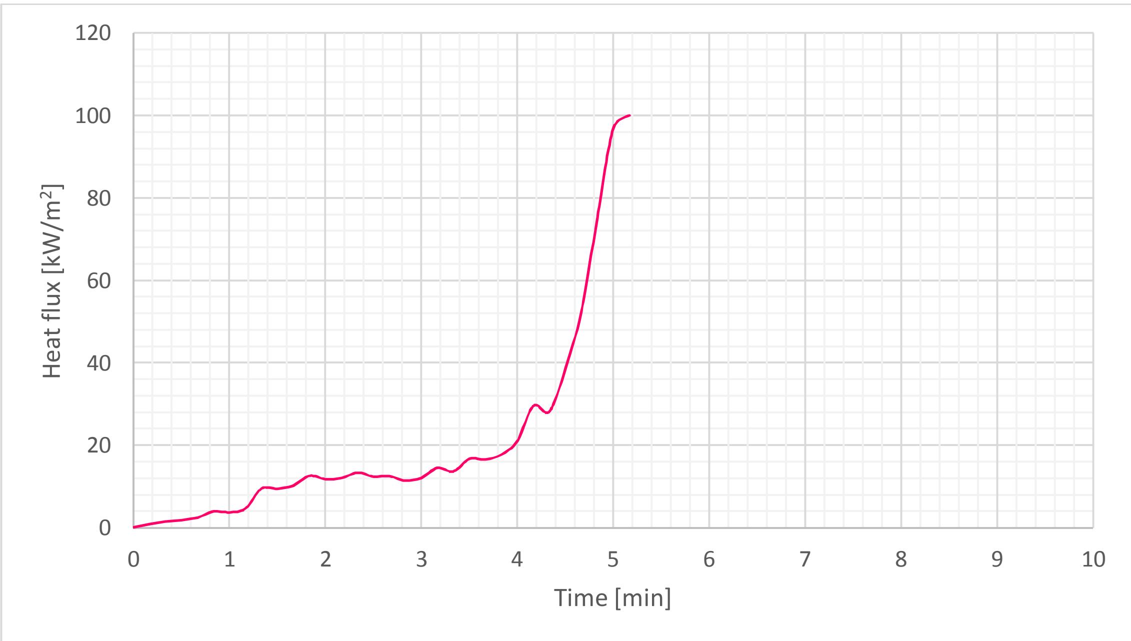


Figure D36 – Heat flux recorded during the fire at 3.0 m height

Table D11 shows the maximum external temperature, the maximum cavity temperature, the maximum temperature at 3.0 m, the time to peak heat release rate (HRR), the peak HRR, the maximum heat flux (HF) at 3.0 m and the total heat release (THR) over a period of 30 minutes.

Table D11 – Summary of different measured parameters during the experimental fire

Maximum external temp. [°C]	Maximum cavity temp. [°C]	Maximum H=3.0m Temp. [°C]	Time to peak HRR [min]	Peak HRR [kW]	Maximum H=3.0m Heat flux [kW/m^2]	THR [MJ]
944	1003	656	8.7	1425	>100	964

A summary of the visual observations is presented in Table D12.

Table D12 – Visual observations during the experiment

Burning droplets	Burn through (30 min)	Time to burn through [min]	Area consumed [m^2]	Vertical flame spread	Horizontal flame spread
Significant including pool fire	Yes	2	≈5.1	Yes	Yes

Figure D37 shows the sample after the fire. The ACM PE panels were mostly consumed. Fragments of the aluminium faces could be observed hanging on the remaining rails. An unconsumed strip of approximately 300 mm of ACM PE could be observed on the right-hand side of the rig.

Figure D37 – Post fire observations

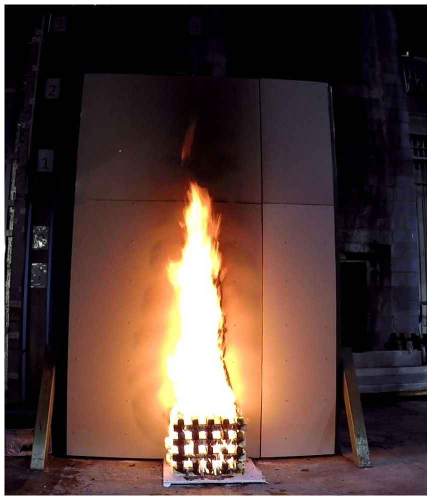
D3.5.2.3 ACM calibration fire 3 with ACM A2

The third ACM calibration fire was carried out with aluminium composite material with A2 core (ACM A2). Figure D38 shows the material installed on the experimental rig ready prior to the fire. One vertical joint and one horizontal joint of approximately 10 mm were provided within the installation process as shown in Figure D38.

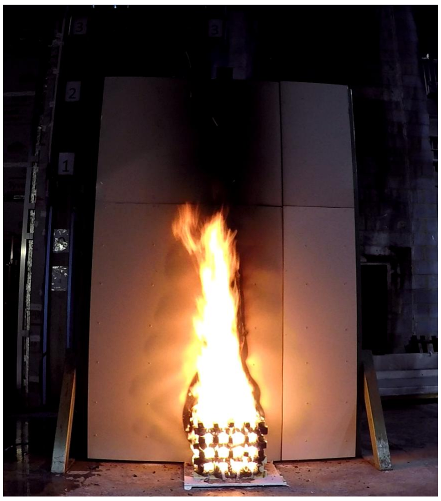
Figure D38 – ACM A2 panels installed on the experimental rig

Figure D39 shows photographs during the fire exposure at specified times.

5 minutes from ignition



10 minutes from ignition



20 minutes from ignition

25 minutes from ignition

Figure D39 – Photographs during the fire at 5, 10, 20 and 25 minutes from ignition

No significant falling debris or burning droplets were observed during the experimental fire. A discoloration of the panels was observed in the area of direct flame exposure.

The aluminium face started to delaminate from the core in the direct flame impingement location. Local buckling and distortion could be observed on the panels.

No significant vertical or horizontal flame spread on the surface of the ACM A2 panels was recorded.

Figure D40 shows the heat release rate as a function of time during the fire exposure, including the contribution from the fire source. Based on the original crib calibrations and measured values from the calorimetry it is assumed that the peak heat release rate for the crib alone is approximately 300 (±20) kW. It can therefore be concluded that the ACM A2 had a negligible contribution to fire growth.

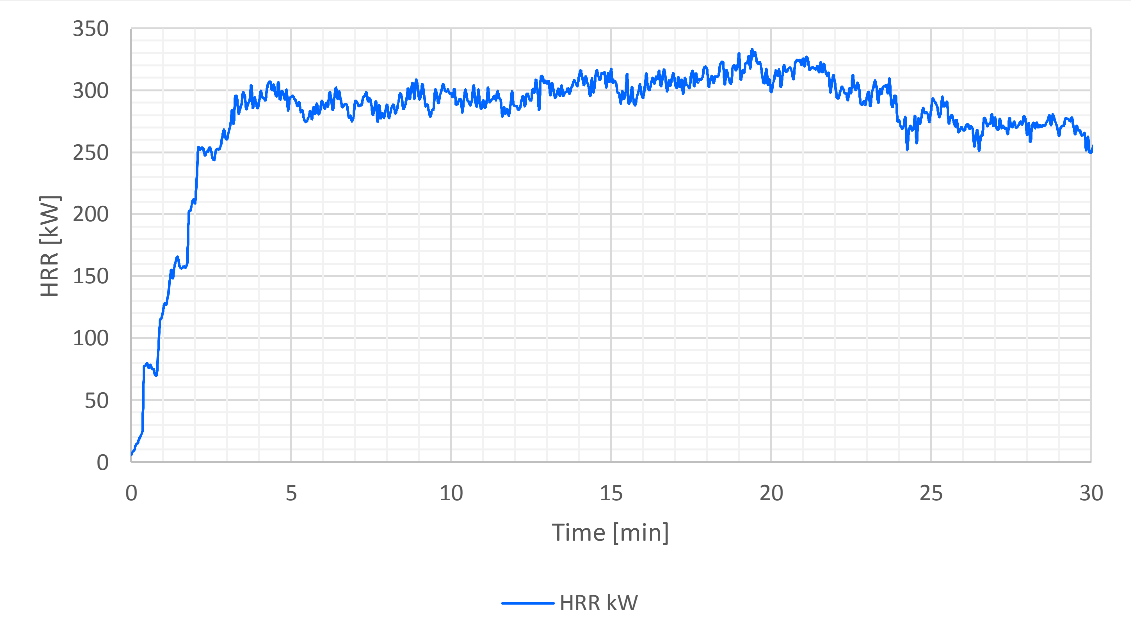


Figure D40 – Heat release measured during the experimental fire for ACM A2 material including the fire source

Figure D41 shows the heat flux recorded during the fire at a height of 3.0 m from the ground.

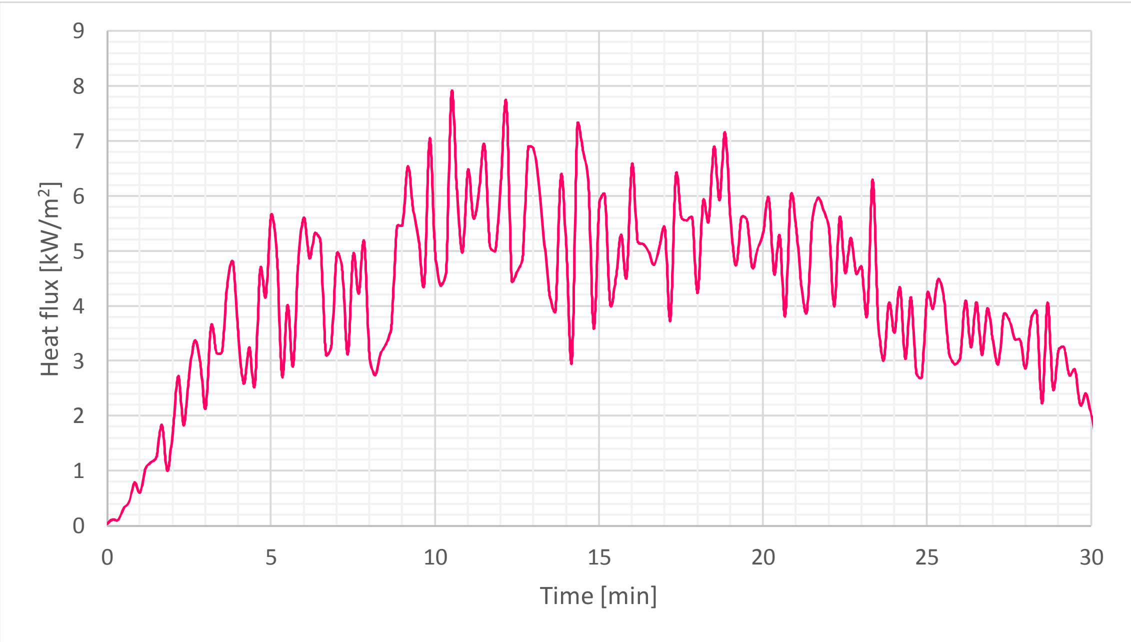


Figure D41 – Heat flux recorded during the fire at 3.0 m height

Table D13 shows the maximum external temperature, the maximum cavity temperature, the maximum temperature at 3.0 m, the time to peak heat release rate (HRR), the peak HRR, the maximum heat flux (HF) at 3.0 m and the total heat release (THR) over a period of 30 minutes.

Table D13 – Summary of different measured parameters during the experimental fire

Maximum external temp. [°C]	Maximum cavity temp. [°C]	Maximum H=3.0m Temp. [°C]	Time to peak HRR [min]	Peak HRR [kW]	Maximum H=3.0m Heat flux [kW/m²]	THR [MJ]
706	140	176	19.4	333	8	504

A summary of the visual observations is presented in Table D14.

Table D14 – Visual observations during the experimental fire

Burning droplets	Burn through (30 min)	Time to burn through [min]	Area consumed [m²]	Vertical flame spread	Horizontal flame spread
No	No	N/A	≈0.25	No	No

Figure D42 shows the sample after the fire. The ACM A2 panels were consumed locally in the zone of direct flame impingement. Discoloration and distortion could be observed on the surface of the panels. Smoke damage and discoloration could be observed up the top of the rig.

Figure D42 – Post fire observations

D3.5.2.4 ACM calibration fire 4 with ACM FR

The fourth ACM calibration fire was carried out with an aluminium composite material with a FR core (ACM FR). Figure D43 shows the material installed on the rig ready for the experiment. One vertical joint and one horizontal joint of approximately 10 mm were provided within the installation process as shown in Figure D43.

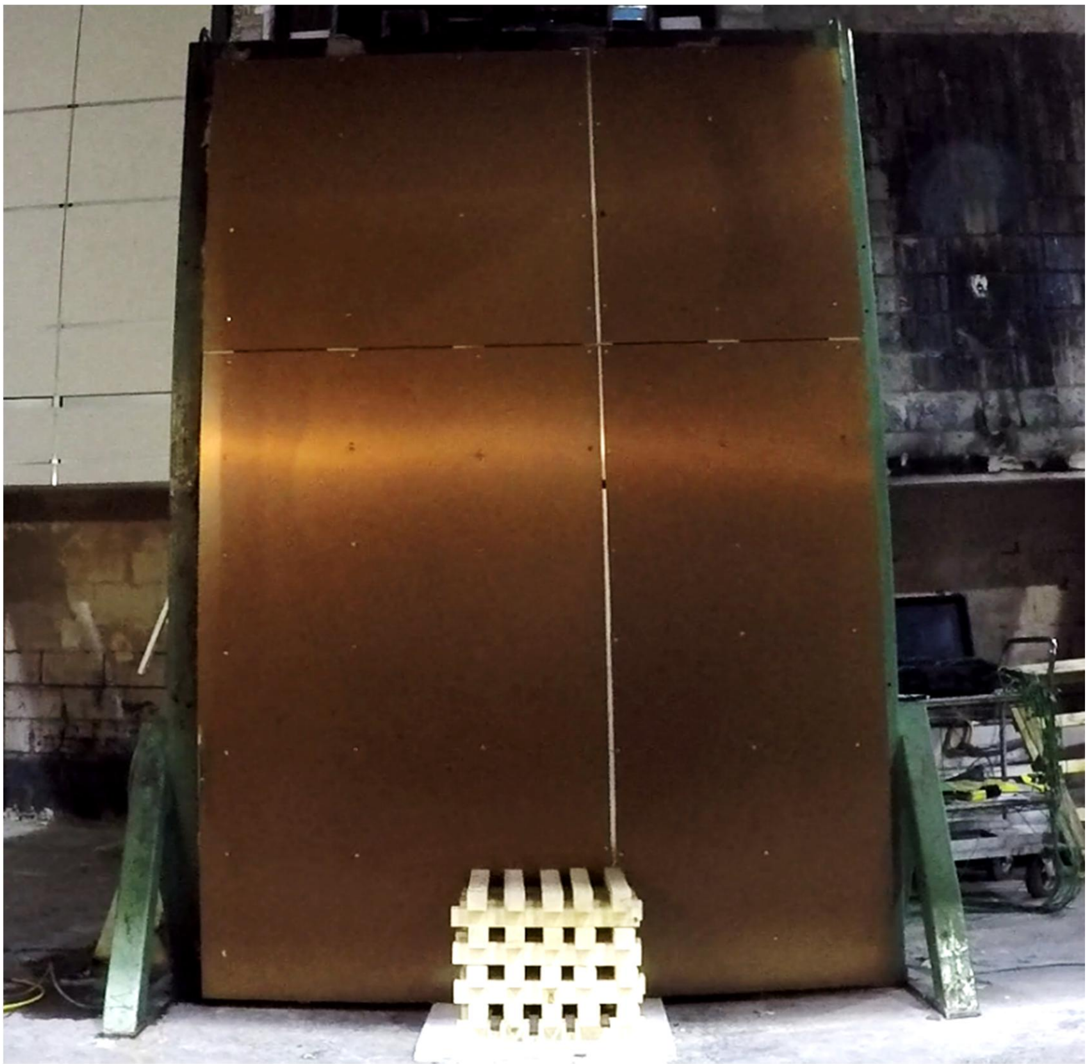
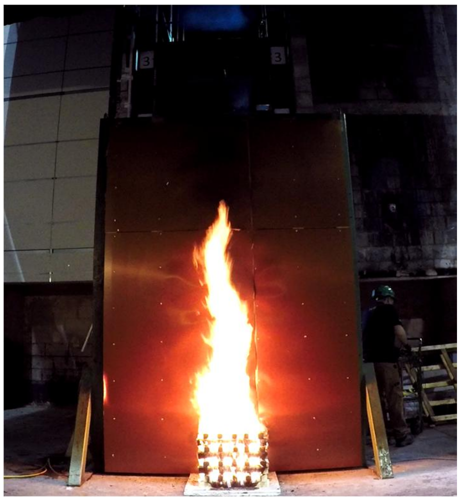


Figure D43 – ACM FR panels installed on the experimental rig

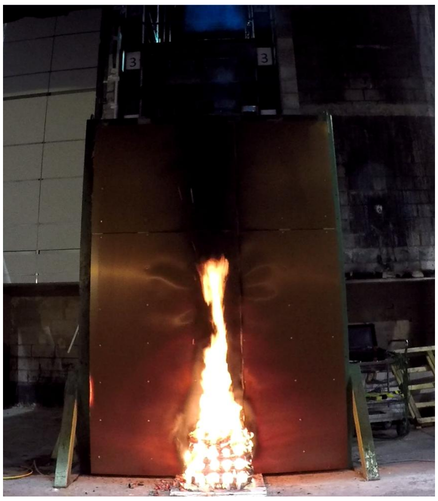
Figure D44 shows photographs during the fire exposure at specified times.

5 minutes from ignition



10 minutes from ignition

20 minutes from ignition



25 minutes from ignition

Figure D44 – Photographs during the fire at 5, 10, 20 and 25 minutes from ignition

No significant falling debris or burning droplets were observed during the experimental fire. A discoloration of the panels was observed in the area of direct flame exposure. The ACM FR panels were distorted and buckled in the area of direct flame impingement.

No significant vertical or horizontal flame spread on the surface of the ACM FR panels was recorded.

During the 30 minutes experiment no cavity fire was observed.

Figure D45 shows the heat release rate as a function of time during the fire exposure, including the fire source. Based on the original crib calibrations and the measured values from the calorimetry, it is assumed that the peak heat release rate for the crib alone is approximately 300 (±20) kW. It can therefore be concluded that the ACM FR had a limited contribution to fire growth.

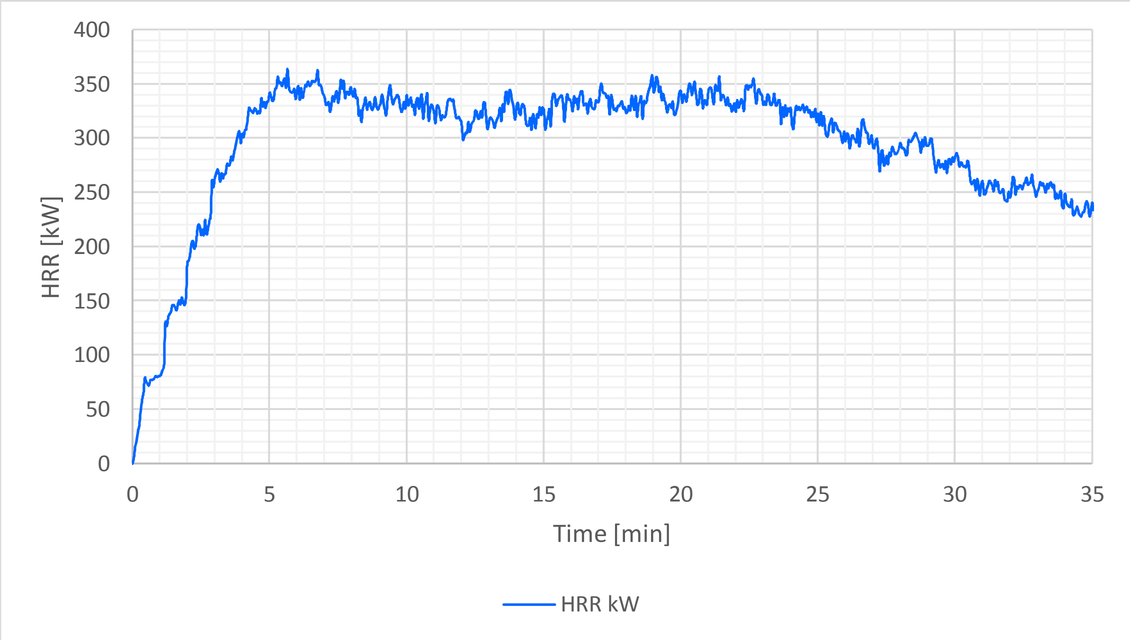


Figure D45 – Heat release measured during the experimental fire for ACM FR material including the contribution of the fire source

Figure D46 shows the heat flux recorded during the fire at a height of 3.0 m from the ground.

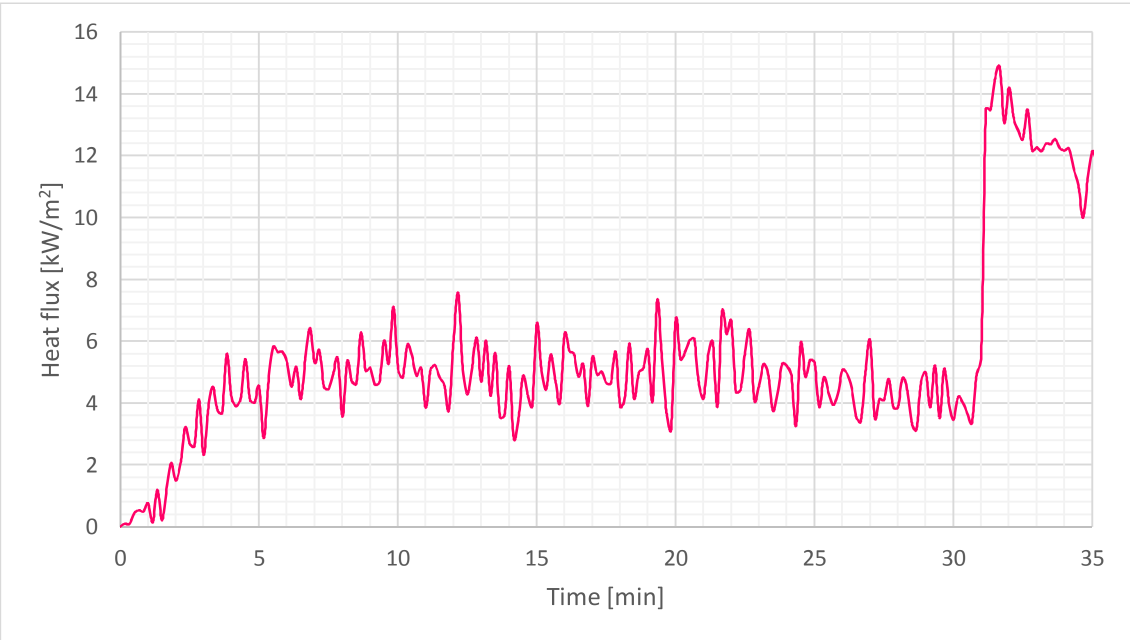


Figure D46 – Heat flux recorded during the experimental fire at 3.0 m height

Table D15 shows the maximum external temperature, the maximum cavity temperature, the maximum temperature at 3.0 m, the time to peak heat release rate (HRR), the peak HRR, the maximum heat flux (HF) at 3.0 m and the total heat release (THR) over a period of 30 minutes.

Table D15 – Summary of different measured parameters during the experimental fire

Maximum external temp. [°C]	Maximum cavity temp. [°C]	Maximum H=3.0m Temp. [°C]	Time to peak HRR [min]	Peak HRR [kW]	Maximum H=3.0m Heat flux [kW/m^2]	THR [MJ]
854	814	164	5.7	364	14.9	549

A summary of the visual observations is presented in Table D16.

Table D16 – Visual observations during the experimental fire

Burning droplets	Burn through	Time to burn through [min]	Area consumed [m^2]	Vertical flame spread	Horizontal flame spread
Not significant	Yes	32	≈0.36	No	No

Figure D47 shows the sample after the fire. The ACM FR panels were consumed locally in the zone of direct flame impingement. Discoloration, smoke damage and distortion could be observed on the surface of the panels up to the top of the rig mainly in the central area. Next to the fire source the ACM FR panels were consumed locally, and the fire breached into the cavity at 32 minutes.

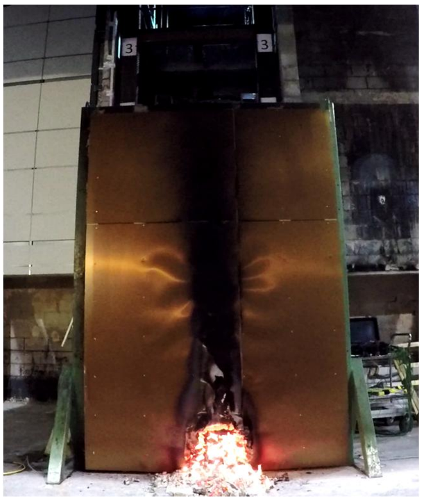


Figure D47 – Post fire observations

D3.5.2.5 ACM calibration fire 5 with ACM A2

The fifth ACM calibration fire was carried out with an aluminium composite material with A2 core (ACM A2). Figure D48 shows the material installed on the rig prior to the experimental fire. One vertical joint and one horizontal joint of approximately 10 mm were provided within the installation process as shown in Figure D48.

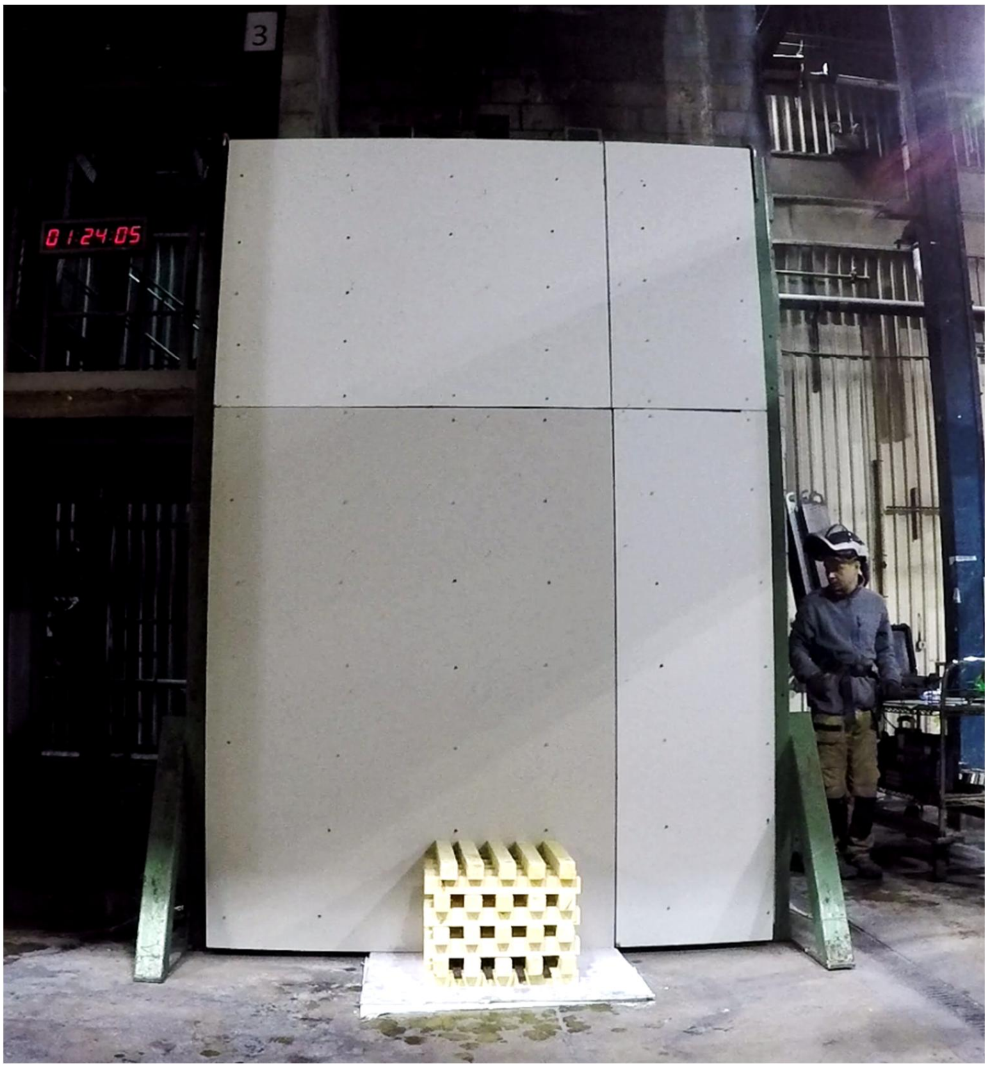
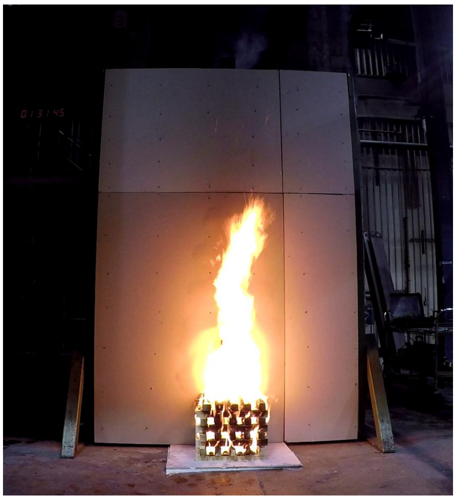


Figure D48 – ACM A2 panels installed on the experimental rig

Figure D49 shows photographs during the fire exposure at specified times.



5 minutes from ignition

10 minutes from ignition

20 minutes from ignition

25 minutes from ignition

Figure D49 – Photographs during the fire at 5, 10, 20 and 25 minutes after ignition

No significant falling debris or burning droplets were observed during the experimental fire. A discoloration of the panels was observed in the area of direct flame exposure. Local buckling and distortion could be observed on the panels.

The aluminium external face of the panel was consumed in the area of direct flame exposure. In some localised areas the fire penetrated the ACM A2 panel.

No significant vertical or horizontal flame spread on the surface of the ACM A2 panels was recorded.

Figure D50 shows the heat release rate as a function of time during the fire exposure, including the fire source. Based on the original crib calibrations and measured values from the calorimetry, it is assumed that the peak heat release rate for the crib alone is approximately 300 (±20) kW. It can therefore be concluded that the ACM A2 had a negligible contribution to fire growth.

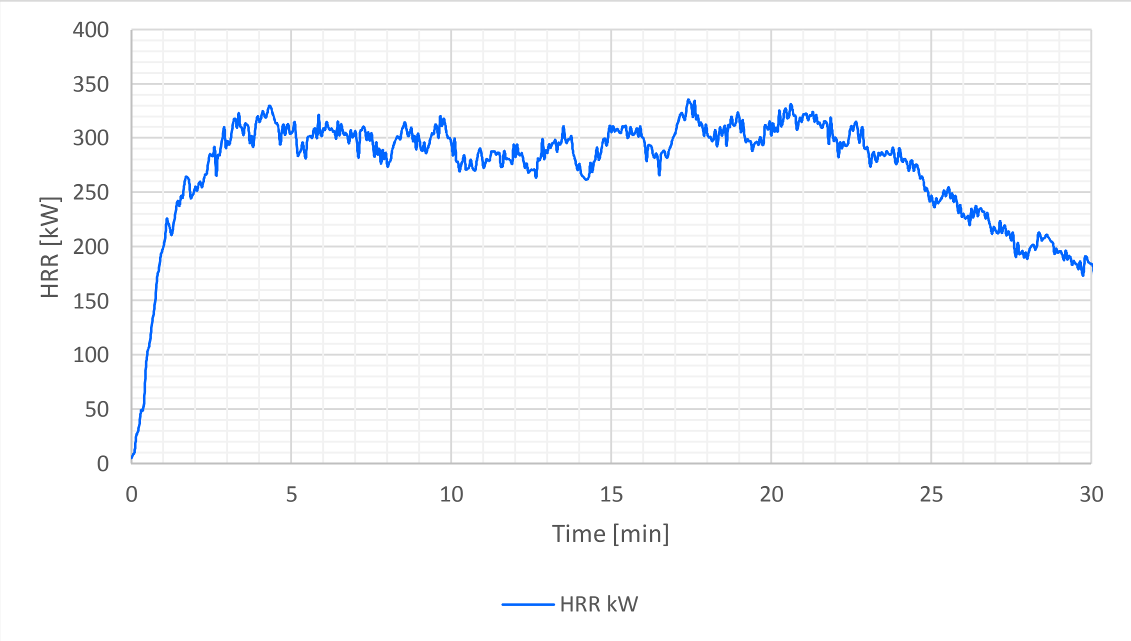


Figure D50 – Heat release measured during the fire for ACM A2 material including the fire source

Figure D51 shows the heat flux recorded during the experimental fire at a height of 3.0 m from the ground.

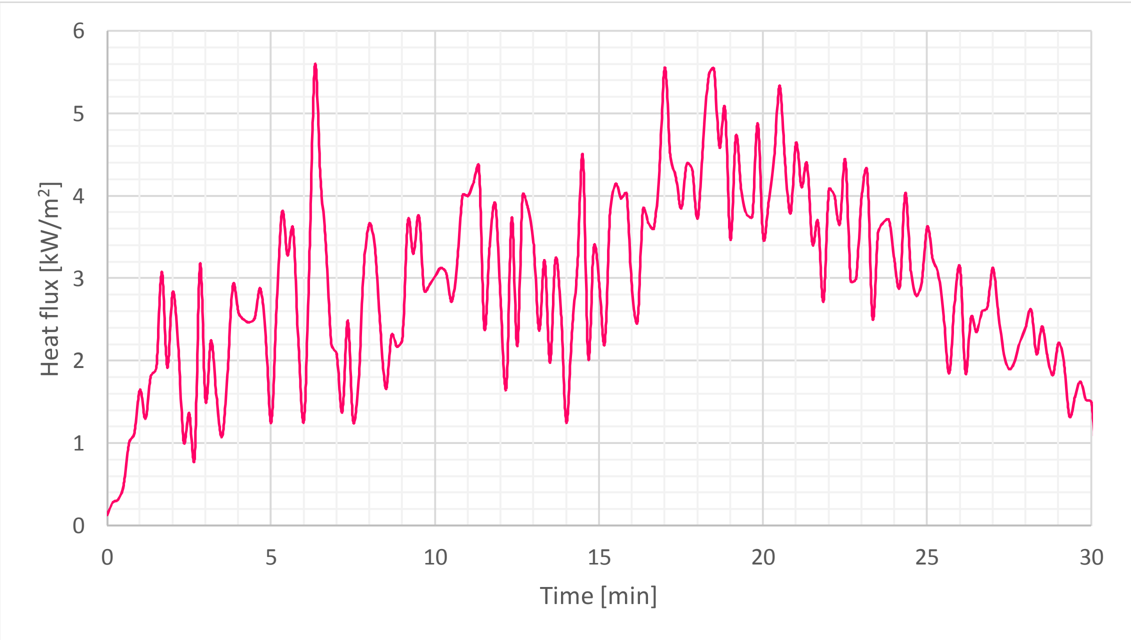


Figure D51 – Heat flux recorded during the fire at 3.0 m height

Table D17 shows the maximum external temperature, the maximum cavity temperature, maximum temperature at 3.0 m, time to peak heat release rate (HRR), peak HRR, maximum heat flux (HF) at 3.0 m and total heat release (THR) over a period of 30 minutes.

Table D17 – Summary of different measured parameters during the experimental fire

Maximum external temp. [°C]	Maximum cavity temp. [°C]	Maximum H=3.0m Temp. [°C]	Time to peak HRR [min]	Peak HRR [kW]	Maximum H=3.0m Heat flux [kW/m^2]	THR [MJ]
883	262	134	17.4	336	5.6	494

A summary of the visual observations is presented in Table D18.

Table D18 – Visual observations during the experimental fire

Burning droplets	Burn through (30 min)	Time to burn through [min]	Area consumed [m^2]	Vertical flame spread	Horizontal flame spread
No	No	N/A	≈0.21	No	No

Figure D52 shows the sample after the fire. The ACM A2 panels were consumed locally in the zone of direct flame impingement. Discoloration and distortion can be observed on the surface of the panels. Smoke damage and discoloration can be observed up the top of the rig.


Figure D52 – Post fire observations

D3.5.2.6 ACM calibration fire 6 with ACM PE

The sixth ACM calibration fire was carried out with aluminium composite material with PE core (ACM PE). Figure D53 shows the material installed on the rig ready for experiment. One vertical joint and one horizontal joint of approximately 10 mm were provided within the installation process as shown in Figure D53.

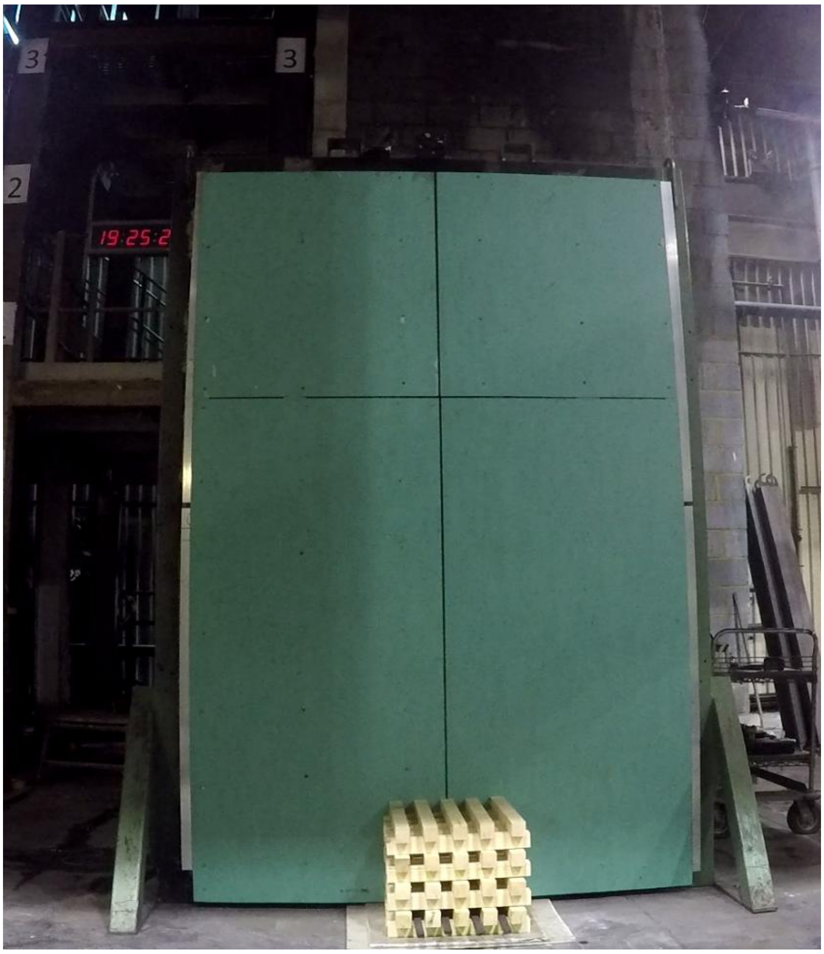
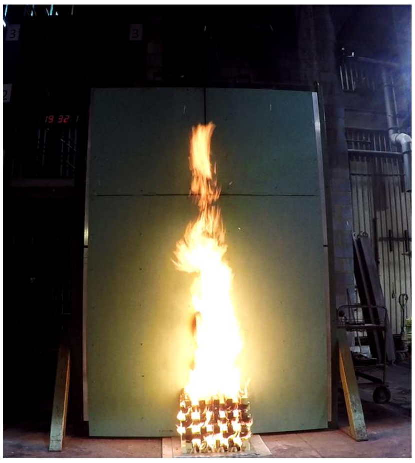
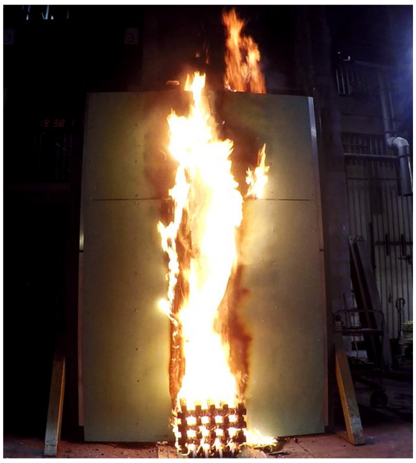


Figure D53 – ACM PE panels installed on the rig

Figure D54 shows photographs during the fire exposure at specified times.



5 minutes from ignition



10 minutes from ignition

15 minutes from ignition

20 minutes from ignition

Figure D54 – Photographs during the fire at 5, 10, 15 and 20 minutes from ignition

Flames were observed in the cavity between 5 minutes and 6 minutes after ignition. After 6 minutes a chimney effect was formed in the cavity and continuous flaming was observed at the top of the rig. At this stage, molten plastic accumulated at the bottom of the rig creating a pool fire. After approximately 8 minutes the flame height above the rig was between 1.8 m and 2.0 m. Sustained flaming could be observed inside the cavity and on the outer surface of the panels.

After 10 minutes, the fire started to spread laterally involving more material. The ACM PE panels were consumed in the central flame axis from bottom to the top of the rig. In the central area, all the T-shaped aluminium rails were consumed due to the high temperatures. Falling debris and burning droplets were observed during the experimental fire. At the end of the experiment, most of the ACM PE panels were consumed.

Figure D55 shows the heat release rate as a function of time during the fire exposure, including the fire source. Given the nominal peak heat release rate for the crib of 300 (±20) kW, then the peak contribution of the panel is approximately four to five times that of the fire source.

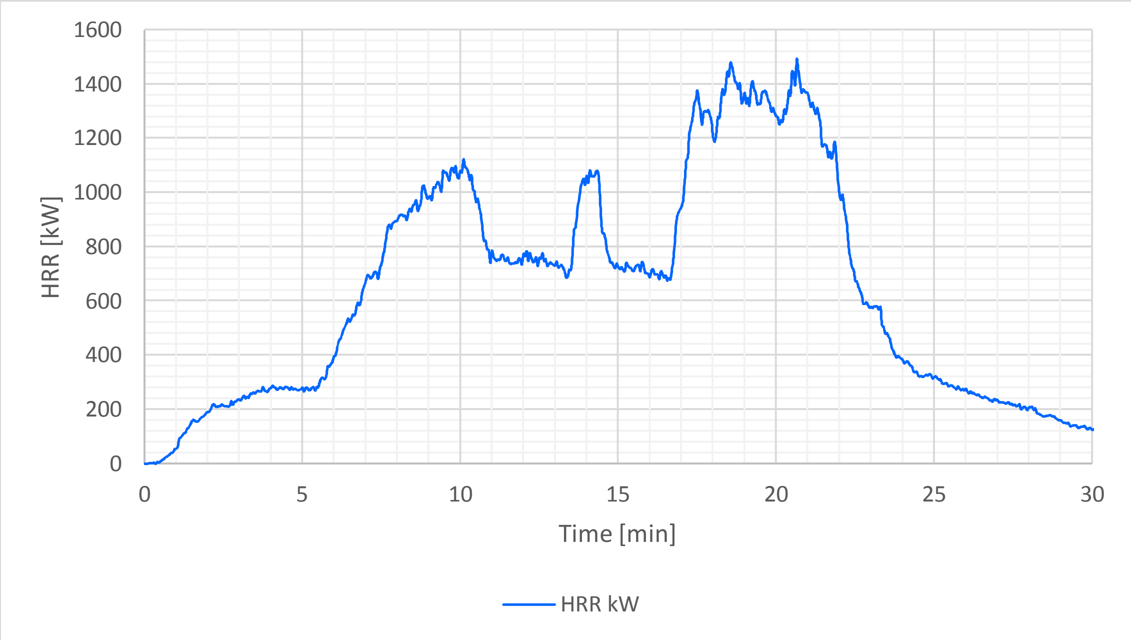


Figure D55 – Heat release measured during the fire for ACM PE material including the fire source

Figure D36 shows the heat flux recorded during the fire at a height of 3.0 m from the ground. The maximum range of the heat flux meter of 100 kW/m^2 was reached 5.8 minutes into the experimental fire.

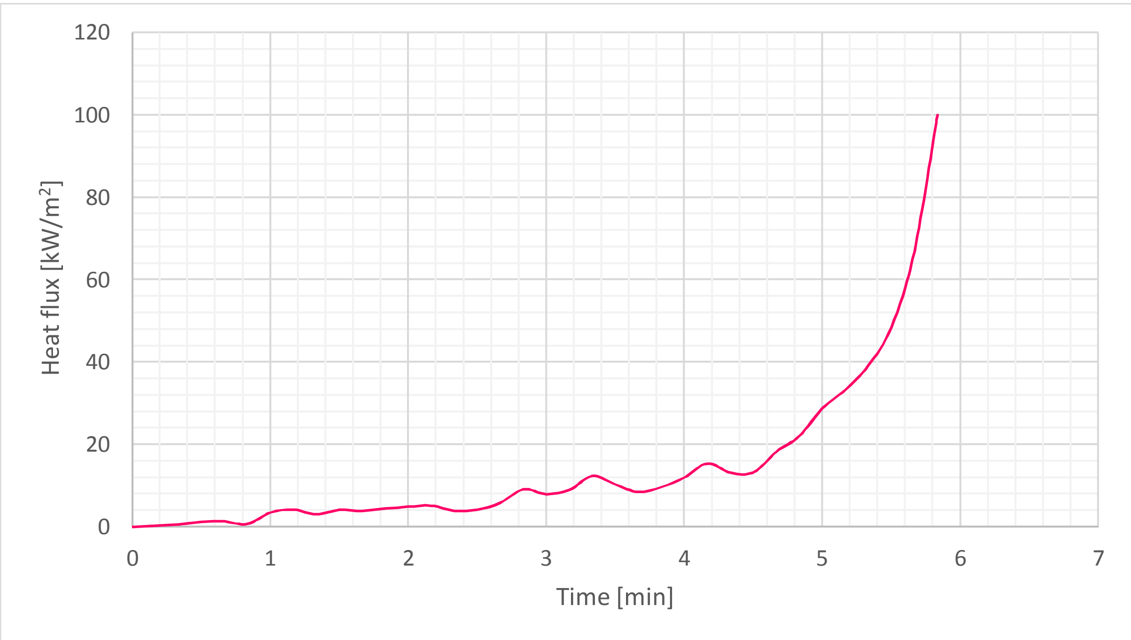


Figure D56 – Heat flux recorded during the fire at 3.0 m height

Table D19 shows the maximum external temperature, the maximum cavity temperature, the maximum temperature at 3.0 m, the time to peak heat release rate (HRR), the peak HRR, the maximum heat flux (HF) at 3.0 m and the total heat release (THR) over a period of 30 minutes.

Table D19 – Summary of different measured parameters during the experimental fire

Maximum external temp. [°C]	Maximum cavity temp. [°C]	Maximum H=3.0m Temp. [°C]	Time to peak HRR [min]	Peak HRR [kW]	Maximum H=3.0m Heat flux [kW/m^2]	THR [MJ]
867	996	456	20.6	1492	>100	1158

A summary of the visual observations is presented in Table D20.

Table D20 – Visual observations during the experimental fire

Burning droplets	Burn through (30 min)	Time to burn through [min]	Area consumed [m^2]	Vertical flame spread	Horizontal flame spread
Significant including pool fire	Yes	4	≈5.9	Yes	Yes

Figure D57 shows the remaining sample after the fire exposure. The ACM PE panels were mostly consumed. Fragments of the aluminium faces can be observed hanging on the remaining rails. An unconsumed strip of approximately 100 mm of ACM PE can be observed on the left-hand top side of the rig.

Figure D57 – Post fire observations

D4 Summary of results and discussion

All of the ACM materials (PE, FR and A2) were experimentally examined in identical conditions using a consistent fire source, fixing positions and panel gaps. The only difference between experiments was the location of the joints between panels which were dependent on the panel sizes of material supplied. The impact of varying the joint location in the experiments has not been systematically examined as there was insufficient material. This is an area that would require further work in the future.

Figure D58 shows a comparison between the HRR measured in the two experiments of the ACM PE configuration. The heat outputs in the two experiments carried out are similar and significantly exceed the contribution from the crib ignition source of 300 kW +/-20 kW. It can be concluded that the ACM PE panels made a significant contribution to the heat release rate during this experiment.

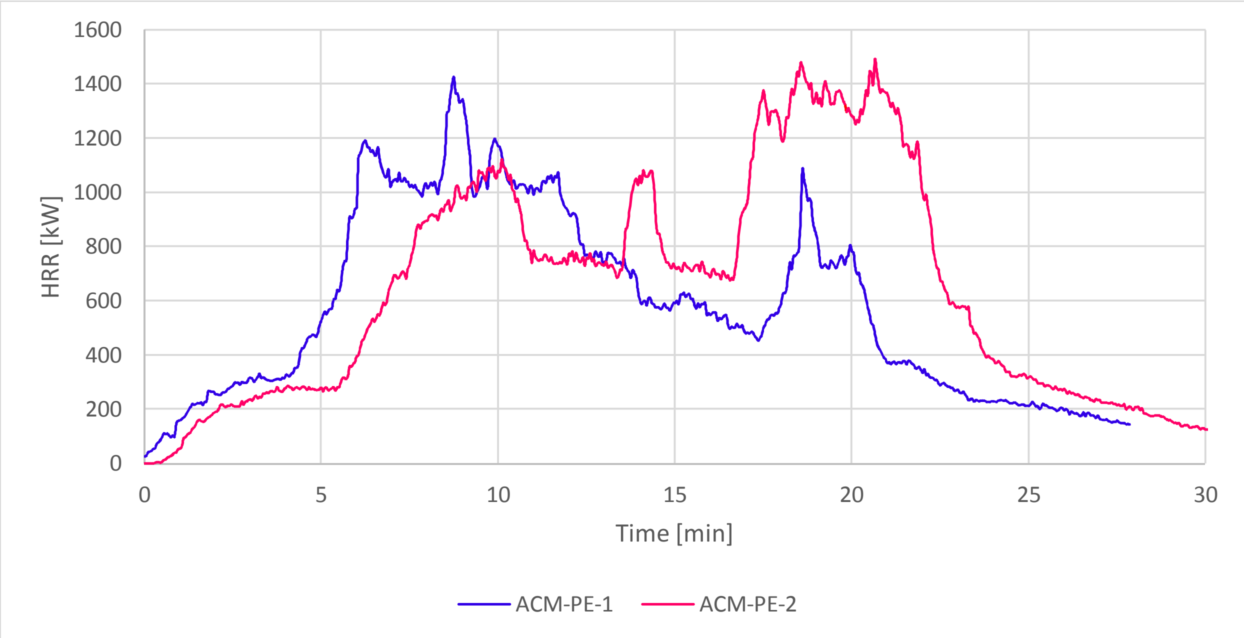


Figure D58 – Comparison between the measured HRR for the two ACM PE fires

Figure D59 shows a comparison between the HRR measured in the two experiments of the ACM FR configuration. The measured heat release rates in the two experiments carried out are similar. Given that the crib contribution of 300 (±20) kW, it can be concluded that the ACM FR panels made a limited contribution to the measured heat release rates during the experiments.

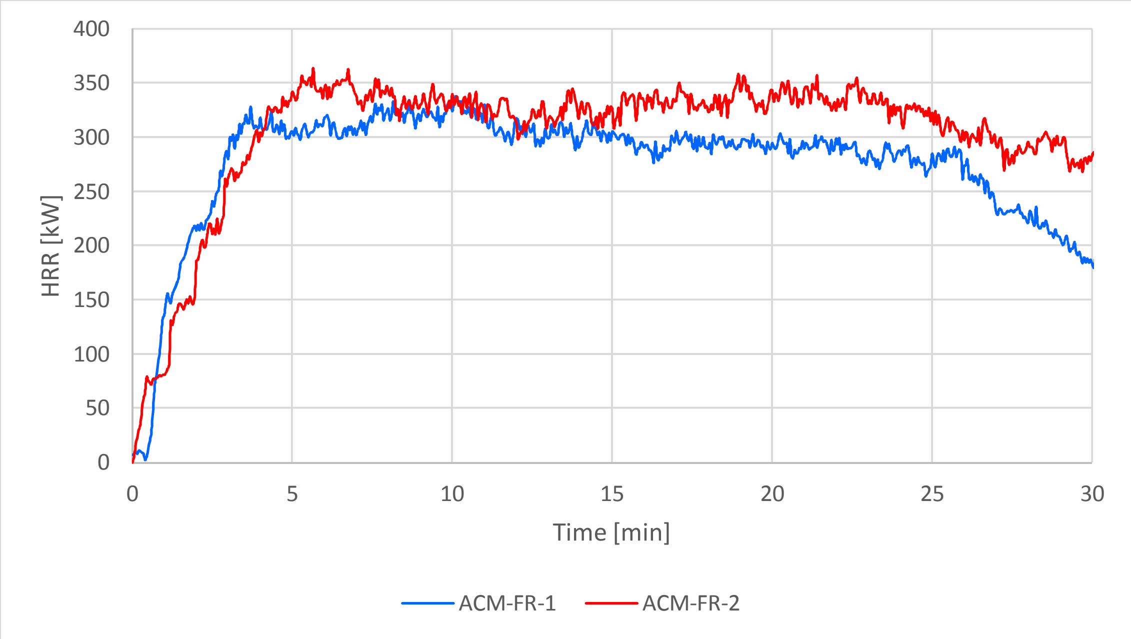


Figure D59 – Comparison between the HRR of two ACM FR experimental fires

Figure D60 shows a comparison between the HRR measured in the two experiments of the ACM A2 configuration. The results clearly show that the ACM A2 panels made a negligible contribution to the hear release rates measured during the experiments.

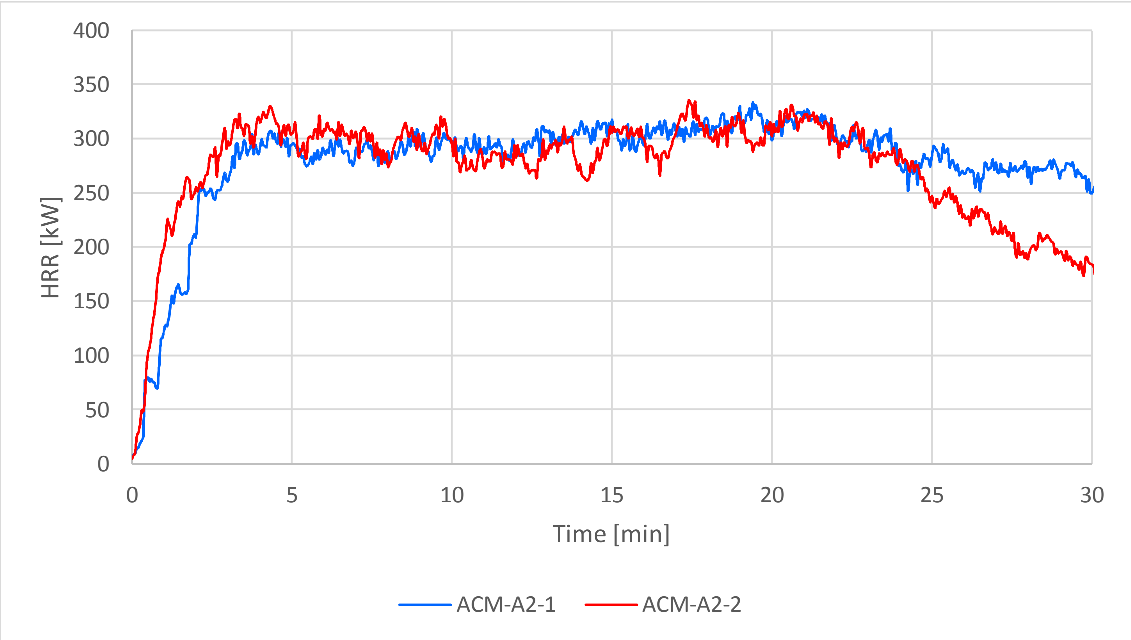


Figure D60 – Comparison between the measured HRR of two ACM A2 experimental fires

Figure D61 shows a comparison between all the samples including the calibration burns of the crib in the two different scenarios. It can be observed that ACM A2 and ACM FR do not exceed a peak HRR measured value of 400 kW. For the ACM PE samples, the peak HRR measured value is 1400 kW, showing a significant contribution and difference in relation to burning characteristics when exposed to fire.

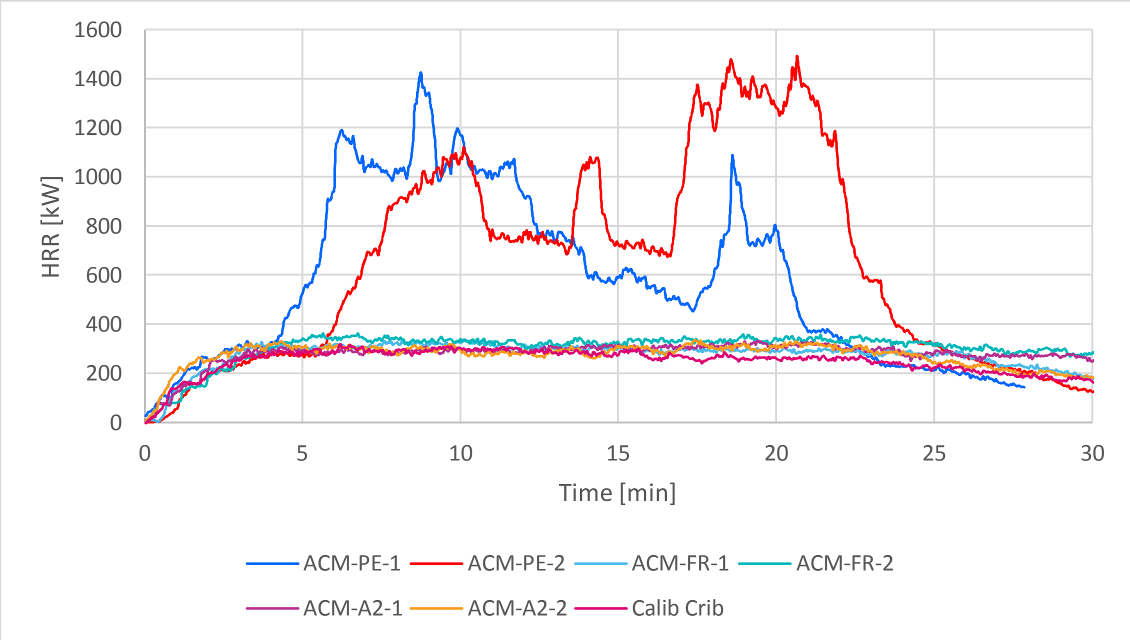


Figure D61 – HRR comparison between all the calibration samples

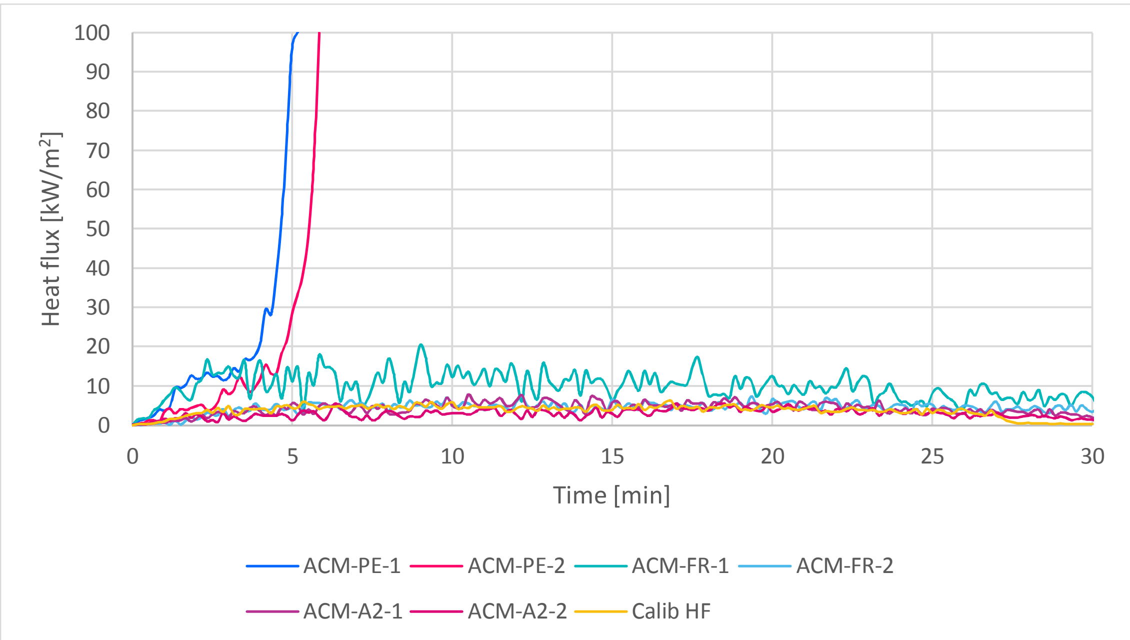


Figure D62 – Comparison between all heat fluxes measured for each sample including calibration

Figure D62 shows a comparison between all the heat fluxes measured for all the samples including the values measured during the calibrations using non-combustible calcium silicate board. ACM A2 and ACM FR did not exceed a measured peak heat flux of 20 kW/m^2.

For both of the ACM PE samples, the peak heat flux measured (maximum achievable with the instrument) was 100 kW/m^2 in less than 6 minutes.

Figure D63 shows a comparison of the total heat release (MJ) during the 30 minutes period for all the samples including the wood crib (on its own). The results for ACM PE calibration fires 1 and 2 show that the samples released a significantly greater amount of heat over the 30 minute experimental period than any of the other materials or the crib ignition source. The ACM FR and ACM A2 have comparable results and show a limited or no significant contribution in relation with the crib ignition source. A comparison of the heat fluxes measured for the samples including the calibration heat fluxes show a similar pattern of behaviour.

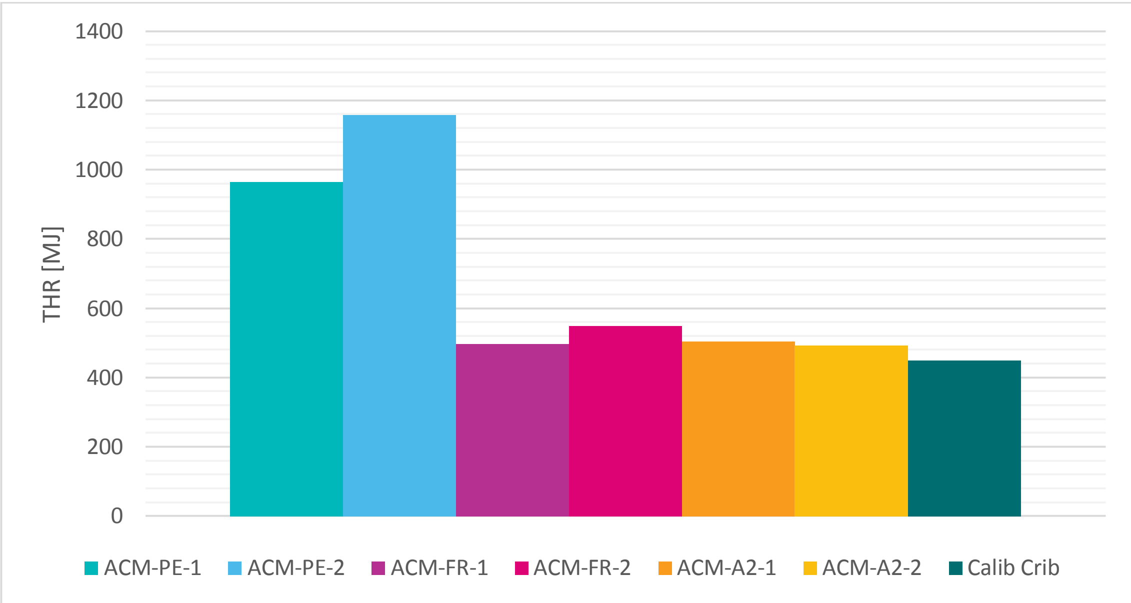


Figure D63 – Total heat release measured for all samples

A summary of the parameters measured during the experiments is shown in Table D21.

Table D21 – Summary of different measured parameters during the experiments

Sample	Maximum external temp. [°C]	Maximum cavity temp. [°C]	Maximum H=3.0m Temp. [°C]	Time to peak HRR [min]	Peak HRR [kW]	Maximum H=3.0m Heat flux [kW/m^2]	THR [MJ]
ACM-PE-1	944	1003	656	8.7	1425	>100	964
ACM-PE-2	867	996	456	20.6	1492	>100	1158
ACM-FR-1	975	1017	198	10.1	338	20.5	497
ACM-FR-2	854	814	164	5.7	364	14.9	549
ACM-A2-1	706	140	176	19.4	333	8.0	504
ACM-A2-2	883	262	134	17.4	336	5.6	494

A summary of the visual observations during the experiments is presented in Table D22.

Table D22 – Summary of the visual observations during the experiments

Sample	Burning droplets	Burn through (30 min)	Time to burn through [min]	Area consumed [m^2]	Vertical flame spread	Horizontal flame spread
ACM-PE-1	Significant including pool fire	Yes	2	≈5.1	Yes	Yes
ACM-PE-2	Significant including pool fire	Yes	4	≈5.9	Yes	Yes
ACM-FR-1	Not significant	Yes	22	≈0.5	No	No
ACM-FR-2	Not significant	Yes	32	≈0.36	No	No
ACM-A2-1	No	No	N/A	≈0.25	No	No
ACM-A2-2	No	No	N/A	≈0.21	No	No

D5 Next stage

The next stage of the project was to carry out the non-ACM experimental material fires.

D6 References for Appendix D

1 British Standards Institution BS 8414-1: 2015 + A1: 2017, Fire performance of external cladding systems – Part 1: Test method for non-loadbearing external cladding systems applied to the masonry face of a building, BSI London, 2015.

2 British Standards Institution BS 8414-2: 2015 + A1: 2017, Fire performance of external cladding systems – Part 2: Test method for non-loadbearing external cladding systems fixed to and supported by a structural steel frame, BSI London, 2015.

3 McGrattan K, Klein B, Hostikka S, Floyd J - Fire Dynamics Simulator (Version 5) User's Guide, NIST Special Publication 1019-5, Fire Research Division, Building and Fire Research Laboratory in cooperation with VTT Building and Transport, Finland, National Institute of Standards and Technology, USA, 8 January 2008.

4 K, Hostikka S, McDermott R, Floyd J, Weinschenk C and Overholt K, Fire Dynamics Simulator Technical Reference Guide, Volume 3: Validation, NIST Special Publication 1018-3, Fire Research Division, Building and Fire Research Laboratory in cooperation with Aalto University, Finland, Jensen Hughes, USA and Continuum Analytics, USA, National Institute of Standards and Technology, USA, 18 January 2017.

5 McGrattan K, Hamins A, Hostikka S, Floyd J, Klein B - Fire Dynamics Simulator (Version 5) Verification & Validation Guide - Volume 1. Verification Fire Research Division, Building and Fire Research Laboratory in cooperation with VTT Building and Transport, Finland, National Institute of Standards and Technology, USA, 30 May 2007.

6 NUREG-1824, Verification and Validation of Selected Fire Models for Nuclear Power Plant Applications, Volume 1, 2007.

7 Kristopher J O, Verification and Validation of Commonly Used Empirical Correlations for Fire Scenarios, NIST Special Publication 1169, USA.

8 British Standards Institution PD 7974-1, Application of fire safety engineering principles to the design of buildings. Initiation and development of fire within the enclosure of origin (Sub-system 1), BSI London, 2019.

9 British Standards Institution BS EN 13823:2010 + A1: 2014, Reaction to fire tests for building products. Building products excluding floorings exposed to the thermal attack by a single burning item, BSI London, 2010.

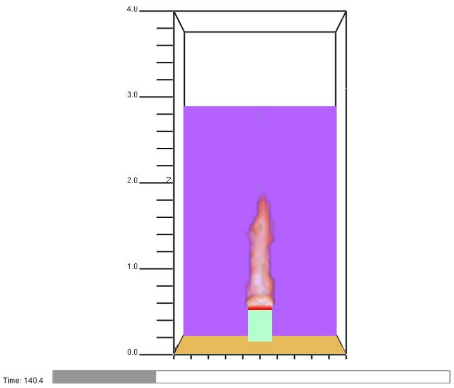
10 ISO 24473, Fire tests. Open calorimetry. Measurement of the rate of production of heat and combustion products for fires of up to 40 MW, ISO, 2008.

11 British Standards Institution BS EN ISO 1716, Reaction to fire tests for products. Determination of the gross heat of combustion (calorific value), BSI London, 2018.

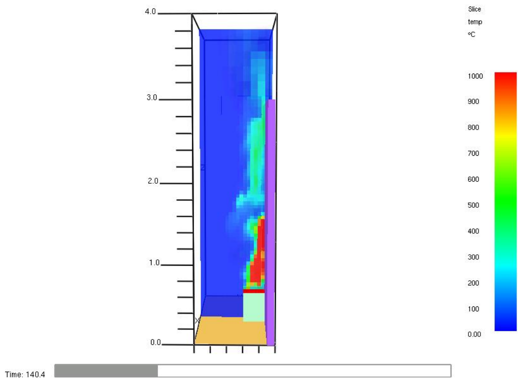
Appendix D1 CFD preliminary findings for gas burner

Gas burner positioned against the rig

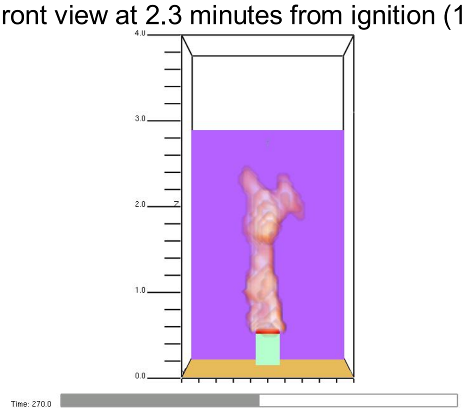
The findings presented for the gas burner positioned against the experimental rig are as follows. Figure D64 presents snapshots capturing flame heights at different times.



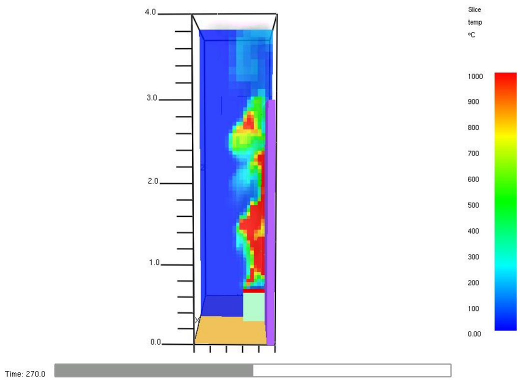
Front view at 2.3 minutes from ignition (100 kW)



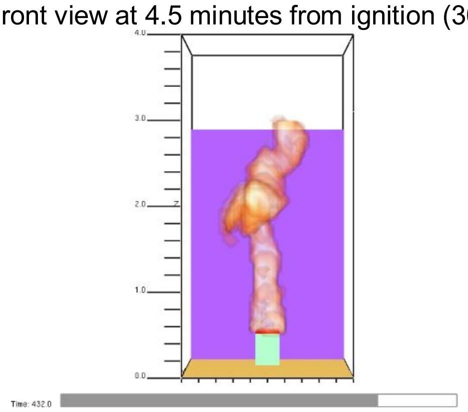
Section at 2.3 minutes from ignition (100 kW)



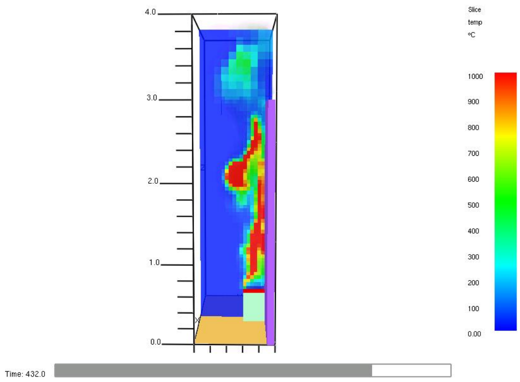
Front view at 4.5 minutes from ignition (300 kW)



Section at 4.5 minutes from ignition (300 kW)



Front view at 7.2 minutes from ignition (400 kW)

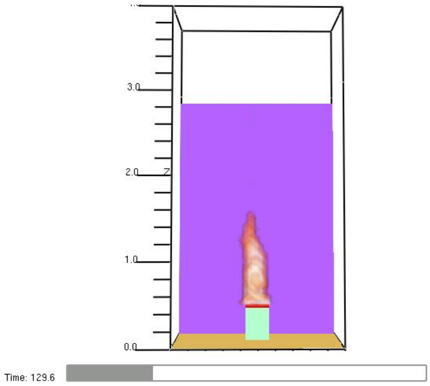


Section at 7.2 minutes from ignition (400 kW)

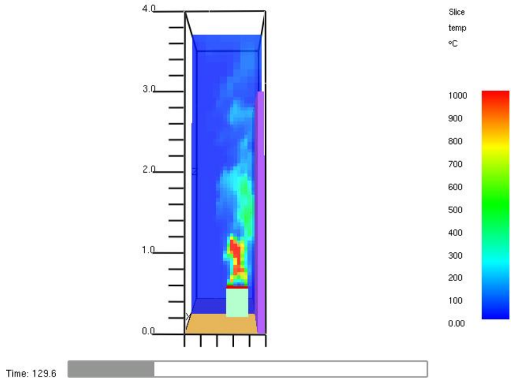
Figure D64 – Snapshots for 100 kW, 300 kW and 400 kW fire size (flame height on the left-hand side and temperature profile on the right-hand side)

Gas burner positioned 100 mm away from the rig

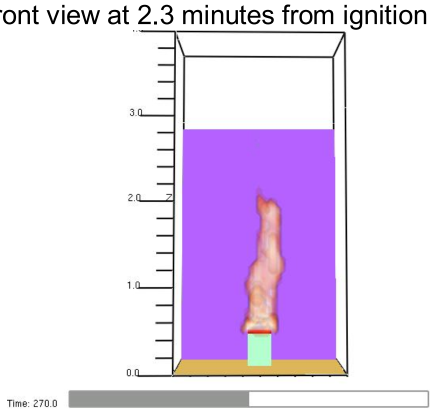
The findings presented for the gas burner positioned 100 mm away from the experimental rig are as follows. Figure D65 presents snapshots capturing the fire development at different times.



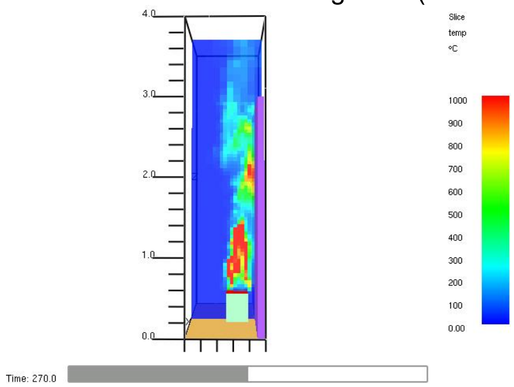
Front view at 2.3 minutes from ignition (100 kW)



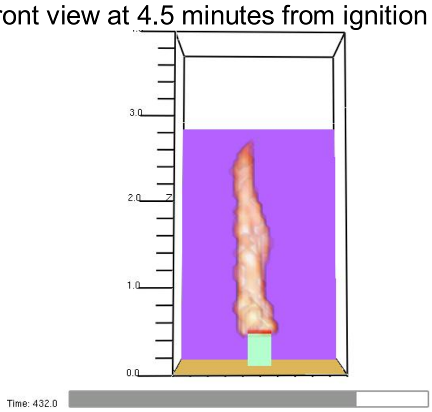
Section at 2.3 minutes from ignition (100 kW)



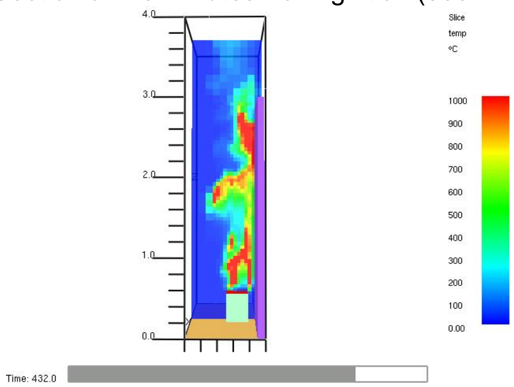
Front view at 4.5 minutes from ignition (300 kW)



Section at 4.5 minutes from ignition (300 kW)



Front view at 7.2 minutes from ignition (400 kW)



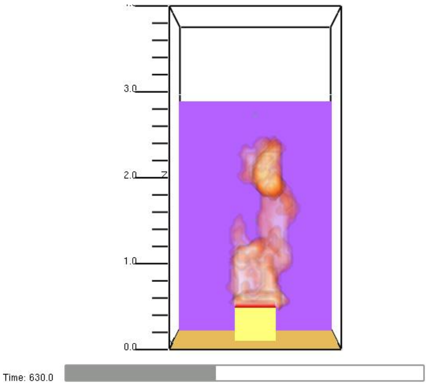
Section at 7.2 minutes from ignition (400 kW)

Figure D65 – Snapshots for 100k W, 300 kW and 400 kW fire size (flame height on the left-hand side and temperature profile on the right-hand side)

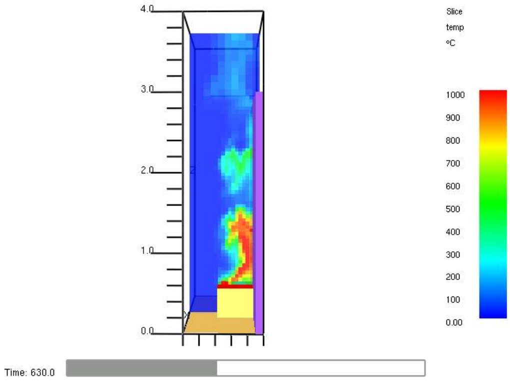
Appendix D2 CFD findings for wood crib

Wood crib located against the experimental rig

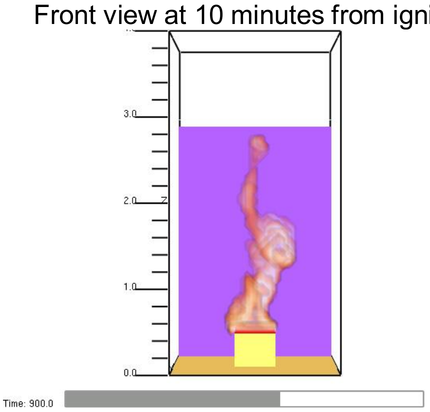
The findings presented for the wood crib positioned against the experimental rig are as follows. Figure D66 presents snapshots capturing fire development at specified times.



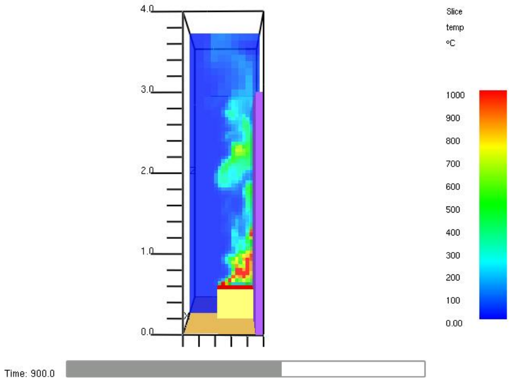
Front view at 10 minutes from ignition



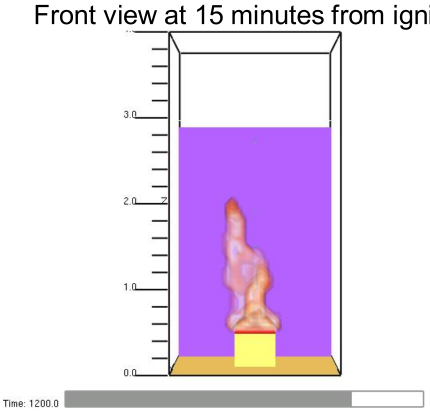
Section at 10 minutes from ignition



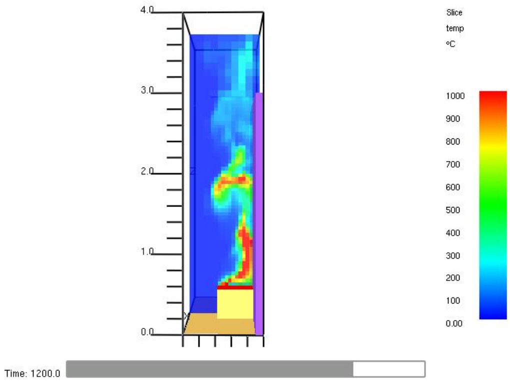
Front view at 15 minutes from ignition



Section at 15 minutes from ignition



Front view at 20 minutes from ignition

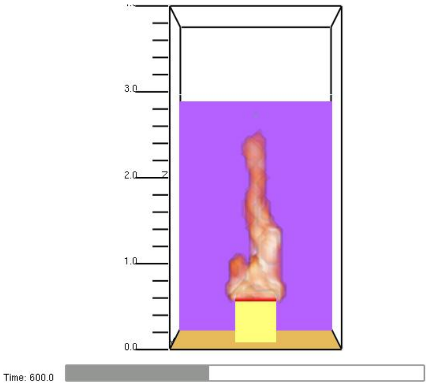


Section at 20 minutes from ignition

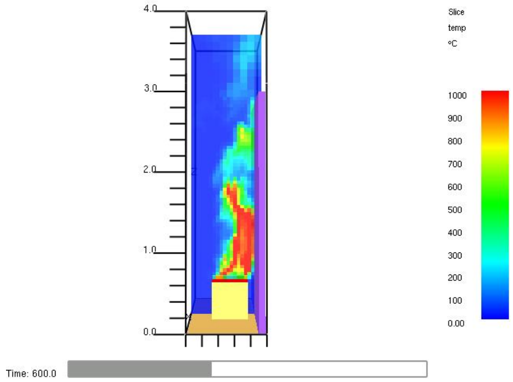
Figure D66 – Snapshots for wood crib 330 kW fire size (flame height on the left-hand side and temperature profile on the right-hand side)

Wood crib located 100 mm from the experimental rig

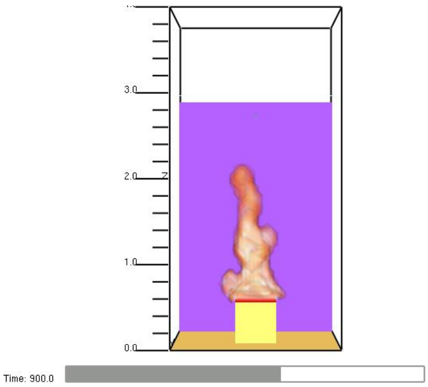
The findings presented for the wood crib positioned 100 mm from the experimental rig are as follows. Figure D67 presents snapshots capturing flame heights at different times.



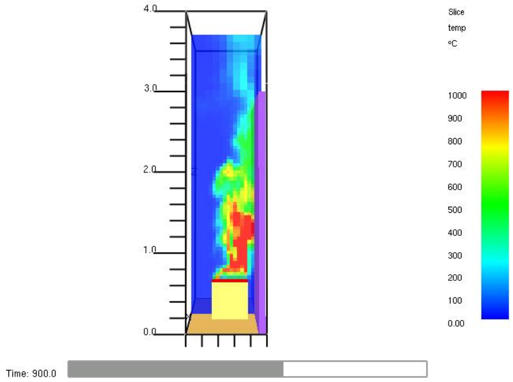
Front view at 10 minutes from ignition



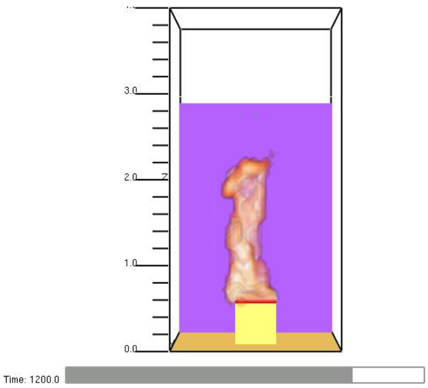
Section at 10 minutes from ignition



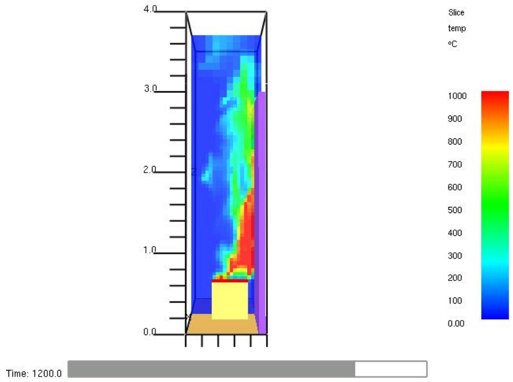
Front view at 15 minutes from ignition



Section at 15 minutes from ignition



Front view at 20 minutes from ignition



Section at 20 minutes from ignition

Figure D67 – Snapshots for wood crib 330 kW fire size (flame height on the left-hand side and temperature profile on the right-hand side)

Appendix D3 Temperature measurements for the ACM calibration fires

This appendix presents the measured external and cavity temperatures on the central axis of the experimental rig for the ACM calibration fires.

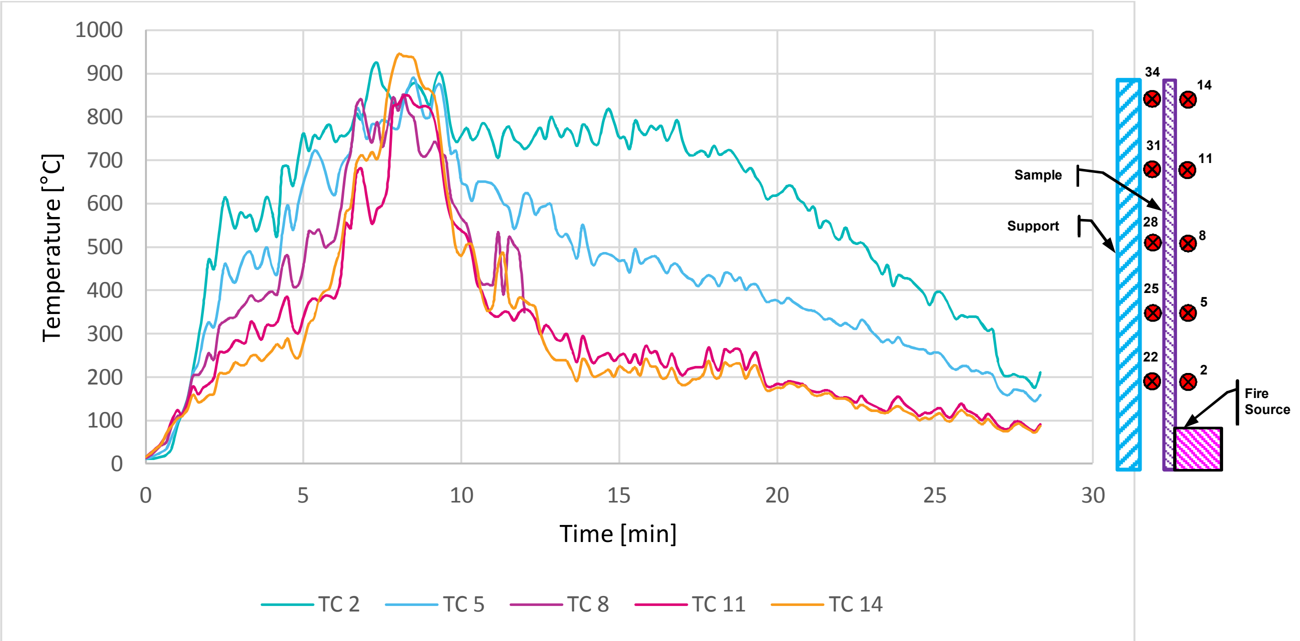


Figure D68 – Temperatures measured on the external central axis for ACM PE sample 1

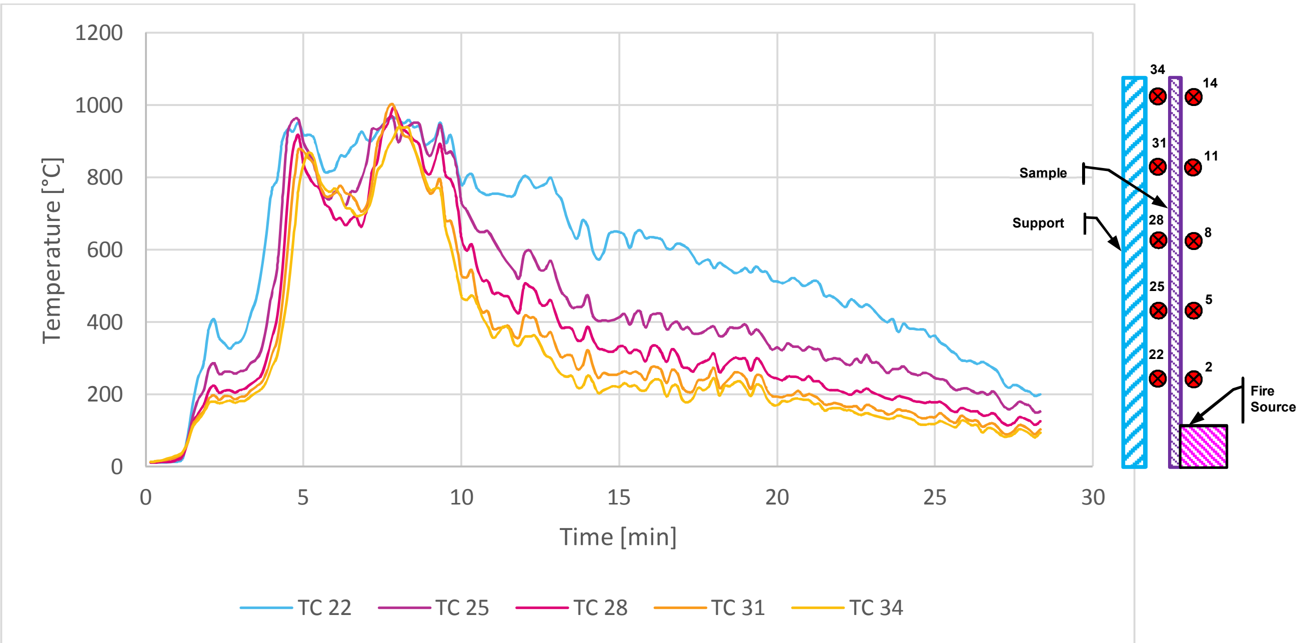


Figure D69 – Temperatures measured on the cavity central axis for ACM PE sample 1

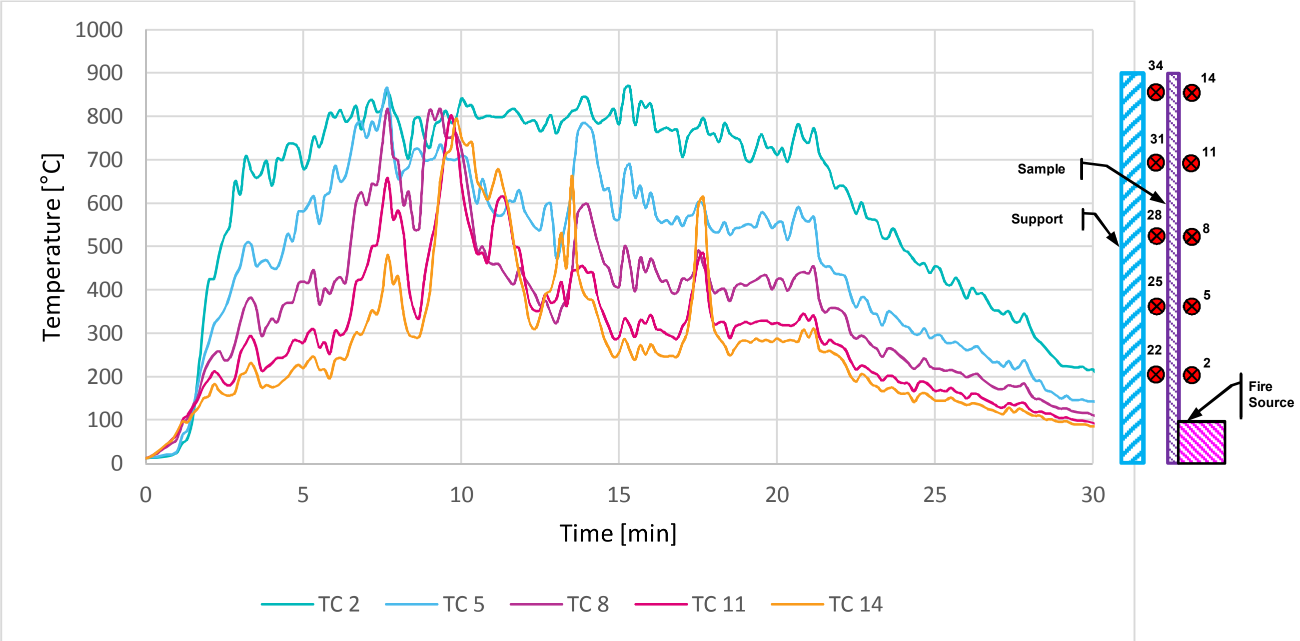


Figure D70 – Temperatures measured on the external central axis for ACM PE sample 2

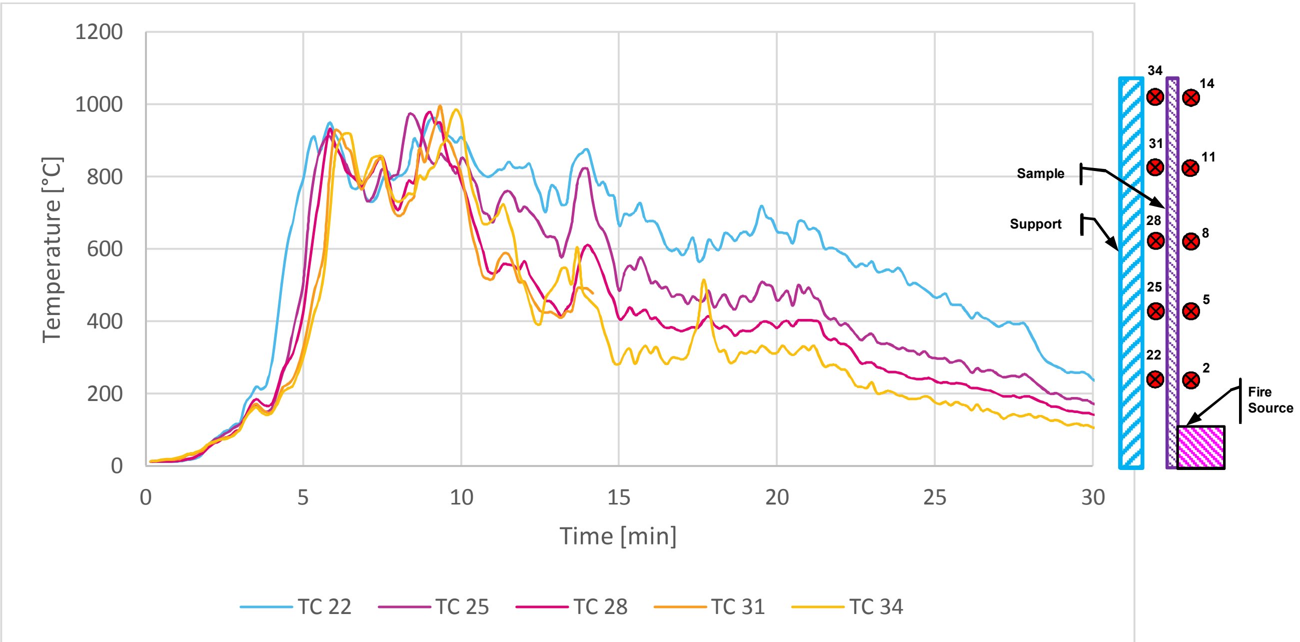


Figure D71 – Temperatures measured on the cavity central axis for ACM PE sample 2

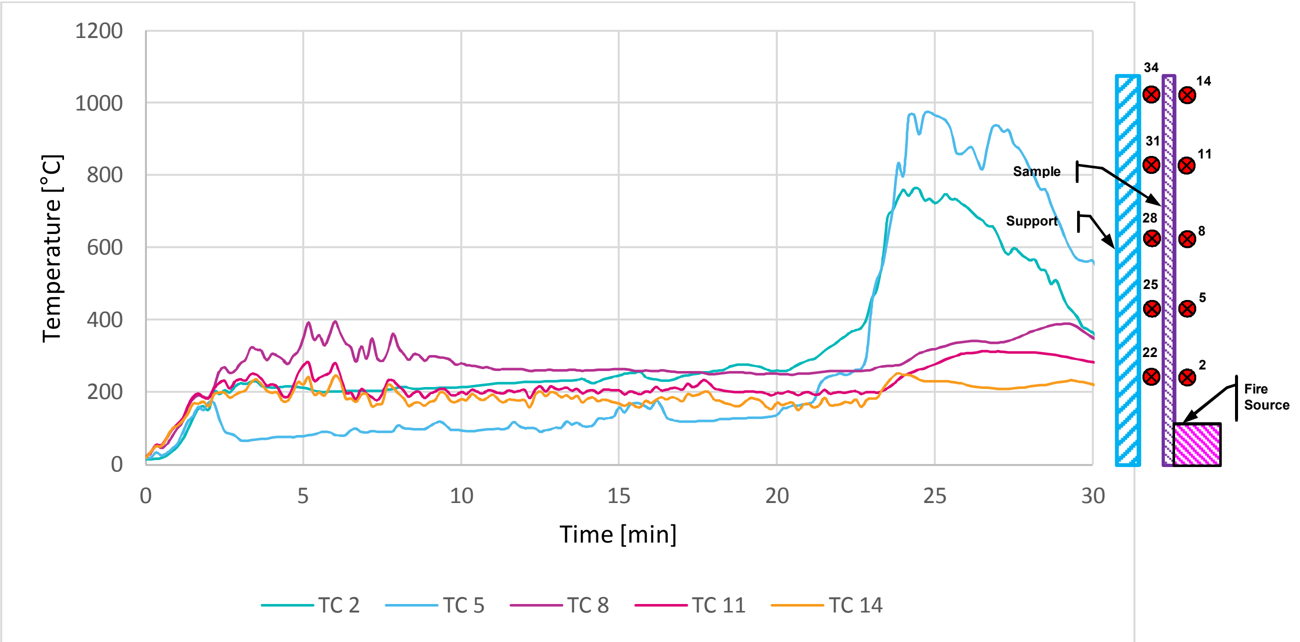


Figure D72 – Temperatures measured on the external central axis for ACM FR sample 1

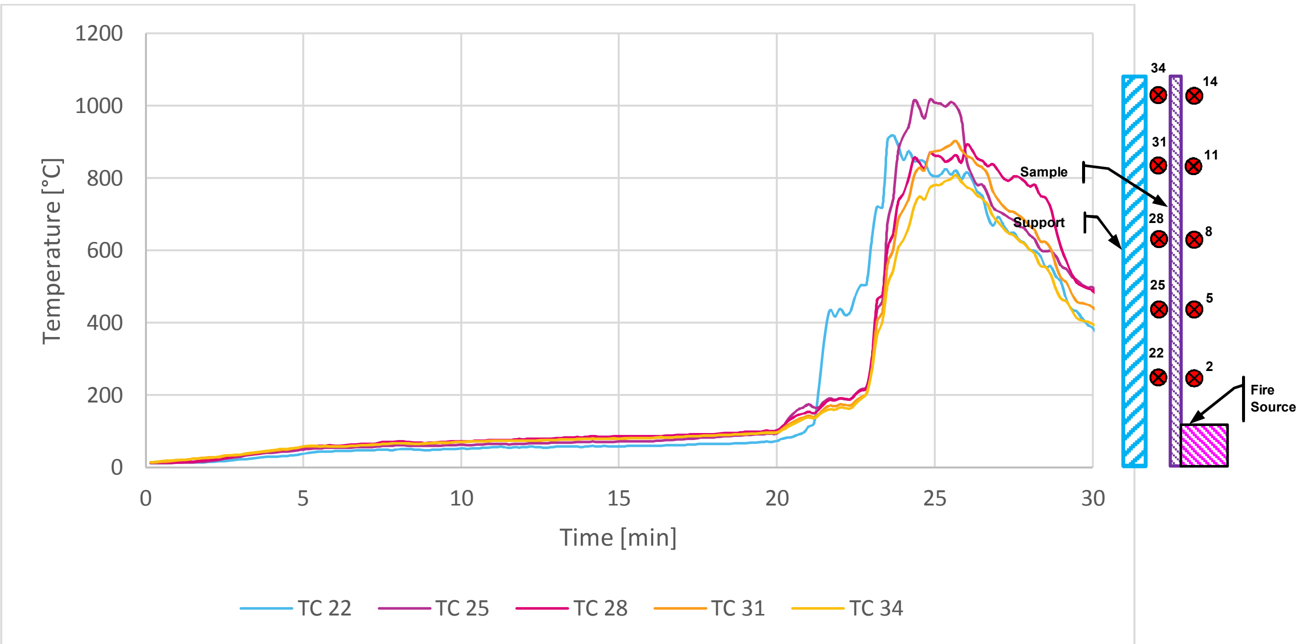


Figure D73 – Temperatures measured on the cavity central axis for ACM FR sample 1

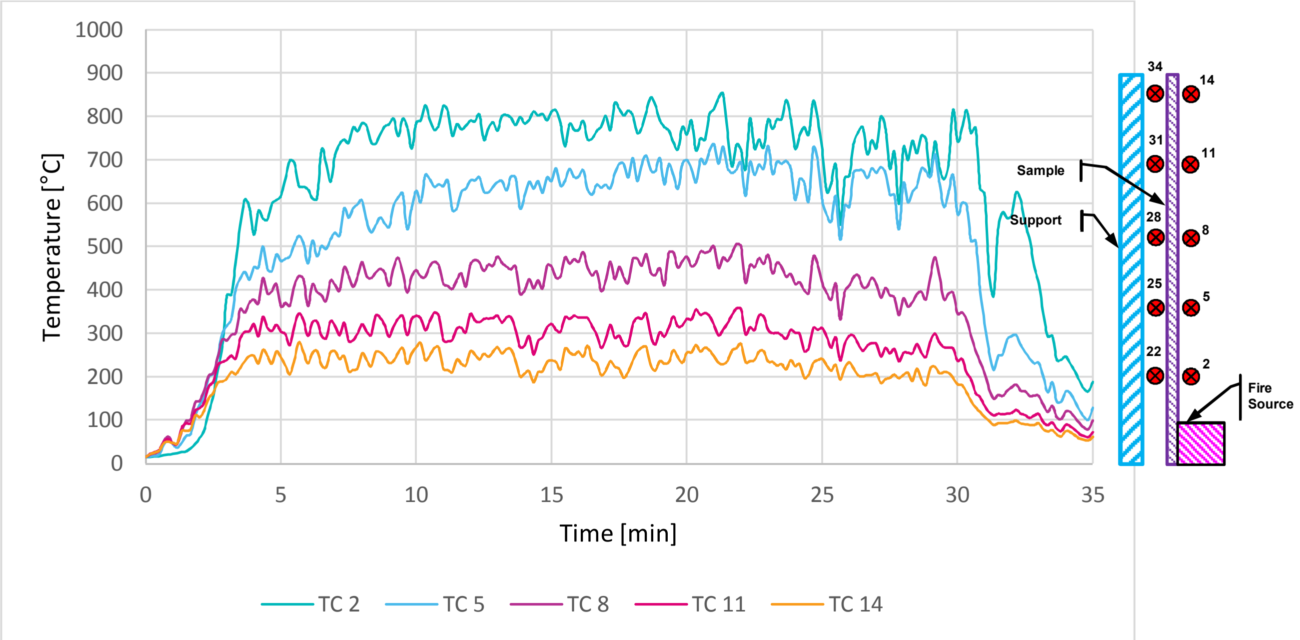


Figure D74 – Temperatures measured on the external central axis for ACM FR sample 2

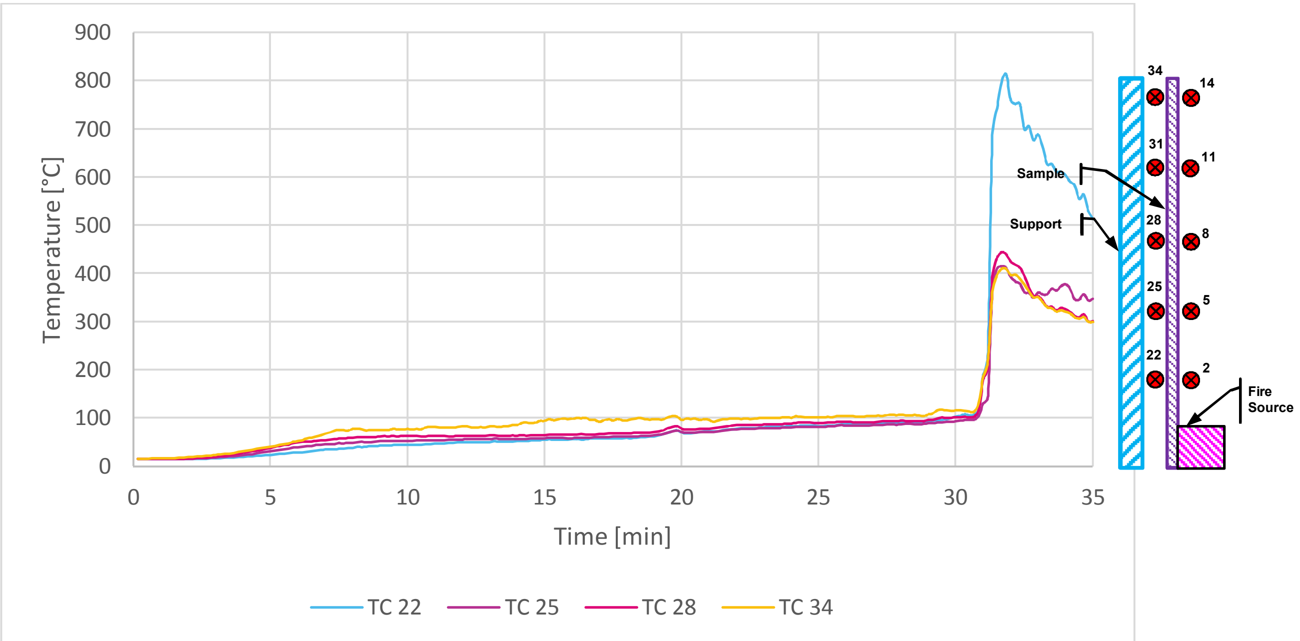


Figure D75 – Temperatures measured on the cavity central axis for ACM FR sample 2

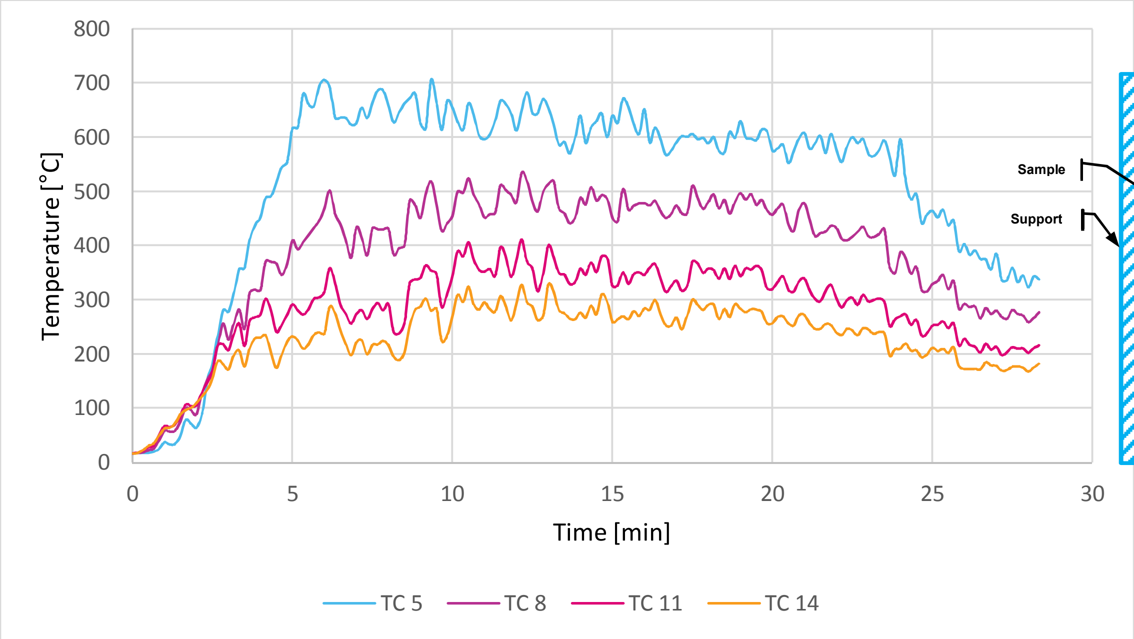


Figure D76 – Temperatures measured on the external central axis for ACM A2 sample 1

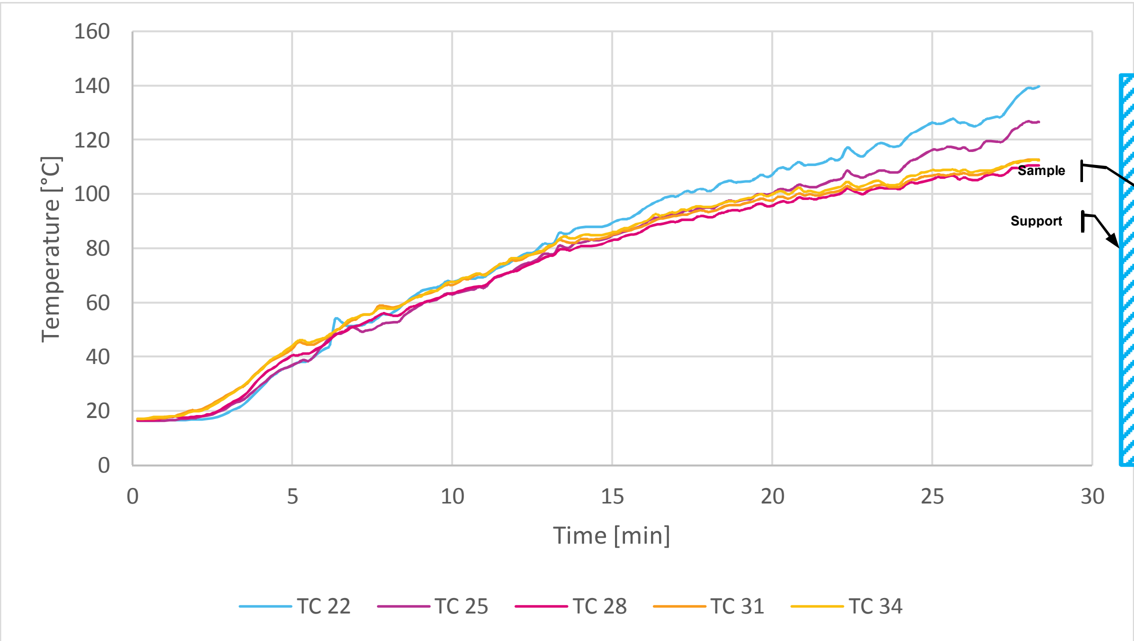


Figure D77 – Temperatures measured on the cavity central axis for ACM A2 sample 1

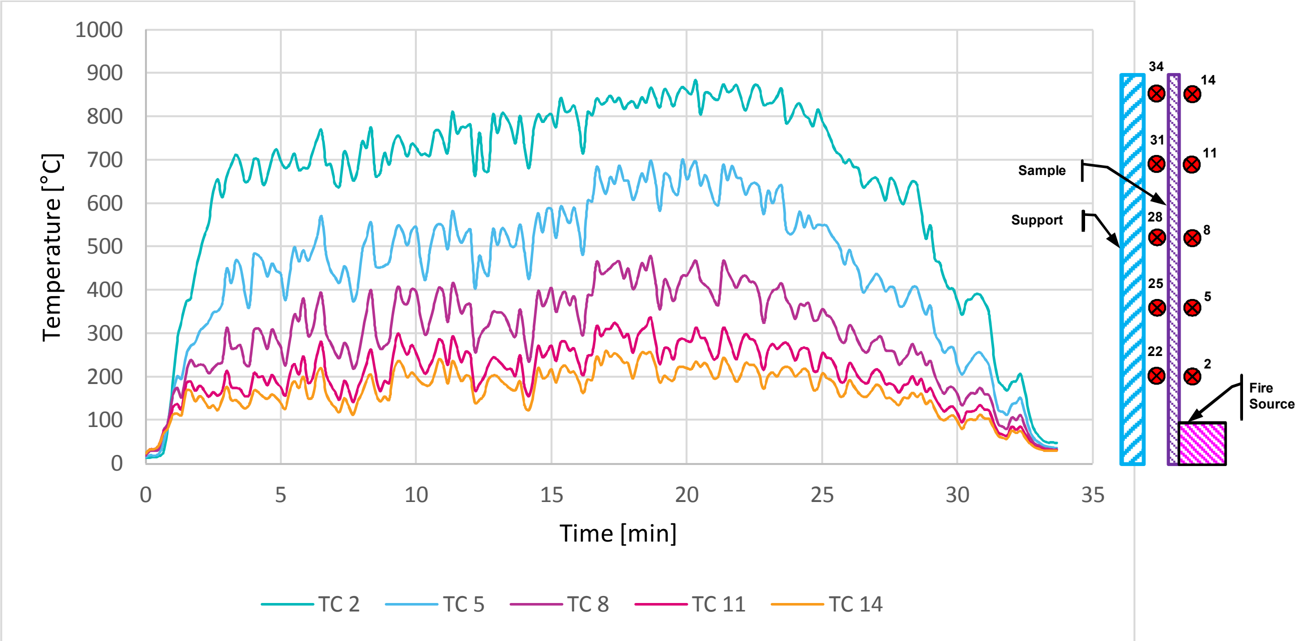


Figure D78 – Temperatures measured on the external central axis for ACM A2 sample 2

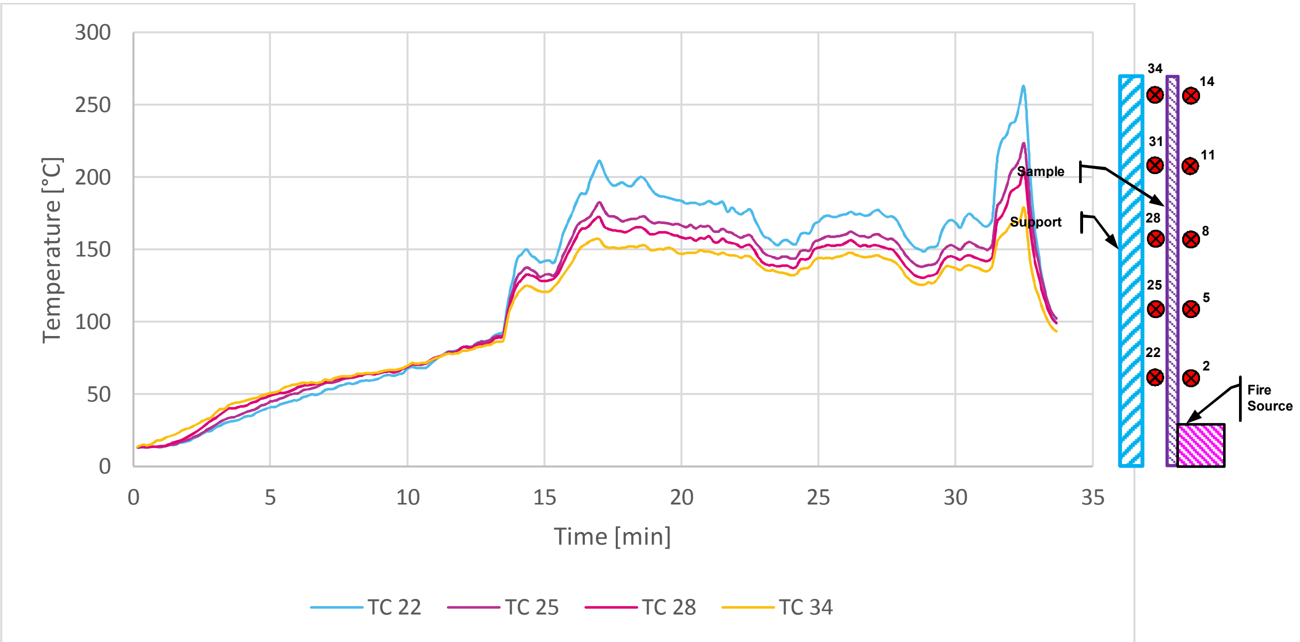


Figure D79 – Temperatures measured on the cavity central axis for ACM A2 sample 2

Report Ends