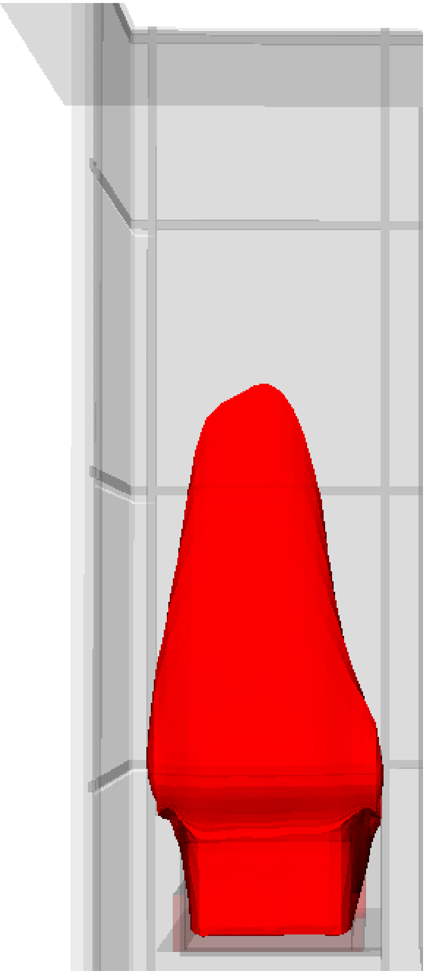
VALIDATION OF A BS 8414 FIRE MODEL FOR CLADDING SYSTEMS INCLUDLING TOXIC GAS GENERATION



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  - Dr John Ewer,
  - Dr Fuchen Jia
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https://doi.org/10.1016/j.firesaf.2025.104366.

- Special thanks to Prof Richard Hull and his colleagues from University of Central Lancashire and FPA for providing access to BS8414 test data involving toxic gas generation.

(i) Jones N., Peck G., McKenna S., Glockling J.L.D., Harbottle J., Stec A.A., Hull Richard., Burning behaviour of rainscreen façades, Journal of Hazardous Materials, 2021(403).
(ii) Peck G., Jones N., McKenna S., Glockling J.L.D., Harbottle J., Stec A.A., Hull Richard, Smoke toxicity of rainscreen façades, Journal of Hazardous Materials, 2021(403).

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- High-rise building demonstration analysis
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- Conclusions

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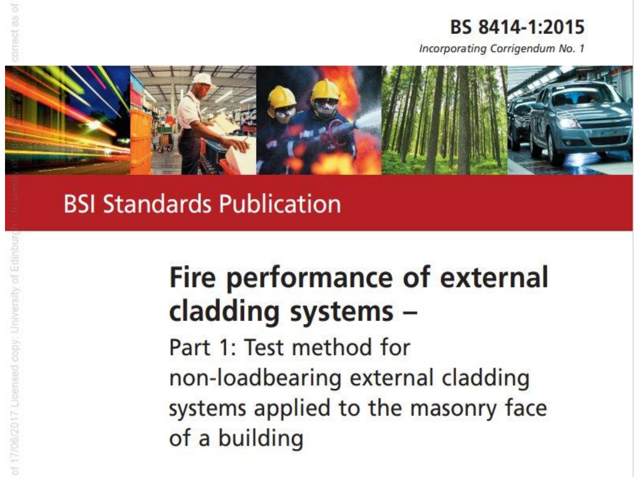
BS 8414 Test

BS 8414 Test

- Recommended in ADB (Item 12.3 b) as one of the methods to assess external building walls using the performance criteria given in BRE report BR 135.
    - **Large size**: The BS8414 (2015) test represents an external building corner formed by two faces at least 8.0 m high with 1.5 m (wing) and 2.6 m (main face) wide surfaces.
    - **Large fire:** The fire chamber is represented by a 2.0 m wide by 2.0 m high chamber in the main face and the fire source is a wood crib producing 3 MW peak output and 4500 MJ over 30 min (however, peak can range from 2.5 MW and 3.5 MW).
    - **System test:** BS8414 test attempts to treat the building façade as a complex system taking into consideration how each component of the façade system reacts to a representative fire threat.
- The current BS8414 2020 test methodology has some improvements:
    - o Detail requirements for the distance between cavity barriers
    - o Increase of test facility height from 8m to 9.7 m
    - o Additional temperature measurement at level 3 (7.5m high)


BS 8414-1:2015
Incorporating Corrigendum No. 1
BSI Standards Publication
Fire performance of external cladding systems –
Part 1: Test method for non-loadbearing external cladding systems applied to the masonry face of a building

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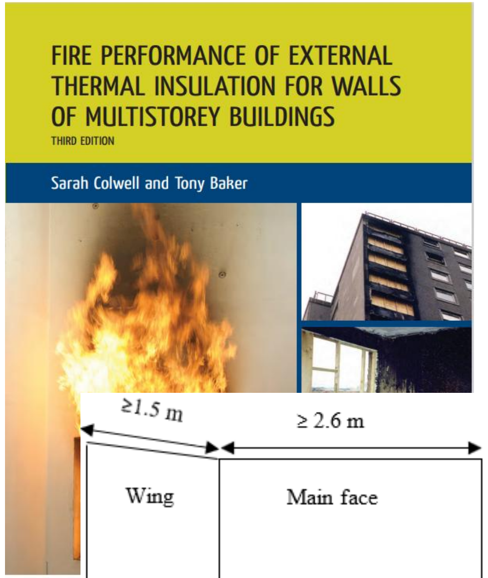
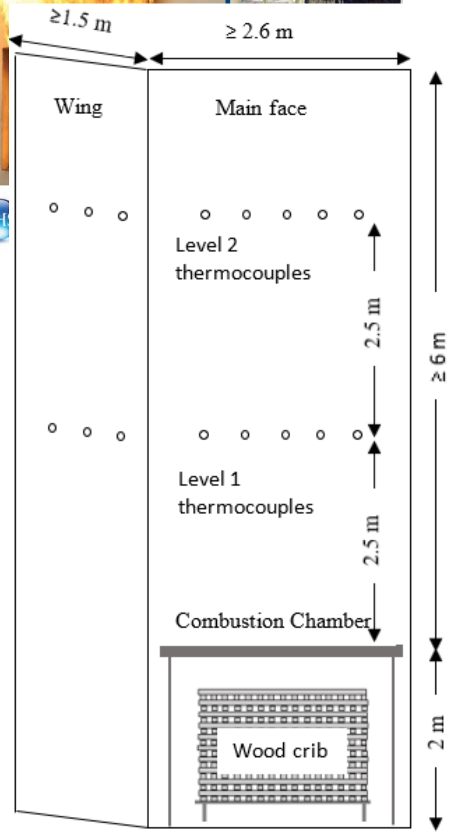
BS 8414 Test: Pass/fail criteria

BRE report BR 135

- T_s **– Start Temperature:** mean temperature of thermocouples at Level-1 during 5 minutes prior to the ignition of the wood crib fire.
- t_s **– Start time:** time when the temperature at any external thermocouple at Level-1 ≥ a 200 ^{O}C temperature rise above T_s and remains above this value for at least 30 seconds.
- **Failure Criterion**
  - **1:** failure due to external fire spread being deemed to have occurred if the temperature rise above T_s, of any of the external thermocouples at Level-2, exceeds 600 ^{O}C for a period of at least 30 seconds, within 15 minutes of the start time (t_s).
  - **2:** failure due to internal fire spread being deemed to have occurred if the temperature rise above T_s, of any of the internal thermocouples at Level-2, exceeds 600 ^{O}C for a period of at least 30 seconds, within 15 minutes of the start time (t_s).
  - **3:** failure due to flame spread extending above the test apparatus at any time during the test duration.



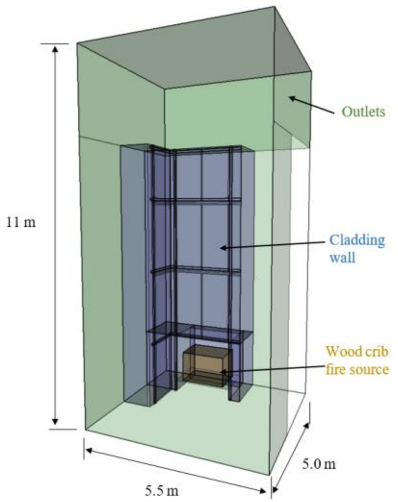


BS 8414 SMARTFIRE CFD Fire Model

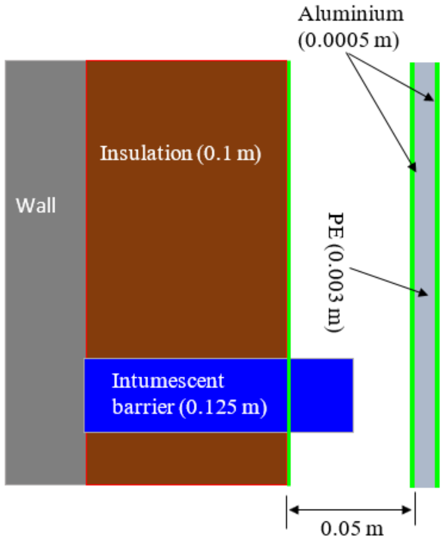
The fire model is developed by FSEG using SMARTFIRE (see Wang Z, et al 2025 for details)

- Computational domain 5.5 m × 5.5 m and 11 m high (adjustable). Ignition criteria include:
  - For ACM surface, ignition temp set to 550 ^{O}C for all core materials with ignition temperature below this value (e.g.. PE, FR PE). Temp corresponds to value at which aluminium loses its strength.
  - For ACM exposed edge, ignition temp set to maximum of 480 ^{O}C and core material ignition temp.
    - Value determined by calibration from CFD simulation.
  - This is different to commonly adopted approach which is based on the ignition temperature of the ACM core material (e.g., Dréan V. et al., 2019).
  - Flame spread rate (from experiments) (this criterion has negligible impact for the DCLG test simulations)
- Burning rate: once a cell is ignited, it releases gaseous fuel based on cone calorimeter data

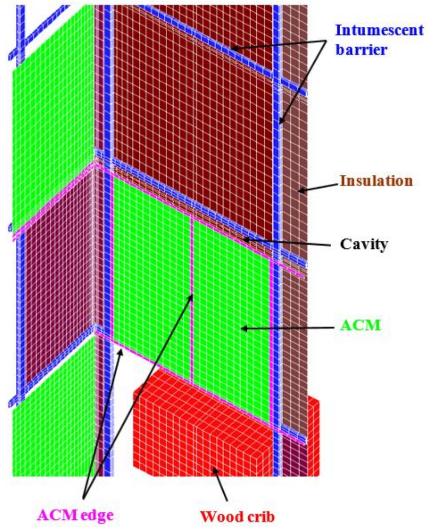
BS8414 CFD simulation domain



Side view of the cladding system (element size adjustable)



Details of ACM panel, insulation and barriers



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Fire Model Input Parameters

- **The computational domain**
  - The configuration of the test facility
  - The installation details of the cladding system
  - Boundary conditions
- **Mass loss rate of the wood crib fire**
- **Material properties**
  - Molecular structure of wood and ACM core (required for the different chemical reaction equations of the wood crib fire and cladding fire)
  - Surface and edge ignition temperature (^{O}C) of the ACM panel and the insulation
  - Thickness (m) of the cladding panels and insulation
  - Density (kg/m^3) of each material used in the cladding system
  - HRR per unit area (kW/m^2) of ACM core and insulation materials
  - Specific heat (J/kg) of all materials
  - Thermal conductivity (W/mK) of all materials
  - Critical temperature (^{O}C) and the delay duration (s) for the intumescent to be activated
  - Yields of toxic gases (kg/kg) from tube furnace test (under certain combustion conditions).

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Fire Model Output (predicted)

- **The fire model produces:**

- **Key test data and fire behaviour consistent with the current requirements of the BS 8414 protocol including:**
  - the temperature profiles, as a function of time, at individual locations
  - the developing fire plume as a function of time
  - the final state of damage of the cladding system including the burn through regions etc.
  - a pass/fail result for the cladding system with the cause identified

- **Additional quantification of relevant fire behaviour including:**
  - the HRRs for each material component of the cladding system such as the ACM panel
  - the lateral and vertical flame spread rates of the cladding system
  - the burning/burnt-off locations of the ACM panel and insulation, as a function of time
  - the activation state of barrier intumescent strips, as a function of time
  - the toxic gas concentrations

Validation Using DCLG BS 8414 Test Data

- **DCLG BS 8414 tests (BRE, 2017)**
  Seven different cladding-insulation combination fire tests
- **Common material properties**
  Most required data are derived from the work by McKenna S.T. et al. (2019)
  https://doi.org/10.1016/j.jhazmat.2018.12.077
- **Key unavailable parameter data required by the model**
  - **Thermal properties of FR PE:** the impact of fire-retardant materials used in the fabrication of FR PE on fire development is complex.
    - As a first approximation, its density and thermal conductivity are simply assumed to be the same as PE but with a higher specific heat capacity derived by comparing the times to ignition for PE and FR PE in cone calorimeter experiments (see Wang. Z., et al, 2025 for details)
  - **HRR of wood crib fire:** the burning rate of the wood crib in the DCLG tests are unavailable. A HRR curve derived from experimental data for a BS 8414 test without a cladding system, producing a peak value of 2.5 MW is used.

Simulated crib fire plume (525 ^{O}C) with a HRR of 2.5 MW and a test without a cladding system

- **Computational cost**
  - One simulation requires an average of 120 hrs, for a mesh consisting of 300,348 (54×103×54) cells;
  - PC: 4.0 GHz eight-core processor and 64 GB of memory

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Validation Using DCLG BS 8414 Test Data

Pass/fail results and fail causes

- The BS 8414 model correctly reproduced both the pass/fail results for all seven DCLG BS 8414 tests;
- The model correctly identified the failure causes (i.e. **Criterion 3**: flame spread extending above the test apparatus at any time during the test duration) and approx failure time.

DCLG test	Cladding materials	Experiment	Simulation
1	PE; PIR	Fail due to Criterion 3 at approx 360s	Fail due to Criterion 3 at approx 360s
2	PE; Stone wool	Fail due to Criterion 3 at 275s	Fail due to Criterion 3 at approx 360s
3	FR PE; PIR	Fail due to Criterion 3 at approx 1390s	Fail due to Criterion 3 at approx 1310s
4	FR PE; Stone wool	Pass	Pass
5	Limited combustibility mineral core; PIR	Pass	Pass
6	Limited combustibility mineral core; Stone wool	Pass	Pass
7	FR PE; Phenolic insulation	Fail due to Criterion 3 at approx 1525s	Fail due to Criterion 3 at approx 1360s

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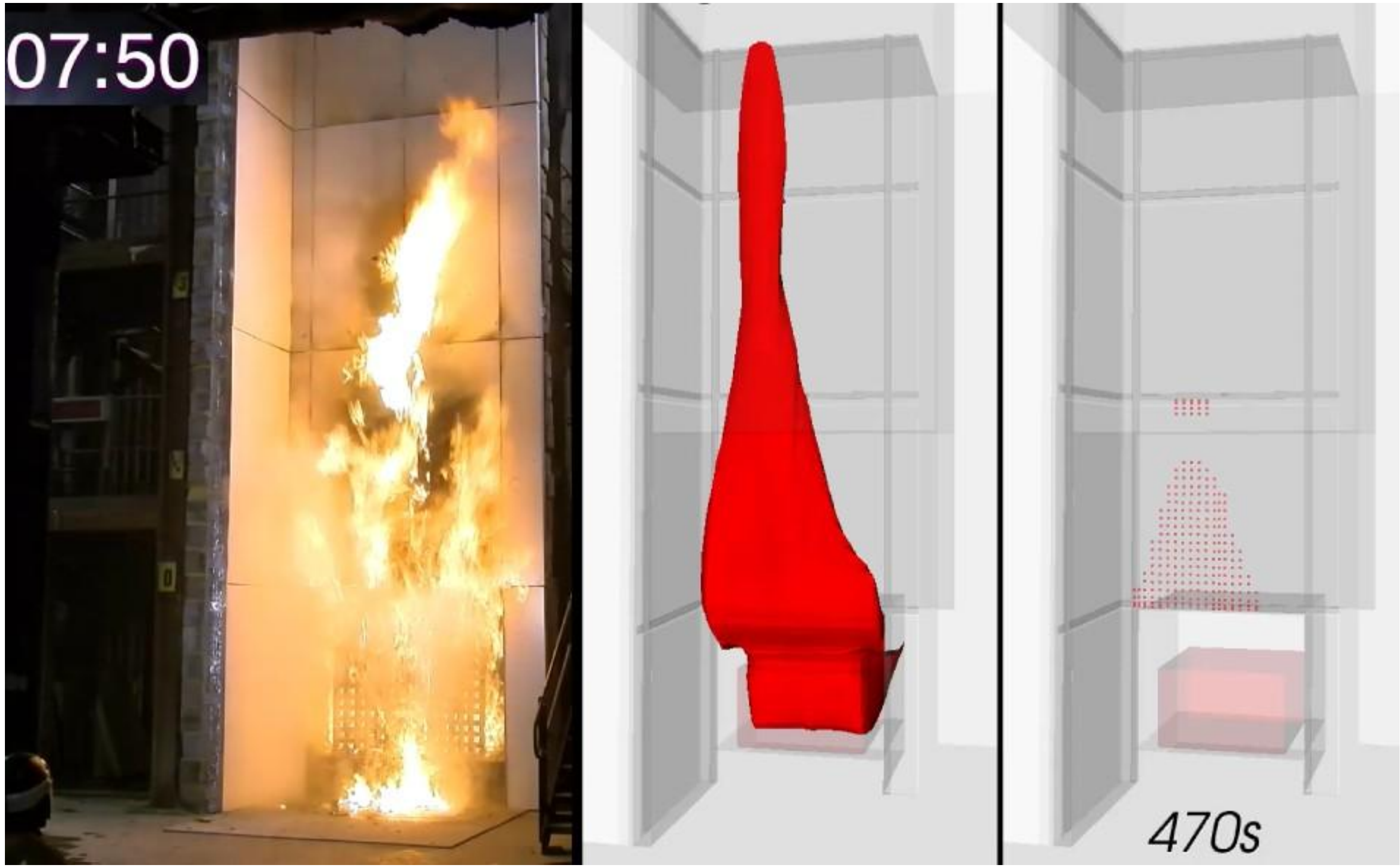
Validation Using DCLG BS 8414 Test Data

DCLG Test 1 (PE/PIR) Failed due to flame spreading extending above the test apparatus

- Failed at approx.:
  - 7:50 (470s) video time
  - 360 s in both the test and simulation measured from t_s.

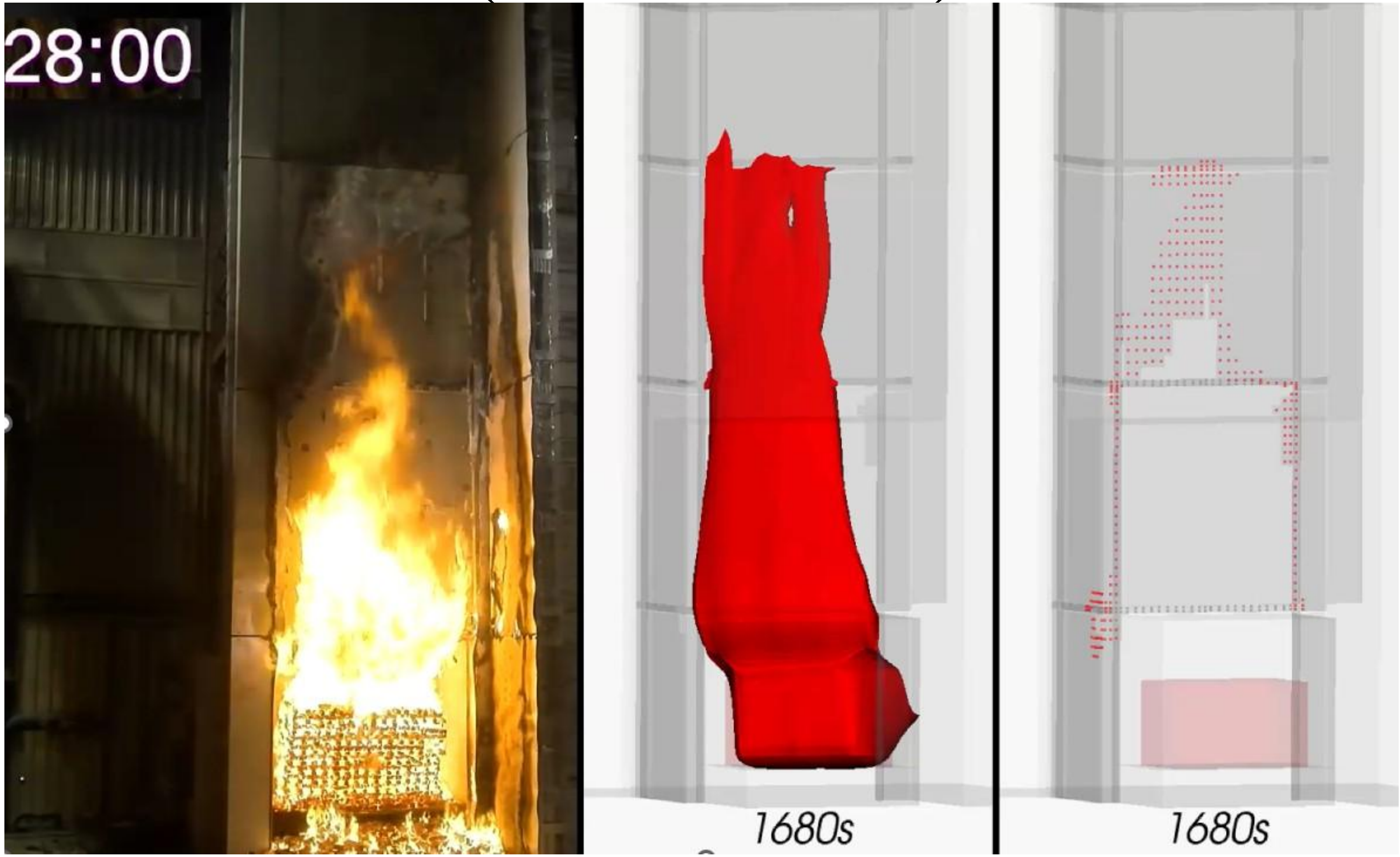
- NOTE: Time to fail is measured from the start time, t_s i.e. approximately 110 s after the ignition of the wood crib for Test 1 in both the experiment and simulation



Test 1 | Fire plume (525 ^{O}C iso-surface) | Burning ACM (red dots)

Validation Using DCLG BS 8414 Test Data

DCLG Test 4 (FR PE/Stone wool) Passed



Test 4

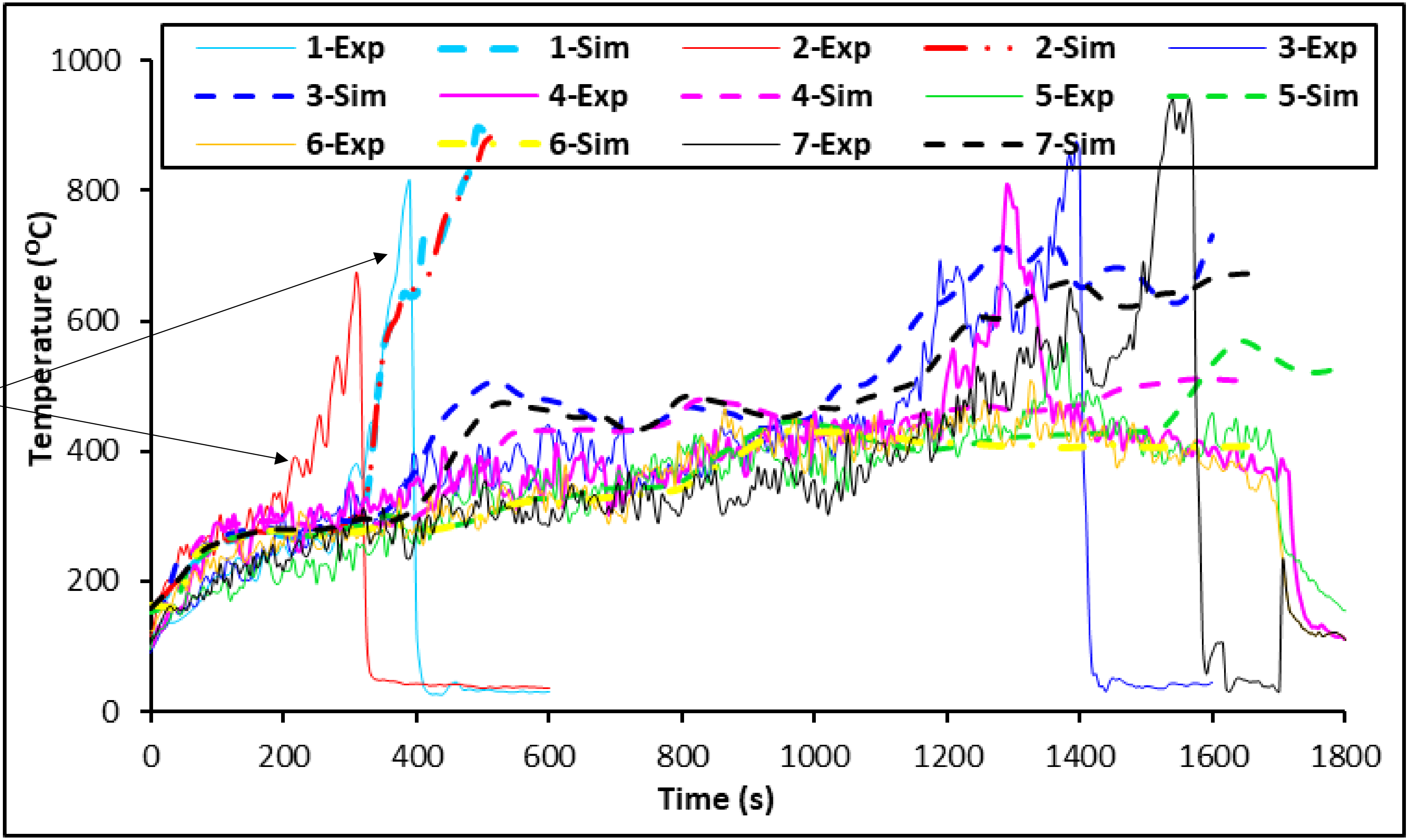
Fire plume
(525 ^{O}C iso-surface)

Burning ACM
(red dots)

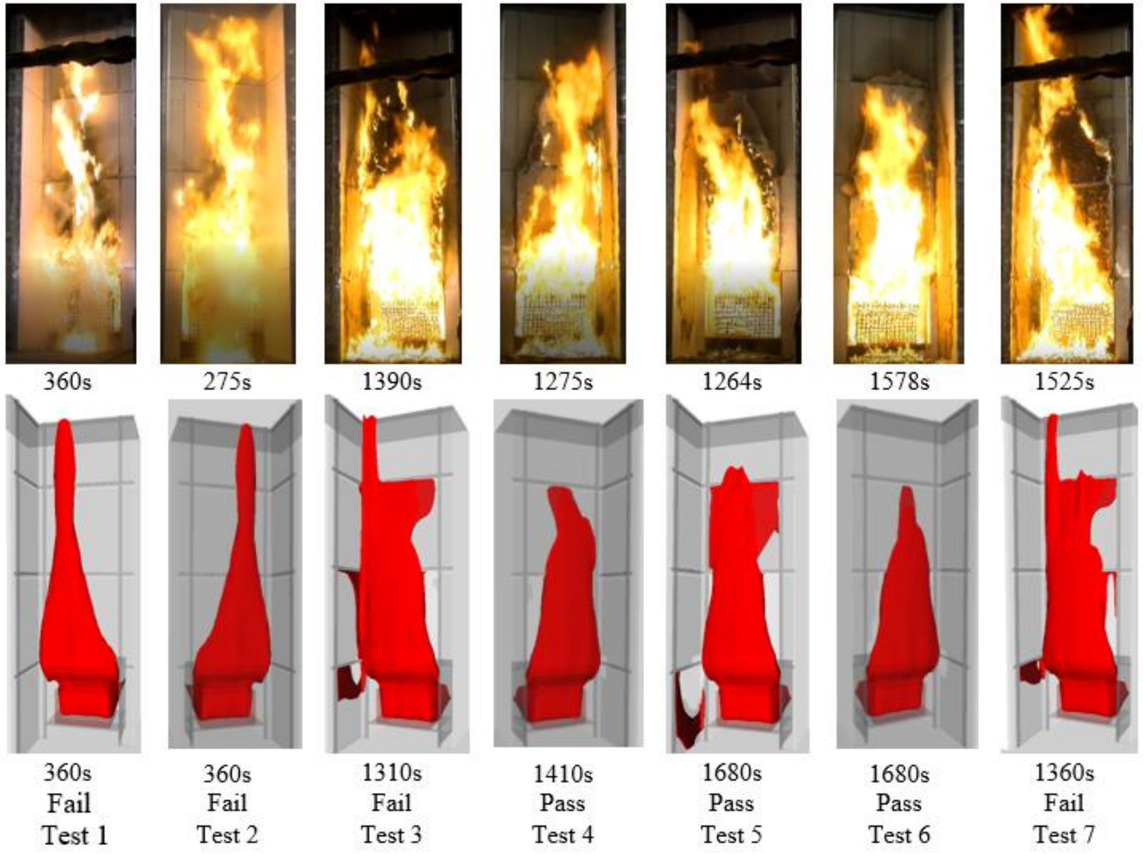
Validation Using DCLG BS 8414 Test Data

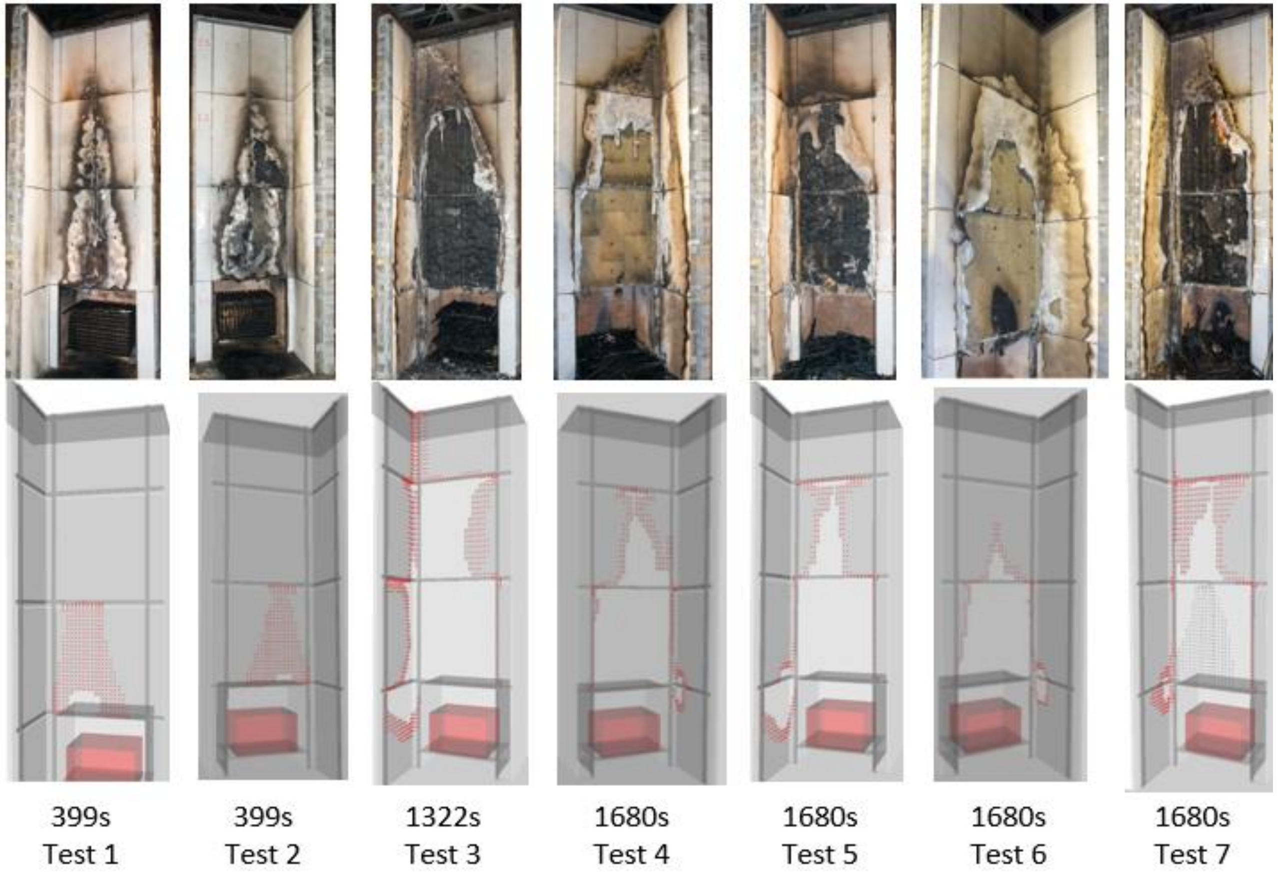
- **Maximum Level-2 external temperatures**

- Predicted temp generally follows measured trends.
- Temp curve for Trial 2 (PE, RW) rises sooner than Trial 1 (PE, PIR).
- Counter intuitive as PIR (T1) contributes to fire while RW (T2) does not.
- Also, predicted curves for T1 and T2 are almost identical as expected, as PIR only makes a small contribution.
- Difference in T1 and T2 probably due to differences in crib fire HRR for T1 and T2.



Validation Using DCLG BS 8414 Test Data





- Observed and simulated flames (simulated visible flame envelopes are defined using a 525 ^{O}C temp iso-surface), at the time to fail or the maximum height (if cladding system passes the test)

- Burnt off ACM panel in the experiments and the predictions (white area) (red dots represent actively burning locations)

Observations from DCLG BS 8414 Test Simulations

Impact of wood crib fire

- In the BS 8414 test standard, the peak HRR of the wood crib fire can vary between 2.5 MW and 3.5 MW.
- The wood crib HRR curve used in the simulations of all the DCLG tests has a peak value of 2.5 MW.
- While the ACM system with **FR PE core and stone wool insulation** (i.e., T4) **PASSED** the test and is also predicted to pass the simulation with a peak HRR for the wood crib fire of 2.5 MW, it would **FAIL** the simulation test if the peak HRR of the wood crib fire was 20% higher (i.e. 3.0 MW), but still within the acceptable range for the BS 8414 standard.
- This suggests that given the natural variation in HRR produced by wood crib fires utilised in the BS 8414 test, a cladding system could pass or fail simply depending on the natural variation in the wood crib HRR.

- **(Left)** Max fire plume height in DCLG Test 4 (pass),
- **(Middle)** Max fire plume height in simulation with peak wood crib HRR of 2.5 MW (pass),
- **(Right)** Fire plume at 1250 s with peak wood crib HRR of 3.0 MW (fail)

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Validation Using FPA BS 8414 Test Data

FPA tests (Peck et al. 2021 and Jones et al. 2021)

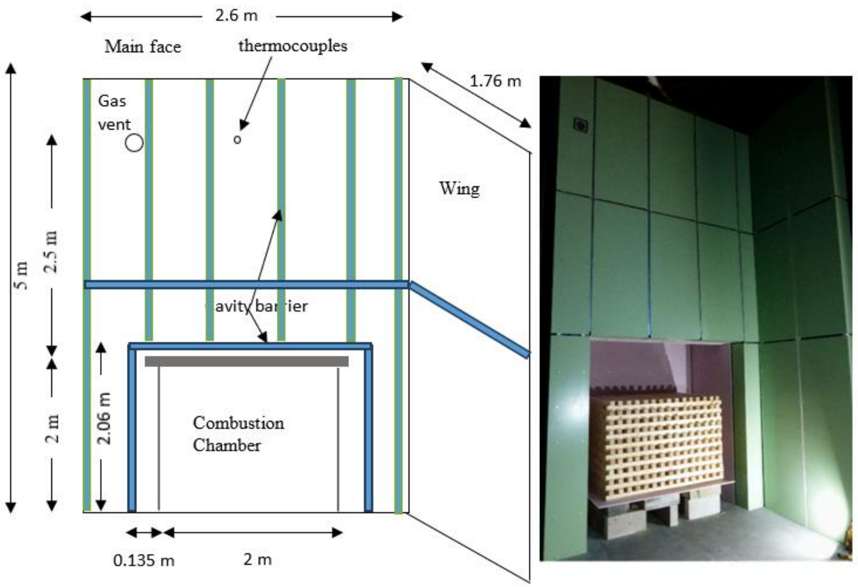
- Two FPA BS 8414 tests have been selected for validation of model toxic gas concentration predictions; one with an ACM core of PE and one with an A2 core; both cladding systems include PIR insulation.

Assumption

- As the toxic gases in the FPA tests are extracted via a vent within the cladding system (see the right figure), it is assumed **the combustion of the wood crib is at well-ventilated conditions**, while the **combustion of the ACM panel and the insulation material are at under-ventilated conditions**.

Vent Extraction

- Measured extraction rate applied as inlet condition
- Extracts gases from outside and inside the cavity – limited by cavity barriers



Schematic of test facility and the finished cladding panels

Yields of toxic gases (based on the above assumptions)

		Wood (Hansen-Bruhn et al. 2023)	PE (McKenna S.T., 2019)	Stone wool (A2) (McKenna S.T., 2019)	PIR (McKenna S.T., 2019)
Yield (kg/kg)	CO	0.007	0.14	0.005	0.316
	CO_2	1.64	1.594	0.031	0.549
	HCN	0	0	0	0.0142

Computational cost

- One simulation requires an average of 95 hrs, for a mesh consisting of 642,600 (100×63×102) cells;
- PC: 4.5 GHz 10-core processor and 128 GB of memory

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Validation Using FPA BS 8414 Test Data

Assumption

As the toxic gases in the FPA tests are extracted via a vent within the cladding system (see the figure on the previous slide), it is assumed the combustion of the wood crib is at well-ventilated conditions, while the combustion of the ACM panel and the insulation material are at under-ventilated conditions.

Governing Equations

$$\frac{\partial \rho Y_i}{\partial t} + \nabla \cdot (\rho \vec{U} Y_i) = \nabla \cdot (\rho \Gamma \nabla Y_i) + S_{Y_i} \qquad (1)$$

Gas mass fraction contributed from combustion of individual materials

$$Y^{CO} = \sum_i Y_i y_i^{CO} \qquad (2)$$

$$Y^{CO2} = \sum_i Y_i y_i^{CO2} \qquad (3)$$

$$Y^{HCN} = \sum_i Y_i y_i^{HCN} \qquad (4)$$

$$Y^{H2O} = \sum_i Y_i y_i^{H2O} \qquad (5)$$

$$Y_{O2} = A(1 - \sum_i Y_i) - \sum_i Y_i Y_i^{O2} \qquad (6)$$

- i stands for burnable materials including wood, ACM core and insulation.
- Y_i is the fraction of mass i which is generated from material i.

- y_i^j is the yield of species j (CO, CO_2, HCN, etc.) under the combustion assumptions described above (consumption for O_2) derived from tube furnace data.
- A is the ambient mass fraction of O_2.

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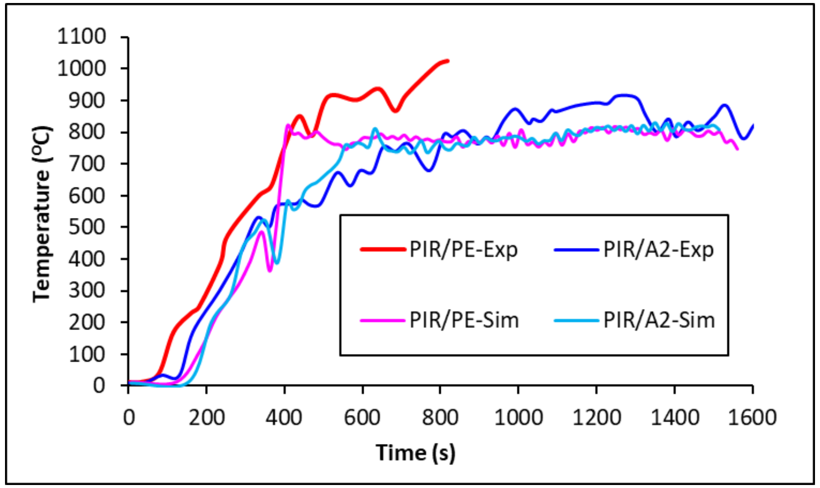
Validation Using FPA BS 8414 Test Data

Temperature profiles

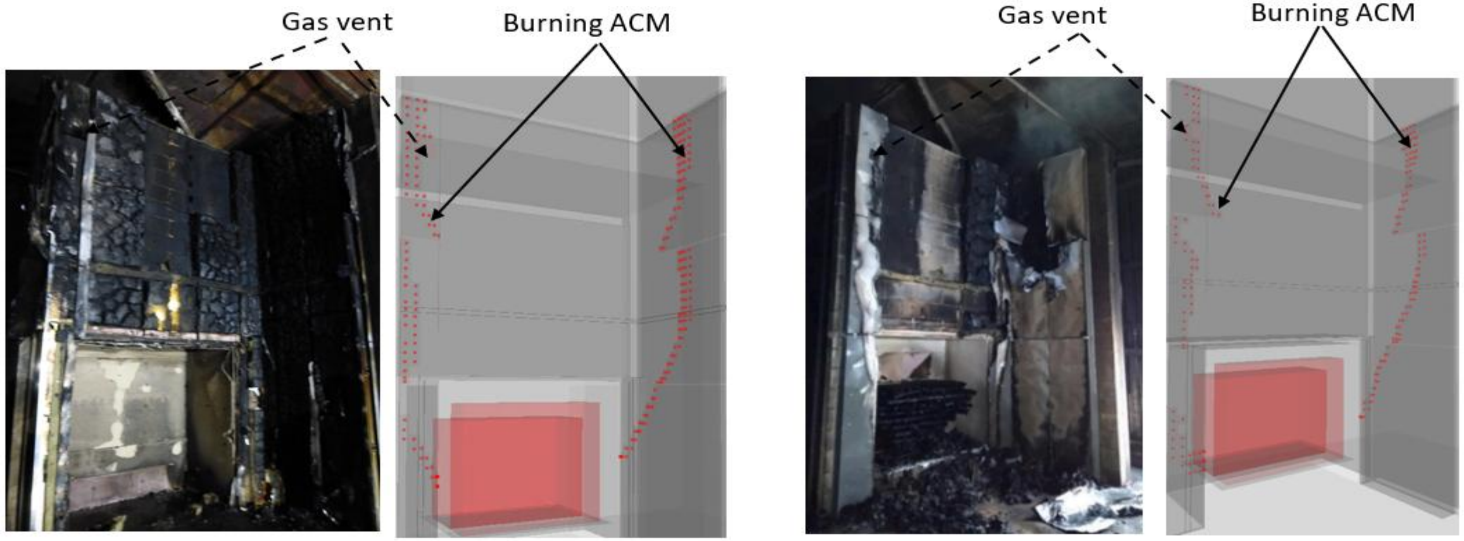
- The PIR/PE test was extinguished at 810 s for safety reasons;
- The predictions of temperature generally in good agreement with the measured data for the two tests.

Burnt off ACM panels

- For the PIR/PE test, while the ACM on virtually all of the wing wall was consumed in the fire experiment, only approximate half of the wing wall is burnt off at the time when the fire was extinguished in the simulation.
- The predicted burnt off locations on both the main wall and the wing wall for the FPA PIR/A2 test are comparable with that observed in experiment



Measured and predicted temp at thermocouple location 0.05 m in front of the cladding



Observed damage of the PIR/PE (left) and PIR/A2 (right) cladding system and the predicted burning ACM (red dots) at the end of simulation.

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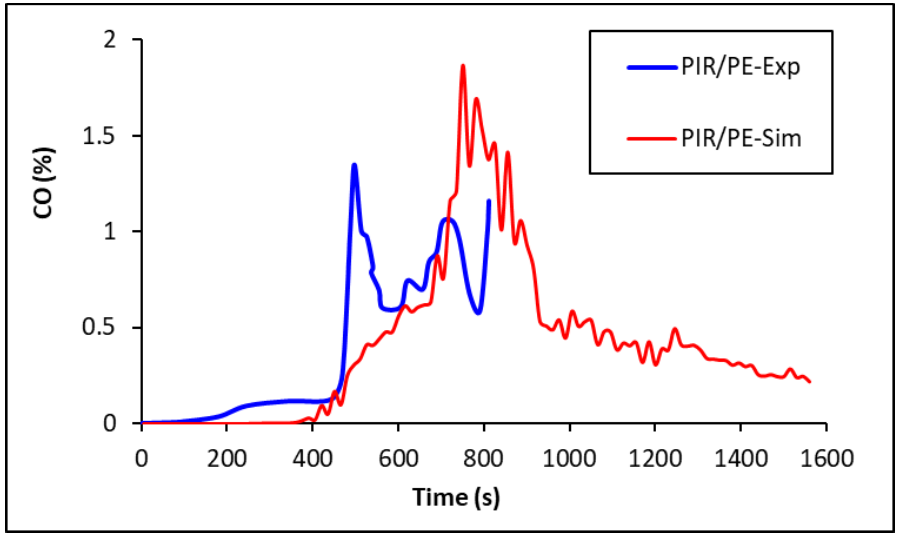
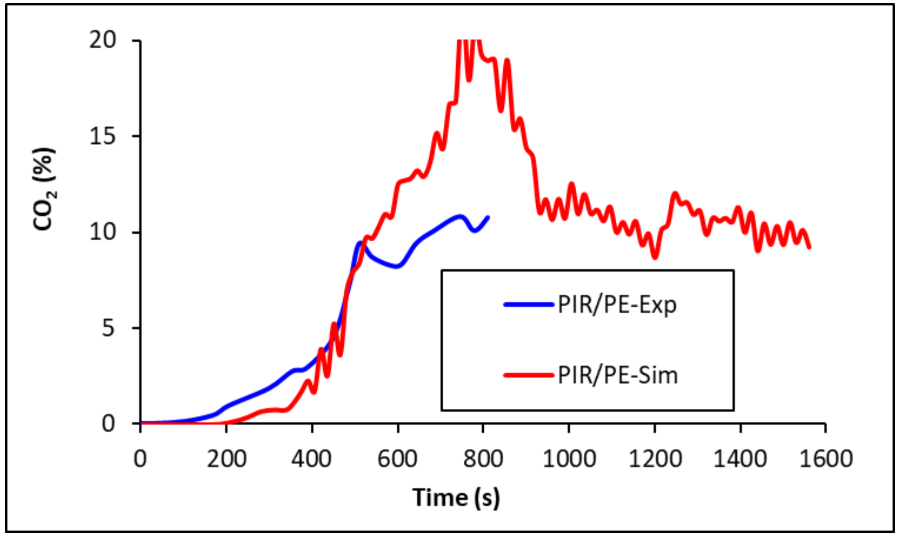
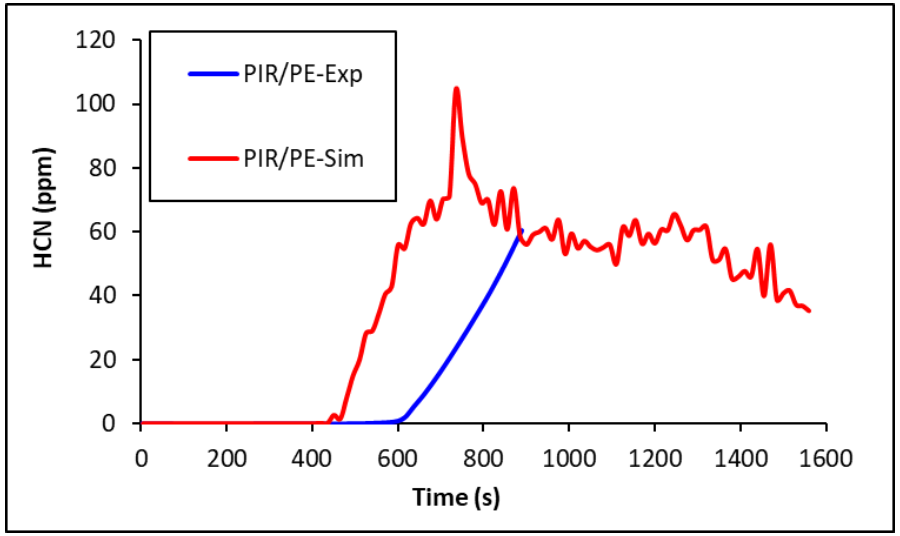
Validation Using FPA BS 8414 Test Data

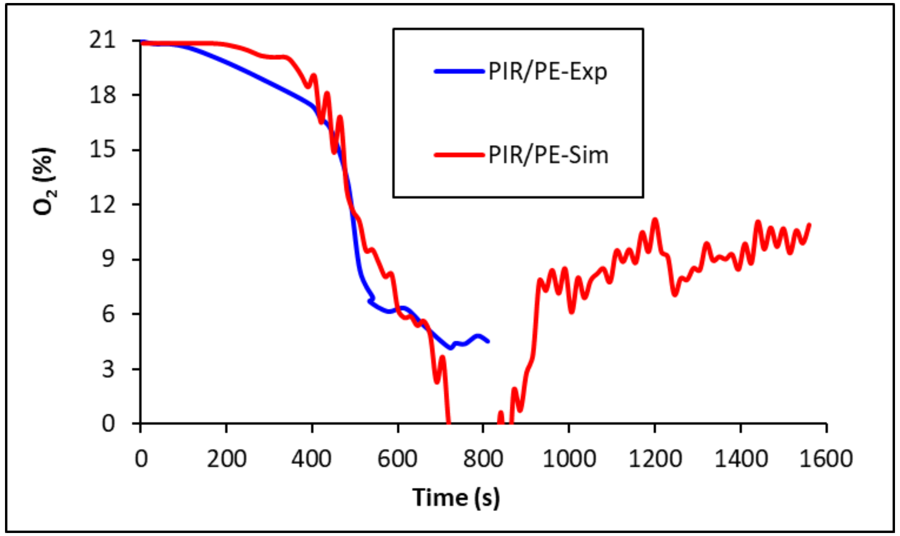
Gas concentrations in PIR/PE test

- The PIR/PE test was extinguished at 810 s for safety reasons;
- The predictions of gas concentrations generally follow the measured trends.
- Predicted HCN occurs earlier than measured (possibly due to the measuring process?).









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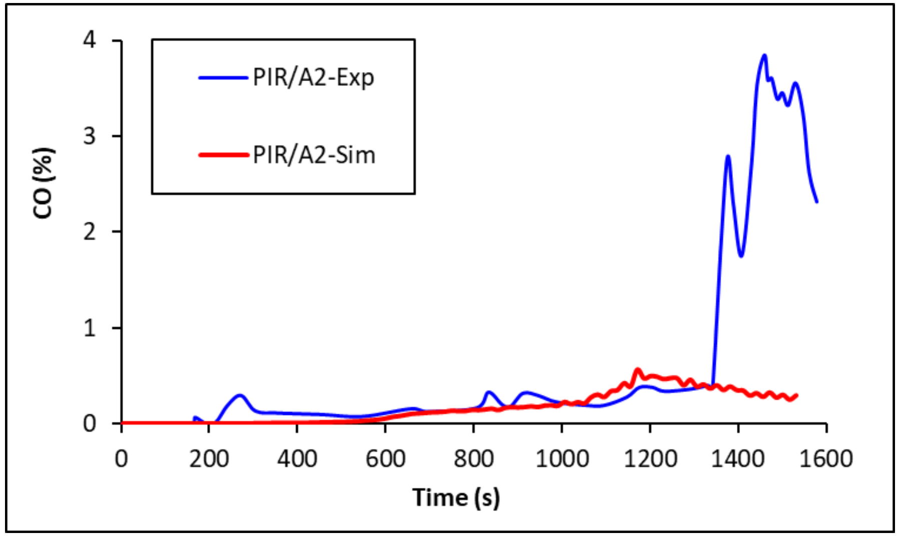
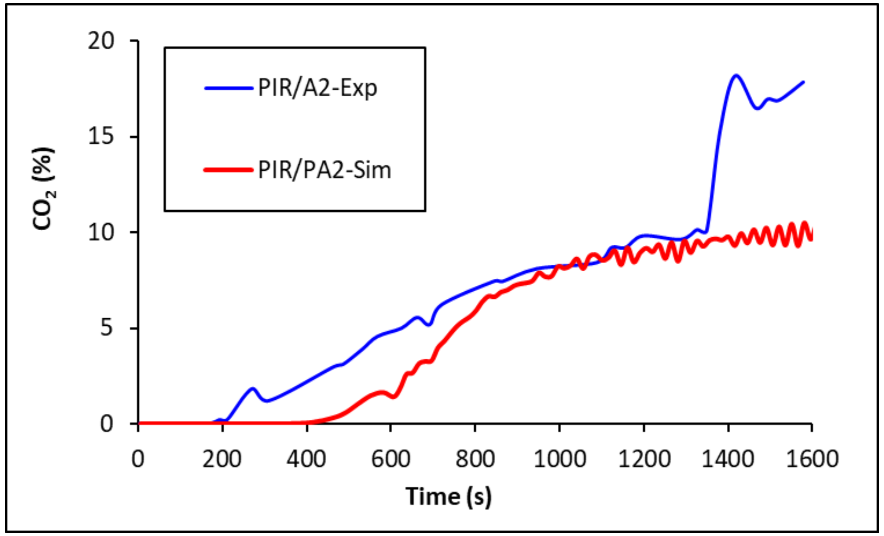
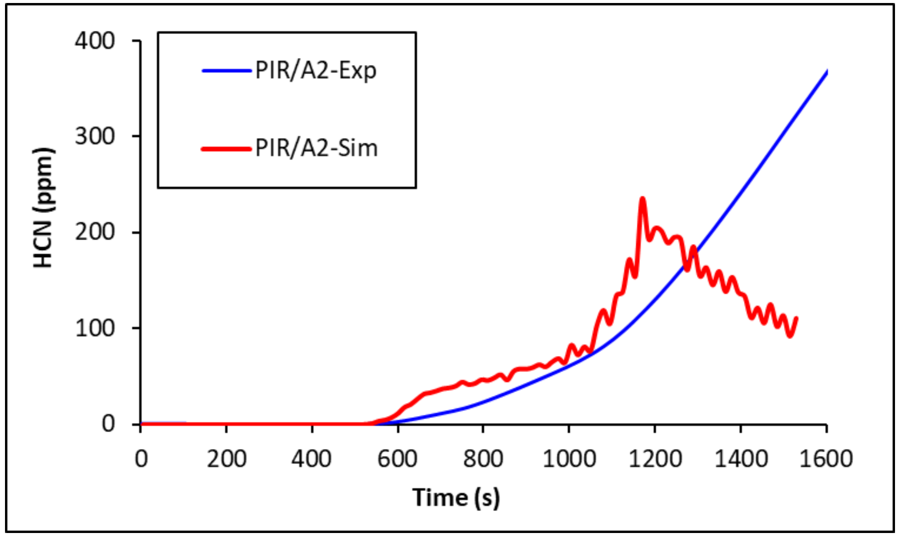
Validation Using FPA BS 8414 Test Data

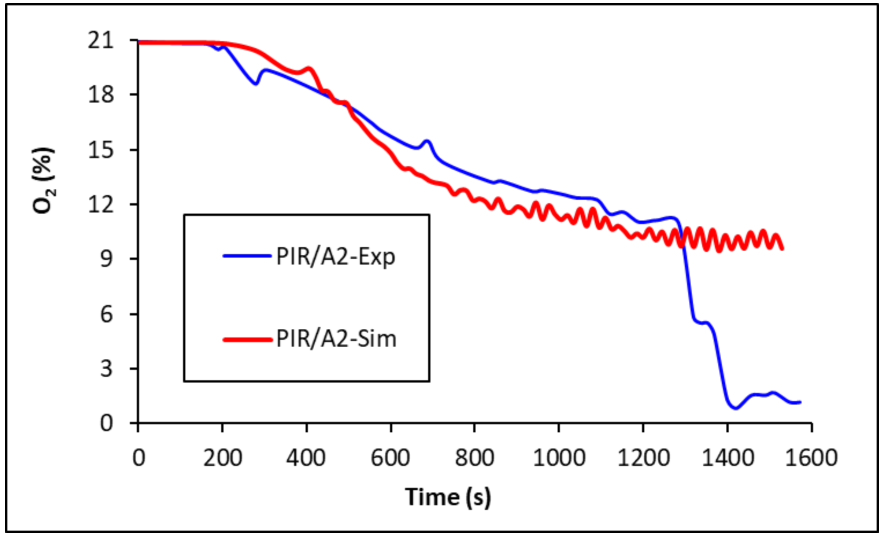
Gas concentrations in PIR/A2 test

- The predictions of gas concentrations generally follow the measured trends up to 1380 s.
- The simulation failed to reproduce the measured peak $CO/CO_2/HCN/O_2$ concentrations around 1500 s.
- The discrepancy is due to the insulation panel becoming dislodged in the experiment and moving into the cavity after 1380 s, resulting in the gas extraction vent being surrounded by burnable PIR









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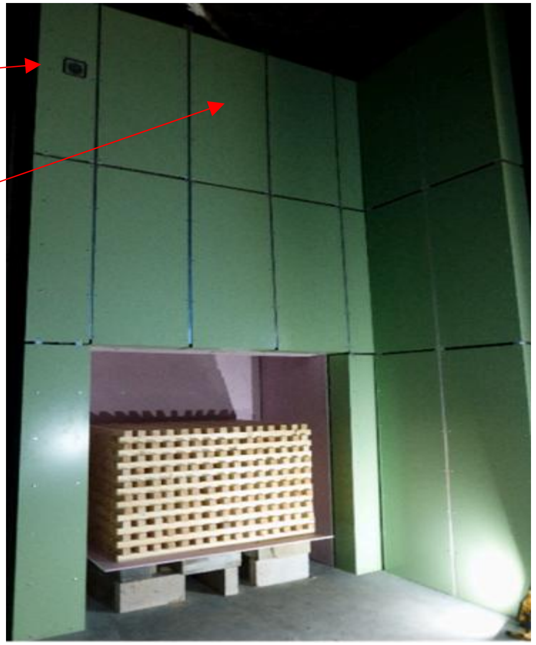
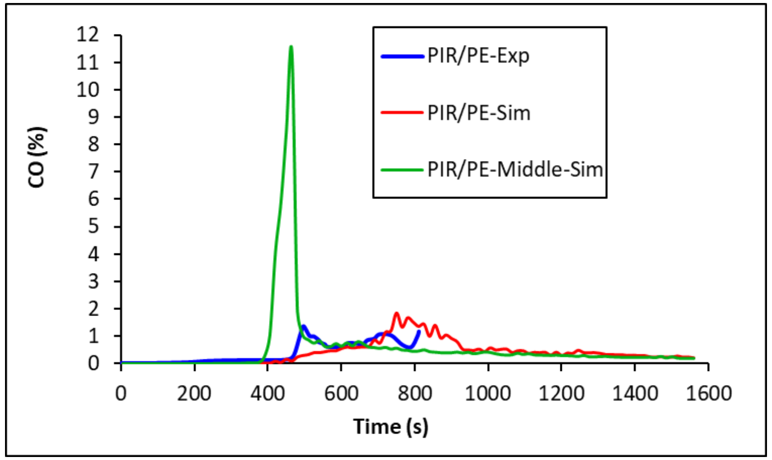
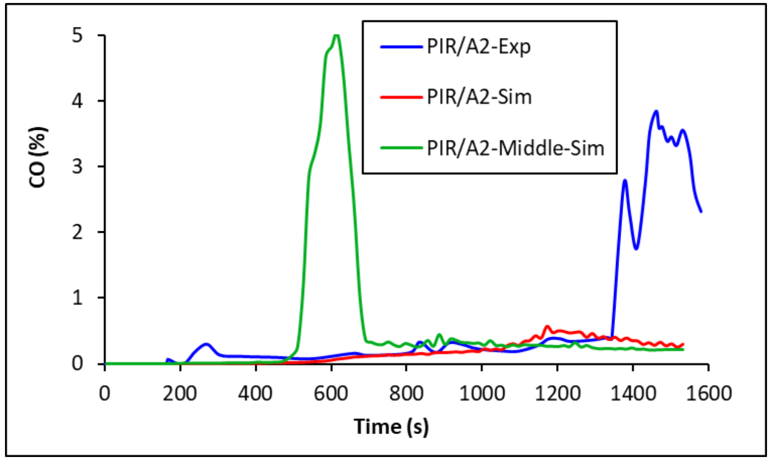
Observations from FPA Test Simulations



Gas concentration in the middle of the wall cavity

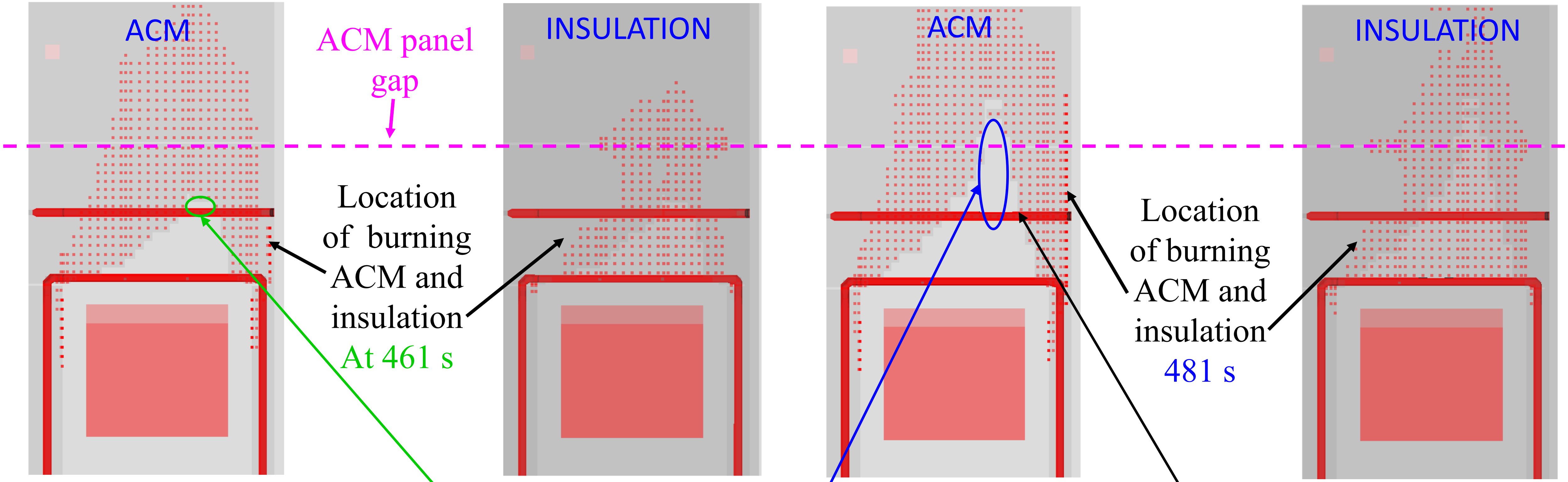
- **PIR/PE:** The peak CO concentration at the gas vent in the test is 1.87%.
  - However, the predicted cavity CO concentrations in the middle of the main wall is as high as 11.4% at 466 s.
- **PIR/A2:** The predicted cavity CO concentrations in the middle of the main wall is as high as 5.0%.
- The measured CO concentrations in the tests possibly under-estimate the toxicity potential of cladding fires.





Measured and predicted CO concentrations in the PIR/PE test (left) and PIR/A2 test (right).

Observations from FPA Test Simulations



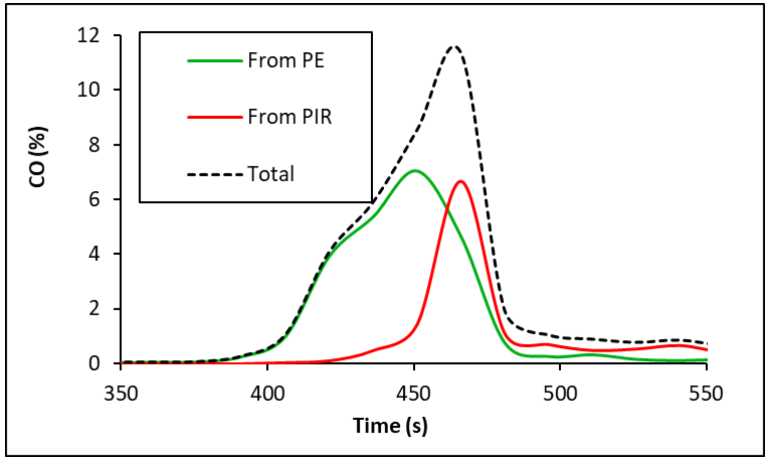
Peak CO concentration in PIR/PE case 11.4% at **466 s**.

- At 461 s, there is only a small portion of ACM burn-through above the top horizontal barrier (with activated intumescent) and some of the insulation under the ACM has already been ignited.
- At 481 s, a large part of the ACM is burnt-through above the top horizontal barrier; the fire on the insulation has spread to the top of the cladding.

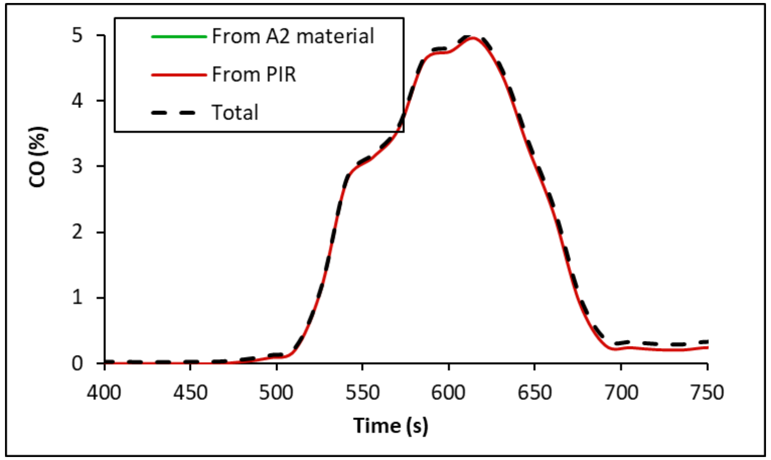
Observations from FPA Test Simulations

Gas contributions

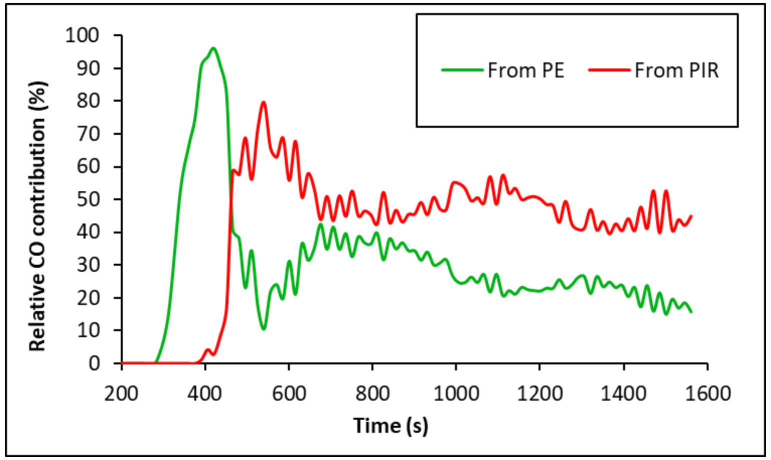
- In the PIR/PE test, the predicted CO concentration within the cavity is generated primarily from the burning of PE and PIR, producing peak CO concentration of 11.4% in the middle of the main wall.
  - The relative contributions to this peak CO value is: wood crib - 0.5%, PE - 40.8%, and **PIR - 58.7%.**
  - **The total CO exposure dose (CO (ppm) * exposure time (min)) between 390 s and 510 s is 87300 ppm.min; with PE contributing 67%.**
- In the PIR/A2 test, almost all the predicted cavity CO concentration in the middle of the main wall is from the burning of PIR, producing a peak CO concentration of 5.0%.
  - 98.6% of this predicted peak CO concentration is derived from the burning of PIR insulation and only 1.4% from the ACM core.



The CO contributions from the burning of PE/PIR



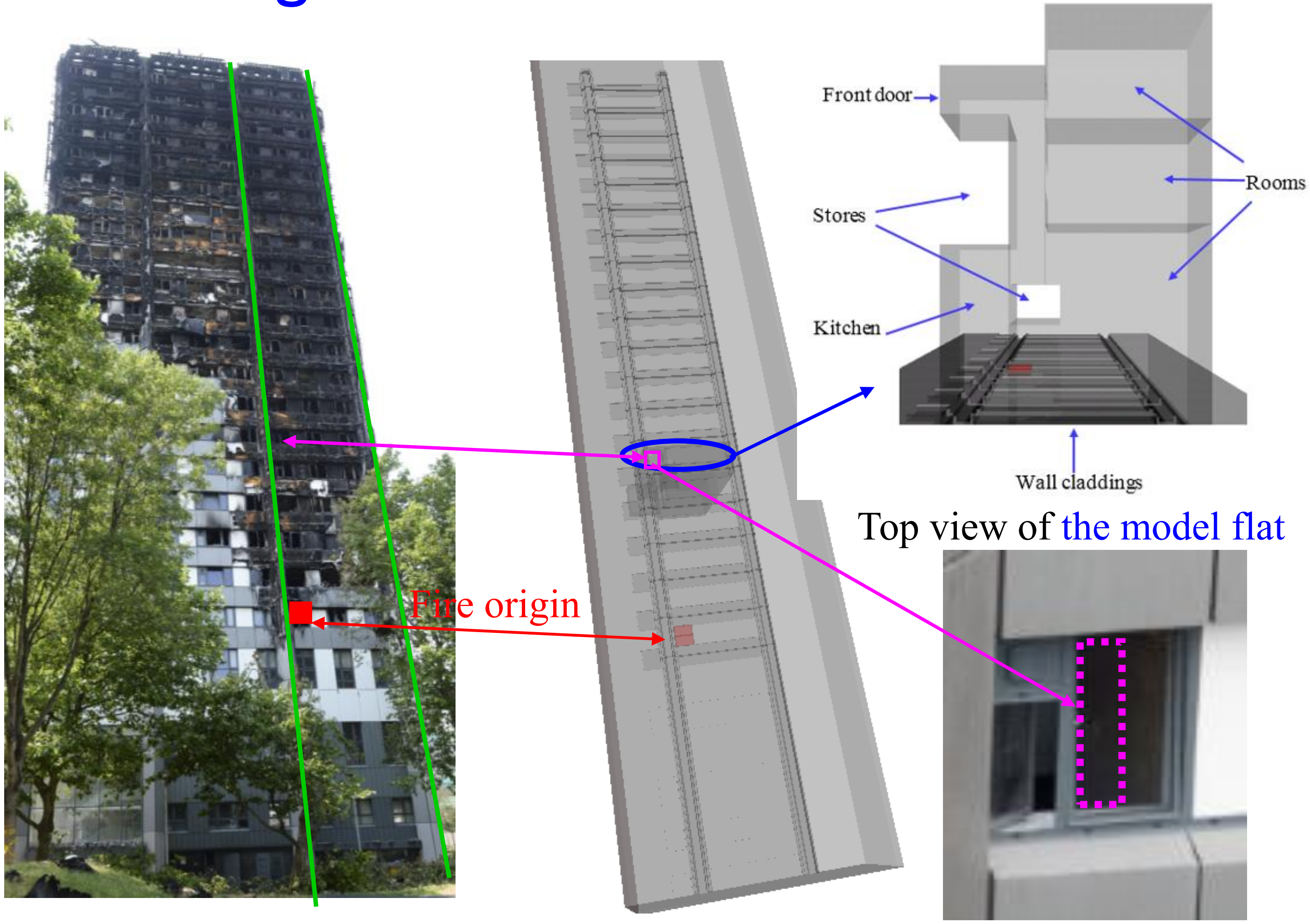
The CO contributions from the burning of A2/PIR



Relative CO contributions in the PIR/PE test

High-Rise Building Demonstration

- High-rise building demonstration using a section of a building **similar** to Grenfell tower (PE ACM, with PIR insulation).
- A fire source of 1 MW (for 240 s) applied to a kitchen window of a lower corner flat.
- An external wind with components of 1.0 m/s normal to the window and 0.5 m/s from left to right is adopted.
- Species concentrations in a target flat 5 floors above the fire floor are monitored.
- Large window in kitchen of target flat is half open (**i.e., worse case scenario**).
- Simulation domain - 1,000,000 cells.
- PC: 4.5 GHz 10-core processor and 128 GB of memory.
- One simulation (600 s fire) requires 18 hrs using research version of SMARTFIRE.
- NOTE: this simulation is not intended to reproduce the Grenfell fire.



Top view of the model flat

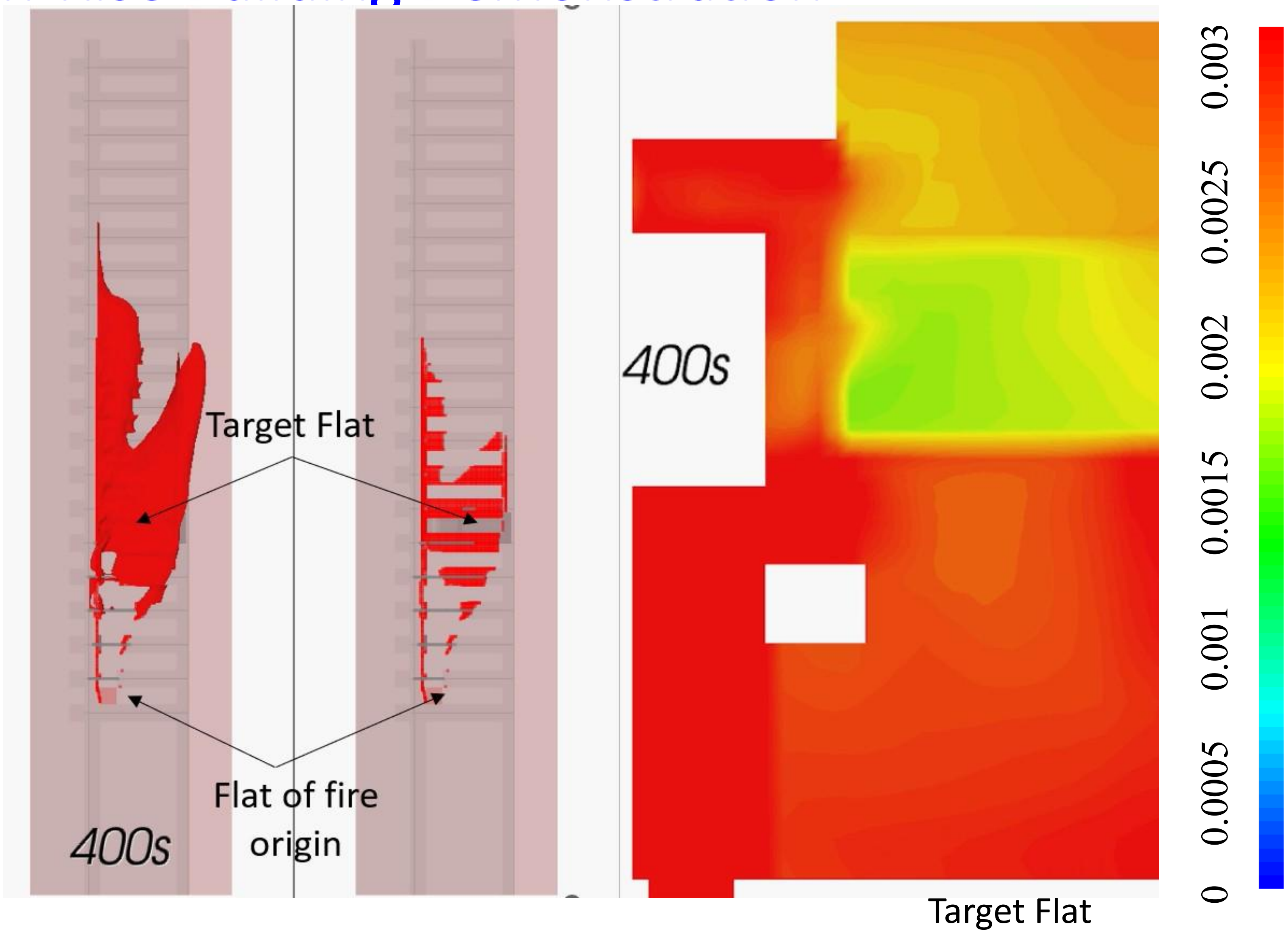
the Grenfell Tower

Modelled cladding wall

Kitchen window (half open)

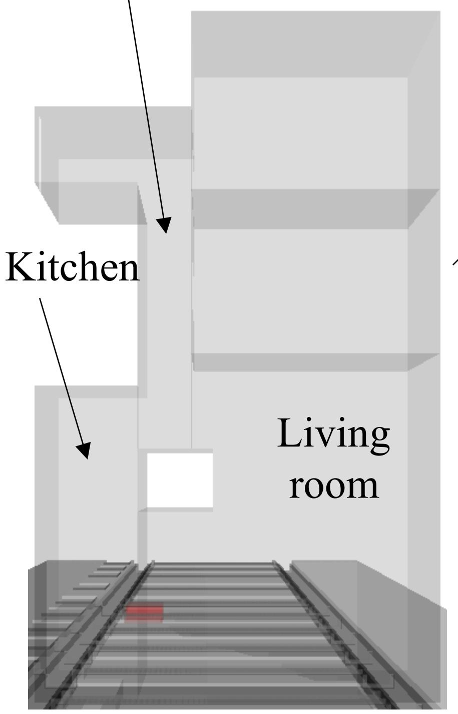
High-Rise Building Demonstration

- Left: external fire plume (represented using 525 ^{O}C temp iso-surface)
- Middle: burning ACM panels
- Right: Head height CO mass fraction in the flat five floors above the fire floor

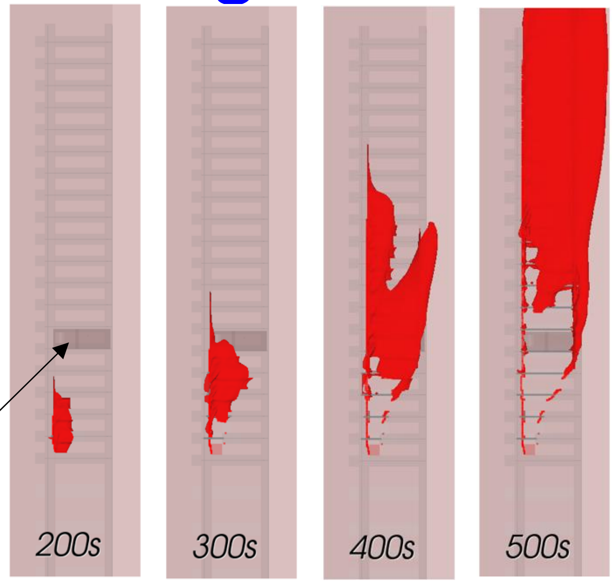


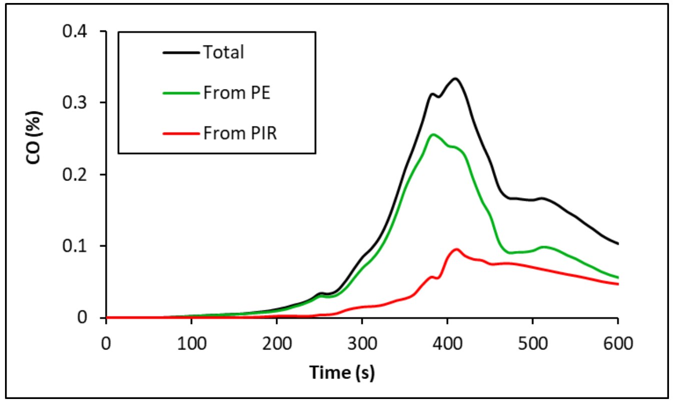
High-Rise Building Demonstration

Average CO concentration in upper and lower layer of corridor

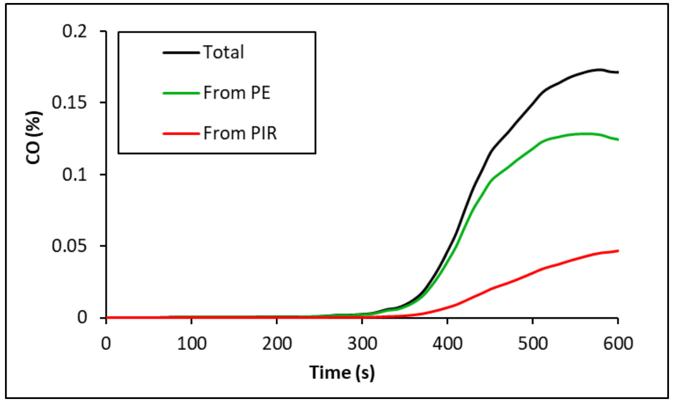


Plan view of target flat





Average CO conc. in corridor upper layer (1.5-2.0 m)



Average CO conc. in corridor lower layer (0.3-0.8m)

- At 200s, external fire plume (represented by 525 ^{O}C iso-surface) is 2 floors below target flat
- At 300s, fire plume reaches the kitchen window of the target flat.
- At 400s, fire plume fully covers target flat, peak upper layer CO (0.3%) occurs within flat corridor.
- At 500s, the external fire plume passes the target flat.
- At 580s, peak CO (0.17%) in lower layer occurs.
- Time to incapacitation is approximately 10 min for a CO concentration of 0.3%
- Time to incapacitation is approximately 20 min for a CO concentration of 0.15%
- With half the kitchen window open, the CO concentration within the flat is untenable even without the contribution from interior fires that may develop

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Limitations

- Within the model, the **surface ignition temperature** for an ACM panel is assumed to be 550 ^{O}C; This modelling approach would benefit from additional experimental data characterising the ignition conditions of cladding materials.
- The **HRR curve for the wood crib fires** used in each of the DCLG BS 8414 trials is unknown. When the model is used to investigate an arbitrary BS 8414 test, it should be kept in mind that the HRR curve of the actual wood crib fire can be different from the HRR curve adopted in this study.
- The **properties of FR PE** are strongly temperature dependent, especially during the endothermic decomposition process of the retardant components. In this study, the endothermic decomposition process is omitted.
- The **dripping behaviour** resulting from the burning/melting of ACM core material has not been modelled in this study (see Wang Z, et al 2025 for details).
- **Falling debris** (parts of cladding panels) has not been considered in the model.
- The calculation of toxic gases assumes certain **ventilation conditions**, which depends on the gas monitoring location of interest.

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Conclusions

A recently developed BS 8414 model has been validated using data from nine BS 8414 tests (seven DCLG tests and two FPA tests) involving seven cladding systems.

- The model is able to:
    - correctly predict pass/fail results and mechanisms leading to failures.
    - reproduce flame size and shape as part of the pass/fail process,
    - predict Level-2 temperature profiles in good agreement with experimental results,
    - predict the locations of burnt/burning cladding components.
    - reproduce trends in measured toxic gas concentrations for two BS 8414 tests under appropriate combustion condition assumptions.
- In the FPA tests, the measured CO concentrations may not provide a good representation of the potential toxicity generated from burning wall cladding materials due to limitations associated with the gas sampling location.
- Both the ACM and Insulation can make significant contributions to toxic gas generation.
- For PE/A2 ACM with PIR insulation, predictions suggest that the majority of the peak CO is produced by the burning of the PIR insulation.
- When attempting to reproduce an actual BS 8414 test, it should be kept in mind that the wood crib fire could be significantly different due to natural variations in how wood cribs burn.