Supplementary Materials for the paper:
Fire safety risks of external living walls and implications for regulatory guidance in England

Dr Benz Kotzen[a], Professor Edwin R Galea[b], Shelley Mosco[a], Dr Zhaozhi Wang[b], Dr John Ewer[b], Dr Fuchen Jia[b]

[a] School of Design, Integrated Nature and Technology Research Group (INTENT RG), University of Greenwich, UK
[b] School of Computing and Mathematical Sciences, Fire Safety Engineering Group (FSEG), University of Greenwich, UK

Corresponding author: Prof Edwin Galea e.r.galea@gre.ac.uk

The information presented in this document is the supplementary material for the paper [S1]. There are five sections describing, previously reported living wall (LW) fires (Section S1), the characterisation of plant flammability (Section S2), the classification system used to characterise material reaction to fire (Section S3), the resistance to fire and structure integrity of LW systems (Section S4), and Computational Fluid Dynamics (CFD) simulations of the BS8414 fire test (Section S5).

S1 Fire incidents and experiments involving living walls

Reports of fire incidents involving LWs are comparatively rare. It is not clear if this is due to the limited number of currently implemented LWs, or because the incidence of fire in LWs is currently a rare event or if they are being under-reporting simply because the fires that do occur are seldom of sufficient severity or perceived significance e.g., the 2017 fire at Bligh Street Sydney [S2, S3]. A search of the academic literature and popular media revealed only four reported LW fire incidents since 2012, three of which were potentially significant, one in Sydney, Australia in 2012 and two in London, UK in 2018.

(a) Living Wall Fire, Sydney Australia 2012

The LW caught alight in a semi enclosed beer garden when a patron used a candle to light a cigarette and one of the ferns caught alight resulting in fire spread across the wall in a few seconds [S4]. The newspaper report on the fire noted that some of the plants used on the wall were synthetic '*The plants on the outside were real and maybe the ferns were real but the moss and some of the leaves were definitely plastic'* [S4]. Other notable comments from this journalistic report, which included comments by manufacturers and the fire service, are:

- The installer thought that their LWs were not a fire risk '*as long as there is healthy plant growth, a working irrigation system and an adequate maintenance regime, they are in fact the reverse, fire dampening*';
- Anyone could '*throw up a green wall without knowing what they're doing'*; and
- *'Dead or dry vegetation up the side of a building could certainly present a significant risk of fire spread'* [S4].

The article also drew attention to a new high-rise residential vegetated building at "One Central Park", Sydney where LWs cover approximately 50% of the building's façade area [S5] (see Figure S1). Here the Patrick Blanc designed vertical gardens stretch, '*42m up the building's various faces, they cover 1100 m^2 and incorporate 383 species, 200 of which are native to South East Australia.*

Designed to withstand seasonal conditions, plants which thrive with large exposure to sunlight were selected for the top of the wall, such as Acacias (wattles) and Poa (grasses) while more delicate plants such as Goodenia (hop bush) and Viola (native violet), were chosen for the bottom' [S6]. It is apparent that the plant selection has been in part due to each species' fire response characteristic as certain wattles are known to actually be fire retardant [S7] and *Goodenia* (hop bush) is known as a '*hard to burn'* plant [S8]. However, it is unclear whether all the plants that are used are always fire retardant or resistant, especially the grasses which produce dry stems and seed heads. It is presumed that this potential risk is addressed during routine maintenance visits. The point here, however, is that when it comes to fire, all the risks that can be reasonably known should be addressed within the regulations.

Figure S1. One Central Park, Sydney Australia. (Photograph by Rob Deutscher https://www.flickr.com/photos/bobarc/13160592113, accessed 03.02.2022, licensed under CC BY 2.0 [S9])

(b) Living Wall Fire, Mandarin Oriental Hotel, London UK, 2018

A large LW caught fire at the, then newly refurbished, Mandarin Oriental Hotel Hyde Park, London on 6 June 2018. The London Fire Brigade reported that, '*the fire is believed to have been caused by the by-product of arc welding landing on the felt lining of the planting facade*' [S10]. The hotel had installed green LWs across five facades of its inner courtyard as part of its renovation. '*The fire is believed to have spread across the vertical facade for plants and vegetation and into several floors of the hotel, before it was eventually brought under control'* around 5 hours after it started. *'The external planting facade was damaged along with small parts of several floors of the hotel, the roof and plant machinery on the roof*' [S10]. Unlike the Grenfell Tower fire, where the fire is believed to have started inside the building and spread to the exterior from where it spread up and around the building and back into the building [S11], according to newspaper accounts, the '*fire is believed to have started when plants on outside of hotel burst into flames*' [S12]. Thankfully, there were no casualties or injuries resulting from this fire. A literature search on the causes, results and consequences of the fire yielded few results and whilst it is considered that the fire started from sparks from arc welding, nothing additional has been written on how it spread across the LW, how the fire entered the building from the outside, what parts of the LW were involved in the fire and what parts were not? The important issue here is that the LW, like the cladding at Grenfell, acted as a propagation route for the fire over the building exterior as well as into the building. The consequences of this fire, and the much smaller Sydney fire, were fortunately only financial and reputational; however, it is suggested that as a result of these fires confidence in the fire safety of LWs has been damaged until the appropriate testing and other regulatory measures are put in place.

(c) Living Wall Fire, Block of Flats, Ealing, London, UK 2018

This fire, which occurred on 5 August 2018, destroyed a LW and decking on the 7th floor of a residential building (see Figure S2) [S13]. The external fire gained entry into the building damaging parts of the 7th and 8th floor corridors. Videos of the fire from a nearby block of apartments show dry vegetation burning fiercely and crossing over from one part of the LW across a door onto the 7th floor roof and a window on the 8th floor. As can be seen in video footage, the speed of fire propagation is remarkably fast [S13, S14]. The cause of the fire was most likely a discarded cigarette or match (London Fire Brigade) [S15].

Figure S2 Green wall fire in London in 2018 (image is reproduced from video clip on twitter by @Miss_AnitaRaj 5 August 2018 [S13])

(d) Experimental fire study involving living walls, City University of Hong Kong, Hong Kong, China

A numerical study undertaken by the University of Hong Kong involved igniting a LW in an underground corridor [S16]. The study used three plants of different leaf thicknesses relating to variable leaf moisture content. The findings demonstrated that while it was not possible to ignite the LW composed of fresh living plants, fire risk increases gradually with the drying out of plants. In addition to the simulated underground corridor fire, a scaled corridor fire experiment using Bermuda grass demonstrated that the fire propagated rapidly in the vertical direction of the LW, whereas fire propagation in the horizontal direction was slower [S16]. The study illustrated the importance of proper plant selection and that dried out plants easily ignite and propagate fire and smoke upwards in a short period of time. This in turn can have a significant impact on the evacuation of building occupants should the fire and smoke gain access to the building interior. This study also highlights the importance of proper maintenance of vegetation to minimise fire risk.

S2 Plant flammability

Unfortunately, to date, there has been little research concerning the flammability properties of plant species used in LWs. One exception is the work of Dahanayake et al. [17], who conducted cone calorimeter experiments for three species of plants used in LWs, namely: Hedera helix, Peperomia obtusifolia and Aglaonema commutatum. They evaluated the peak Heat Release Rates (HRR) of both moist and dry specimens and also the Total Heat Release (THR). The average physical characteristics of these plant species and the key experimental results are presented in Table S1. The moisture content (i.e., the mass ratios of water to dry plants), for the three plant species are 326%, 1371% and 1150% respectively. When the plants were fresh and green, no ignition was observed for all three species. Hedera helix started to ignite once the moisture concentration was lower than 243%, at a constant heat flux of 50 kW/m^2. Peperomia obtusifolia began to ignite once the moisture concentration dropped below 200%, at a constant heat flux of 20 kW/m^2. Ignition occurred in the Aglaonema commutatum plant, once the moisture concentration was lower than 316%, at a constant heat flux of 50 kW/m^2. The peak HRRs for the three plant species, when dry, are 200 kW/m^2, 202 kW/m^2 and 121 kW/m^2 respectively, while the THR are approximately, 10 MJ/m^2, 5 MJ/m^2 and 3 MJ/m^2 respectively. The combustibility data for these three LW plant species suggest:

- Maintenance of LWs is critical for fire safety in order to ensure that plants are kept healthy and moist, and that dry, dead and overgrown plant material is removed. This makes it more difficult for the plants to ignite, reduces the risk of fire spread and lowers the total heat release potential.
- The risk of fires in LWs can be reduced by selecting plants with low peak HRRs and low THR.

Table S1. Characteristics and cone calorimeter data of three LW plant species [S17]

	Hedera helix	Peperomia obtusifolia	Aglaonema commutatum
Height (mm)	300	150	300
Branch diameter (mm)	20	60	90
Leaf thickness (mm)	1	3	1
Weight (g)	30	70	30
Density (g/cm^3)	0.1	0.08	0.08
Moisture content (%)	326	1371	1150
Time to dry (day)	20	75	75
Maximum Relative moisture concentration (%) for ignition (under a given heat flux (Kw/m^2))	243 (50)	200 (20)	316 (50)
Peak HRR for fresh plant (kW/m^2)	3	1	3
Peak HRR for plant after 75 days (kW/m^2)	200	202	121
Total heat release (MJ/m^2)	10	5	3

In contrast to the plants used in LWs, plant flammability is an area of significant research interest in regions where wildfires (also known as forest fires and bush fires) are prevalent e.g., California, Oregon, the western provinces of Canada, Southern France, Portugal (particularly where eucalyptus estates have replaced traditional cork oak groves), Greece and Victoria and New South Wales, Australia. While this research is primarily concerned with trees and shrubs found in forests, it is relevant to LWs in terms of the methods and principles for how LW plantings and their design may be approached. The Country Fire Authority (CFA) in Victoria, NSW and FIRESafe Marin, Marin County, California, have each produced guides for residential gardens and landscape, to help reduce the risk of fire in urban settings. The components of plant flammability defined by

White and Zipperer [S18] is, *'ignition (heat source and time to ignition), combustibility (time of combustion after ignition), consumability (amount of plant material consumed by combustion) and sustainability (degree of combustion sustained once ignited, with and without continued heat source)'*. Their research was used to inform the guides produced by FIRESafe Marin and CFA Victoria. A report by the University of California Cooperative Extension [S19] adds that determining plant flammability, *'is complex due to the multiple perspectives that may be tested and the interdependence between the components (e.g., combustibility, consumability and sustainability are dependent on ignitability)'*. To assist in the selection of plants that are fire-resistant and to identify, and hence avoid, plants that are fire-hazardous, FIRESafe Marin (of Marin County California) have developed a plant catalogue specifically taking into consideration common plants found in the region. The catalogue also identifies plant characteristics to avoid in order to reduce fire risk [S20].

In Australia, the CFA (Country Fire Authority) of the state of Victoria published 'Landscape for Bushfire' [S21]. Of particular note is 'Section 5 Choosing Suitable Plants' which details criteria for plant flammability based on environmental (real world) conditions, which includes the importance of maintenance. The document also notes that it is imperative to appreciate that plant attributes cannot be assessed in isolation to determine their risk of ignition and combustibility and that plant flammability will vary depending on the following:

- A plant's age, health, physical structure and chemical content;
- Daily and seasonal climatic variations;
- Location of the plant in relation to other vegetation and flammable objects; This is also considered in 'good planting design' i.e., the selected placement of plants in proximity to each other (choosing less flammable varieties of plants to act as 'fire-breaks' in a design mix);
- The specific part of a plant – some parts of plants are more flammable than others;
- Plant moisture content: foliage moisture content is the most critical factor that determines plant flammability. It influences how readily a plant will ignite. It is also related to environmental conditions, age and growth stage of a plant;
- Branching pattern: in reference to foliage distribution and density – a loose open pattern is less flammable;
- Texture: With regards to surface area to volume ratio – fine textured plants (e.g. Common box, *Buxus sempervirens*) are more flammable;
- Density: Describes the amount of fuel within a plant – very dense plants have a higher fuel load (and are therefore more flammable);
- Leaves: This relates to their moisture content. Wide, flat, thick leaves and soft and fleshy leaves usually have a higher moisture content relative to their surface area and so take longer to dry out and are less likely to catch fire;
- Oils, waxes and resins: Leaves of plants containing significant amounts of oils, waxes and resins will often have a strong scent when crushed. For example, rosemary and lavender have oil in their foliage and pines can have high resin content; and
- Retention of dead material: This relates to maintenance operations. Dried seed heads, dead leaves, stems or twigs can increase the fuel present and flammability.

And more generally, plant flammability and ignition characteristics will depend on plant seasonality and natural patterns of growth. Appropriate plant maintenance and care is of paramount importance in maintaining the health of plants and ensuring that they do not become dry or die, and thereby potentially changing their flammable characteristics. Changes in plant flammability characteristics resulting from poor maintenance may be gradual and occur over an extended period of time. A LW that has acceptable fire safety characteristics while the plants are healthy, may become non-compliant as the plants dry out or once the majority of the plantings are dead. Thus, without appropriate maintenance, the fire rating of a LW can change and degrade over time. This also has implications for regular compliance checking, including the competence of the assessors.

S3 Reaction to fire material classifications

Presented in Table S2 is a summary of the reaction to fire material classifications extracted from BS EN 13501-1: 2018 [S22]. Please refer to the standard for a full description of the classification system.

Table S2: Summary of the classes of reaction to fire performance for construction products excluding floorings and linear pipe thermal insulation products (For full details relating to the superscripts please refer to the original table in [S22]).

Class	Test method(s)	Classification criteria	Additional classification
A1	EN ISO 1182 and	$\Delta T \leq 30$ °C; and $\Delta m \leq 50$ %; and $t_f = 0$ s (i.e. no sustained flaming)	-
	EN ISO 1716	$PCS \leq 2{,}0$ MJ/kg and $PCS \leq 2{,}0$ MJ/kg and $PCS \leq 1{,}4$ MJ/m² and $PCS \leq 2{,}0$ MJ/kg	-
A2	EN ISO 1182 or	$\Delta T \leq 50$ °C; and $\Delta m \leq 50$ %; and $t_f \leq 20$ s	-
	EN ISO 1716 and	$PCS \leq 3{,}0$ MJ/kg and $PCS \leq 4{,}0$ MJ/m² and $PCS \leq 4{,}0$ MJ/m² and $PCS \leq 3{,}0$ MJ/kg	-
	EN 13823	$FIGRA_{0,2\,MJ} \leq 120$ W/s and LFS < edge of specimen and $THR_{600s} \leq 7{,}5$ MJ	Smoke production and Flaming droplets/particles
B	EN 13823 and	$FIGRA_{0,2\,MJ} \leq 120$ W/s and LFS < edge of specimen and $THR_{600s} \leq 7{,}5$ MJ	Smoke production and Flaming droplets/particles
	EN ISO 11925-2 : Exposure = 30 s	$F_s \leq 150$ mm within 60 s	
C	EN 13823 and	$FIGRA_{0,4\,MJ} \leq 250$ W/s and LFS < edge of specimen and $THR_{600s} \leq 15$ MJ	Smoke production and Flaming droplets/particles
	EN ISO 11925-2 : Exposure = 30 s	$F_s \leq 150$mm within 60 s	
D	EN 13823 and	$FIGRA_{0,4\,MJ} \leq 750$ W/s	Smoke production and Flaming droplets/particles
	EN ISO 11925-2 : Exposure = 30 s	$F_s \leq 150$ mm within 60 s	
E	EN ISO 11925-2 : Exposure = 15 s	$F_s \leq 150$ mm within 20 s	Flaming droplets/particles
F	EN ISO 11925-2 : Exposure = 15 s	$F_s > 150$ mm within 20 s	

S4 Resistance to fire and structure integrity

In terms of fire safety, the suitability of building materials can be assessed and ranked by measuring the fundamental fire properties of the materials using specific fire tests. These tests determine fire related properties such as, ease of ignition, ease of flame propagation and the amount of heat released. The metal structure used to support or install the LW module panel will, generally, not contribute to the combustion or heat released in a fire; however, fire temperatures may be sufficient for the metal to lose a significant proportion of its strength and deform, or even to melt, resulting in the full or partial collapse of the LW system. This may further aid fire spread as well as presenting an additional risk to people at ground level.

The importance of the fire performance of structural materials supporting a LW was demonstrated in series of five fire tests described in GWGD [S23]. The tests involved five different LW systems, excluding the plantings but including the growth medium and support structures which included, HDPE boxes filled with rockwool, HDPE modules filled with substrate, Aluminium mesh cassettes filled with growing medium, Porous plastic irrigated boards and Stacked HDPE planters filled with growing medium. The tests were undertaken using the SBI protocols (see section 3 and Section 4.2 of the main paper [S1]). All five LW systems failed the SBI test. For three of the samples the test was terminated before 10 minutes due to the heat release exceeding 350 kW and for the other two samples the tests were terminated because the specimens collapsed onto the burner.

S5 CFD simulations of BS 8414 fire test

SMARTFIRE has been used to develop a simulation fire test environment for assessing fire spread on rainscreen cladding wall systems. The simulation system has been successfully used to simulate seven DCLG cladding wall tests with generally good agreement between the full-scale burn experiments in the BS8414 reports and the simulation findings. These agreements concur both on the approximate times to failure and the mode of failure, indicating that CFD simulation is a viable tool when adequate material properties data is available for the materials and components of the tested systems.

Presented in Figure S3 is a representation of the BS8414 [S24] test geometry and configuration implemented within the SMARTFIRE CFD fire simulation software [S25-S28] for wall cladding applications. Within the model, the software represents the ACM cladding panels, insulation, intumescent barriers, and wood crib fire volume. The pyrolysis of the ACM core material and the insulation material is simply modelled using the surface ignition temperature with prescribed fuel release rates. The material properties for Polyethylene and PIR etc., from the experimental work by McKenna S.T. [S30], are used in the simulations. Presented in Figure S4 is a representation of simulation results produced by the SMARTFIRE BS8414 model for a hypothetical ACM cladding material [S29]. The figure represents snapshot of the predicted results at the time of specimen failure.

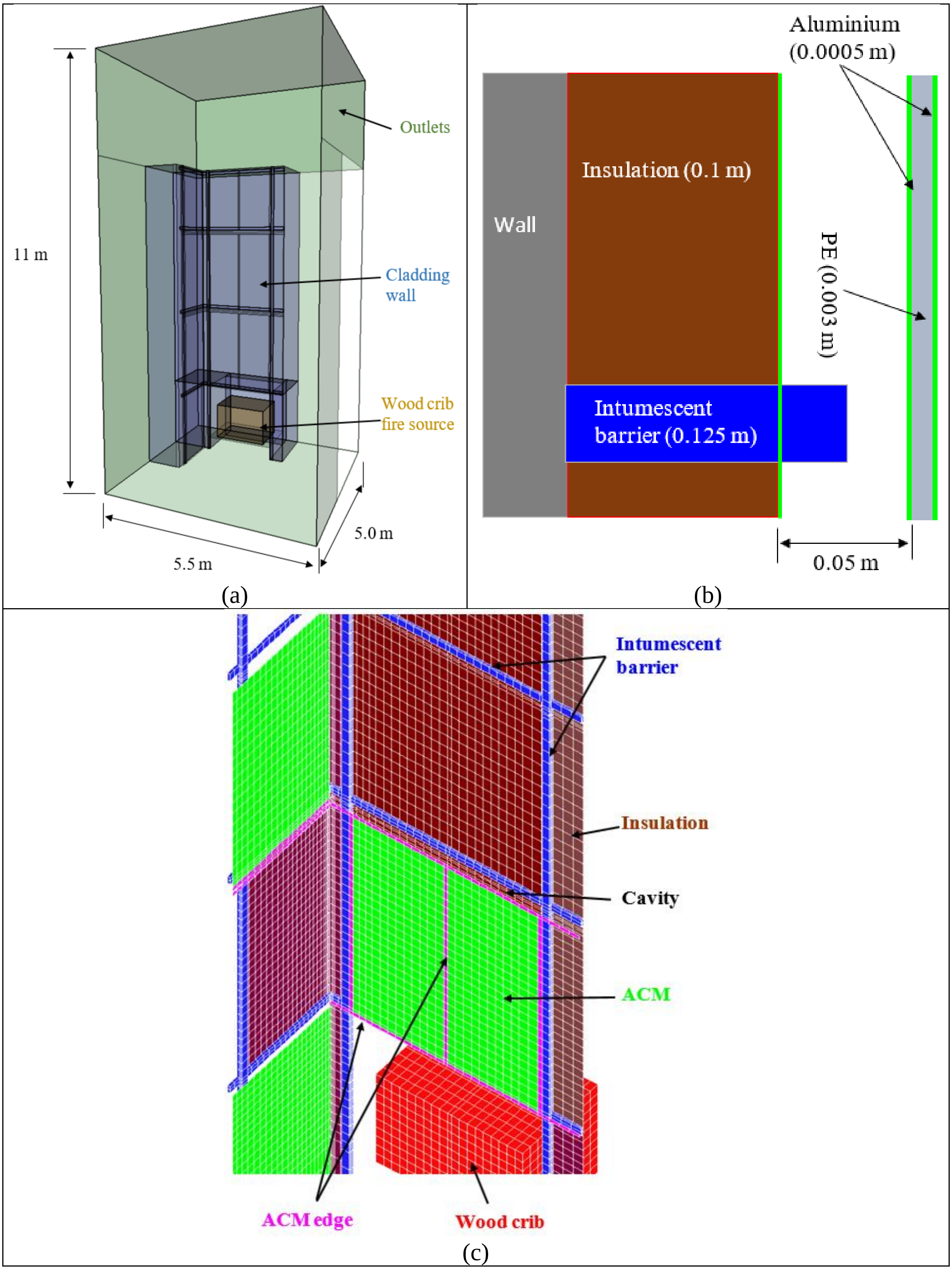

Figure S3. Representation of the BS8414 test within the SMARTFIRE CFD fire simulation software (a) computational domain for the BS8414 test simulation; (b) schematic showing a side view through the modelled cladding system; (c) detailing of the modelling representation of the ACM panels, insulation, intumescent barriers, and wood crib fire volume.

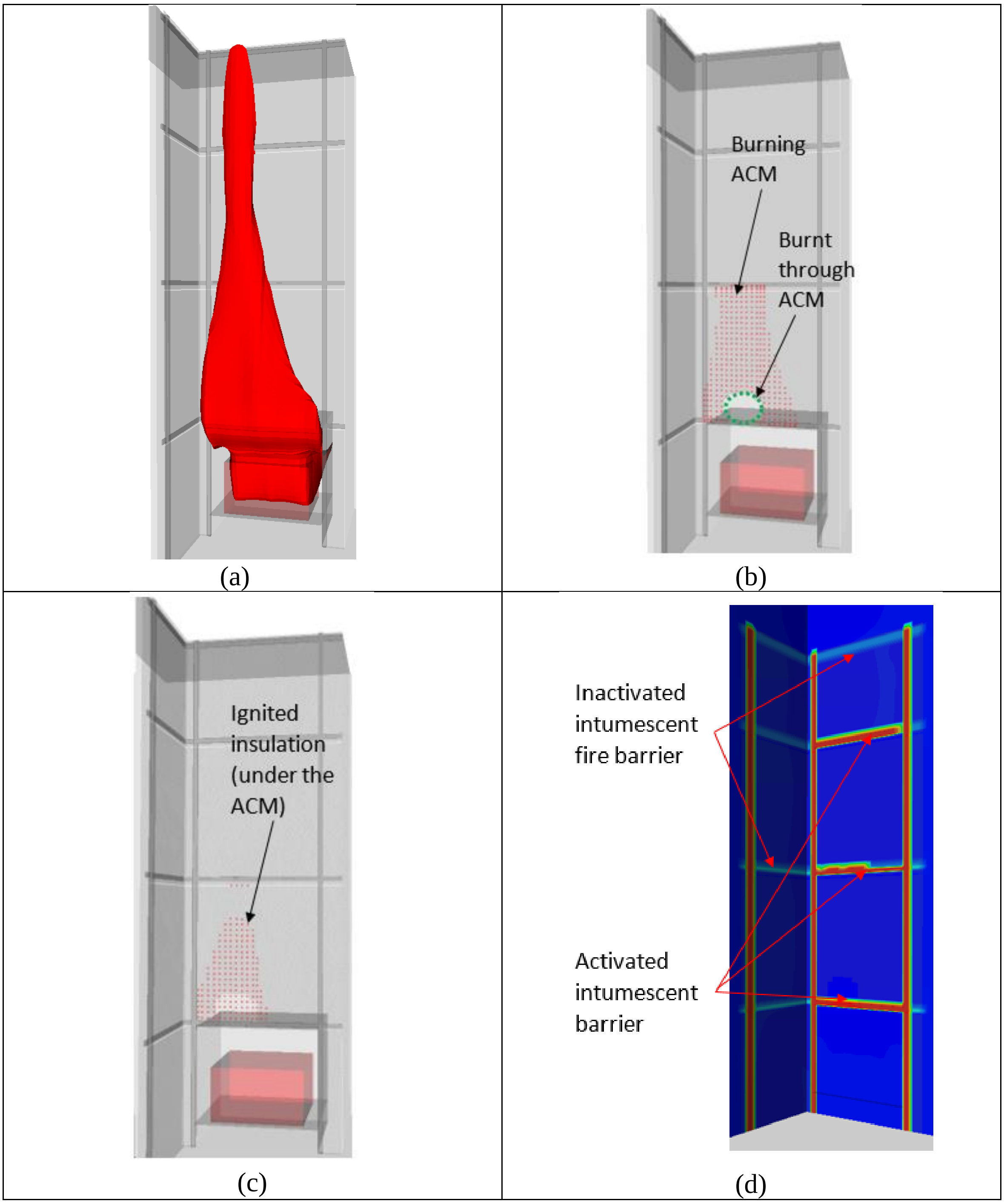

Figure S4. Predicted status at the time of specimen failure during simulated BS8414 test (a) 525 ^{O}C temperature iso-surface (minimum temperature of visible flame) depicting fire plume; (b) the burning ACM panel (dots) and the burn-through area (circled); (c) the ignited insulation layer under the ACM; and (d) active state of the intumescent in the horizontal wall barriers.

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