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Guillaume, E., Drean, V., Girardin, B., & Fateh, T. (2022). Reconstruction of the Grenfell tower fire—Part 6—Numerical simulation of the Grenfell tower disaster: Contribution to the understanding of the tenability conditions inside the common areas of the tower. *Fire and Materials*, 46(7), 1061-1079.
<https://doi.org/10.1002/fam.3053>

[Link to publication record in Ulster University Research Portal](#)

Published in:
Fire and Materials

Publication Status:
Published: 03/10/2022

DOI:
[10.1002/fam.3053](https://doi.org/10.1002/fam.3053)

Document Version
Publisher's PDF, also known as Version of record

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RESEARCH ARTICLE

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Reconstruction of the Grenfell tower fire—Part 6—Numerical simulation of the Grenfell tower disaster: Contribution to the understanding of the tenability conditions inside the common areas of the tower

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Summary

The recent dramatic events at Grenfell Tower in London involving a combustible façade system have raised concerns regarding the fire risk that these systems pose. The spread of fire over the façade of the Tower was previously modelled numerically and the results of this modelling were validated by comparison with observations of the real fire. This model was used to determine the fire behaviour of the façade and the propagation of the façade fire into the apartments through windows. The modelling used an impact model according to ISO 13571 and included fire loads from the façade and, when relevant, from apartment contents. Tenability levels inside the apartments were quantified by an analysis of the toxic and thermal conditions due to the combustion of the façade materials and the apartment contents. In the present paper, the conditions inside the lobbies and stairs of the Tower are investigated, building on the previous analysis of the apartments. This allows an understanding of the evolution of toxic and thermal conditions whilst the fire spread, and their impact on egress during the fire event.

KEYWORDS

façade system, fire propagation, impact model, numerical simulation, toxicity

1 | INTRODUCTION

Grenfell Tower is a 24-storey high-rise building located in London, refurbished in the period 2012–2016 with a new insulated ventilated façade system and new windows installed on all of the building's elevations.

The Grenfell Tower tragedy happened on June 14th 2017. The fire spread to the façade via external flaming from an apartment located in a lower residential floor of the east face of the Tower. This has been extensively detailed in expert reports to the Grenfell Tower Inquiry^{1–5} and in video and photographic records of the real fire. These records were used to provide an analysis of the post-break-out

vertical and horizontal fire propagation over the whole façade of Grenfell Tower in reference 6.

The Grenfell Tower fire resulted in 71 fatalities. Fire smoke leads to reduced visibility, burning of exposed skin due to radiant and convected heat, and burns to the mouth and nose if hot air is inhaled. Effects of heat exposure are dose-related, depending on the intensity of heat radiation, smoke temperature and exposure duration. Smoke also contains irritant and asphyxiant gases. As tenability becomes compromised, irritant species will affect the eyes, nose, throat and cause breathing difficulties. They also affect behaviour to a certain degree, causing tears and coughing, limiting visibility and movement.⁷ The effects of exposure to asphyxiants, including carbon monoxide

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(CO), hydrogen cyanide (HCN) and carbon dioxide (CO₂), depends on the inhaled dose over a period of time and, thus, on the concentrations of these species and the duration of the exposure. Effects depend on the variability of human responses to toxicological injuries. Depleted oxygen may also be a parameter driving tenability.⁸ Thus, the contribution of any burning materials in terms of mass loss rate, yields of products released, etc., as well as the conditions under which they burn (well- or under-ventilated conditions), must be considered, in order to evaluate tenability in terms of toxicity and thermal effects.⁹⁻²²

Observations from the disaster have shown that the fire spread over the Tower can be split in different periods. During the period from 01:08 a.m. to 01:29 a.m., approximately, external flames spread over its east face. After this, dense irritant smoke started to accumulate in the burning apartments, and spread via the front doors of these apartments into common lobbies and stairwell, because of the weak fire performance of the doors, and because the doors were left open during egress or because of the actions of firefighters. The smoke gradually caused occupants to evacuate their apartments, and moved, either to apartments on the same floor or to apartments on lower or upper floors via the stairs. Occupants who remained in their apartments were affected by increasing amounts of toxic smoke from outside (from the façade fire and from the burning contents of lower apartments) and from the lobbies. As the fire spread over the façade, window failures led to the development of more and more apartment content fires. The applicable Building Regulations required prescribed levels of fire resistance between apartments and between each apartment and common areas, such as the lobbies, and the façade was supposed to “adequately resist the spread of fire.” The common lobbies should be fire resisting and be able to remain separated from the main escape stair for at least for 30 min, in a fully developed fire. Naturally, this value is highly theoretical and does not consider smoke leakage, such as the opening of a door during a fire. Regardless, these measures should prevent smoke from entering the lobbies and stairs, allowing occupants to evacuate in safe conditions without exposure to toxic smoke and heat.

Numerical simulation is a useful investigative tool to understand and analyse such a disaster, and it makes the evaluation of particular phenomenon easier. The fire behaviour of the Grenfell Tower façade build-up was simulated using the computational fluid dynamics (CFD) code Fire Dynamics Simulator (FDS)²³⁻²⁶ to determine the vertical and later horizontal fire spread over the façade in references 28 and 29. The model was validated^{29,30} by comparison with the results of intermediate and large scale fire tests,^{31,35-39} and showed that the Aluminium Composite Material (ACM) with a polyethylene (PE) core (ACM-PE) cladding was the main element driving the global fire behaviour of façade construction, regardless of the insulant used. The fire development inside the initial apartment of Grenfell Tower and its behaviour at the kitchen window was numerically investigated in reference 32. A complementary thermomechanical analysis of window failure was performed previously and reported in reference 33. The simulated fire propagation was consistent with observations from the night of the disaster.⁶ The simulation allowed the evaluation of local concentrations of effluents and temperature conditions in each room

(kitchen, living room and bedroom) of each apartment. In reference 34, an impact model was considered including fire loads from the façade system and from apartment contents, where relevant. This allowed the quantification of the conditions inside the Tower, by an analysis of the toxic and thermal contributions from combustion of both the façade components and each apartment's contents. The analysis of tenability conditions inside Grenfell Tower showed that the same conclusion can be made regardless of the input data for toxic gas yields or the model used, within the limits of the studied dataset and conditions. The overall conclusion was that the effluent from burning apartment contents quickly drove tenability conditions.

This multi-step research was performed with highly interdependent parts, both experimental and numerical. The diagram in Figure 1 describes the whole approach from the very first step of this research.

In the present paper, a detailed model of the four uppermost floors (20th to 23rd) of the Tower is addressed, because the higher floors of the Tower experienced the worst tenability conditions. An additional model for the lower floors (10th to 13rd) was developed to provide adequate boundary conditions to upper floors, since both firefighters and occupants reported untenable conditions in lobbies and the stairwell between the 10th and the 16th floors. Floors 14th to 19th were not modelled since it is assumed that there was no contribution from these lobbies because no occupants left these floors after 01:50 a.m.

The simulation takes into account the real geometry of each apartment, lobby and stairs. For each room in each apartment, the effluent concentrations and temperature are fixed by prior analysis of the horizontal fire spread over the Tower. The tenability conditions, in terms of carbon monoxide, hydrogen chloride, hydrogen cyanide and gas temperature can thence be evaluated for each lobby and the stairwell.

This investigation sheds light on the impact of toxic and thermal conditions inside the Tower depending on the evolution of the fire spread over the four faces of the Tower.

This publication does not assess tenability conditions for individual occupants, for two reasons. First, such analysis requests a lot of behavioural and movement data that is not necessarily available and may be highly speculative, reducing the validity of the analysis. Second, individual cases are ethically difficult to analyse in such recent fire with many fatalities and an inquiry still undergoing. So, only general tenability conditions are presented hereafter. In this research, individual situations are not addressed. The work presented is very sensitive to the assumptions made, and it is our decision not to extrapolate to individual cases.

SPECIAL ATTENTION: in this research, the situations of individuals are not addressed. The work presented is very sensitive to the assumptions made, and the results cannot and should not be extrapolated to the plight of individuals.

2 | UNDERSTANDING THE TENABILITY CONDITIONS INSIDE THE APARTMENTS FOLLOWING THE FAÇADE FIRE

The study addressed in this paper is the culmination of a multi-step research approach (Figure 1). A brief summary of this approach is

addressed in this section. It allows synthesizing the assumptions and results from the previous steps that are used in the present research.

The three-dimensional CFD model of Grenfell Tower, addressed in references 27, 28 (Figures 2 and 3), was constructed using component data that had been validated by a study of the thermal and combustible characteristics of façade systems at experimental scales.^{29,30} The heat release rates of apartment content fires detailed in reference 32 were used for each floor of the Tower. The apartments are

numbered as follows: X1 for the one bedroom apartment on the east face of the Tower, X2 for the south east two bedrooms apartment, X3 for the south west two bedrooms apartment, X4 for the one bedroom apartment on the west face of the Tower, X5 for the north west two bedrooms apartment and X6 for the north east two bedrooms apartment. The failure criteria of windows assessed in reference 33 were implemented for each apartment opening. In the global model of the Tower, no path was provided for fire spread between apartments by

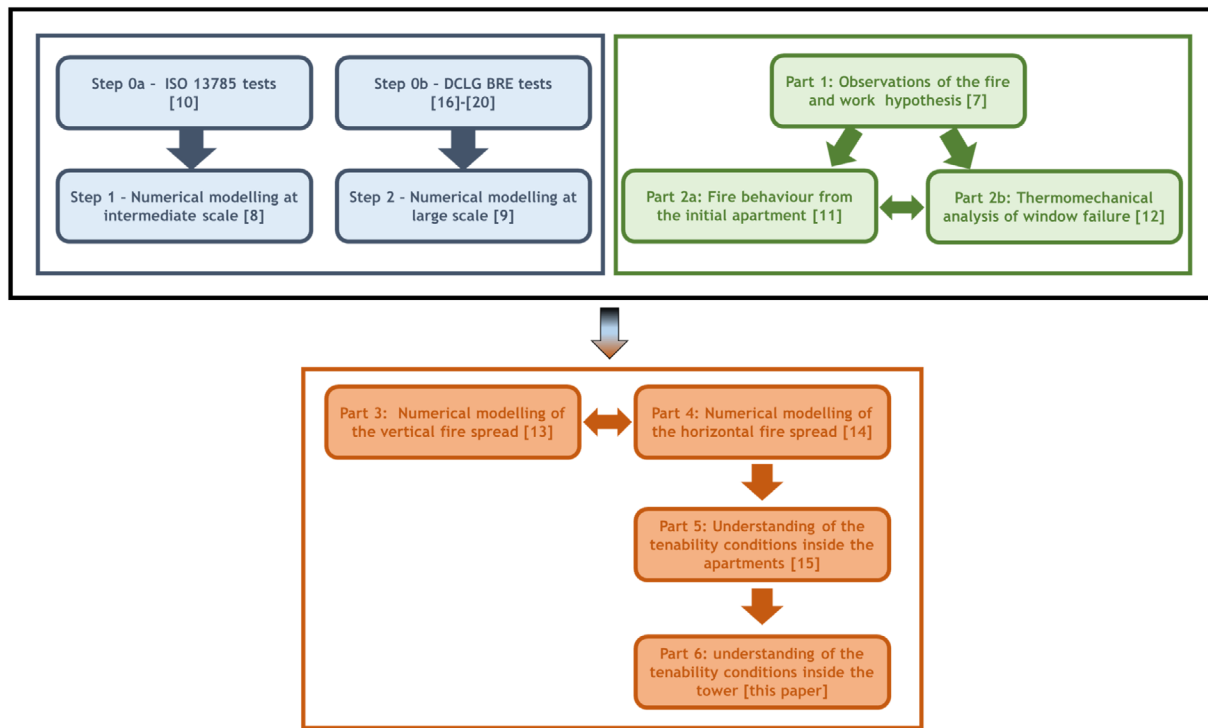


FIGURE 1 Synthesis of the whole approach from the very first step of this research to the actual paper—highly interdependent parts, both experimental and numerical

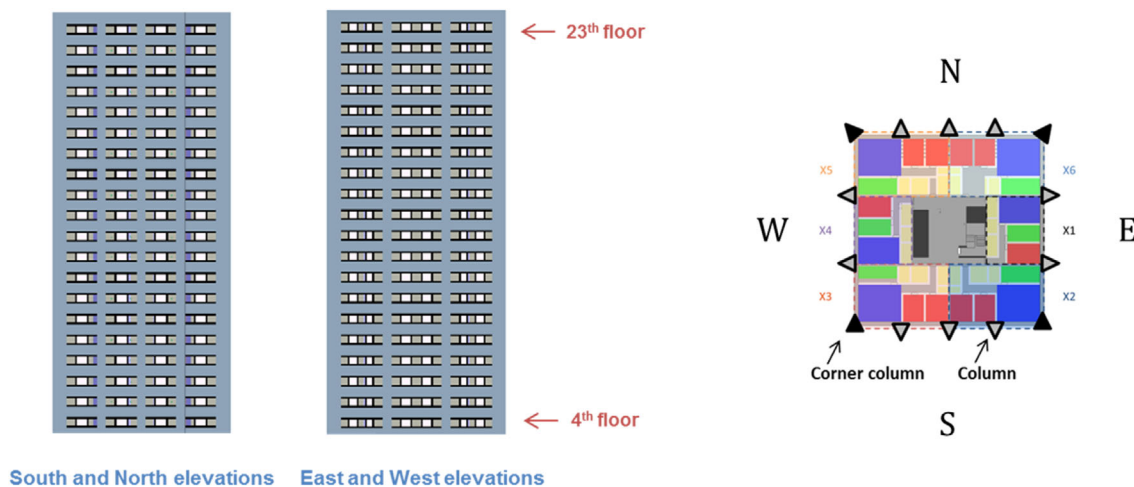


FIGURE 2 Numerical models of the south/north and east/west faces of the Tower—Overview of the spatial arrangement of apartments and columns

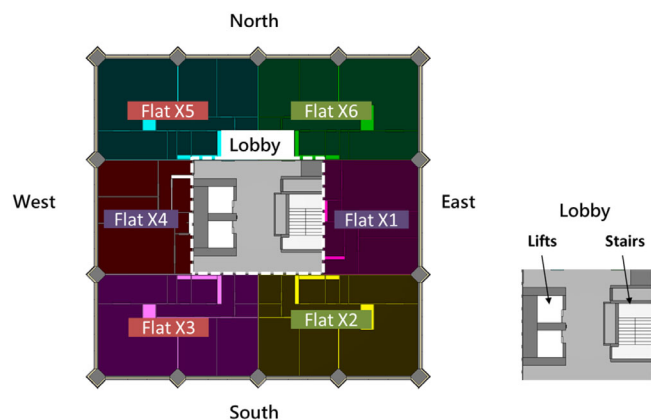


FIGURE 3 Schematic of the spatial arrangement of each floor

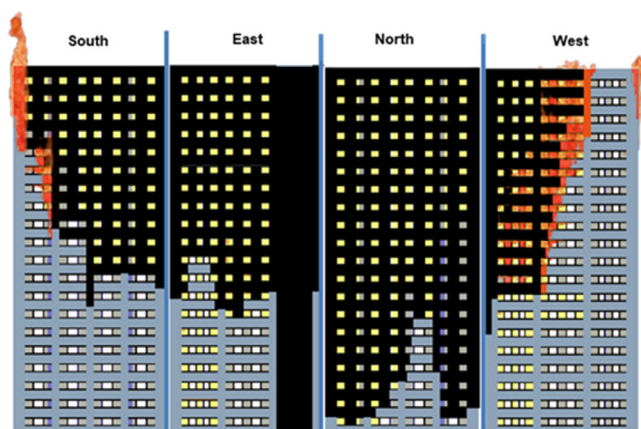


FIGURE 4 Numerical simulation of fire propagation over the four faces of the Tower at 04:00 a.m.²⁸

ducts, HVAC systems, or by holes in ceilings or walls. Fire propagation between apartments (horizontally or vertically) could only occur via the façade and subsequent window failure. This work calculated the fire conditions, over time, at every location on the façade and inside the apartments, in terms of burning condition, window failure, heat release rate and effluent concentrations (Figure 4).

This whole approach allowed the understanding of the interactions between apartments and the façade fire,³⁴ and highlighted the importance of the apartment contents themselves as the main contributor to the loss of tenability conditions (via both thermal and toxic effects) inside the Tower. An impact model was created including fire loads from the façade system and apartment furniture (as and when the fire propagated into the apartments). The study addressed the analysis of different apartments in Grenfell Tower, taken as examples, to assess tenability conditions inside the Tower. Tenability was assessed in terms of toxicity according to ISO 13571^{7,40} and recent proposed alternative method.⁴¹ An extensive literature review was conducted to investigate the CO and HCN yields that were assumed in simulations when calculating toxicity effects.

Three different combustion gas yield assumptions were investigated for both the apartment furniture and the PIR façade insulant, leading to nine combined combustion gas yield scenarios. This led to the quantification of the individual contributions of the façade components and the apartment's contents to the impact of toxicity on apartment occupants. The analysis showed that just after window breakage, effluents from the external combustibles such as the ACM-PE cladding and polyisocyanurate (PIR) façade insulant were dominant. Some contribution of the apartment furniture was already contained inside the plume from apartment fires lower in the Tower. When the apartment contents ignited, a few minutes after the

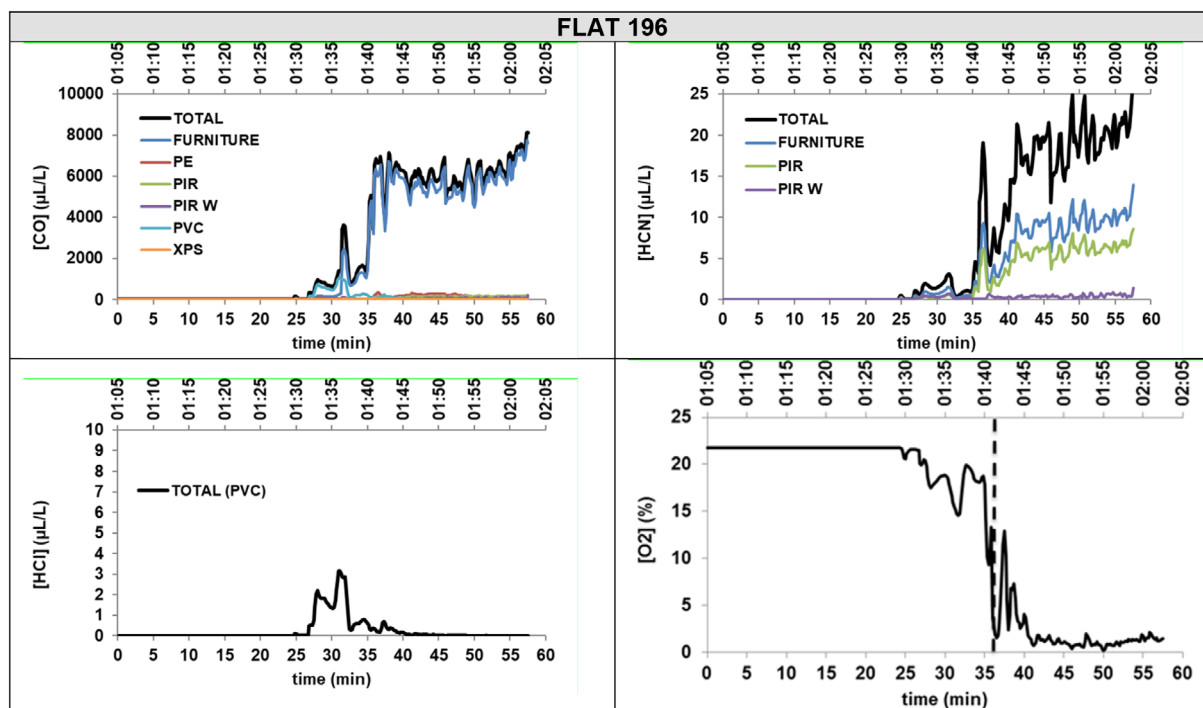


FIGURE 5 Example of species concentrations and main contributors in the living room of Flat 196—Gas yield scenario 1 from reference 34

window breakage, their contribution increased and those of the PIR façade insulant decreased as the incoming flow from the exterior reduced. The contributions from the façade infill panels and the window reveal insulant appeared to be negligible in all scenarios. For the majority of the apartment locations and nine gas yield scenarios investigated, due to the ignition of the apartment contents, oxygen depletion was reached first, or at a similar time to the thermal or toxic FED. This occurred less than 15 min after window failure and fire entry. An example of results for species concentrations in the living room of Flat 196 evaluated in reference 34 is addressed in Figure 5. These evolutions are used as input for each room of each flat in the present research, depending on the flat location. The different yields used in the initial study³⁴ are reminded in Table 1.

The analysis of tenability conditions inside Grenfell Tower showed that, within the limits of the studied dataset and conditions, the same conclusion can be made regardless of the input data for toxic gas yields and the model used. The overall conclusion was that fires involving apartment contents quickly drive tenability conditions, independently of the dataset and model used, and even if non-combustible insulant is used instead of PIR as façade insulant. Thus, the temperature and toxicity conditions were evaluated numerically in every apartment of the Tower, and the authors have estimated the

TABLE 1 Synthesis of the yields for the gas species considered in reference 34 to assess tenability conditions in each flat of the Tower with time, depending on ventilation conditions and leading to 9 ventilations scenarios

		Well-ventilated (g/g)		Under-ventilated (g/g)	
		[CO]	[HCN]	[CO]	[HCN]
Apartment furniture	MAX	0.060	0.006	0.290	0.013
	AVE	0.037	0.003	0.160	0.007
	MIN	0.015	0.001	0.029	0.001
PIR façade insulant	MAX	0.070	0.0050	0.350	0.025
	AVE	0.060	0.0045	0.210	0.015
	MIN	0.050	0.0040	0.070	0.005

most severe and the most probable of the nine scenarios that were calculated.

In this paper, based on these conclusions, a further analysis of conditions in the uppermost four storeys (floor 20th to 23rd) of the Tower is described. It was on these floors of the Tower where the most fatalities occurred and for which observational data exists on the opening and closing of apartment front doors and the evolution of tenability conditions. Furthermore, the worst tenability conditions occurred in the higher floors of the Tower. The simulation takes into account the real geometry of each apartment, lobby and stair. For each of those rooms, the local effluent concentrations as well as the local temperature are set numerically from the previous analysis of the tenability conditions in each apartment.³⁴ Carbon monoxide, hydrogen cyanide and hydrogen chloride concentrations, and gas temperature can thus be evaluated in the lobbies and stairwell.

3 | EVALUATION OF THE CONDITIONS INSIDE THE COMMON AREAS OF THE TOWER

Following on from the analysis of tenability conditions inside the different apartments, summarized earlier, a detailed model of the uppermost four floors (floors 20th to 23rd) of the Tower was created. This allows an understanding of the evolution of the toxic and thermal conditions in the lobbies and stairwell of the Tower, as influenced by the smoke and heat migration from the various apartments.

The numerical simulations were performed with the Computational Dynamics (CFD) code Fire Dynamics Simulator (FDS) version 6.7.0. FDS is a computational code in fluid dynamics that incorporates a combustion model and a large scale model (LES) for the description of turbulent flows. This tool allows 3D modelling of the computational domain. It considers heat transfer at walls, ventilation conditions for the removal of hot gases and air intake. The Navier-Stokes equations are solved in the limit of low Mach number, thermally driven flow with an emphasis on smoke and heat transport from fires. The radiative heat transfer is included in the model through the solution of the radiative transport equation for a grey gas. The default sub-models of FDS were used for the gas phase radiation exchanges with

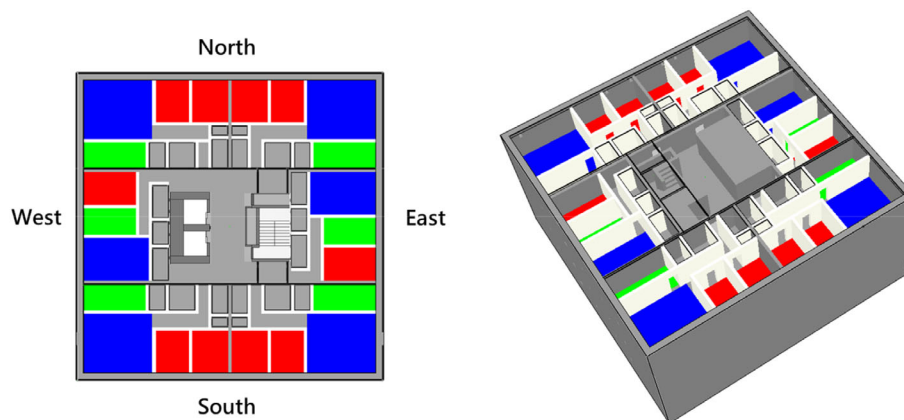
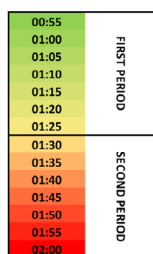


FIGURE 6 Schematic of the numerical model from reference 34—spatial arrangement of apartments, lobby and stairs

TABLE 2 Synthesis of the conditions in each apartments from the 1st to the 23rd floors from the analysis of expert report's¹⁻⁵ and from 999 calls of the occupants⁵

FLOOR	FLATS F	CONDITIONS in LOBBY (am)		CONDITIONS in STAIRS (am)		FIRES in FLATS (am)			DOORS OPENINGS (am)	EGRESS by FLOOR and TIME (am)				
		LIGHT SMOKE	THICK SMOKE	LIGHT SMOKE	THICK SMOKE	Fire in X6 flats (F)	Fire in other flats (F)	Fire in other flats (F)						
1	-	01:08								nobody at 11h after 02:00				
2	-			01:30						nobody at 2th after 02:00				
3	-			01:30						nobody at 3th after 02:00				
4	1X	00:56	from F16	01:10	01:30	01:48	00:54	F16	01:05	nobody at 4th after 02:00				
5	2X	01:20		01:31	01:30	01:48	01:15	F26	01:20	nobody at 5th after 02:00				
6	3X	01:00	from air vents	01:21	01:30	01:35	01:17	F36		nobody at 6th after 02:00				
7	4X	01:21	between lift/stairs	01:35		01:35	01:21	F46		nobody at 7th after 02:00				
8	5X	01:10	from F56	01:21		01:35	01:10	F56		nobody at 8th after 02:00				
9	6X	01:30	from hole in the wall	01:35		01:35								
10	7X	01:28		01:28		01:35			01:50					
11	8X	01:26	from air vents	01:28	01:40	01:50	01:20	F86	02:53	F81	01:25			
12	9X	01:24	from F96	01:30		01:50	01:24	F96						
13	10X	01:30				01:50					nobody at 13th after 02:00			
14	11X	01:25		01:40	01:25	01:50	01:29	F116	02:22	F111	02:22	F115	01:38	nobody at 14th after 02:53
15	12X	01:30		> 03:00		01:50			02:22	F122				
16	13X	01:10		01:40	01:38	01:46	01:10	F136	02:20	F135	02:22	F132	01:30 + 01:40 + 01:38	nobody at 16th after 01:35
17	14X	01:20	from F146	01:30		01:50	01:20	F146	02:25	F142	> 03:43	F144		nobody at 17th after 01:30
18	15X	01:20		01:43	01:33	01:50			01:52	F151	02:22	F155		nobody at 18th after 02:00
19	16X	01:25		01:56	01:25	01:50	01:30	F166	01:52	F161	02:22	F162		nobody at 19th after 01:30
20	17X	01:20		01:35	01:35	01:40	01:40	F176	02:09	F172	02:22	F175	01:40	
21	18X	01:30		01:38	01:38	01:50	01:26	F186	01:52	F181	02:01	F182		
22	19X	01:26		01:30	01:26	01:50	01:30	F196	01:50	F191	02:34	F192		
23	20X	01:20	smell at 01:10	01:30	01:50	01:50	01:30	F206	02:06	F201	02:40	F205		



100 (default value) solid angles. The default Deardorff model is used for the LES sub-grid modelling. Detailed information is provided in reference 24.

Unlike the analysis performed in reference 34, which was based on tenability models applied in each room of the different apartments, the analysis performed in lobbies and stairs is limited to gas concentrations and temperatures. A toxicity model presupposes a behavioural scenario; in lobbies and stairs individuals were mobile, and the pattern of their movement is only partly understood but variable. For this reason, the tenability models are not applied but the gas concentrations and temperatures provided allow such analysis in the future.

3.1 | INITIAL CONDITIONS IN THE APARTMENTS, LOBBIES AND STAIRWELL

The simulation takes into account the real geometry of each apartment, lobby and the stairwell as shown in Figure 6. Regular Cartesian cells with dimensions of $0.25 \times 0.25 \times 0.25 \text{ m}^3$ are used. The blue, green and red areas correspond respectively to living room, kitchen and bedroom. For each of those rooms, the local effluent concentrations and temperature come from the previous analysis described earlier, and correspond to ventilation conditions from the scenario thought to be the most probable in reference 34. In the simulation addressed in this paper, each species (CO, HCl and HCN from furniture, façade insulant, PVC and soot) are modelled so that individual transport equations are solved. A total 22 equations are thus defined in the numerical model from reference 34, using yields and their time

evolutions indicated as example in Table 1 and Figure 5. Carbon monoxide, hydrogen chloride and hydrogen cyanide concentrations, and gas temperature can thus be evaluated in the lobbies and stairs.

The numerical model of the conditions inside the lobbies and stairs was based on two key input datasets.

First, the thermal and toxic conditions inside the apartments, as derived from previous modelling.³⁴

Second, the status of doors, as derived from a detailed review and analysis of the expert report's to references 2-5, and the final Phase 1 report of, the Grenfell Tower Inquiry,¹ which allowed the definition of a general scenario for resident evacuation at different times during the disaster.

The results of the simulation were validated by comparison with data on local conditions in the Tower over time, from an analysis of resident testimony during 999 calls recorded during the event.⁵ Observations and evidence from the disaster have shown that the fire spread over the Tower can be split in different periods. Three distinct periods were observed for conditions inside the Tower, with major impacts on egress.

The first period corresponded to the initial fire-spread over the east face of the Tower, from 01:00 a.m. to 01:30 a.m.. Light smoke was reported early in lobbies from the first to the 23rd floor, coming from apartments through their front doors and from air vents in lobbies on some floors (6th, 9th, 11th). The initial vertical façade fire reached all "X6" apartments from the 4th to the 23rd floor at this time. As the fire spread over the façade, window failures led to more and more fire propagation into apartments and internal fires were observed early, between the 4th and the 17th floors. Firefighters or

occupants reported front doors of apartments with internal fires being left open, for example, Flats 16, 26 and 86 on the 4th, 5th and 11th floors respectively. In the lobbies, conditions changed quickly, in 5 to 10 min, when dense and hot smoke migrated from burning “X6” apartments. Smoke was also reported early in one of the lift. At the same time, the stairs remained relatively clear of smoke until 01:25 a.m. Some doors between the stairs and lobbies were opened relatively early (e.g., on the 4th and 11th floors). Conditions in the stairwell worsen rapidly, and on some floors, especially the uppermost floors, they were worse than in the lobbies. This first period corresponded also to the main evacuation period. By 01:30 a.m., 112 persons have evacuated. In particular, between 01:15 a.m. and 01:30 a.m., 77 persons evacuated, leading to lot of people in the stairs at the same time. At 01:30 a.m., there was nobody left on the 17th and 19th floors. The majority of the people found on the highest floors after the disaster were already there at 01:30 a.m., after having moved upward via the stairs.

The second period corresponded to the events between 01:30 a.m. and 02:00 a.m.. All “X6” apartments were now involved in the fire as well as “X1” apartments from the 14th to the 23rd floors. Doors between the stairwell and lobbies were reported to have been opened on the 4th, 5th, 14th, 16th and 20th floors, and smoke entered in stairwell from lobbies, mainly between the 4th and 10th floors at 01:40 a.m., and between 4th and 14th at 01:50 a.m.. Conditions worsen in lobbies and stairwell, and one of the lifts stopped at the 10th floor. More and more smoke entered lobbies and the stairwell while people opened doors during a mass and fast evacuation period. Between 01:30 a.m. and 01:36 a.m. (in 6 min) and between 01:40 a.m. and 01:50 a.m. (in 10 min), respectively, 36 and 20 people evacuated. No more evacuation is reported for 20 min after 01:50 a.m. due to untenable conditions in lobbies and the stairwell between the 6th and the 16th floors.

After this second period, dense irritant smoke has started to accumulate in the burning apartments, and it spread out through the front doors of these apartments to the lobbies and the stairwell, because of the doors' weak fire performance or because they were left open during egress. This gradually forced occupants to evacuate their apartments, and move to apartments either on the same floor or lower floors via the stairs. Occupants who remained in their apartments were affected by increasing toxic smoke from the outside (from the façade fire and from the burning contents of lower apartments) and from smoke in the lobbies, and supposedly closed their front doors in response to the smoke in the lobbies. However, although the doors were closed, the smoke still got through from lobbies. The conditions reported for each of the 1st to the 23rd floors are synthetized in Table 2.

3.2 | INVESTIGATION OF THE CONDITIONS ON FLOORS 10–13

The numerical investigation of conditions inside the lobbies of, and stairwell at, upper floors requires knowledge of the gas temperature and toxic gas concentrations on lower floors that spread upwards via

the stairwell. Both firefighters and occupants reported untenable conditions in lobbies and the stairwell between the 10th and the 16th floors.

According to Dr Lane's post-fire observations,³ several front doors appeared to be open or missing on the 12th, 13th, 14th and 16th floors, with severe damage to their lobbies and the stairwell. The application of external firefighting water was observed on levels lower than the 13th floor in the early stages of the fire. According to Prof. Torero's observations,⁴ smoke was reported in the 11th to 14th and 23rd floor lobbies, for the first time, 30–35 min after the first 999 call at 00:54 a.m., and internal apartment fires were reported simultaneously between the 12th and the 22nd floors. At the same time as the report of a fire on 12th floor (01:24 a.m.), the 14th floor lobby was impassable due to smoke. Two minutes after the fire being reported (01:26 a.m.), smoke came through the front door of Flat 96 into the 12th floor lobby. Four minutes after the fire report (01:28 a.m.), smoke was reported in the 11th floor (both in lobby and flats) and prevented the occupant leaving. This early smoke migration (01:24 a.m. to 01:28 a.m.) on the 11th and 14th floors would have to be through open doors. Although post-observation indicated that Flat 96 (12th floor) suffered severe damage with the door found broken, the rate of smoke spread was rapid and not compatible with the only fire being that in Flat 96 as discussed in reference 4. Thus, other mechanisms must have existed and led to a single apartment fire compromising the stairs and lobbies of the 10th to 14th floors.

A detailed numerical model was created, similar to that shown in Figure 6, of the 10th to 13rd floors. The times of internal fire development for each apartment and for each room inside each apartment, and the times of door opening for apartments and lobbies are those indicated in Table 2.

The main assumptions in the simulation of the toxicity scenario are:

- the different times of window failure are known for each room (kitchen, living room, and bedroom) of each apartment^{32,33};
- the fire starts in a room 4 min after window failure, corresponding to the delay for flame re-entry and local furniture ignition³²;
- when a door between an apartment and lobby is closed, due to the weak fire performance of the door (less than 15 min^{3,4}), leakage is assumed to appear 10 min after the fire has started inside the apartment (modelled by removing a range of numerical cells from the upper and lower parts of the door);
- in a given apartment, when people are evacuating, the door between the apartment and the lobby is left open for 10 min.

Examples of temperatures and CO concentrations predicted at a height of 1.5 m above floor level (corresponding to typical mean nose and face height), on the 13th floor are shown in Figures 7 and 8 respectively.

The thermal and toxicity conditions, in terms of gas temperature and effluent concentrations, were evaluated for the stairwell at the

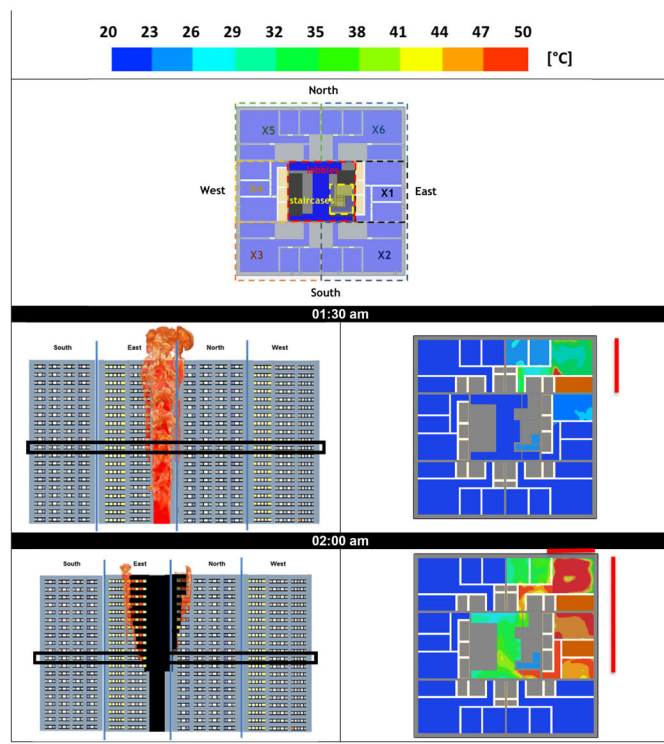


FIGURE 7 Numerical evaluation of temperature at a height of 1.5 m above floor level—plan view of the 13th floor—comparison with the fire spread simulation from reference 28—façade fire location highlighted with red lines

13th floor. These data were then used as boundary conditions for the stairwell at the base of the 20th floor, to simulate the effluent migration from lower floors. It is assumed that there was no contribution from the lobbies of the 14th to 19th floors because no occupants left these floors after 01:50 a.m. (Table 2).

The simulated conditions in the lower (10th to 13rd) floors indicates severe toxicity and thermal conditions in lobbies and the stairwell. Gas temperature was locally higher than 50°C, with carbon monoxide concentrations up to 3000 $\mu\text{L/L}$ for more than 20 min. Changes in conditions were also observed in the simulations, due to successive apartment fires beginning or ending and cyclic door opening between lobbies and the stairwell. Between 03:30 a.m. and 04:30 a.m., conditions seem hotter in the stairwell than in lobbies. This confirms the observations reported in experts' reports and occupants' testimonies (Table 3). However, evacuation is thought to be

possible during short periods, for example between 02:10 and 02:40 a.m., and after 03:30 a.m..

Early, at around 01:30 a.m., an increase in the temperature is already observed in the stairwell at the 13rd floor. The temperature in the stairwell and lobbies on the 10th to 13rd floors remains around 20°C above ambient until 04:30 a.m., however the toxic concentrations are negligible after 02:50 a.m.. This is due to the decrease in apartment fires from this time on the lower floors of the Tower.

However, there are some limitations in the numerical model: the actions of firefighters, which may have had a significant impact on the fire, were not included in the simulations. Only time-temperature and time-concentration evolutions are assigned to each apartment, and do not take into account local combustion. Thus, no flames or smoke radiation are simulated. This will impact (underestimate) the thermal exposure in lobbies and the stairwell because when filled with hot

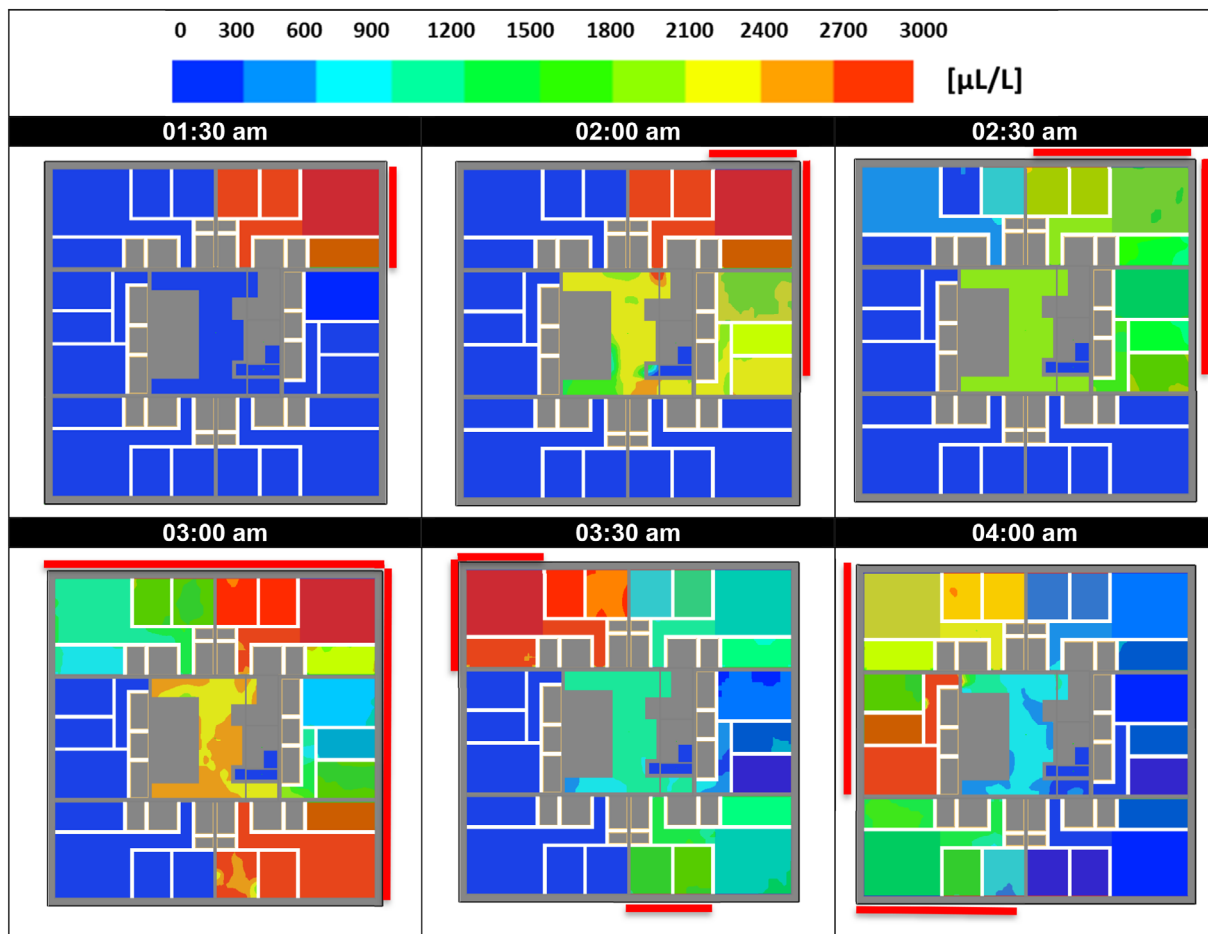


FIGURE 8 Numerical evaluation of the CO concentration at a height of 1.5 m above floor level—plan view of the 13rd floor—façade fire location highlighted with red lines

smoke, radiation could be important on walls or surfaces, and can worsen the conditions for evacuation. For example, thermal degradation of plastic elements was observed post-fire in the stairwell and lobbies. This would be associated with local temperatures on these surfaces of between 100°C and 200°C. In the simulations, only gas temperature is evaluated. Pressure gradients due to the opening of doors and windows is also a limitation that could lead to an underestimation of the conditions, both thermal and toxicity, in the stairwell.

Different periods were identified in the evolution of temperatures and toxic gas concentrations in the lobbies and stairwell (Figures 9 and 10). Seven main sequences appear to correlate with the events reported during the fire and are summarized in Table 3.

3.3 | INVESTIGATION OF THE CONDITIONS ON FLOORS 20–23

A detailed numerical model, illustrated in Figure 6 and corresponding to the 20th to 23rd floors, was created. Same numerical model and geometry, including the grid size, than for the lower floors (Section 3.2) are used. The time of internal fire development for each apartment and the time of opening of apartment front doors and doors between lobbies

and the stairwell are those indicated in Table 2. The temperatures and gas concentrations inside the lobbies and stairwell on the 10th to 13rd floors derived from the numerical investigation, were applied as instantaneous boundary conditions at the bottom of the stairwell at the 20th floor, to simulate heat and toxicity migration from lower floors. The approach is illustrated in Figure 11.

It is assumed that there were no major contributions from the 14th to 19th floor lobbies, because no occupants evacuated these floors after 01:50 a.m. (Table 2), and thus the doors between these lobbies and the stairwell were not opened. Through this simplified hypothesis, any losses, either thermal or toxic, are considered in the model.

Temperatures and CO concentrations predicted at a height of 1.5 m above floor level on the 23rd floor are addressed in Figures 12 and 13, respectively.

Gas temperature and effluent concentrations were evaluated for the 23rd floor, and indicate severe toxicity and thermal conditions in the lobby and the stairwell. Gas temperature was locally higher than 60°C, with carbon monoxide concentrations up to 4000 $\mu\text{L/L}$ for more than 20 min. Sudden changes in conditions are also observed in the simulations, due to successive apartment fires beginning or ending, and cyclic door opening between lobbies and the stairwell. This confirms the observations detailed in experts' reports and occupants' testimonies. However,

TABLE 3 Phenomenology and numerical evaluation of the conditions over time in lobbies of the 10th to 13rd floors

Period	Observation from experts' reports	Observation from numerical model
1 01:20–01:30 a.m.	<ul style="list-style-type: none"> Vertical fire spread over the east face of the Tower; the fire reaches the crown at 01:29 a.m.; kitchens of all “X6” apartments involved. Flats 76 to 106 (10th to 13rd floors) reported to be involved in the fire between 01:20 and 01:26 a.m. Front doors of some of these apartments, in particular Flat 86, observed to be left open, before 01:25 a.m.. 	<ul style="list-style-type: none"> Light increase in temperature (~5°C). Light increase in toxic gas concentrations (CO, HCN, HCl) mainly from the façade fire.
2 01:20–01:40 a.m.	<ul style="list-style-type: none"> Smoke from façade fire and “X6” burning apartments started to fill the lobbies, but the smoke is still reported as light. Mass-evacuation noticed at same time, leading to constant opening of doors between apartments and lobbies, and then between lobbies and stairwell as observed by firefighters. Numerous people were in the stairwell where the conditions were reported better than in lobbies. 	<ul style="list-style-type: none"> Increase in temperature (~20°C) in all lobbies from 10th to 13th floors. Increase in toxic gas concentrations, in particular in the 11th floor lobby, mainly CO from the façade fire.
3 01:40–01:50 a.m.	<ul style="list-style-type: none"> Hot and thick smoke filled the lobbies, where conditions worsened in less than 10 min. Degraded conditions also reported in the stairwell, but evacuation was still possible. 	<ul style="list-style-type: none"> Quick increase in temperature (~20°C) in all the lobbies from 10th to 13th floors. Increase in toxic gas concentrations, in 12th and 13th floor lobbies, mainly from the apartment contents fires.
4 01:50–02:10 a.m.	<ul style="list-style-type: none"> Conditions were untenable both in lobbies and stairwell. No evacuation during this period. Stairs impassable between the 10th and 14th floors around 01:50 a.m.. 	<ul style="list-style-type: none"> Temperatures of up to 50°C, mainly in 10th and 11th floor lobbies. Associated with high CO and HCN concentrations, with a peak value at 13th lobbies.
5 02:10–02:50 a.m.	<ul style="list-style-type: none"> Lobbies were reported full of smoke although temperature conditions seemed better. No more occupants evacuated during this period, the doors between stairwell and lobbies remained closed. Lower apartments ceased burning. 	<ul style="list-style-type: none"> Decrease in temperatures and toxic gas concentrations.
6 02:50–03:30 a.m.	<ul style="list-style-type: none"> “X1” and “X5” apartments involved. Burning of “X6” apartments decreasing and front doors probably missing. Front door of Flat 75, on the 10th floor is also reported as open. However, because no more evacuation happened during this period, the doors between stairwell and lobbies remained closed while lower apartments were no longer burning. 	<ul style="list-style-type: none"> Increase in temperature and toxic gas concentrations in lobbies. Sudden decrease of toxic gas concentrations in stairwell, with temperatures between 25°C and 40°C.
7 After 03:30 a.m.	<ul style="list-style-type: none"> Decay phase of “X6”, “X1” and “X5” fires, while “X4” apartments, mainly bedroom and kitchen, and “X5” kitchens were locally on fire. Around 03:30 a.m., one person evacuated from the 21st floor and reported better conditions in the stairwell at 10th floor while descending. 	<ul style="list-style-type: none"> Lower temperature and toxic gas concentrations in lobbies and stairwell.

evacuation is thought to have been possible during short periods, for example between 02:40 a.m. to 03:00 a.m., and after 03:30 a.m., but in degraded conditions at certain floors such as the 20th floor.

However, the same limitations as discussed for the lower floors appear in the numerical model and could lead to an underestimation of the conditions, both temperature and toxicity, mostly in the stairwell due to the initial boundary conditions from the simulation of the lower floors.

Different periods were identified in the evolution of temperatures and toxic gas concentrations in the lobbies and stairwell (Figures 14 and 15). Five main sequences appear to correlate with the events reported during the fire and are summarized in Table 4.

When analysing the contribution of the different toxic effluents in Figures 14 and 15, it is of interest to compare the main effluents (CO, HCN and HCl) on a common scale based on toxicity contribution. For acute toxicity, and in a first approach, one can consider a toxic

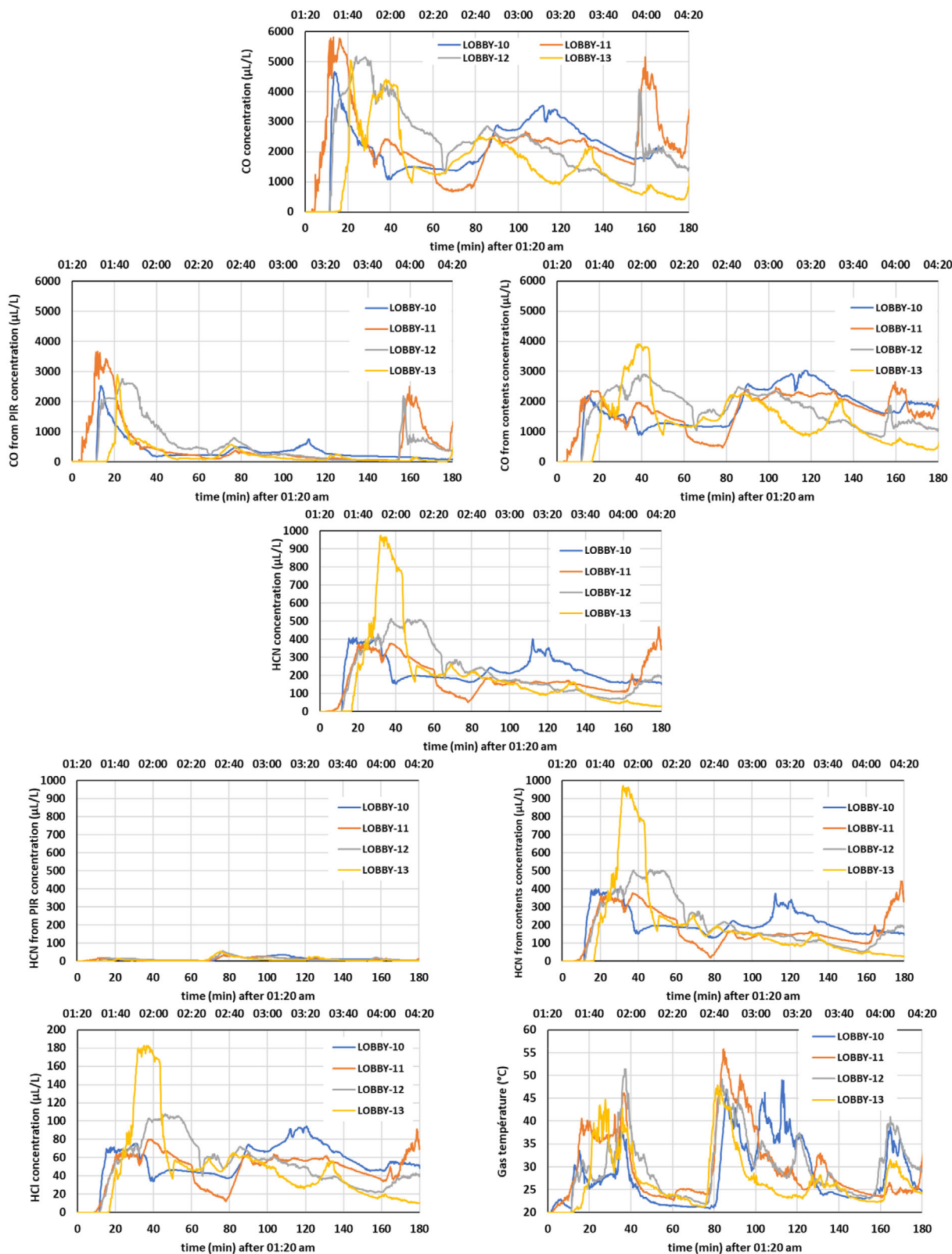


FIGURE 9 Numerical evaluation of the toxic effluent concentrations and temperature at a height of 1.5 m above floor level over time in the 10th to 13rd floor lobbies

effect equivalence between CO and HCN with approximately a factor between 18 and 246. In the same way, one can consider a toxic equivalence level between CO and HCl with a factor 3. This is calculated

using toxic loads from ISO 13571⁷ and from SLOT values as proposed in reference 41, as well as for other toxicological thresholds such AEGs 10 min or IDLH. In Figure 16, an example of the toxic effluent

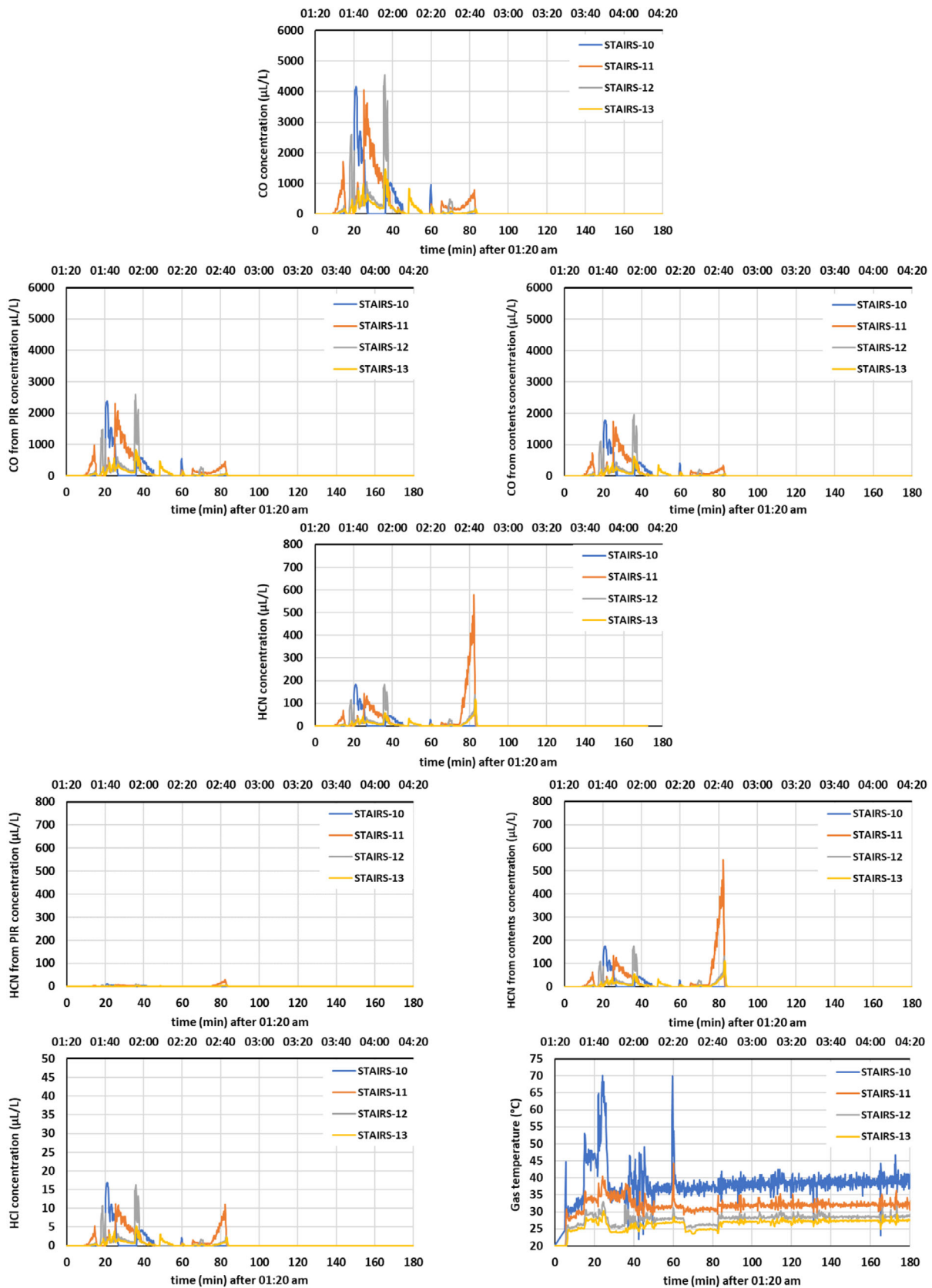


FIGURE 10 Numerical evaluation of the toxic effluent concentrations and temperature at a height of 1.5 m above floor level over time in the stairwell at the 10th to 13rd floors

FIGURE 11 Application of the model of the middle floors to the basement of stairwell at the 20th floor as instantaneous boundary conditions for the numerical investigation of the conditions inside the lobbies and stairs at higher floors

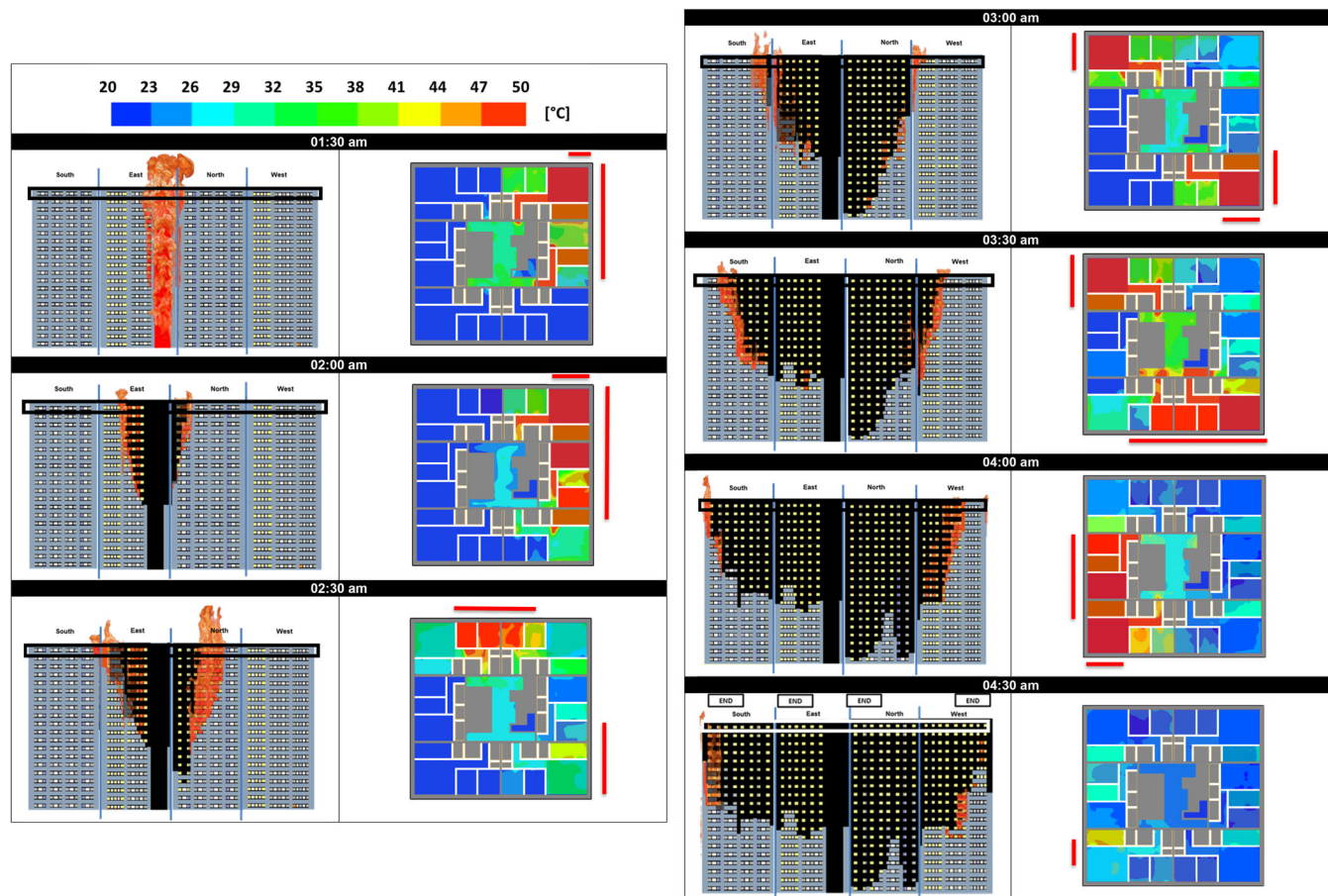
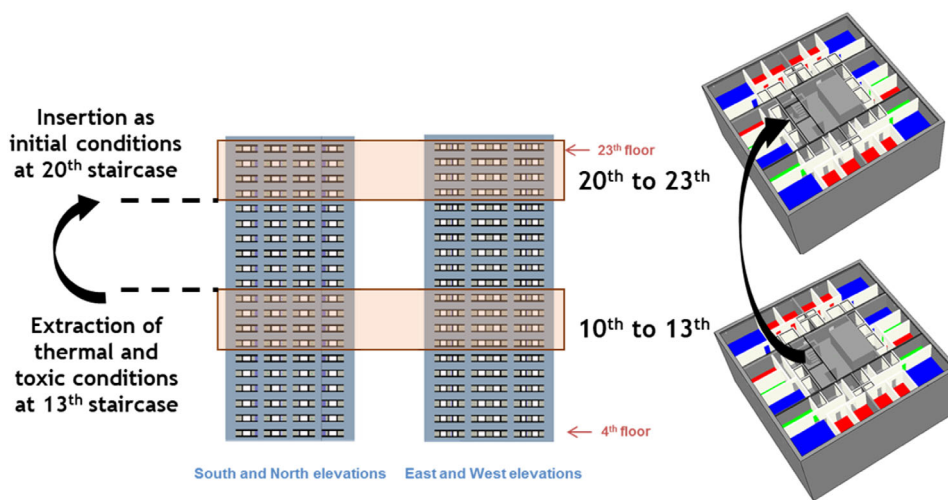


FIGURE 12 Numerical evaluation of temperature at a height of 1.5 m above floor level—plan view of the 23rd floor—comparison with the fire spread simulation from reference 28—façade fire location highlighted with red lines

concentrations at 20th floor evaluated numerically and plotted using the representative toxic scale is provided. This analysis shows the proportion of each effluent based on a comparable scale of contribution. It is observed that CO and HCN are the main effluent contributing to the degradation of tenability conditions, both in lobby and stairwell and HCN coming in a large proportion from contents. Similar conclusion is found for the other 21th to 23rd floors.

4 | CONCLUSIONS

A detailed numerical model of the uppermost four floors (floors 20 to 23) of the Grenfell Tower was created, taking into account the real geometry of each apartment and lobby, and the stairwell. For each room in each apartment, the toxic gas concentrations and temperatures were fixed by prior analysis of the horizontal fire spread over the Tower.

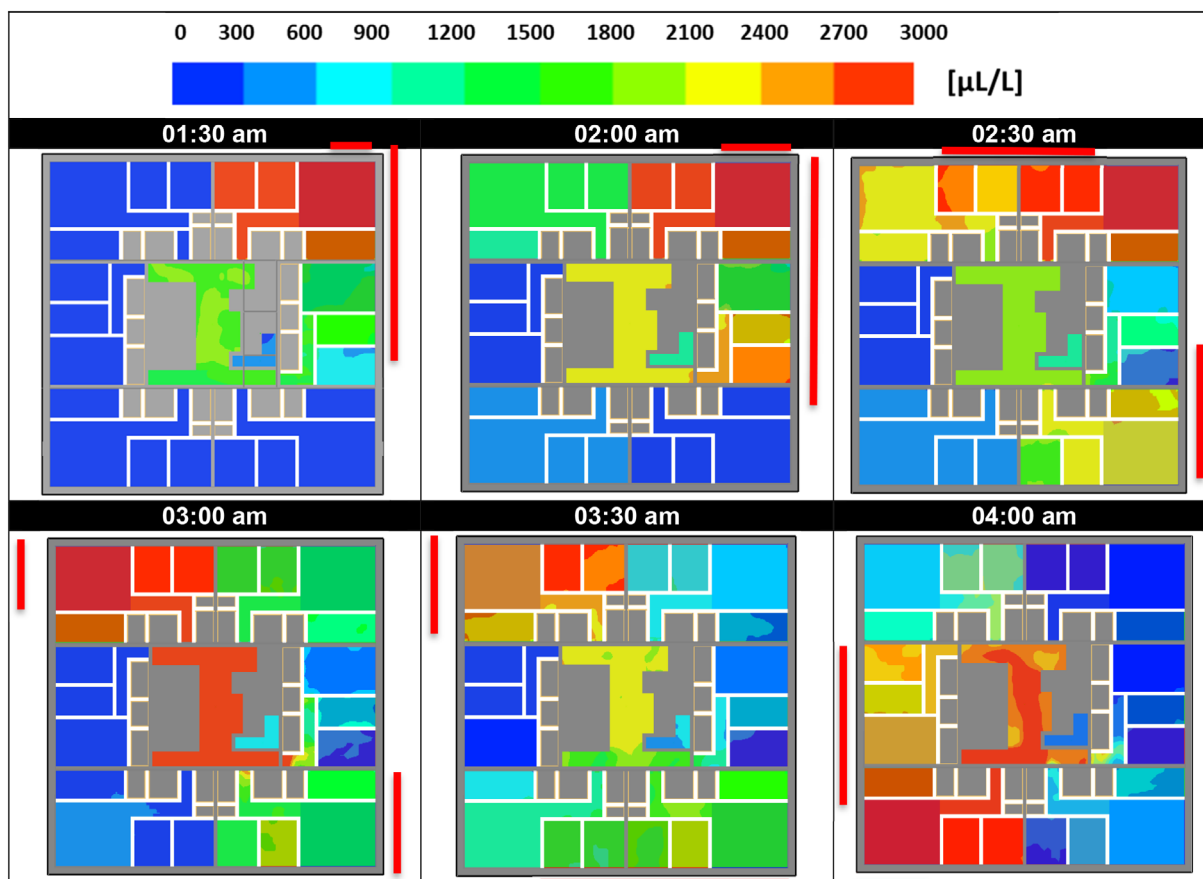


FIGURE 13 Numerical evaluation of the CO concentration at a height of 1.5 m above floor level—plan view of the 23rd floor—façade fire location highlighted with red lines

Carbon monoxide, hydrogen cyanide and hydrogen chloride concentrations, and gas temperature were evaluated for each lobby and the stairwell. This led to an analysis of the toxic gas concentrations due specifically to both the façade insulant and the apartments' contents.

After the first period of vertical fire spread, the fire reached the crown of the Tower and enhanced the horizontal spread. More and more apartments became involved in the fire. Dense irritant smoke started to accumulate in the burning apartments, and spread through the front doors of these apartments, because of their weak fire performance or because they were left open upon egress, into common lobbies and in the stairwell. Occupants gradually evacuated their apartments, to apartments either on the same floor or to other floors via the stairs. Occupants who remained in their apartments were affected by increasing toxic smoke from the outside (from the façade fire and from the burning contents of lower apartments) and from smoke in the lobbies, and supposedly closed their front doors in response to the smoke in the lobbies. However, although the doors were closed, the smoke still got through.

As a first step, gas temperature and toxic gas concentrations (CO, HCN, HCl) were numerically modelled at a height of 1.5 m above floor level in the lobbies and in the stairwell at the 10th to 13rd floors. These data were used as boundary conditions for the stairwell at the base of the 20th floor, to simulate the effluent migration from lower floors. The

simulated conditions in the 10th to 13rd floors indicated severe toxicity and temperature conditions in lobbies and the stairwell. Gas temperature was locally higher than 50°C, with carbon monoxide concentrations up to 3000 μL/L for more than 20 min. Changes in conditions were also observed in the simulations, due to successive apartment fires beginning or ending and cyclic door opening between lobbies and the stairwell. This confirms the observations reported in experts' reports and occupants' testimonies. Different periods were identified in the evolution of temperatures and toxic gas concentrations in the lobbies and the stairwell, with seven main sequences that appear to correlate with the events reported during the fire. This is reflected in the numerical model, and in particular, periods where conditions worsen, sometimes in less than 10 min, and periods where degraded conditions were also reported in the stairwell, but evacuation was still possible. This is the case between 01:50 and 02:10 a.m., conditions were untenable both in lobbies and stairwell, and no evacuation occurred during this period, with stairs reported impassable between the 10th and 14th floors.

The detailed numerical model corresponding to the 20th to 23rd floors was created. The temperatures and gas concentrations inside the lobbies and stairwell on the 10th to 13rd floors derived from the numerical investigation, were applied as instantaneous boundary conditions at the bottom of the stairwell at the 20th floor, to simulate heat and toxicity migration from lower floors. Gas temperature and

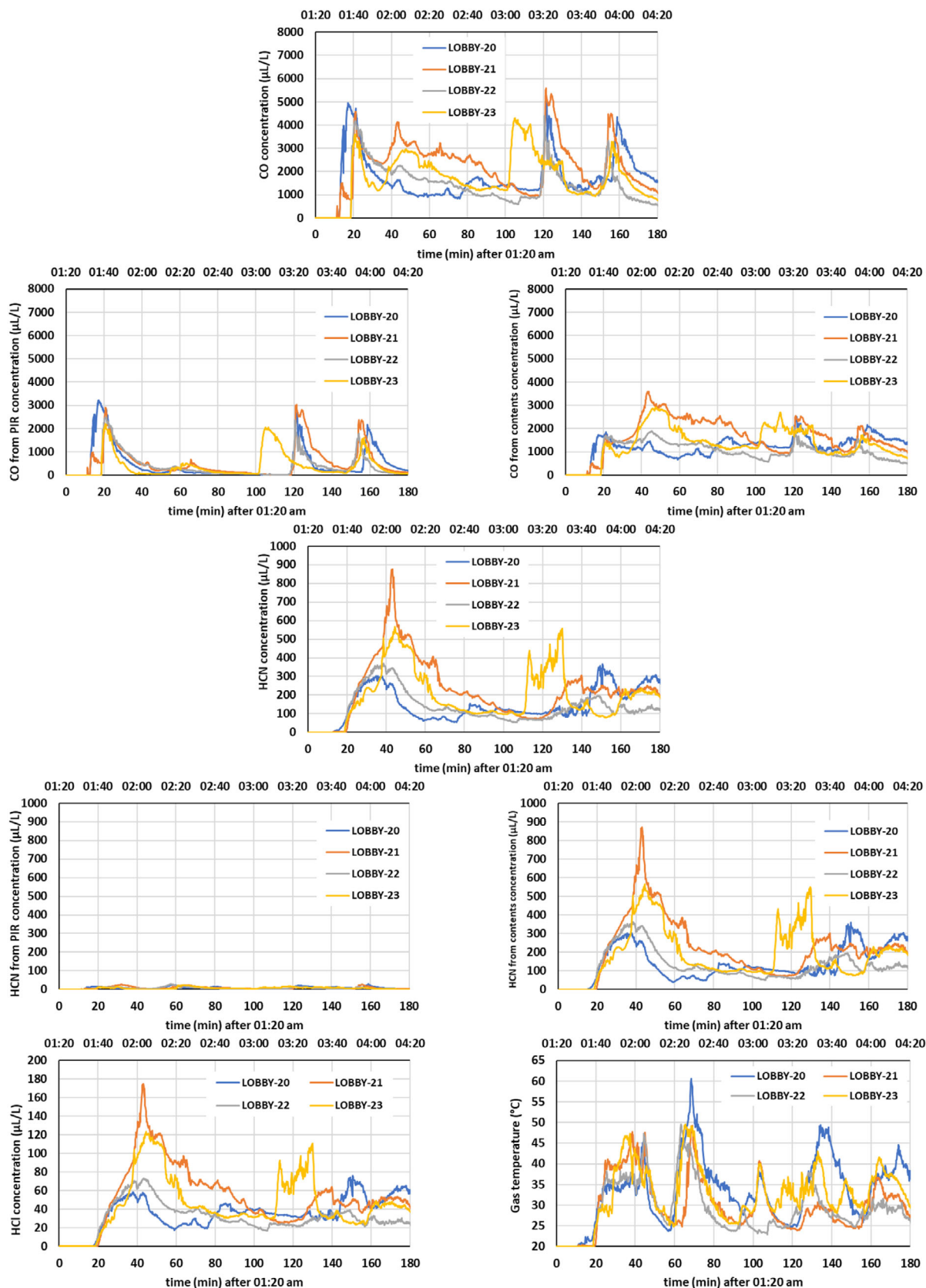


FIGURE 14 Numerical evaluation of the toxic effluent concentrations and temperature at a height of 1.5 m above floor level over time in of 20th to 23rd floor lobbies

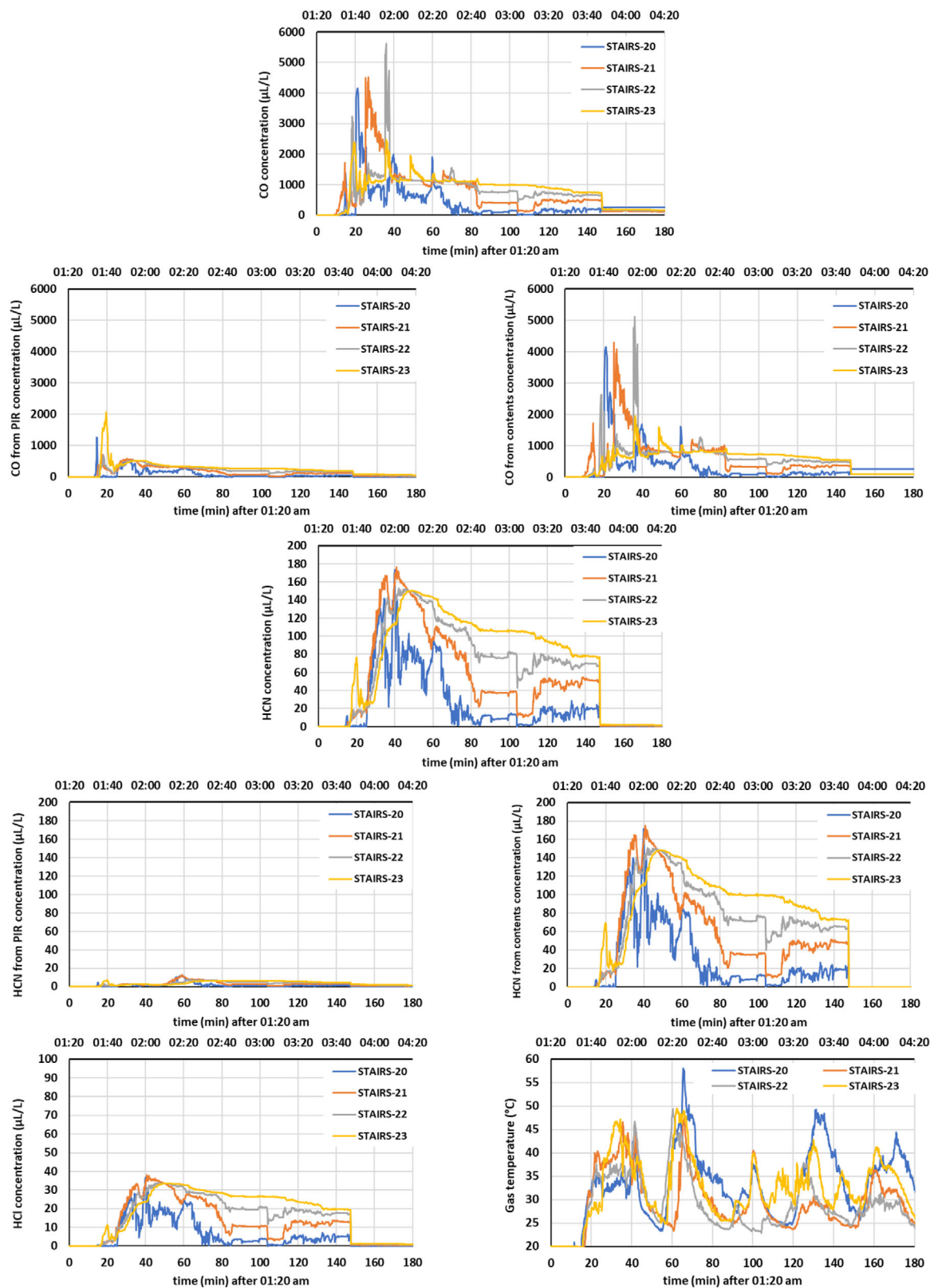


FIGURE 15 Numerical evaluation of the toxic effluent concentrations and temperature at a height of 1.5 m above floor level over time in the stairwell at the 20th to 23rd floors

effluent concentrations were evaluated for the 23rd floor, and indicate severe toxicity and thermal conditions in lobby and stairwell. Gas temperature was locally higher than 60°C, with carbon monoxide

concentrations up to 4000 µL/L for more than 20 min. Sudden changes in conditions were also observed in the simulations, due to successive apartment fires beginning or ending, and cyclic door

TABLE 4 Phenomenology and numerical evaluation of the conditions over time in lobbies of the 20th to 23rd floors

Period	Observation from experts' reports	Observation from numerical model
1 01:20–01:30 a.m.	<ul style="list-style-type: none"> Vertical fire spread over the east face of the Tower; the fire reached the crown at 01:29 a.m. Flats 176 to 206 (20th to 23rd floors) reported to be involved in fire between 01:26 and 01:30 a.m. 	<ul style="list-style-type: none"> Light increase of temperature ($\sim 5^{\circ}\text{C}$). Light increase of toxic gas concentrations (CO, HCN, HCl) mainly from the façade fire and from lower floors.
2 01:30–01:50 a.m.	<ul style="list-style-type: none"> Beginning of horizontal fire spread. Smoke from façade fire and “X6” burning apartments started to fill the lobbies, but the smoke is still reported as light. Mass-evacuation occurred, leading to constant opening of doors between apartments and lobbies, and then between lobbies and the stairwell as observed by firefighters. Numerous people were in the stairwell where the conditions were reported better than in lobbies. Front doors of some apartments, in particular Flat 176, reported as open at 01:40 a.m. 	<ul style="list-style-type: none"> Increase of temperature ($\sim 25^{\circ}\text{C}$) in all lobbies and the stairwell from 20th to 23rd floors. Increase of toxic gas concentrations, in particular in the 23rd floor lobby and stairwell, mainly CO from the façade fire.
3 01:50–02:10 a.m.	<ul style="list-style-type: none"> Hot and thick smoke filled the lobbies, where conditions worsened in less than 10 min. Degraded conditions also reported in the stairwell. One person evacuated from the 23rd floor around 02:00 a.m. and reported degraded conditions in stairwell. 	<ul style="list-style-type: none"> Temperatures of up to 50°C, mainly in 20th floor lobby, associated with high carbon monoxide concentration.
4 02:10–02:40 a.m.	<ul style="list-style-type: none"> Conditions were untenable both in lobbies and stairwell. No evacuation during this period; 	<ul style="list-style-type: none"> Temperatures of up to 60°C, mainly in 20th floor lobby. Associated with high CO and HCN concentrations, mainly from apartment fires.
5 After 02:40 a.m.	<ul style="list-style-type: none"> Lobbies were reported full of smoke between 02:40 a.m. and 03:30 a.m. All the apartments located on the east and north faces (“X6,” “X1” and “X5” apartments) were involved in the fire. The fire was spreading to the south and west faces. Around 03:30 a.m., one person evacuated from the 21st floor and reported hot conditions in lobbies and stairwell while descending until 10th floor. After 03:30 a.m., fires were decreasing and no more occupants evacuated from these floors. The doors between the stairwell and lobbies remained closed and lower apartments were no longer burning. 	<ul style="list-style-type: none"> Increase in temperature and toxic gas concentrations both in lobbies and stairs. In lobbies, there are constant temperatures and decreasing toxic gas concentrations. In the stairwell, there is a sudden decrease of toxic gas concentrations, with temperatures between 25 and 45°C.

opening between lobbies and stairwell. This confirms the observations detailed in experts' reports and occupants' testimonies. Five main sequences appear to correlate with the events reported during the fire.

The numerical investigation reproduces the changes in the conditions in lobbies and stairwell, and in particular the untenable conditions reported by both firefighters and occupants, for example, between the 10th and the 16th floors inside the lobbies and stairwell. It explains by the variability of the fire around the tower, the cyclic door status, the delay for a given flat to be involved in the fire while another flat fire was decreasing.

Even if the numerical simulations correlate with the events reported during the fire, some limitations appear in the numerical model: the actions of the firefighters, which may have had a significant impact on the fire, were not included in the simulations. Only time-temperature

and time-concentration evolutions are assigned to each apartment, and do not take into account local combustion. Thus, no flames or smoke radiation are simulated. This will impact (underestimate) the thermal exposure in lobbies and the stairwell because when filled with hot smoke, radiation could be important on walls or surfaces, and can worsen the conditions for evacuation. For example, thermal degradation of plastic elements was observed post-fire in the stairwell and lobbies. This would be associated with local temperatures on these surfaces of between 100°C and 200°C . In the simulations, only gas temperature is evaluated. Pressure gradients due to the opening of doors and windows is also a limitation that could lead to an underestimation of the conditions, both thermal and toxic, in the stairwell. For the simulation of the uppermost floors, it is assumed that there were no major contributions from the 14th to 19th floor lobbies because no occupants evacuated these floors after 01:50 a.m., and thus the doors between these lobbies

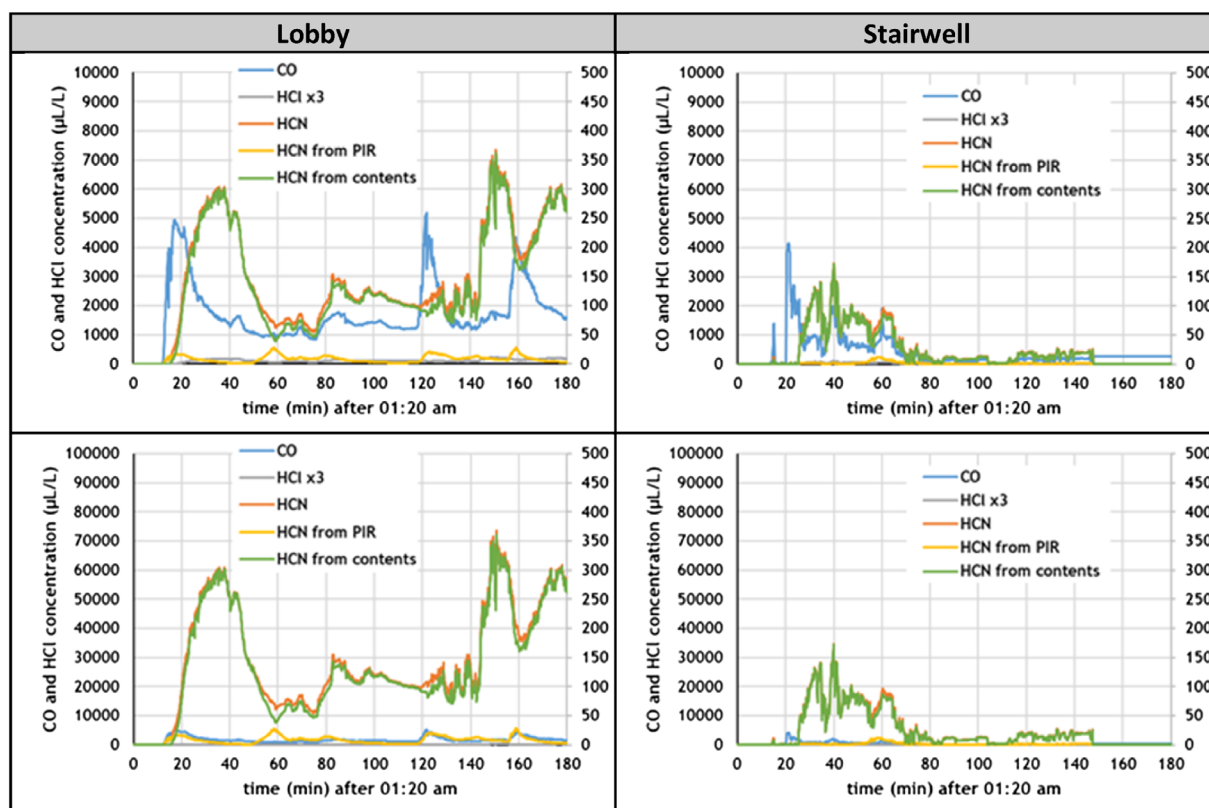


FIGURE 16 Numerical evaluation of the toxic effluent concentrations at a height of 1.5 m above floor level over time in the lobby and stairwell at the 20th floor—analysis with comparable toxic scales. Top line presents a CO/HCN ratio of 20 (Approximately value from AGL2-10 min, IDLH or Pauluhn⁴¹) and bottom line represents a CO/HCN ratio of 200 (Approximately value from ISO 13571)

and the stairwell were not opened. Through this simplified hypothesis, any losses, either thermal nor toxic, are considered in the model.

This investigation allows an understanding of the evolution of toxic and thermal conditions inside the Tower while the fire spread over the four faces of the Tower.

ACKNOWLEDGEMENTS

This work has been partially financed by Kingspan. The sponsor has not been involved in the results nor the conclusions of this paper. This reconstruction only uses inputs publicly available data from Grenfell Tower Inquiry or data published in the scientific literature.

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How to cite this article: Guillaume E, Drea V, Girardin B, Fateh T. Reconstruction of the Grenfell tower fire—Part 6—Numerical simulation of the Grenfell tower disaster: Contribution to the understanding of the tenability conditions inside the common areas of the tower. *Fire and Materials*. 2022;46(7):1061-1079. doi:10.1002/fam.3053