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Grenfell Tower Fire

Firefighters' Activities and Their Exposure to Fire Smoke and Heat

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Objective: This study aimed to characterize the smoke exposure of firefighters who attended the Grenfell Tower fire during the initial 20 hours. **Methods:** As no compilation of exposure data exists, data were compiled from nine unconnected sources, including the Grenfell Tower Inquiry, firefighters' statements, incident logs, and the UK Firefighter Cancer and Disease Registry. **Results:** Of the 628 firefighters who attended, information was available from 524. Eighty-nine percent reported exposure to smoke without respiratory protection equipment (RPE), of whom 23% also reported exposure to excessive heat. Common reasons for smoke exposure were assisting casualties (18%), running out of air (15%), and climbing stairs without activating RPE to conserve air (17%). **Conclusions:** A significant proportion of firefighters reported inhaling smoke during the incident with potentially debilitating health effects.

Keywords: Grenfell tower, firefighter, exposure, smoke, heat, breathing apparatus, respiratory protection equipment

LEARNING OUTCOMES

- Evaluates firefighters' exposure to smoke and heat in relation to their activities and RPE use during a major high-rise building fire incident.
- Demonstrates that failure to activate RPE beyond the entry control point, as well as engaging in various tasks without proper protection, increases firefighters' exposure to toxic fire emissions.
- Outlines that emergency services need to improve their anticipation of, and response to, extraordinary events, placing a high priority on personnel safety.

The Grenfell Tower fire, which occurred in London in June 2017, burned for around 60 hours, and killed 72 people, was the UK's worst residential fire since the second world war.

The Grenfell Tower was a 23-storey residential block with six flats per floor, linked by a single central stairwell and two lifts in centrally located lobbies. It was a reinforced concrete structure, originally designed to be impervious to fire. The only means of entry/exit were the lifts (which stopped operating during the fire) and the narrow central stairwell.[1]

In 2016, the Tower was refurbished with exterior facade of combustible insulation clad with polyethylene-filled aluminum composite panels.[2] A fire occurred in a fourth floor flat, which spread into the facade and then rapidly around the outside of the building. Smoke and flames from the burning facade entered individual flats and then ignited their contents. The severity of the fire and the failure of flat doors to close automatically led to most of the lobbies and much of the stairwell being filled with toxic smoke. The 7-year Grenfell Tower Inquiry recently concluded that all those who died in the building were victims of inhalation of asphyxiant gases, such as carbon monoxide and hydrogen cyanide.[3]

From 2017 to 2024 (March), Fire and Rescue Services in England have attended over 5381 fires in purpose-built high-rise (10+ storeys) apartments.[4]

This research collected and analyzed data from the firefighters attending the Grenfell Tower fire. The aim was to assess the Grenfell Tower firefighters' exposure to smoke and heat during the initial 20 hours, in relation to their activities and the use of respiratory protective equipment (RPE).

METHODS

The project was approved by the Science Ethics Review Panel at the University of Central Lancashire (SCIENCE 01043).

Data Sources

The Grenfell Tower Inquiry provided publicly accessible databases containing names and activities of firefighters. Data on firefighters' arrival, attendance, activities, and their exposure to smoke and heat during and after attending the Grenfell Tower fire were collated from nine different sources. These data sources were as follows:

1. Chronology of events from the Grenfell Tower Inquiry (GTI): providing initial firefighters' timings and activities, from 00:50 am to 2:00 am[5]
2. Grenfell Tower Inquiry Excel spreadsheet: containing London Fire Brigade firefighters, their rank, description, time they were mobilized, and attendance time (n = 2000). This includes the Riders and Roles data.[6]
3. A list of firefighters who attended Grenfell Tower during the course of the fire and the immediate aftermath, which watch/crew they belonged to, the fire station where they were based, and their rank. This information, reported to the Grenfell Tower Inquiry, has

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Ethical considerations and disclosures: The project was reviewed and approved by the Science Ethics Review Panel at the University of Central Lancashire (SCIENCE 01043).
Funding sources: None to disclose.
Conflicts of interest: None declared.
Author contributions: A.A.S. collected and analyzed the data, and drafted the first iteration of the manuscript. A.A.S., D.A.P., and T.R.H. reviewed and edited the final version of the manuscript for publication.
Data availability: The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.
Supplemental digital contents are available for this article. Direct URL citation appears in the printed text and is provided in the HTML and PDF versions of this article on the journal's Web site (www.joem.org).
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DOI: 10.1097/JOM.0000000000003271

been taken and collated from an existing spreadsheet, which consists of information taken from the Incident Management System (IMS) and the Staff Attendance Rota System (StARS) (n = 988).[7]
4. Grenfell Tower Inquiry breathing apparatus (BA) telemetry data (breathing apparatus or "BA" is the colloquial name for respiratory protective equipment [RPE] used by the firefighters): provided by London Fire Brigade (LFB) listing firefighter arrival time, duration, BA cylinder's initial and final pressure, BA tally's time in and off, air used, duration of wear, highest breathing rate, etc. This was listed for all firefighters who used RPE between 1.04 am and 8:00 pm on the 14th of June 2017 (n = 186).[8]
5. Grenfell Tower Inquiry witness statements: firefighters recounted their activities, experiences, exposure conditions, and health symptoms, among others, on the night of the fire (n = 350)[9]
6. Grenfell Tower Inquiry firefighters' incident log report: provided by London Fire Brigade and listing arrival time and duration of a firefighter on the scene (ie, whether wearing RPE or not) (n = 125)[10]
7. UK Firefighter Cancer and Disease Registry (FCDR)[11]: all serving and retired UK firefighters have been invited to complete a detailed survey about their occupational exposure and health. Firefighters who indicated their attendance to the Grenfell Tower Fire (n = 558) answered additional questions about their role and activities at the incident and any potential exposures they may have received, among others.
8. London Fire Brigade Health and Safety Incident Log: listing a firefighter hazard classification, event classification, injury type, etc. These included firefighters who attended the first 20 hours of the fire (n = 208).
9. Fire Brigades Union Firefighters Sickness Reports: listing Grenfell firefighters' diseases/injuries (n = 96)

All data were collected for the 3 years following the fire incident (July 2020). The nine data sources, produced by different parties (LFB, FCDR, GTI, etc) all contained common elements such as firefighters' first and last names, along with other information, such as firefighters' roles, activities, and exposure to smoke. Extracts from these data sources were merged, and firefighters' first and last names and their roles were extracted from each source and used as unique identifiers to compile a single and unique "record" for each firefighter. A total of 2146 names (n = 2146) were identified.

Figure 1 summarizes the process of merging the databases. Information from sources 2 to 8 gave 2146 data entries. After resolving duplicate names, there were 1633 firefighters' records, of whom 1487 were operational firefighters. A total of 628 attended the fire in the first 20 hours, for whom details of exposure are available for 524.

Comparison of the 9 data sources showed that many firefighters had multiple records. Duplicate firefighter records were removed after merging the databases in order to avoid the loss of valuable information or entire records. For example, the GTI Riders and Roles (GTI) data source records the mobilization, arrival, and return times of firefighters for the entire duration of the incident (from 14th to 30th of July 2017). As a result, a firefighter who was deployed inside the Tower more than once would have a separate record for each attendance. Furthermore, the same firefighter might also appear in BA telemetry data, FCDR (with details on their exposure to fire and smoke), or/and in witness statements (detailing their activities and timings), resulting in multiple records containing different types of information being recorded for the same firefighter.

Any apparent repetition of a firefighter's name across these data sources was carefully compared and verified using other identifying variables such as firefighter rank, day, time and duration of fire attendance, activity, and team members. If these variables matched between data sources, firefighters with the same name were considered to be the same person (n = 513). If these variables did not match, firefighters with the same name were considered to be different individuals. Thus, after elimination of duplicate names, the merged database contained records of 1633 individual firefighters (Fig. 1).

The data analyses that follow are based on the 524 operational firefighters who attended in the first 20 h, for whom activity information is available.

Firefighters' Activities and Smoke Exposure

Free-text data sources (eg, witness statements, FCDR, and BA Telemetry Data) were manually and iteratively coded. Assessment of each firefighter's location, duration of specific activity, and smoke exposure was coded across the data sources using identical questions, shown in the Results section. Additionally, instances of firefighters running out of air while wearing RPE inside Grenfell Tower were based on firefighters' statements in one of the data sources, eg, witness statements or FCDR.

Firefighters' exposure to smoke, as discussed in the Results section under Demographics and Breathing Apparatus Usage, was obtained from the FCDR and witness statements. In these data sources, firefighters reported their sensory perceptions and smoke conditions in free text, describing visibility, opacity, and smell/odor.

The information was correlated against firefighters' time on each activity provided either in the other datasets or from firefighters in their witness statements. This allowed for a comparison of smoke visibility and opacity against the time and location within the Tower (as reported at the start of the Results section). Further data reconciliation was carried out by comparing information from the witness statements of other firefighters who worked together or carried out the same tasks at the same time.

Based on this information, smoke exposure was categorized into three levels: light, moderate, and dense.

- Light smoke was commonly associated with descriptors such as clear, fine or transparent vision, accompanied by negligible, wispy, light, and faint smoke, as well as a light smell of smoke.
- Moderate smoke was described by firefighters as cloudy, smoky, hazy, or "manageable" atmosphere. Visibility was impaired to some extent, making the air "just"/"enough" or barely breathable. The smell of smoke was more frequently reported, with descriptors such as distinct, strong, or intense.
- Dense smoke was characterized by its thickness and discomfort. It was described as acrid, uncomfortable, "choking" smoke that "stuck" to the throat. Firefighters reported distressing sensations in the eyes, nose, and throat, including stinging eyes and coughing. Vision was severely impaired, resulting in zero visibility and an opaque appearance, with objects completely obscured.

Data on exposure to heat were obtained in a similar way to firefighters' exposure to smoke. Information was provided by firefighters as free text in the GTI witness statements and the FCDR. Descriptors associated with exposure to heat included the following: "steam and heat strenuous/unbearable," "my skin was burning," "steam was coming out of my head/body," "face/ear/neck/back burning/melting from the heat," "cooling down with buckets of water," "feeling sick from the heat," and "heat stroke." The absence of such comments was interpreted as no exposure to heat.

Firefighters' Exposure Time

The majority of firefighters provided self-reported estimates of the time they spent carrying out various activities during the incident (details provided in Supplementary Data 1, http://links.lww.com/JOM/B789). The data were categorized into different time ranges: 0 to 15 minutes for heavy smoke exposure and 0 to 30 minutes, 0.1 to 1.0 hours, 1 to 2 hours, 2 to 4 hours, 4 to 6 hours, and >6 hours for light and moderate smoke exposure.

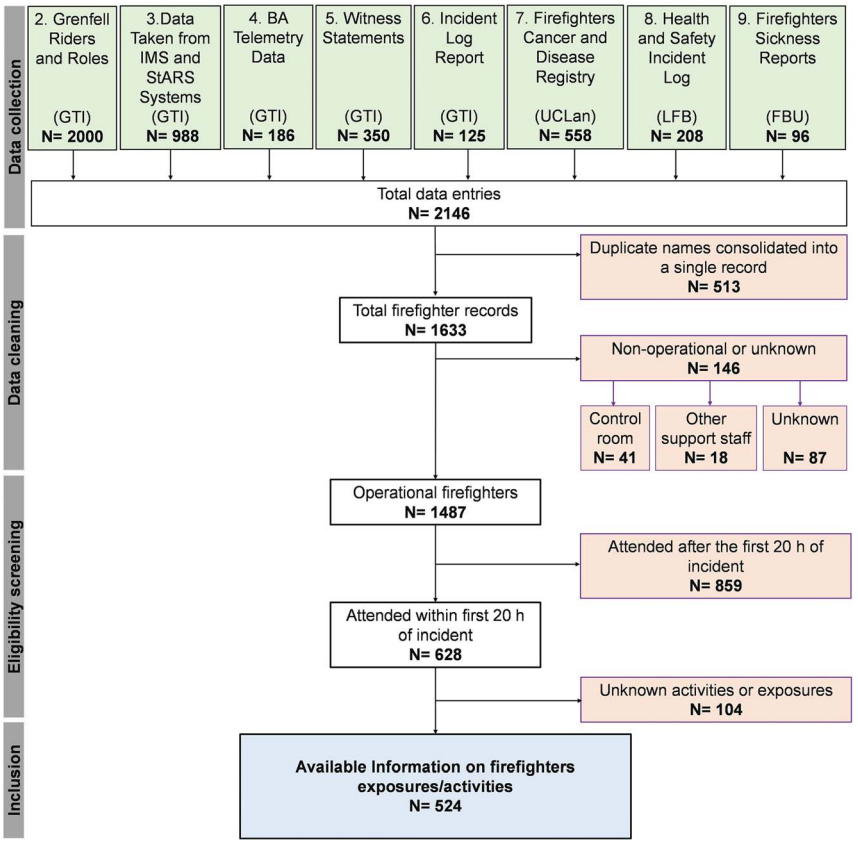

FIGURE 1. Inclusion/exclusion decision tree from the nine data sources (green boxes, data sources; white boxes, total numbers; orange boxes, data excluded; blue box, data included). n, number of firefighters; GTI, Grenfell Tower Inquiry; IMS, Incident Management System; StARS, Staff Attendance Rota System; LFB, London Fire Brigade; UCLan, University of Central Lancashire.

Firefighters' Breathing Apparatus

During the major fire phase, firefighters wore either standard duration breathing apparatus (SDBA) or extended duration breathing apparatuses (EDBA). SBDA weighs around 15 kg and contains a single cylinder of compressed air that can supply approximately 48 minutes of air (at a rate of 50 L/min). EDBA consists of a double cylinder system, weighing approximately 23 kg that can provide around 70 minutes of air (at a rate of 58 L/min).[12,13] Reserve EDBA units from the Protective Equipment Group are referred to as AAAB sets.

BA telemetry data (including the initial and final pressure of firefighters' BA cylinders, the time the BA tally was on and off, air usage, duration of wear, highest breathing rate, etc) were used to determine the likelihood of a firefighter running out of air, described in the Results section, on Firefighter Demographics and Breathing Apparatus Usage. This calculation was made by using information from Department for Communities and Local Government and a standard formula provided in Supplementary Data 1 (http://links.lww.com/JOM/B789) and published data.[8,14,15] Firefighters were also coded as running out of air if they indicated this eventuality in another data source, eg, witness statements.

Breathing rates for firefighter's BA usage during the Grenfell Tower fire were assumed: 5 to 10 L/min for resting; 15 to 30 L/min for moderate to average work (walking); 30 to 70 L/min for running, climbing stairs; and 70 to 150 L/min for hard to very hard work (although values greater than 150 L/min, considered as exceptionally high, have been also reported).[16]

RESULTS AND ANALYSIS

The timeline of the Grenfell Tower fire is presented in Figure 2. This shows the events that occurred, particularly in the development of the fire.

Conditions in flats and lobbies changed rapidly as presented in Table 1. Between ~1:15 and 1:30 am, the fire spread up the exterior east side of the Tower, with smoke penetrating flats on all floors. At this stage, the main fuels were cladding and insulation materials (polyethylene from aluminum composite panels, polyisocyanurate and phenolic insulation foams, polyvinyl chloride window surrounds, and other construction products surrounding the windows, including rigid foams and polystyrene panels). After reaching the crown of the Tower, the exterior fire spread laterally around the Tower in both directions, penetrating flats in sequence with smoke and then interior fires. Later, the fire increasingly involved the contents of the flats (upholstered furniture containing polyurethane foam, carpets, wooden furniture, etc).[1,2,17] By ~1:30 am, the lobbies on most floors, particularly in the upper half of the Tower, became filled with dense black, irritant smoke from burning cladding and the contents of the flats through leakage paths and open front doors to the flats. Subsequently, through slow leakage, as escaping occupants opened the stair doors on different floors and as some fire doors from the lobbies to stairwell on lower floors were kept open by the firefighters' hoses and equipment, smoke penetration into the stairwell from smoke-filled lobbies on most floors resulted in it filling with toxic smoke with very limited visibility and untenable conditions from just a few minutes' exposure.[2,17] During the next 6 hours, smoke filled flats on most floors, by slow leakage from the lobbies and by penetration from the exterior fire as it spread around the Tower. During this period, lobbies and stairwells were filled with hazardous concentrations of toxic smoke, often with near-zero visibility.[18]

Outside the Tower, according to firefighters' Grenfell Inquiry witness statements, collected by the Grenfell Tower Inquiry, firefighters waited for up to 6 hours between 50 and 60 m from Grenfell

TABLE 1. Fire Conditions in the Communal Areas of the Tower, as Described by Firefighters (Zero Visibility Is <0.5 m)

		Stairwell (Floor Numbers)				
Time:	**Comment**	**Ground Floor Entrance Area**	**1–4**	**5–8**	**9–11**	**12+**
1–1:30 am	Smoke density progressively increasing	Clear of smoke	3rd to 4th floor: slightly smoky	Light smoke, but periods of poor visibility	Very thick smoke above seventh floor	15+: Conditions deteriorating, thickening smoke, unbearable heat
1:30–2 am	Visibility deteriorating on upper floors	Light, wispy smoke, noticeable smell (of plastic)	Negligible amount of smoke	Hazy, wispy smoke	Visibility 0–0.5 m, thickening, acrid smoke	Visibility 0–0.5 m, thickening until very thick smoke, hot
2–3 am	Humidity, temperature, and visibility deteriorating above fifth floor	Light smoke getting thicker (irritating) as ventilators installed	From 4th floor up: visibility low, thick, chocking, black smoke	White cloudy, choking smoke From seventh floor: not seeing hand in front of a face	Zero visibility, eyes stung, difficult to breathe and see, getting hotter	Zero visibility, thick, sticking smoke, getting hotter
3–6 am	Seventh and 11–12th floor flats: gas pipes on fire	Light smoke	A lot of water cascading down the stairwell	Visibility poor, humid	Zero visibility, very hot	Zero visibility, unbearable heat
6–7 am	Building still alight from around seventh floor	Positive pressure ventilation installed: heavy smoke (CO 74 ppm)			Zero visibility, getting hotter	Zero visibility
7–8 am	The first 4–5 floors being a waterfall (dripping from ceilings)	Heavy smoky smell of the smoke (coughing and choking)	Visibility nearly zero, thick smoke (from 4th floor only few steps)	By seventh floor visibility dropping to zero, really hot (BA sets steaming up)	Zero visibility, heavy thick smoke, hot	Zero visibility, unbearable heat from 100% alight flats
9–11 am	Crews were not getting past 14th floor	Visibility fine, air breathable, 2–3 inches of water on the ground	Slightly smoky	Slightly smoky	From ninth floor up to the top building being 100% alight.	Gas pipes ruptured in flats on the 14th floor, zero visibility, unbearable heat
12–3 pm	Fire still fought from 11th floor; pockets of gas still ongoing	Smoke clear, enough to breathe		From seventh floor hot and smoke heavily logged (gas pipe rupture in the flat)	Visibility very poor, heavy smoke, unbearable heat	Amount of steam reduced visibility, from 15th floor unbearable heat
After 4 pm	Gas supply isolated at midnight	Fires in flats continuing until 3–4 pm on 15th June				

BA, breathing apparatus; CO, carbon monoxide; GF, ground floor.

Tower, where the air was filled with dust and smoke.[1] Many of these firefighters reported smelling a strong "plastic" or "synthetic" smoke that stuck in the back of their noses and throats. That smell was reported up to 3 km from the Tower. When called to enter the Tower, firefighters had to be protected by police holding riot shields above their heads due to constantly falling fire debris from the external fabric of the building. The debris comprised cladding components, mostly from aluminum composite panels, foam insulation, window frames, and glass and included metal shards and molten material, some of which was still flaming. Firefighters also reported smaller pieces of charred insulation foam floating in the air, and mesh or fibers deposited on their personal protective equipment (PPE).[1]

Firefighters' Demographics and Breathing Apparatus Usage

Out of 628 operational firefighters who attended the first 20 hours of the fire, data on firefighting activities and exposure were available for 83%, totaling 524 individuals.

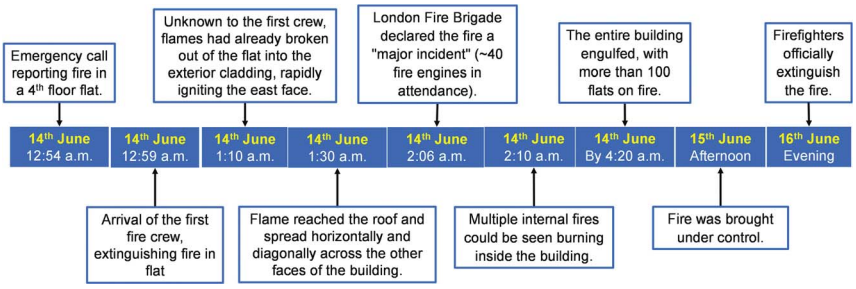

FIGURE 2. The timeline of the Grenfell Tower fire.[5]

TABLE 2. Firefighter's Demographics

Demographics Total Number of Firefighters, n = 524	
Gender	
Males	491
Females	33
Rank	
Regular firefighter	319
Crew manager	74
Watch manager	69
Station manager	30
Group manager	18
Area manager	1
Other	13

Most of the firefighters who attended were male (94%, n = 491), showing a typical distribution of ranks of a firefighting organization, as presented in Table 2. The majority are in operational roles, with regular firefighters accounting for 61% (n = 319). Fewer individuals 37% (n = 192) held management positions, which involved overseeing operations and managing teams. The "Other" category, representing 2.5% (n = 13), includes roles that are higher than the managerial positions shown.

Table 3 summarizes BA usage between 1 am and 8 pm on 14th of June. It contains 302 records for 246 firefighters who were deployed at the bridgehead inside the Tower, to fight the fire. In total, 183 SDBA, 100 EDBA, and 19 AAAB sets were employed by firefighters.

The majority of firefighters who entered the Tower used BA once (n = 198) remained under air for 20 to 29 minutes with a final BA pressure of 86 to 159 bar. Forty firefighters were deployed twice, and another eight were deployed three times with breathing apparatus (BA). Eighty-two percent (n = 203) of firefighters had a breathing rate classed as "very hard," indicating physical exertion. There were several records with missing data, eg, where a BA tally was not returned to the bridgehead, illustrating the difficulties and disarray experienced during the night of the fire. Some firefighters' witness statements also indicated activities of colleagues, for example, removing BA sets and offering them to casualties. Thus, Table 3 may not precisely reflect the number of firefighters' and their time wearing and using BA.

Firefighters' Locations, Activities, and Their Exposure to Fire Smoke

Figures detailing firefighter's activities and their exposure to fire smoke, along with other variables, are summarized in Table 4. Firefighters will have been in multiple locations/categories at different points during the incident.

Overall, 76% (n = 397) firefighters reported working inside the Tower at some point. Fifty-three percent (n = 280) of all firefighters reported working outside, within close vicinity of the Tower at some point (eg, firefighting, turning over fallen debris, and hose management). Twenty-six percent (n = 72) of firefighters assisted casualties in leaving the Tower, whereas 14% (n = 38) reported holding police riot shields to protect others from the falling debris and get them safely into and out of the Tower.

During the initial 20 hours of firefighting operations, 89% (n = 466) of operational firefighters, both within and outside the Tower, reported not wearing RPE at some point during their activities (Table 4). These firefighters also reported exposure to either smoke (74%, n = 344) or both smoke and heat (26%, n = 122) (as every firefighter who reported exposure to heat also reported exposure to smoke). Thirty-seven percent (n = 173) of firefighters in this group either removed BA, assisted casualties, or ran out of air. Twelve percent (n = 58) of firefighters in this group experienced a burning sensation through their fire gear and felt pain due to the intense heat on their face

TABLE 3. BA Usage During the Grenfell Tower Fire, From 1 am to 8 pm on 14th of June

	Firefighters BA Usage																					
	Number of Entries to the Tower			Duration Firefighters Spent in BA (min)				The Final BA Pressure (Bar) (Average Initial Pressure = 284 ± 13 Bar)								Firefighters Breathing Rates (L/min)					
	1	2	3	10–19	20–29	≥30	Unknown	≥160 (<~40% used)	86–159 (~40%–70% used)	≤85 (More than ~70% used)	Not reported	Resting		Moderate/ average	High and very high	Exceptionally high						
Number of firefighters	198	40	8	54	156	87	5	65	170	59	8	7		51	198	5						

BA, breathing apparatus.

TABLE 4. Summary of Coded Variables, Describing Number of Firefighters and Their Different Activities and Their Exposure to Smoke and Heat

	Total Number of Firefighters (n = 524)			
	Inside the Tower (Only)	**Outside of the Tower (Only)**	**Both Inside and Outside**	**Unknown Location**
Location (n = 524)	234	117	163	10
Not wearing RPE (n = 466)	206	95	159	6
Exposure to smoke (only) (n = 344)	128	94	116	6
Exposure to both smoke and heat (n = 122)	78	1	43	
Reason for Exposure to Smoke				
RPE run out of air (n = 54)	31		23	
Removed RPE (n = 25)	12		13	
Casualty handling without RPE (n = 94)	22		72	
BA tally not returned and exposure to smoke reported (n = 70)	44		26	
To ascend stairwell without activating RPE (n = 92)	42		50	
To work on the bridgehead without RPE (n = 58)	31		27	
To work in stairwell (hose management) without RPE (n = 93)	50		43	
While waiting inside of the Tower without activating RPE (lobby/bridgehead) (n = 189)	119		70	
Assisting with holding police riot shields without RPE (n = 38)		3	35	

Data are collected from all data sources for 524 firefighters.
BA, breathing apparatus; RPE, respiratory protection equipment.

(eyes, nose), neck, ears, and lungs. Ten percent (n = 47) of firefighters in this group received assistance from their colleagues in mitigating the effects of heat. This support included cooling (pouring water from buckets over their colleagues) and removing their fire gear or BA sets.

The extent of fire smoke exposure was dependent on the firefighter's locations and activities. Data in Supplementary Data 1 (Supplementary Table S1, http://links.lww.com/JOM/B789) and Figures 3 to 5 present the firefighters' location, duration of specific activities, and the type and length of smoke exposure. Each area in the chart represents the duration of the different type of firefighter activity or task performed.

Figure 3 shows the reasons 96 firefighters were exposed to heavy smoke for up to 15 minutes. Within this exposure time frame, the majority (n = 54) ran out of air, whereas 25 removed their RPE, and 17 firefighters assisted casualties without wearing RPE.

Detailed information was available for those firefighters who tackled fire inside the Tower. Those who did not wear RPE, removed it to assist casualties, or ran out of air (44%, 173 out of 397) have been categorized in the highest smoke exposure group (zero visibility). They reported exposure to heavy smoke for up to 15 minutes.

Eighteen percent of firefighters (70 out of 397) were deployed at the bridgehead with their BA switched on but did not return their BA tally. Although they reported exposure to smoke, it is not possible to determine the duration or type (light, moderate, or heavy) of smoke exposure they experienced. The failure to follow procedures and return their BA tally suggests mental or physical trauma, so this study is likely to underestimate actual smoke exposure.

The bridgehead, or entry control point, is chosen to demark the transition from a safe area to the fire. It should be the closest point to the fire that ensures the safety of those based there. The reported conditions ranged from a hazy, smoke-logged lobby that was deemed "manageable" to an acrid, irritating, and choking environment. On average, firefighters waited 1.3 hours (±1.1). The movements of the bridgehead during the first 20 hours of the fire indicate not only the unpredictable spread of the fire, but also the chaotic nature of the incident and the emergency services' response.

Although firefighters working at the entry control point (bridgehead) (15%, 58 out of 397) should have minimal exposure, they frequently reported fluctuating smoke conditions, ranging from light to heavy smoke (due to fire re-ignition in one of the flats below or at the bridgehead level), leading to coughing, eye irritation, headache, etc. On average, at the bridgehead, firefighters worked for 4.6 hours (±2.8), with almost half (n = 26) working between 5 and 10 hours.

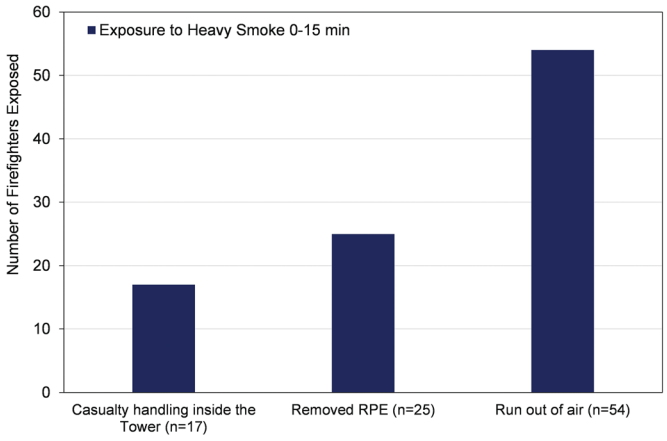

FIGURE 3. Firefighters' location, duration of specific activities, and exposure to heavy smoke. Figure excludes firefighters with unknown time.

To conserve air, 23% (92 out of 397) firefighters also reported ascending to the highest reachable floors (reported as having near-zero visibility or the presence of irritating and choking smoke) without activating their BA. Out of these, only 14% (n = 13) activated their BA on the fourth floor (when the bridgehead was situated on the ground floor) with the majority of firefighters switched on their BA on the higher floors, 46% (n = 42) between the fifth and 10th floor, and 30% (n = 28) above the 10th floor.

Twenty-three percent (93 out of 397) of firefighters also reported seeing and smelling smoke while working in the stairwell above the bridgehead, without wearing RPE. Some, avoiding heavy smoke exposures, particularly on the higher floors (sixth to 12th) were taking breaks on lower floors to alleviate coughing or choking due to smoke. Over half of these firefighters (n = 50) worked during the night of the fire (2 am to 8 am), on floors 6 to 15, for an average of 2.1 hours (±1.4).

Forty-eight percent (189 out of 397) of firefighters also reported waiting inside of the Tower, before being actively engaged in firefighting. Most firefighters were waiting in the lobby, on the ground floor, reporting smoke presence at some point. Less than 6% (n = 11) of these firefighters waited at the flats near the bridgehead, located on the fourth floor.

Figure 4 shows a large number of firefighters (n = 264 out of 524) involved in different tasks who were exposed to moderate smoke. The highest number of exposures, within the first 2 hours, was related to ascending the stairs without using RPE and working outside the Tower. Fewer firefighters were exposed to moderate smoke for over 1 hour, with a progressive decrease up to 7 hours, as tasks such as casualty handling, deploying riot shields and operating within 0 to 50 m of the Tower continued.

Figure 5 presents firefighters (n = 335 out of 524) exposed to light smoke. Results show that a large proportion of firefighters were exposed to light smoke for up to 2 hours during the incident. A significant number of firefighters were still involved with the hose management and working at the bridgehead, or waiting outside the Tower for over 6 hours.

Forty-four percent (123 out of 280) of the firefighters who were outside the Tower within 50 m, either firefighting or assisting access (with the riot shields), reported a "hazy" or "foggy" atmosphere. The majority described the working environment as "manageable." Thirty-two percent (n = 89) were positioned at greater distances (50–300 m) and reported seeing and/or smelling light smoke, the intensity of which was influenced by the direction of wind.

Fire Effluents in the Grenfell

Although many firefighters attending the Grenfell Tower fire reported exposures to smoke, no attempts were made to monitor fire effluents at the time of the incident. By assuming the smoke within the Tower to be of uniform composition but diluted to different degrees based on the time and location, the visibility through the smoke can be correlated to the concentrations of carbon monoxide (CO), hydrogen cyanide (HCN), and particulate matter. Specifically, because visibility through smoke is proportional to the smoke particulate concentration, it is possible to estimate exposure hazard. This has been cross-correlated to witness statements, pathology, and health data from occupant survivors and dissidents, based on the toxic product yield of the materials involved.[2,18,19] Figure 6 shows the approximate concentrations of CO, HCN, and smoke particulates as a function of visibility through smoke.

Professor Purser's Grenfell Tower Inquiry report describes occupants and firefighters entering the lobbies during the period between 2 and 8 am reporting very dense, irritant smoke. The composition of the lobby smoke on the higher floors was estimated to have averaged approximately 5000 to 10,000 ppm CO, 200 to 400 ppm HCN, and 2000 to 4000 mg/m³ smoke particulates with associated acid gas and organic irritants (Fig. 6).[19]

The composition of the smoke in the stairwell during this period varied with time and floor level. Based on data from Table 1 and Figure 6, the average concentrations of the main fire effluents throughout the stairwell are summarized in Table 5. Although the temperatures in most lobbies remained tenable for extended periods, heat and flame penetration occurred over time. Temperatures in the lobbies of around 650°C were recorded, which were to be lower than in the flats, where thermal image cameras worn by firefighters recorded temperatures around 800 to 1000°C, often with the screen displaying blank/white (indicating exceedance of the camera's detection limits).[1,9]

Hazard Assessment

The potential inhaled dose of smoke particulates or other toxicants depends on the concentration in the location, the volume of air breathed per minute (V_E) depending on work level, and the total exposure time at any location without BA or other respiratory protection (calculation details are presented in Supplementary Data 1, http://links.lww.com/JOM/B789).[20]

Table 5 shows the calculated smoke particulate doses inhalable for a firefighter in each location, exposed without respiratory protection and engaged in resting, moderate and heavy work with the volume of air breathed per minute (V_E) of 7, 20, and 40 L/min, respectively.[21] BA telemetry records show that firefighters working with heavy equipment and those climbing the Tower experienced V_E levels of up to 190 L/min. If such high V_E levels occurred during any periods without BA (eg, running out of air or assisting casualties), the uptake

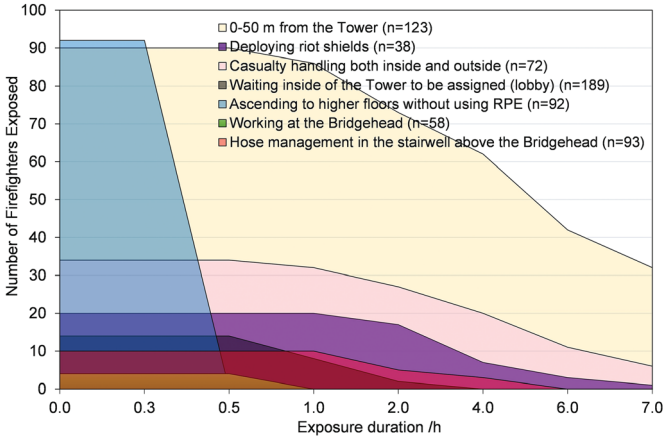

FIGURE 4. Firefighters' location, duration of specific activities, and exposure to moderate smoke. Figure excludes firefighters with unknown time.

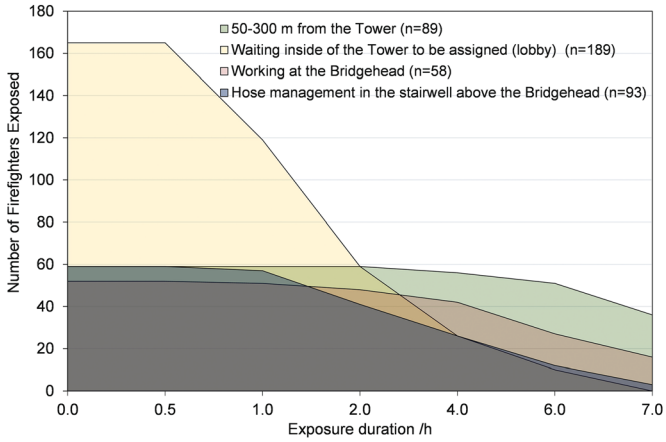

FIGURE 5. Firefighters' location, duration of specific activities, and exposure to light smoke. Figure excludes firefighters with unknown time.

of smoke particulates or any other gases would be increased in proportion.

The highest exposure risk would be for a firefighter in one of the lobbies or stairwell above 10th floor filled with dense smoke, where a 1-minute exposure could result in the inhalation of 68 to 136 mg of smoke particulates. As the smoke was very thick and visibility was near zero, it is assumed that most firefighters were fully protected by their RPE.

The fire effluent concentrations on the lower floors (fifth to ninth floor) were lower, so that an unprotected firefighter might inhale somehow similar dose after being up to 15 minutes (41–408 mg) in the stairwell. This is relevant as data show one third of firefighters (n = 173 out of 524) running out of air, removing their masks and assisting casualties. It is likely that these individuals may have inhaled a significant dose of smoke particulates during such periods or any other periods when individual firefighters reported movement (ascending or hose management) in the smoke-filled stairwell while not wearing BA.

It is more challenging to estimate smoke inhalation exposure for firefighters during periods when they were operating in low smoke contamination areas including the bridgehead, ground floor entrance area, and outside the Tower. If unprotected firefighters (no RPE) were experiencing exposure to conditions with visibility through smoke 10 to 50 m, then they might have inhaled a dose of 67 to 326 mg after 4 hours of heavy work in these conditions. As shown in Table 1, firefighters at the Bridgehead, waiting in the ground floor entrance area and outside the Tower, reported varying periods of exposure from light to heavy smoke, in some cases forcing them to withdraw from the area.

Table 5 also gives an indication of the firefighters' potential exposure hazards from asphyxiant gases such carbon monoxide and hydrogen cyanide, based on the assumption that the smoke had constant composition. For smoke, the greatest hazard was in the lobbies and stairwell above 10th floor. A 1-minute exposure in a dense smoke environment could result in inhalation of approximately half an incapacitating dose of asphyxiants, whereas 10-minute unprotected exposure in the Tower stairwell could result in inhalation of a dose close to that capable of causing collapse and loss of consciousness. This is consistent with reports of occupants collapsing on the stairs while trying to escape.[18,19] The hazard on the lower floors (fifth to 10th) was lower and strongly linked to the time firefighters spent on activities such as hose management or assisting casualties. This is a potential concern particularly for firefighters working in the moderately smoke-filled stairwell for several minutes without RPE. Inhalation of a significant dose of asphyxiant gases coupled with ultrafine smoke particulates and hard physical work may also present an acute cardiovascular system and neurological hazard for up to 24 hours after exposure.

DISCUSSION

This work has compiled data from all available sources in order to quantify the exposure of Grenfell Tower firefighters to smoke and toxic fire effluents. The highest risk to firefighters from being exposed to toxic components of smoke is believed to result from prolonged and repeated workplace exposure over a period of years.

Workplace exposure limits have been set for carbon monoxide at 23 mg/m^3 for an 8-hour time-weighted average and for hydrogen cyanide 1 mg/m^3.[22] The hazard from inhaled smoke particulates might be considered approximately comparable to that from workplace exposure to diesel smoke particulates, for which recent

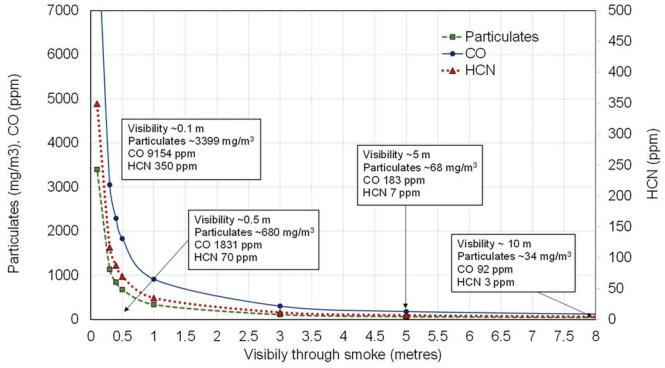

FIGURE 6. Approximate relationship between visibility through smoke and concentrations of CO, HCN, and smoke particulates.[19,20]

TABLE 5. Approximate Average Estimated Exposure Conditions to Inhalable Gases and Smoke Particulates in Grenfell Tower

				Inhaled Dose (mg)					
	Visibility (m)	Breathing Rates	Fire Effluent	1 min	15 min	30 min	1 h	2 h	4 h
Smoke Particulates (mg/m^3)									
Outside the Tower 0–50 m	10–50	Resting (waiting)	7–34	<1	1–4	1–7	3–14	6–29	12–57
		Heavy work	7–34	0–1	4–20	8–41	17–82	34–163	67–326
Ground floor entrance area	10–50	Resting (waiting)	7–34	<1	1–4	1–7	3–14	6–29	12–57
Bridgehead	10–20	Moderate work	17–34	0–1	2–10	4–20	8–41	17–82	34–163
Stairwell, floors: 1–4	10–20	Moderate work	17–34	0–1	2–10	4–20	8–41	17–82	34–163
Stairwell, floors: 5–9	0.5–5.0	Heavy work	68–680	3–30	40–400	80–800	160–1600	330–3300	650–6500
Stairwell, floors: 10–23	0.1–0.2	Heavy work	1700–3400	68–136	1000–2000	2000–4100	4100–8200	8200–16,000	16,000–33,000
CO (ppm)									
Outside the Tower 0–50 m	10–50	Resting (waiting)	18–92	0–1	2–10	4–19	8–39	15–77	30–155
		Heavy work	18–92	1–4	11–55	22–110	43–221	86–442	173–883
Ground floor entrance area	10–50	Resting (waiting)	18–92	0–1	2–10	4–19	8–39	15–77	30–155
Bridgehead	10–20	Moderate work	46–92	1–2	14–28	28–55	55–110	110–221	221–442
Stairwell, floors: 1–4	10–20	Moderate work	46–92	1–2	14–28	28–55	55–110	110–221	221–442
Stairwell, floors: 5–9	0.5–5.0	Heavy work	183–1831	7–70	110–1100	220–2200	440–4400	880–8800	1800–18,000
Stairwell, floors 10–23	0.1–0.2	Heavy work	4577–9154	180–400	2700–5500	5500–11,000	11,000–22,000	22,000–44,000	44,000–88,000
HCN (ppm)									
Outside the Tower 0–50 m	10–50	Resting (waiting)	1–3	0.01–0.02	0.11–0.32	0.21–0.63	0.42–1.26	1–3	2–5
		Heavy work	1–3	0.04–0.12	1–2	1–4	2–7	5–14	10–29
Ground floor entrance area	10–50	Resting (waiting)	1–3	0.01–0.02	0.11–0.32	0.21–0.63	0.42–1.26	1–3	2–5
Bridgehead	10–20	Moderate work	2–3	0.04–0.06	0.60–0.90	1–2	2–4	5–7	10–14
Stairwell, floors: 1–4	10–20	Moderate work	2–3	0.04–0.06	0.60–0.90	1–2	2–4	5–7	10–14
Stairwell, floors: 5–9	0.5–5.0	Heavy work	7–70	0.28–2.80	4–42	8–84	17–168	34–336	67–672
Stairwell, floors: 10–23	0.1–0.2	Heavy work	175–350	7–14	105–210	210–420	420–840	840–1700	1700–3400

Large values are approximated to two significant figures. The inhaled dose is calculated using the VEs: 7 L/min for resting, 20 L/min for moderate, and 40 L/min for heavy work.
CO, carbon monoxide; HCN, hydrogen cyanide; VE, ventilation rate.

(2023) HSE guideline limits have been set at 0.05 mg/m^3 as carbon for an 8-hour shift.[23]

In contrast, Figure 6 shows the particulate concentration of smoke at 8-m visibility as 34 mg/m^3, a factor of 700 greater than the occupational exposure level. Even for wildland fires, the predicted exposure in the Tower is 50 times greater than the published occupational exposure level. Recently, an occupational exposure limit for PM_4 particulates from wildland fires of 0.7 mg/m^3 has been proposed. PM_4 represents the particulate fraction below 4 μm diameter, which is a proportion of the total smoke particulates.[24] The maximum inhaled doses for any worker engaged in different activities are presented in Table 6.

A firefighter engaged in heavy work without RPE ($V_E = 40$) inside Grenfell Tower would inhale a total of 200 mg of smoke particulates according to Table 5. Attendance at this one incident would result in inhalation of a dose equivalent to 200-day exposure to diesel fume at the workplace limit concentration or 15-day exposure to the wildland fire PM_4 limit concentration. Although similar toxic and carcinogenic volatile organic compounds (VOCs) and related substances occur in wildland and other fire and combustion smoke and diesel fumes, the large difference between the diesel and wildfire smoke limits reflects the different exposure scenarios. With any fire smoke, there are considerable uncertainties in the yields and toxicity from the chemical mixes derived from these sources. The yields and mix of toxic products from the fuel mixes in buildings, burning in underventilated conditions, are likely to be greater than those released from open air burning of cellulosic fuels in wildland fires, with a wider mix of VOCs and carcinogens than diesel particulates.[25]

Is It Acceptable to Expose Firefighters to Toxic Smoke?

The 2017 Grenfell Tower fire prompted a wave of revisions to existing legislation and policies to ensure that such tragic events in high-rise blocks could never happen again. This included changes in policy identifying the control and mitigation measures, in the case of fires in high-rise buildings covered in Generic Risk Assessment 3.2 (GRA 3.2),[26] published by the central government as guidance for local fire services, and PN633,[27] a London Fire Brigade document, which enacts the principles set out in GRA 3.2 (such as firefighting, evacuation and rescue).

One of the key changes introduced in PN633 allows firefighters to be deployed above the entry control point (bridgehead) in a high-rise building fire without activating their breathing apparatus, under exceptional circumstances.[27] Allowing firefighters to be deployed above the bridgehead without activating their RPE may increase the duration that they can engage in firefighting or rescue operations. However, removing this protection will put firefighters at greater risk. Firefighters' perception of what constitutes sufficient smoke to justify activation of RPE will vary and undoubtedly expose some firefighters to unnecessary hazards. The assumption of smoke having a consistent composition made earlier in this article to estimate the asphyxiant's firefighters may have been exposed to cannot be used to justify potentially endangering firefighters in the future. The main asphyxiant gases (CO and HCN) are invisible and almost odorless at lethally incapacitating concentrations, leading to immediate risk of operational dysfunction (such as loss of orientation, dizziness, incapacitation and loss of consciousness), whereas other toxicants, such as acid gas irritants, organo-irritants, polycyclic aromatic hydrocarbons, and particulate matter, may lead to both immediate discomfort (coughing, choking, etc) and long-term health disorders (cancers and other diseases).

Strengths and Limitation

In order to undertake this study, it was necessary to collate information from nine different sources in order to understand the health threats to firefighters. Collecting information from the various datasets provided greater insight into the extent of firefighters' exposure to smoke and heat in relation to their activities and the utilization of RPE during a major high-rise building fire incident, for the first time. Failure to activate RPE above the bridgehead or engaging in various tasks without proper protection increases the risk of exposure to toxic fire emissions. These insights are invaluable for enhancing firefighter safety protocols and optimizing the effectiveness of firefighting strategies in high-rise building scenarios.

Based on the reported data, it is possible to estimate firefighters' exposures to smoke (optical density) and other smoke components (such as carbon monoxide, hydrogen cyanide, and particulate matter) and investigate any correlations with health outcomes (reported in the other studies[28]). Some firefighters may have engaged in multiple activities over a 20-hour period and, therefore, may be reported in multiple categories/tasks. This also includes their exposures to smoke, which may occur multiple times.

Although this study provides greater insight into the extent of firefighters' activities and their exposure to fire smoke, the limited information available from the disparate sources, and the high reliance on interpreting free-text information, which is subject to recall bias and misinterpretation, there is a need for a standardized protocol for consistent collecting and recording data from such extraordinary incidents in a single repository. This includes a robust debriefing of every individual involved, as soon as possible after the incident, recording locations, activities and durations, types and concentrations of fire emissions, and firefighters' smoke exposures (duration, types, etc), as well as their access and use of respiratory protection, among others. This necessity is evidenced by the multisource data collection exercise that was necessary in order to prepare this article.

CONCLUSIONS

This publication provides novel insights into firefighters' exposure and responses during high-rise building fires but also underscores the importance of implementing robust safety measures and policies to safeguard the well-being of firefighters in hazardous environments.

The rapid early development and severity of the fire, with the need to assist the occupants trapped in the 23-storey tower over an extended period, resulted in crews making extraordinary efforts beyond their normal working practice and putting their health and safety at risk in order to tackle the crisis before them. As a result, many firefighters

TABLE 6. Fire Effluents 8-Hour Time-Weighted Average Workplace Exposure Limits and the Maximum Inhaled Doses for Firefighters Engaged in Different Activities

		Maximum Inhaled Dose (mg)		
Fire Effluent	**Workplace Exposure Limits (mg/m^3)**	**Resting V_E = 7 L/min**	**Moderate V_E = 20 L/min**	**Heavy Work V_E = 40 L/min**
Particulate matter	0.05 Diesel smoke	0.2	0.5	1.0
	0.7 Wildland smoke	2	7	13
Carbon monoxide	23	77	221	442
Hydrogen cyanide	1	3	10	19

were exposed to smoke and heat, potentially leading to debilitating health effects.

Rapid fire spread, from the external facade to the contents of the flats, in the Grenfell Tower put firefighters and their managers in situations beyond anything they had experienced before. The proposed change of protocol, allowing firefighters to go above the bridgehead without activating their RPE, absolves firefighter management of responsibility and their ability to monitor and supervise the BA usage, leaving the decision to activate the RPE to individual firefighters. Many will lack the experience to recognize, control, or mitigate some aspects of such high-risk, high-stress working environments. Others may consider delay in activation of their RPE as heroism. The number of firefighters exposed to fire smoke in the Grenfell fire shows the need for clear guidance and management instruction to ensure that RPE is always deployed before exposure to smoke.

ACKNOWLEDGMENTS

We would like to acknowledge the London Fire Brigade and the Fire Brigades Union for giving access to their data sources.

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