Hostikka, Simo; Veikkanen, Eetu; Hakkarainen, Tuula; Kajolinna, Tuula

Experimental investigation of human tenability and sprinkler protection in hospital room fires

Published in:
Fire and Materials

DOI:
10.1002/fam.2893

Published: 01/10/2021

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

Received: 24 October 2019 | Revised: 29 April 2020 | Accepted: 29 June 2020
DOI: 10.1002/fam.2893

INTERFLAM SPECIAL ISSUE

WILEY

Experimental investigation of human tenability and sprinkler protection in hospital room fires

Simo Hostikka[1] | Eetu Veikkanen[1] | Tuula Hakkarainen[2] | Tuula Kajolinna[2]

[1]Department of Civil Engineering, Aalto University, Espoo, Finland
[2]Risk Management, VTT Technical Research Centre of Finland, Espoo, Finland

Correspondence
Simo Hostikka, Department of Civil Engineering, Aalto University, Espoo, Finland.
Email: simo.hostikka@aalto.fi

Funding information
Palosuojelurahasto

Summary

The effectiveness of sprinklers in protecting hospital patients in the room of fire origin was investigated by 14 experiments with a residential-grade sprinkler system, and by two free-burns. The fire load was UL 1626 corner fire. Tenability conditions were evaluated for the UL 1626 corner fire using gas temperature and species concentration measurements, and by calculating the fractional effective dose (FED) and fractional irritant concentration (FIC) with the comprehensive model of Purser and a more simplified method of ISO 13571. In the sprinklered tests, the average FED at 15 minutes was 0.8 ± 1 with 95% confidence, when using the Purser's method, and 0.2 ± 0.2 with ISO 13571. The difference was mainly caused by the assumption in the Purser's method that all NO_x gases behave like NO_2. Ignoring the NO contributions decreased the Purser's FED values very close to those of ISO 13571. In non-sprinklered tests, the FED and FIC values indicated definite incapacitation and possibly death 3 minutes after ignition. The sprinklers effectively increase the possibility of surviving, but the toxic effects may still be dangerous. In hospital and health care environments, many of the exposed persons may have lower-than-average tolerance.

KEYWORDS
experiment, FED, fire suppression, fire toxicity, hospital fire, sprinklers

1 | INTRODUCTION

Water sprinklers are commonly used to improve the fire safety in spaces where the early suppression by people is not guaranteed to occur. In health care units, water sprinklers can be used to protect patient rooms, common spaces, and auxiliary spaces. Primary response to a fire in a patient room is to evacuate the people from the room of fire origin, but it is often questionable if the health care personnel can perform the task without proper training and equipment. It may be possible that the fire service eventually evacuates the room, and the effectiveness of sprinklers in protecting the patients inside the room becomes then in question.

The fire protection performance of sprinklers has been widely investigated, and they have been found to be effective in cooling the room of fire origin and restricting the fire spread.[1] It is commonly understood that the major threat to occupants is caused by hazardous gases. The effects of different asphyxiant and irritating gases have been studied extensively, and the mechanisms of the major asphyxiant gases are well understood.[2-5] Two widely used engineering methods for toxicity assessment are the models of ISO 13571[6] and the model by Purser[3] taking into account wider range of gases than the ISO standard.

Previously, several full-scale fire tests studying smoke gas toxicity and tenability have been performed, both without and with sprinklers. For example, Blomqvist et al[7] used Fourier transform infrared (FTIR) analysis to measure CO, HCl, and HCN concentrations in a reconstruction of a hospital fire that occurred in Sweden in the 1990's. The hospital and the reconstruction had no sprinklers. The results showed that after a smoldering phase of ca. 500 seconds, all the measured gas concentrations increased rapidly and reached their maxima at ca. 600 seconds. After that, the concentrations decreased quickly so that at ca. 700 seconds, they resembled the pre-flashover state. More recently, Guillaume et al[8] made a tenability assessment of non-sprinklered bedroom fires. It was concluded that the smoke alarms activated before the tenability was compromised. The analysis was done by using method described in ISO 13571 standard. Based on the gas analysis, nitric oxide (NO) was determined to be most important irritant.[8]

The effect of the sprinklers on toxicity has not been studied very recently. O'Neill et al[9] have investigated the effect of sprinklers to toxic yields in the 1980's, concluding that sprinklers prevented flashover and cooled the room, but the hazardous threshold for carbon monoxide were exceeded at the test area. In the 1990's, Hietaniemi et al[10] studied the effect of water suppression on toxic yields in the small scale using controlled-atmosphere cone calorimeter with water spray inlet. It was concluded that water suppression can even double the yields of CO and HCN. However, even though the yield in g/g increases, water suppression can reduce the total yield in g, since the mass of burned material decreases, which has a positive effect on the safety of occupants. Shelley et al[11] have performed tenability analysis of TV set fires in a sprinkler protected compartment, inspecting survivability in post-sprinkler activation environment. fractional effective dose (FED) method by Purser was used to assess the tenability conditions. It was deemed that FED < 0.1 should allow for safe escape of nearly all exposed individuals.

In Finland, residential sprinkler systems are sometimes used in health care buildings. These systems are then classified according to the Underwriters Laboratories (UL) test standard UL 1626.[12] In this work, we investigated the efficiency of a real, installed sprinkler system in suppressing or controlling the UL 1626 corner fire scenario in hospital rooms. The assessment was done by measuring thermal and toxic conditions during 15 minutes fires. With gas concentration measurements and FED and fractional irritant concentration (FIC) indices we try to conclude whether the conditions are compromising tenability. Both Purser's and ISO 13571 models are used, and their differences discussed.

2 | MATERIALS AND METHODS

2.1 | Building and sprinkler system

The experiments were performed in a 1960's health care center facility of Sysmä, Finland. The building was taken out of use 2 weeks before the experiments. Fires were burnt in 14 different patient rooms and two storage rooms, having the ceiling height of 2.8 m and varying between 16 and 21 m^2 in floor area. The walls between the rooms and the horizontal slabs were concrete, but inside the room there were some light-weight structures, such as closets. These structures did not participate in fires. The rooms were connected to centralized supply and exhaust ventilation ducts with an air handling unit serving about 20 rooms. In seven sprinklered experiments, the ventilation ducts of the fire room were closed to investigate the effect of air exchange on tenability and the role of ventilation network in smoke spread to neighboring rooms.

The building had been retrofitted with a wet sprinkler system 10 years before the experiments. The sprinkler system was designed according to standard SFS 5980 which is normally used for residential buildings. Each room had two horizontal, wall mounted sprinkler nozzles (Tyco 1334, K = 60.5 L/min/$bar^{1/2}$, T_{act} = 68°C and RTI = 35 $ms^{1/2}$). The system was inspected just before the experimental campaign. The pipe pressure in the vicinity of the test rooms was measured continuously. Before activation the pressure was 5.7 ± 0.2 bar, and after the activation of one nozzle, it was 2.7-2.8 bar which, according to the manufacturer's data, corresponds to a horizontal throw of 6.1 m and a flow rate of 100 L/min from one nozzle. As a result, 1.4 m^3 of water was poured to the room during each experiment. For the water management, holes were drilled to the floor to lead the water to the collecting system one floor below.

2.2 | Fire load

The fire load was as close to the UL 1626 living room scenario[12] as possible (Figure 1) with three main elements[1]: A square pool (300 mm × 300 mm) containing 2.4 dL heptane on a water layer. On top of the heptane pool, a wooden crib 305 mm × 305 mm × 152 mm was placed.[2] The corner was built from 1.2 m wide spruce plywood boards reaching from the floor to the ceiling, and gypsum boards behind the boards.[3] Polyether foam mattresses placed vertically and ignited from the bottom edge using fabric strips soaked in heptane. The foam slabs were 800 mm × 800 mm × 75 mm in size and they were installed at height of 25 mm. The foam slabs were glued to 12.7 mm plywood boards to prevent the sprinklers from fully wetting the foam. The polyether material was 2/3 polyol, 1/3 TDI with water as blowing agent. The density of the foam was 36.3 ± 1.1 kg/m^3, that is, about 20% higher than the UL 1626 specification (27.2-30.4 kg/m^3). Based on the cone calorimeter experiments at 30 kW/m^2 heat flux, ignition time was 3 ± 1 second, the HRR per unit area 286 kW/m^2 was slightly higher than UL specification (230 ± 50 kW/m^2), and the effective heat of combustion 22.7 MJ/kg was in the expected range (22 ± 3 MJ/kg).

According to the full-scale laboratory measurements by UL,[13] the heat release rate (HRR) of UL 1626 corner fire scenario is initially about 100 kW, increasing in t^2-manner to 300-500 kW at 60 seconds, and reaching a level of 1500 kW in 80-95 seconds.

Experiments with UL 1626 fire load were repeated 14 times with the sprinkler system and twice with sprinkler system closed (free-burn). The corner of the fire inside the room was chosen randomly to cover the possible orientations and distances to sprinkler nozzles. In six of the sprinklered tests, the sprinkler nozzles were at the wall next to the corner of the fire. The horizontal distance from the wood crib to the nearest nozzle was then in the range 0.8-1.4 m. In the rest of the experiments, the sprinklers were on the opposite wall relative to the corner of the fire, and the distance to the nearest nozzle was in the range 3.2-3.8 m.

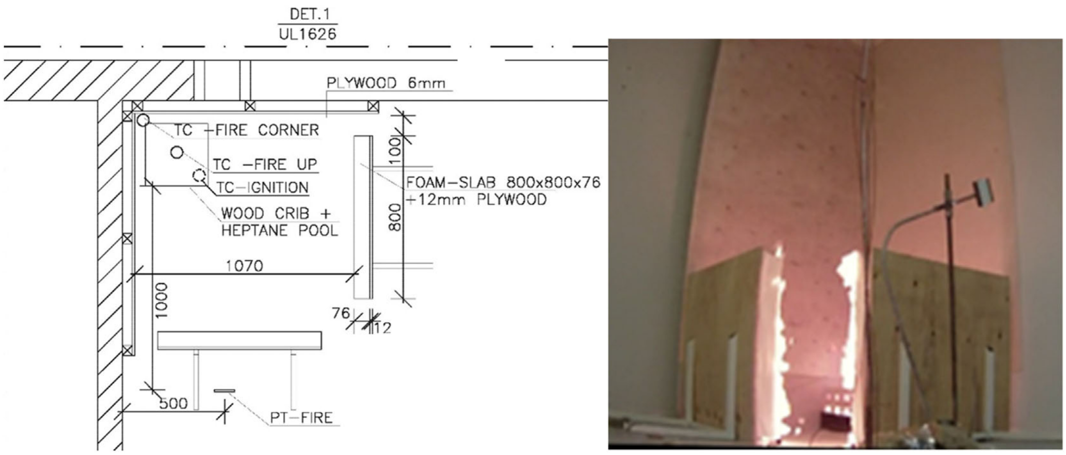

FIGURE 1 Details of the UL 1626 fire load seen from top, A, and the flames 20 seconds after the ignition, B [Colour figure can be viewed at wileyonlinelibrary.com]

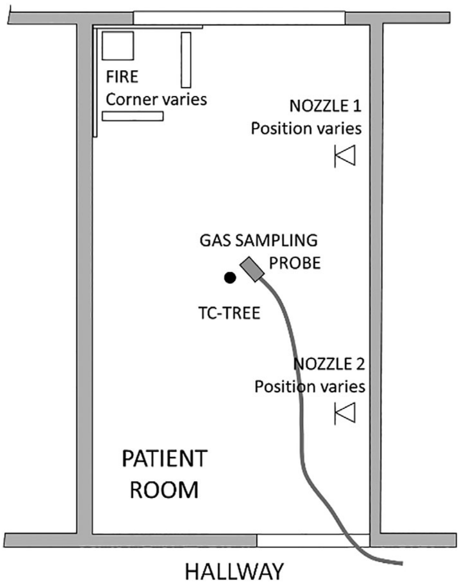

FIGURE 2 Exemplary fire load and measurement positions in the test room

2.3 | Measurements

Fire load and measurement positions are illustrated in Figure 2. The gas temperatures were measured with type-K thermocouples placed in the middle of the room with 5, 55, 155, 205, and 255 cm vertical distances from the ceiling. The thermocouples were unprotected, and soon after sprinkler activation, they were affected by water. There was one thermocouple above the heptane pool to indicate ignition. The temperatures were stored with 1 second time intervals.

Smoke gas analysis was done using FTIR technique, Gasmet Dx4000. The sample was taken through a heated probe and filter followed by 35 m of heated Teflon line. All sampling equipment were protected against water and heat. Sampling flow through the gas analysis system was 4 L/min and the average measuring time was 5 seconds. The response time of the gas measurement system was measured to be between 5 and 10 seconds due to the long sample line. Oxygen analysis was performed with zirconium oxide cell built-in to Portable Sampling System. The sampling point was located 98 cm above the floor level and within a 20 cm distance from the thermocouple tree in the middle of the room. The analysis of the smoke gas compounds was based on the individual infrared spectra of each gas and their absorption. The measurement uncertainties were estimated using the Technical Specification CEN/TC 264 N 2719. The estimated relative measurement uncertainties were typically in the range of 4-12 rel-%, with the exception of compounds present in very small concentrations with higher uncertainties.

2.4 | Test procedure

Each test lasted 15 minutes, approximation of the average time in Finland that it takes from fire department to arrive at the scene and start an effective operation. Before each test, the sprinkler system was initialized to the city water system pressure. A fireman with breathing apparatus went inside the room, the door was closed, and the fireman ignited the pool and fabric strips using a torch. Measurements were started about 1 minute before ignition. The fireman stayed inside the room for the entire experiment, delivering observations through radio. After 15 minutes of fire test, the sprinkler system water source was closed, remaining HRR was manually extinguished, and the smoke ventilated through an open window.

3 | TOXICITY ANALYSIS

Gases have two major ways of affecting people, by asphyxia or by irritation. The required exposure times and incapacitating concentrations of asphyxiant gases are significantly smaller than those for irritants. Thus, asphyxiant gases have more potential to incapacitate humans. Irritants, however, can cause inflammation in lung tissue and thus be lethal hours or even days after the initial exposure.[4,5]

The asphyxiant effect of different gases to humans can be assessed using FED method that compares the cumulative dose of different inhaled gases to observed thresholds of incapacitation. The heat effect is not considered in this article because the temperatures and heat fluxes were low in the fires with sprinklers. We calculate FED values using two alternative methods: a comprehensive method of Purser[3] and more simplified method of ISO 13571 standard.[6]

The Purser's method considers the following asphyxiants: carbon monoxide (CO), hydrogen cyanide (HCN), and nitrogen oxides (NO_x). The irritant gases are: hydrogen chloride (HCl), hydrogen bromide (HBr), hydrogen fluoride (HF), sulfur dioxide (SO_2), nitrogen dioxide (NO_2), acrolein (C_3H_4O), and formaldehyde (CHOH). The effect of asphyxiant and irritant gases toward incapacitation is calculated as:

$$\mathrm{FED}_I(t) = \int_0^t [(F_{I,\mathrm{CO}} + F_{I,\mathrm{CN}} + F_{I,\mathrm{NOx}} + \mathrm{FLD})V_{\mathrm{CO2}} + F_{\mathrm{O2}}]dt, \tag{1}$$

where t is time, subscript I refers to incapacitation as a toxic endpoint, and

$$F_{I,\mathrm{CO}} = \frac{3.317\cdot 10^{-5} X_{\mathrm{CO}}^{1.036} \times \dot{V}}{D}, \tag{2}$$

$$F_{I,\mathrm{CN}} = \left[\frac{\exp(X_{\mathrm{CN}}/43)}{220} - 0.0045\right], \tag{3}$$

$$F_{I,\mathrm{NOx}} = \frac{(X_{\mathrm{NO}} + X_{\mathrm{NO_2}})}{1500}, \tag{4}$$

$$V_{\mathrm{CO2}} = \frac{\exp(0.1903\cdot X_{\mathrm{CO_2}} + 2.0004)}{7.1}, \tag{5}$$

$$F_{I,\mathrm{O2}} = \frac{1}{\exp[8.13 - 0.54(20.9 - \%X_{\mathrm{O_2}})]} \tag{6}$$

In above, X_i is the concentration of gas i at given time in ppm (except for O_2 which is expressed in volume %), $\dot{V}$ is the volumetric flow of breathing (l/min), assumed 8.5 L/min for a person at rest and 25 L/min for light activity. NO and NO_2 are assumed to protect from cyanide poisoning, and thus $X_{\mathrm{CN}} = X_{\mathrm{HCN}} - X_{\mathrm{NO}} - X_{\mathrm{NO_2}}$. D is the assumed incapacitating level of COHb% in blood, being 30% for light activity and 40% for rest. Presented formula for V_{CO2} is a correlation that describes hyperventilation, that is, caused by carbon dioxide. Denominator 7.1 (l/min) in Equation (5) is a suggested value for the respiratory minute volume of resting person at background CO_2 concentration. The effect of irritants is consider in the FED calculation with a factor called fractional lethal dose (FLD) that calculates a sum of normalized doses of N individual irritants

$$\mathrm{FLD}(t) = \int_0^t \sum_{i=1}^{N} \frac{X_i(t)}{\mathrm{FLD}_i} dt, \tag{7}$$

where FLD_i are lethal doses (Table 1).

In ISO 13571, the FED calculation method only considers the asphyxiant effects of CO and HCN:

$$\mathrm{FED}_I(t) = \sum_0^t \frac{X_{\mathrm{CO}}}{35\,000}\cdot v_{\mathrm{CO_2}}\Delta t + \sum_0^t \frac{X_{\mathrm{HCN}}^{2.63}}{1.2\times 10^6}\cdot v_{\mathrm{CO_2}}\Delta t, \tag{8}$$

where Δt is a time increment between measurement time instances, and

$$v_{\mathrm{CO2}} = \exp\left[\frac{X_{\mathrm{CO_2}}}{5}\right]. \tag{9}$$

In the ISO 13571 calculation method, the person is assumed to be in a light work. The lack of other asphyxiant gases is based on the assumption that 'CO and HCN are the only asphyxiant combustion products that exert a significant effect on the time to compromised tenability.' This is a strong statement, considering the lack of recent experiments regarding the compromising tenability concentrations of NO_x. NO_x gases affect like CO, that is, through hemoglobin bonding (methaemoglobin formation) with affinity of 1500 greater than oxygen, whereas CO's affinity is 200 to 250 times that of oxygen.[5] As in ISO 13571 standard, it is often stated that NO_x gases could be

TABLE 1 Lethal doses[3] and incapacitating concentrations for different irritants[3,6]

Gas	Lethal doses FLD_i (ppm × min)	Incapacitating concentration FIC_i purser (ppm)	Incapacitating concentration FIC_i ISO 13571 (ppm)
HCl	114 000	900	1000
HBr	114 000	900	1000
HF	87 000	900	500
SO_2	12 000	120	150
NO_2	1900	350	250
C_3H_4O (Acrolein)	4500	20	30
CHOH (Formaldehyde)	22 500	30	250

Abbreviations: FIC, fractional irritant concentration; FLD, fractional lethal dose.

ignored without significant error to FED value. However, Tsuchiya[14] cites the work of Montgomery et al who estimated that 1-hour lethal concentration (LC_{50}) of NO_x is approximately 200 to 400 ppm. In the same experiments, the 1-hour lethal concentration for HCN was determined to be 200 to 300 ppm. In addition, Tsuchiya[14] cites Higgins et al who determined that, for rats and mice, the 5-minute LC_{50} of NO_2 were 831 and 1880 ppm, and of HCN 503 and 323 ppm, respectively. Purser and McAllister[3] present 30-minute LC_{50} to be 170 ppm for NO_2 and 165 ppm for HCN. These data indicate that the toxic potency of NO_2 is comparable or slightly less than the potency of HCN. This means that NO_x could produce significant contribution toward incapacitation.

In addition to Fractional Lethal Dose, the effect of irritants can be assessed by FIC. Unlike FED or FLD, the irritant concentration simply measures the ratio of the present and incapacitating concentrations. The FIC can be calculated by the method described by Purser,[3] or as described in ISO 13571 standard, where it is actually named fractional effective concentration (FEC). The difference between these two methods is that the incapacitating concentrations are different (see Table 1). The formula for FIC is:

$$\mathrm{FIC}(t) = \sum_{i=1}^{N} \frac{X_i}{\mathrm{FIC}_i}. \tag{10}$$

The incapacitation concentrations in the two methods are of similar magnitude in general, but the incapacitating concentration for CHOH is eight times higher in ISO 13571 than in the Purser's method. The interpretation of the FIC/FEC calculations is also slightly different in two methods: Purser suggests that the FIC values exceeding 1.0 will significantly impair the escape efficiency of occupants and the FIC values exceeding 5.0 will cause incapacitation in 50% of the exposed population. ISO 13571 suggests that FEC exceeding 1.0 will cause incapacitation in 50% of population. This is a major difference and will significantly affect the results as the incapacitation concentrations of the individual gases are of the same magnitude.

4 | RESULTS

4.1 | General observation

The sprinkler fully suppressed the fire in only three experiments, one of which was caused by a fluorescence lamp directing water directly to the point of ignition. Generally, three distinct types of behavior were observed[1]: both mattresses burned well with a final mass loss greater than 50%,[2] one mattress burning well and one only partly, and[3] both mattresses burning only slightly. The sprinklers activated between 53 and 102 seconds, in average 72 seconds with SD of 13 seconds. In all cases the sprinkler prevented the fire from spreading to the plywood corner.

In the sprinklered experiments where the ventilation inlets and outlets of the fire room were left open, small amounts of smoke spread to the adjacent rooms and the corridor, but their CO concentrations remained below dangerous levels. Effects on the fire development were not observed.

In free-burns, a rapid fire development was observed till about 2 minutes, after which the fire became underventilated and suppressed itself. At the same time, the pressure inside the room increased significantly, up to the point that the door opened to the corridor despite two men trying to keep it closed by pushing.

4.2 | Thermal environment

Temperatures of the thermocouple tree were averaged over the sprinkler tests, and separately over the two free-burns (Figure 3). In tests with sprinklers (left), the temperatures remained low, peaking at 100°C at the ceiling and sub 35°C at the level of patients (205 cm from the ceiling). Due to the high slopes in temperature at the time of sprinkler activation, even small differences in sprinkler activation times (2σ = 26 seconds) caused large variation between experiments. This can be seen in the dashed line in Figure 3, showing the 95%

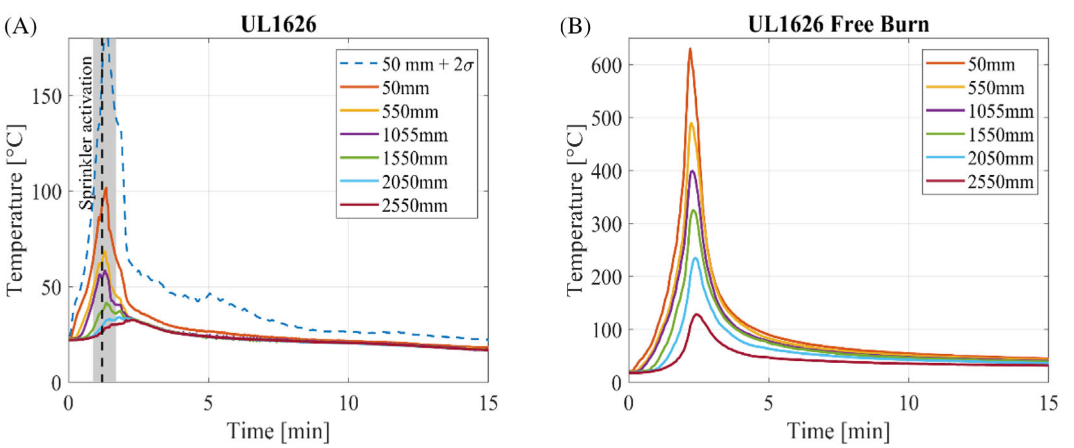

FIGURE 3 Average temperatures from the thermocouple tree in sprinklered, A, and free-burns, B. Legend shows the distance of each thermocouple from the ceiling. The dashed line presents an upper 95% confidence limit for the readings of the highest thermocouple. The range of sprinkler activation times is shown as a shaded area, and the mean activation time as a vertical dashed line [Colour figure can be viewed at wileyonlinelibrary.com]

confidence limit for the temperature at the highest location. After sprinkler activation, temperatures decrease rapidly, even though the uncertainty of wet thermocouples must be kept in mind. In the free-burns, the temperature at the patient level exceeded 200°C momentarily, which would cause a thermal hazard to occupants.

4.3 | Gas concentrations

Figure 4 shows the CO concentrations as average and median values for the sprinkler tests (left) and as an average for the free-burns (right). In sprinkler tests, the CO concentration gradually increases over time, indicating the continuation of the smoldering combustion despite the operating sprinklers. The average value of the peak CO concentrations in the sprinkler tests was 585 ppm with 381 ppm SD. In the two free-burns, the peak CO concentrations were 37 600 and 17 800 ppm.

Concentrations of other toxic gases (gases considered by Purser's FED model) with peak concentrations above 2 ppm are shown in Figure 5. In the sprinkler tests, the highest asphyxiant concentrations (excluding CO) were observed for NO, for which the concentration rose quickly to a level of 50 ppm. In free-burns, multiple gases exceeded 400 ppm, including HCN at 440 ppm, hydrogen chloride (HCl) at 440 ppm and CHOH at 550 ppm. It is interesting that while in sprinkler tests the concentrations either increased or remained at the same level (no washing by droplets), the concentrations of the free-burn clearly decreased after suppression. One possible reason is the dilution by the mechanical ventilation, but this has not yet been confirmed.

4.4 | Toxicity assessment

FED values of all sprinklered experiments are shown in Figure 6. These FED values were calculated using the Purser method for persons at rest (left figure) and at light work (right figure). Despite the seemingly consistent performance of the sprinklers in suppressing the

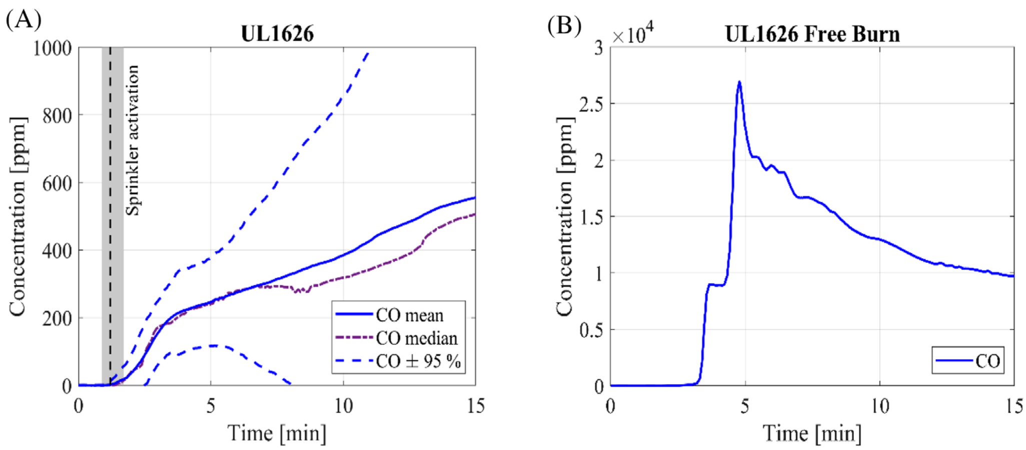

FIGURE 4 CO concentrations in sprinklered, A, and free-burns, B. The range of sprinkler activation times shown as a shaded area, and the mean activation time as a vertical dashed line [Colour figure can be viewed at wileyonlinelibrary.com]

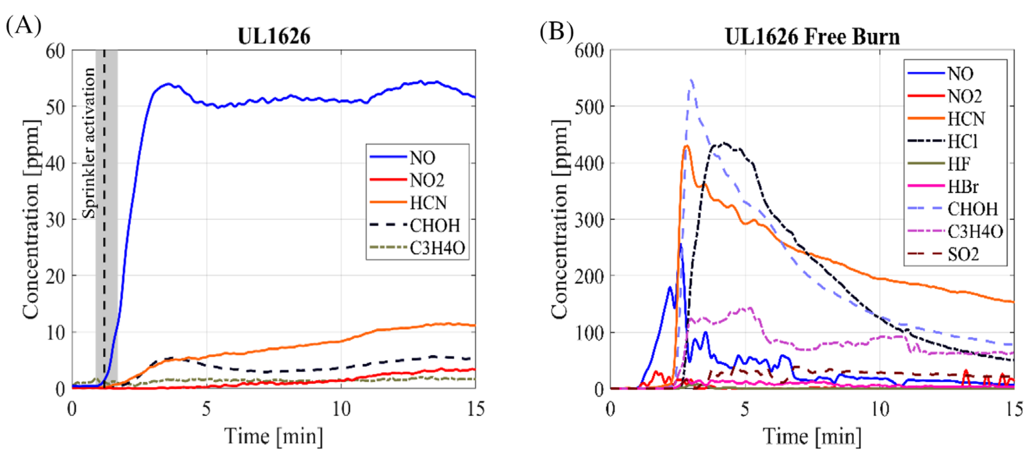

FIGURE 5 The average concentrations of gases other than CO. Only gases which are considered in Purser's FED model and their concentration exceeds 2 ppm are shown. The range of sprinkler activation times shown as a shaded area, and the mean activation time as a vertical dashed line [Colour figure can be viewed at wileyonlinelibrary.com]

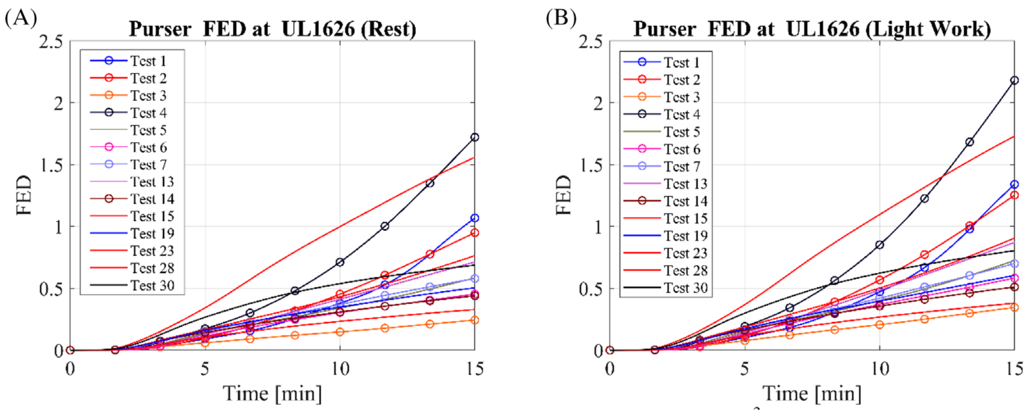

FIGURE 6 FED results for each sprinkler test using the 'Purser'-method.[3] A, Person is assumed to be at rest, and B, in a light work. Tests with closed ventilation are shown with circles. F [Colour figure can be viewed at wileyonlinelibrary.com]

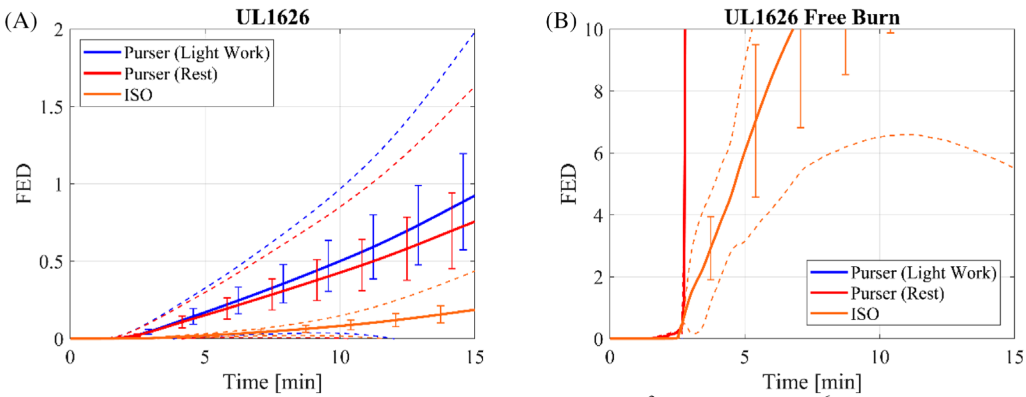

FIGURE 7 The average FED values using the Purser's method[3] and ISO 13571[6] for sprinkler tests, A, and free-burns, B. Solid lines are average FED, dashed lines are the 95% statistical confidence interval, and error bars are the ±35% methodological uncertainties [Colour figure can be viewed at wileyonlinelibrary.com]

fire within a fairly narrow time margin, there is a large scatter among the FED values. Closer look at the results reveals that the toxic hazard seems to be dependent on how much the mattresses kept burning. For example, in Test 3 one foam slab did not even ignite, while tests 28 and 4, both slabs burned for long after sprinkler activation. The light activity of the person increases the FED values in some tests in comparison to being at rest, but not very significantly. The tests where the ventilation system was closed are shown with circle symbols, but there seems to be no effect on the FED values.

The FED values obtained using different calculation methods are compared in Figure 7. In this figure, the average values for FED are shown as solid lines; the dashed line present the scatter in terms ±2σ, corresponding to the 95% confidence interval. In sprinkler tests, there is a significant difference between the two Purser results and the results according to ISO 13571: The Purser's method, which takes into account a wider range of gases, shows FED values around 0.8 at 15 minutes. ISO method, in turn, remains at level 0.2. In free-burns, the conditions can be considered lethal in 3 minutes, regardless of the calculation method. The sudden increase in FED values is caused by the smoke layer coming down and reaching the level of gas sampling point.

To understand the reason between the different FED results, we calculated the contribution of each gas to the outcome of Equation (1) in the end of the tests. Figure 8 shows these contributions for sprinkler tests and free-burns. In the sprinkler tests, NO_x gases cause 71% of FED when the person is assumed to be at light work, and the contribution would be even higher for a person at rest. CO is the second most important gas, and the irritants (FLD) and O_2 depletion follow with similar contributions. ISO standard ignores NO_x as asphyxiant gases, which leads to much lower FED values in Figure 7. In free-burns, HCN clearly dominates with 95% contribution, reflecting the dependence of gas formation mechanisms on fire temperature.

The averaged results of the FIC calculations using both Purser's and ISO 13571 methods are presented in Figure 9. The ISO method shows significantly lower FIC values than the Purser's method because it assumes much higher irritant concentration for formaldehyde (see Table 1), which is present in 8 ppm average peak concentration. In sprinkler tests, the average FIC values remain below 0.3 but

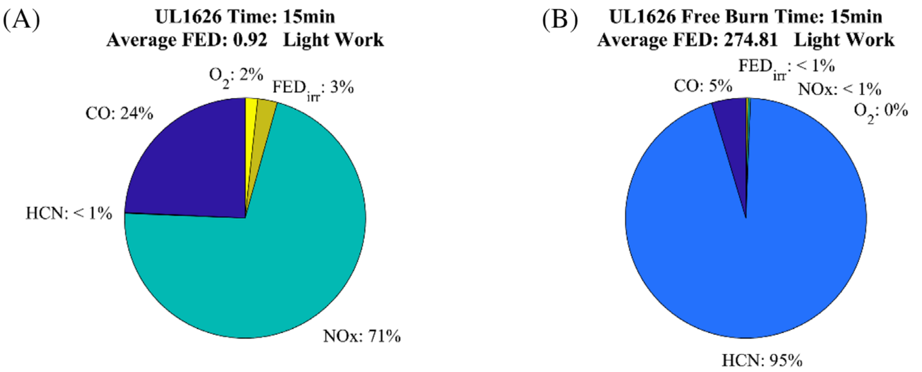

FIGURE 8 The contributions of individual gases to FED at 15 minutes for a person at light work using Purser's method (light work). Sprinkler tests in, A, free-burns in, B [Colour figure can be viewed at wileyonlinelibrary.com]

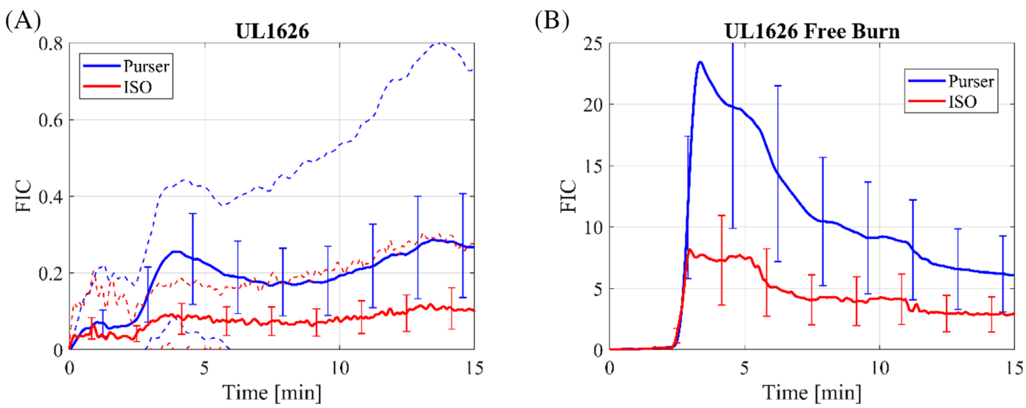

FIGURE 9 Average FIC values for sprinkler tests, A, and free-burns, B. The dashed lines show the 95% (±2σ) statistical confidence intervals, and error bars show the ±50% methodological uncertainties [Colour figure can be viewed at wileyonlinelibrary.com]

FIC = 0.8 would be possible in few percent of cases. The peak FIC is observed at approximately 5 minutes, that is, 3-4 minutes after the sprinklers activated, and another peak close to the end of the experiments. This may be since the sprinkler sprays mix the gas layer and accelerate the advection of irritants to the level of the sampling probe. It may also indicate that the sprinkler water interferes with the burning process, increasing the irritant yields. In general, FIC values did not turn to decline, which is in line with observations that only three fires were fully extinguished by the sprinkler spray. As for the FED, the free-burns resulted much higher FIC values, basically exceeding the critical threshold of FIC = 1.0 in 3 minutes. Sprinklers have a clearly positive effect on the possibility to perform any activity during this kind of fires.

4.5 | Uncertainty of FED and FIC results

ISO 13571 states that the uncertainties of FED and FIC calculations are ±35% and ±50%, respectively. The uncertainty is related to the calculation models and thus to the whole principle of FED or FIC. The same uncertainty estimate is here used for the Purser models as well. These uncertainties are presented in Figures 6 and 8 as vertical error bars. We can observe that the differences between the ISO 13571 and Purser's methods are significant in comparison to the methodological uncertainties. The difference between the FED results corresponding to different activity levels, in turn, are not significant considering these model uncertainties. The statistical uncertainties, caused by the different conditions and geometries, and reported as 95% confidence intervals, are found to be larger than the methodological uncertainties.

5 | DISCUSSION

The current FED models assume that all nitrogen oxides (NO_x) behave like nitrogen dioxide (NO_2), despite the fact that these two gases have very different toxic potencies and toxic mechanisms, NO_2 being clearly more toxic than NO.[15] The justification is that although nitrogen oxides are initially formed as NO, they gradually oxidize into NO_2. To investigate the sensitivity of our results to this assumption, we recalculated the Purser's FED values of the sprinklered tests, where NO_x had high contribution, by assuming zero NO. The results are shown in Figure 10. The Purser's FED values at 15 minutes decreased with factors three (light work) and six (rest), being now about 35% higher (light work) and 40% lower (rest) than the FED given by ISO 13571. NO_2 still contributes to 6% of the total FED, but the comparison with

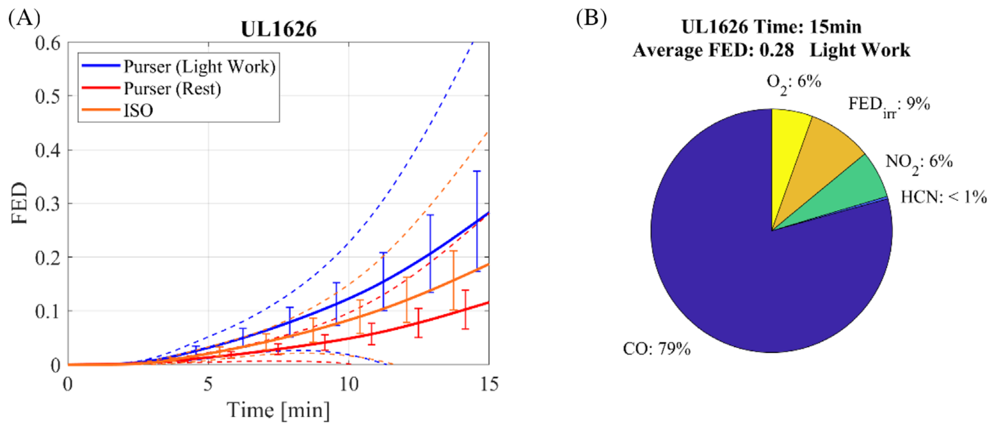

FIGURE 10 The FED results of the sprinklered tests when NO-gas is ignored. The average FED, A, and the relative contributions of different gases on 15-minutes FED, B [Colour figure can be viewed at wileyonlinelibrary.com]

Figure 8 shows that the roles of CO, irritants and oxygen depletion have increased significantly. In the light of these results, we can conclude that NO and NO_2 should be treated separately in the fire toxicity analyses.

The FED and FIC calculations were based on the incapacitating doses, and they should be considered conservative if used for lethality assessment. From the viewpoint of the sprinklers' life-saving effectiveness, it could be more appropriate to use nonlethal thresholds LC_{01} as the reference level. Although the current, incapacitation-focused models are frequently used in fire safety engineering, the relations between the incapacitating and lethal doses are not clear. In his SFPE handbook section[4] (p. 2235), Purser states that an incapacitating dose for fire toxicants is approximately one third of a lethal dose. On the other hand, Pauluhn[16] performed a meta-analysis of CO and HCN toxicity and observed that the doses leading to incapacitation or 'impairment to escape' were difficult to distinguish from those indicative of impending death.

Besides the question of toxicological endpoint, one must keep in mind that the incapacitating dose of irritants and asphyxiant is not constant among humans. It can be assumed that the effects of certain toxic gas concentrations are more severe for elderly and ill persons than for young and healthy. As this research focuses on hospital and health care environments, many of the exposed persons would have lower-than-average tolerance. Purser suggests that if the different sensibility of population is considered, a FED value below 0.1 should provide safe conditions.[5] In the sprinkler tests, the limit of FED = 0.1 was exceeded with certainty, if calculated with Purser's method, and very likely, if using the ISO standard method. According to the ISO 13571 standard, the probability of incapacitation can be related to FED using a log-normal distribution with median at FED = 1 and SD of 1.

The irritancy assessment using FIC leads to similar conclusions. According to the Purser's method, the escape impairment level FIC = 1.0 might be exceeded in some sprinklered fires, but the incapacitating levels were only reached in nonsprinklered fires. If we assume that the effects of FIC also follow the curve shown in Figure 11, the conditions of all fires would be considered unsafe for the weakest individuals. More work is needed for the estimation of the actual survivability probabilities.

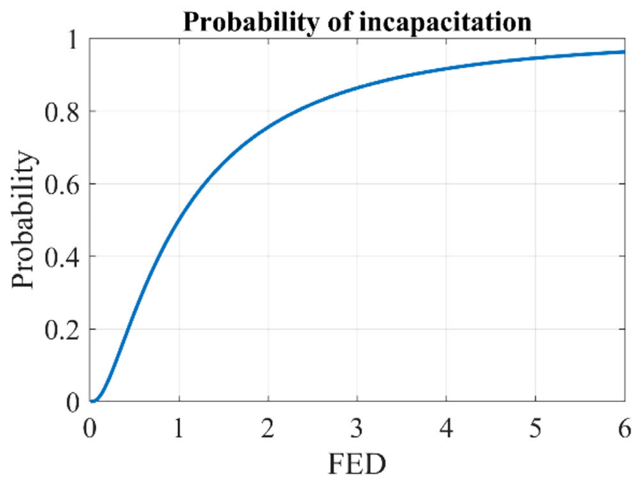

FIGURE 11 The probability of incapacitation as a function of FED, proposed in ISO 13571 [Colour figure can be viewed at wileyonlinelibrary.com]

6 | CONCLUSIONS

Fire experiments with UL 1626 fire source were performed in a real health care center equipped with a residential sprinkler system. In addition to the gas temperatures and toxic gas concentrations, we reported the results of the life safety assessment based on the FED and FIC.

The sprinkler system suppressed the fire in all cases and fully extinguished it in three out of 14 tests. Based on the experimental observations, we can conclude that the sprinklers clearly improve the life safety but do not completely remove the risk of incapacitation caused by toxic gases. The expected improvement in survivability depends on the assumptions concerning the critical levels (incapacitating or lethal dose) and the population sensitivity. If the population is assumed to be more sensitive than in average, which is probably the case in a hospital, the measured asphyxiant doses and irritant concentrations would have been dangerous in both nonsprinklered tests and in many of the sprinklered tests. More work is needed for quantitative survivability estimates.

A significant contribution to the overall FED came from NO_x gases. The FED model of ISO 13571 does not take these gases into account at all, which led to significantly lower FED values than what were obtained with the Purser's method. This indicates that the historical assumptions about CO and HCN being the only important sources of incapacitation should be treated with caution. On the other hand, treating NO as NO_2 in the Purser's method was found to lead three to six times higher FED values than the analysis where NO was simply ignored. As the toxic potencies of NO and NO_2 are known to be very different, combining them in the FED calculation seems to be a strongly conservative approximation. Finding and assigning the lethal, incapacitating and escape impairment doses for these gases individually is essential for the accuracy of fire toxicity analyses.

ACKNOWLEDGEMENTS

The research was funded by the Finnish Fire Protection Fund (Palosuojelurahasto). The authors would like to thank the project collaborators, Sysmä Municipality, the Finnish Association of Fire Officers, and Päijät-Häme rescue services. The authors also would like to thank Magnus Arvidson (RISE, Sweden) and Underwriters Laboratories for the HRR data of the UL 1626 tests. Advice and insights from Prof. David Purser are greatly acknowledged.

ORCID

Simo Hostikka https://orcid.org/0000-0002-3581-1677

Tuula Hakkarainen https://orcid.org/0000-0001-9706-5318

REFERENCES

1. Frank K, Gravestock N, Spearpoint M, Fleischmann C. A review of sprinkler system effectiveness studies. *Fire Sci Rev*. 2013;2(1):6.
2. Stec AA, Hull TR, eds. *Fire Toxicity*. Oxford: Woodhead Publishing Ltd.; 2010:688.–.
3. Purser DA, McAllister JL. Assessment of hazards to occupants from smoke, toxic gases, and heat. *SFPE Handbook of Fire Protection Engineering*. 5th ed. New York, NY: Springer; 2016:2308-2428.
4. Purser DA. Combustion toxicity. *SFPE Handbook of Fire Protection Engineering*. 5th ed. New York, NY: Springer; 2016:2207-2307.
5. Purser DA. Asphyxiant components of fire effluents. Stec AA, Hull TR, *Fire Toxicity*. Oxford: Woodhead Publishing Ltd.; 2010: 118–198.
6. ISO 13571. *Life-threatening Components of Fire—Guidelines for the Estimation of Time to Compromised Tenability in Fires*. Geneva, Switzerland: International Organization for Standardization; 2012.
7. Blomqvist P, Simonson-McNamee M. Large-scale generation and characterisation of fire effluents. In: Stec AA, Hull TR, eds. *Fire Toxicity*. Oxford: Woodhead Publishing Ltd.; 2010:461-514.
8. Guillaume E, Didieux F, Thiry A, Bellivier A. Real-scale fire tests of one bedroom apartments with regard to tenability assessment. *Fire Saf J*. 2014;70:81-97.
9. O'Neill JG, Hayes WD, Zile RH. *Full-Scale Fire Tests with Automatic Sprinklers in a Patient Room: Phase II*. Gaithersburg, MD: US Department of Commerce, National Bureau of Standards; 1980.
10. Hietaniemi J, Kallonen R, Mikkola E. *Fires at Chemical Warehouses. A Cone Calorimeter Study on the Burning Characteristics and Fire Effluent Composition of Selected Chemical Compounds*. VTT Research Notes 1810. Espoo, Finland: VTT Technical Research Centre of Finland. 56 p. + app. 35 p. ISBN 951-38-5085-4; 1997.
11. Shelley J, Spearpoint M, Bittern A. Tenability analysis of television set fires in a sprinkler protected compartment. *Fire Sci Technol*. 2009;28 (1):1-32.
12. UL 1626. *Standard for Residential Sprinklers for Fire-Protection Service*. 4th ed.Northbrook, IL: Underwriters Laboratories; 2008.
13. Underwriters Laboratories. *Report on Residential Fire Test Research*. Northbrook, IL: Underwriters Laboratories; 2001:42.
14. Tsuchiya Y. Relative significance of NO_x and HCN in fire gas toxicity. *Fire Safety Sci*. 1989;2:381-390.
15. Paul KT, Hull TR, Lebek K, Stec AA. Fire smoke toxicity: the effect of nitrogen oxides. *Fire Saf J*. 2008;43:243-251.
16. Pauluhn J. Acute inhalation toxicity of carbon monoxide and hydrogen cyanide revisited: comparison of models to disentangle the concentration × time conundrum of lethality and incapacitation. *Regul Toxicol Pharmacol*. 2016;80:173-182.

How to cite this article: Hostikka S, Veikkanen E, Hakkarainen T, Kajolinna T. Experimental investigation of human tenability and sprinkler protection in hospital room fires. *Fire and Materials*. 2021;45:823–832. https://doi.org/10.1002/fam.2893