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Effect of sprinklers on the patient's survival probability in hospital room fires

Simo Hostikka [a,*], Eetu Veikkanen [a], Tuula Hakkarainen [b], Tuula Kajolinna [b], Terhi Kling [b]

[a] Aalto University, Finland
[b] VTT Technical Research Centre of Finland Ltd., Finland

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ABSTRACT

The effectiveness of sprinklers in protecting a patient in a hospital room fire was investigated by performing 26 sprinklered and four free-burn experiments in real hospital rooms equipped with water-based automatic suppression system. Three different fire loads were used: UL 1626 corner test fire and two different textile fires. The measurements included temperatures, pipe pressure, and concentrations of about 20 different gas compounds. Based on the measurement results, we calculated the Fractional Effective Dose (FED) and Fractional Irritant Concentration (FIC) –values, and estimated the likelihood of incapacitation as a function of time. The results showed that sprinklers maintained temperatures at low level and reduced toxicity, mainly through fire development control. In UL1626 and large textile fires, sprinklers decreased the patient's incapacitation probability from 0.9 or above to the level of 0.4. In small textile fires, the difference between the incapacitation probabilities of sprinklered fires and free-burns was less than the measurement uncertainty. FED results were sensitive to the calculation method due to the different treatment of NO_x –gases.

1. Introduction

Water sprinklers are commonly used to improve the fire safety in spaces where the occupants cannot be assumed to perform manual suppression in the early stages of the fire. In hospitals and other health care units, water sprinklers can be used to reduce the risk of fire in patient rooms. It is questionable if the health care personnel can evacuate a patient from a fire room without proper training and equipment. Often, it may be more rational for them to ensure the safety of other patients and leave the fire room evacuation to the fire service. The capability of sprinklers in protecting people inside the room becomes then in question.

The effectiveness of sprinklers in limiting fires has been widely investigated, and their performance in cooling the room of fire origin and restricting the fire spread is undeniable [1]. However, as most fire casualties are caused by the inhalation of toxic gases, we can assume that knowing the toxic gas concentrations after sprinkler activation will be necessary for the estimation of their effectiveness in protecting people. The physical effects of different asphyxiant and irritating gases have been studied extensively, and at least the most important mechanisms of incapacitation are currently understood [2–4]. O'Neil et al. [5] investigated the effect of sprinklers to toxic yields and concluded that sprinklers prevented flashover and cooled the room, but the hazardous threshold for carbon monoxide was exceeded at the test area. More recently, Guillaume et al. [6] made a tenability assessment of bedroom fires, but their experiments did not include sprinklers. It was concluded that the smoke alarms activated before the tenability was compromised. The analysis was done by using the method described in the ISO 13571 standard [7]. Based on the gas analysis, nitric oxide (NO) was determined to be the most important irritant. Based on the above-mentioned studies, we do not have sufficient information to answer the question of sprinkler effectiveness in protecting people.

In this work, we investigated the effectiveness of residential sprinkler systems in protecting life in a patient room fire by carrying out experiments in real hospital rooms. Residential sprinkler systems are sometimes used in the Finnish hospitals because the patient rooms are typically similar to homes considering the room size and fuel types. As these systems are tested according to the UL 1626 standard, we adopted the UL 1626 corner fire as one of the three fire scenarios. The major fuel in the standard test is polyurethane foam. The results concerning the thermal environment and toxicity assessment of the UL 1626 fires have been presented in Ref. [8], but partially included here for the

* Corresponding author.
E-mail address: simo.hostikka@aalto.fi (S. Hostikka).

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completeness of the presentation. Two other fire scenarios were developed specifically for this study, using hospital textiles. The sprinkler performance assessment was done by measuring thermal and toxic conditions during 15 min fires. With gas measurements and Fractional Effective Dose (FED) calculations, we estimate the probability that a person becomes incapacitated during the fire. We assume that the incapacitation, which we can conclude using FED, gives an indication of lethal conditions, although a recent study of Pauluhn [4] concluded that passing the FED based escape paradigm cannot be used as direct equivalent of post-fire survival.

2. Materials and methods

2.1. Building and sprinkler system

The experiments were performed in a 1960's health care center facility of Sysmä municipality in Finland. The building was taken out of use only weeks before the experiments. Fires were burnt in 14 different patient rooms and two storage rooms, varying between 16 and 21 m^2 in size. The ceiling height of the rooms was 2.8 m. 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 air handling unit serving about 20 rooms. In some experiments, the ventilation system of the fire room was closed (ducts plugged) to investigate the effect of air availability. A single door led from each room to the hallway, where the data loggers were placed and measurement personnel, as well as safety team were waiting during the experiments (Fig. 1a).

The building had been retrofitted with a wet sprinkler system about ten years ago. The sprinkler system was designed according to the standard SFS 5980 which is normally used for residential buildings. Each room had two horizontal wall mounted type 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 a single nozzle, it was 2.7 … 2.8 bar. This corresponds to a flow rate of 100 L/min from one nozzle, that is, 1.4 m^3 of water poured to the room during a typical experiment. For water management, holes were drilled to the floor to lead the water to the collecting system one floor below.

2.2. Fire loads

Three different types of fire loads were used (Fig. 2). The first type followed the corner fire load of UL 1626 standard, consisting of three main elements: (1) Square pool (300 mm × 300 mm) containing 2.4 dl heptane and a layer of water below it. On top of the heptane pool, a wooden crib of size 305 mm × 305 mm x 152 mm was placed. (2) Plywood corner was built with 1.2 m wide boards reaching from floor to ceiling. Gypsum boards were placed behind the boards. (3) Polyether foam mattresses placed vertically and ignited using strips of fabric soaked in heptane. The foam slabs were 800 mm × 800 mm x 75 mm in size and they were installed at height of 25 mm. The backsides of the slabs were glued to 12.7 mm plywood to prevent the sprinkler of fully wetting the foam. The polyether foams were 2/3 polyol, 1/3 TDI, and water as blowing agent. The density of the foam was 36.3 ± 1.1 kg/m^3, i. e. about 20% higher than the UL 1626 specification (27.2–30.4 kg/m^3). The flammability properties of the foam were measured in three replicate tests using cone calorimeter at the irradiance of 30 kW/m^2. Based on the results, summarized in Table 1, the peak HRR per unit area was slightly above the UL specification (230 ± 50 kW/m^2), but the effective heat of combustion was in the expected range (22 ± 3 MJ/kg). According to the full-scale laboratory measurements by Underwriters Laboratories [9], the heat release rate (HRR) of UL 1626 corner fire scenario is initially about 100 kW, and then increases in t^2-manner, being in the range 300–500 kW at 60 s, and reaching a level of 1500 kW in 80 … 95 s. The average of three HRR measurements is shown in Fig. 1b, with error bars indicating a combination of two standard deviations and 5% measurement errors. High uncertainty in the end is caused by the growth rate differences among the three repeats.

Two other fire loads were built from used hospital textiles placed in a trolley with three metal grill shelves. The smaller one (denoted TEX 150) included flame retarded curtains or bedsheets freely laying on the lowest shelf and work clothes (blended fabrics of cotton and polyester) in plastic bags on the second shelf. A larger textile fire (TEX 1500) was made of cotton, work clothes, and flame retarded fabrics on the first, second and third shelves, all in plastic bags. The flammability parameters and the average masses of each fabric in the fire load types are shown in Table 1. Fig. 1b shows the HRR of both fire loads, measured under the hood of a Single Burning Item (SBI) apparatus. The larger fire was manually suppressed at 95 s for safety. By that time, it had reached 1400 kW. Smaller textile fire was allowed to burn to completion, reaching a peak HRR of 160 kW. The measurement error is ±5%, but the repeatability error cannot be estimated from a single measurement.

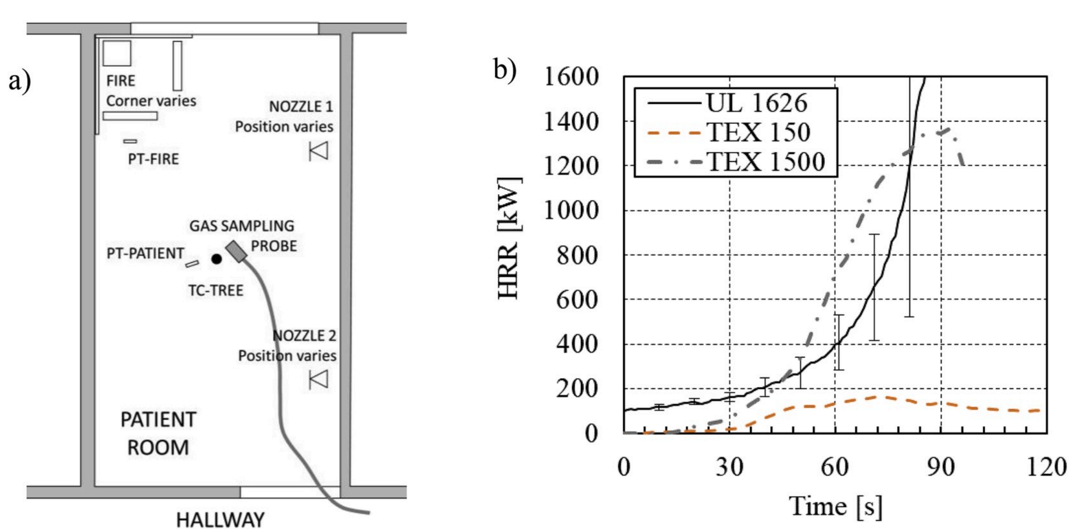

Fig. 1. a) Room layout with one possible fire position (which varied between tests) and measurement locations; b) Measured HRR of UL 1626 corner fire [9] and large and small textile fires (this work).

Fig. 2. Fire load types UL 1626 (a), small textile fire (b), and large textile fire (c).

Table 1
Fuel material performance in cone calorimeter tests in terms of mean (standard deviation in parentheses) of time to ignition (t_{ig}), peak HRR (pHRR) and the effective heat of combustion (EHC), and the amount of each material (Mass) in the three fire load types.

	t_{ig}		pHRR		EHC		Mass (kg)		
	(s)		(kW/m^2)		(MJ/kg)		UL 1626	TEX 150	TEX 1500
Foam	3.0	(0.8)	290	(24)	23	(3.2)	3.5		
Cotton fabric	32	(4.2)	160	(3.0)	15	(0.5)			2.5
FR fabric	330	(36)	320	(68)	16	(0.8)		1.4	5.6
Work clothes	25	(4.3)	280	(15)	16	(0.7)		1.8	7.3

2.3. Measurements

The temperatures in each test room were measured with type-K thermocouples (0.5 mm diameter) and two plate thermometers, which were later used to estimate the incident heat flux [10]. Five thermocouples were placed in the middle of the room at distances of 5 cm, 55 cm, 155 cm, 205 cm and 255 cm from the ceiling. The first plate thermometer was placed 50 cm from the fire and 50 cm from the adjacent wall. The second plate thermometer was placed in the middle of the room, next to the gas measurement nozzle and the thermocouple tree. The temperatures were stored with one second time intervals. Uncertainty of the temperature measurements is <5% before sprinkler activation, but much greater afterwards because the thermocouples were non-protected. Heat flux uncertainties are ±15% [10].

Smoke gas analysis was done using the Fourier Transform InfraRed (FTIR) technique, Gasmet Dx4000. The sample cell volume was 400 ml and spectral resolution of the analyzer 8 cm^{-1}. The sample was taken through a heated stainless steel probe and stainless steel filter followed by 35 m of heated Teflon line. All sampling equipment were heated to 180 °C and protected against water and heat. Sampling flow through the gas analysis system was 4 l/min and the averaging measuring time was 5 s. The response time of the gas measurement system was measured to be between 5 and 10 s due to the long sample line. Oxygen analysis was performed with zirconium oxide cell built-in to Gasmet 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 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 [11] which was preliminary version of Technical Specification CEN/TS 17337. 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. Experimental campaign and procedure

UL 1626 experiments were repeated 14 times with the sprinkler system and twice with sprinkler system closed (free-burn). For both textile fires, six sprinklered experiments and one free-burn were performed. The corner of fire origin inside the room was chosen randomly to cover the possible orientations and distances to sprinkler nozzles.

Each test lasted 15 min, which is the approximate average intervention time of fire departments in Finland. 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 he ignited the pool and fabric strips using a torch. Measurements were started about one minute before ignition. The fireman stayed inside the room for the entire experiment, delivering observations through a radio. After the test, the fire was extinguished, sprinkler system closed, and 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 of 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 [2].

The asphyxiant effect of different gases to humans can be assessed using Fractional Effective Dose (FED) method that compares the cumulative dose of different inhaled gases to observed thresholds of incapacitation. The heat effect is not considered in this paper because the temperatures and heat fluxes were low in the fires with sprinklers. We calculated FED values using two alternative methods: a comprehensive model developed by Purser [3] and a more simplified method of ISO 13571 standard [7]. Purser's method considers the following asphyxiants: carbon monoxide (CO), hydrogen cyanide (HCN) and nitrogen oxides (NO_x). The irritant gases are: hydrogen cloride (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 towards incapacitation is calculated as

$$FED_{in}(t) = \int_0^t [(F_{I,CO} + F_{I,CN} + F_{I,NOx} + FLD)V_{CO2} + F_{I,O2}]dt' \quad (1)$$

where

$$F_{I,CO} = \frac{3.317 \cdot 10^{-5} X_{CO}^{1.036} \dot{V}}{D} \quad (2)$$

$$F_{I,CN} = \frac{\exp(X_{CN}/43)}{220} - 0.0045 \quad (3)$$

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

$$V_{CO2} = \frac{\exp(0.1903 X_{CO_2} + 2.0004)}{7.1} \quad (5)$$

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

In the above, X_i is the volumetric concentration of gas i at given time in ppm (vol % for O_2), and $X_{CN} = X_{HCN}$-X_{NO}-X_{NO2}. $\dot{V}$ is the volumetric flow of breathing (L/min), assumed 8.5 L/min for a stationary patient and 25 L/min for light activity. D is the assumed incapacitating level of COHb% in blood, being 30% for light activity and 40% for rest. Equation (4) lumps NO and NO_2 together despite the fact that NO_2 is about ten times more toxic than NO. This has been justified by the assumption that NO may eventually oxidize into NO_2, but it is uncertain if this assumption holds in sprinklered compartment fires. To investigate the influence of the failing NO oxidation -assumption, we performed alternative FED calculations where the NO concentrations were set zero.

The presented formula for V_{CO2} is a correlation that describes hyperventilation caused by carbon dioxide. The denominator 7.1 is a suggested value for $\dot{V}$ in rest at the background CO_2 concentration. The effect of irritants is considered in the FED calculation with a factor called Fractional Lethal Dose (FLD) [3], that integrates the ratios of concentration-time products and lethal doses FLD_i (Table 2). Alternatively, one could use LC50 values from ISO 13344.

$$FLD(t) = \int_0^t \sum_{i=1}^{N} \frac{X_i(t')}{FLD_i} dt' \quad (7)$$

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

$$FED_{in}(t) = \sum_{t_1}^{t_2} \frac{X_{CO}}{35000} \exp\left(\frac{X_{CO2}}{5}\right) \Delta t + \sum_{t_1}^{t_2} \frac{X_{HCN}^{2.63}}{1.2 \cdot 10^6} \exp\left(\frac{X_{CO2}}{5}\right) \Delta t \quad (8)$$

The ISO 13571 method does not differentiate between different levels of physical activity, although the breathing rate enhancement due to the increased carbon dioxide concentration is taken into account. The method assumes that CO and HCN are the only asphyxiant combustion products that exert a significant effect on the time to compromised tenability.

The effect of irritants is assessed by Fractional Irritant Concentration (FIC) [3] or Fractional Effective Concentration (FEC), as described in ISO 13571. The formula for both is

$$FIC(t) = \sum_{i=1}^{N} \frac{X_i}{FIC_i} \quad (9)$$

where FIC_i are the incapacitating concentrations of the gases, listed in Table 2. The incapacitating 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 Purser's method. Also, Purser assumes that the population median is at FIC = 5, instead of FIC = 1 of the ISO 13571 standard. This is a major difference and will significantly affect the results as the incapacitation concentrations of the individual gases are of the same magnitude.

ISO 13571 makes an *a priori* assumption that the FED = 1 corresponds to a median value of log-normal response distribution, with one-half of the population being less susceptible, and one-half more. The probability of incapacitation for a random individual is therefore

$$P\left(I \middle| x\right) = \frac{1}{2} + \frac{1}{2} \mathrm{erf}\left(\frac{\ln(x)}{\sqrt{2}}\right) \quad (10)$$

The effects of toxic gases can be different for elderly and ill persons than what they are for young and healthy persons. As this research focuses on hospital and health care environments, many of the exposed persons would have lower-than-average tolerance. There is no empirical justification for the log-normal distribution of Eq. (10). It is used here in the absence of any better information.

4. Results

4.1. General observation

The sprinkler fully suppressed the fire in three UL 1626 experiments, one of which was caused by a fluorescence lamp directing water directly to the point of ignition, and in three smaller textile fires. The sprinkler activation times are presented Table 3. UL 1626 and larger textile fires were well repeatable, but the smaller textile fire led to significantly different activation times, with mean of 122 s and standard deviation of 83 s. In all tests, the sprinkler prevented the fire from spreading to the plywood corner (only in UL 1626) and other structures of the room. Smoke spread to the adjacent room was observed in only a few tests.

In UL 1626 and large textile fire free-burns, fire size increased about 2 min, after which the fire became under-ventilated and was self-suppressed. During the growth stage, the pressure inside the room increased significantly, opening the door to the corridor for short times despite manual attempts to keep the door closed.

The visibility went close to zero in both UL 1626 and large textile fires, both with and without sprinklers. With sprinklers, the room appeared less sooty after the fire, but the water spray mixed the smoke layer effectively. In small textile fires, the visibility was reduced.

4.2. Thermal environment

Thermal environment was evaluated using the patient-level (z = 0.8 m) thermocouples. Results for textile fires are shown in Fig. 3. See Ref. [8] for UL 1626 temperatures. In tests with sprinklers, the temperatures peaked at 50 °C. After the sprinkler activation, temperatures decrease rapidly, even though the uncertainty of wet thermocouple readings must be kept in mind. In the free-burns, the UL 1626 and large

Table 2
Lethal doses [3] and incapacitating concentrations FIC_i for different irritants [3, 7].

Gas	Lethal Dose FLD_i (ppm × min)	FIC_i - Purser (ppm)	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)	4 500	20	30
CHOH (Formaldehyde)	22 500	30	250

Table 3
Number of tests (N), sprinkler activation time t_a statistics and the number of extinguished fires (N_{ext}) for each fuel type.

	N	mean(t_a) (s)	std(t_a) (s)	min(t_a) (s)	max(t_a) (s)	N_{ext}
UL 1626	14	72	13	53	102	3
Textile 150	6	122	83	65	287	3
Textile 1500	6	41	14	37	73	0

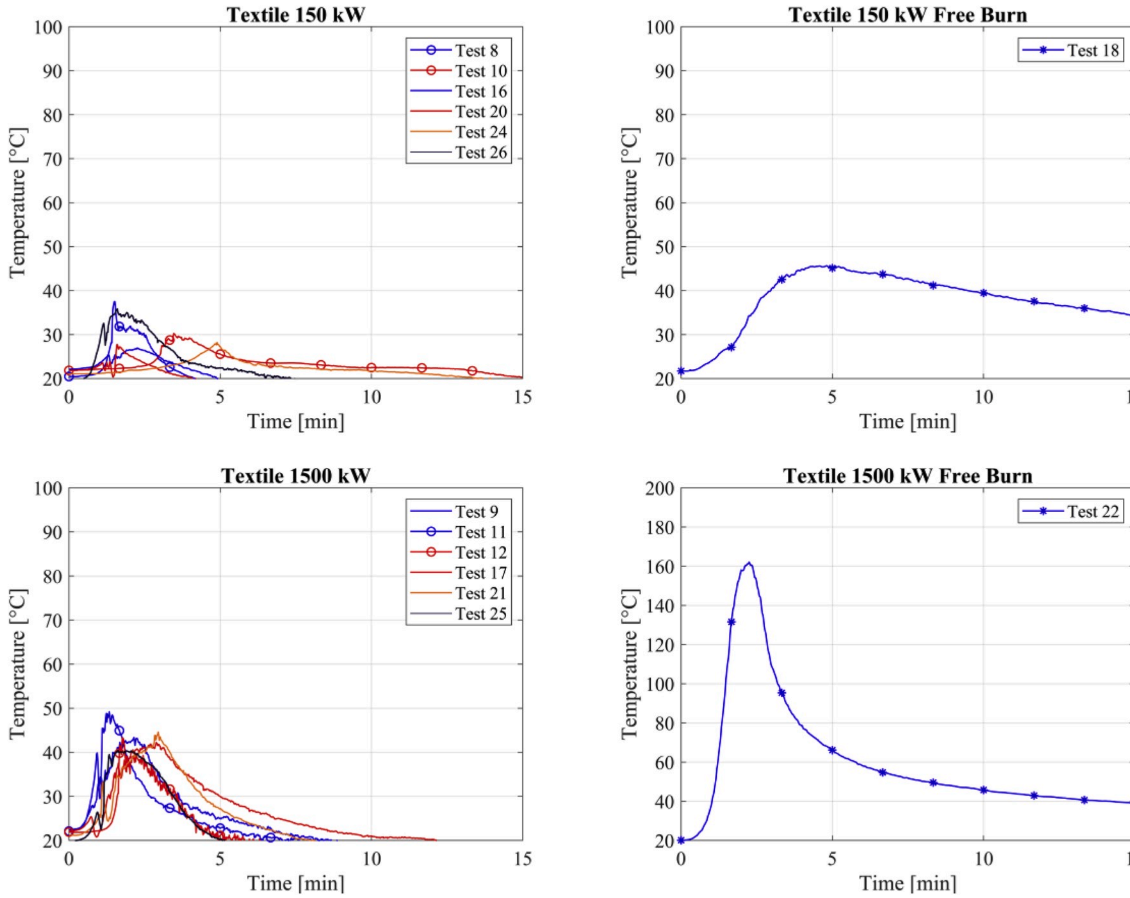

Fig. 3. Gas temperatures at level z = 0.8 m in sprinklered tests (left) and free-burns (right).

textile fires, the peak temperatures were above 200 °C and 160 °C, respectively, indicating dangerous conditions. The 150 kW textile fires would not have induced thermal hazard to patient, regardless of sprinklers.

The peak heat fluxes in the middle of the room ranged between 0.5 and 6 kW/m^2 in the sprinklered fires. Severe injuries would not be expected. In free-burns, they were 13 kW/m^2 for UL 1626, and 3.1 and 13 kW/m^2 for small and large textile fires, respectively.

4.3. Gas concentrations

Fig. 4 shows the CO concentrations as average values for the sprinkler tests (left) and for the free-burn tests (right). The CO concentration of the sprinklered UL 1626 corner tests gradually increases even after sprinkler activation, indicating the continuation of foam smouldering. Textile fires show a decreasing trend. The peak CO concentrations of the sprinklered UL 1626 and TEX 1500 fires are between 450 ppm and 2500 ppm, i.e. one order of magnitude smaller than for the corresponding free-burns. The CO concentrations of the sprinklered and free small textile fires are very close to each other.

Concentrations of other toxic gases considered by Purser's FED model with peak concentrations above 2 ppm are shown in Fig. 5. In the sprinklered UL 1626 fire, the highest asphyxiant concentrations (excluding CO) were observed for NO, about 50 ppm. In UL 1626 free-

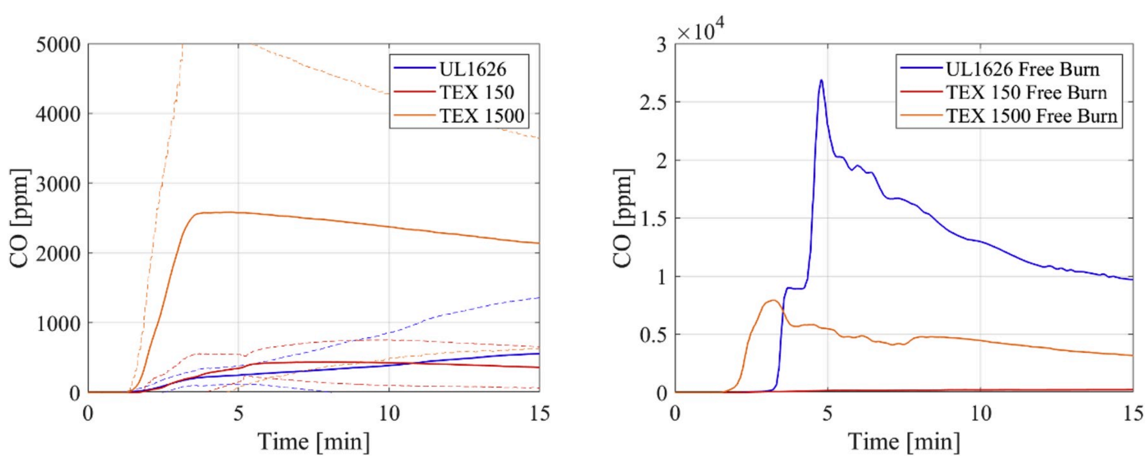

Fig. 4. Average (solid lines) CO concentrations in sprinklered tests (left) and free-burns (right). Dashed lines show 95% confidence bands.

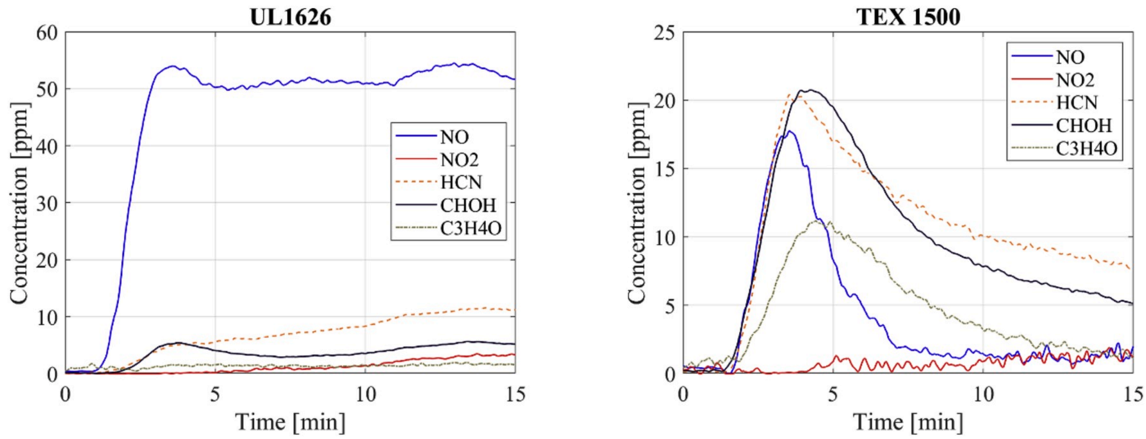

Fig. 5. Average gas concentrations (excl. CO) in sprinklered UL 1626 and large textile fires.

burns (not shown here), multiple gases exceeded 400 ppm, including hydrogen cyanide (HCN) at 440 ppm, hydrogen chloride (HCl) at 440 ppm and formaldehyde (CHOH) at 550 ppm. It is interesting that while in sprinklered tests the concentrations either increased or remained at the same level (no washing by droplets), the concentrations of the free-burn tests clearly decreased after suppression. One possible reason is the dilution by the mechanical ventilation, but this has not yet been confirmed. In the large textile fires, NO, HCN, CHOH and C_3H_4O were observed with average peak concentrations above 10 ppm. From the viewpoint of FED modelling, it is important to notice that NO_2 was present in <5 ppm concentrations in both fires types.

4.4. Toxicity assessment

Fig. 6 shows the development of averaged FED values over time for each fire type, calculated with three different methods: Purser - light activity, Purser - rest, and ISO 13571. The dashed line present the statistical uncertainty in terms of two standard deviations, corresponding to the 95% confidence interval. In sprinklered UL 1626 tests, there is a significant difference between the two Purser results and the ISO 13571 results: Purser's method, taking into account a wider range of gases, shows FED values around 0.7 at 15 min. The ISO 13571 method, in turn, remains at level 0.2. The difference is significant even if we consider the $\pm$35% uncertainty associated with the FED concept according to ISO 13571.

The variability of experimental conditions is found to be even more significant than the difference between methods; the 95% confidence limit corresponds roughly to a factor of two in FED value uncertainty. A closer look of the UL 1626 FED values revealed that the toxic hazard was mainly dependent on how much the polyurethane mattresses burned. Closing the room ventilation or keeping it in operation did not have any significant effect. In free-burns, the conditions can be considered lethal in 3 min, regardless of the calculation method. The sudden increase in FED values (see Fig. 6) is caused by the smoke layer coming down and reaching the level of the gas sampling point.

In small textile fires, the 15 min FED values are between 0.1 and 0.3, being independent from the use of sprinklers. This result indicates that sprinklers cannot improve tenability in fires that would remain small even without them. Large textile fires resulted in highest FED values in the sprinklered scenario. Calculation using the ISO 13751 method resulted in FED values between the light work and rest activity levels of the two Purser methods.

The contributions of different gases to the value of Eq. (1) at 15 min are shown in Fig. 7. The calculation method was Purser's method for a person at rest. In the sprinklered UL 1626 experiments, NO_x gases cause 87% of FED index. In free-burns, HCN clearly dominates, reflecting the dependence of gas formation mechanisms on fire temperature and oxygen availability. Textile fires' toxic effects mainly come from CO, expect the freely burning small textile fire, which again showed higher NO_x contributions. The high NO_x contributions do not support the ISO 13571 assumption that CO and HCN are the dominant asphyxiant gases. However, as the NO_x mainly consisted of NO, which would not constitute a health hazard in concentrations below 80 ppm [13], it is interesting to investigate the sensitivity to the role of NO. In fact, the FED results of sprinklered UL 1626 would change significantly if NO was excluded from Eq. (4). FED values would then decrease to the level of the ISO 13571 results, and CO would become the most important species with 49% contribution, followed by irritants and NO_2 with 21% and 15% contributions, respectively. In textile fires, the changes would be much smaller.

The available evacuation times can be estimated by finding the times when FED exceeds a specific threshold value. Table 4 shows the times when FED exceeds values 0.1, 0.3 or 1.0. In free UL 1626 and large textile fires, safe evacuation is only possible before 2.1 … 3.2 min, but sprinkler activation extends this time with several minutes in most cases. In small textile fires, only the lowest criterion (FED = 0.1) is met, and the differences between the sprinklered and free-burn cases are small.

The averaged results of the FIC calculations using both Purser's and ISO 13571 methods are presented in Fig. 8. ISO 13571 method shows significantly lower values than Purser's method. In UL 1626 fire, the average FIC in sprinklered tests remains below 0.3 but FIC = 0.8 would be possible in a few percent of cases. In many fires, FIC values did not turn to decline, which is in line with observations that most of the fires burned throughout the experiments. As for the FED, the free-burns resulted much higher FIC values, exceeding FIC = 1.0 in 3 min. Sprinklers have a clearly positive effect on the possibility to perform any activity during this kind of fires.

In large textile fires, the free-burn FIC is only about five times the sprinklered value. Nevertheless, effective rescue operations would not be possible in either case without protective equipment. Only small textile fires, and the free-burns in particular, might allow some unprotected activity, mainly because the smoke layer was not mixed by the spray.

4.5. Likelihood of incapacitation

FED values were used to estimate the likelihood of incapacitation, but FIC/FEC were not included because their effect on the lethality at 15 min endpoint is unclear. Incapacitating doses are typically taken as fixed fractions of lethal doses, and the correlation between incapacitating and lethal FED can be assumed. Instantaneous FED values from different repeated experiments for each fire load type were assumed to represent a sample of the statistical distribution of possible FED values. The best-fitting analytical distribution was found to be Gamma-distribution

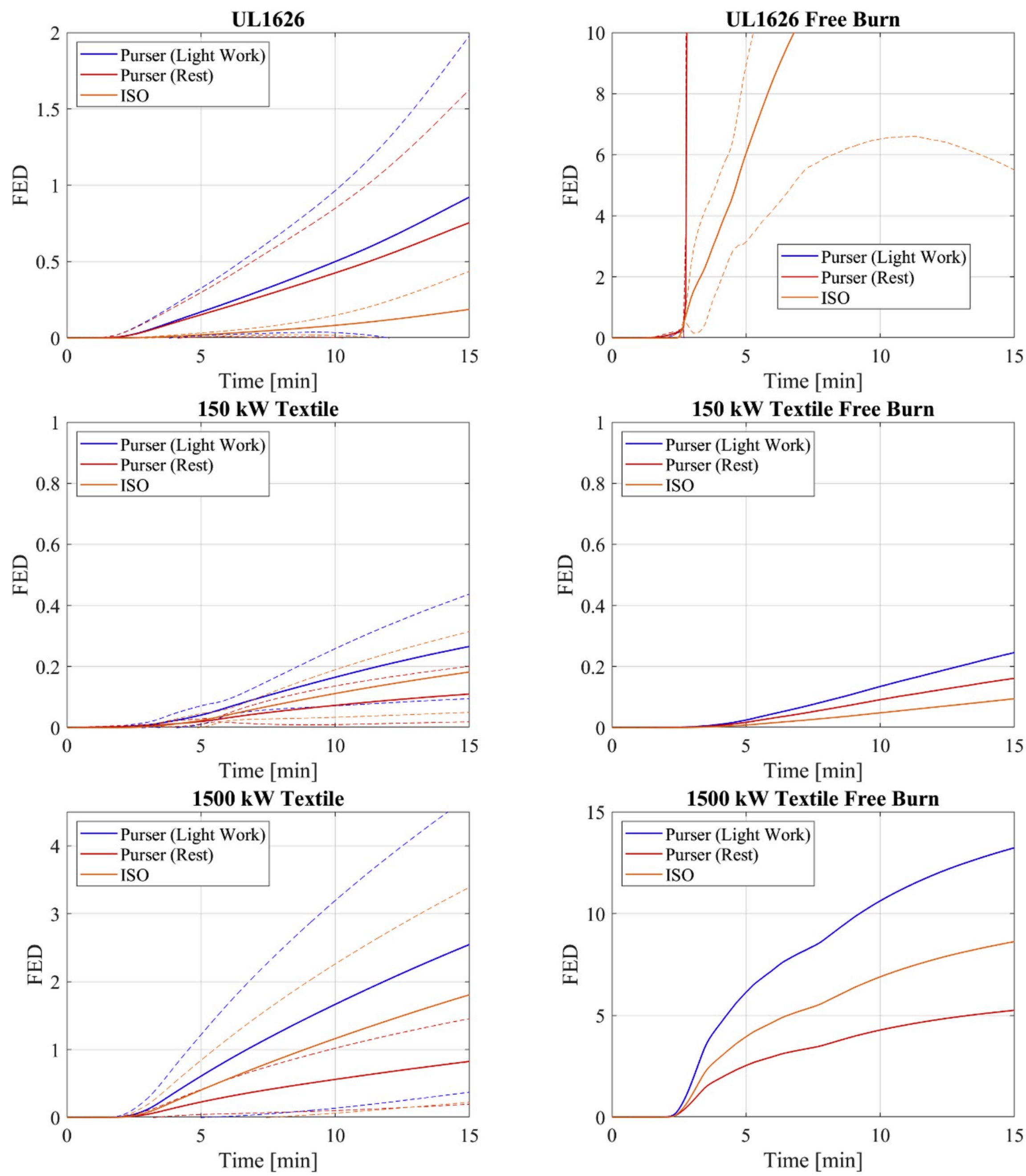

Fig. 6. The average FED values using the Purser's method and ISO 13571 for sprinklered tests (left) and free-burns (right). Solid line is average FED, dashed line for 95% confidence band.

$$f(x,t) = f(x,\alpha(t),\theta(t)) = \frac{x^{\alpha-1}e^{-x/\theta}}{\theta^{\alpha}\Gamma(\alpha)} \tag{11}$$

where α and θ are the shape and scale parameters. These parameters were estimated for each time instance using a least-squares method. The distributions of the free-burns, for which repeated tests were not available, were assumed to have the same shape but a mean corresponding to the measured value (or an average of two in case of UL 1626). Combining the experimental variability of FED values, Eq. (11), and the range of human responses to a given FED-value, Eq. (10), the probability of incapacitation at each time can be calculated as

$$P_I(t) = \int_0^{\infty} P(I|x)f(x,t)dx \tag{12}$$

Values of $P_I(t)$ for each fire type and different FED calculation methods are shown in Fig. 9. The UL 1626 free-burn seems to lead to definite incapacitation in less than 5 min, but the sprinkler keeps the probability below 0.45 (Purser) or 0.05 (ISO 13571). In the large textile fire, the situation is quite similar: Without sprinklers, 90 … 95% of patients would be incapacitated in 15 min, but sprinkler would take this probability down to about 0.8 and 0.4 for people in light work and rest, respectively, with ISO 13571 ending up between these values. In the small textile fire, sprinkler protection does not have a significant effect on the incapacitation probability, which is below 0.1 even in the case without sprinklers. The greatest difference between the Purser and ISO 13571 methods is seen in the UL 1626 fire, where the ISO 13571 method indicates much lower hazard.

Ignoring NO gas from Eq. (4) would drop the Purser's FED values for the sprinklered UL 1626 and the free-burn of the small textile fire to the same level with the ISO 13571 method. In the textile fires, where CO was

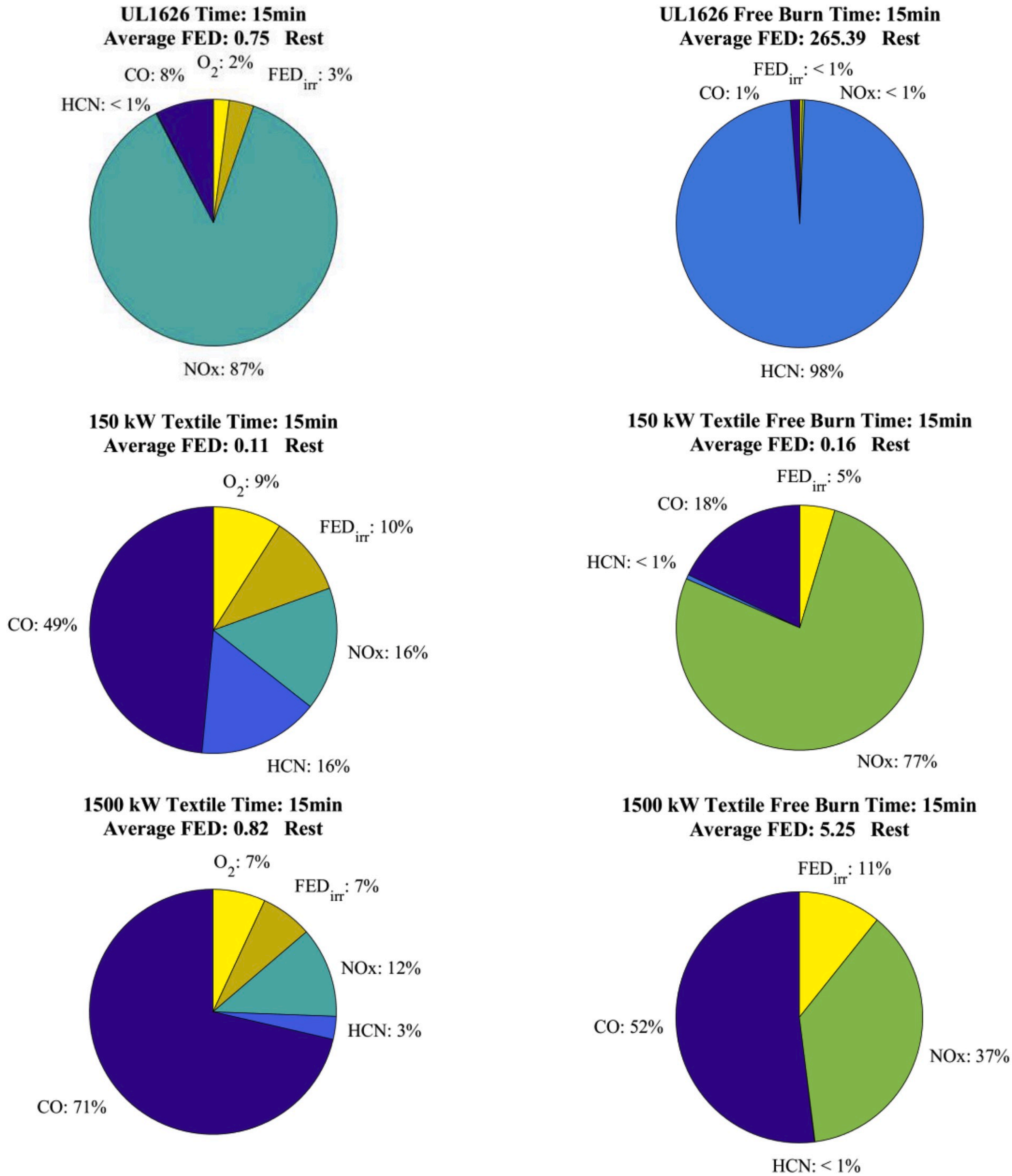

Fig. 7. The contributions of individual gases to FED at 15 min for a person at rest using Purser's method. Sprinklered tests on the left, free-burns on the right.

Table 4
Time in minutes for FED value to exceed common safety criteria.

Fire type	Purser Rest			Purser Light work			ISO 13571		
	FED threshold								
	>0.1	>0.3	>1.0	>0.1	>0.3	>1.0	>0.1	>0.3	>1.0
UL 1626	4.0	7.8	–	3.8	7.1	–	11	–	–
UL 1626 Free	2.1	2.6	2.7	2.1	2.6	2.7	2.5	2.6	2.8
Textile 150	13	–	–	7.3	–	–	9.3	–	–
Textile 150 Free	11	–	–	8.6	–	–	–	–	–
Textile 1500	3.6	5.9	–	2.9	3.8	6.7	3.2	4.4	8.9
Textile 1500 Free	2.4	2.6	3.2	2.3	2.4	2.7	2.4	2.5	2.9

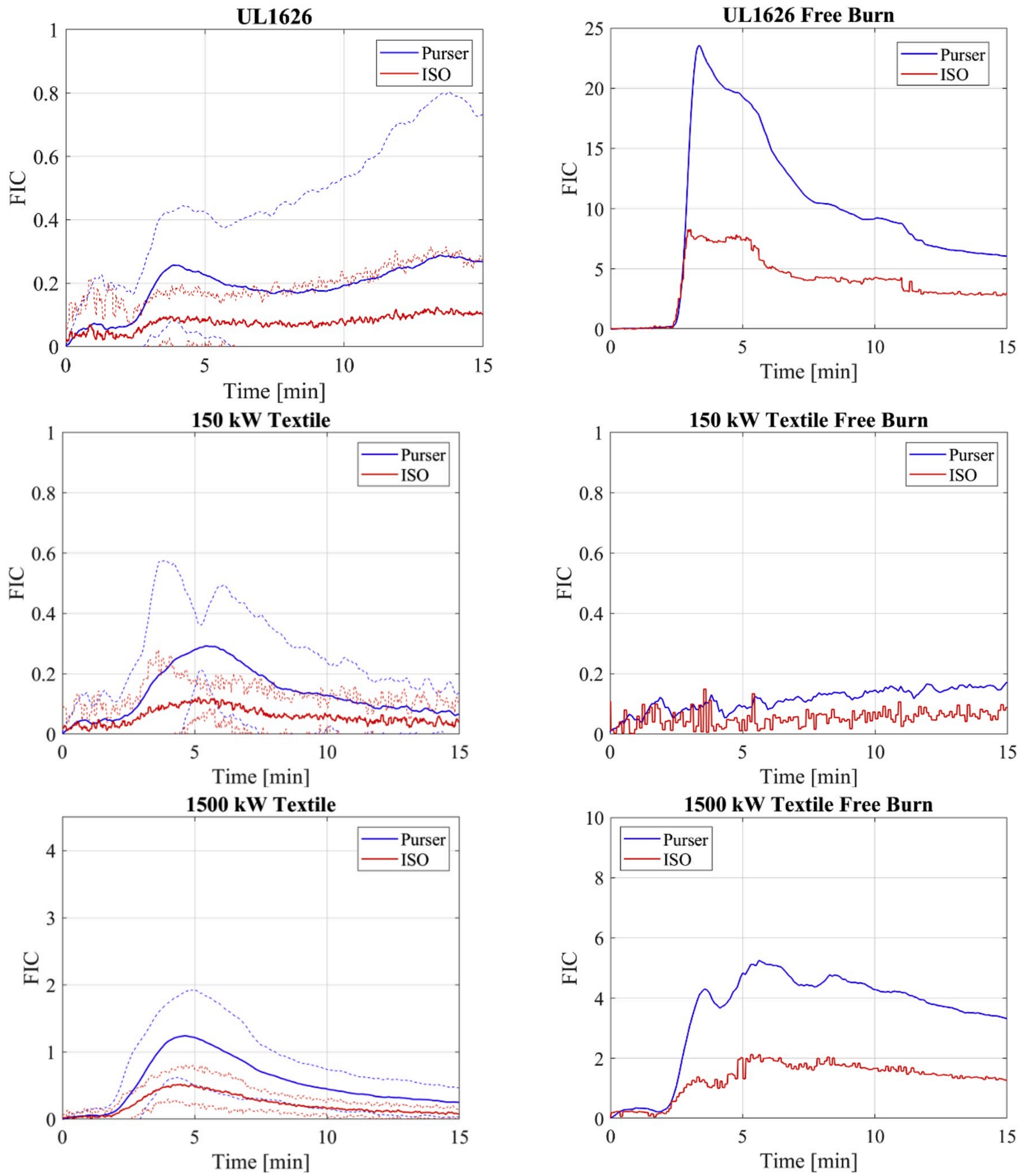

Fig. 8. FIC values for sprinklered tests (left) and free-burns (right), averaged over repeated tests. The dash line presents the confidence level of 95% (±2σ).

the most dominant source of toxicity, the activity level in the Purser method has a great influence on the incapacitation probability.

4.6. Discussion

Four main sources of uncertainty in the tenability analysis are: (1) gas concentration measurement uncertainty, which was found to be only a few %, and therefore ignored in the probability calculation; (2) statistical uncertainty of fire conditions, covered by samples of repeated experiments, (3) human sensitivity uncertainty, for which we use the log-normal function proposed by ISO 13571; and (4) the FED index calculation uncertainty, for which the standard gives an estimate ±35%. The actual meaning of this FED uncertainty is not explained in the standard, and therefore not included in the probability calculation directly. Letting this 35% uncertainty propagate to the probabilities would indicate a possibility of 100% incapacitation probability in the sprinklered large textile fires. In UL 1626 fires, the FED uncertainty reduces the significance of the difference between two Purser's method results, yet the ISO 13571 results for incapacitation probability still remain clearly lower.

The analysis concerning the role of NO gas showed that the assumption of NO oxidation into NO_2 is important. Based on their literature study, Paul et al. [12] concluded that at fire temperatures, NO is the stable oxide but at less than 200 °C and high concentrations of NO, most of the gas should end up in NO_2 or dinitrogen tetroxide (N_2O_4). Although the oxidation may occur at the concentrations and temperatures of the current study [13], the suitability of the existing kinetic models to predict the rate of oxidation in cold and wet compartments is unclear [12]. In the large textile fires (Fig. 5), the NO concentration decreased much faster than NO_2 increased, possibly due to the high

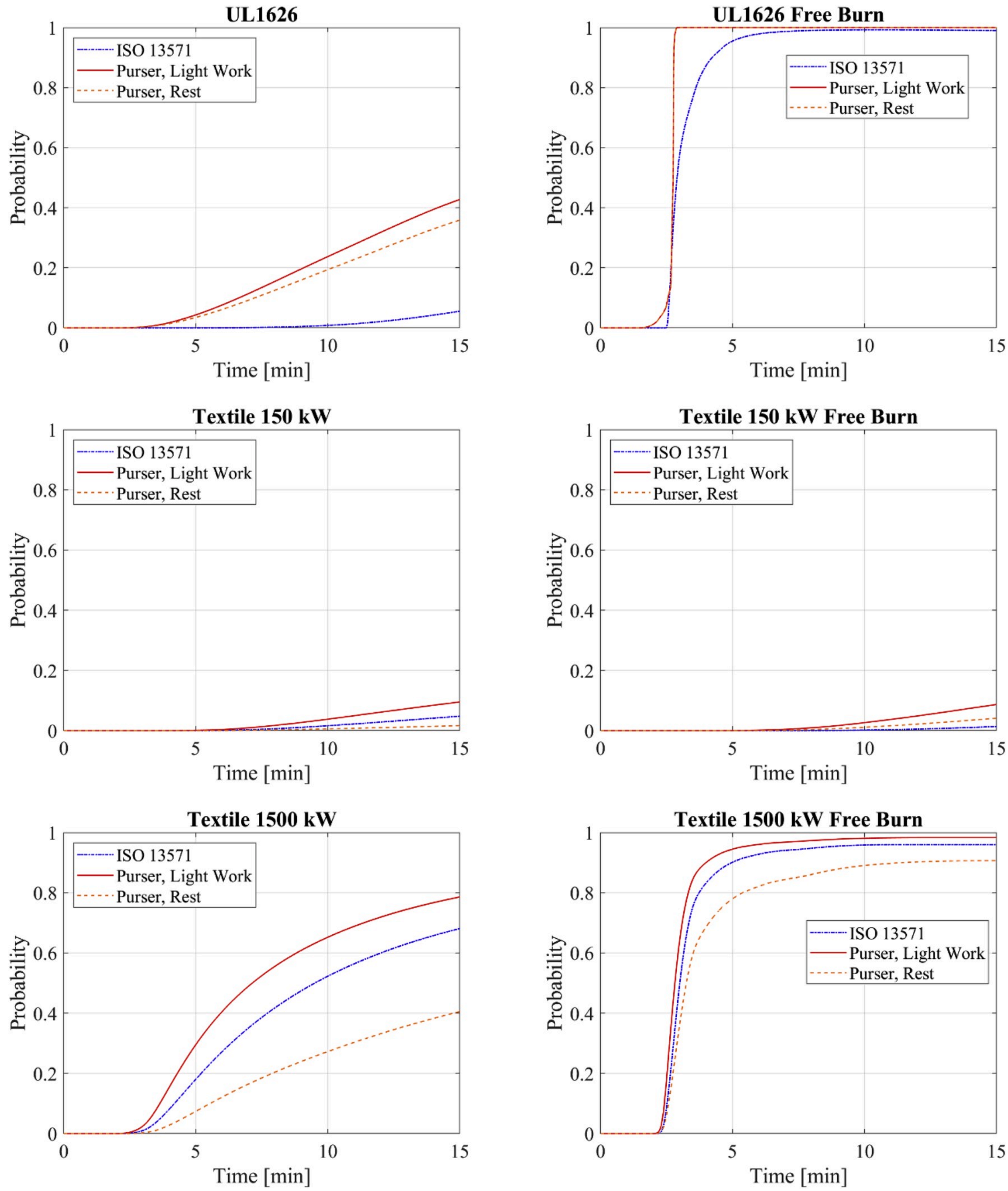

Fig. 9. Incapacitation probabilities of an individual patient for each fire load type in sprinklered (left) and free-burn (right) fires.

solubility of NO_2 in water, and the oxidation assumption cannot be confirmed. Failure of the oxidation assumption behind Eq. (4) would mean that the NO_x contribution and FED are significantly over-predicted. For instance, excluding NO from Eq. (4) reduced the UL 1626 incapacitation probabilities from 0.4 to 0.1.

The results can be used for estimating post-fire lethality, but as the asphyxiant doses are meant for incapacitation assessment, with lower than lethal $C \times t$ -products, the current results should be conservative. One difficulty of choosing the FLD_i values is the non-linearity of lethal doses. For instance, the AEGL-3 model of lethal doses $(C^{3.5} \times t) = k$ corresponds to a 15-min lethal concentration of 30 ppm [13]. This corresponds to a linear dose $C \times t = 455$ ppm min, a much lower than the lethal dose of NO_2 in Table 2 (1900 ppm min).

5. Conclusions

In this paper we have reported the results of fire experiments where the effect of an automatic fire extinguishing system was investigated in a real hospital environment. The main objective of the study was to evaluate the effect of the sprinkler on human rescue. Based on the gas concentration measurements, we calculated the Fractional Effective Dose (FED) values, and estimated the likelihood of incapacitation as a function of time. Incapacitation probabilities can be used as conservative estimates of the lethal conditions.

The effectiveness of sprinklers in protecting the patient until fire brigade arrives was clear in those fires that had a potential to grow in size and power. The sprinklers maintained temperatures at tolerable level and reduced toxicity, mainly through fire development control. In

UL 1626 and large textile fires, sprinklers decreased the incapacitation probabilities of a person at rest from 0.9 to 1.0 to about 0.4. In small textile fires, the difference between the incapacitation probabilities of sprinklered and non-sprinklered fires was less than the measurement uncertainty.

The FED results were very sensitive to the choice of the calculation method. A significant contribution of the overall FED came from NO_x gases, which the FED model of ISO 13571 standard does not take into account at all. On the other hand, assuming the complete oxidation of NO to NO_2 in the Purser's equation for asphyxiants may not be justified in sprinklered fires. Nevertheless, the assumption of CO and HCN being the only important sources of incapacitation should be treated with caution.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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