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Real-scale fire tests of one bedroom apartments with regard to tenability assessment

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ABSTRACT

Statistics reveal that people mostly die in bedrooms or lounges, from smoking-related fires. However, at present, little is known of this phenomenon, especially in terms of identifying which fire effects first injure people. Through several real-scale fire tests, two different sets of fire scenarios are explored in a single bedroom apartment. As in everyday life, the test room is equipped with furniture, clothes and items supplied from major retailers. It is heavily instrumented with sensors to record tenability-related data (thermocouples, heat fluxmeters, gas analyzer including 3 FTIRs, opacimeters and several cameras for video recording).

The first set of tests explores a bed fire scenario, in which a person has fallen asleep, accidentally lighting its quilt, and then its mattress, e.g. with a cigarette or a small flame. The door and window remain closed during the entire test, and the fire decreases rapidly to become insignificant because of a lack of oxygen.

The second set of tests explores a wastepaper basket fire scenario, with a first person leaving the room quickly, while a second person – who is potentially disabled – cannot leave the room. As the door remains open, there is enough oxygen supply, and the fire grows to flashover.

The test results are designated as reference for calculation models validation. In addition, their interpretation in terms of tenability is presented; fire effects are classified and discussed. All this work also highlights the importance of smoke alarms in such premises.

1. Introduction and background

1.1. Objectives

Small-room fires are frequent and may have fatal consequences. People have to be alerted and have to evacuate before the situation becomes untenable. Adverse fire effects on people are related to thermal and/or toxic effects which are indirectly enhanced by the loss of visibility. Although it is considered that people mostly die from toxic effects during a fire, there is a lack of knowledge on what effect drives tenability conditions in a given situation and fire scenario.

The main objective of the study is to determine which fire effect occurs first in a few simple scenarios using ISO 13571 [1] as a tool to carry out tenability assessment. Another objective is to produce a set of data for various fire scenarios, in order to further validate fire models. An additional objective of this study is to investigate the efficiency of smoke alarms regarding the tenability conditions at the moment alarm activates and during escape, as France recently adopted a regulation introducing smoke alarms in dwelling.

1.2. Background

Experiments accompanied with an analysis of tenability conditions during fire growth have seldom been the object of an in-depth study. Condit et al. conducted one of the first attempts in 1978 [2]. They studied well-ventilated fire scenarios of room corner tests, where walls include combustible insulation protected by gypsum boards. The tenability conditions were studied using animal models. They concluded that the toxic threat from combustible insulation materials was secondary to that of combustible furnishings of the room from fire initiation to an advanced growth stage when the insulation protected by gypsum thermal barrier became involved.

In 1985, a series of similar experiments was performed at South-West Research Institute on furnished rooms [3]. Grand et al. [4] studied fully furnished and finished 20 m² rooms reproducing a typical

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hotel arrangement. The test facility consisted of a fire room at right angles to the end of a corridor with another room off the corridor. The second room contained animals to assess both pre-flashover and flashover toxic effects. Both room doors were open. The fire ignition scenario was sufficient to allow flashover conditions in the fire room. The rooms and corridor were fully instrumented with thermocouples, heat flux meters, smoke opacimeters, and gas sampling trains. In the few minutes prior to visual flashover, the toxic hazard of this fire scenario increased dramatically. At a 1.7 m height in the fire room, the temperature rose to 650 °C, carbon monoxide concentration reached 70,000 μL/L, dioxygen concentration dropped to zero, and the hydrogen cyanide level exceeded 1000 μL/L. Nevertheless, the analysis techniques available at the time didn't allow differentiating which fire effect occurred first in the fire room.

In Japan, Morikawa et al. [5,6] performed similar studies in the eighties, focusing only on toxicity. Two compartment fire experiments were conducted in a two-storey building to investigate the evolution of toxic gases and atmosphere toxicity in the burn room and its surrounding area. The first fire was set to analyze the combustion of natural polymer contents, and the other, synthetic polymer contents. Major toxicants evolved including CO, HCN, HCl, SO_2, NO and formaldehyde were measured and toxic effects were evaluated by applying a simple toxicity model. Mice and rabbits were used as test animals and exposed to fire effluent gases in the burn room and exposure boxes. For rabbits, blood analysis and other biological examinations were carried out to find out the cause of the death or incapacitation. The results suggest that HCN contributes to some extent to death or incapacitation in the fires studied. The analytical techniques available at the time were not accurate enough to have proper time-resolved information for all species. Nevertheless, the use of animal model allowed in some terms the validation of indirect toxicity models.

In Sweden, in 1987, Sundström performed full-scale tests of upholstered furniture [7]. The tested item was ignited with a small wood crib and then it was allowed to burn freely without restriction of air supply. The parameters measured were heat release, the mass burning rates and carbon oxides release. Results have been introduced in a simple fire model in order to illustrate the risk for further fire spread and visibility for escape in addition to the toxicity due to carbon monoxide production. This calculation did not consider the evolution of fire conditions with time, and so did not allow tenability conditions in a room scenario to be differentiated.

In 2000, Purser applied more modern assessment techniques for compartment fires as fire scenario, the ventilation, etc. and dose-related tenability models [8] were taken under consideration, using the Fractional Effective Dose methodology. He studied tenability conditions outside the fire room – in connected corridors and additional rooms. Purser concluded that fires are likely to become oxygen vitiated, producing large amounts of smoke and toxic products, be it in conditions prone to induce flashover or largely under ventilated. One conclusion was that the main hazard which affects building occupants was the rapid contamination of building spaces by toxic smoke. In his study, visual obscuration and smoke irritancy limited escape efficiency which, by way of consequence, affected escape behavior and reduced travel speed. This may be followed by incapacitation, primarily due to the exposure to asphyxiant gases (mainly CO and HCN), leading to death. Purser presented a series of full-scale fire tests conducted in enclosed test rigs and buildings, in which detailed smoke, heat, toxic gases and detections measurements were made. However, the gas measurement techniques used at that time were not as accurate as nowadays.

In 2003, Gann et al. studied experimental room-scale fire tests to produce data on toxic products yields in both pre-flashover and post-flashover fires [9]. The examined combustible products were individual items, such as a sofa made of upholstered cushions on a steel frame, particleboard bookcases with a PVC-laminated finish, and household electric cable. They were burned in a room with a long adjacent corridor. The yields of CO, CO_2, HCN, HCl, and carbonaceous soot were determined. Other toxicants (e.g., NO_2, formaldehyde and acrolein) were not found. The toxicant yields from sofa cushion fires in a closed room were similar to those from pre-flashover fires of the same cushions in a room with the door open. The use of Fourier transform infrared (FTIR) spectroscopy was shown to be useful to obtain toxicant concentration data. The losses of CO, HCN, and HCl as they flowed down the corridor were found to be dependent on the combustible. The data provided turned out useful for modeling, although limited because of their uncertainties. Hirschler [10] argued that, consequent to these uncertainties, the work overestimated the quantities of HCl and HCN released. In consequence, it seriously overestimated the toxicological importance of gases such as HCN and HCl in post-flashover conditions. In addition, the very low concentrations of toxicants measured at pre-flashover conditions might have indicated that such pre-flashover fires do not generate extremely toxic atmospheres. This study only considered individual items in well-ventilated fire scenarios.

In 2004, Peacock et al. [11] performed a large number of simulations using zone models to predict the relative times at which smoke inhalation and heat exposure would result in incapacitation. Fires in three building types were modeled with gas species yields. Rates of heat release for design fires derived from a review of real-scale fire test data. Incapacitation equations were taken from ISO 13571. Sub-lethal smoke effects were deemed important when incapacitation from smoke inhalation occurred prior to thermal effects. Real-scale HCl yield data were incorporated when available. The modeling indicated that the yield would need to be 5–10 times higher for incapacitation from HCl to precede incapacitation from narcotic gases, including CO, CO_2, HCN and reduced O_2 concentration. In addition, fires originating from concealed spaces in any type of occupancy were a real threat. Sublethal effects of smoke appeared not likely to be of prime concern for open fires in single or two-compartment occupancies themselves. Sublethal effects, however, may be important in adjacent spaces or buildings with high ceilings and large rooms and occupancies in which fires would be detected promptly and from which escape or rescue would require a few minutes. This study introduced ISO 13571 for tenability calculation. It should be recalled that the standard was at a preliminary drafting stage at this time. The study was a numerical one based on experimental input data, but results were not compared with experimental identical situations in the analysis.

More recent real-scale tests focused on fire dynamics and structural assessment, such as the Dalmarnock experiments [12,13]. Consequently, these tests did not focus on tenability assessment during fire growth phase, as they were not designed for such purpose. Only CO, CO_2 and O_2 gas measurement were performed, to monitor combustion efficiency.

This review highlights that very few room experiments have been performed using enclosures equipped as in everyday life; they mainly concerned single items fires. The large majority of studies focused on well-ventilated scenarios that led to flashover. Tenability conditions were assessed in corridors adjacent to the room involved in fire, but few studies were performed on tenability conditions in the room of fire itself at the early stages of fire growth. FTIR gas analysis and consideration of more recent assessment techniques such as ISO 13571 have been introduced in few recent studies; these techniques have been improved since. The present publication intends to complement these former studies by providing a series of well instrumented dwelling scenarios and their interpretation according to state-of-the-art tenability models. The studied bedroom apartment is a small 9-m² room, equipped with finishes and furniture as in everyday life. Various scenarios of ignition source, origin and events – such as door openings – have been tested. The room has been instrumented with a large number of sensors, in order to measure physical and chemical parameters of such fire scenarios, and to produce tenability data for some behavioral scenarios. The data are needed for fire risk analysis, and also as dataset for validation of Computed Fluid Dynamics models for small room scenarios.

1.3. *Statistical overview*

In France, 312,100 fires occurred in 2008 [14] and led to 592 fatalities on site, and hospitalization after evacuation [15]. It corresponds to an average of 9.2 deaths per million inhabitants due to fire, and to 1 fatality every 527 fires. More detailed statistics give a 2/3 ratio of dead victims on the location of the fire and 1/3 at the hospital, due to post-exposure phenomena. 17% of the severely injured people died at the hospital. 94% of the fatalities come from dwelling fires (2008) [14]. Detailed studies from the USA [16] or Ireland [17] indicate a proportion of around 70% of victims that were in sleeping rooms and lounges (70 and 72%, respectively). Additional data highlight that 70% of these victims were in fires that occurred between 18:00 and 6:00 [16,18]. Consequently the large majority of fatalities are due to dwelling fires, during the night, in sleeping rooms or lounges – in France as in many other countries.

From the analysis of various data sets [16,19], activities associated with smoking (involving cigarettes, lighters, etc.) ignition scenarios represent one third of fire origins and are largely dominant. Other origins such as arsons, cooking devices or electric fires represent a lower proportion.

All these elements obtained from statistical overview are used to define several scenarios to be reproduced by series of real-scale experiments. These experiments are especially designed to be as representative as possible of dwelling fires, with test equipment and an analysis procedure defined to provide tenability data.

2. Experimental procedure

2.1. *Description of the tested room*

The test room is a realistic 9 m² bedroom apartment (3 m × 3 m ground surface) with a ceiling height of 2.5 m. The room, served by a corridor through a door, is the object of the test configuration. The door opening is 0.83 m wide and 2.04 m high. A window is placed on another wall, facing a space connected with the outside. The entire arrangement is shown in Fig. 1.

To imitate real life conditions, the test room is decorated, furnished and equipped with objects encountered in everyday life, e.g. a wardrobe, clothes, a desk with paper, books, towels, bed pillow and bed linen. One of the room corners is equipped with a corner sink. Apart from the ceiling, the finishing work is made of a large proportion of PVC-based products (35% in mass of combustible materials corresponding to 22% of pure PVC resin), allowing the evaluation of the impact of chlorinated materials in fire scenarios. Both furniture and ordinary objects were provided from retail stores. They are made of standard materials similar to those usually encountered. The arrangement is almost identical for both sets of tests.

2.1.1. *Finishing work*

The test room consists in two walls made of concrete and the two other made of gypsum. Each wall is covered with BA13 gypsum boards. The ceiling is positioned at a height of 2.50 m by PPF15 gypsum boards held by steel wires connected to the roof slab. The ceiling covers the test room and the adjacent corridor. Both walls and ceiling gypsum boards are changed between each series of tests to avoid contamination. No decorative coating is applied on the ceiling. The floor of the test room is covered with PVC floor covering rated $B_{fl}s1$ or $C_{fl}s1$ in accordance with EN 13501-1 [20]. The walls of the test room are covered with a PVC wall covering rated B-s2, d0 in accordance with EN 13501-1 [20]. The window is a PVC double-glazed frame, 1.20 m × 1.25 m in size, and is topped by a box with a rolling shutter, also in PVC. Both window and shutter parts are rated M2 in accordance with French standard NF P 92-507 [21].

2.1.2. *Plumbing*

The test room is equipped with a corner ceramic sink with a metal tap and a spinning sewage system (in PVC, rated B-s2, d0 in accordance with EN 13501-1) which runs along one of the interior sides up to a C-PVC, 150 mm diameter down-comer pipe in the next room corner. In addition, the corner to the sink corner is equipped with PVC paneling for the entire height, 1 m wide on each wall from the corner. This PVC paneling is rated M1 in accordance with NF P 92-507 and C-s3, d0 in accordance with EN 13501-1.

2.1.3. *Electricity*

The test room is equipped with a PVC raceway (rated as non-flame propagating in accordance with EN 50085-1 [22]) and fittings, placed at the bottom of the walls except for the door where the raceway runs around the door. The raceway is connected to a socket outlet under the desk, and another one under the

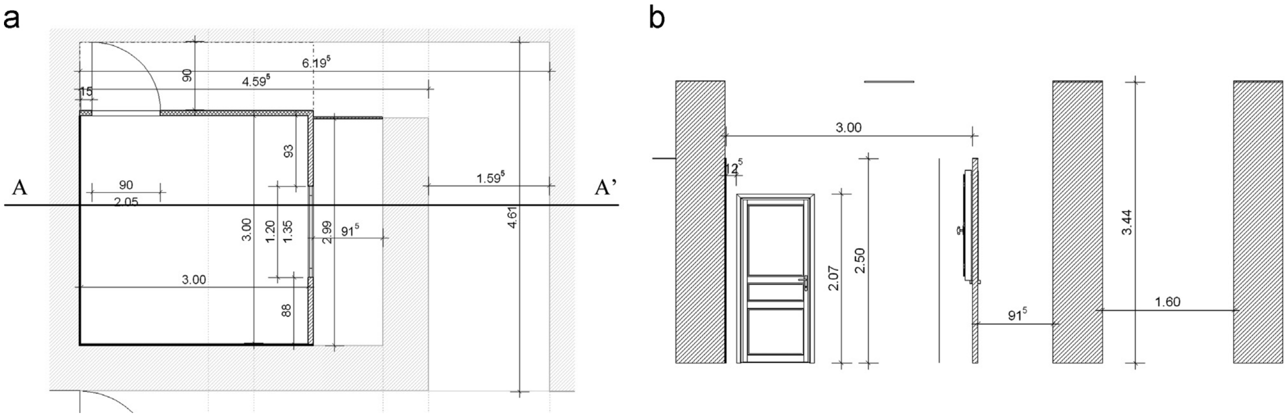

Fig. 1. Top and cut sectional view of the test arrangement: (a) top view, (b) cut sectional view according to A-A′.

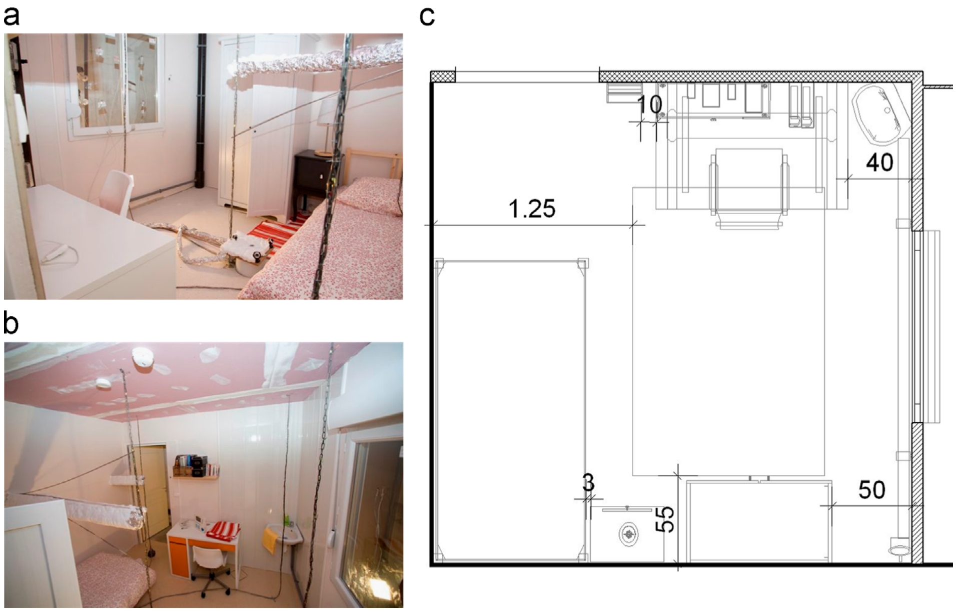

Fig. 2. Arrangement of the tested room: (a) view from the door, (b) view from the wardrobe corner, and (c) quotation of the position of tested elements (top view).

Table 1
Tested elements – finishing.

Element	Dimensions	Mass (kg)	Nature (main material)
Electricity	2.1 m	1.67	Raceway (rigid PVC)
	–	0.17	Socket-outlet (undefined)
	–	0.02	Fittings (undefined)
	–	0.06	Switch (undefined)
Plumbing	2.5 m	8.41	Evacuation pipe, ⌀110 (rigid PVC)
	–	0.11	Fixing kit for pipe ⌀110 (rigid PVC)
	2.5 m	1.05	Evacuation pipe, ⌀32 (rigid PVC)
	–	0.03	Fixing kit for pipe ⌀32 (rigid PVC)
	–	0.14	Siphon (rigid PVC)
	–	0.07	Elbow ⌀32 (rigid PVC)
	–	0.02	Sleeve ⌀32 (rigid PVC)
Window with frame, shutter and shutter box	1.5 m^2 (1.20 m × 1.25 m)	24.64 (Excluding glass)	Rigid PVC
Window joint	–	0.60	Polyurethane
Floor covering	9 m^2	27.36	Flexible PVC. Density 3040 g/m^2
Floor covering glue	9 m^2	2.57	Not defined, but not chlorinated
Wall paneling	5 m^2	9.7	Rigid PVC
Wall covering	26 m^2	9.29	40% PVC based, density 0.350 g/m^2
Wall covering glue	26 m^2	1.17	Glue 0.180 g/m^2 wet, 0.045 g/m^2 dry
Door and door frame	1.7 m^2 (2.04 m × 0.83 m)	23.00	Painted solid pine
Angle sink	–	–	Ceramic

bedside table. A switch is installed at a standard hand level at the door. The raceway is empty (neither cables nor insulated conductors inside).

2.1.4. Furnishing

The room is furnished with a bed made of a solid pine spring-bed, a mattress (cotton–polyester fabric external liner, polyurethane foam padding and polyester), a pillow and a quilt (cotton–polyester fabric, polyester lining), both equipped with a cotton pillowcase. The room also contains a bedside table in solid pine (with fiberboard backside panel) with a lamp, a wardrobe (fiberboard backside panel), an office desk (fiberboard backside panel) with a wooden shelf above, a metallic wastepaper basket placed on the floor next to the desk, an office chair (polypropylene seat shell) and a cotton rug. All these items come from major retailers, and belong to traceable collections.

In addition to finishing and furniture, ordinary objects were placed in the test room. Clothes are arranged in the wardrobe and a gym bag containing a wool sweater is placed on it. The wardrobe is left ajar for the tests. A towel and a bottle of shower gel are placed on the sink. Paper and CD cases are arranged on the desktop. Books, magazine racks with magazines, small storage boxes and a box of cereal are placed on the shelf.

2.1.5. Detection

Two different kinds of smoke alarms are placed at the centerline of the ceiling. The same couple of alarms is also placed in centerline of corridor's ceiling. These smoke alarms are residential single station smoke detectors, based on optical principle. They are certified under CE-marking and NF-labeling.

Fig. 2(a–c) present pictures of the test arrangement. Tables 1 and 2 present the description of the tested elements, respectively finishing and furnishing.

Table 2
Tested elements – furniture.

Element	Size (cm)	Mass (kg)	Nature (main material)
Bed	207 × 97 × 33	11.8	Solid pine
Mattress	200 × 90	5.8	Ticking: cotton 62% polyester 38% PU Foam + polypropylene fabric
Duvet cover and pillowcase	–	0.9	Cotton 100%
Pillow	–	0.8	External fabric: polyester 65%, cotton 35% Polyester flake packing
Duvet	–	1.42	External fabric: polyester 65%, cotton 35% Polyester flake packing
Wardrobe (2 doors)	190 × 91 × 54	49.3	Particleboard and fiberboard, acrylic paint
8 Hangers	–	1.2	Wood, metal, varnish
Wall shelf	70 × 24 × 17	1.4	Wood, metal
Bedside lamp	–	1.7	Cast iron, glass, plywood
Bedside table	–	7.2	Solid pine
Carpet	180 × 120	1.5	Cotton
Office desk	–	26.5	Particleboard, fiberboard, acrylic paint and ABS
Chair	–	1.47	Polypropylene shield
CD case	–	0.56	Cardboard, paint
2 book cases	–	1	Wood
Sport bag	–	0.8	Polyester PVC fabric
Paper (A4 ream)	–	2.57	Paper
Books	–	1.77	Paper
Magazines	–	2.41	Paper
CD	–	0.54	Polycarbonate
Terry towel (close to sink)	–	1.2	Cotton
Clothes (wardrobe)	–	2.6	Misc.
Others (soap, food, etc.)	–	0.75	Misc.

2.2. Description of the test design

2.2.1. Fire scenarios and tests performed

Two series of tests are performed. All elements are fully renewed identically between the series, except for the floor covering which was modified between the two series from a PVC-floor rated $B_{fl}s1$ in accordance with EN 13501-1 [20] to a $C_{fl}s1$.

The first series ("Tests 1") consists in a closed room night dwelling scenario. The ignition sequence is performed on the mattress equipped with its bedding components. The first ignition source is a standard cigarette in accordance with EN 597-1 [23]. If there is no significant fire growth with this source, a standard small flame equivalent to a match in accordance with EN 597-2 [24] is used, then if it fails, a #5 crib in accordance with BS 6807 British standard [25] is used. The room door remains shut during all tests of this series. The tests were conducted on September 22nd, 2011. The three tests in this first series are identified in chronological order: 1A (cigarette), 1B (small flame) and 1C (#5 crib).

The second series ("Tests 2") illustrates the case of a ventilated fire in a small living space. The window remains closed, but the door is opened 2 min 30 s after ignition, to simulate an occupant's pre-movement and escape after having detected the fire. Ignition sequence consists of a scenario of an accidental fire in the metal wastepaper basket, at office desk. The tests were carried out on October 26th, 2011. Two sequences of ignition were carried out, and identified in chronological order: 2A and 2B. In Test 2A, the metal paper basket is filled with 500 g of creased paper balls, and ignited with a cigarette, in order to produce a smoldering fire first, then a flaming combustion. In Test 2B, a second paper basket is put alongside the first one. Both are filled with 500 g of creased paper balls. A match-like flame burner ignites the fire in one of the wastepaper baskets.

The tests will be stopped if a 200 °C temperature is reached in the corridor, as thermal effects would compromise tenability along the whole escape route and inside the bedroom.

2.2.2. Instrument description

The instrumentation of the test room and the adjacent corridor is designed to collect data necessary for estimating tenability conditions and their evolution over time. Sensor locations are presented in Fig. 3 and Table 3. The various measuring instruments have the following functions.

2.2.2.1. Measurement of temperature and heat fluxes. Thermocouples trees (ATC1 to ATC5) measure information on the temperature (°C) in the test room. They allow estimating the tenability conditions associated with convective thermal effects. They each contain 10 class A-Type-K thermocouples for measuring the temperature at heights from 0.80 m to 2.40 m. Uncertainty in thermocouples measurement is estimated at ±4 K, including sensor and acquisition errors.

Water-cooled tangential gradient heat fluxmeters (FLT1 to FLT3) are installed to measure irradiance levels (kW/m²), allowing the tenability conditions related to the radiative thermal effects. Two heat fluxmeters (one at the door and one at the window) are fixed to the corresponding partition at 1.5 m in height. They measure the flux level in the direction they are facing. The third heat fluxmeter is placed on the ground and measures the flux density from the ceiling and smoke at the floor. Thus the effect of hot gases on tenability in the test room can be taken into account. The view angle of the sensors is close to 180° in accordance with Ref. [26]. Heat fluxmeters have been calibrated against a primary calibrated Schmidt-Boelter heat fluxmeter (±4% at 50 kW/m² for the primary heat fluxmeter [27,28]). Uncertainty in the end-use condition is unknown, and estimated at ±10%. The minimum heat flux detection threshold has been evaluated as 0.6 kW/m².

2.2.2.2. Measurement means for the estimation of effluent toxicity effects. Three Fourier transform infrared analyzers (FTIR) have their heated sampling probe (FT1 to FT3) in the room, 1.5 m high to simulate nose level (except for the FT2 set to 0.60 m high for

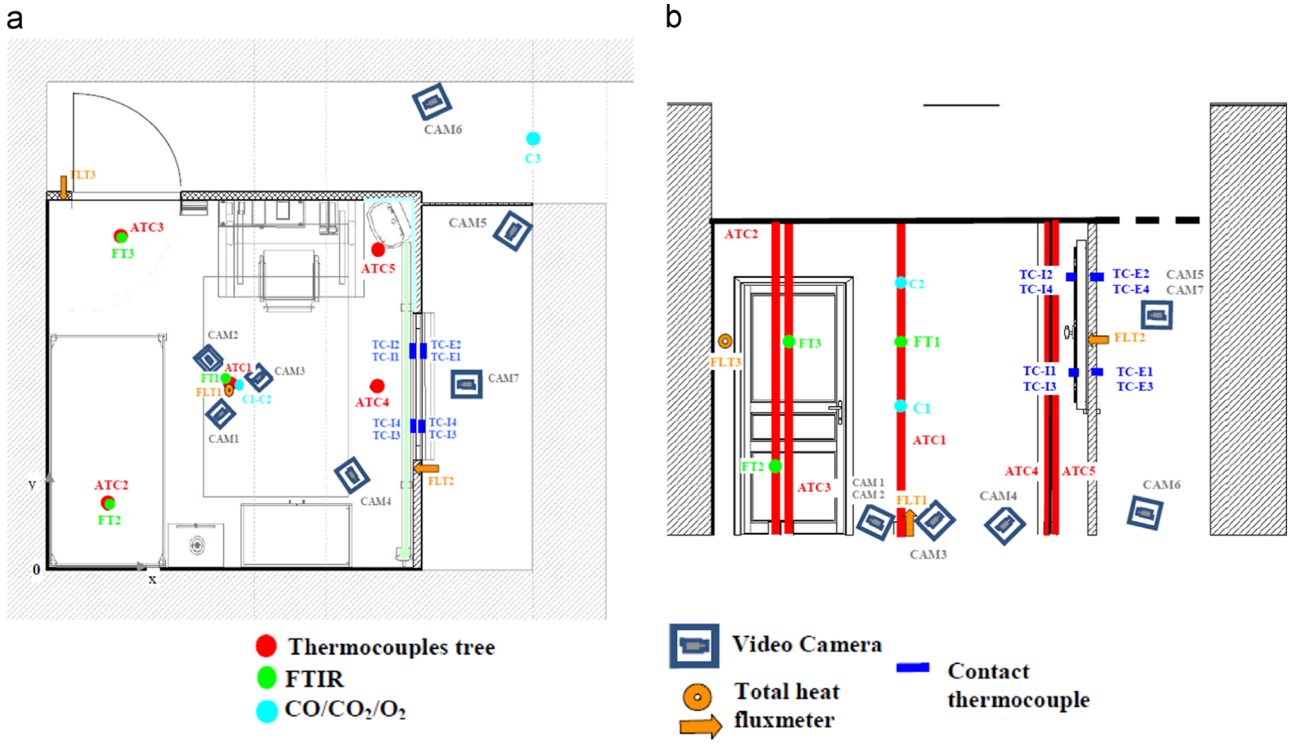

Fig. 3. Instrumentation description: (a) top view and (b) side view.

Table 3
Detailed Sensors Position. Origin is wall corner, bed side, as stated in Fig. 3a.

Designation	Sensor	Coordinates		
		x **(m)**	***y*** **(m)**	***z*** **(m)**
ATC1	Thermocouple trees, 10 TC's each	1.50	1.50	0.80 1.10
ATC2		0.48	0.50	1.40 1.50
ATC3		0.60	2.70	1.60 1.70
ATC4		2.70	1.48	1.80 1.90
ATC5		2.75	2.65	2.00 2.40
FLT1 (orientation $z+$)	Heat fluxmeters	1.50	1.50	0.20
FLT2 (orientation $x-$)		3.00	0.85	1.50
FLT3 (orientation $y-$)		0.10	3.00	1.50
FT1		1.50	1.50	1.50
FT2	FTIR gas analyzers sampling probe + thermocouples	0.48	0.50	0.60 (Test series 1) 1.50 (Test series 2)
FT3		0.6	2.70	1.50
C1	CO/CO_2 NDIR analyzers	1.50	1.50	1.00
C2	O_2 paramagnetic analyzers + thermocouples	1.50	1.50	2.00
C3		4 (Corridor)	1 (Corridor)	1.50
OPA1	Opacimeter tree	2.65	2.75	0.90 1.10 1.50 1.90 2.30

“Tests 1” series, to evaluate gases composition at head level for an asleep person). They provide access to all the information required to estimate tenability conditions related to acute exposure to asphyxiant and irritant gases [29,30]. These analyzers have been calibrated for a quantitative analysis of given species of interest (CO, CO_2, HCl, HBr, HF, HCN, SO_2, NO, NO_2, N_2O, formaldehyde), and interfering species for correction purposes (H_2O, CH_4, C_2H_2, C_2H_4, NH_3). Additional species (e.g. acrolein) are considered in the qualitative analysis. Calibration has been performed in accordance with Refs. [31–33] using reference gas cylinders and the mass-flow dilution technique. FTIR's operate using a 10 m pathlength gas cell working at 180 °C/650 Torr, and a MCT detector. This allows a typical quantification limit of approximately 1 μL/L. Spectral range is 650–4000 cm^{-1} with a resolution of 0.5 cm^{-1} so as to consider interferences properly. Calibration has been checked (in wavelength and in concentration) just before initiating the tests, using reference gas cylinders for 4 species absorbing at different regions of the spectral range. Uncertainty has been calculated as $\pm 5\%$. It has been assumed that interfering species have been properly taken into account.

CO and CO_2 non-dispersive infrared (NDIR) analyzers and O_2 paramagnetic analyzers are used at C1, C2 (middle of the room, respectively, 1 m and 2 m high) and C3 (corridor, 2 m high) points, to measure some of the information necessary for the estimation of tenability conditions related to toxic effects. Such analyzers and their limitation in fire applications are fully described in Ref. [34]. NDIR analyzers also help to calculate the spread of species measured exclusively by FTIR analyzers, according to the hypothesis of identical diffusion for all species. Over very short distances such as those that are involved in the test room and its corridor, this assumption is quite valid. These analyzers have been calibrated on their whole range just before the tests using reference gas cylinders. Uncertainty has been calculated as $\pm 5\%$.

2.2.2.3. Measurement Means for the estimation of visibility loss. Specific white light opacimeters (OC1) have been designed to provide local, instantaneous and non-intrusive information about soot optical density [35]. The operating principle of opacimeters is based on an optic attenuation measurement. These opacimeters have a pathlength of 0.05 m and operate with white light. 5 Opacimeters are placed vertically close to the sink, at levels ranging from 0.9 m to 2.3 m. Following the Beer–Lambert law, the optical density is derived from the output and the maximum opacimeter voltage. In Eq. (1), α is the calibration coefficient, U_{out} the output voltage [V], and $U_{\max}$ the maximum value of the output voltage. Opacimeters have been calibrated against reference KODAK WRATTEN neutral filters. However, uncertainty has not been estimated.

$$OD = \alpha \log_{10} \frac{U_{\max}}{U_{out}} \qquad (1)$$

2.2.2.4. Additional measurements

- Contact thermocouples at the window, in order to measure its heating.
- High definition cameras, recording visual and audio information during tests:
  - One of them covers the corridor, including the opening of the door;
  - two of them are positioned behind the window:
    - The first covers the bed (wide shot);
    - the second covers any flue outlet at the window or from the shutter trunk.
- Four webcams are positioned in the room itself:
  - The first covers the door;
  - the second covers the desk, and the paneling between the sink and the desk;
  - the third covers the bed (close-up);
  - the fourth covers the top of the downcomer pipe.
- Control thermocouples to ensure staff safety and testing devices.

3. Results and discussion

3.1. Results – series “Tests 1”

3.1.1. Test 1A (ignition with cigarette in accordance with EN 597-1)

The cigarette is placed on the quilt with its cover, approximately at the center of the mattress. The cigarette has burned out completely without causing inflammation either of the cover or the underlying quilt. The cover shows evidence of browning where the cigarette was. No significant elevation of temperature, heat flux or gas concentration is recorded in the room.

Once test 1A is completed, proper ventilation is applied to the testing room after which test 1B is carried out.

3.1.2. Test 1B (ignition with match in accordance with EN 597-2)

The simulated match is placed on the quilt with its cover, approximately in the center of the mattress, on a pristine area away from the degraded spot during Test 1A. The application duration is 15 s.

During the test, no significant rise in temperature, heat flux or gas concentration is recorded. At the end of the application, the quilt cover is deteriorated at the point of application. The quilt padding is slightly degraded in depth. There is neither flame propagation nor smoldering combustion.

Once test 1B is completed, adequate ventilation is applied to the testing room after which test 1C is carried out.

3.1.3. Test 1C (ignition with wood crib #5 in accordance with BS 6807)

This standardized crib consists of small wood sticks, with a tissue at the base. This tissue is impregnated with approximately 1.4 mL of propanol just before the test, and then ignited. The crib is placed on the quilt cover, approximately in the center of the mattress, on an intact area remote from the ones locally degraded during tests 1A and 1B. Events and observations during the test are detailed in Table 4. The test is stopped more than 28 min afterwards; there are no visible flames for over than 10 min and all sensors present a slow evolution (e.g. temperatures are slowly decreasing).

The Fig. 4(a–d) shows the yields of carbon monoxide (CO), carbon dioxide (CO_2), and hydrogen cyanide (HCN) and hydrogen chloride (HCl) observed during the duration of the test 1C at the headboard (Point FT2) or other locations when specified. The yield of carbon monoxide at 2 m high begins to rise significantly approximately 2 min after ignition of the source (Fig. 4(a)). It should be highlighted that the first room smoke alarm activates at 2 min 10 s. The growth rate of CO is very regular and almost linear between 11 min and 28 min 31 s (end of test). The consistency of three analyzers using two different measurement techniques (FTIR and NDIR) excludes any metrological bias for this linearity. The evolution of the CO_2 concentration at the headboard is much faster than the CO concentration (Fig. 4(b)): fire is initially well ventilated. Some 3 min 30 s after ignition, the $[CO]/[CO_2]$ ratio increases. The fire turns gradually to under-ventilated conditions. After 3 min, the hydrogen cyanide (HCN) concentration increases at the headboard (Fig. 4(c)). This increase is likely due to the degradation of the polyurethane foam of the mattress. The concentration of hydrogen chloride (HCl) in the room is likely due to the pyrolysis of PVC products. It increases measurably from 11 min after ignition (Fig. 4(d)) to the end of the test. HCl concentration,

Table 4
Time events table for test 1C.

Time (hh:mm:ss)	Event
00:00:00	Crib ignition
00:00:16	First visible smoke on the camera covering the bed
00:00:26	Door is shut
00:00:44	First visible flames on the camera covering the bed
00:02:10	First smoke alarm of the room activates
00:03:27	The sound produced by the smoke alarm begins to change
00:04:00	Smoke alarm of the corridor activates
00:28:31	End of test. Intervention order addressed to firefighters

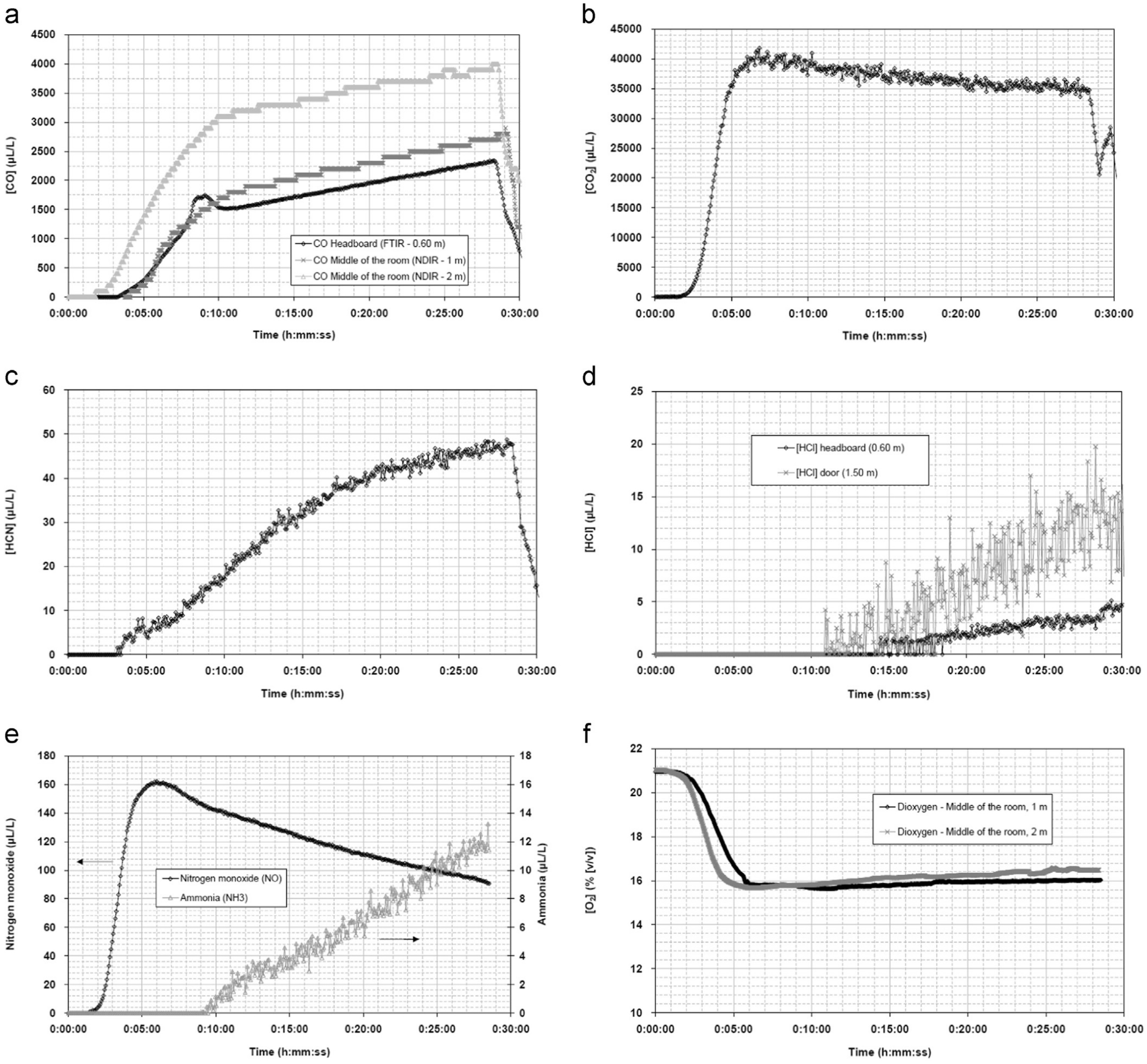

Fig. 4. Measurement results for gases, Test 1C: (a) CO concentration, (b) CO_2 concentration (headboard), (c) HCN concentration (headboard), (d) HCl concentration, (e) nitric oxides and ammonia (at door), and (f) O_2 concentration.

however, remains very low (near detection limits), which explains the large scatter in measurements. Results also highlight the presence of nitrogen monoxide (NO). Traces of ammonia (NH_3) were also observed (see Fig. 4(e)). Therein, nitrogen dioxide (NO_2) was under the quantification limit. Results on other gases highlight significant concentrations of hydrocarbons: concentration in methane is close to 400 μL/L at the door at the end of the test, which correspond to the release of unburnt pyrolysis gases. Fig. 4(f) presents the variation of dioxygen concentration. It shows a rapid stabilization of dioxygen in the enclosure at 16%. This concentration is in the order of the magnitude of critical concentrations which stop combustion at such temperatures. This shows that the fire probably stopped because of the lack of oxygen available for combustion.

Fig. 5 shows the results for the temperature measured with the thermocouple trees for point ATC3, close to the door. The

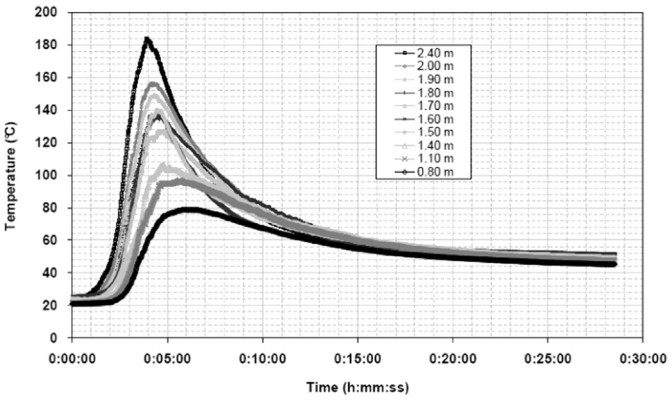

Fig. 5. Measurement results by temperatures, Test 1C (point ATC3 – close to the door).

temperature rises quickly to about 160–180 °C, then decreases and stabilizes around 50 °C. During the first 3 min of the test, temperature increases at the ceiling. The smoke layer develops, and a fresh air layer remains in the lower volume of the room. Between 3 min and 7 min, a vertical temperature gradient exists. However, after 3 min, the temperature in the lower part of the room started to increase. Smoke started to mix with air. As a consequence, stratification is broken. This is confirmed by visual observation. After 8 min, the temperature is homogeneous in the room from floor to ceiling. From then on; it decreases slowly – from 80 °C to 50 °C – during the next 20 min. All other thermocouple trees show a similar trend, which demonstrates that the system is homogenous horizontally.

Fig. 6 shows the results of smoke opacity. Unfortunately, the opacimeters located at 1.1 m and 0.7 m stopped working after, respectively, 2 min 17 s and 2 min 30 s. The signal starts to grow for all sensors between 1 min 41 s and 2 min 30 s, as smoke is filling the room. The optical density then increases with the fire growth until around 4 min, which corresponds to the peak temperature and an dioxygen level of 16%, as seen, respectively, on Fig. 5 and 4(f). The opacity presents later a second significant increase with a maximum at 12 min, when all other variables are stagnant or decreasing. These measurements show the changing nature of the soot and the increase of production rates when combustion changed to an under ventilated regime. After this second maximum, values decrease slowly until the end of the test. The fire source is probably too weak for the size of the room to lead to a strongly stratified situation. At the beginning, the smoke is well stratified, then thermal convection tends to homogenize the concentration of smoke in the room.

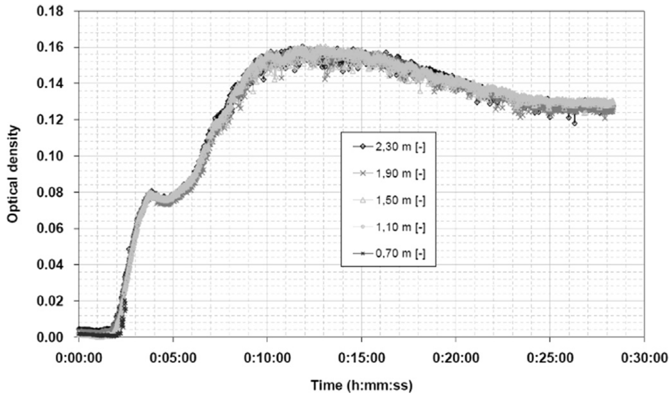

Fig. 6. Measurement results for opacimeters, Test 1C.

Fig. 7(a) presents the picture of the mattress after the test. The extent of degradation is used to estimate the amount of burned polyurethane foam. This quantity is about 1 kg. The slatted bed base was slightly impacted during the combustion of the mattress, as presented in Fig. 7(b). Finally, the bed frame has been slightly degraded, as shown in Fig. 7(c). The wall closest to the fire shows some slight damage to the PVC paneling (Fig. 7(d)). This localized degradation might explain the presence of hydrogen chloride (HCl) in the smoke from the 11th min after ignition onwards. The rest of the room seems unaffected, except for the soot deposit on all horizontal surfaces.

3.2. Results – series "Tests 2"

3.2.1. Test 2A (ignition with cigarette in wastepaper basket)

Fire is ignited in the wastepaper basket containing a plastic trash bag and 500 g of creased paper balls. The basket is placed under the edge of the vertical wall to the right of the desk. A cigarette is placed on the paper. This moment is taken as the beginning of test (t_0). Test staff leaves the test room and closes the door.

Fig. 7. Observations after test 1C: (a) mattress after test, (b) slatted bed base after test, (c) bed frame after test, and (d) deformation of PVC wall paneling.

Events and observations during the test are detailed in Table 5. The test is stopped beyond 22 min and above. There are no visible flames. A very slow smoldering fire started. Finally, the criteria of 200 °C has not been reached in the corridor.

Fig. 8 shows the results of measured gases. Fig. 8(a) presents the concentrations of gases which were observed at the middle of the room, 1.5 m high. These concentrations show no significant increase at this level before 9 min. Carbon dioxide reaches a maximum close to 6000 µL/L, and the carbon monoxide reaches about 400 µL/L. Low quantities of nitrogen monoxide and hydrogen chloride (less than 10 µL/L) are observed at the end of test. The presence of hydrogen chloride may be due to the localized impact of fire on the floor covering material under the basket, as well as on the paneling at the right side of the desk. The contribution of some chlorinated material mounted on the desk (such as polychloroprene glue) is not excluded. The concentrations observed at the door (Fig. 8(b)) are very similar to those at the middle of the room, especially for carbon oxides. In the corridor, the dioxygen decay remains small, and carbon oxides reach concentrations similar to those observed inside the test room.

Fig. 9(a and b) shows the results for the temperature measured with the thermocouple trees and in corridor. There is no temperature rise before 10 min. Then, temperature increases during the next 2 min 30 s, and reaches a maximum close to 60 °C at ceiling level after 12 min 30 s. After, temperature decreases progressively. This is consistent with the observations in Table 5, as there are neither flames visible nor smoke generation from the paper basket 12 min 39 s after the test beginning, and only a small contribution from the desk drawer. There is no significant temperature rise observed at any point below 1.50 m. All other thermocouple trees results are very close which demonstrates that the system homogenous horizontally. Temperature in the corridor follows a similar trend (Fig. 9(b)), with a maximum of 41 °C. Heat flux measurements remain under the measurement limit (< 0.6 kW/m²) during the whole test, and they are consequently not plotted.

Table 5
Time events table for test 2A.

Time (hh:mm:ss)	Event
00:00:00	The cigarette is put on paper balls.
00:00:37	Door is shut (operator leaves after ignition).
00:02:40	Door is opened.
00:06:43	Activation of smoke alarm in room.
00:07:27	Activation of smoke alarm in corridor.
00:08:40	Visible flames in the paper basket.
00:11:15	Propagation to the desk drawer.
00:12:07	No more visible flames on paper basket.
00:12:39	No more smoke production from paper basket.
00:13:21	Flaming droplets fall down from the back of the drawer. Smoke is visible down to floor level.
00:14:47	No more visible flames on desk drawer, but smoke production from smoldering combustion continues.
00:22:42	End of test. Intervention order addressed to firefighters.

Fig. 10(a–d) presents pictures at the end of the test. After this test, the desk has been brought out of the testing room to be extinguished, as there was smoldering on its drawer, and then returned to its original place. Adequate ventilation has been applied to the testing room to allow a return to baseline of measurement devices. The decision was to conduct a second test, test 2B, keeping facilities (finishing, furniture, etc.) as they were, i.e. with the damage from the test 2A, including on the desktop, paneling and flooring.

3.2.2. Test 2B (ignition with flame in wastepaper basket, 2 wastepaper baskets)

Ignition is carried out in a wastepaper basket by setting fire to a plastic trash bag and 500 g of creased paper balls. This wastepaper basket is placed under the edge of the vertical wall to the right of the office at exactly the same location as in the test 2A. A second identical wastepaper basket is placed next to its left under the desk. Ignition is achieved with a small flame simulating a match similar to the EN 597-2 source. The simulated match is placed on the top of the wastepaper basket to cause ignition of the paper. The beginning of the application corresponds to the beginning of the test (t_0). Test staff then leaves the test room and closes the door.

Events and observations during the test are detailed in Table 6. The condition of 200 °C in the corridor, implying the end of test, is reached at 6 min and tenability assessment is therefore performed between 0 min and 6 min. Additional information is however available for further model validation purposes from thermocouples and heat flux meters between 6 min and firefighters intervention.

Fig. 11 presents all the gases measurements results for test 2B. Dioxygen decreases and CO_2 concentration increases until the flashover, and reaches 8% at ceiling height (Fig. 11(a–c)). A small amount of CO is produced during the first minutes, and then CO rises quickly at 5 min 30 s, in pre-flashover phase. Hydrogen chloride (HCl) only appears in small quantities when flashover conditions are reached a few seconds before the end of the test (Fig. 11(c–e)). Nitrogen monoxide (NO) is present at the early stages of fire, as for hydrogen cyanide (HCN), as seen in Fig. 11(d–f). These two trends highlight the combustion of nitrogen-containing species, with different local combustion conditions to produce both species. Ammonia is visible on the same

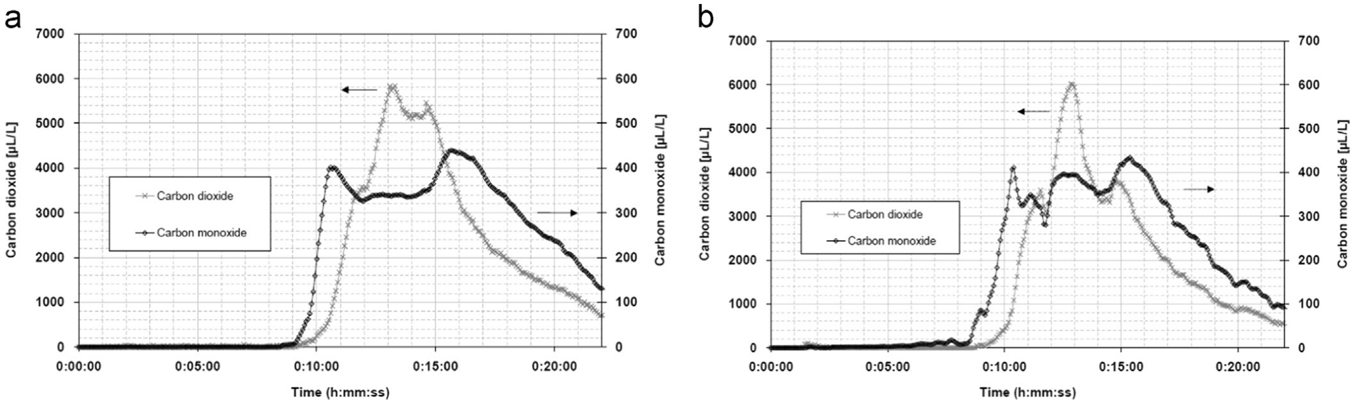

Fig. 8. Measurement results for gases, test 2A: (a) FTIR gases concentration (CO, CO_2), point FT1 (middle of the room, 1.5 m high) and (b) FTIR gases concentration (CO, CO_2), point FT2 (door, 1.5 m high).

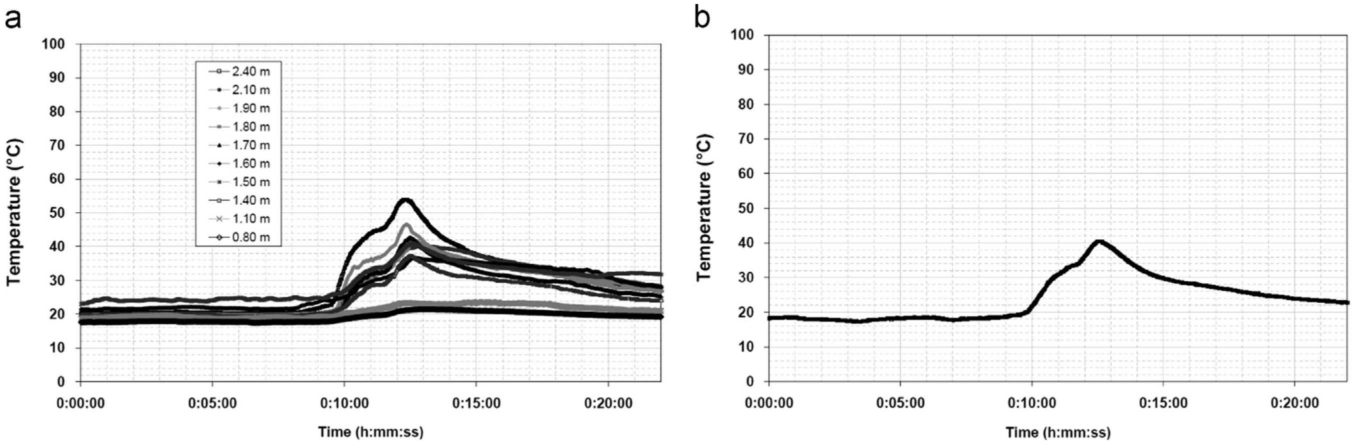

Fig. 9. Measurement results for temperatures, test 2A: (a) temperature tree, point ATC1 (in the middle of the room) and (b) temperature at ceiling level in corridor (point C3).

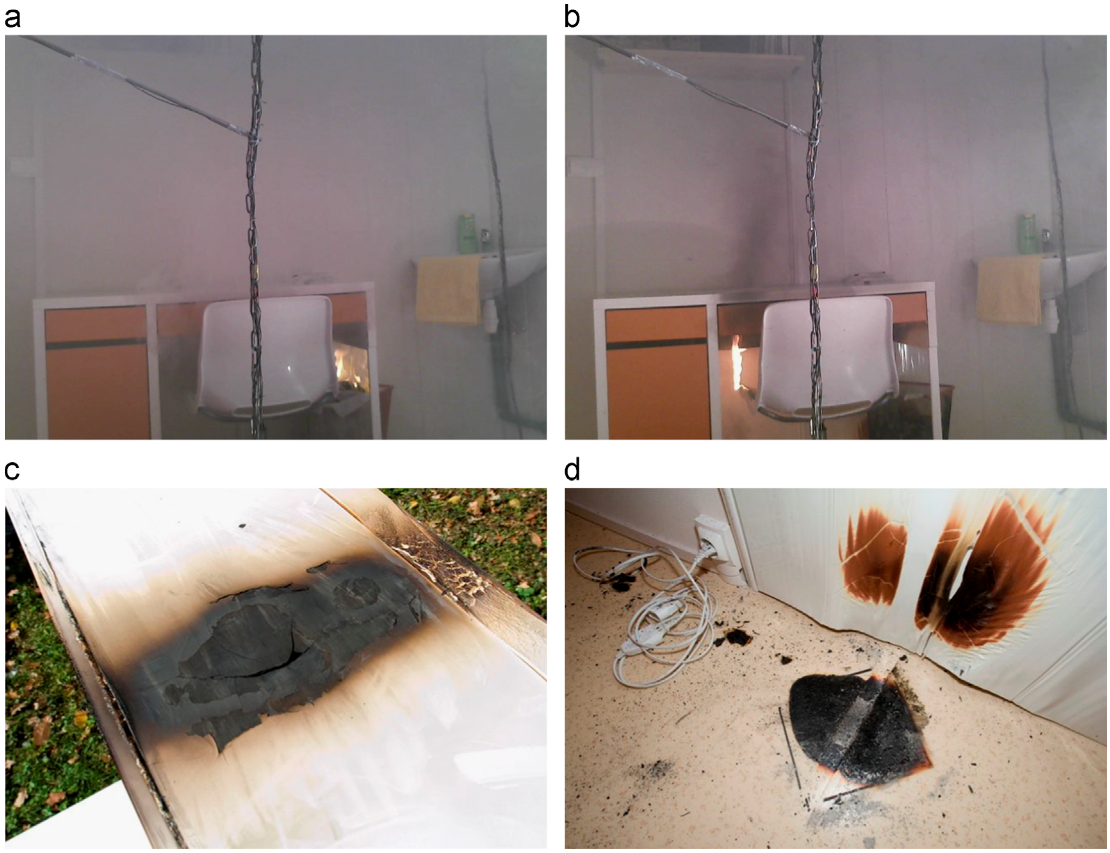

Fig. 10. Observations during and after test 2A: (a) fire on paper basket, 8 min 40 s after the beginning of test, (b) flame propagation under the office desk, (c) localized burnt parts on right panel of the desk, and (d) degraded parts on wall behind the desk. Mark on the floor is due to the paper basket.

figures in first stage of the test, but its decay is probably linked to its consumption after 5 min 30 s – when temperature conditions change in the room. Unburnt hydrocarbons remain very low during test, highlighting a complete combustion of pyrolysis gases before flashover.

Fig. 12 presents temperature measurements. Temperature of gases in upper parts starts to increase after 3 min. Until 5 min 30 s, the system is stratified, with also no temperature rise at both 1.1 m and 0.8 m. The interface is located between 1.1 m and 1.4 m. Then, the temperature rises rapidly in one minute and eventually reaches about 700–900 °C at each location and each height. Regarding temperatures, flashover conditions are reached from 6 min 15 s. This is shown for thermocouple tree ATC1 in Fig. 12(a), but identical for all other measurement points. Temperature in the corridor (Fig. 12(b)) follows the same trend, with a difference of about 100 °C with the room. Fig. 13 presents the measured total heat fluxes. Flashover conditions are reached when a heat flux from ceiling to floor is between 17 kW/m² and 35 kW/m², in accordance with literature [48]. These conditions are reached after 6 min 15 s. Previously, the heat flux sensor located at door sees an important increase of heat flux, corresponding to an important but localized fire growth from 5 min 30 s to 6 min 15 s. Post-flashover conditions at the end of test present heat fluxes over 100 kW/m² at 8 min.

Table 6
Events table for test 2B.

Time (hh:mm:ss)	Event
00:00:00	Beginning of ignition sequence.
00:00:48	End of ignition sequence. Staff leaves the room.
00:01:14	Door is shut.
00:02:01	Activation of smoke alarm in the room.
00:02:15	Visible flames out of the volume under the desk.
00:02:31	Second paper basket ignites.
00:03:12	Door opened, 1 min 58 s after it was shut.
00:03:22	Fire grows and flame reaches the shelf.
00:03:31	Activation of smoke alarm in corridor.
00:03:42	Flashes of flames from backside of the desk.
00:04:55	After 10 s of softening, the shell of the seat finally produces flaming drops.
00:04:59	PVC wall panels start to collapse.
00:05:00	Smoke opacimeters are saturated. No optical density data afterwards.
00:05:54	200 °C reached in the corridor. First flames visible from the corridor, at the top of the doorframe.
00:06:00	End of test. Intervention order given to firefighters.
00:06:15	Growth to flashover.
00:06:34	Visible flames, probably from the bed on fire.
00:08:10	Effective intervention of firefighters.

Fig. 14 presents results for optical density. The smoke opacimeter device fails after 5 min, no optical density values are available then after. First smoke rise is detected on the highest sensor (2.30 m) after 3 min 20 s, then followed by the 1.90 m sensor at 3 min 35 s and by the 1.50 m sensor at 3 min 52 s. After 4 min, the 1.50 m high sensor indicates a variable signal that could correspond to the presence of a rather thin interface between air and smoke. Under 1.10 m, no smoke is measured during the whole measurement period. For the period of data collection, it is interesting to note the gradient of optical density from top to bottom, with an interface established close to 1.5 m.

The damages in the room are extensive, but the intervention of firefighters limited their consequences. Thus, despite the very high temperatures reached in the room, many elements are relatively poorly degraded, especially when shadowed by another element.

4. Interpretation on fire effects to people

4.1. Tenability assessment methodology

The tenability calculation is performed in accordance with ISO 13571 [1]. This method is based on those proposed by Purser [8] and refined by Peacock et al. [11]. ISO 13571 defines tenability as the ability of humans to perform cognitive and motor-skill functions at an acceptable level when exposed to a fire environment. If exposed individuals are able to perform cognitive and motor-skill functions at an acceptable level, the exposure is said to be tenable. If not, tenability is compromised.

The tenability is assessed in accordance with ISO 19706 [36] recommendations. It uses an adaptation of ISO 13571 models to estimate the effects of fire on people and to evaluate a time after which the tenability is likely to be compromised for a given exposure scenario. Since tenability depends on the specific susceptibility of the individuals to exposure to fire products, wide variation of responses might be anticipated. The ISO 13571 standard describes the sensitivity curve of the population as an *a priori* lognormal distribution. For a given exposure to the effects of fire, one part of the population is in tenable conditions, while the other part of the population suffers from compromised tenability conditions. For a given exposure scenario, it is therefore appropriate to think in terms of percentage of the population that could be affected, with reference to sensitivity model described in the standard. The tenability can be affected by the following factors [37]:

- Effects related to the toxicity of fire effluents [38]. This mechanism may be due to effects of asphyxiating or irritant effects.
  - Asphyxiating (or narcotic) effects: these effects are cumulative and related to the absorbed dose. They depend on both the concentration of asphyxiant gas and the exposure time for the exposed person. The carbon monoxide gas (CO) and hydrogen cyanide (HCN) are the only asphyxiant gases included in ISO 13571 standard. Their effect may be increased by the presence of carbon dioxide (CO_2). The corresponding evaluation criterion is FED_{tox} (Fractional Effective Dose due to toxicity). Purser [39] and Kaplan et al. [40] developed the calculation formula as detailed in Eq. (2):

$$FED_{tox} = \sum_{t_1}^{t_2} \frac{[\mathrm{CO}]v_{\mathrm{CO_2}}}{35,000}\Delta t + \sum_{t_1}^{t_2} \frac{([\mathrm{HCN}]v_{\mathrm{CO_2}})^{2.36}}{1.2\times 10^6}\Delta t$$
$$v_{\mathrm{CO_2}} = e^{[\mathrm{CO_2}]/5} \qquad (2)$$

  In this equation, CO and HCN concentrations are expressed in μL/L and CO_2 concentration is in volume percentage. The time is expressed in minutes. The uncertainty on FED_{tox} is estimated as ±35% in accordance with reference [1].
  - Irritating effects: these effects are immediate and related to the concentration of irritating gases. Hydrogen chloride (HCl) and nitric oxide (NO) are the irritating gases found in significant concentration during the tests. Ammonia (NH_3) has been found too, but this gas is only irritant at concentrations slightly higher than those encountered; its effect is neglected hereafter. No other irritant has been found during the tests. The corresponding evaluation criterion is *FEC* (Fractional Effective Concentration). It means that irritancy of smoke is concentration-related at tenability level. This hypothesis is not valid at lethality level. *FEC* calculation is described in Eq. (3), as derived from Purser [39] and Kaplan et al. [40] and considering irritant species effectively measured:

$$FEC = \frac{[\mathrm{HCl}]}{F_{\mathrm{HCl}}} + \frac{[\mathrm{NO}]}{F_{\mathrm{NO}}} \qquad (3)$$

  In this equation, concentrations are expressed in μL/L. F_{HCl} is the critical concentration for HCl to compromise tenability. The value $F_{HCl}=1000$ μL/L is used, as proposed in ISO 13571. There is no critical concentration proposed for NO in ISO 13571. However, AEGL guidelines [41] propose to use NO_2 value instead of NO in the absence of other data. The value $F_{NO_2}=250$ μL/L as proposed in ISO 13571 is used for F_{NO}. Additional analysis of the term related to HCl is also performed to check at the contribution of HCl in irritancy, because of large amount of PVC used in the enclosure. The uncertainty on *FEC* is estimated as ±50% in accordance with reference [1].
  - Interpretation of effects due to dioxygen depletion is also included in the analysis. A simple analysis of a threshold of 16% of dioxygen is considered as a concentration sufficient to compromise tenability.
- Thermal effects: these effects may be due to the temperature of the air (convective effect) or to the received radiation (radiative effect). These two effects are cumulative and dose-related. The corresponding evaluation criterion that combines these two effects is FED_{therm} (Fractional Effective Dose due to thermal effects). The model has been developed in accordance with the work of Purser [39] and Wieczoreck et al. [42]. It is presented in

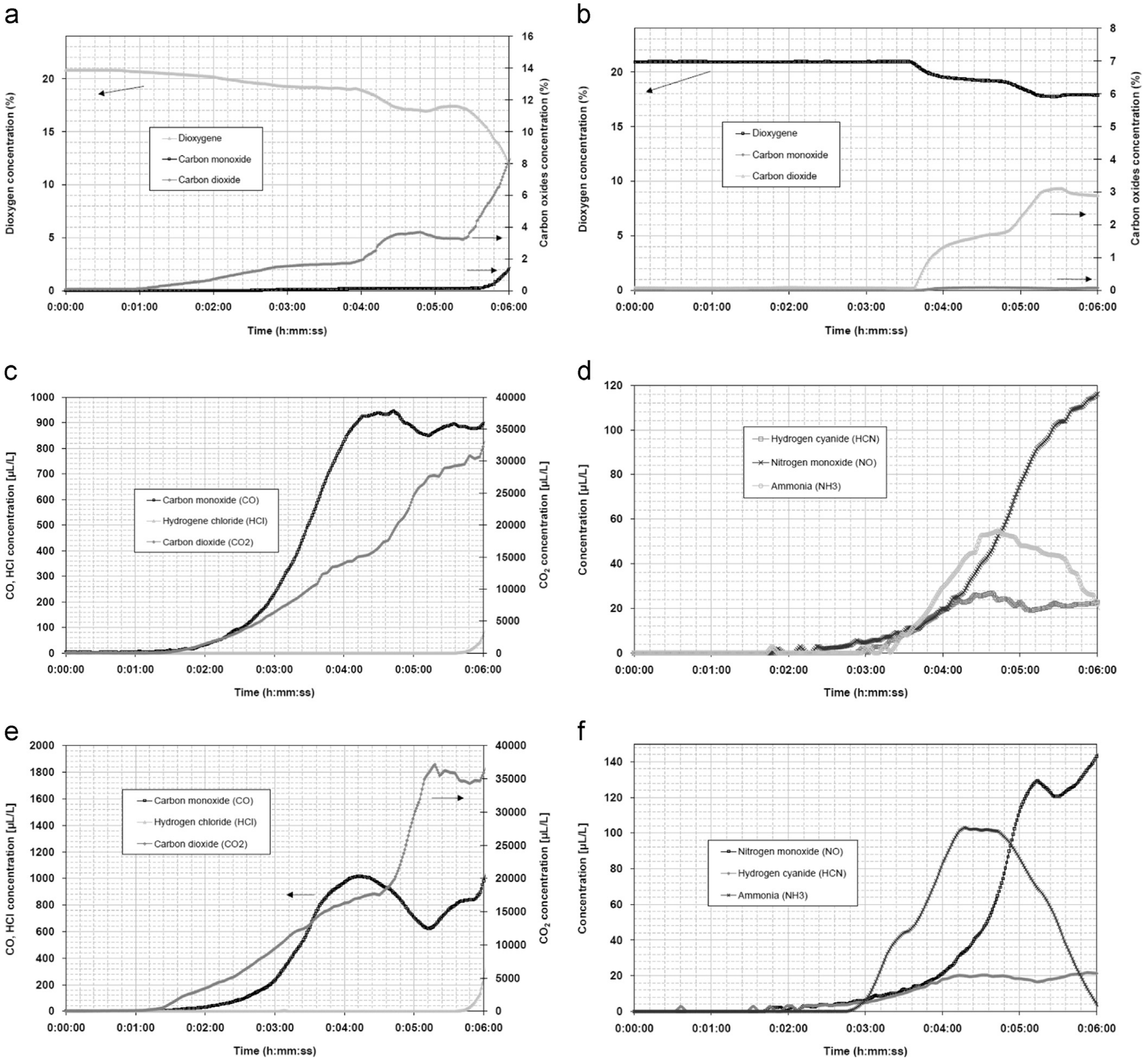

Fig. 11. Measurement results for gases, test 2B: (a) O_2, CO and CO_2 concentration, point C2 (middle of the room, 2 m high), (b) O_2, CO and CO_2 concentration, point C3 (corridor, 2 m high), (c) FTIR gases concentration (CO, CO_2, HCl), point FT1 (middle of the room, 1.5 m high), (d) FTIR gases concentration (HCN, NO, NH_3), point FT1 (middle of the room, 1.5 m high), (e) FTIR gases concentration (CO, CO_2, HCl), point FT2 (door, 1.5 m high), and (f) FTIR gases concentration (HCN, NO, NH_3), point FT2 (door, 1.5 m high).

Eq. (4), using the hypothesis of lightly clothed persons;

$$FED_{therm} = \sum_{t_1}^{t_2} \left(\frac{1}{t_{Irad}} + \frac{1}{t_{Iconv}} \right) \Delta t$$

$$t_{Irad} = 4.2q^{-1.9} \text{ if } q > 2.5 \text{ kW}/m^2 \text{ and } \frac{1}{t_{Irad}} = 0 \text{ if } q < 2.5 \text{ kW}/m^2$$

$$t_{Iconv} = (5 \times 10^7)T^{-3.4} \qquad (4)$$

In this equation, time is expressed in minutes. The incident heat flux q is expressed in kW/m² and the temperature T in °C. The uncertainty in this equation is estimated as ±25% in accordance with reference [1].

- Effects related to visibility: they are considered as worsening the ability of people to move. Interpretation is performed in accordance with Jin [43] and Rasbash [44]. For an unknown evacuation path, Jin proposed a limit of optical density equal to $OD = 0.06$, and Rasbash proposed a limit $OD = 0.08$. For a known evacuation path, Jin proposed a limit of $OD = 0.2$.

The tenability must be assessed through an exposure scenario, resulting in the synthesis of a fire scenario and an evacuation scenario [45,46]. The detailed calculation methods to determine the FEC, FED_{therm} and FED_{tox}, have to consider the position of the occupant at each time increment. When the position of the occupant is unknown, e.g. in the room or in the corridor, an average value is considered. For example, the average value of gas concentration at 1.5 m may be used to represent the mean composition that the occupant may breath. The time increment chosen for the analysis is 30 s.

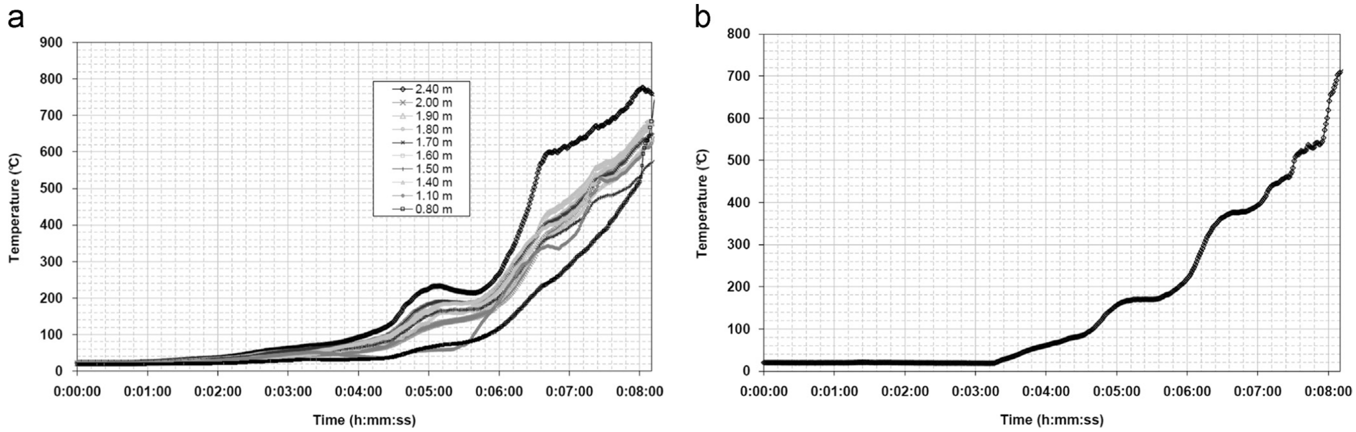

Fig. 12. Measurement results for temperatures, test 2B: (a) temperature tree, point ATC1 (in the middle of the room) and (b) temperature at ceiling level in corridor (point C3).

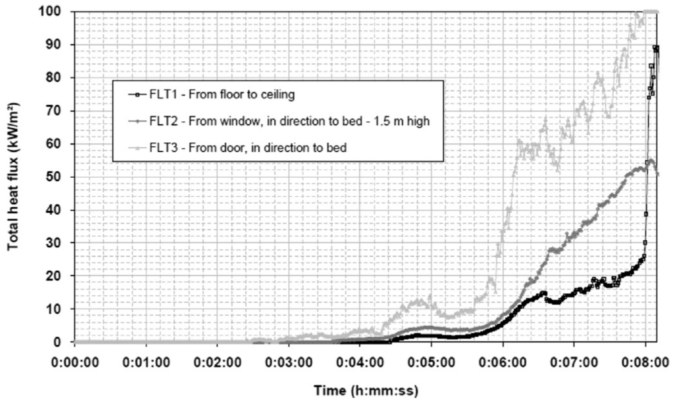

Fig. 13. Measurement results for total heat fluxes, test 2B.

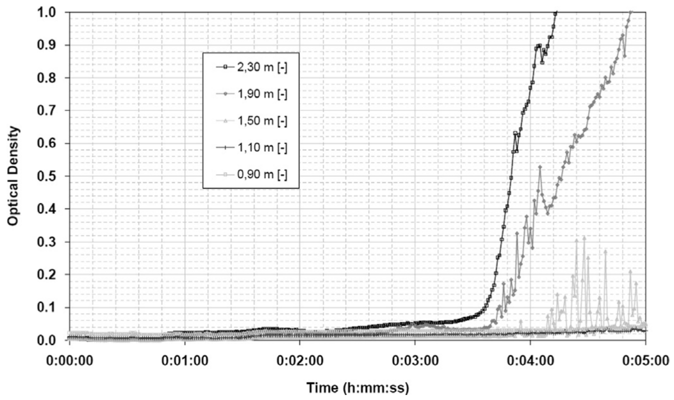

Fig. 14. Measurement results for opacimeters, test 2B.

4.2. *Interpretation of test series 1*

The scenario of the test series 1 is an accidental fire on a mattress. The occupant does not wake up and does not evacuate. A direct burn by the combustion of the mattress is not considered for the tenability assessment. The openings (doors, windows) remain closed all test long. In tests 1A and 1B, no significant effect of fire is observed. In test 1C, the effects are significant. Fig. 15 shows the interpretation of the results, considering the exposed occupant head at a height of 0.6 m. Fig. 15(a) shows the results of FED/FEC, while Fig. 15(b) interprets these results in terms of proportion of the population that is affected, assuming a lognormal distribution of the sensitivity in population, in the absence of other distribution. In this interpretation, the effects of asphyxiant (narcotic) gases (CO, HCN) are predominant. The effects of temperature impact a lower percentage of the population. Finally, the irritating effects are of the same order of magnitude as the thermal ones in this scenario. These irritant effects are due to NO, and there is no significant contribution from hydrogen chloride due to the combustion of PVC. The olfactive detection threshold for HCl (0.77 μL/L in accordance with Ref. [47]) is reached after about 10 min, but this value is between limit of detection and limit of quantification, and the confidence may be estimated at ±50% in such measurement.

Dioxygen concentration reaches about 16% in 4 min. Such dioxygen concentration is likely to compromise tenability [37]. It should be noted that smoke alarms are activated early, about 3 min before the onset of any asphyxiating effects from CO and HCN, and 1 min before the O_2 concentration becomes too low.

Smoke optical density reaches values that could compromise evacuation for an unknown travel path after 3 min (OD=0.06 or OD=0.08), when limit for a known path is never reached during the test (OD=0.2).

Within the frame of this test 1C, the main conclusions are the following:

- At the end of the test, 87% of people facing this exposure scenario are in compromised tenability conditions, as a result of the action of the asphyxiant gases (CO and HCN);
- at the end of the test, approximately 16% people facing this exposure scenario are in compromised tenability conditions because of thermal effects and irritant effects;
- irritant effects are due to nitric oxide in this scenario, hydrogen chloride contribution remains negligible;
- smoke alarm activates before any compromised tenability conditions are observed in the room.

4.3. *Interpretation of test series 2*

The scenario 2A corresponds to an accidental fire in a single wastepaper basket full of paper. This scenario does not lead to any flashover and fire decreases when the fuel available in wastepaper basket has been consumed. The exposure scenario analyzed is an occupant standing in the middle of the room, without escape, breathing at 1.5 m height. The concentration used for the calculation has been given by FTIR measurement point FT1. Calculation of FED_{therm}, FED_{tox} and FEC are presented in Fig. 16. The results show that effects start to be visible after 10 min of the test. During the first 10 min, there is no fire effluent at the measurement point. After 10 min, values of FED/FEC remain very low, impacting only

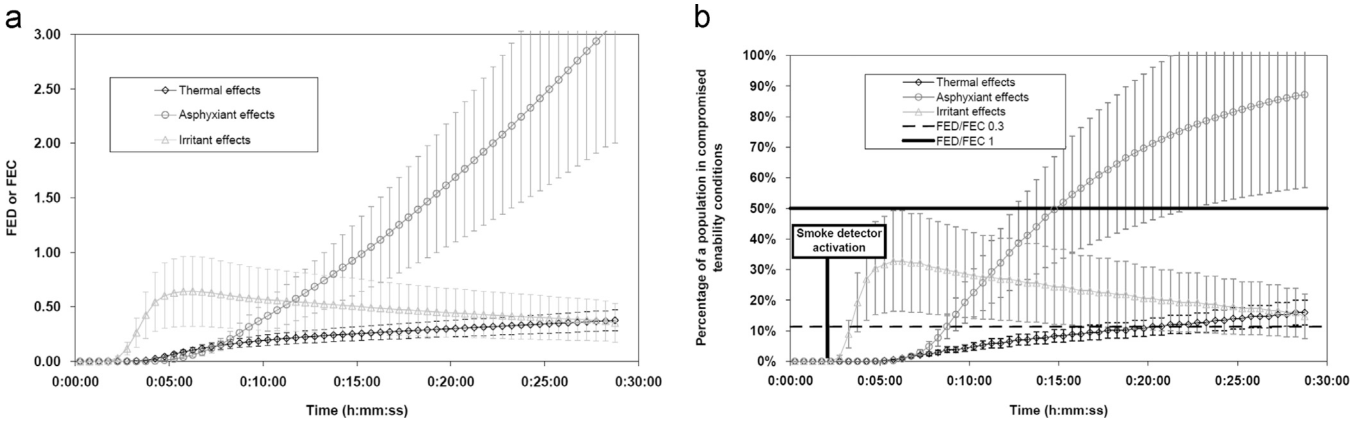

Fig. 15. Interpretation of the test 1C: (a) FED and FEC calculation at 0.6 m height and (b) percentage of the population in compromised tenability conditions.

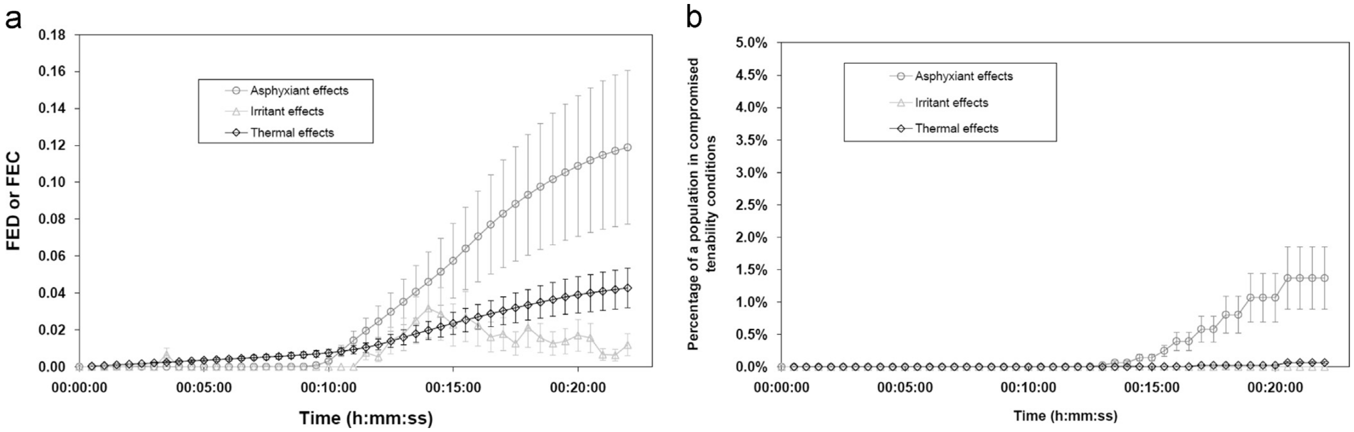

Fig. 16. Interpretation of the test 2A: (a) FED and FEC calculation at 1.5 m height and (b) percentage of the population in compromised tenability conditions.

the more susceptible percentage of population for FED_{tox}. The main effect of combustion gases is the asphyxiant effect for only 1.4% of the population. Irritants or thermal effects remain low in comparison during whole test. Smoke alarm has been activated after 6 min 43 s. This early detection allows a safe evacuation delay in comparison with the time when first effects are noted.

The scenario 2B corresponds to an accidental fire in a couple of wastepaper baskets full of paper. Two different occupant behaviors are considered.

In occupancy scenario 2B I, two minutes after having closed the door (because of ignition sequence), the occupant gets out of the room and leaves the door opened. The window remains closed. This scenario may include an occupant localized at bed level, waking up with alarm and escaping quickly. The travel delay is negligible in comparison with the pre-movement delay. For the calculation of fire effects, values considered are the average gas concentrations and temperatures at head level in the room between 0 min and 3 min 15 s (as the occupant position is not determined), then values in the corridor for the next minute, supposed to correspond to an escape along the corridor. Except for people with extremely high sensitivity to the effects of fire, any people who leave the room before 3 min 15 s after the beginning of a fire (or 2 min after closing the door and about 1 min after the activation of the alarm of the test room) do not suffer from deterioration of tenability conditions.

In occupancy scenario 2B –II, a first occupant escapes in the same conditions as in scenario 2B I and leave the door open. A second occupant does not evacuate and stands in the middle of the room. Tenability is calculated for this second occupant. Values considered for the calculation are the average gas concentration and temperatures at head level during the whole test, as the occupant position is not determined. In such a scenario, the first and main impact on remaining persons is the thermal effect of fire. It occurs after 4 min, with a tenability being quickly compromised for the whole population within the following 2 min (see Fig. 17(a and b)). Effects of asphyxiant and irritant gases appear around 6 min, when the tenability is already compromised for the whole population by thermal effects. Smoke opacity remains low under 1.50 m height (see Fig. 14) for the first 5 min, thus not compromising evacuation, even for unknown path.

4.4. Synthesis

The synthesis of results is presented in Table 7. For all the studied scenarios, the smoke alarm activates earlier than the time for significant effects of fire to occur. In the room studied, with a closed underventilated mattress fire, the tenability is firstly conditioned by irritants (NO due to the combustion of mattress foam), then the fire becomes underventilated and tenability is driven by asphyxiant gases (CO and HCN). In the well-ventilated scenario with door open, if flashover conditions are not reached, then untenable conditions are reached for the more sensitive members of the population, due to asphyxiant gases. When the initial fire is powerful enough to go to flashover, an early evacuation means no effects from fire to the evacuee. If evacuation is not performed, thermal effects condition tenability few minutes before flashover.

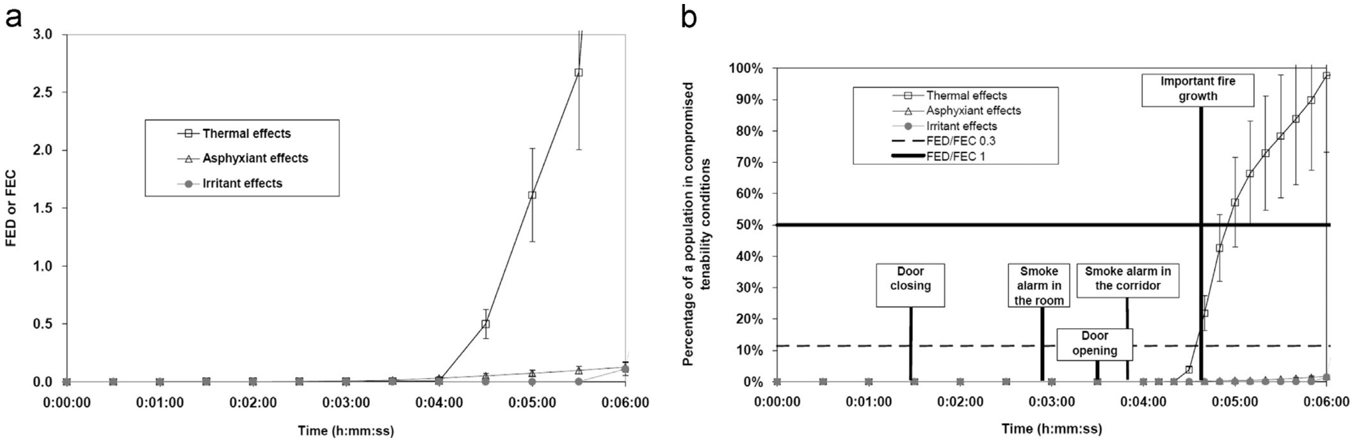

Fig. 17. Interpretation – Scenario 2B-II: (a) FED and FEC calculation at the room center and (b) percentage of the population in compromised tenability conditions.

Table 7
Summary of tenability results.

Scenario and fire type		Evacuation		Time to *FEC* or *FED*=0.3	Thermal effects	Toxic effects		First significant fire effect	Major fire effect reached
		First smoke alarm activation	Max ideal time requested to complete evacuation*		Max FED_{therm}	Asphyxiant Max FED_{tox}	Irritant Max *FEC*		
1C	Underventilated mattress fire, person sleeping	00:02:10 (In the room)	Not applicable (no evacuation)	00:03:30 (FEC due to NO)	0.38	3.08	0.64 (At 00:06:00)	Irritant (NO)	Asphyxiant (CO, HCN)
2A	Well ventilated wastepaper basket fire, self extinguishes	00:06:43 (In the room)	00:10:00 (In the room)	Not reached	0.04	0.12	0.03	Asphyxiant (CO, HCN)	
2B-I	Well ventilated wastepaper basket fire, growth to flashover	00:02:01 (In the room)	00:04:15 (00:03:15 In the room +00:01:00 in the corridor)	Not reached	< 0.02	< 0.02	< 0.02	None	
2B-II			Not relevant	00:04:00 (FED_{therm})	7.80 (At 00:06:00)	0.13 (At 00:06:00)	0.11 (At 00:06:00)	Thermal	

* Considering maximum time when *FED* or *FEC* < 0.01.

5. Conclusions

After a selection of scenarios to be reproduced, two series of real-scale fire tests have been performed on instrumented single bedroom apartments. During these tests, data have been recorded by a large number of sensors. They include thermocouples, heat fluxmeters, opacimeters and gas analyzers. These test series could be used as reference tests to validate fire-modeling tools.

The first series concerned a fire starting on a bed quilt, with a door kept closed during the whole test sequence. This scenario leads to an under-ventilated condition. Main results obtained from the first series are:

- Alarm is activated before any compromised tenability effect is reached in the room, which highlights the importance of dwelling smoke alarms.
- The fire is limited by ventilation in a few minutes. In this situation, tenability inside the room is driven by the toxic effect related to asphyxiant gases, and effect due to dioxygen decay. In the studied scenario, the thermal and irritant effects remain negligible in comparison.

The second series concerned a fire starting on a wastepaper basket, with door opened about 2 min 30 s after ignition. In this series, the conditions of flashover are reached if the initial fire is strong enough. Main results obtained from this second series are:

- Alarm is activated before any compromised tenability effect is reached in the room, which highlights the importance of dwelling smoke alarms.
- When the occupant evacuates the room quickly after the alarm activates, he is not affected by any significant impact due to fire effects.
- When the door remains open, fire may grow to flashover, depending on the initial fire source. In this situation, thermal effects drive tenability inside the room. Toxic effects (asphyxiant or irritant) appear inside the room only when thermal effects have already compromised tenability.

The results have demonstrated the applicability of ISO 13571 tenability calculation concepts to experimental results. On the basis of this assessment tool, results obtained demonstrate experimentally their extreme dependence to the particular conditions evolved during the tests: changes in the ignition sources and ventilation scenarios have proved completely different outcomes. In some cases, the fire toxicity may drive tenability, where in some others the thermal effects are predominant. Therefore, tenability assessment in fires has always to be scenario related; fire growth and effluents released are attached to materials and products involved in fire as well as ignition sequence or ventilation. Tenability calculation is in addition associated with a behavioral scenario and may not be a static value. Its expression as percentage of the population affected has proved its applicability.

The information provided in this publication regarding the interpretation of the test data – including the results in terms of percentage of the potentially affected population – are only valid in the context of the tests that were performed and the models extracted from ISO 13571. These elements shall not be transposed to another scenario nor generalized without justification of the relevance of this approach.

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