Fire Development in a Two-Bed Hospital Ward

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ABSTRACT

Increasingly there is a need for data on "real" fires, whether it be as an aid for fire engineering assessments or for testing mathematical models. This paper describes four large-scale fire experiments that were performed in a simulated two-bed hospital ward. Both smouldering and small flaming ignition sources were employed in the experiments. The smouldering stages of the fires did not produce a buoyant hot layer. The flaming stages of the fires produced similar fire growth curves irrespective of whether there had been a prolonged smouldering stage. A number of criteria for untenability have been compared.

KEYWORDS: Large-scale fire experiments, fire scenarios, hospital fires, furniture fires.

INTRODUCTION

Fires in hospitals are a cause for concern worldwide. Whilst there are many causes of hospital fires, those that lead to deaths often involve bedding [1–3].

Four large-scale fire experiments were performed on a simulated two-bed hospital ward. The purpose of the experiments was to gain an understanding of how typical contents behaved in the event of a hospital fire so that appropriate fire safety measures could be implemented. The focus of this paper is to study the development of the fires and determine how this information can be used in designing fire safety systems for hospitals.

Two different scenarios were explored – ignition of a fully made up hospital bed by a smouldering source and by a small flaming source. Two experiments were performed with the smouldering source and two with the flaming source.

DESIGN OF WARD

The simulated ward was designed to fit the maximum dimensions of the fire test facility. These dimensions (5 × 3.6 × 2.7 m high) are not unusual for a two-bed hospital ward [4]. The door size was 1.2 × 2 m high and opened under a 3 × 3 m hood which was part of an exhaust system capable of collecting all of the combustion products. This exhaust system conformed to the design described in ISO 9705 [5], the ISO room fire test.

The walls and ceiling of the ward were 16 mm painted gypsum plasterboard (glass-reinforced and paper-faced). The floor was 16 mm plasterboard overlaid with a vinyl floor covering (see later). The ward was fitted with window curtains, but there were no windows.

MATERIALS

A list of combustible materials involved in the experiments is contained in Table 1. The major fire load items are the two mattresses. In Experiment 1 the foam in the mattress where the fire was initiated was latex rubber foam; in Experiments 2 and 3 it was a non-fire-retarded polyurethane foam; in Experiment 4 it was a fire-retarded polyurethane foam. The foam in the front mattress was a non-fire-retarded polyurethane foam in all experiments. Most of the materials were used items obtained from a hospital and therefore varied slightly from experiment to experiment.

Despite information to the contrary, it was determined in preliminary experiments that none of the fabrics in the bedding, curtains or privacy screens were fire retarded.

INSTRUMENTATION

The instrumentation used in the experiments is listed in Table 2 and the locations of sampling points are shown in Figure 1. The ward was instrumented to measure rate of heat release, rate of smoke production, carbon monoxide levels in the ward, radiation and temperature, and it was fitted with smoke and thermal detectors. An air-pressurised dry sprinkler was used in one experiment. The sprinkler head was a fast-response type with an RTI of 42.5 $s^{0.5}/m^{0.5}$. The time of activation of the sprinkler was determined by monitoring the air pressure in the sprinkler pipe.

IGNITION SOURCES

The smouldering ignition source was a glowing electrical coil designed to represent a lighted cigarette [6]. It was applied for 20 minutes.

The flaming ignition source was a small gas flame controlled to be the size of a match flame. It is flaming source 1 described in BS 5852 [7]. It was applied for 20 seconds.

TABLE 1. Typical fire load for hospital ward experiments

Item and number	Combustible components	Mass of combustibles per item (kg)
Floor covering	Vinyl, 2.3 mm, fixed	46.8
Beds (2)	• Mattress; foam, covered with cotton ticking and vinyl	*
	• Sheets (2), polyester/cotton	0.6 each
	• Pillow	0.7
	• Blanket; open weave cotton	0.8
	Bed cover; polyester/cotton	0.5
Window curtains (3)	Open net polyester/cotton	5.8
Privacy screens (4)	Cotton	5.8
Wastepaper basket	• Container; polypropylene	1.0
	• Contents; paper towel	0.6
Bedside tables (2)	Particleboard top	11.5
Bedside chairs (2)	Cushions of polyurethane foam vinyl-coated cotton cover	3.5
Bed table (1)	Melamine-faced particleboard top	6.4
Visitor's chairs (5),	Polypropylene shell, stacked	3.1
Stuffed ornaments (5)		1.5
Television set (1)	Wood case with plastic components	5.5/2.6
Newspaper (0.5)	A1-size sheets, in 4 folded sections	1.7

* Rear bed mattresses: Experiment 1 – latex rubber foam (ca 20 kg); Experiments 2 and 3 – polyurethane foam (10 kg); Experiment 4 – fire-retarded polyurethane foam (10 kg). Front bed mattress: All experiments; polyurethane foam (10 kg).

TABLE 2. Instrumentation used in experiments

Instrumentation	Experiments
Heat release; instrumentation as in ISO 9705	All
Ceiling temperatures, 5 locations 100 mm below ceiling	All
Temperatures, 100 mm below top of door frame	All
Temperature, 1.9 m	All
Temperature, 1 m (at pillow)	All*
Carbon monoxide, 1.9 m	All
Carbon monoxide, 1 m (at pillow)	2, 3, 4
Smoke detector, ionisation, 2 locations	2, 3, 4
Smoke detector, photoelectric, 2 locations	All
Thermal detectors, 2 locations	2, 3, 4
Mechanical ventilation	3
Sprinkler head	4

* Data from Experiments 2 & 3 showed evidence of shielding of thermocouples by debris.

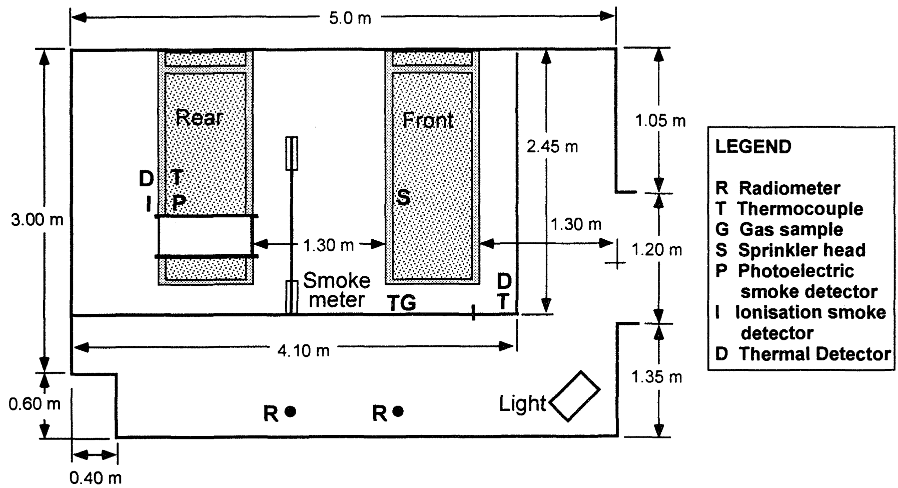


FIGURE 1. Location of instrumentation and sampling points

THE EXPERIMENTS

All experiments were initiated on the rear bed, which is further from the door.

Experiment 1, smouldering ignition of bed with latex rubber foam mattress

A smouldering fire was initiated in the rear bed by placing the igniter between the pillow and the made up but disturbed bed. The bed was disturbed by pulling one corner of the covers (top sheet, blanket and bed cover) back, exposing most of the pillow and a section of bottom sheet. A vinyl mattress cover had deliberately been damaged in the vicinity of the coil igniter, in a manner similar to damage observed in covers on mattresses in use in the hospital. As a result, there was only the crumpled sheet and cotton ticking between the igniter and the latex rubber foam mattress. There was no mechanical ventilation, and all natural ventilation was via the one open door.

Experiment 2, smouldering ignition of bed with polyurethane foam mattress

This experiment was similar to Experiment 1 and had similar instrumentation but with extra detectors. These were ionisation smoke detectors and thermal detectors. In this experiment, the mattress on which the smouldering fire was started had a core of polyurethane foam instead of the rubber latex foam of the mattress in the Experiment 1. Once again the vinyl mattress cover was damaged in the vicinity of the ignition point.

Experiment 3, flaming ignition of bed with polyurethane foam mattress

In this experiment, the flaming source was used and the mattress on which the fire was started had polyurethane foam, as in Experiment 2. The sheet in the vicinity of the pillow was crumpled to give raised sections that were amenable to ignition by the small flame source. As usual one corner of the covers had been turned down. Both ionisation and photoelectric smoke detectors were installed. A mechanical ventilation system was installed. The ventilation system was set to introduce air at the ceiling at a rate of 6 room changes per hour (80 L/s). When the first detector (smoke or thermal) activated, the ventilation system was manually switched to exhaust at 80 L/s.

Experiment 4, flaming ignition of bed with fire-retarded polyurethane foam mattress
This was a flaming ignition experiment similar to Experiment 3, but without the mechanical ventilation. The mattress on which the fire was started had a core of fire-retarded polyurethane foam. An air-pressurised dry sprinkler was included along with the smoke detectors.

RESULTS AND OBSERVATIONS

Logs of events and graphs of heat release versus time; smoke production versus time; carbon monoxide production versus time; radiation at floor level versus time; and temperature versus time are presented for Experiments 2 to 4.

Experiment 1, smouldering ignition of bed with latex rubber foam mattress
As soon as the igniter was applied, a wisp of smoke visible to observers outside the ward commenced rising to the ceiling. There was insufficient smoke produced to activate the nearest smoke detector for almost 9 minutes. The front smoke detector did not activate until almost 15 minutes. After the igniter was removed at 20 minutes the latex rubber foam mattress continued to smoulder at a slowly increasing rate for some hours. No transition to flaming occurred, even though at a later stage a hole was poked through the smouldering mattress in an attempt to encourage the transition from smouldering to flaming combustion. Data graphs and logs are not included in this paper for Experiment 1.

Experiment 2, smouldering ignition of bed with polyurethane foam mattress
The smoke built up far more rapidly in this experiment (Table 3; Figure 2), apparently due to the greater involvement of the polyurethane foam in the mattress compared with the involvement of the rubber latex foam in the previous experiment. The rear smoke detector activated at 1.0

TABLE 3. Log of events for Experiment 2

Time (min:sec)	Event
00:00	Igniter applied to bed
01:35	Rear smoke detector alarms
20:00	Igniter removed from bed
39:29	Flaming drips fall from bed
39:40	Flames visible on bed
41:30	Thermal detector alarms
43:22	Privacy screen at side of bed 1 falls burning to floor
43:25	Privacy screen at end of bed 1 falls burning to floor
43:29	Privacy screen at end of bed 2 falls to floor
43:35	Flames out door
43:42	Paper target alight
43:42	Upper layer temperature at centre greater than 600°C
43:47	Fire choking due to lack of oxygen
43:52	Radiation at floor greater than 20 kW/m^2
43:52	Upper layer temperature at door greater than 600°C
44:34	Experiment terminated

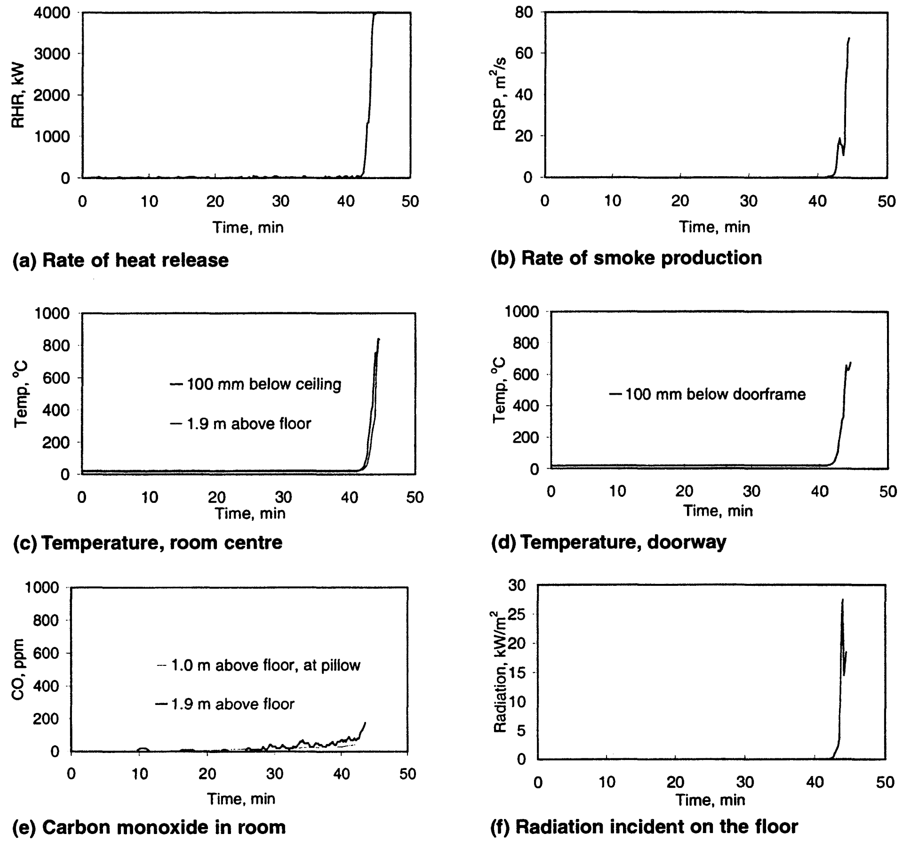


FIGURE 2. Data for Experiment 2

minutes, although once again smoke was clearly visible to observers outside the ward almost from the start of the experiment. The igniter was removed at 20 minutes and the bed continued to smoulder strongly.

At just after 39 minutes the first flames were observed as flaming drips fell from the mattress to the floor. Such flaming drips are often associated with the burning of flexible polyurethane foam. Their appearance indicated that the mattress had smouldered through its entire thickness. The improved air access allowed the growth of flaming combustion and the fire began to grow rapidly. Flames became visible on the top of the bed and within 2 minutes the thermal detector activated.

The mattress, preheated by the smouldering, now commenced to burn rapidly. Just 2 minutes after the thermal detector activated, but 42 minutes after the rear smoke detector activated, the majority of combustibles in the room were involved in the fire and flames were lapping out the door.

Experiment 3, flaming ignition of bed with polyurethane foam mattress
The small flame was applied to the bunched bottom sheet in the vicinity of the pillow and the sheet began burning readily (Table 4; Figure 3). There was sufficient smoke for the nearer ionisation smoke detector to activate within 40 seconds.

When the rear smoke detector activated, the ventilation system was switched manually from introducing air to exhausting combustion products. At this time the fire was confined to the sheet on the rear bed. The fire continued to grow and the rear photoelectric smoke detector activated 41 seconds after the ventilation system was switched to exhaust. Thirty-four seconds later both the front smoke detectors (ionisation and photoelectric) activated. At this point it was still mainly bedding that was involved in the fire, the polyurethane foam in the mattress only igniting 10 seconds after the activation of these two smoke detectors, and 1.5 minutes after the rear smoke detector had activated.

Once the polyurethane foam was alight the fire began to grow more rapidly. The rear and front thermal detectors activated about 1 minute and 2 minutes respectively after the polyurethane foam had begun to burn. The fire continued to grow and involve all the combustibles in the ward, with flames licking out of the door about 6 minutes after the rear smoke detector activated. The exhaust system was not of sufficient capacity to noticeably influence the rate of accumulation of combustion products.

TABLE 4. Log of events for Experiments 3 and 4

Event	Exp. 3 Time (min:sec)	Exp. 4 Time (min:sec)
Standard flame source applied to bed	00:00	00:00
Flame source removed from bed; sheet burning	00:20	00:20
Rear ionisation smoke detector alarms	00:40	00:29
Mechanical ventilation switched from inwards to outwards	00:45	00:35
Rear photoelectric smoke detector alarms	01:26	01:13
Front ionisation smoke detector alarms	02:00	01:42
Front photoelectric smoke detector alarms	02:00	01:48
Polyurethane foam alight	02:10	02:10
Rear thermal detector alarms	03:24	02:24
Front thermal detector alarms	04:23	03:30
Sprinkler head activates	None	05:00
Upper layer temperature at centre greater than 600°C	06:40	09:08
Paper target alight	06:49	—
Radiation at floor reaches 17.7 kW/m^2	06:50	09:18
Upper layer temperature at door greater than 600°C	06:50	09:18
Flames out door	06:50	09:25
Experiment terminated	06:55	09:26

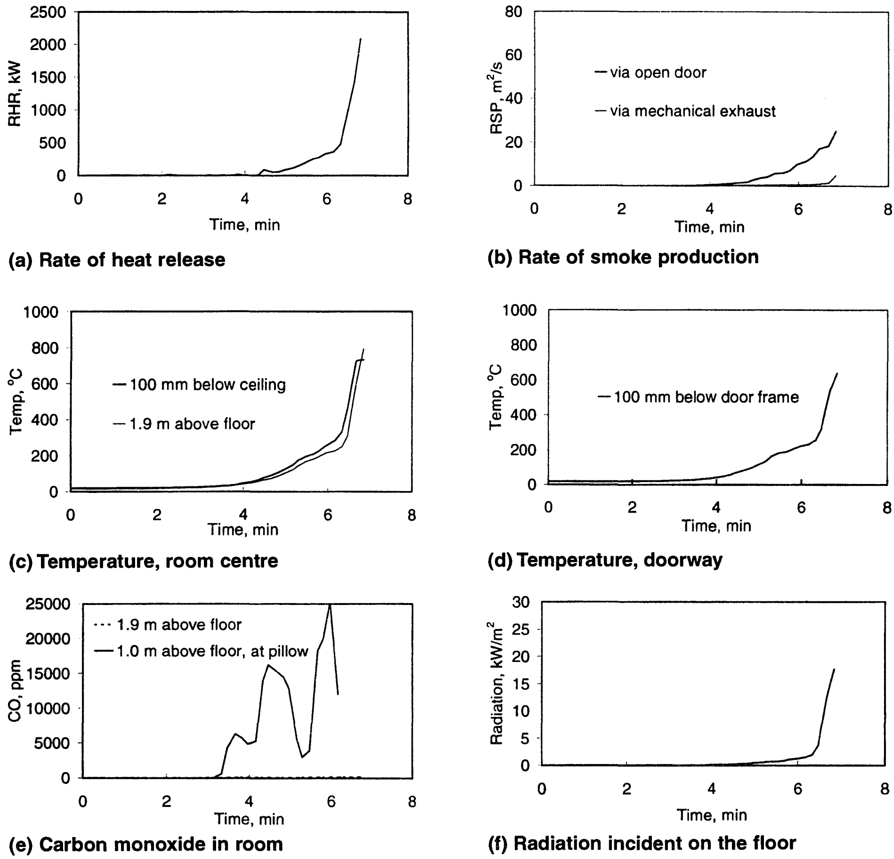


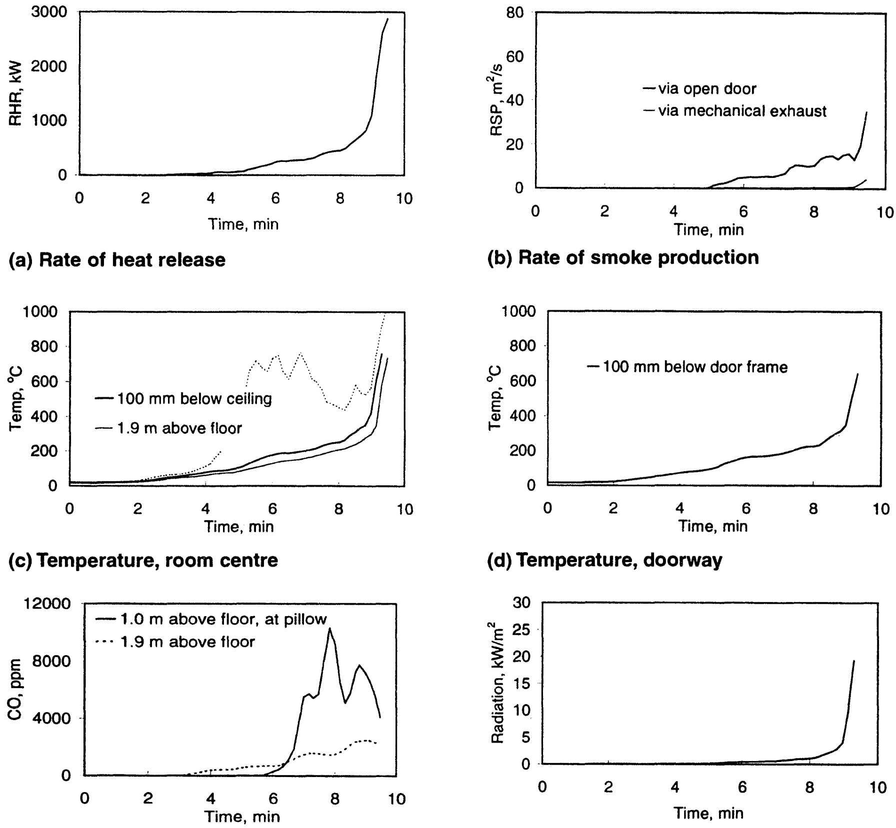
FIGURE 3. Data for Experiment 3

Experiment 4, flaming ignition of bed with fire-retarded polyurethane foam mattress

As in the previous experiment the small flame was applied to the bunched bottom sheet in the vicinity of the pillow and the sheet began burning readily (Table 4; Figure 4).

This time the rear ionisation smoke detector activated within 30 seconds. The rear photoelectric smoke detector activated 44 seconds later. At the times the first two smoke detectors activated the fire was confined to the bedding, as in the previous experiment. The mattress only ignited over 1.5 minutes after the rear smoke detector activated.

The rear and front thermal detectors activated 14 seconds and 80 seconds respectively after the mattress began to burn. The sprinkler head activated almost 3 minutes after the mattress began to burn. At this stage the fire was only about 70 kW, and would have been readily controlled by an active sprinkler.



(a) Rate of heat release

(b) Rate of smoke production

(c) Temperature, room centre

(d) Temperature, doorway

(e) Carbon monoxide in room

(f) Radiation incident on the floor

FIGURE 4. Data for Experiment 4

As the sprinkler contained no water, the fire continued to grow, although at a similar rate to the previous experiment. There was insufficient difference in growth rates to distinguish between the fire-retarded polyurethane foam and the non-fire-retarded polyurethane. Flames were licking out the door less than 9 minutes after the rear smoke detector activated.

DISCUSSION

Both carbon monoxide and temperature were monitored inside the ward at 1.9 m above floor level ("head height") near the centre of the ward and, in the smouldering experiments, just above pillow height on the bed where the fires were initiated. This allowed the time at which untenable conditions occurred to be monitored. A number of criteria for untenability were compared. These included the toxic dose (carbon monoxide only) of 4.5%.min. [8] and thermal dose of 4000 K^2.s [9] (Table 5).

TABLE 5. Time to untenable conditions inside ward

Tenability criteria	Time to untenable conditions (minutes)			
	Exp. 1	Exp. 2	Exp. 3	Exp. 4
Toxic (CO) @ 1.9 m: Dose = 4.5%.min.	269	NA	NA	NA
Resting (COHb = 40%)	NA	NA	NA	NA
Light work (COHb = 30%)	262	NA	NA	8.5
Heavy work (COHb = 20%)	190	NA	NA	6.3
Thermal @ 1.9 m: Dose = 4000 K^2.s	50	42	3.1	2.8
Pain	NA	43	2.8	5
Incapacitation	NA	43.5	4.5	6
Hot layer at 1.9 m	—	—	3.5	2.5
Toxic (CO) @ 1 m (at pillow): Dose = 4.5%.min.	—	NA	NA	NA
Thermal @ 1 m (at pillow): Dose = 4000 K^2.s	64	43	4.8	2.3

NA = not achieved.

In Experiments 1 and 2, which commenced as smouldering fires, none of the untenability criteria were achieved until 41 minutes and 40 minutes respectively after the first smoke detectors activated. In Experiments 3 and 4, which commenced as flaming fires, the first criteria for untenability were attained 2.1 minutes and 1.8 minutes after the first smoke detector activated. In Experiments 2, 3 and 4 the first criteria for untenability were attained prior to flashover, though the times varied, being 1.5, 4 and 7.2 minutes respectively. In Experiment 4, the sprinkler head did not operate until 2.7 minutes after the first criterion for untenable conditions was attained.

For fire engineering purposes the growth stage of a fire is often represented by the equation:

$$\dot{Q} = \alpha t^2$$

where $\dot{Q}$ is the rate of heat release (MW); t is the time from the effective ignition time (s); and α is the fire growth coefficient (MW/s2).

The growth stage of these fires was taken to be the curve leading up to flashover, with the effective ignition time being determined by extrapolation. The estimated values of α for Experiments 2, 3 and 4 are 4×10^{-5}, 9.5×10^{-5} and 5×10^{-5} MW/s^2 respectively. According to the fire categories presented in NFPA 72E [10], the first fire almost meets the criterion for 'fast' (4.44×10^{-5} MW/s^2) while the next two fires exceed the criterion for "fast" but do not meet the criterion for "ultrafast" (17.7×10^{-5} MW/s^2). The value for the fire-retarded polyurethane (Experiment 4) falls between the values for the non-fire-retarded polyurethanes.

Experiments have shown that fire growth is also a function of the room size [11]. In larger rooms the value of α might be lower. This experimental value of α may be conservative for larger wards.

Hot layer heights have been determined where possible (Table 6). The smouldering stages of the fires (Experiments 1 and 2) did not produce a buoyant hot layer. These results will be undergoing further analysis and comparison with model predictions.

TABLE 6. Time for hot layer to descend

Height above floor level (m)	Time for hot layer to reach level (minutes)			
	Exp. 1	Exp. 2	Exp. 3	Exp. 4
1.9	I	I	3.5	2.5
1.5	I	I	4	3
1.0	I	42.5	6.3	5.7
0.8	I	43	6.8	7.3
0.5	I	—	—	9
0.2	I	43.7	7.1	9.5

I = Indeterminate.

CONCLUSIONS

These experiments have given valuable insight into the development of bedding fires in hospitals. By performing the experiments in a facility capable of measuring total heat release, data that can be used for calibrating fire growth models was obtained. The smoke detectors operated well before untenable conditions were achieved in the fires that had a smouldering stage, but there was far less time available for evacuation in the fires that started on beds from a flaming source. Some criteria for untenability had been attained prior to the sprinkler head activating, although at this stage the fire was only small. In all the experiments where flaming combustion of the bedding occurred, the fires went to flashover, although this may not be the case in larger wards. In all experiments where flashover occurred, some criteria for untenable conditions were attained prior to flashover. There was no discernible difference in the fire behaviour of the particular fire-retarded and non-fire-retarded mattresses used.

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