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BURNING CHARACTERISTICS OF POTENTIAL IGNITION SOURCES OF ROOM FIRES

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ABSTRACT

A total of 18 different experiments on 5 different types of potential ignition sources of room fires are described. The ignition sources studied comprised television receivers, paper baskets, curtains, chairs, and Christmas trees. In the experiments the rate of heat release, rate of smoke production, intensity of thermal radiation, and gas temperatures were measured.

The ignition sources can be divided into three groups according to the measured maximum rate of heat release: 1) paper baskets, 2) television receivers, curtains, chairs, and 3) Christmas trees. The most intense fire of a single ignition source was found in one of the Christmas trees: the maximum rate of heat release was about 650 kW and the maximum temperature above the burning tree as high as 1300 °C.

PREFACE

This research was carried out in the Fire Technology Laboratory of the Technical Research Centre of Finland by Dr. Antti Ahonen, Dr. Matti Kokkala, and Mr. Henry Weckman. The work was financed by the Rescue Department of the Ministry of Interior (Finland) and by the Fire Technology Laboratory.

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CONTENTS

1 INTRODUCTION

The first minutes of a fire are the most decisive for the success in extinction or rescue operations, because it is still possible to get the fire under control. The rate of heat release at the primary ignition source is the most important single variable as far as the spread of a developing fire is concerned.

In addition to the rate of heat release, the prediction of the fire growth and of the possiblity of saving human lives requires knowledge of the intensity of thermal radiation and gas temperatures in the surroundings. The success of rescue operations also depends on the rate of smoke production.

The goal of this study was to obtain quantitative data related to some typical ignition sources of apartment fires. We did not aim at any complete overview of potential ignition sources, but wanted to get of-the-order-of - estimates which could be used in the future research projects on fire growth. We tried to find answers to the question: "How does an ignited fire grow within the ignition source?" We did not even try to study the causes of ignition.

In Chapter 2 of this report we first describe the experimental methods. In Chapters 3 and 4 we then describe the burned items, the methods of ignition, and the results of the measurements. The common features of the results are discussed in Chapter 5, and finally in some conclusions are drawn in Chapter 6.

2 EXPERIMENTAL

Figure 1 shows schematically the experimental arrangement. The items were burned in the rear corner of the room originally built for full-scale fire tests /1, 2, 3/. The dimensions of the room are: length 3.6 m, width 2.4 m, and height 2.4 m. Clean air and the combustion gases flow through 2.0 m high and 0.8 m wide door in the middle of the front wall.

In normal room fire tests there is a gas burner in the rear corner as shown in Fig. 1. In the present experiments the burner was removed and the items to be burned were put to the corner corresponding to their normal use in apartments.

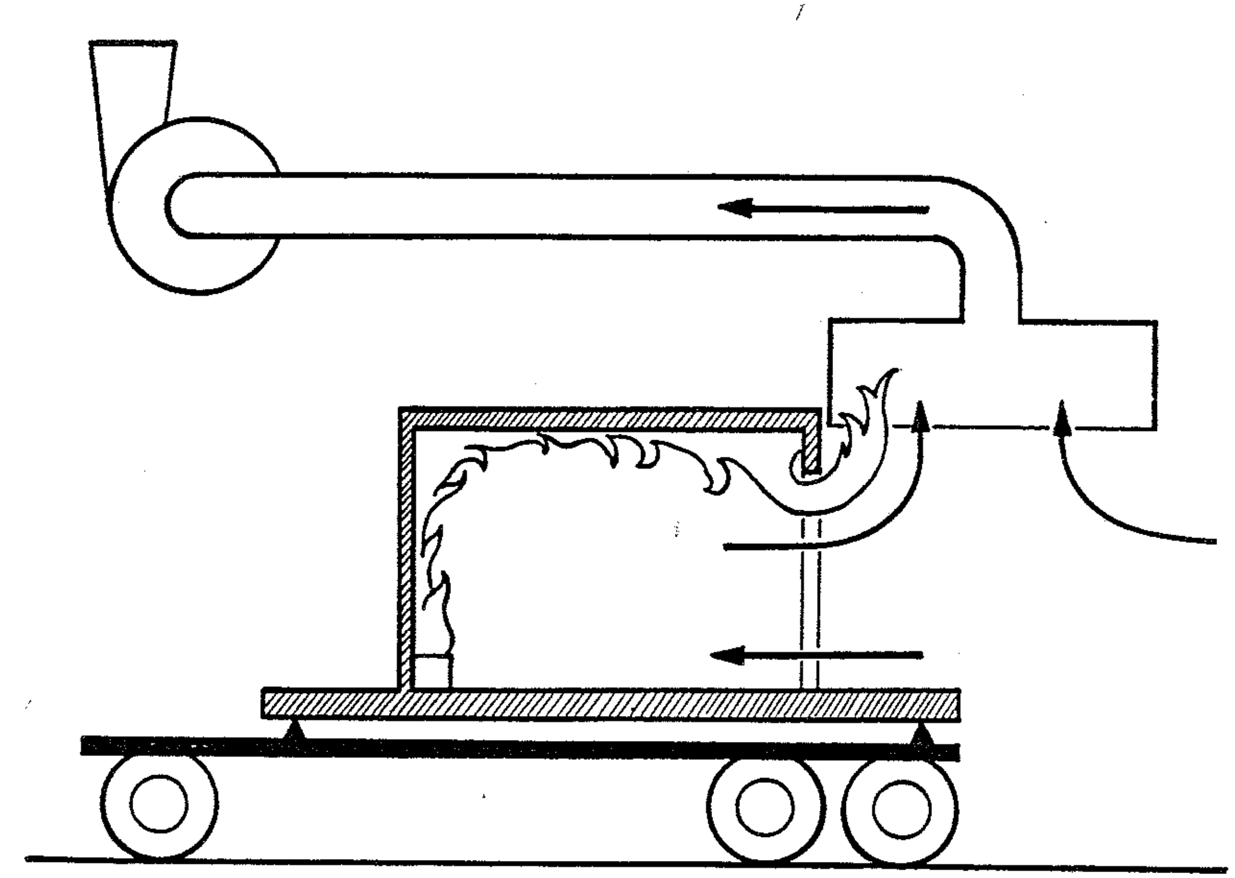

Fig. 1. A schematic picture of the fire test room and the gas collection system at the Fire Technology Laboratory of the Technical Research Centre of Finland.

The gas temperatures 10±1 cm below the ceiling were measured right above the burning object and at the centre of the ceiling. For thermometry, suction pyrometers /3/ were used. The pyrometer right above the burning object measures the maximum temperature of the gases touching the ceiling. The pyrometer at the centre of the ceiling measures roughly the average temperature of the upper gas layer.

The total heat flux was measured at the centre of the floor. The surface of the gauge was about 1 cm above the surface of the floor. Since cool air flows over the gauge towards the fire, the measured heat flux is mainly due to the thermal radiation.

The rates of heat release and smoke production were measured using the gas collection system shown in Fig. 1. In front of and above the door there is a hood with a cross-section of 3 m x 3 m and a height of 1.2 m. The suction duct leaves the hood at its centre. The diameter of the duct is 0.5 m. The maximum flow through the duct is about 3 m^3/s of NTP-air.

In the straight part of the suction duct there is a standard orifice plate /4/. By means of the orifice plate and five thermocouples 1.5 m down-stream of the plate both the real volumetric flow and the volumetric flow reduced to normal conditions can be measured.

The measurement of the rate of heat release is based on oxygen consumption calorimetry /5,6/. Burning reactions on a microscopic scale are usually oxidization reactions of carbon-carbon and carbon-hydrogen bonds. This fact makes it plausible that in a burning reaction a constant amount of heat is released per constant amount of oxygen consumed, independent of the fuel. Experimentally it has been observed that the amount of energy released E per unit volume of oxygen at 20°C is 17.3 MJ/ m^3. For the majority of

organic compounds E is constant within ±5 % /5/. The rate of heat release is now determined indirectly by measuring the rate of oxygen consumption. This is accomplished by continuously measuring the oxygen concentration and the flow rate of the gas flowing in the collecting duct.

If we know the mass flow in the duct, we also know, how much oxygen would flow, if there were no fire at all. When we now measure the oxygen concentration, we also know, how much oxygen is missing. As practically all the combustion gases are collected into the hood and the duct, we know that all the missing oxygen is consumed in the fire. The amount of diluting air does not affect the results.

A mathematical expression for the rate of heat release is /7,8/.

$$\dot{Q} = E_m \dot{n}_m (X_o - X_m)/ (1 + KX_o), \qquad (1)$$

where E_m is the energy released per mole of oxygen consumed, $\dot{n}_m$ is the molar flow of the collected gas, X_o is the concentration of oxygen in clean and dry air (20.9 %) X_m is the measured concentration of oxygen in the collected gas and K is a constant depending on the materials participating in the reaction ($0 \leq K \leq 1$). Even the constant K were not known, the systematic error would be less than ±15 %. In the experiments of this work we used K = 0.8, which is close to the material constant of cellulose or wood..

In the gas collecting duct there is an optical densitometer measuring the light obscuration within the wavelength range of visible light. The light source and the detector are on the same side of the duct. The light beam is reflected from a mirror located on the opposite side of the channel. Thus the beam traverses a distance of 1 m, i.e., twice the diameter of the duct.

The intensity of the light is reduced exponentially

$$I = I_o \exp(-\sigma n l), \tag{2}$$

where I_o is the intensity of the beam in clean air, l is the distance traversed by the light, n is the number density of the smoke particles and σ is the average total optical cross-section of the particles, which for big particles equals their cross-sectional area.

The optical smoke density is often given in units of dB/m by the optical absorbance index

$$m = (10/l) \lg (I_o/I). \tag{3}$$

The rate of smoke production S is now defined as the product of the absorption index m and the volumetric flow $\dot{V}$,

$$S = m \dot{V}. \tag{4}$$

From equation (2), (3), and (4) we easily obtain

$$S = 4.34 \sigma dN/dt, \tag{5}$$

where dN/dt is the rate of particle production, i.e., the number of particles produced per unit time. Also in this connection it is worth noting that the amount of diluting air does not have an effect on the measured rate of smoke production.

3 THE BURNED OBJECTS AND THE METHODS OF IGNITION

In the experiments the burning characteristics of three television sets, four paper baskets, four curtains, three chairs and three Christmas trees were determined.

3.1 Television sets

All the three black and white TV receivers were manufactured in the early 1960's. Owing to the massive frame most of the combustible material was wood. The back cover and part of the components contained plastics. The TV sets given in Table 1 were chosen, because they contained a lot of ignitable materials and because during the twenty years of use a lot of dust had been accumulating on the components.

Table 1. Televisions.

Expt. no.	Type of the receiver	Total mass
1	Luxor Carina, 24"	32.7 kg
2	Finlux Teletop, 24"	27.2 "
3	Luxor Continental, 26"	39.8 "

The TV sets were ignited with 100 ml of isopropanol in a shallow tray with a liquid surface area of 80 cm^2. The tray was located in the left rear corner inside the receiver, and it was ignited using a 1 m long cotton thread wetted in isopropanol. The free burning of the isopropanol took approximately 10 min. The rate of heat release of the alcohol tray was thus about 4 kW, i.e., vanishingly small compared with the rate of heat release of a burning receiver during its full involvement.

3.2 Paper baskets

All the paper baskets were made of polyethene (see Table 2). The volume was chosen to be 14 l, which is a very common size of a paper basket at home or in an office. In Experiments 4 and 5 the wall of the basket was tight, whereas in Experiments 6 and 7 the wall was a net consisting of 5 mm x 3 mm plastic strips. In Experiments 4 and 6 the basket was filled with strips taken from a paper shredder, and in Experiments 5 and 7 with milk cans made of parafinized cardboard.

Table 2. Paper baskets.

Expt. no.	Basket		Fillings	
	Material	Mass	Type	Mass
4	polyethene	0.63 kg	shredded paper	0.20 kg
5	"	"	milk cans	0.41 "
6	"	0.53 kg	shredded paper	0.20 "
7	"	"	milk cans	0.40 "

In Experiments 4, 5, and 6 the paper was ignited with a 20 cm long cotton wire wetted in isopropanol, where as in Experiment 7 there was 10 ml of isopropanol on a tray with a free surface area of 20 cm^2. Even in the latter case the heat release rate of the alcohol was only of the order of 1 kW.

3.3 Curtains

In the experiments with curtains two different materials were used. In Experiments 8 and 9 the drapery was of cotton velvet with a density of 0.31 kg/m^2, whereas in Experiments 10 and 11 the material consisted of cotton (39 %), polyester (16 %), and polyacrylic (45 %). The acryl-polyester-cotton drapery, as the material is also called, had a density of 0.23 kg/m^2. The cotton velvet has earlier been ranked as "normally ignitable", whereas the acryl-polyester-cotton is "easily ignitable" /9/. The properties of the curtains are summarized in Table 3.

Table 3. Curtains.

Expt. no.	Name/Manufacturer	Material	Square mass	Total mass
8	Serenadi/ Sellgren	cotton velvet	0.31 kg/m^2	1.88 kg
9	"	"	"	1.87 "
10	Regina II/ Finlayson	45 % PC, 16 % PE, 39 % CO	0.23 kg/m^2	1.43 "
11	"	"	"	1.43 "

In each experiment there were two curtains of standard width hanging from a rod at a distance of 50 mm from the ceiling and 100 mm from the wall. The rod was inserted into a welt sewn to the upper end of the curtain. The total vertical length of the piece of cloth was 2.32 m. The lower end of the cloth was from 50 to 100 mm above the floor. The curtains had a nominal width of 1.24 m and were folded to half width. The curtains on the back and side walls were touching slightly at the corner.

The curtains were ignited with 5 ml of isopropanol poured on a 20 cm^2 tray. The tray was put under the curtains at the corner in order to get both pieces of cloth to ignite at the same moment. The isopropanol was ignited with an electric spark.

As the folds in the cloth may have a significant effect on the burning rate, two identical tests were performed with both materials.

3.4 Chairs

Of the four chairs, the data of which are given in Table 4, only the last one was "commercially available". For Experiments 12 and 13 a small chair was built according to the British standard BS 5852 /10/. The dimensions of the pillows of both the seat and the back were 500 mm x 500 mm x 75 mm. The density of the polyurethane foam in the seat was about 35 kg/m^3 and that of the back about 20 kg/m^3. The 0.43 kg/m^2 covering of the pillows contained 52 % linen and 48 % cotton.

Table 4. Chairs.

Expt. no.	Model	Pillow		Covering		Total mass
		Material	Mass	Material	Mass	
12	BS 5852	PUR foam	0.94 kg	linen/ cotton	0.43 kg	
13	"	"	0.95 "	"	0.41 "	
14	doubled BS	"	1.90 "	"	0.87 "	
15	arm chair					25.8 kg

The chairs were standing on a support lifting the upper surface of the seat to 0.4 m above the floor. In Experiment 12 two methenamine pills at the junction of the seat and the back were used as the ignition source. In Experiment 13 only one pill was used.

For Experiment 14 a sofa was set up using two adjacent BS-chairs. The pillows and the coverings were the same as in Experiments 12 and 13. The sofa was ignited using two methenamine pills, one at the junction of each pair of pillows.

The arm-chair of Experiment 15 was made of combustible materials, mainly of wood, excluding the springs under the seat and the few nails used in the joints. We first tried to ignite the chair with methenamine pills. When the smouldering fire had continued for 12 min, the fire was enhanced by throwing 15 ml of heptane on the smouldering area. Even this was not enough to actually ignite the chair. Thus, after 26 minutes, a 80 cm^2 tray filled with 100 ml of isopropanol was ignited under the seat finally causing a full involvement of the chair.

3.5 Christmas trees

Spruce (Picea excelsa) is a traditional Christmas tree in Finland. The live candles on the branches may cause a severe fire, as unfortunately just too often has happened. The trees in the experiments were of the normal size, i.e., the top barely touching the ceiling. The trees were conditioned in different ways as shown in Table 5.

Table 5. Christmas trees.

Expt. no.	Mass	Conditioning		
		in forest	in the hall (+15 °C)	in the room (+25 °C)
16	6.5 kg	14 d	2 d	0 d
17	7.0 "	"	2 "	3 "
18	7.4 "	"	5 "	1 "

The trees were ignited using a 80 cm^2 isopropanol tray standing on the floor under the undermost branches. In Experiment 16 there was 300 ml of isopropanol in the ignition tray, whereas in the other two experiments 200 ml of isopropanol was used. The rate of heat release of the ignition source was thus only a few kilowatts.

4 EXPERIMENTAL RESULTS

Rate of heat release, rate of smoke production, gas temperature at the ceiling and the intensity of thermal radiation towards the centre of the floor were measured continuously in all the experiments. The results of the experiments and the visual observations during the experiments are discussed in the following chapters.

4.1 Television sets

The measured rate of heat release, rate of smoke production, intensity of thermal radiation, and gas temperatures are shown in Figs. 2 to 5, respectively.

In Expt. 1 the rear cover of the TV started to burn almost immediately after the ignition of the isopropanol pool. The intensity of the fire started to increase considerably about 1 min after the ignition.

The maximum value of the rate of heat release, $\dot{Q}_{max}$ = 230 kW, was reached after 4 min. The rate of heat release was more than 100 kW for approximately 10 min. Still after half an hour, the rate of heat release was about 20 kW.

The rate of smoke production, S, clearly correlates with the rate of heat release, $\dot{Q}$. The maximum of S ≈ 22 (dB/m) m^3/s was reached 3.5 min after ignition. The total amount of smoke produced integrated over the whole length of the experiment was S_{tot} ≈ 6700 (dB/m) m^3.

The intensity of the thermal radiation ϕ at the centre of the floor was not very high at any moment. However, it stayed between 0.10 an 0.15 W/cm^2 for 8 min. The period of the maximum heat release rate cannot be resolved from the measured values of the intensity of the thermal

radiation, because for a long time at the beginning of the experiment, i.e., at the most intense phase of the fire, the back of the TV was in flames, and the front acted as a radiation shield.

The maximum of the gas temperature right above the burning TV-set was almost 500°C. At the midpoint of the ceiling the maximum temperature was about 300°C. Above the receiver the temperature remained above 250°C for about 10 min, and at the midpoint of the ceiling for about 7 min.

The total amount of energy released was 150 MJ corresponding to an effective heat of combustion of about 15 MJ/kg.

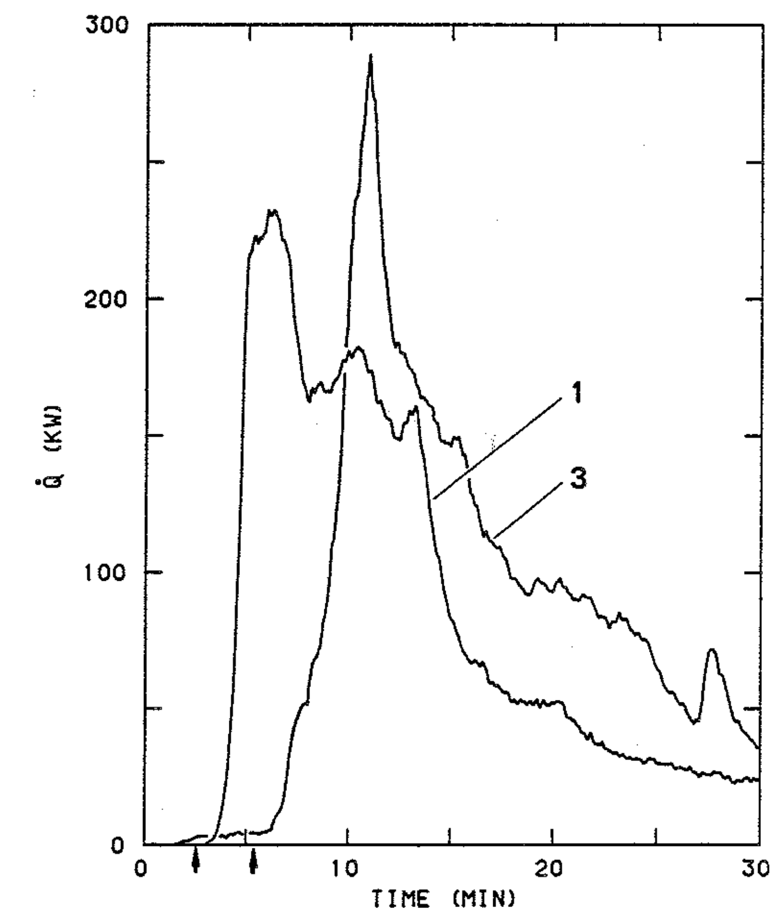

Fig. 2. Rate of heat release as a function of time in Expts

In Expt. 2 the amount of combustible materials was only about half of that of the TV receiver in Expt. 1. The difference can be clearly seen in all the results. Qualitatively the fire spread was similar to that in Expt. 1. The time dependence of the burning was quite similar in both cases, but the absolute values of the measured quantities differed considerably.

The maximum rate of heat release was 120 kW, and the maximum rate of smoke production 7.2 (dB/m) m^3/s. The maximum the intensity of thermal radiation was only one fifth of that in Expt. 1, i.e., $\phi_{max} \approx 0.03$ W/cm^2.

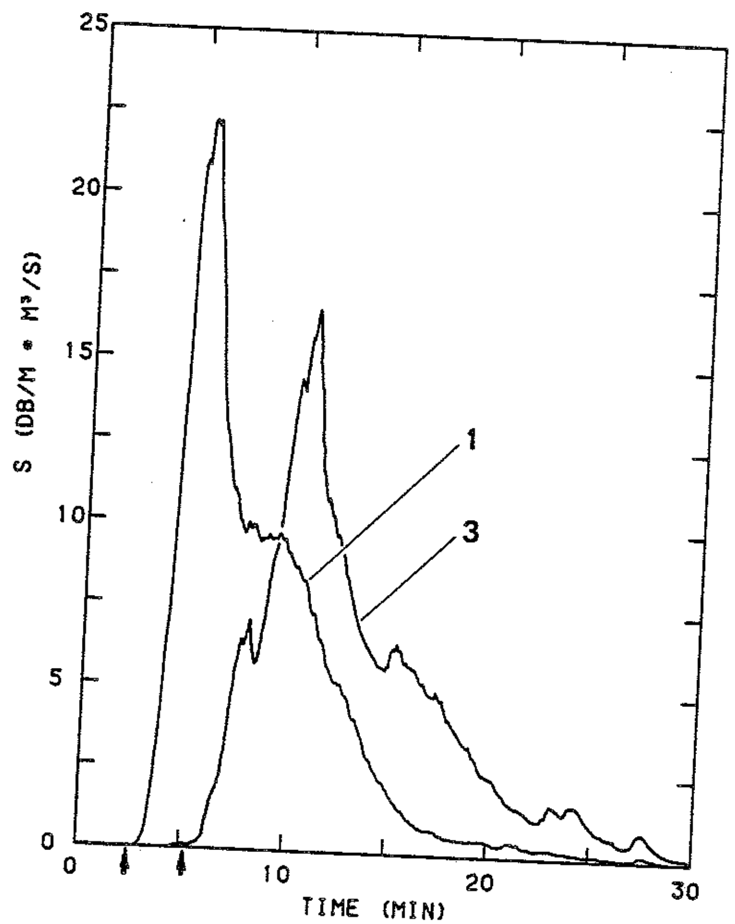

Fig. 3. Rate of smoke production as a function of time in Expts 1 and 3 on TV receivers. The moments of ignition are shown by the arrows on the time-axis.

At the ceiling right above the burning TV the gas temperature reached a maximum of 290°C, and it remained above 250°C for 3 min. At the midpoint of the ceiling the maximum gas temperature was only 180°C.

The TV receiver of Expt. 3 burned in the same way as the one in Expt. 1, excluding the short period of very intense fire due to the implosion of the tube resulting in the bursting of the front glass. In Expts 1 and 2 the front glass remained undamaged almost to the very end of the experiment. When the front glass was broken already after a few minutes, the fire became better ventilated. At about 9 min $\dot{Q}_{max} \approx 290$ kW was reached.

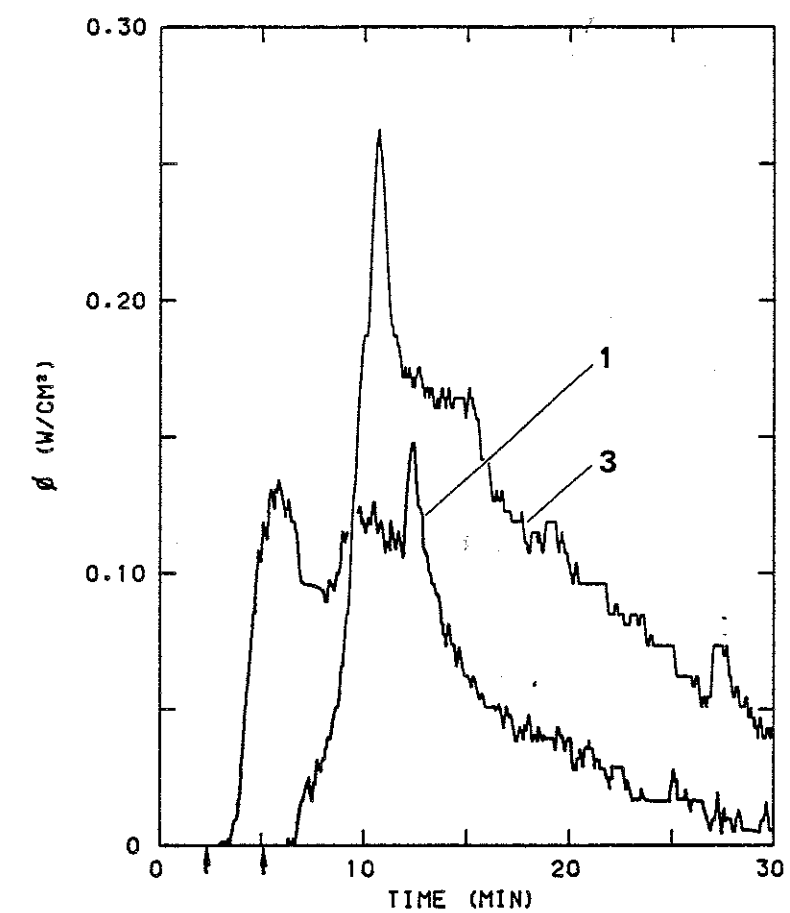

Fig. 4. Intensity of thermal radiation at the centre of the floor as a function of time in Expts 1 and 3 on TV receivers. The moments of ignition are shown by the arrows on the time-axis.

Almost at the same moment the rate of smoke production, the intensity of the thermal radiation, and the gas temperatures reached their maximum values.

The maximum of the rate of smoke production was $S_{max} \approx 16.3\ (dB/m)m^3/s$. Probably due to the fire being better ventilated the smoke production was smaller than that in Expt. 1. The total amount of smoke produced was $S_{tot} \approx 6300\ (dB/m)m^3$, i.e., close to that in Expt. 1.

The intensity of the thermal radiation at the floor reached a maximum $\phi_{max} = 0.26\ W/cm^2$, and it stayed above $0.1\ W/cm^2$ for 11 min.

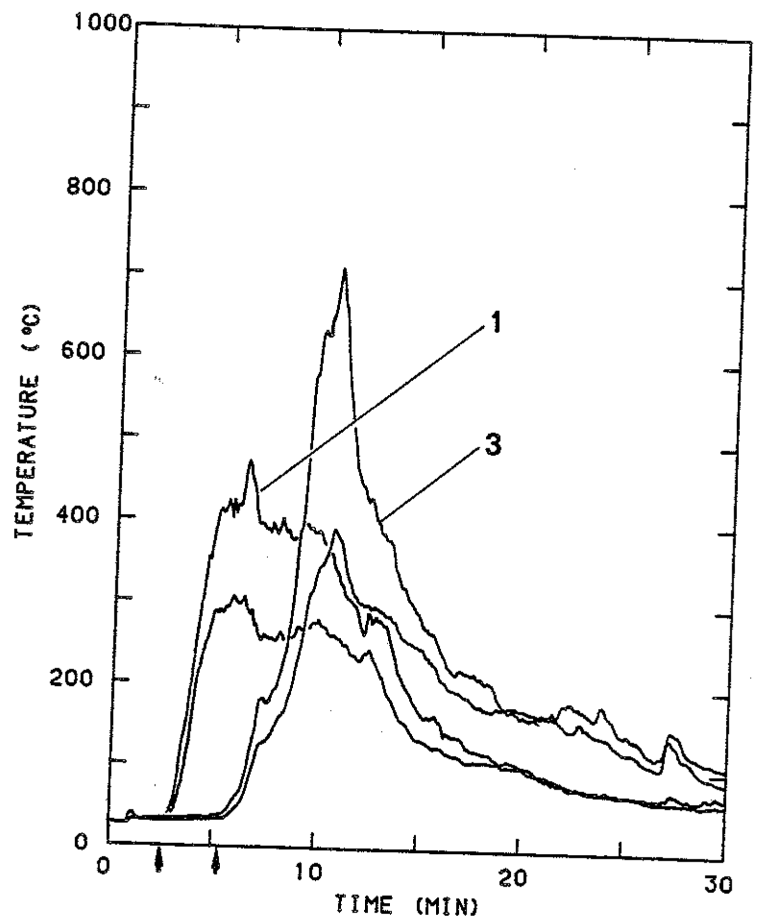

Fig.5. Gas temperature above the burning TV receivers (upper curves) and at the centre of the ceiling (lower curves) as a function of time in Expts 1 and 3. The moments of ignition are shown by the arrows on the time-axis.

The maximum values of the gas temperatures at the ceiling were higher than in Expt. 1. The highest temperatures above the receiver and at the midpoint of the ceiling were 710 °C and 390 °C, respectively. Above the receiver and at the midpoint of the ceiling the temperature stayed above 250 °C for 7 min and 5.5 min, respectively.

4.2 Paper baskets

The measured rate of heat release is shown in Fig. 6, and the measured gas temperatures in Figs 7 and 8.

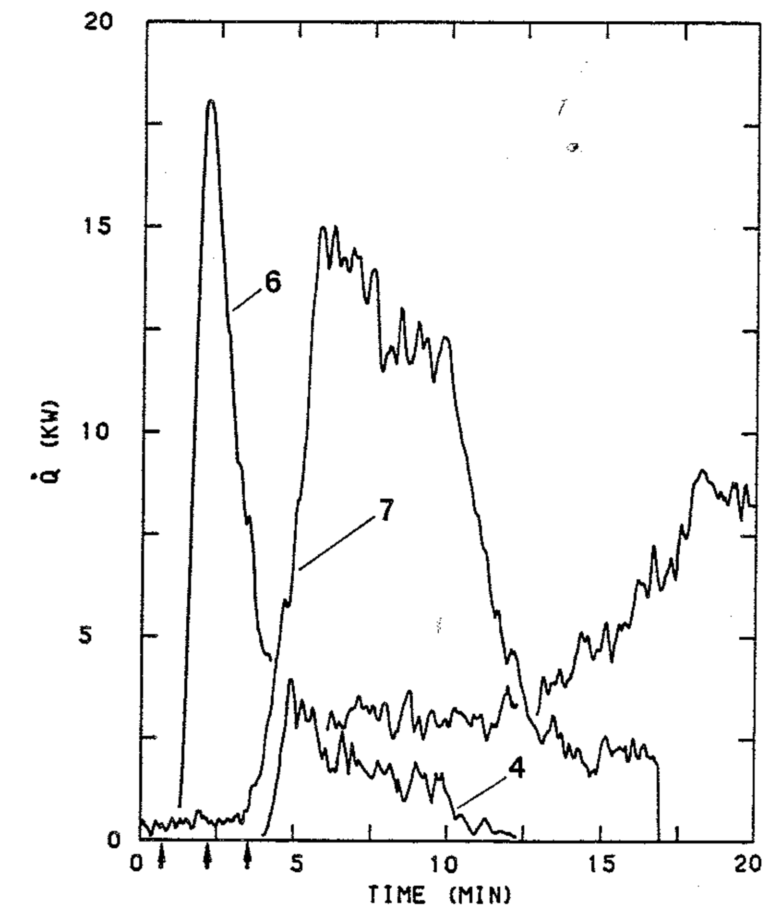

Fig. 6. Rate of heat release as a function of time in Expts 4, 6, and 7 on paper baskets. The moments of ignition are shown by the arrows on the time-axis.

In all the experiments with the paper baskets the intensity of the fire was very low. In Expts 4 and 5 practically only the contents of the baskets were burning. The basket itself only melted. When the basket was filled with shredded paper, the maximum rate of heat release was only 3 kW, whereas in the case of cardboard milk cans the corresponding value was 13 kW. In both cases flames could be seen only for about 5 min.

The gas temperature at the ceiling above the baskets reached a value of about 100°C during a very short peak after ignition. During the more or less stabilized phase of the fire the temperature was only 50°C. The basket filled with milk cans burned more evenly. The gas temperature at the ceiling never exceeded 70°C.

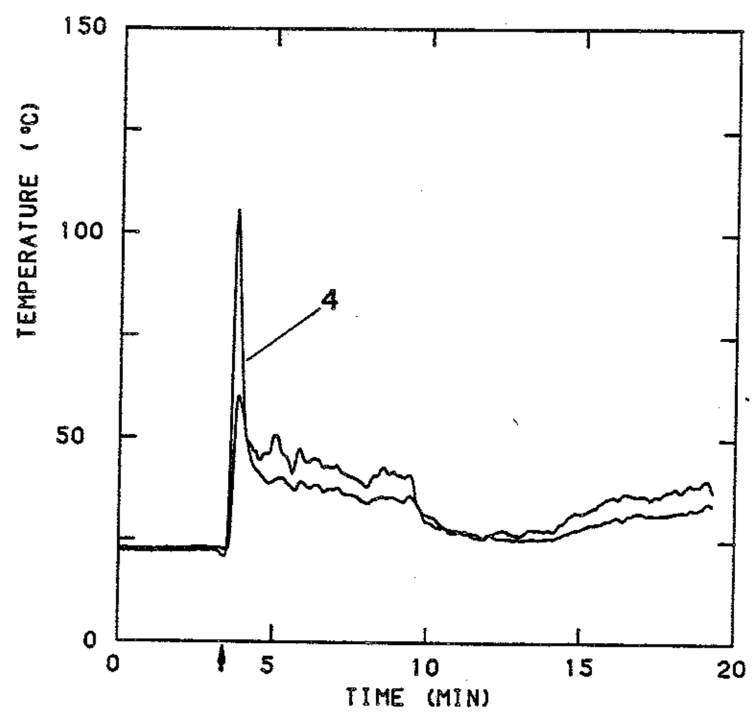

Fig. 7. Gas temperature above the burning paper basket filled with shredded paper (upper curve) and at the centre of the ceiling (lower curve) as a function of the time in Expt. 4. The moment of ignition is shown by the arrow on the time-axis.

The intensity of thermal radiation and the rate of visible smoke production was negligible in both experiments.

In Expts 6 and 7 also the plastic net basket participated in the burning. The maximum rate of heat release was 18 kW and 14 kW for the baskets filled with shredded paper and milk cans, respectively.

The intensity of the thermal radiation remained below the resolution of the measurement system in these experiments, too. Smoke production was hardly visible.

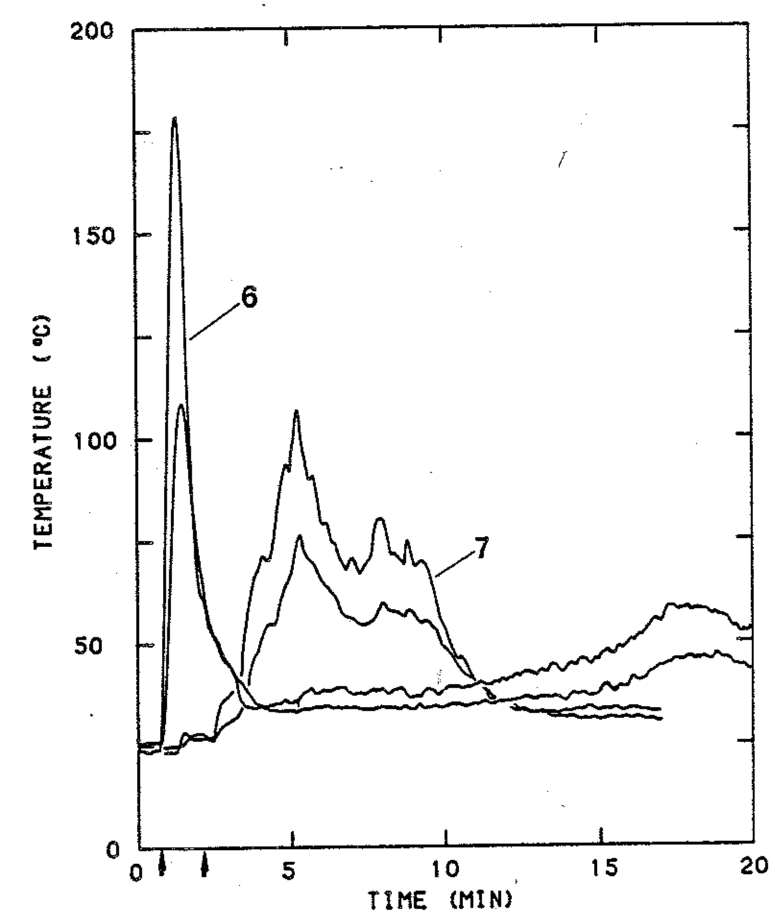

Fig. 8. Gas temperature above the burning plastic net paper basket (upper curves) and at the centre of the ceiling (lower curves) in Expts 6 and 7. The moments of ignition are shown by the arrows on the time-axis.

4.3 Curtains

The measured rate of heat release, rate of smoke production, and intensity of thermal radiation are shown in Figs 9, 10 and 11, respectively. The measured gas temperatures are shown in Figs 12 and 13.

Curtains are almost "ideal" structures for the propagation of flames. The fire is ventilated from both sides of the cloth, and the fire ignited at the lower end spreads upwards rapidly.

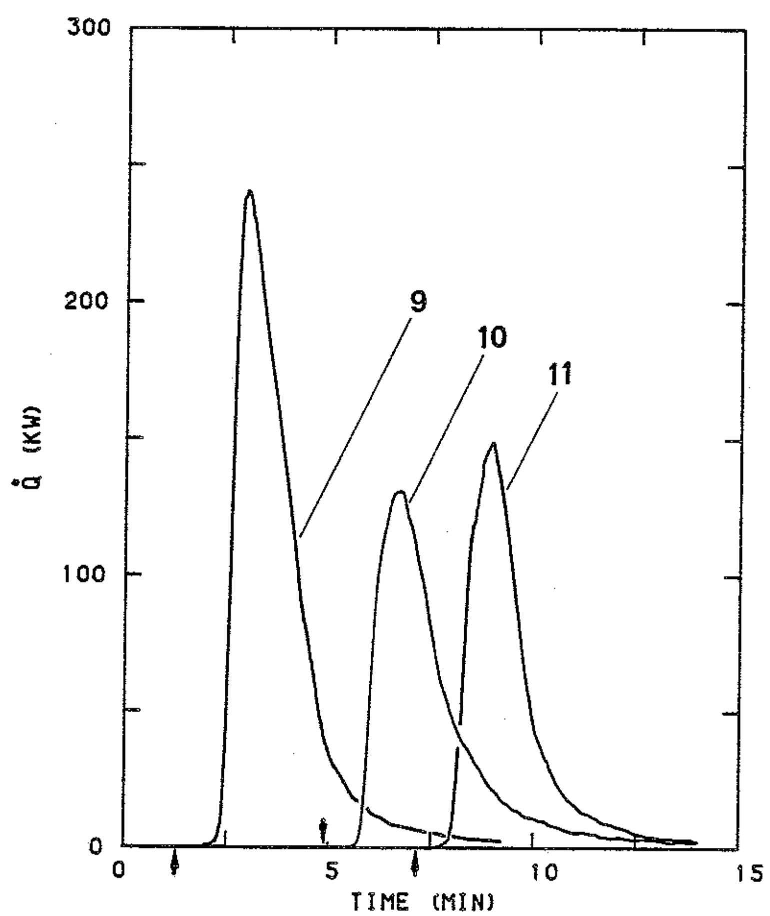

Fig. 9. Rate of heat release as a function of time in Expts 9, 10, and 11 on curtains. The moments of ignition are shown by the arrows on the time-axis.

In the velvet curtains of Expts 8 and 9 the fire started to spread immediately after the ignition. The maximum of the rate of heat release was reached within 1 minute, in the first experiment $\dot{Q}_{max}$ = 160 kW and in the second one $\dot{Q}_{max}$ = 240 kW. Immediately when the maximum rate of heat release was reached, the fire started to diminish rapidly. The rate of heat release was more than 100 kW only for 1.5 min. However, the complete extinction of the fire took about 10 min, because the pieces of cloth fallen down to the floor burned very slowly. The measured heat of combustion was only about 11 MJ/kg.

Owing to the intense burning the rate of smoke production

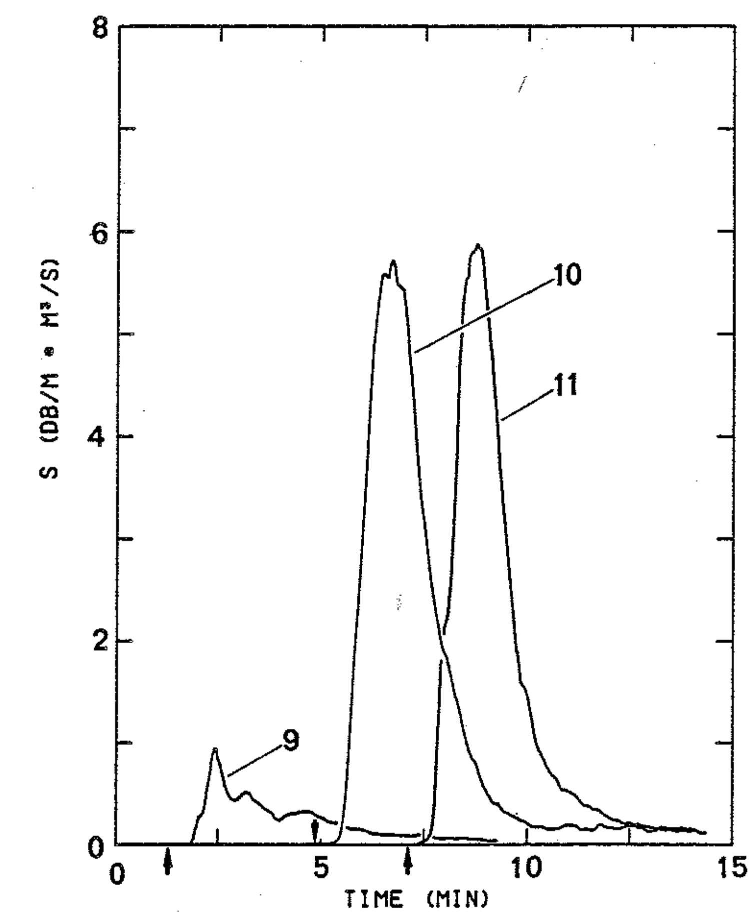

Fig. 10. Rate of smoke production as a function of time in Expts 9, 10, and 11 on curtains. The moments of ignition are shown by the arrows on the time-axis.

was less than 1 (dB/m) m^3/s. The total amount of smoke produced was S_{tot} = 100 (dB/m) m^3.

The maximum of the intensity of thermal radiation was 0.13 W/cm^2 and 0.34 W/cm^2 in Expts 8 and 9, respectively.

Although the peak values of the rate of heat release were of the same order of magnitude as in the experiments with the TV-receivers, the gas temperatures above the ceiling were higher. This was due to the burning taking place at a higher elevation. Thus the dilution of the combustion gases was considerably smaller. In Expts 8 and 9 the maximum

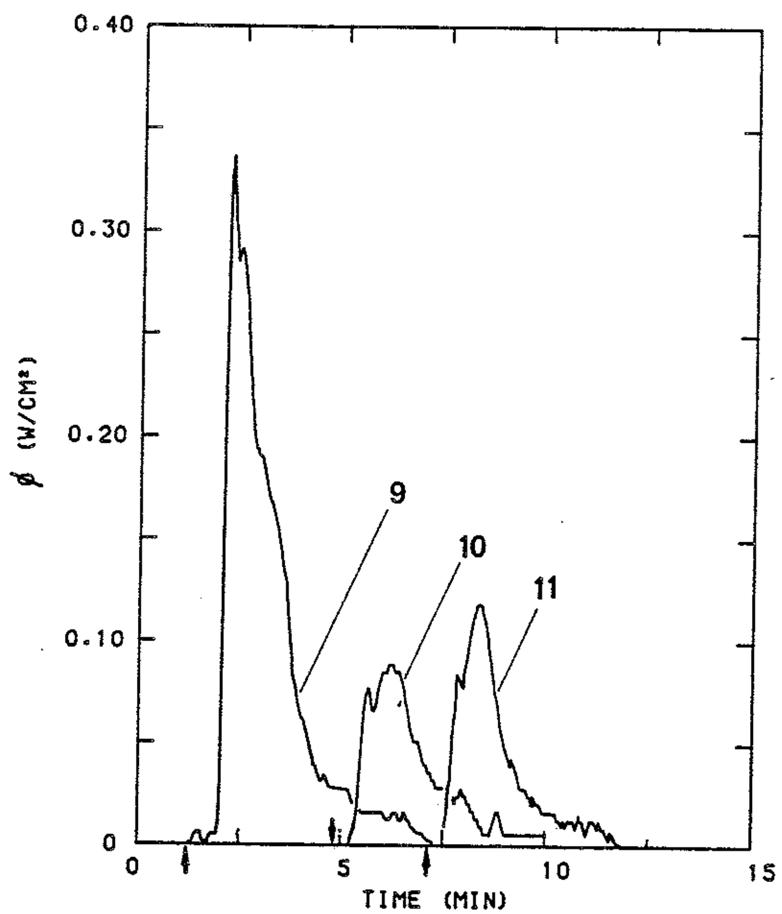

Fig. 11. Intensity of thermal radiation at the centre of the floor as a function of time in Expts 9, 10, and 11 on curtains. The moments of ignition are shown by the arrows on the time-axis.

temperature at the ceiling near the curtain was 830°C and 1030°C, respectively. The corresponding temperatures at the centre of the ceiling were 500°C and 710°C. The temperature was higher than 250°C only for about two minutes.

Although the acrylic blend curtains of Expts 10 and 11 are more easily ignitable than the cotton velvet curtains of Expts 8 and 9, the results shown in Figs 9, 11, 12, and 13 suggest that are not more dangerous. The maximum rate of heat release was reached also within one minute, but now the maximum values were much lower, i.e., only 130 kW and

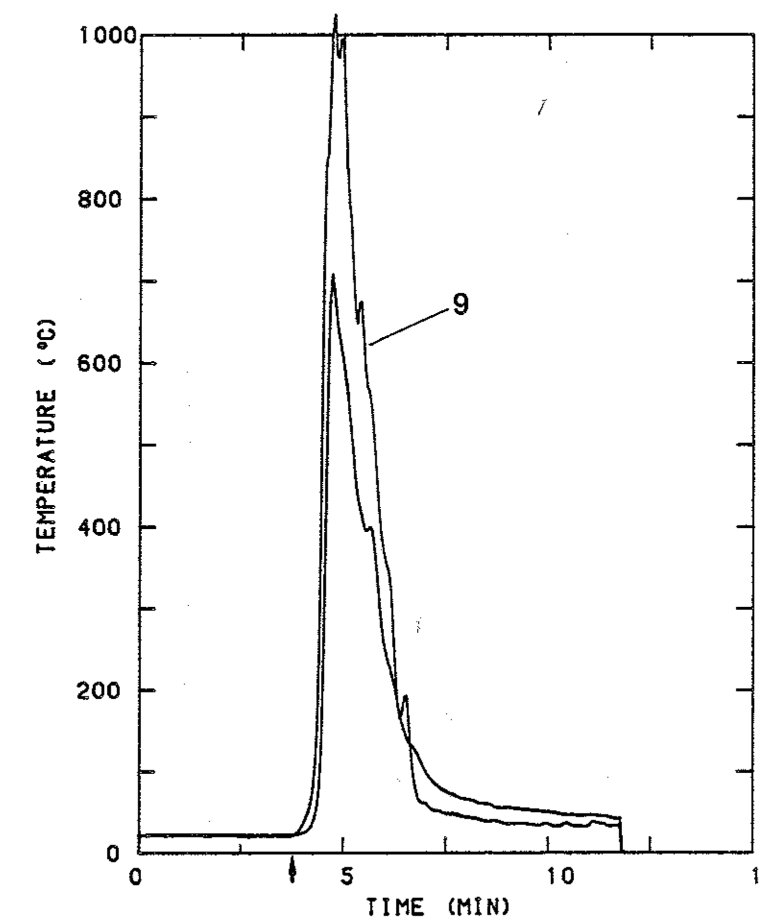

Fig. 12. Gas temperature above the burning velvet curtain (upper curve) and at the centre of the ceiling (lower curve) as a function of time in Expt. 9. The moment of ignition is shown by the arrow on the time-axis.

150 kW in Expts 10 and 11, respectively. The duration of the phase with $\dot{Q}$ > 100 kW was only about 1 min. The final extinction took again a long time because of the fallen pieces of cloth. The measured heat of combustion was about 12 MJ/kg.

The rate of smoke production of the acrylic blend curtains was 6 to 7 times higher than that of the cotton velvet curtains. In both experiments the maximum rate of smoke production was about 5.7 (dB/m) m^3/s. The total amount of smoke produced was 670 (dB/m) m^3 and 590 (dB/m) m^3 in Expts 10 and 11, respectively.

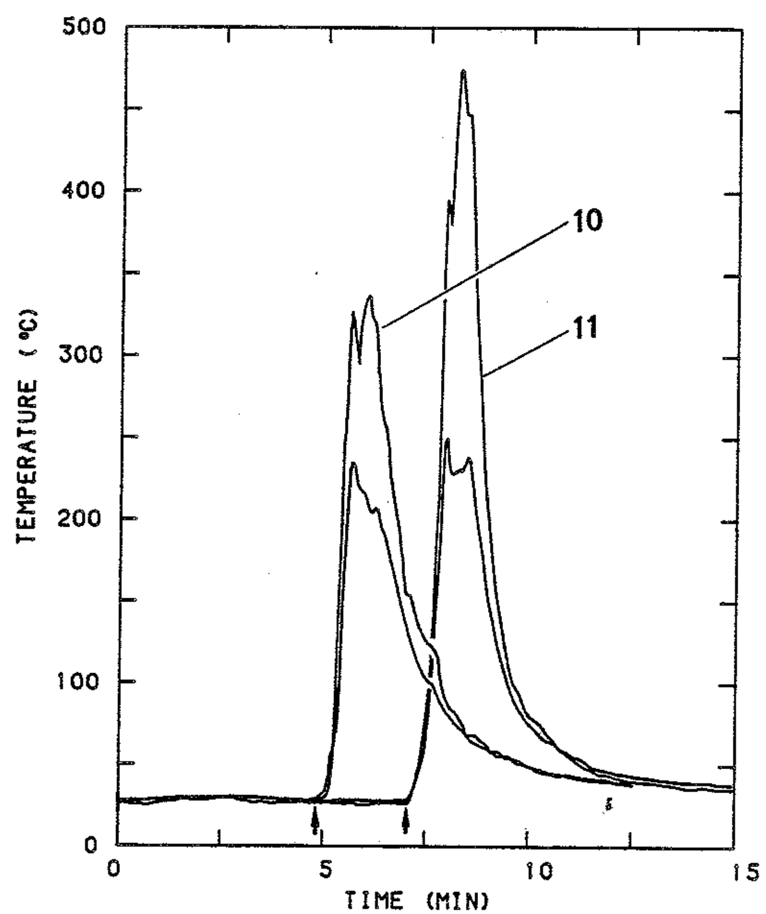

Fig. 13. Gas temperature above the burning acrylic curtains (upper curves) and at the centre of the ceiling (lower curves) as a function of time in Expts 10 and 11. The moments of ignition are shown by arrows on the time-axis.

In Expts 10 and 11 with the cotton velvet curtains the maximum intensity of the thermal radiation was only about 0.1 W/cm^2.

From the burning acrylic curtains pieces of cloth started to fall much earlier than from the cotton velvet curtains. Thus the gas temperatures at the ceiling remained lower. At the corner above the curtains we measured T_{max} = 340°C and 470°C in Expts 10 and 11, respectively. At the centre of the ceiling the corresponding temperatures were 230°C and 250°C.

4.4 Chairs

The measured rate of heat release, rate of smoke production, and intensity of thermal radiation are shown in Figs 14, 15, and 16, respectively. The measured gas temperatures are shown in Figs 17 and 18.

In Expts 12 and 13 with the BS-type chairs the initial spread of fire was very slow due to the tiny ignition power of the methenamine pills. It took 3 min until the rate of heat release had risen to above 10 kW. The maximum power $\dot{Q}$ ≈ 65 kW was reached at about 6 min. This coincided with the intense burning of the back of the chair. The seat flashed over only after the rate of heat release was already decreasing. Owing to the flash-over of the seat the rate of heat release started to re-increase, and at about 9 min reached a second maximum of $\dot{Q}$ = 40 kW. The duration of the fire was about 20 min, and at the end almost all of the materials had burned off. The total energy released was 20 MJ, corresponding to an effective heat of combustion of 15 to 16 MJ/kg.

The rate of smoke production was smaller than that of the acrylic curtains, but larger than the smoke production of the cotton velvet curtains although the mass of the combustible materials was of the same order of magnitude in all the three cases. The maximum rate of smoke production was $S_{max} \approx$ 1 (dB/m) m^3/s and the total amount of smoke produced was $S_{tot} \approx$ 300 (dB/m) m^3.

The intensity of thermal radiation was very low, even at its maximum only about 0.05 W/cm^2.

The gas temperatures were lower than in the case of burning curtains, as we can easily infer from the rates of heat release. In Expt. 12 the gas temperature at the ceiling reached a maximum of 310°C, and the temperature stayed above 250°C for a period of about 1 min. In Expt. 13 the

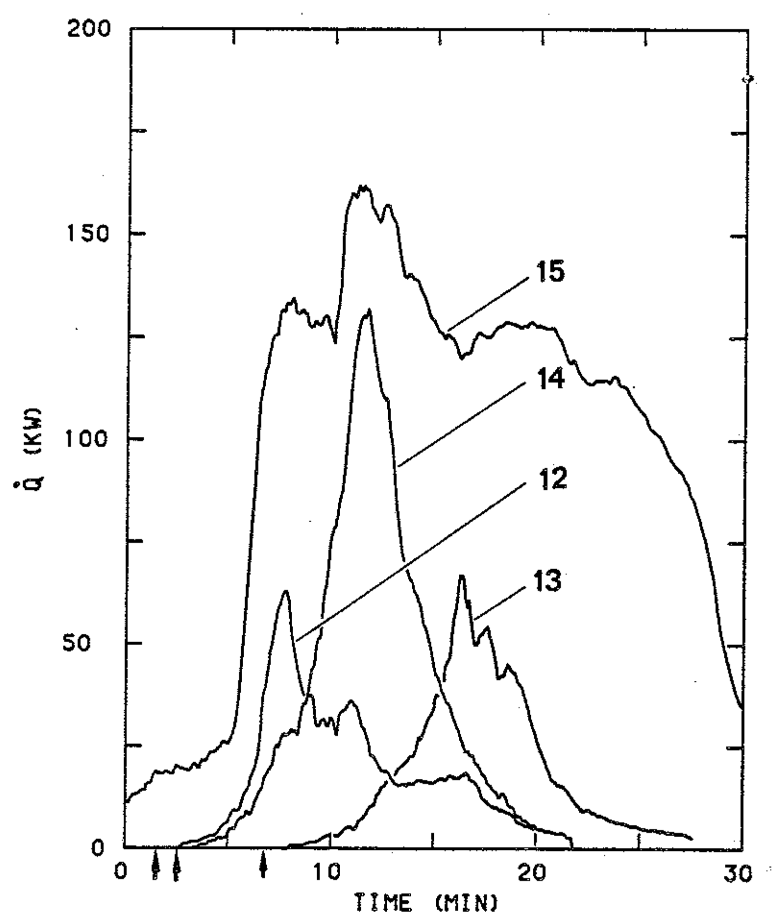

Fig. 14. Rate of heat release as a function of time in Expts 12 to 15 on chairs. The moments of ignition are shown by arrows on the time-axis. The curve of Expt. 15 starts 46 min 30 s after the ignition.

maximum temperature was only 240°C. At the centre of the ceiling the maximum temperatures were 190°C and 160°C in Expts 12 and 13, respectively.

In the case of the small sofa of Expt. 14, the rate of heat release increased with an accelerating speed for the first 10 minutes. As the mass of combustible material was twice as large as that of the single BS-type chairs, it is only natural that also the maximum values of the rate of heat release, the rate of smoke production and the intensity of thermal radiation were approximately doubled. For the sofa we measured $\dot{Q}_{max}$ = 130 kW, S_{max} = 2.7 (dB/m) m^3, and ϕ_{max} = 0.09 W/cm^2. When the maximum intensity was reached the

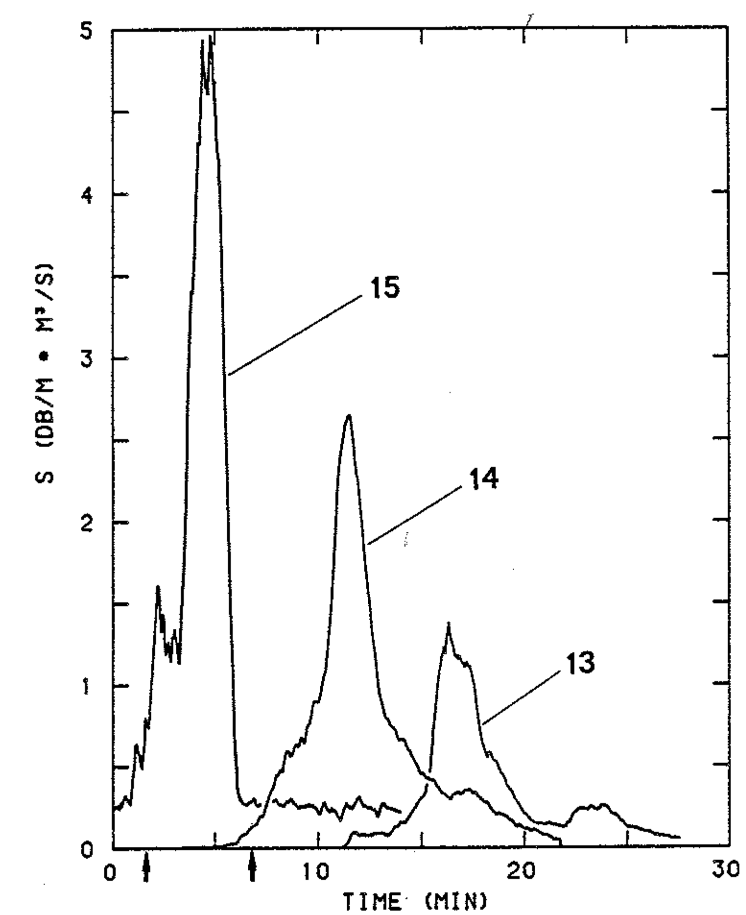

Fig. 15. Rate of smoke production as a function of time in Expts 13 to 15 on chairs. The moments of ignition are shown by arrows on the time-axis. The curve of Expt. 15 starts 46 min 30 s after the ignition.

fire started to diminish so that all the curves of the measured quantities are almost symmetrical with respect to the moment of maximum intensity. The fire was completely extinguished 20 min after the ignition.

Neither in this case did the gas temperatures get close to those measured in the television or curtain experiments. At the corner of the ceiling the maximum temperature was 280°C, and it stayed above 250°C for 1 min. At the centre of the ceiling the gas temperature never exceeded 230°C.

The arm-chair of Expt. 15 was much bigger than the BS-type

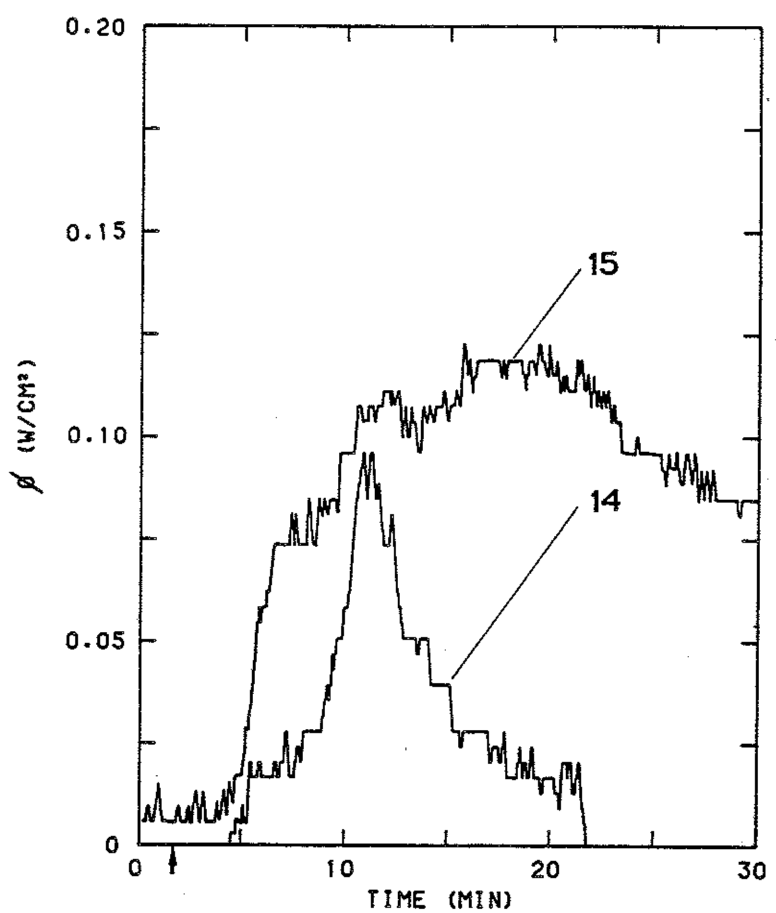

Fig. 16. Intensity of thermal radiation at the centre of the floor as a function of time in Expts 14 and 15. The ignition in Expt. 14 is shown by the arrow on the time-axis. The curve of Expt. 15 starts 46 min 30 s after the ignition.

chairs. The ignition of the arm-chair turned out to be very difficult. At the beginning the fire was only smouldering resulting in thick smoke. Flames appeared only after the addition of liquid fuel at 26 min. In spite of the attempts to ignite it, the chair burned still very slowly for almost half an hour. Because of this the time scales of the curves representing Expt. 15 in Figs 14 to 18 start at 46 min 30 s.

Because of smouldering, the rate of smoke production was high compared with the rate of heat release. The maximum rate of smoke production 4.6 (dB/m) m^3/s was reached at 50 min 30 s. As the smoke was not very warm, it stayed inside the room for a long time. Owing to the long accumalation

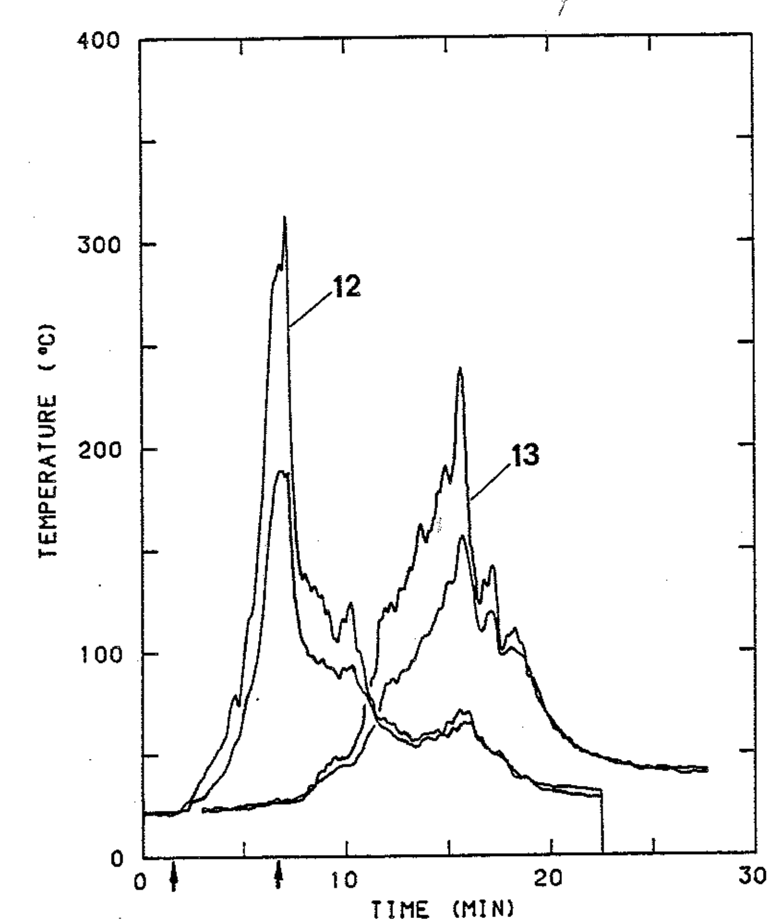

Fig. 17. Gas temperature above the BS-type chairs (upper curves) and at the centre of the ceiling (lower curves) as a function of time in Expts 12 and 13. The moments of ignition are shown by the arrows on the time-axis.

time and the slow air circulation, the smoke density inside the room was so high that at worst it was not possible to see the chair from the door. Immediately when the size of the flames started to increase considerably, i.e., at about 52 min, the measured rate of smoke production decreased rapidly.

When the rate of heat release had risen to 20 kW at 52 min, the fire had reached the critical size, and it started to grow very rapidly. In about one minute the rate of heat release exceeded 100 kW. The maximum value $\dot{Q}_{max}$ = 160 kW was reached at 58 min, at which moment the back and the

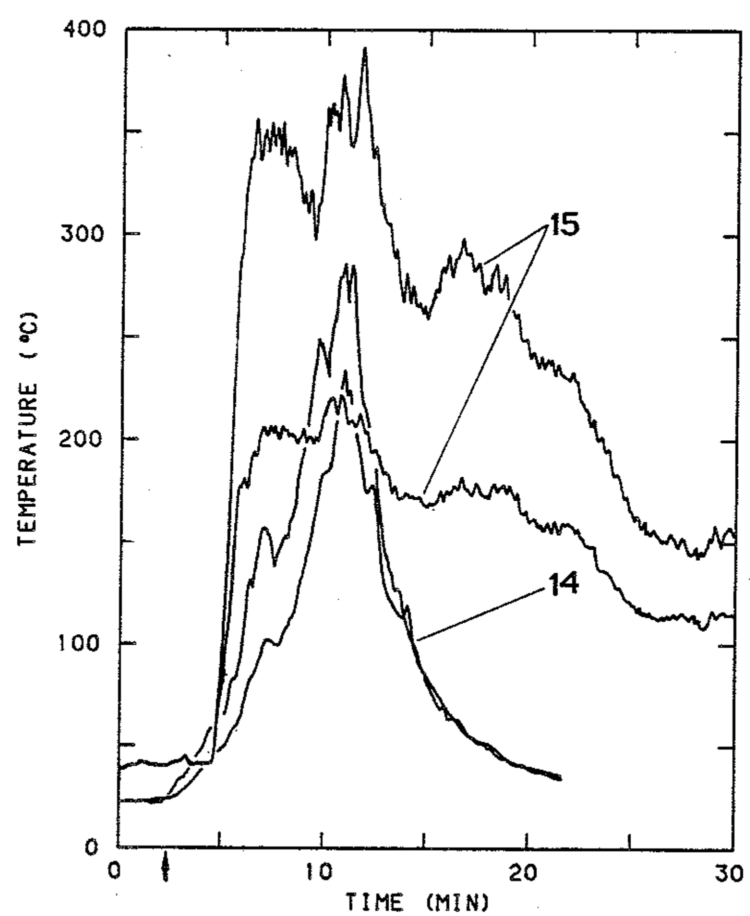

Fig. 18. Gas temperature above the burning chairs (upper curves) and at the centre of the ceiling (lower curves) as a function of time in Expts 14 and 15. The ignition in Expt. 14 is shown by the arrow on the time-axis. The curves of Expt. 15 start 46 min 30 s after ignition.

hand-rests were almost completely covered with flames. Simultaneously big holes were formed in the seat and the fire became well ventilated. The rate of heat release was more than 100 kW for 20 min and more than 20 kW for 25 min.

At the time of the flash-over the intensity of thermal radiation very rapidly increased to ϕ = 1.0 kW/m^2. The maximum value was ϕ_{max} = 0.11 W/cm^2. Because of the long duration of the fire, the ceiling and the walls near the chair warmed up considerably. Therefore, although the rate of heat release decreased, the intensity of thermal radiation stayed constant for a long period of time.

As the chair was standing on the floor, the gas temperatures at the ceiling were lower than in the curtain experiments, although the maximum rate of heat release was of the same order of magnitude. Right above the chair a maximum of 390 °C was reached, and the temperature stayed above 250°C for 14 minutes. At the centre of the ceiling the maximum gas temperature was 220 °C.

4.5 Christmas trees

The measured rate of heat release, rate of smoke production, and intensity of thermal radiation are shown in Figs 19, 20, and 21, respectively. The measured gas temperatures are shown in Figs 22 and 23.

In the fire tests with the Christmas trees we noticed, how critical a factor the humidity of the needles is. In Expt. 16, where the tree had been out in the forest for 2 weeks after cutting and thereafter about 2 days in the +15°C hall, only those twigs ignited which actually touched the flames of the ignition source. About 3 min after the first flash the twigs above the pool fire had become dry enough and a second flash, bigger than the first one, occurred.

Even now the flash was not intense enough to spread the flames over the whole tree. Owing to the pool fire the drying of the uppermost twigs continued. Seven minutes after the ignition a big flash occurred once again, but even this was not enough to burn all the twigs and needles. When the isopropanol had completely burned out, no re-flaming appeared.

During the last flash the maximum values of the measured variables were: $\dot{Q}_{max}$ = 69 kW, S_{max} = 0.7 (dB/m)m^3/s, ϕ_{max}= 0.09 W/cm^2. The maximum temperatures were 350°C and 290°C at the corner and the centre of the ceiling, respectively.

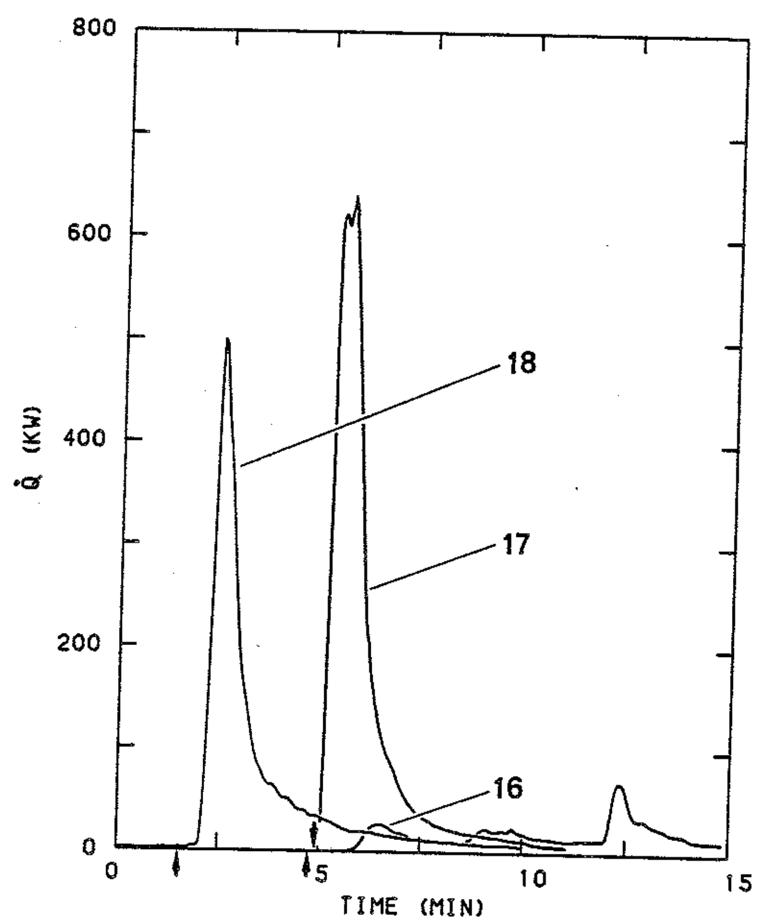

Fig. 19. Rate of heat release as a function of time in Expts 16, 17, and 18 on Christmas trees. The moments of ignition are shown by the arrows on the time-axis. The time delays of the measurement system are not taken into account in the results.

The total thermal energy released was about 11 MJ and the amount of smoke produced 100 (dB/m) m^3, i.e., of the same order of magnitude as from the velvet curtains.

Before Expts 17 and 18 the trees had been dried in the test room using a 1000 W incandescent lamp. The equilibrium temperature was then about 25 °C, and the relative humidity about 30 %. The needles were so dry in both the experiments that most of the needles fell off, if the twigs were shaken. The drying was not unrealistic; one week after Christmas the trees can easily be equally dry.

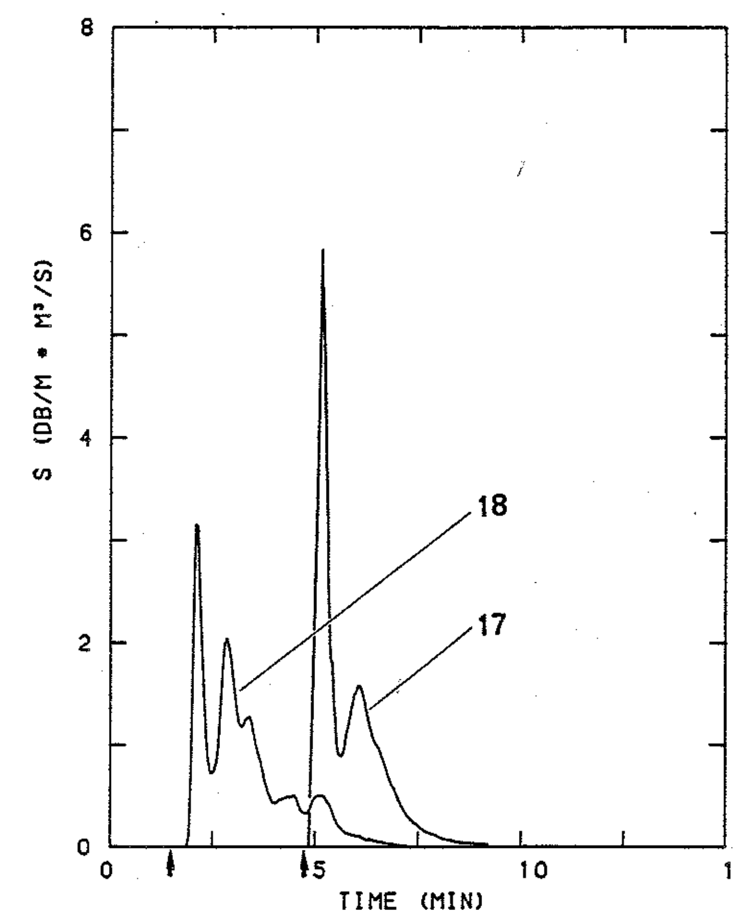

Fig. 20. Rate of smoke production as a function of time in Expts 17 and 18 on Christmas trees. The moments of ignition are shown by the arrows on the time-axis. Notice the local minima at the moments of the most intense fire.

In both the experiments the flash-over occurred almost immediately. Within 5 s the fire had spread over the whole tree. The burning of the needles and the smallest twigs lasted for only 10 s. Because of the delays in the measuring system, the curves of Figs 19 to 23 do not completely describe the fire. For example, the actual maximum of the rate of heat release is higher than that shown in Fig. 19.

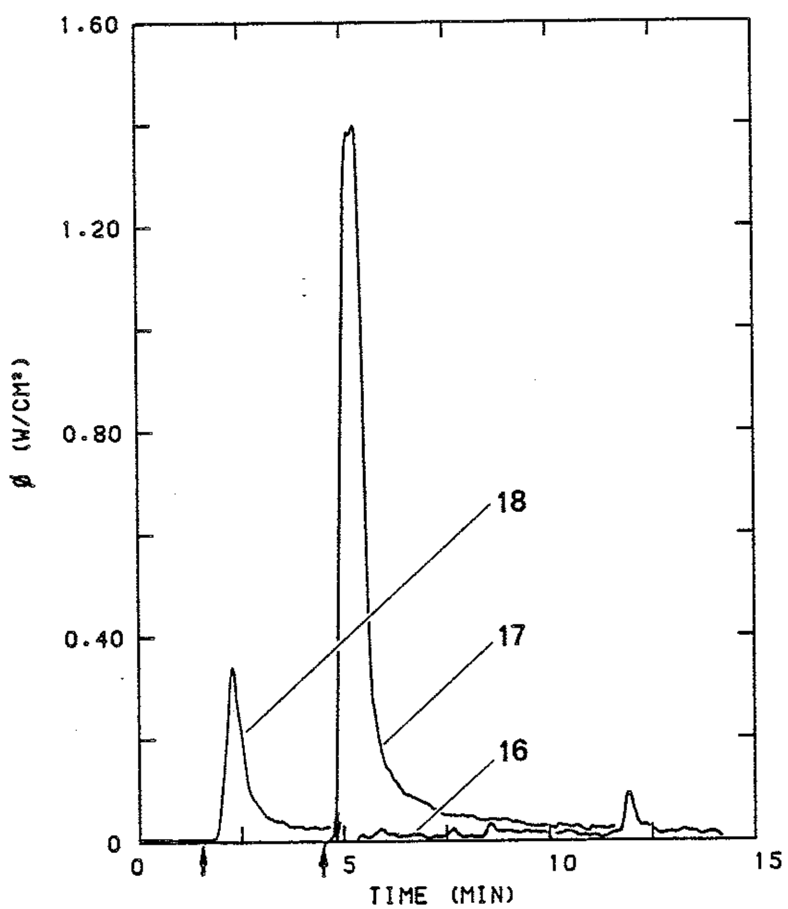

Fig. 21. Intensity of thermal radiation at the centre of the floor as a function of time in Expts 16, 17, and 18 on Christmas trees. The moments of ignition are shown by the arrows on the time-axis.

In Expt. 17 the maximum values were the highest in the whole series of experiments: $\dot{Q}_{max}$ = 650 kW, ϕ_{max} = 1.4 W/cm^2, temperature at the corner 1240°C, and temperature at the center of the ceiling 750°C. The maximum rate of smoke production was 5.8 (dB/m) m^3/s. A total amount of 41 MJ of heat was released and 220 (dB/m) m^3 of smoke was produced. Although the fire went out within 10 s, the hot combustion gases remained in the room for a long time and the mid-ceiling temperature was higher than 250°C for a period of 1 min.

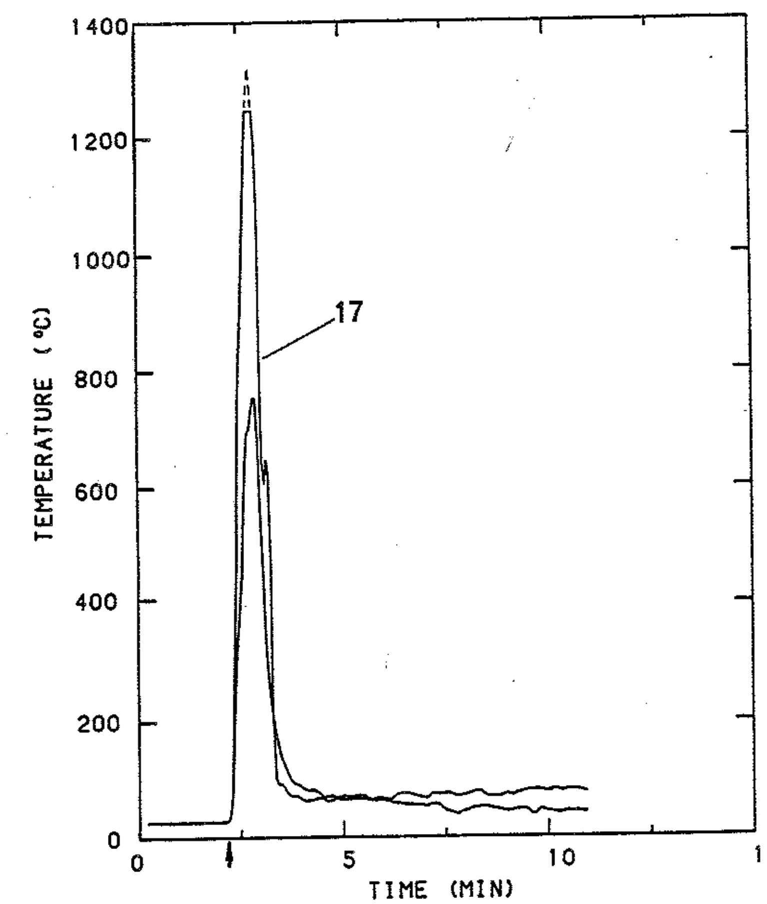

Fig. 22. Gas temperature above the burning Christmas tree (upper curve) and at the centre of the ceiling (lower curve) as a function of time in Expt. 17. The moment of ignition is shown by the arrow on the time-axis. The peak has been extrapolated to the most probable value because of the upper limit of the temperature measurement at 1240 °C.

The tree of Expt. 18 burned qualitatively in the same way as the one in Expt. 17. As there were less needles the fire was less intense than in Expt. 17. The maximum values of the measured variables were: $\dot{Q}_{max}$ = 500 kW, S_{max} = 3.1 (dB/m) m^3/s, ϕ_{max} = 0.34 W/cm^2, temperature at the corner 830 ^oC, and at the centre of the ceiling 510 ^oC. The total amounts of heat and smoke produced were Q_{tot} = 30 MJ and S_{tot} = 210 (dB/m) m^3.

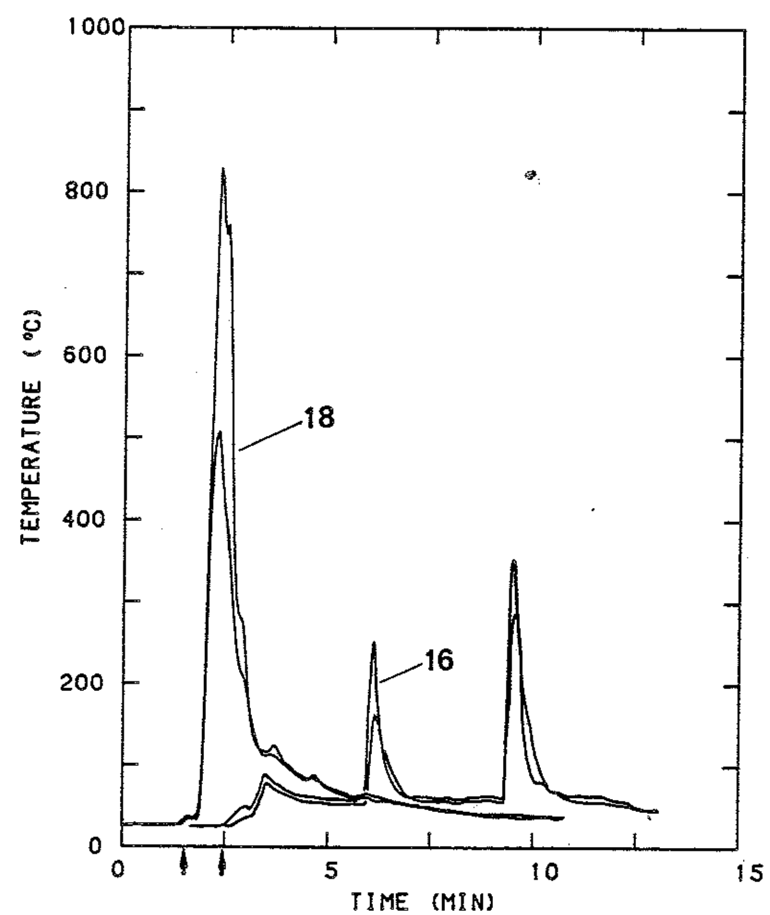

Fig. 23. Gas temperature above the burning Christmas tree (upper curves) and at the centre of the ceiling (lower curves) as a function of time in Expts 16 and 18. The moments of ignition are shown by the arrows on the time-axis.

4.6 Summary of results

Some of the most important results have been collected to Table 6.

Table 6. Experimental results.

Expt. no.	Burning object	$\dot{Q}_{max}$ (kW)	S_{max} $(\frac{dB}{m}\cdot\frac{m^3}{s})$	ϕ_{max} (W/cm^2)	$T_{corner,\ max}$ (^oC)	$T_{centre,\ max}$ (^oC)	ΔM (kg)	Q_{tot} (MJ)	S_{tot} $(\frac{dB}{m}\cdot m^3)$	$Q_{tot}/\Delta M$ (MJ/kg)
1	Television	230	22	0.15	470	310	10.2	146	6700	14
2	"	120	7.2	0.03	290	180	5.8	-	-	-
3	"	290	16	0.26	710	390	10.2	150	6300	15
4	Paper basket	4	<0.1	<0.01	110	60	-	0.7	6	-
5	"	13	<0.1	<0.01	-	-	-	3.0	15	-
6	"	18	0.2	<0.01	180	110	-	7.3	82	-
7	"	15	0.1	<0.01	110	75	-	5.8	46	-
8	Velvet curtain	160	0.5	0.13	830	500	1.7	-	-	-
9	"	240	0.9	0.34	1030	710	1.7	24	100	14
10	Acrylic curtain	130	5.8	0.09	340	230	1.3	16	670	13
11	"	150	5.9	0.12	470	250	1.3	15	590	12
12	BS-chair	63	0.9	0.04	310	190	1.4	21	290	15
13	"	66	1.4	0.05	240	160	1.4	22	320	16
14	BS-sofa	130	2.7	0.09	280	230	2.5	42	600	17
15	Armchair	160	4.9	0.12	390	220	21.2	>180	>600	-
16	Christmas tree	69	0.7	0.09	350	290	-	11	100	-
17	"	650	5.8	1.4	1300	750	-	41	220	-
18	"	500	3.1	0.34	830	510	-	30	210	-

$\dot{Q}_{max}$ = maximum rate of heat release
S_{max} = maximum rate of smoke production
ϕ_{max} = maximum intensity of thermal radiation at the centre of the floor
$T_{corner,\ max}$ = maximum gas temperature above the burning object
$T_{centre,\ max}$ = maximum gas temperature at the centre of the ceiling
ΔM = total mass loss
Q_{tot} = total amount of thermal energy released
S_{tot} = total smoke production
$Q_{tot}/\Delta M$ = effective heat of combustion

5 DISCUSSION

The results of the 18 different experiments give us some guidance in assessing the relative danger of the potential ignition sources of apartment fires. In the following some general features of the results are described.

Traditionally the fire load has been defined as the product of the mass and the heat of combustion of the combustible materials divided by the floor area of the room where these materials are located /11/. The correlation between the fire risk and the traditionally defined fire load is not always evident. For example, Fig. 24 shows the measured relative change of temperature as a function of the fire load. It can be noticed that the maximum change of

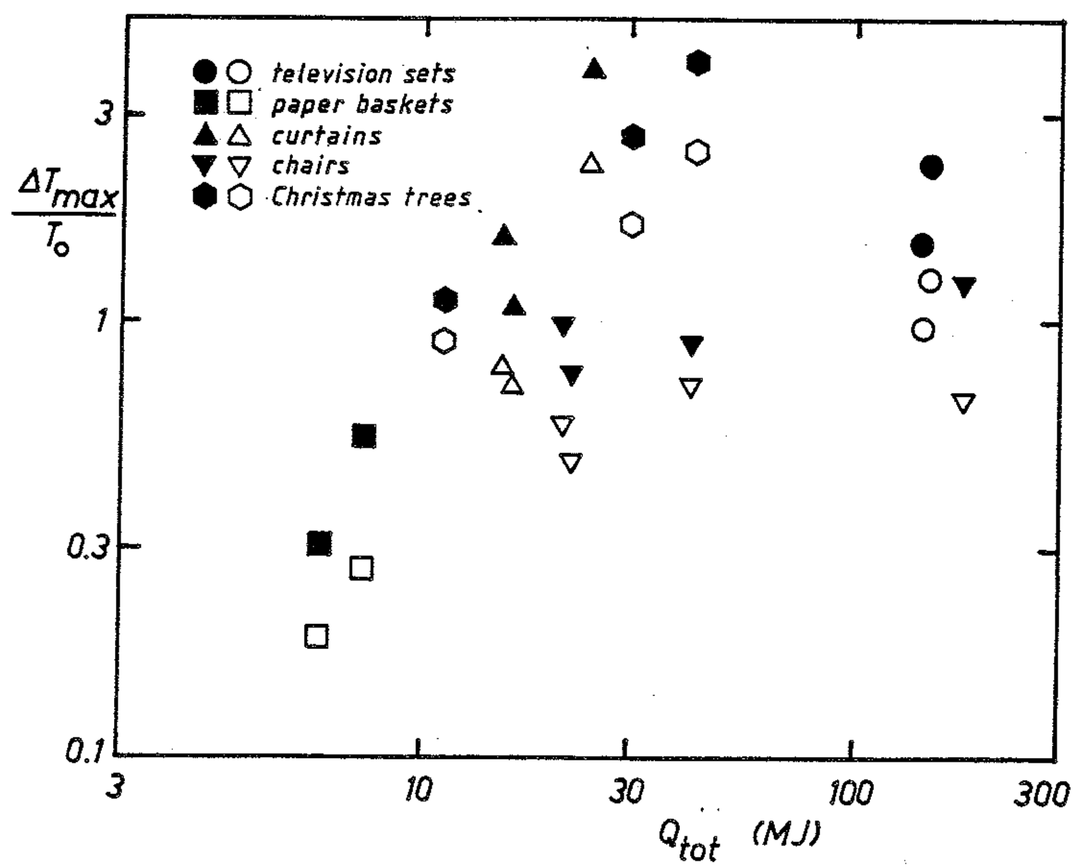

Fig. 24. Maximum relative change of gas temperature as a function of the total energy released. Black and open symbols correspond to the temperatures above the burning items and at the centre of the ceiling, respectively. The initial temperature T_o is 293 K.

temperature increases as the total amount of energy released increases, but the correlation is so poor that it is impossible to make any prediction on the basis of the results.

In Fig. 25 the maximum relative change of temperature is presented as a function of the maximum rate of heat release. The data have been compared with the formula for the relative change of temperature $\Delta T/T_o$ in free space above a burning object /12/,

$$\frac{\Delta T}{T_o} = 0.08 \left[\frac{\dot{Q}}{kW}\right]^{2/3} \left[\frac{Z}{m}\right]^{-5/3}, \qquad (6)$$

where T_o = 293 K is the initial temperature and Z the vertical distance from the burning item. In the present

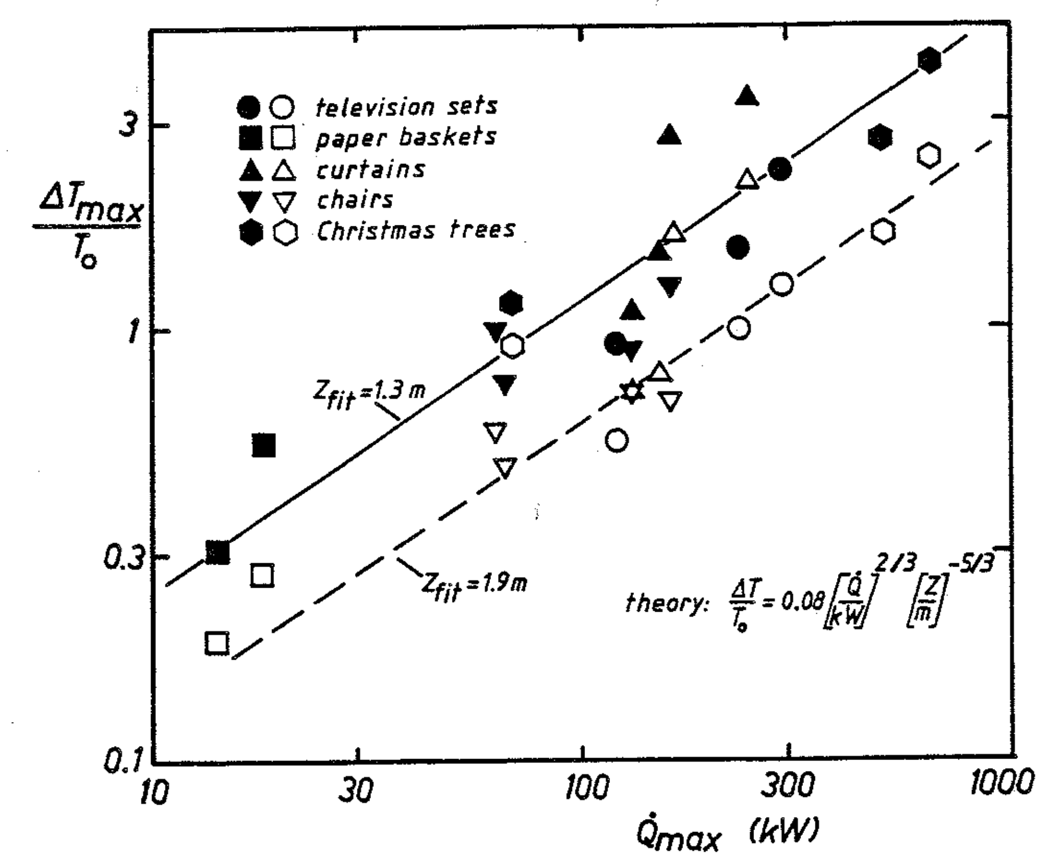

Fig. 25. Maximum relative change of temperature as a function of maximum rate of heat release. Black and open symbols correspond to the temperatures above the burning items and at the centre of the ceiling, respectively.

experiments the value Z to be used in Eq. (6) depends on the objects due to their different sizes and heights. However, we can see from Fig. 25 that the power law $\Delta T/T_o \propto \dot{Q}^{2/3}$ fairly well agrees with the experimental results, especially with regard to the temperature at the centre of the ceiling. The cotton velvet curtains and the first Christmas tree are the major exceptions. In these three experiments the burning took place mainly close to the ceiling at the most intense phase of the fire. The flames were then even touching the temperature sensors, and the scaling law of Eq. (6) is not valid anymore. We should emphasize that in Eq. (6) there is only one free parameter (Z), and even that can be estimated rather accurately from the geometry of the experiments.

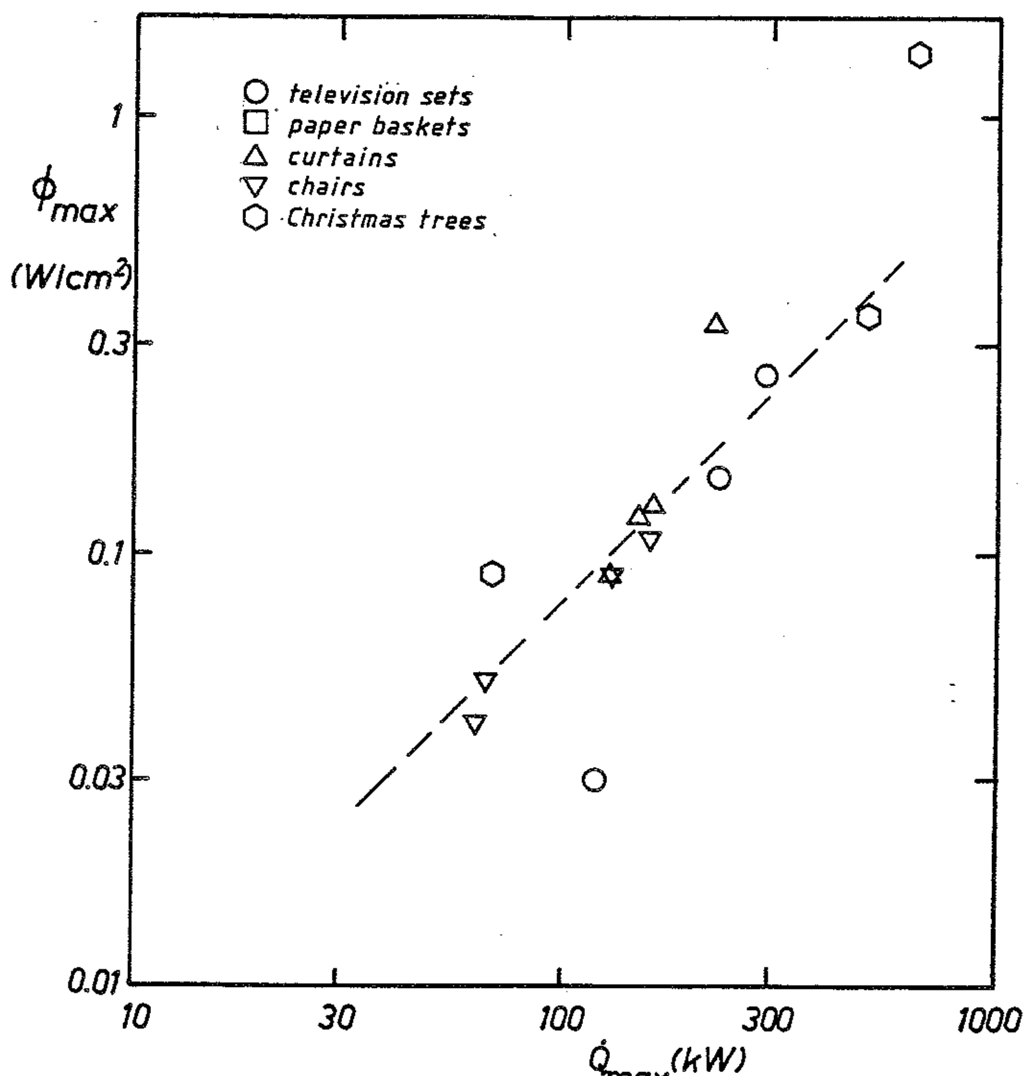

Fig. 26. Maximum intensity of thermal radiation at the centre of the floor as a function of maximum rate of heat release.

Fig. 26 presents the maximum intensity of the thermal radiation ϕ_{max} at the centre of the floor as a function of the maximum value of the rate of heat release $\dot{Q}_{max}$. In most of the experiments, the linear relationship $\phi_{max} = 7.7 \times 10^{-3}\ \dot{Q}_{max}/m^2$ describes rather well the measured intensities of thermal radiation in the present fire room.

The rate of smoke production depends so much on the composition of the materials that no general dependencies can be deduced.

6 CONCLUSIONS

The potential ignition sources studied in this work can be divided into three groups according to the maximum rate of heat release: 1) paper baskets, 2) television receivers, curtains and chairs, and 3) Christmas trees.

The maximum rate of heat release in the paper basket fires is so small that they cannot alone ignite, e.g., wood objects unless these are not right above the basket. For example, the ceiling of a room is too far above.

The maximum rates of heat release from TV receivers, curtains and from chairs is of the same order of magnitude, i.e., from 100 kW to 200 kW. The TV receivers are rather massive, and the fire continues for a long time resulting in a heavy fire exposure on the surrounding structures. Polyurethane foam in the chairs produces a very high rate of heat release per unit mass of the burning matter. Thus massive furniture, like sofas, may cause a high fire risk. The curtains, of course depending on the materials used, burn very rapidly. As the fire takes place very close to ceiling, special attention should be paid to the lining materials used in the upper parts of the room.

The Christmas trees form a very high risk, if they are so dry that the needles are beginning to fall off. The maximum rate of heat release is typically 500...600 kW. The Christmas trees burn so intensely and rapidly that people who are near the tree at the moment of ignition hardly have time enough to escape before the thermal radiation, and the hot gases cause serious injuries. In practice, the extinction of the intense fire of a Christmas tree is impossible. However, the trees which are fresh, e.g., due to regular watering, do not spread a fire even from a rather strong ignition source.

The present results show that the ignition power of 176 kW used so far in the ASTM-type room fire tests /13/ is of the right order of magnitude. The continuous exposure of 20 min so far used in the Finnish room fire tests is, however, unrealistic at least when compared with the ignition sources studied in the present experiments.

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Titel

BURNING CHARACTERISTICS OF POTENTIAL IGNITION SOURCES OF ROOM FIRES

Abstract

A total of 18 different experiments on 5 different types of potential ignition sources of room fires are describes. The ignition sources studied comprised television receivers, paper baskets, curtains, chairs, and Christmas trees. In the experiments the rate of heat release, rate of smoke production, intensity of thermal radiation, and gas temperatures were measured.

The ignition sources can be divided into three groups according to the measured maximum rate of heat release: 1) paper baskets, 2) television receivers, curtains, chairs, and 3) Christmas trees. The most intense fire of a single ignition source was found in one of the Christmas trees: the maximum rate of heat release was about 650 kW and the maximum temperature above the burning tree as high as 1300 ^{0}C.

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Burning characteristics of potential ignition sources of room fires