FULL PAPERS

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CONTROL OF SMOKE PRODUCTION FOR WALL, CEILING AND FLOOR LININGS

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ABSTRACT

This paper discusses the scientific background for deciding whether smoke production regulation of room linings in buildings is needed. Two relevant issues are analysed using existing experimental data (a) how smoke yields vary with ventilation restrictions and (b) whether increased smoke yields can lead to untenable conditions owing to smoke stratification. Two examples are presented to illustrate the points of this paper.

INTRODUCTION

Smoke production is currently regulated for room linings in Australia by specifying a smoke index in the EFH test depending on occupancy[1,2]. It is generally assumed that smoke hazard is directly related to toxicity hazard.

The issue has been raised by ABCB (Australian Building Code Board) whether regulation for smoke production is needed assuming that material fire growth is appropriately controlled and regulated. In the lack of effective control for building contents, special consideration is given to fixed enclosure components such as wall and floor linings.

A basic question is whether room linings can contribute enough smoke to the burning of the fuel load in a room to create untenable conditions during evacuation in buildings in situations where it would have been safe without the contribution of the linings. Namely, will the ASET (available time) be greater than the RSET (required time) for evacuation?

Two situations are examined, before and after flashover. Before flashover (full room involvement) the contribution of heat and smoke by room linings is not significant if fire growth for room linings is appropriately controlled. An analysis for carpets included here, supports this statement. After flashover (which involves all the room), the fire can be either ventilation (under-ventilated fire) or fuel controlled (over-ventilated fire). In either case, the linings can significantly increase the smoke concentration from the fire in addition to the contribution of the rest of the fuel load. For example, smoke production would be much more severe if a synthetic lining was used instead of timber lining in rooms with otherwise the same contents.

Experimental data show that the smoke yield (g/g , gram of smoke produced per gram of material burned) in under-ventilated fires is proportional to smoke yield in ventilated fires (Figure 1) taken from Tewarson[3]. So, if a material has a high smoke yield for well-ventilated conditions compared to another material, it would have a proportionally higher yield for under-ventilated conditions when compared to the same material.

Review of practices

Use of smoke production for classification of building products or contents has been a controversial issue[1,2]. The reasons for this state of affairs might be the difficulty in measuring smoke well, and the more predominant need to first regulate fire growth and fire size so that smoke seems to be a secondary issue. It is true that limiting fire spread and fire growth reduces the total production rate of smoke and the smoke hazard to people. Nonetheless, many countries have adopted smoke control regulations. Australia, the Nordic countries, Germany and France have regulations for smoke production in buildings from floor coverings[1,2,4] whereas USA and other countries do not. The new SBI (Single Burning Item) test method in Europe also calls and allows for reliable smoke production classification whereas smoke production in the ISO Room Corner Test is not a reliable measurement and is not used for regulation. The reason is that in the ISO Room Corner Test part of combustion near the ceiling occurs at under-ventilated conditions that may not be reliably reproduced from test to test.

Which test is appropriate for measuring and regulating smoke production is not addressed in this work[1,2,3,4,5,6]. The objective of this paper is to put forward the proper scientific material needed to justify a decision on whether smoke production control for building materials (such as linings) is needed. It is pointed out here that manufacturers tend to make products that meet the regulations of the country's building codes. Thus, a product may be formulated that has low fire spread properties but produces copious amounts of smoke.

Scientific basis for smoke propensity assessment of wall, ceiling and floor linings

There are two simple concepts that can help someone make the right decision:

- Change in smoke yield from well ventilated to under-ventilated fires
- How smoke yield affects ASET and RSET.

Smoke yield

Consider a room that has additional fuel load to that of wall, ceiling and floor linings such as furniture, curtains, books, cabinets and benches. Also assume that the linings have been so selected that they do not allow fast flame spread and fire growth and hence, the development to a flashover fire without the assistance of another (e.g. furniture) fire in the room[6,7]. Under these conditions, that can presumably be met by current regulations of fire growth control in developed countries, the contribution of linings to the smoke and fire hazard in the room of fire origin is negligible (later in the paper a specific example will be presented).

The situation where smoke production of linings is critical is for rooms away from the room of fire origin (including corridors and stairs), when the room of fire origin may become fully involved.

For fully involved room fires, all wall linings (being flammable) will be burning or pyrolysing and they can contribute significantly to the fire growth (for well ventilated conditions) and to the smoke production for both over and under-ventilated conditions. In the case of over-ventilated conditions, the burning rate is proportional to total area (linings and exposed fuel load area). In the case of under-ventilated conditions, the total burning rate is fixed by the room geometry and openings but the contribution to it is proportional to the area of items involved (linings and other fuel load). In the latter case, the smoke production is also proportional to the area of items involved. Thus the smoke production rate of wall linings plays an important role in the total smoke production yield when the room is fully involved in fire.

As Figure 1, and Figures 2 and 3[1,2] show, smoke yield levels for materials increase with the same factor from ventilated to under-ventilated conditions. The implication is that if a material has a high smoke yield for well-ventilated conditions compared to another material, it will have proportionally and relatively higher yield for under-ventilated conditions when compared to the same material.

ASET versus RSET

Currently the smoke hazard is addressed in a performance-based approach by calculating the ASET (Available Safe Evacuation Time). The available safe evacuation time is specified by the time at which the height of the clear layer is 2.1 m or the heat flux from the upper hot layer is 2.5 kW/m^2. By this specification, evacuation time depends only on the magnitude of heat release rate (which dictates the depth of smoke layer) but not on the smoke concentration or the smoke yield from the material. The smoke yield from a material may be quite high but the heat release so small that the clear layer remains higher or equal to 2.1 m and the conditions would be considered tenable as long as the RSET (Required Safe Evacuation Time) is less than ASET.

However, definition of the “clear” layer interface in a two-zone situation is not precise using two-zone or CFD models. There is always a smoke gradient that allows the smoke to exist below the clear layer height, as shown in Figure 4[6]. Figure 4 shows temperature rise distributions at different times in a room where furniture burning was tested[6]. It should noticed that local smoke concentrations, C_{sm}, are proportional to local temperature rise ΔT (that are shown in Figure 4) for a given material. In addition, the height of the smoke layer depends only on the heat release rate and not on the smoke yield, Y_s, of the material. However, concentrations will increase with the material’s smoke yield. Equation 1 shows the relationship between local smoke concentration and local temperature rise and smoke yield of the material:

$$\frac{C_{sm}}{c_p \Delta T} = \frac{Y_s}{\Delta H_c} \tag{1}$$

Equation 1 is based on energy ($c_p \Delta T \dot{m} = \Delta H_c \dot{m}_{fuel}$) and mass ($C_{sm} \dot{m} = Y_s \dot{m}_{fuel}$) conservation balances where ΔH_c is the heat of combustion of the material.

It follows that incapacitation and / or lethal conditions may develop below the 2.1 m criterion even if the clear layer is calculated to be over or near 2.1 m because of the stratification (gradient) of the smoke layer near the hot-cold interface (Figure 4). This observation is also well illustrated in Figure 5. Therefore the available safe evacuation time (ASET) may be less than that calculated by using two-zone models.

In addition the RSET may also increase because concentrations of smoke in the lower (clear) layer may cause incapacitation.

There is another case wherein high smoke yields significantly affect tenability conditions. This case involves areas away from the room of fire origin where well-mixed conditions for the smoke prevail. In this case, tenability conditions will worsen as the smoke yield from materials increases for the same fire size. This type of modelling is included in Canada’s (NRC model) risk analysis tool for buildings.

It is clear that high production yields contributed by linings can cause unanticipated untenable conditions. Next, two examples are presented to make the previous discussion transparent.

A simple example

Consider a room adjacent to a corridor. The room has a fuel loading of 35 kg/m^2 and carpet, wall and ceiling linings. Assume also that the linings themselves, although flammable, cannot promote fire growth so that during the fire growth period the contribution of linings to fire growth is minimal. This will be shown to be true for certain carpets in the next example.

If the fire is not controlled all the room will be involved in flames. The wall and floor linings will pyrolyse at a rate that is proportional to their exposed area. Burning can be ventilation or fuel controlled.

Assume also that the rest of fuel load when tested in the Cone Calorimeter has an SEA (Specific Extinction Area) of 200 m^2/kg while the carpets have an SEA of 1000 m^2/kg. (The SEA is proportional to smoke yield[1]). Both fuels can have similar burning rates per unit area (as it happens for example for carpets).

The burning conditions in the cone calorimeter are well ventilated but, as discussed earlier with regard to Figure 1, the ratio of smoke yields of materials is fixed at under-ventilated conditions versus ventilated conditions. It follows that the relative yields of materials will remain the same, namely 1000/200 = 5 at whatever conditions they burn. At the same time the fire size will not change for ventilation controlled conditions as the fire size is determined by the opening factor of the enclosure. Thus the variation of height with time of the clear layer in a corridor adjacent to the fire room will not change.

It is obvious that by using these linings the amount of smoke and the local concentrations will be three times more than if these linings had the same yield as the rest of the materials in the room. The reasonable assumption has been made that the surface of the linings is at least the same as the surface of the rest of the fuel load in the room. Because local concentrations will be three times larger, both the ASET and RSET calculations may in fact be compromised to make the 2.1 m criterion ineffective.

It is clear that high production yields contributed by linings can cause unanticipated untenable conditions.

A full carpet evaluation example

1. Selection of building geometry

The following room geometries were selected:

- a characteristic enclosure size in a Class 9a (hospital) building, 20 m x 6 m x 3 m high.
- Class 3 (hotel) accommodation, 4 m x 8 m x 2.4 m high.
- ISO room, 3.6 m x 2.4 m x 2.4 m high – the room dimensions represent the smallest room that is likely to occur in a Class 9a Building and are those used by the International Standards Organization (ISO 9705:1993).

When considering the effects of floor coverings, the concerned is with the early stages of fire development. In the early stages of a fire in a small room, the radiant flux to the floor from both the flame and the hot layer is greater than in a large room, making the fire more hazardous. The analysis begins in the smallest enclosure, i.e., the ISO room. If the carpet does not represent a hazard in a small room, then analysis for a large room will not be necessary.

2. Fire scenario specification

The following fire scenarios were selected:

Scenario 1: Isolated ignition source (50 cm alcohol spill with point ignition source, with no other heat source).

Scenario 2: t^2 fire in small enclosure (ISO room, 3.6 m x 2.4 m x 2.4 m high). When will carpet ignite? Will carpet spread fire? Will carpet contribute to flashover?

Scenario 3: Same fire in large enclosure.

Scenario 4: Flashover fire in room adjacent to corridor. Will carpet in room spread smoke to corridor? Will fire spread to corridor? In addition, the possibility of smoke spread to remote parts of the building were considered in the event of a flashover fire occurring in the room of fire origin.

3. Fire test data used for carpet X

Data from fire tests to Carpet X is needed to provide properties for calculations and to support the conclusions. The following properties will be used obtained from Cone Calorimeter (Standards Australia, 1998) and Flooring Radiant Panel (ASTM, 1997) results:

1. Early Fire Hazard Test (EFH) data
2. The heat release rate per unit area (HRR) at an appropriate heat flux (CONE)
3. The average smoke yield = g (smoke) /g (pyrolysed) (CONE)
4. The burnout time of carpet, namely the time for the carpet to burn through, t_B (CONE)
5. The critical heat flux for the FRP, $\dot{q}''_{cr}$
6. The average spread speed obtained from the FRP, u_s.

Results were initially obtained from the FRP using a maximum radiant flux of 24 kW/m². Comparison with the current standard test method using a maximum radiant flux of 12 kW/m² produced the same value of Critical Radiant Flux.

A simple result that will be useful many times in the following discussion provides the “moving” carpet length over which burning occurs:

$$L_f = u_s t_B \tag{2}$$

The test outputs are confidential and not very critical for the present case.

4. Evaluation of fire and smoke spread

Scenario 1: Isolated Ignition Source

This scenario aims to assess if the carpet can sustain flame spread once it is ignited by a 50 cm x 50 cm alcohol spill. The heat release rate of this alcohol ignition source is 200 kW, which is lower than the 300 kW heat release rate of the source in Scenario 2. For a 300 kW fire in a corner without the involvement of the upper layer, the carpet will not sustain flame spread because the critical FRP heat flux for this carpet is 12.2 kW/m², which is greater than the radiation from the flame to the floor.

Scenario 2: t² fire in small enclosure

An ultra-fast fire that reaches a maximum heat release of 300 kW in the room corner was analysed. The conclusions are the same for slower fires. The maximum value was chosen to simulate a fire from limited room contents that would not lead to flashover, in order to investigate the contribution of the carpet. The heat flux the carpet receives in this case is the sum of radiation from the hot layer and the fire.

The heat release rate of the carpet fire is calculated to be 70 kW, which is small compared to 300 kW and will not lead to flashover.

The heat release rate contributed by the carpet is 1/4 of the heat release rate of the fire source. Assume that the Specific Extinction Area (SEA) of the smoke from the fire without carpet is 200 m²/kg [4]. The average SEA for Carpet X is 600 m²/kg. The smoke generated by a fire is proportional to the heat release rate times the SEA of the material involved. Based on this relation, the additional contribution of the carpet to the smoke generated in the room is 38%.

Scenario 3: Same fire in large enclosure.

As pointed out in Section 1, investigation into this scenario is not necessary because a similar scenario in a small enclosure, which is more hazardous, has already been analysed.

Scenario 4: Flashover fire in small enclosure

The room will become fully involved when the fire reaches 700 kW. According to CFAST calculations, this will be about 1 min. Such a fire will not spread fire to the corridor, as experience with corridor tests has shown[9,10].

After flashover, the contribution of a material to the smoke depends on its surface area times its mass loss rate (or heat release rate for similar values of heat of combustion) times its smoke yield (proportional to SEA). The fuel load in the room is about 40 kg/m² (this represents an office-type room in a hospital) plus the carpet which is 5.1 kg/m², namely about 1/8 of the room fuel load.

Using Cone data (at 25 kW/m²) an estimate the contribution to the smoke of the carpet relative to the other fuel load can be made (see above). The smoke yield for this carpet is three times as large as for the other fuel load and the exposed surface area of the floor can be the same as the exposed surface area of the other room contents, and the heat release rate per unit area (250 kW/m²) is less or equal. Simple calculation shows that the contribution of the carpet to the smoke is 400% more than it would be if the carpet had the same smoke yield as the other room contents.

CONCLUSIONS

Smoke production from wall, ceiling and floor linings has been shown to be a serious hazard issue for adjacent spaces after the room of fire origin reaches flashover conditions for two reasons:

1. Smoke yield from a material continues to increase proportionally as ventilation is decreased (Figures 1,2,3).

2. There is always a stratification of smoke extending below the (calculated) clear layer height so that smoke concentrations in this area may increase to untenable conditions if the smoke yield of the room linings is higher than the smoke yield of the other room fuel loading (Figures 4,5).

Statistics show that about 20% of building fires reach flashover in Canada[8]. Accounting for control of fire growth only may allow bad smoking products onto the market.

The best test methods to characterise smoke yield[1,2] are methods where well-ventilated conditions exist such as the Cone Calorimeter, the SBI and the EFH (if modified to effect forced exhaust of combustion products). The ISO room test is not an appropriate method for smoke regulation after flashover occurs.

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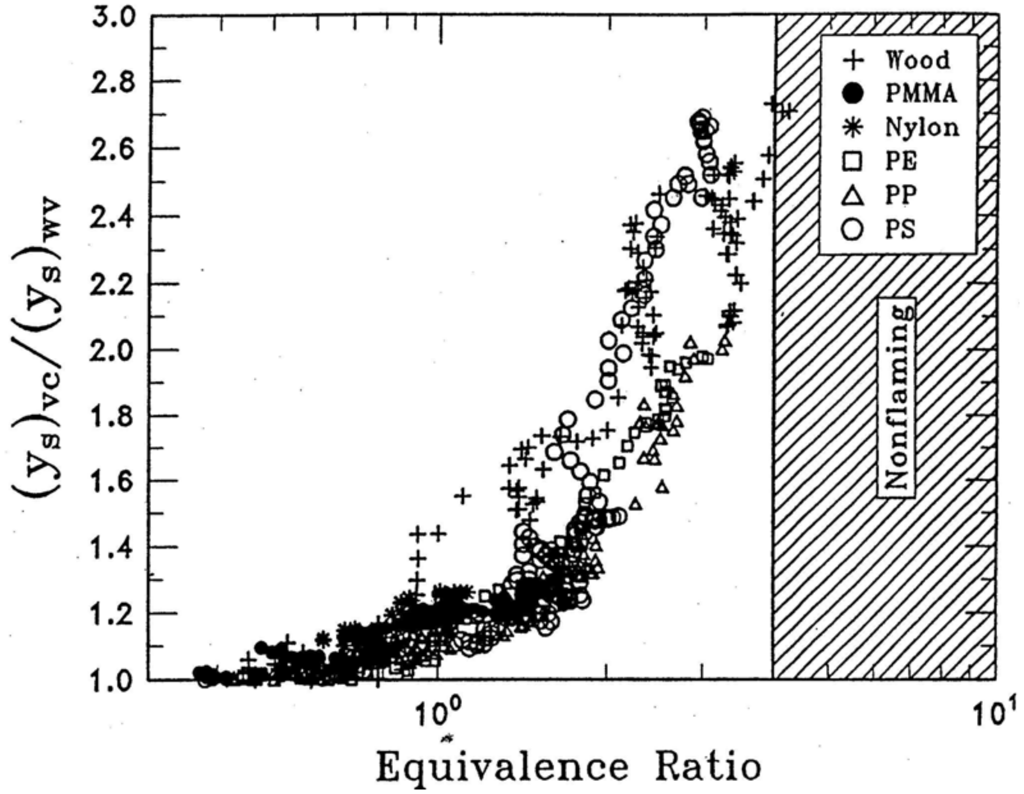

Figure 1: Relative smoke yield at ventilated versus well-ventilated conditions for various materials[3] .

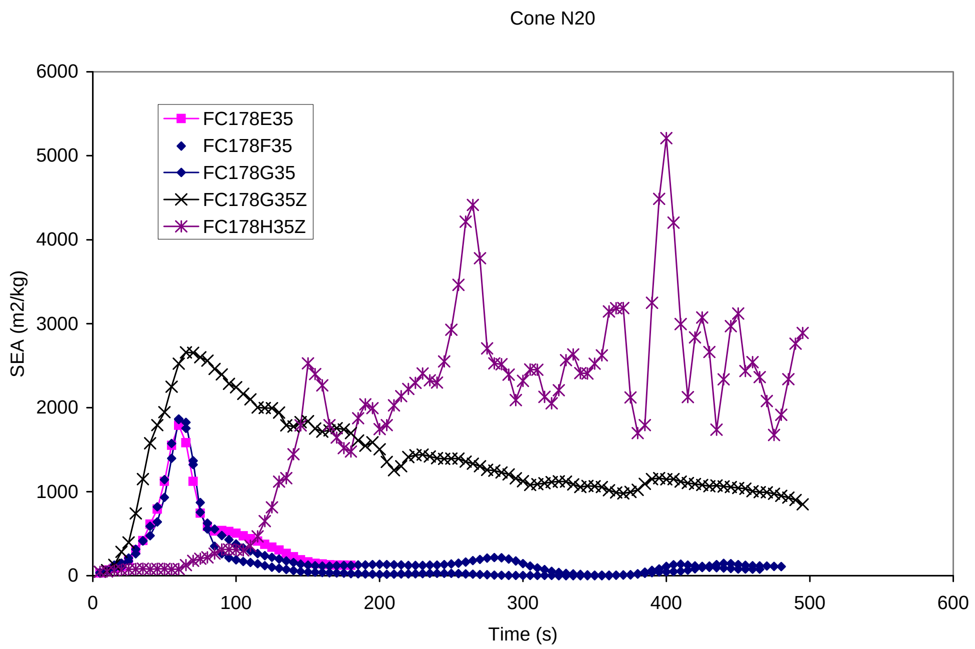

Figure 2: Smoke yield (expressed as specific extinction area, SEA) for well ventilated conditions and in a Nitrogen atmosphere: comparison with Figure 3 shows that relative yields remain the same further supporting the results in Figure 1. The symbol Z in the legend stands for tests in N_2.

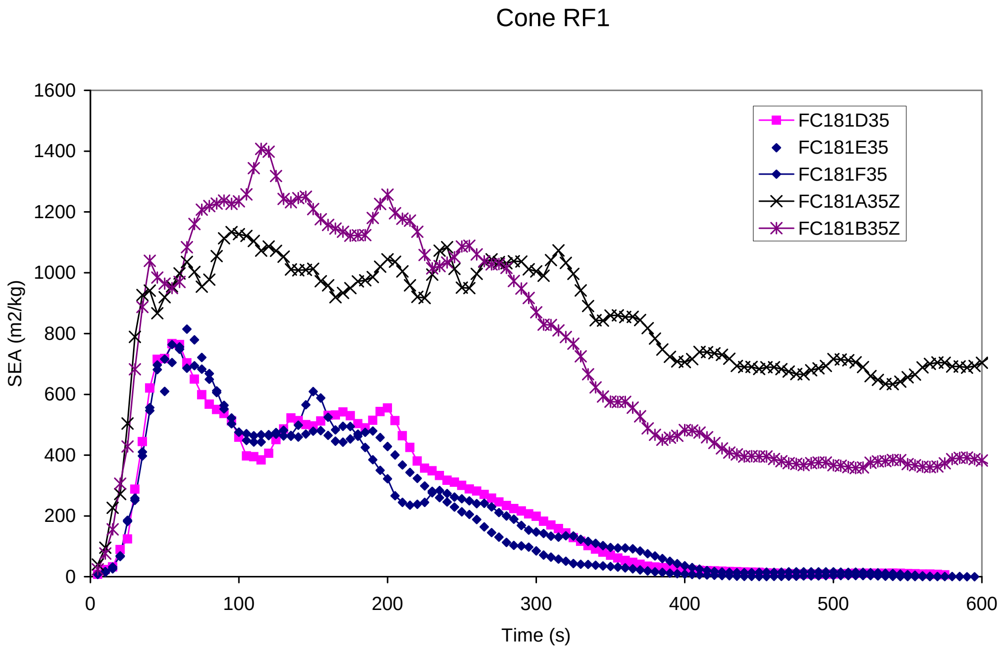

Figure 3: Smoke yield (expressed as specific extinction area, SEA) for well ventilated conditions and in a Nitrogen atmosphere: comparison with Figure 2 shows that relative yields remain the same. The symbol Z in the legend stands for tests in N_2.

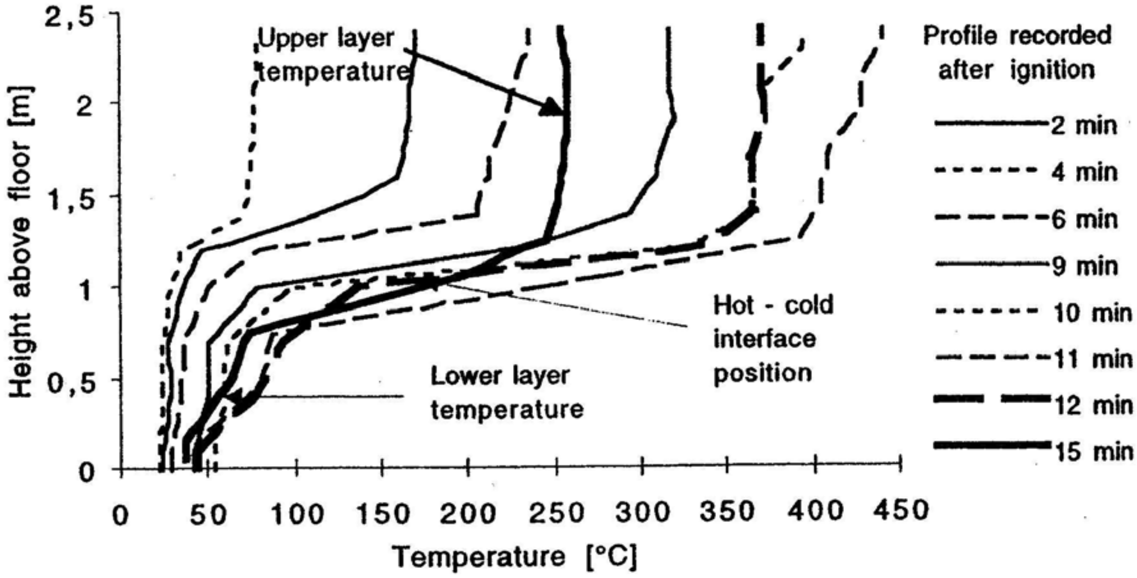

Figure 4: Temperature distribution in a room from a furniture fire at different times of the fire growth: notice the distinct stratification.

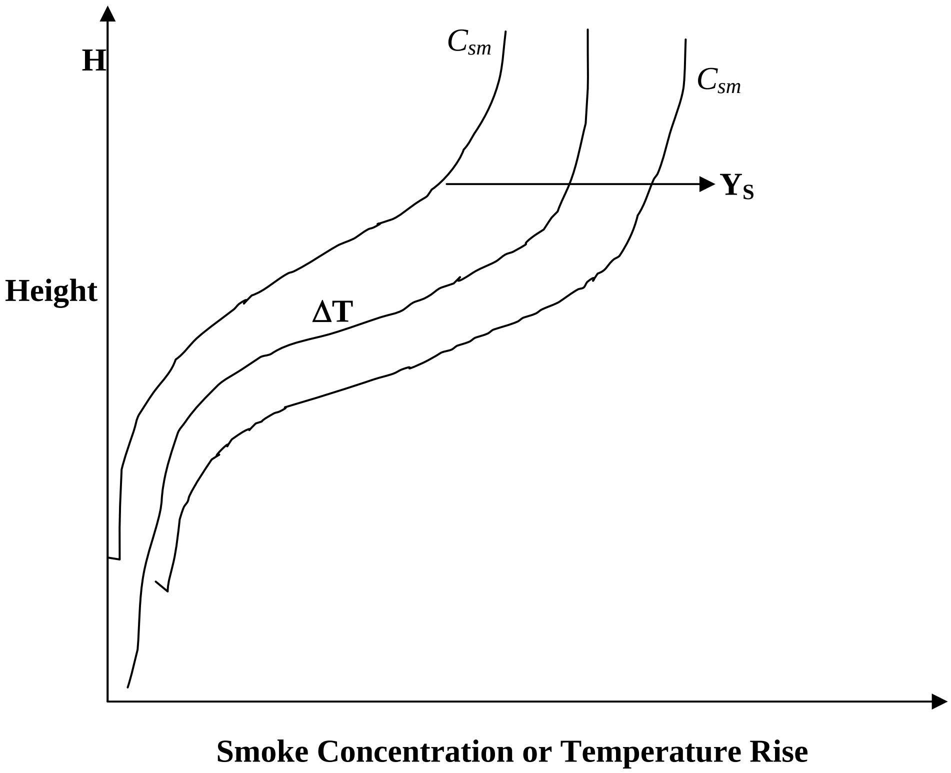

Figure 5: An illustration of how smoke concentrations increase at a given height as smoke yields increase for the same heat release rate whereas temperature rise does not change (Equation 1 should be reviewed in conjunction with this Figure).