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# A MODEL FOR CALCULATING THE PROBABILITIES OF SMOKE HAZARD FROM FIRES IN MULTI-STOREY BUILDINGS

by

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## SUMMARY

This paper presents a simplified model for calculating the probabilities of smoke hazard in multi-storey buildings. This model first establishes the fire development in a compartment on any floor, using the results from a one zone fire growth model[1], and then computes the smoke movement in the building, yielding the temperature and concentration of toxic gases at any location in the building. At a critical time, which is defined as the time when the conditions in the stairs leading to an exit are lethal, such that occupants are trapped and cannot evacuate, the smoke movement calculations are terminated and the probabilities of smoke hazard are computed based on the temperature and concentration of toxic gases in the building. The procedure used for the calculation of smoke movement, the critical time and the smoke hazard probabilities is described in this paper. Results are presented, as an example, for a twenty-five storey apartment building.

## INTRODUCTION

In the assessment of fire risks in multi-storey buildings, consideration of smoke movement in the building is of great importance. It has long been recognized that the exposure to toxic products and not the fire itself is the main cause of death[2,3]. This is especially true in multi-storey buildings where the movement of the toxic gases in the stairshafts often blocks the only escape routes.

Determining smoke movement in multi-storey, multi-compartment buildings is a difficult task due to the complexity of the problem and the large number of equations involved. The problem becomes even more difficult when dealing with risk analysis where all possible fire scenarios must be considered. For this project, three different design fires are used as representative fires with each having a probability of starting on every floor in the building. In addition, the effect of these fires must be examined during spring/fall, summer and winter seasons and for door open and door closed conditions. For example, the number of scenarios considered for a 10 storey building is: (10 floors) x (3 design fires) x (3 seasons) x (2 door conditions); a total of 180 different fire scenarios.

A number of researchers have developed models for the prediction of smoke movement and smoke concentrations in buildings. Some of these researchers use field modelling techniques, which apply numerical methods to solve the fundamental mass, momentum and energy equations[4-6]. These models, however, require very large computer times and the use of mainframe computers, even for only one fire scenario. Furthermore, field models are usually applicable to those problems where a single compartment is considered. For multiple compartments, the zone modelling technique is normally used, and a number of models have been developed[7,8]. Zone models with multiple compartments are still complex and require larger computer memory and time, so they are only applicable to small residential buildings with up to six compartments in total. The preferred techniques for multi-compartment buildings are based on network and graph theories[9-13], in which each compartment is one well-stirred cell. Although these models have been applied successfully in the design of smoke control systems in multi-storey buildings, they are very demanding in computer time when used for risk analysis, due to the large number of fire scenarios involved.

In this study, a simplified model is developed for calculating the probabilities of smoke hazard in multi-storey buildings where the probabilities of smoke hazard at different locations are calculated based on the concentrations of CO and $CO_2$ and the temperature at those locations. The effect of the lower visibility due to smoke on the smoke hazard probabilities has not been included in the present model. The lower visibility levels are considered, however, in the determination of the mobility of the occupants during evacuation. The effect of other toxic gases, such as HCN, has not been considered as it is negligible when compared to the effect of CO and $CO_2$[14,15].

The smoke movement model described in this paper is part of an integrated risk-cost assessment model which is being developed at the National Fire Laboratory of the Institute for Research in Construction, National Research Council of Canada in collaboration with the Victoria University of Technology in Australia[16-19]. The risk-cost model consists of a number of stochastic and deterministic sub-models used to simulate the interactions between fire growth and spread, smoke generation and movement, fire detection and suppression systems and egress of occupants. It is intended to be used for the assessment of the relative life risks and protection costs of different fire safety designs in the same building. Due to the complexity of the problem, it is necessary to use simple models to simulate the various problem components. The risk-cost model uses the smoke hazard probabilities, computed by the smoke movement model, together with the fire spread probabilities, computed by another submodel, to calculate the probabilities of death and safety at different locations in the building. These will then be used to compute the expected risk-to-life, which is defined as the expected number of fire deaths from fires in the building over the design life of the building.

## Modelling Approach

As part of the risk-cost model, the smoke movement model has to be a generic model so it can be applied without major modifications to a variety of multi-storey buildings. To achieve this, any multi-storey building is represented in the model in the generic form shown in Figures 1 and 2. On the floor of fire origin, the compartment of fire origin is considered separately while all other compartments are grouped together into one space. On all other floors, all compartments are grouped together into a single compartment. This grouping implies equal probabilities of smoke spread into these compartment. Fire growth in the compartment of fire origin is modelled using a one-zone model[1]. Two zones, however, are considered in the corridor on the floor of fire origin, as the hot gases in the corridor travel near the ceiling with

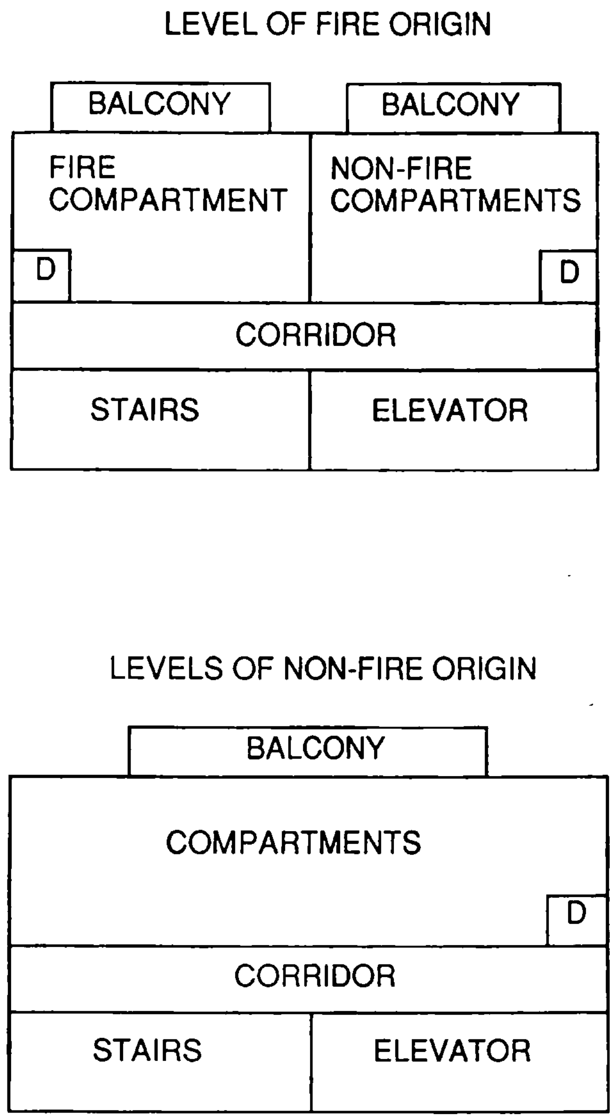


Figure 1. Typical floor layouts used in model.

minimal mixing with the lower cold layer. The hot gases from the corridor enter through doors and other openings to other compartments on that floor and to the stairshafts. In the stairshafts, it is assumed that the hot gases move upward and mix with the air above the floor of fire origin. This assumption is a reasonable one as the presence of the stairs enhances mixing in the stairshafts. As the temperature of the combustion products cools down as they move through the building, all other compartments in the building are modelled as single well stirred cells.

All doors in the building, except the doors leading to the compartment of fire origin, are assumed to have a specified probability of being open. For the door of the compartment of fire origin, two different fire scenarios are considered: one scenario with the door fully open and a second with the door fully closed. The calculations of smoke movement in the building and of the smoke hazard probabilities are done separately for each scenario. This approach was taken as the condition of the door of the compartment of fire origin not only affects smoke movement in the building, but also the rate of fire growth.

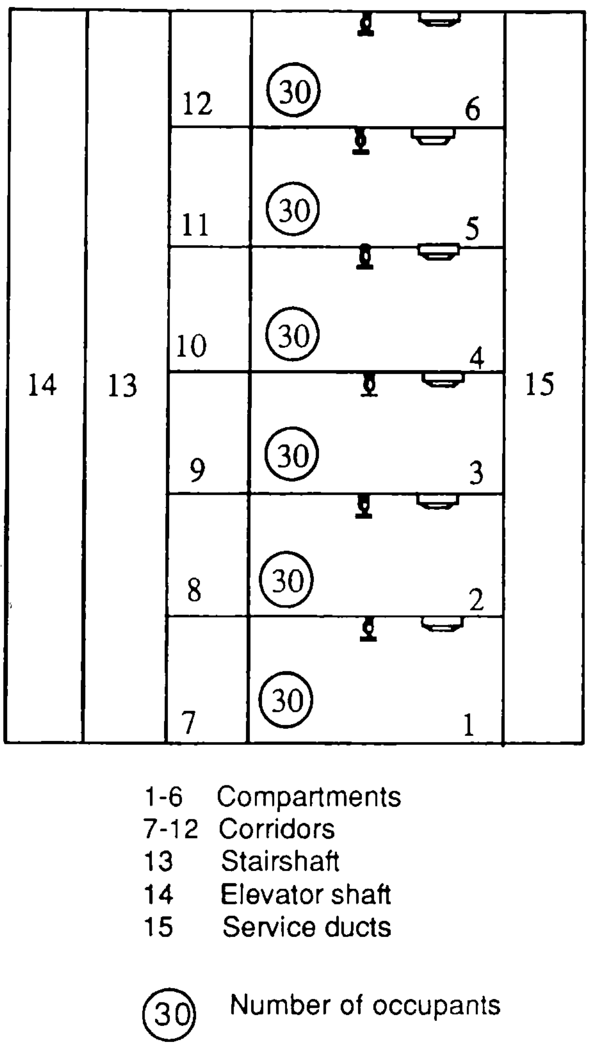


Figure 2. Typical generic building layout.

Another parameter that is considered in the calculation of smoke hazard probabilities is the season during which the fire occurs. As the outside temperature affects the flow of gases in the building due to stack effect, three seasons (winter, spring/fall and summer) are considered separately for the calculation of the smoke hazard probabilities.

For proper risk analysis, all possible fire scenarios should be evaluated and the effect of each one should be considered. The types of fires that can occur in a building, however, can be many which make it impossible to evaluate each one separately. To overcome this problem and still be able to consider the characteristics of various fires, all possible fires are grouped into the following three design fires:

- flashover fire;
- non-flashover flaming fire; and
- smouldering fire.

For this paper, the three design fires are considered independently to show the relative magnitude of smoke hazard probabilities resulting from each fire. Each design fire is considered starting on every floor during winter, spring/fall and summer seasons for door open and closed conditions. Fires are assumed to start in the compartments of the floor and not in the corridors or stairs. It is assumed that the fire load in the corridors and stairs is very little so it cannot sustain a fire.

## A Typical Fire Scenario

In the event of a fire in a compartment of a multi-storey, multi-compartment building, smoke spreads through the building mainly by buoyancy forces and stack effect. Smoke spread is also affected by HVAC systems and the direction and strength of winds. In the compartment of fire origin, the hot gases generated by the fire rise to the ceiling of the fire compartment creating a hot layer. As this hot layer gets thicker, its interface drops below the door height and spreads to the corridor and to other compartments. Since smoke entering the corridor is still hot, it moves near the ceiling and spreads along the corridor. When the interface of the hot gases in the corridor drops below the height of the door leading to the stairshaft, smoke enters the stairshaft and moves upward and mixes with the air in the stairshaft. From the stairshaft, smoke also enters other floors in the building. Evidence from real-world fires shows that smoke is present on floors above the fire floor while floors below the fire floor are usually smoke free. In the case where forces due to stack effect are present, depending on the elevation of the fire floor, smoke movement can either be suppressed or enhanced.

Based on the above description of a typical smoke movement scenario in a multi-storey building, a simple smoke movement model is developed for estimating the probabilities of smoke hazard in these buildings. Wind direction and speed, as well as the HVAC systems, may both affect the movement of smoke through the building, but their effect is not considered in this model. Wind effects are neglected as the model will be used for design purposes and not for the re-creation of fire scenarios, in which case the wind speed and direction are known. The effect of the HVAC system is neglected as it was assumed that the system will be shut off in the event of a fire.

The probabilities of smoke hazard are computed based on the conditions in the building at a critical time. The critical time in this model is assumed to be the time when the conditions in the stairshafts become untenable. For simplicity, the critical time for any fire on a particular floor is assumed to be the one based on a flashover fire on that floor during spring conditions. This conservative critical time is used as the reference time for all fires on that floor and for all seasons. At the critical time, the occupants are trapped in the building and are subjected to the hazard of smoke spread. The calculation of the smoke hazard probabilities is based on the temperature and the concentration of toxic gases in the building at the critical time and it is described in subsequent sections.

# Smoke Movement

The quantity of toxic gases produced by the fire is determined by the fire growth model, details of which can be found in Reference 1. This model includes flame spread and fire growth formulations under fuel controlled, ventilation controlled and oxygen vitiated conditions. The results of the fire growth model which are used by the smoke movement model are the mass flow rate of the hot gases leaving the compartment of fire origin, their temperature and the concentrations of the toxic gases.

## Mass Flow Rate to Corridor of Fire Floor

The gases leaving the fire compartment rise to the ceiling of the corridor and then move along the ceiling. To find the time required for the gases to reach the stairshaft, it is assumed that before the gases start entering the stairshaft, the space in the corridor above the door height must first be filled with smoke. From this assumption, the time required for the gases to reach the stairs is estimated as the time required to fill this volume. This is calculated using the volumetric flow rate of gases into the corridor and the volume above the lintel. The volume of the hot gases in the corridor at any time is given by the integral:

$$V_g = \int_o^t \left(\dot{m}_f / \rho f\right) dt \qquad (1)$$

where:

$V_g$ = volume of gases in the corridor at time $t$;

$\dot{m}_f$ = mass flow rate of hot gases from fire compartment to corridor as a function of time; and

$\rho f$ = density of hot gases coming from fire compartment.

The above equation assumes that there is no mixing between the upper and the lower layer in the corridor. The delay time is then determined as the time at which the volume of the hot gases in the corridor is equal to the volume of corridor above the top of the door.

## Mass Flow Rate to Stairshaft

The force driving the hot gases from the corridor to the stairs is buoyancy coupled with stack effect. In order to estimate the pressure difference due to buoyancy, the temperature in the corridor near the stairshaft door is required. In the present model, however, the heat losses to the walls of the corridor are not computed, therefore, the use of the temperature of the hot gases in the corridor will give an overestimated value of the buoyancy forces. To account for the heat losses, however, the empirical relation given by Evers and Waterhouse[11] is used, in which the temperature of the hot gases under the ceiling is computed as a function of the distance from the door of the fire compartment as follows:

$$\left(T_x - T_z\right) = K_1\left(T_f - T_z\right)\mathrm{Exp}\left(-K_2\,x\right) \qquad (2)$$

where:

$T_z$ = initial temperature in the building;
$T_x$ = temperature of the gases in the hot layer at distance x along the corridor from the fire compartment;
$T_f$ = temperature in the fire compartment;
$K_1$ = empirical constant equal to 0.05 when the fire compartment door to the corridor is closed and 0.5 when the fire compartment door to the corridor is open; and

$$K_2 = \left(K_1\,h\,W\right) / \left(\dot{m}_f\,S\right)$$

where:

$h$ = heat transfer coefficient at the ceiling surface;
$W$ = width of the corridor;
$\dot{m}_f$ = mass flow rate of hot gases into the corridor; and
$S$ = specific heat of smoke.

The temperature of the hot gases near the door leading to the stairs is then used to calculate the pressure difference across the door due to buoyancy. The relation used is:

$$\Delta P_b = K_b\left(1/T_{st} - 1/T_x\right)H/2 \qquad (3)$$

where:

$\Delta P_b$ = pressure difference due to buoyancy;
$K_b$ = constant (3460), $N{\cdot}K{\cdot}m^{-3}$ [20]
$T_x$ = temperature of gases in corridor;
$T_{st}$ = temperature in stairs; and
$H$ = door height.

Due to the temperature differences between the interior and exterior of the building, buoyancy forces are created. These forces cause the flow of gases through the building, a phenomenon known as stack effect. The pressure difference due to stack effect is computed using the relation:

$$\Delta P_s = K_b\left(1/T_a - 1/T_{st}\right)y \qquad (4)$$

where:

$\Delta P_s$ = pressure difference due to indoor outdoor temperature difference;
$T_a$ = temperature of outdoor air;
$T_{st}$ = average temperature in stairshaft; and
$y$ = floor height above neutral plane.

The buoyancy and stack effect forces are combined together yielding the total pressure difference which causes the flow of hot gases in the building. The quantity of gases flowing through an opening is then found using the flow equation;

$$\dot{m} = C_1\,A\left(\rho\,\Delta P\right)^{1/2} \qquad (5)$$

where:

$\dot{m}$ = mass flow rate;
$C_1$ = flow coefficient = 0.65;
$A$ = leakage area; and
$\rho$ = gas density, $P/(R\,T)$;

where:

T = absolute temperature of gases;
$P$ = pressure; and
R = gas constant.

The volume of the stairshaft above the floor of fire origin is assumed to be one cell, hence, the gases entering the stairshaft mix with the air in the stairshaft occupying this volume. This assumption is reasonable as mixing is enhanced by the presence of the stairs.

## Mass Flow Rate from Stairshaft to Upper Floors

It is assumed that the toxic gases in the stairshaft move to spaces above the fire floor. As their temperature is higher than the temperature in the corridors of the upper floors, buoyancy forces cause these gases to move through openings from the stairshaft to the upper floors. Forces due to stack effect also affect this movement. The quantity of hot gases entering the upper floors is determined using Equations 3 and 4. The gases entering the upper floors are assumed to instantaneously mix with the air in the corridors on these floors. From these corridors, the hot gases then move into the compartments adjacent to them. To be consistent with the risk-cost model, the compartments on each floor are combined to form one compartment. This implies that there is an equal probability of smoke spread from the corridor to each compartment.

## Temperature Calculation in a Compartment

Knowledge of the temperature at any location in the building is important because temperature affects the flow of gases through the building, and also is a life threatening property. The temperature, mass and density of the air in a compartment depend on each other and are computed using the mass balance equation:

$$\dot{m}_i - \dot{m}_o = d(m_c) / dt \tag{6}$$

the energy balance equation:

$$\dot{m}_i T_i - \dot{m}_o T_c = d\left(m_c T_c\right) / dt = 0,\ P = \text{constant} \tag{7}$$

and the perfect gas law:

$$\rho = P / \left(R\, T\right) \tag{8}$$

Equations 6 and 7 are integrated over the time step $\Delta t$ and then solved simultaneously resulting in the following equation:

$$T_c\left(t+\Delta t\right) = \left[\left(V_c\, P/R\right) + \dot{m}_i\left(t + \Delta t\right) \Delta t\, T_i\left(t + \Delta t\right)\right] / \left[\dot{m}_i\left(t + \Delta t\right) \Delta t + m_c\left(t\right)\right] \tag{9}$$

Assuming that the pressure in a compartment remains constant, Equations 7 and 8 also give the following:

$$\dot{m}_o\left(t + \Delta t\right) = \dot{m}_i\left(t + \Delta t\right) T_i\left(t + \Delta t\right) / T_c\left(t + \Delta t\right) \tag{10}$$

$$m_c\left(t + \Delta t\right) = V_c\, P / \left(R\, T_c\left(t + \Delta t\right)\right) \tag{11}$$

The flow of gases through any opening (door, window) is computed based on the pressure difference across that opening, due to buoyancy and stack effect, using Equation 5. This calculation, carried out for each opening in the building, yields the maximum possible rates that can occur in the building under the conditions considered; pressure increases in a compartment due to the incoming gases are not considered.

As each opening is considered independently in a once through calculation, the mass flow rate computed by Equation 10 may be different from that computed using Equation 5. This difference is corrected explicitly, as discussed in the following section, to maintain a mass balance in the building. In reality, as the hot gases enter a compartment, cooler gases may flow out near the bottom of the inlet. This flow, however, cannot be computed by the present model as each compartment is modelled as a single zone. This means that through each opening, gases can only flow in one direction as specified by the pressure difference across that opening.

To correct for any mass imbalances resulting from Equations 5 and 10, the following corrections are made:

1. In the case of the corridor on the fire floor, the mass difference is treated as follows:

   a) if the mass flow rate computed by Equation 10 is less than the rate computed by Equation 5, then the rate computed by Equation 10 is used as the mass flow rate into the stairshaft; and

   b) if the mass flow rate computed by Equation 10 is greater than the rate computed by Equation 5, it is assumed that the difference of these mass flow rates enters the non-fire compartments on the same floor.

In other words, this correction implies that no more gases than those coming out of the corridor can flow into the stairshaft, and that if the pressure difference across the door to the stairshaft is such that not all gases can flow through, the remaining gases enter into the other compartments on the same floor.

2. When the compartment is the stairshaft, the mass flow rates from the stairshaft to the floors above the floor of fire origin computed by Equation 5 are adjusted so that their sum equals the rate computed by Equation 10.

With these adjustments, mass balance is maintained through the building and the results are conservative, meaning that the maximum flow rates anticipated in the building are computed. As the results of this model will be used to compare a number of different fire protection systems in the same building, and to determine the relative smoke hazards, this simplified approach is considered adequate.

## Concentration of Toxic Gases and Dosage

The toxic gases considered for this study are CO and $CO_2$ because, for most practical situations, the composition of the fire atmosphere is such that the narcotic effects of CO are the most important toxic effects. The effect of $CO_2$ is that it increases the rate of breathing, thus increasing the intake of CO. The production of these gases is computed by the fire growth model. It is assumed that toxic gases entering a particular compartment mix with the air in that compartment instantly. The average concentration of toxic gases is computed based on the concentration of the incoming gases and the concentration in the compartment calculated in the previous time step. The equation used for the calculation is the differential equation:

$$\dot{m}_i C_i - \dot{m}_o C_c = d\left(m_c C_c\right) / dt \qquad (12)$$

where:

$\dot{m}_i$ = mass flow rate of gases entering a compartment;

$C_i$ = concentration of toxic gases of the incoming gases;

$\dot{m}_o$ = mass flow rate of gases leaving the compartment;

$m_c$ = initial mass of air in the compartment; and

$C_c$ = initial concentration of toxic gases in the compartment.

The solution to Equation 11 can be obtained by numerical integration over a small time step $\Delta t$ as follows:

$$C_c\left(t + \Delta t\right) = \left[\left(\dot{m}_i C_i - \dot{m}_o C_c\right)\Delta t + m_c\left(t\right) C_c\left(t\right)\right] / m_c\left(t + \Delta t\right) \qquad (13)$$

where:

$C_c(t+\Delta t)$ = concentration of toxic gases in the compartment at time $t+\Delta t$; and

$C_c(t)$ = concentration of toxic gases in the compartment at time $t$.

The solution of Equation 13 yields the concentration of the toxic gases with time. The method used to determine the effect of these gases for this study is the one described by Purser[21], in which the concept of fractional incapacitating dose (FID) is used. FID is defined as lethal at a value of 1. The FID due to CO is computed using:

$$FID_{CO} = \int_0^t \frac{8.2925 \times 10^{-4} \cdot \left\{ppm\ CO\left(t\right)\right\}^{1.036}}{30} dt \qquad (14)$$

where:

$FID_{CO}$ = fraction of incapacitating dose of CO; and

ppm CO(t) = concentration of CO at any time in parts per million.

The $CO_2$ concentration is used to determine a factor by which the FID from CO will be multiplied to take into account the increase of the breathing rate caused by $CO_2$. This factor is computed using:

$$VCO_2 = \frac{\exp\left(0.2496 \cdot \%\ CO_2 + 1.9086\right)}{6.8} \qquad (15)$$

where:

$VCO_2$ = multiplication factor for $CO_2$ induced hyperventilation.

The total fractional incapacitating dose is then:

$$FID = FID_{CO} \cdot VCO_2 \qquad (16)$$

FID values are computed at every location in the building, and occupants at those locations are subjected to these values depending on the length of time they stay at those locations. For the calculation of the critical time, that is, the time when the stairshaft becomes untenable, the time period during which FID value is computed is assumed conservatively to be the time required by a person to travel from the top floor to the fire floor. It is assumed that travelling from the top floor to the fire floor will be the maximum length of time occupants will remain in the stairshaft, therefore, this time is chosen as the time period for the calculation of the critical time.

The effects of the temperature in a compartment are also considered. It is assumed that the occupants can survive temperatures up to 100°C[22]. Higher temperatures are assumed to be lethal.

## Calculation of Smoke Hazard Probabilities

The calculation of the probabilities of smoke hazard in the building are based on both the concentration of toxic gases in the building, as well as the temperature in the building at the critical time. At this time, the smoke movement calculation is terminated. It was decided to terminate the calculation of smoke spread beyond the critical time due to the uncertainties involved. For example, it is very difficult to determine the action of the occupants in the event that they discover that they cannot evacuate through the stairshaft. It is assumed that these occupants will remain in their compartments waiting for the firefighters to assist them in evacuating the building and, therefore, they will be subjected to the smoke hazard probabilities in their compartment.

The calculations of the probabilities of incapacitation from toxic gases is based on the assumption that the risk to the occupants of a compartment is proportional to the FID levels and the temperature rise reached in that compartment, i.e., occupants in compartments with high FID values and high temperature increases are exposed to a higher risk than occupants in compartments with low FID and temperature values. Based on this assumption, the probability of incapacitation from toxic gases at any location is set equal to the FID value at that location at the critical time.

The probability of incapacitation from temperature at the critical time is defined as:

$$\mathrm{P}\left[\mathrm{T}\right] = \left(T_S - T_z\right) / \left(100 - T_z\right) \tag{17}$$

where:

$\mathrm{P}\left[\mathrm{T}\right]$ = probability of incapacitation from temperature;
$T_s - T_z$ = temperature rise in building (°C); and
$T_z$ = initial building temperature (°C).

Given that there is a fire in the building and the occupants cannot evacuate the building, the life of the occupants trapped in the building is at some unknown risk. The probabilities of smoke hazard computed provide an estimate of the relative risks at different locations in the building from the effects of toxic gases and temperature rise in their compartments. For example, although a temperature rise in a compartment of 10°C does not provide any cause for concern, it does indicate a risk knowing that this rise is due to a fire in the building, and occupants cannot evacuate.

The risk to the occupants from toxic gases and the risk from temperatures are assumed to be two independent, non-mutually exclusive events, therefore from probability laws[23] the combined probability of smoke hazard can be calculated using:

$$\mathrm{P_{SS}} = \mathrm{FID} + \mathrm{P}\left[\mathrm{T}\right] - \left(\mathrm{FID} \cdot \mathrm{P}\left[\mathrm{T}\right]\right) \tag{18}$$

where $\mathrm{P_{SS}}$ is the probability of death as a result of smoke spread.

The smoke hazard probability calculated with the method described above considers the conditions in the building from the time the fire started to the critical time. Fires, however, may behave differently after the critical time. For example, some fires might be extinguished while others might grow to fully developed fires. To account for this in the probability of smoke hazard, a correction factor is used. This correction factor is calculated using the ASTM standard temperature-time curve as reference and it is defined as the ratio of the area under the computed time-temperature curve divided by the area under the ASTM curve for the same duration. All probabilities are then corrected by multiplying them by this correction factor.

The smoke movement model is a sub-model of a comprehensive risk-cost assessment model which also includes sub-models dealing with fire growth, fire spread and egress of people. Details of the other sub-models can be found in Reference 16. The smoke hazard probabilities computed by the smoke movement model are used together with the probabilities of death due to fire spread to compute the overall probability of death at different locations in the building.

## RESULTS AND DISCUSSION

The smoke movement model described in this paper was used to determine the smoke conditions in a 25-storey apartment building resulting from a fire starting on the first floor, as well as the smoke hazard probabilities in the building from fires starting on each floor and for winter, summer and spring/fall conditions. Three different fires are used for this calculation. These, which represent all fire scenarios encountered in real life, are flashover fires, flaming non-flashover fires and smouldering fires.

The building has 14 apartments on each floor with a total floor area of 1400 m$^2$ and two stairwells located at the two ends of the building. The corridor has a width of 2 m and a length of 50 m.

### Flashover Fires

Figure 3 shows the conditions in the apartment of fire origin on the first floor as a function of time for a flashover fire in terms of temperature and CO and $CO_2$ concentrations[1]. The mass flow rate of the gases leaving through the open apartment door is also shown. The sudden changes of the variables at about 9 min are due to a window breaking at that time. Figure 4 depicts the temperatures at various locations in the building due to this fire. The figure demonstrates that the temperatures in the corridor on the first floor and the stairshaft rise very quickly and reach dangerous levels (100°C) in about 8-10 minutes. It takes approximately 20 minutes, however, for the temperature in the apartments on the 25th floor to reach this critical limit.

Figure 5 shows the fractional incapacitating dose (FID) resulting from the flow of toxic gases

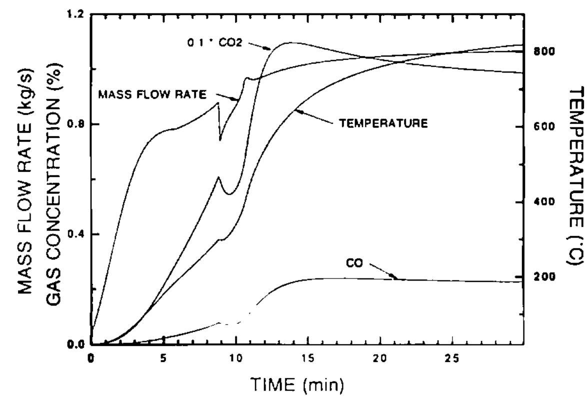


Figure 3. Conditions in apartment of fire for a fully developed fire with door open.

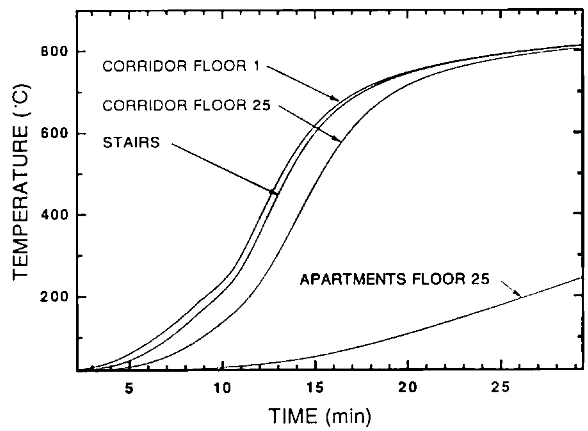


Figure 4. Temperature development at various locations in the building for a fully developed fire with door open on the first floor.

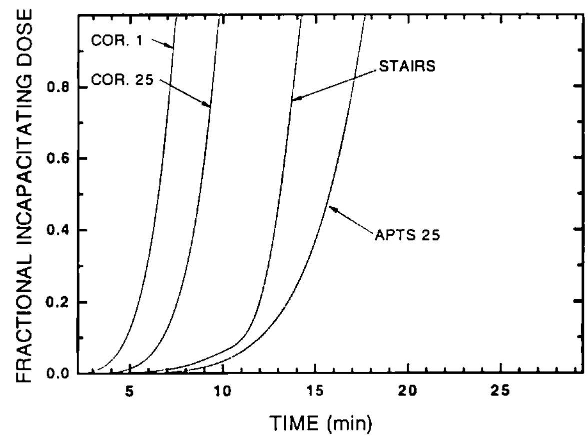


Figure 5. FID values at various locations in the building for the fully developed fire with door open on the first floor.

in the building. In about 7.5 minutes, the FID value in the corridor of the first floor reaches 1 (limit of incapacitation), while it takes about 10 minutes for the corridor on the 25th floor to reach the critical limit. The FID in the apartment on the 25th floor reaches the critical limit within 18 minutes. In the stairshaft, the FID values are lower due to the assumption that the time used for the calculation of the FID value in the stairshaft is the time needed for the occupants to go down the stairs from the top floor to the floor below the fire floor and not the time from the instant when the fire started.

Figure 6 shows the smoke hazard probability distribution in the building due to flashover fires. They are computed for fires starting on each floor with an equal probability of occurrence and for summer, spring/fall and winter conditions. The door of the apartment of fire origin was assumed to have a probability of 0.5 of being open, while the doors to the stairshaft have a probability of 0.2 of being open. The results show that the probabilities of smoke hazard in the stairshaft are the highest followed by the probabilities in the corridors, except for the first and second floor. The smoke hazard probability in the corridor on the first floor is greater than that in the stairshaft while on the second floor it is equal. The probabilities of smoke hazard in the apartments are approximately one order of magnitude less than those in the corridors. All probabilities increase from the ground to the top floor. The jump seen around the thirteenth floor is due to the neutral plane which is at that height.

## Flaming Non-flashover Fires

Figure 7 shows the conditions in the apartment of fire origin on the first floor for a flaming non-flashover fire. The maximum temperature is now below the flashover limit of about 600°C. At approximately 17 minutes, all the fuel is consumed and the fire extinguishes. Figure 8 depicts the temperatures at various locations in the building due to this fire. The temperatures in the corridors and stairs rise quickly to the dangerous level (100°C). At approximately 19 minutes, they begin to drop as a result of the extinguishment of the fire. Figure 9 shows the FID values at various locations in the building.

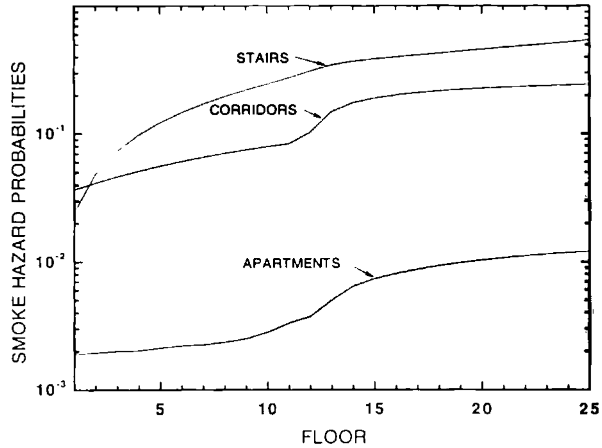


Figure 6. Smoke hazard probabilities on each floor in the building due to fully developed fires on each floor.

The FID values in the stairshaft drop below 1 at approximately 21.5 minutes due to the extinguishment of the fire. In the corridors, the FID values reach 1 at roughly the same time as that of the flashover fire. The reason for this is that, at the initial stages, the two fires develop at the same rate. Figure 10 shows the probabilities of

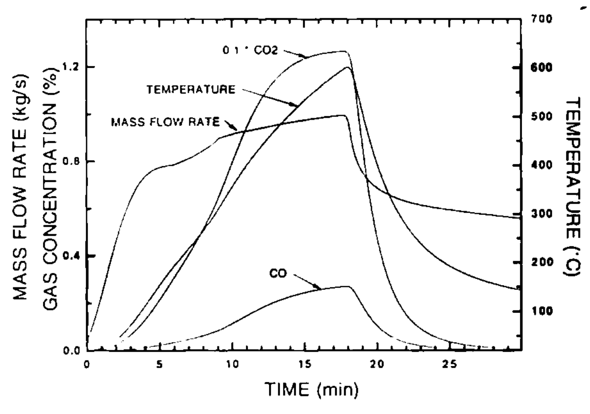


Figure 7. Conditions in apartment of fire for a non-flashover fire with door open.

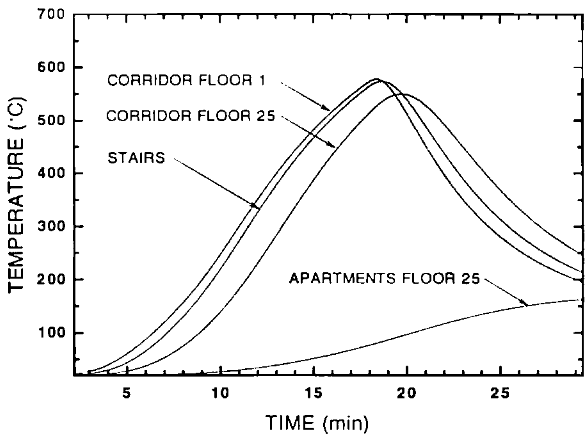


Figure 8.Temperature development at various locations in the building for a non-flashover fire with door open on first floor.

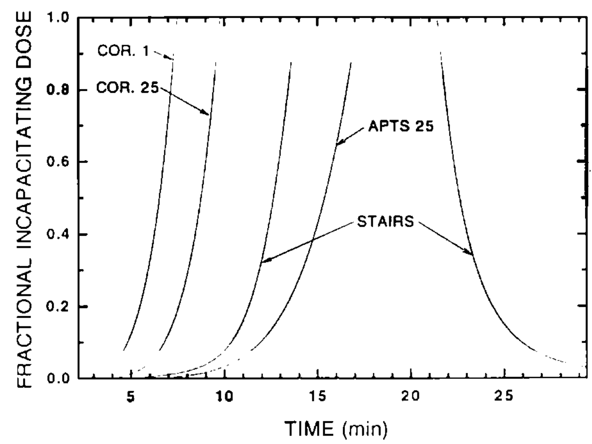


Figure 9. FID values at various locations in the building for a non-flashover fire with door open on the first floor.

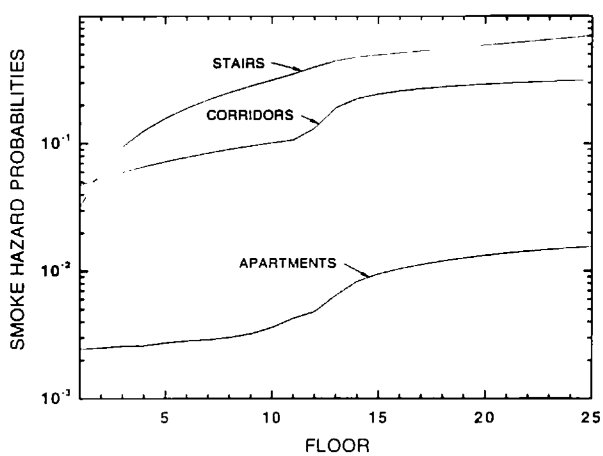


Figure 10. Smoke hazard probabilities at each floor in the building due to non-flashover fires on each floor.

smoke hazard in the building for flaming non-flashover fires starting on each floor and for winter, summer, spring/fall conditions. The values shown are approximately 25% less than those of the flashover fire case.

## Smouldering Fires

Figure 11 shows the conditions in the room of origin for the smouldering fire, in terms of temperature, CO and $CO_2$ concentrations. The probabilities of smoke hazard in the building for smouldering fires starting on each floor are shown in Figure 12. They are about two orders of magnitude less than those of the flashover and non-flashover fires. One main difference between this case and the previous one, is that the probability of smoke hazard in the corridors is greater than that in the stairshaft. This shows that the effect of smouldering fires is greater in areas close to the fire than remote areas.

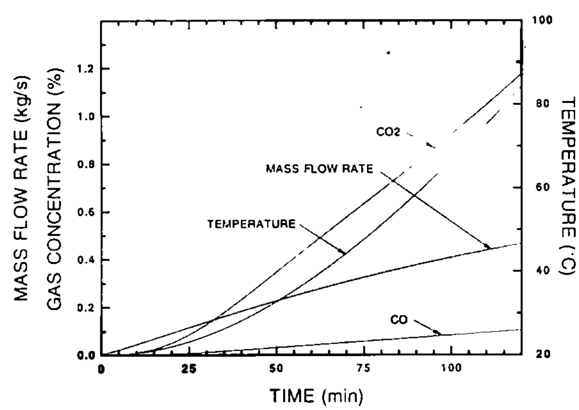


Figure 11. Conditions in apartment of fire for a smouldering fire.

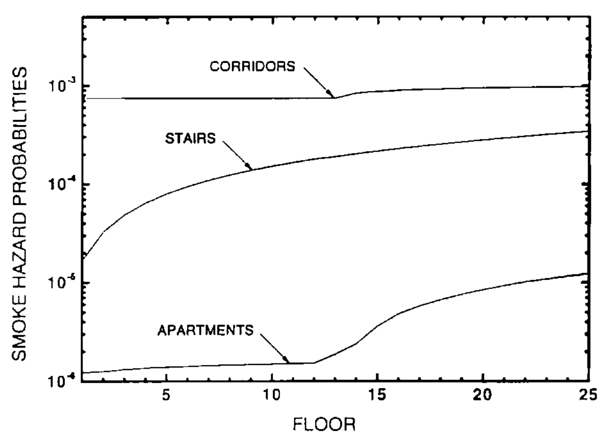


Figure 12. Smoke hazard probabilities at each floor in the building due to smouldering fires on each floor.

## Concluding Remarks

A methodology for determining smoke hazard probabilities in multi-storey buildings has been presented and some of the results that can be obtained using this method have been demonstrated. The probabilities of smoke hazard computed give only an indication of the relative smoke hazards in multi-storey buildings from fires starting on any floor in the building. The method by itself does not consider the effects of fire detection, warning and occupant response, nor the effects of fire spread. Probabilistic information of smoke hazard, however, is very important in the development of computer models that can be used to assess the risks from fires in buildings.

## Nomenclature

A Area ($m^2$)

C Concentration (%)

FID Fractional incapacitating dose

h Heat transfer coefficient ($kW/m^2 \cdot K$)

H Height (m)

m Mass (kg)

P Pressure ($N/m^2$)

P[] Probability of term in square brackets

R Gas constant (8.314 kJ/mol·K)

S Specific heat (kJ/kgK)

T Temperature (K)

t Time (s)

V (Volume ($m^3$)

$VCO_2$ Multiplication factor for $CO_2$ induced hyperventilation

W Width (m)

x Distance (m)

y Height (m)

**Subscript**

a outdoor

b buoyancy

c compartment

f fire compartment

g gas

i incoming

o outgoing

st stairshaft

z initial building condition

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