How design fires can be used in fire hazard analysis

Yung, D. T.; Bénichou, N.

Publisher's version / Version de l'éditeur:
https://doi.org/10.1023/A:1019830015147
Fire Technology, 38, July 3, pp. 231-242, 2002-07-01

How design fires can be used in fire hazard analysis

Yung, D.T.; Bénichou, N.

NRCC-44511

A version of this document is published in / Une version de ce document se trouve dans :
Fire Technology, v. 38, no. 3, July 2002, pp. 231-242

HOW DESIGN FIRES CAN BE USED IN FIRE HAZARD ANALYSIS*

David Yung and Noureddine Benichou

Fire Risk Management Program
National Research Council of Canada
Ottawa, Ontario, K1A 0R6, Canada

ABSTRACT

Many countries have introduced, or are planning to introduce in the near future, performance/objective-based codes. In a performance/objective-based code, the level of safety provided to the occupants in a building by a particular fire safety design will be assessed by the use of engineering analysis of fire development and occupant evacuation. Central to this performance-based approach is the use of suitable design fires that can characterize typical fire growth in a fire compartment. This paper gives a description of how such design fires can help analyze fire hazards to the occupants of a building as a result of fire development, smoke movement, and occupant response and evacuation.

INTRODUCTION

During the past decade, many countries in the world, such as New Zealand, Australia and the U.K., have moved towards performance-based codes. In line with this worldwide trend, the U.S. and Canada are planning to introduce performance/objective-based codes in the near future. In a performance-based code environment, performance fire safety requirements, rather than the current prescriptive requirements, are specified. This performance-based approach allows for flexibility in design that can lead to lower construction costs without lowering the level of safety.

The success of performance-based codes can be facilitated by the availability of risk assessment tools (usually models), that can predict the overall fire safety performance of a building. Other tools that can help with fire safety performance evaluation are suitable design fires that can characterize typical fire growth in a fire compartment. Such design fires can help standardize the fires that are to be used for fire safety evaluation. Without such standardized design fires, different fire safety designers may use different fire characteristics for their fire safety analysis.

How can standard design fires be developed for use in fire risk assessment was proposed by the authors in a previous paper presented at the 1999 symposium[1]. The prediction of fire growth in a compartment, before it happens, is difficult due to the uncertainties in determining the type, quantity, and arrangement of combustibles, as well as the point of ignition of these combustibles.

* Presented at the 5th Fire Risk and Hazard Assessment Research Application Symposium, Atlantic City, New Jersey, June 28-30, 2000.

The proposed design fires depend only on parameters that can be characterized *a priori*, such as the occupancy type, amount of combustibles, size of the compartment and the ventilation conditions. Random parameters, such as the arrangement of the combustibles and the point of ignition, are taken into consideration by using statistical information on probabilities of fire types.

In this paper, the concept of design fires is briefly described. The output of design fires provide information not only on how fast heat and smoke are generated in a compartment of fire origin, but also information that can be used by other models to predict smoke movement and fire spread to other parts of a building. This paper describes how fire hazards to the occupants in a building can be assessed by analyzing fire development, smoke movement and occupant response and evacuation in a building. Some results of a recent application of the National Research Council of Canada's (NRC) risk-cost assessment model FiRECAM™ [2], are given as an illustration.

CONCEPT OF DESIGN FIRES

The concept of design fires[1] was developed based on the following considerations of the probabilistic and deterministic aspects of accidental fires.

Fire Scenarios for Fire Risk Assessment

Proper assessment of the expected risk of loss of life of the occupants and other fire losses, requires that all probable fire scenarios that may occur in a building be considered. A fire scenario is a description of the state of a set of governing parameters that would dictate the outcome of the fire development, smoke movement, occupant evacuation and fire department response. For example, governing parameters, and their possible state and resultant impact, include the:

- location of the fire in a building - a fire occurring on the ground floor poses more hazards to the occupants than a fire occurring on the top floor;
- type of fire that may occur and develop in the compartment of fire origin - a small fire produces little smoke and heat; whereas a flashover fire produces large amounts of smoke and heat and could spread through walls and ceilings as well as openings;
- condition of the door to the compartment of fire origin - an open door allows fire and smoke to spread more readily than a closed door.

The probability of a governing parameter in a particular state can be obtained from statistics or, in the absence of such statistical information, from expert opinion. For example, the probability of a fire occurring in the compartment of fire origin being a flashover fire can be obtained from statistics; whereas the probability of the door to the compartment of fire origin being open or closed can often be obtained from expert opinion. The probability of a fire scenario is the product of the individual probabilities of its governing parameters. The probability of a fire scenario, multiplied by the expected number of occupant deaths as a result of that scenario, gives the expected risk of loss of life of the occupants from that scenario. The summation of the expected risks from all probable fire scenarios gives the overall expected risk of loss of life of the occupants. This is expressed in Eq. (1) as:

$$\text{Expected Risk of Loss of Life} = \Sigma\ P_i \times C_i \qquad (1)$$

where Σ represents the summation of all probable fire scenarios, P_i is the probability of one specific fire scenario and C_i is the expected number of deaths from that fire scenario.

Fire Types and Probabilities of Occurrence

The types of fires that can occur in a compartment in a building can be many, from a small fire to a flashover fire. Obviously, the complete range of fire types cannot be considered in fire risk assessments because the number of calculations involved would be too numerous. One approach, as employed in NRC's FiRECAM™, is to consider only three generic fire types that represent the three distinct types of fires that may occur. They are: (1) smouldering fires where only smoke is generated; (2) non-flashover flaming fires where a small amount of heat and smoke is generated; and (3) flashover fires where a significant amount of heat and smoke is generated with a potential for fire spread to other parts of the building.

The probabilities of these three fire types, for both apartment and office buildings, were obtained for Australia[3], the United States[4] and Canada[5]. They were obtained based on independent analyses of fire statistics in these three countries. The definition of fire type, is based on the severity of the fire when it was observed and recorded by the firefighters upon their arrival. Obviously, small fires can develop into fully-developed, post-flashover fires if they are given enough time and the right conditions. For risk assessment purposes, however, the fire conditions at the time of fire department arrival are the appropriate ones to use. They represent the fire conditions that the occupants are exposed to prior to fire department extinguishment and rescue operations. In the event of no fire department response, then the eventual conditions of the fire at extinguishment, either by itself or by occupant intervention, are the ones to be used. The reason why fires can develop into different types with different probabilities is because they are governed by a number of random parameters that cannot be predicted: the type of ignition source, the point of ignition and the arrangement of the combustibles.

Table 1 shows the probabilities of the three fire types, after ignition, for apartment buildings. It is interesting to note that the probabilities are quite similar among the three countries, even though there is no reason that these numbers should be the same due to climatic and cultural differences. Table 1 also clearly demonstrates the importance of considering all fire types. For example, flashover fires, which can pose significant hazards to the occupants, have a relatively low probability of occurrence; whereas non-flashover and smouldering fires, which pose lower hazards to the occupants, have a higher probability of occurrence.

Table 1. Probabilities of fire types for apartment buildings.

	Australia	U.S.A.	Canada
Smouldering Fire	24.5%	18.7%	19.1%
Non-flashover Fire	60.0%	63.0%	62.6%
Flashover Fire	15.5%	18.3%	18.3%

Design Fires

In addition to the random parameters described in the previous section, that govern the type of fire that can develop, the condition of the door to the compartment of fire origin is another random parameter that also affects the fire growth. The fire type and the door condition can be combined to create six design fires that allow all the random parameters that govern fire growth to be easily considered. The six design fires are:

1. smouldering fire with the fire compartment entrance door open,
2. smouldering fire with the fire compartment entrance door closed,
3. flaming non-flashover fire with the fire compartment entrance door open,
4. flaming non-flashover fire with the fire compartment entrance door closed,
5. flashover fire with the fire compartment entrance door open,
6. flashover fire with the fire compartment entrance door closed.

The probability of each of these design fires is the product of the probability of the fire type (Table 1) and the probability of the door to the compartment of fire origin being open or closed. The probability of the door being open or closed can be estimated based on experience. For example, the entrance door to an apartment unit can be assumed to be mostly closed (for security and privacy reasons); whereas the entrance door to an office room can be assumed to be mostly open (to allow work interaction).

Single Representative Fuel

Other than the above-mentioned random parameters, all other parameters that govern fire growth are deterministic. They are mainly the size of the compartment, ventilation conditions (natural or mechanical), and the type and amount of combustibles. The size of the compartment and the ventilation conditions are design parameters. The type of combustibles can be estimated based on occupancy type. For example, apartments have mainly upholstered furniture whereas offices have mainly paper products. The amount of combustibles can be estimated based on statistics or judgement. For example, apartments have an average of 17 kg/m^2 of furniture[6]. Obviously, not all the furniture is combustible. What percentage is combustible requires further study.

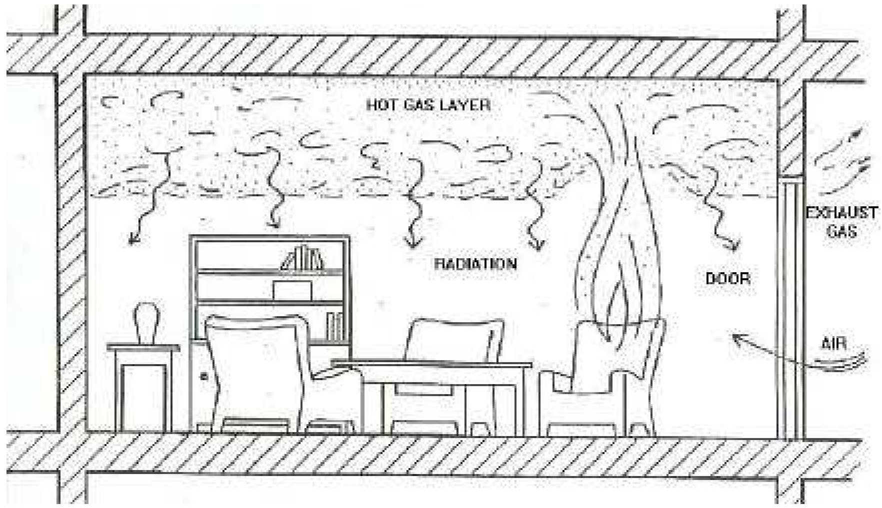
To develop the fire growth characteristics of the six design fires, one simple way to do this is to assume that all the combustibles in the fire compartment can be represented by a single fuel element with the ignition point at the centre. This avoids the difficulties of having to consider the random nature of the arrangement of the furniture, the ignition point and the ignition source. This is depicted in Fig. 1 where a typical furniture layout is represented by a single fuel element with the point of ignition at the centre. The total surface area and mass of the single fuel element can be made equal to those of actual furniture layout to allow the single fuel element to have similar fuel surface area and mass - the parameters that govern fire intensity and duration. By putting all the combustibles together side by side, hence a faster flame spread and a faster fire development, the single fuel element creates a fire that is faster than that which the actual furniture would produce. For conservative risk assessments, however, a quicker fire is more suitable. Also, the actual furniture contains many types of combustible material. The use of a single fuel avoids this difficulty. Obviously, the single fuel element has to be able to create a fire that is representative of fires that involve many types of combustible material.

The size of the fuel element governs the size and intensity of the design fire. A large fuel element that is representative of the total amount of combustibles in a typical apartment unit or office room will easily create a flashover fire. On the other hand, a small fuel element, representing the burning of a small object without spreading to all the combustibles in a room, will create a non-flashover fire because the heat generated is not sufficient to create a flashover fire. As for smouldering fires, a low intensity heat source, such as cigarettes, and special fabrics can be used to create non-flaming smouldering fires. The fire growth model that is employed in the NRC FiRECAM follows this approach[7].

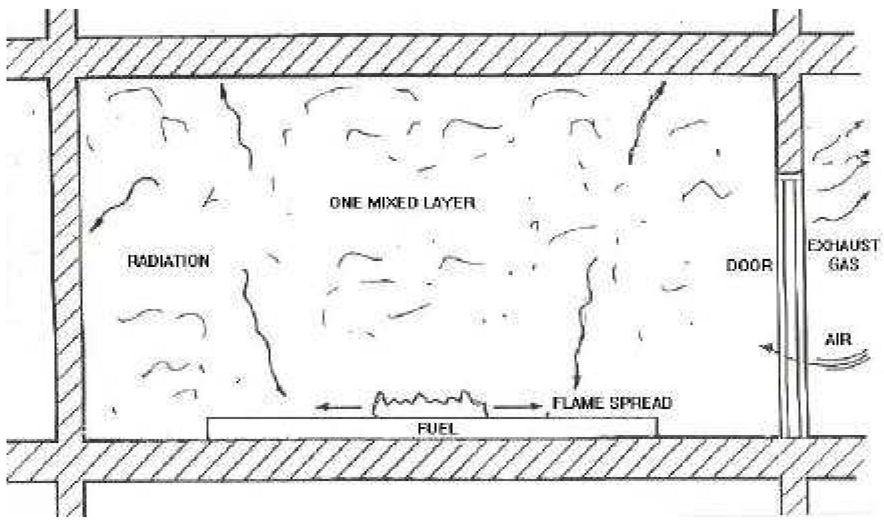
The fire characteristics that are needed for fire risk assessments and fire safety designs include those in the room of fire origin as well as those of the toxic gases that leave the room. The fire characteristics in the room of fire origin include the time-dependent development of the temperature and toxic gases that affect the activation times of detectors and sprinklers, the safety of the occupants and the integrity of the boundary elements. The toxic gases that leave the room of fire origin cause smoke and fire spread that affect the life safety of other occupants in the building. The important parameters to be considered are the flow rate of the toxic gases that leave the room as well as the temperature and concentrations of the toxic gases. Fires, in general, produce many toxic gases. For risk assessment, the basic toxic gases CO and CO_2 should be considered[8]. The composition of typical fire gases 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.

HAZARD ASSESSMENT

The six design fires, described above, can be used to assess the fire hazards to the occupants of a building. The output of a design fire, assumed to have occurred in a



(a)



(b)

Fig.1. (a) Representation of typical furniture layout and burning and (b) by a single fuel element and a one-zone fire model. Although not shown, the position of the single fuel element is to be at a level representative of that of actual burning of real furniture.

particular location in a building, can be used to assess, through the use of fire growth, smoke movement and occupant response and evacuation models, the hazards to the occupants. Hazard assessment is the assessment of the hazards to the occupants as a result of the occurrence of one particular design fire in a particular location in a building. Risk assessment includes the probabilities of occurrence of the design fires. In here, only hazard assessment is considered to illustrate how the design fires can be used for such purposes. It involves the assessment of smoke movement and occupant response and evacuation. For this analysis, the smoke movement and occupant response and evacuation models developed at NRC are used. However, any other credible models that can produce the required outputs, can also be used to carry out the hazard analysis.

Smoke Movement

As described in the Concept of Design Fire Section, the output of design fires includes the flow rate of the toxic gases that leave the room, as well as the temperature and concentrations of the toxic gases. The output of the design fires provides all the initial conditions for a smoke movement analysis. Based on the layout of the building and any internal air movement such as that caused by temperature differences between the inside and outside of a building, one can calculate the smoke movement in the building as a function of time. Such an approach was employed in the Smoke Movement Model in NRC's FiRECAM[8] tool. This model also calculates the critical time in the stairshafts, defined as the time that the buildup of smoke is at a level that the occupants cannot use the stairs to egress. The trapped occupants are then exposed to the buildup of smoke and toxic gases in the building until such time when they are rescued by the firefighters when they arrive. Life hazards to the occupants are assessed by the total dose of toxic gases that the occupants have inhaled into their body up to the time of fire department arrival.

One method to determine the smoke hazard from the buildup of these toxic gases is that employed by NRC's Smoke Movement Model[8], in which the concept of fractional incapacitating dose (FID[9]) and the probability of incapacitation from temperature (PIT) are used. The FID due to the narcotic effects of CO is calculated using:

$$FID_{CO} = \frac{\int_0^t K\ CO^{1.036}\ dt}{D} \qquad (2)$$

where:

- FID_{CO} = fraction of incapacitating dose from CO,
- K = 8.2925×10^{-4} for light activity,
- CO = CO concentration (ppm),
- D = 30 for 30% carboxyhemoglobin concentration at incapacitation,
- t = time (min).

The effect of CO_2 is to increase FID_{CO} as a result of an increase in breathing rate. The multiplication factor is calculated using:

$$VCO_2 = \frac{\exp\ (0.2496 \cdot CO_2 + 1.9086)}{6.8} \qquad (3)$$

where:

VCO_2 = multiplication factor for CO_2 induced hyperventilation,
CO_2 = CO_2 concentration (%).

The total fractional incapacitating dose is then:

$$FID = FID_{CO} \bullet VCO_2 \qquad (4)$$

The probability of incapacitation from high temperatures is calculated using the following simple equation based on the assumption that the incapacitation has a value of 1 when the hot gas temperature reaches 100 °C:

$$PIT = \frac{T_S - T_Z}{100 - T_Z} \qquad (5)$$

where:

PIT = probability of incapacitation from temperature,
$T_s - T_z$ = temperature rise (°C),
T_z = initial building temperature (°C).

The risk to the occupants from toxic gases and from temperature are assumed to be two independent, non-mutually exclusive events. Therefore, the probability of smoke hazard can be calculated using:

$$P_{SS} = FID + PIT - (FID \bullet PIT) \qquad (6)$$

Occupant Response and Evacuation

After a fire has occurred in a compartment, occupant response depends on whether the occupants receive a warning signal. The signals can be from any of the following:

- direct perception of the fire,
- local smoke alarms,
- central fire alarms with bell only,
- central fire alarms with voice messages,
- warnings by others,
- warnings by firefighters.

Depending on where the occupants are located, they receive the various warning signals at different times. As a result, occupants at different locations would respond at different times. Based on the research results of Proulx[10], the response of occupants in an emergency situation follows a process called PIA (perception, interpretation and action). The clearer the signals are that there is an impending danger, the more likely and more quickly the occupants would go through the PIA process and respond. In addition, occupants respond faster when they are awake than when they are asleep.

Once an occupant has decided to respond, the evacuation can be calculated by following the movement of the occupant from the original location, through corridors, stairshafts and eventually out of the building. The occupants would be trapped on their floors if the stairshafts become untenable because of the buildup of smoke. This methodology allows the user to calculate whether the occupants can successfully evacuate a building[11].

EXAMPLE OF A 3-STOREY APARTMENT BUILDING

Based on the methodology described in previous sections, the smoke movement and occupant evacuation as a result of a fire that has occurred in a particular location in a building can be calculated. As an example, the results of a recent study[12] using FiRECAM is described here on the trade-off of mandatory sprinkler protection verses a faster fire department response. In this study, a 3-storey apartment building was used as a model building, assumed to be as shown in Fig. 2. The building is 40 m wide and 21.5 m deep. Each level has 8 apartment units, a central corridor and two stairshafts at the two ends of the corridor. Each apartment unit is assumed to have an area of 100 m^2. A fire could start in any one of the units and spread through the corridors and shafts to other units in the building. The number of occupants per floor is assumed to be 20, approximately 2.5 occupants per unit. The occupants are assumed to evacuate through the stairs. If the stairs become untenable, they are assumed to stay in their apartment units to be rescued by firefighters when they arrive. The building complies with the 1995 National Building Code of Canada requirements, which include a smoke detector in each apartment unit, a central alarm, and self-closing devices on apartment entrance doors as well as stairwell doors.

As an example, to show the prediction of fire growth, smoke movement and occupant evacuation in this building, a non-flashover fire is assumed to have occurred in the centre apartment unit, on the ground floor, with the apartment door open, as shown in Fig. 2. Note that a fire occurring on the ground floor poses more hazards to the occupants than a fire occurring on the upper floors. Figure 3 shows the output of a non-flashover fire, as generated by the Fire Growth Model of FiRECAM. This figure shows the mass flow rate of the toxic gases out of the door, the temperature and concentrations of the toxic gases CO and CO_2. If this is a flashover fire, the fire growth is quicker and stronger; and if this is a smouldering fire, it is much slower and less hot. For this demonstration, we use a not-too-severe fire, a non-flashover fire. Also, a more severe fire is produced when the apartment door is open than that when the door is closed. For this example, the door is assumed open.

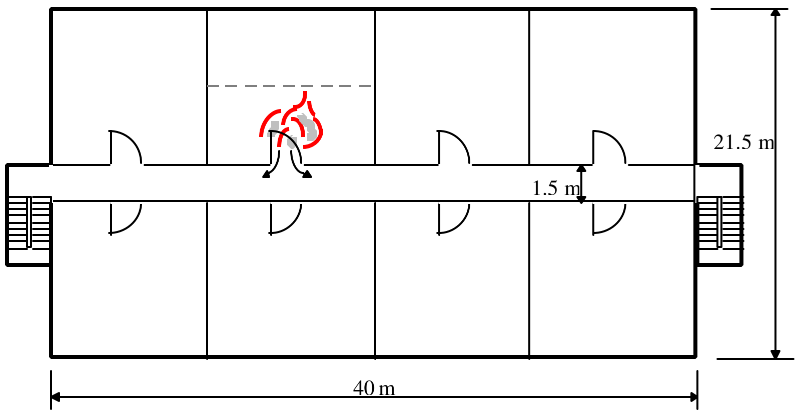


Fig. 2. Floor layout of a 3-storey apartment building.

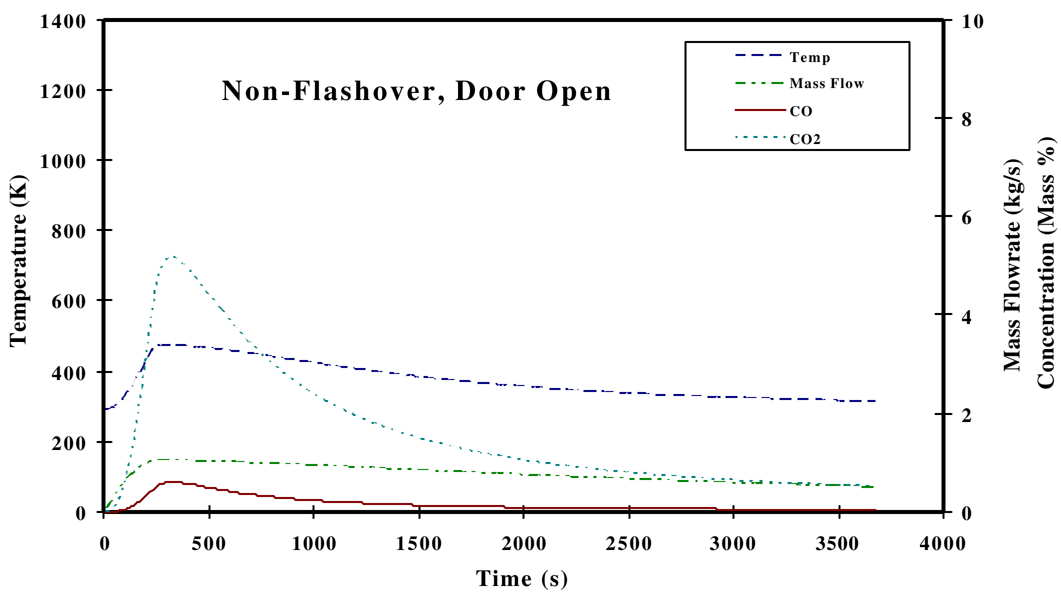
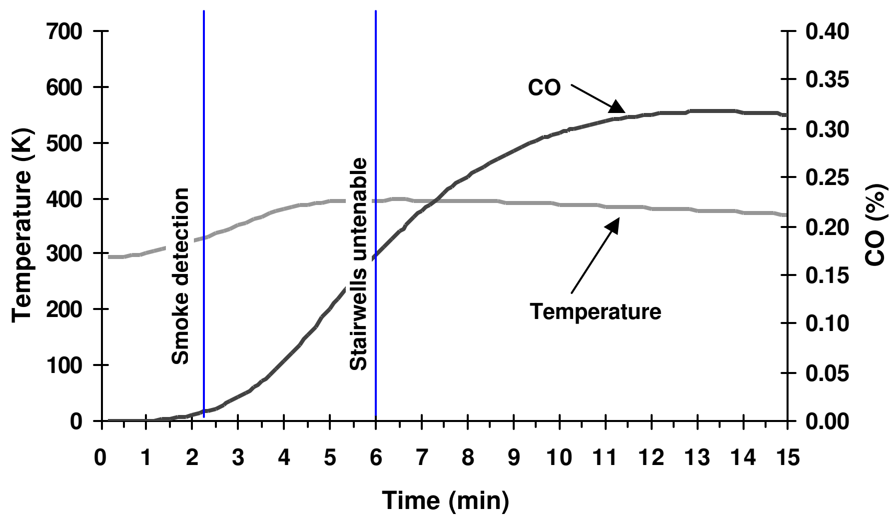


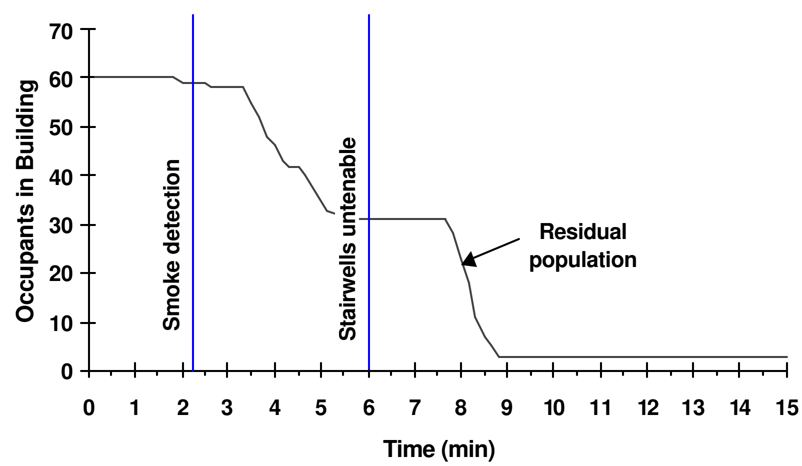
Fig. 3. Output of a non-flashover fire in one apartment unit with the entrance door open.

Smoke build-up in the two stairshafts and the profile of occupant evacuation are shown in Fig. 4(a) and 4(b) respectively. The results are produced by the Smoke Movement Model and Occupant Response and Evacuation Models of FiRECAM. In this example, a fire is assumed to have occurred during waking hours. If the occupants are asleep at night when the fire occurs, the Occupant Response Model assumes a longer response time. Figure 4 also shows the time of activation of smoke alarms at 2.2 min and that the stairs become untenable at approximately 6.0

min. About half of the occupants, mainly from upper floors, are trapped in the building. Figure 4(b) shows the evacuation profile after 6.0 min as if the stairs are still usable. The results in Fig. 4 provide some insight on how long it takes for the stairs to become untenable and how long it takes for the occupants to evacuate



(a)



(b)

Fig. 4. The buildup of smoke and heat in the stairshaft (a) and evacuation of occupants (b) as a function of time for a non-flashover fire occurring on the first floor with the entrance door of the fire apartment open and with occupants in the building awake.

the building. Although not shown here, similar results of a flashover fire on the ground floor show the untenable time in the stairs to be sooner at 4.2 min and about half of the occupants from the upper floors would not be able to evacuate the building.

SUMMARY

Design fires are needed for fire risk assessments and fire safety designs for buildings. Otherwise, different fire safety designers may use different fires for their analysis. In this paper, the concept of design fires and how they can help analyze fire hazards to the occupants are described. The output of design fires can provide the required input into smoke movement models and occupant evacuation models for such analysis. As an example how this can be done, the results of a recent study that was carried out at the National Research Council Canada using FiRECAM were presented.

REFERENCES

1. Yung, D. and Benichou, N., "Design Fires for Fire Risk Assessment and Fire Safety Designs", Fire Risk and Hazard Assessment Research Application Symposium, San Diego, California, June 23-25, 1999, pp.101-112.
2. Yung, D., Hadjisophocleous, G. V. and Proulx, G., "A Description of the Probabilistic and Deterministic Modelling Used in FiRECAM", International Journal on Engineering Performance-Based Fire Codes", 1 (1), 1999, pp. 18-26.
3. Eaton, C., "Fire Probabilities - Smouldering, Flaming or Full Development?", Fire Safety and Engineering Technical Papers, Book 1, Part 3, Chapter 7, The Warren Centre, University of Sydney, Australia, December 1989.
4. Hall, J. R., "U.S. Statistical Data for the Risk-Cost Assessment Model", Contract Report to the Institute for Research in Construction, National Research Council of Canada, Ottawa, Canada, November 1991.
5. Gaskin, J. and Yung, D., "Canadian and U.S.A. Fire Statistics for Use in the Risk-Cost Assessment Model", Internal Report No. 637, Institute for Research in Construction, National Research Council of Canada, Ottawa, Canada, January 1993.
6. Fire Protection Handbook, 16th Edition, National Fire Protection Association, Quincy, MA, 1986, p. 7-112.
7. Takeda, H. and Yung, D., "Simplified Fire Growth Models for Risk-Cost Assessment in Apartment Buildings", J. of Fire Protection Engineering, 4 (2), 1992, pp. 53-66.
8. Hadjisophocleous, G. V. and Yung, D., "A Model for Calculating the Probabilities of Smoke Hazard from Fires in Multi-Storey Buildings", J. of Fire Protection Engineering, 4 (2), 1992, pp. 67-80.
9. Purser, D. A., "Toxicity Assessment of Combustion Products", SFPE Handbook of Fire Protection Engineering, 2nd Edition, National Fire Protection Association, Quincy, MA, 1995, pp. 2-85 to 2-146.
10. Proulx, G. and Hadjisophocleous, G.V., "Occupant Response Model: A Sub-Model for the NRCC Risk-Cost Assessment Model", Proceedings of the 4th International Symposium on Fire Safety Science, Ottawa, Canada, June 13-17, 1994, pp. 841-852.

11. Hadjisophocleous, G.V., Proulx, G. and Liu, Q., "Occupant Evacuation Model for Apartment and Office Buildings", Internal Report No. 741, Institute for Research in Construction, National Research Council of Canada, Ottawa, Canada, May 1997.
12. Benichou, N., Yung, D. and Hadjisophocleous, G.V., "Impact of Fire Department Response and Mandatory Sprinkler Protection on Life Risks in Residential Communities", Interflam '99, 8th International Fire Science and Engineering Conference, Edinburgh, Scotland, 1999, pp. 521-532.