Modelling Concepts for the Risk-cost Assessment Model FIRECAM™ and its Application to a Canadian Government Office Building

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ABSTRACT

To support the introduction of performance-based building regulations in Canada in the year 2001, the National Research Council of Canada (NRC) is developing a computer fire risk-cost assessment model that can be used to assess both the expected risk to life to the occupants and the expected costs of fire protection and fire losses in a building. The computer model that is being developed at NRC is called FiRECAM™ (Fire Risk Evaluation and Cost Assessment Model). This paper provides a description of the modelling concepts of FiRECAM™ and the results of its application to a six-storey Canadian federal government office building where the existing fire protection systems were being re-evaluated to see how they could be upgraded to meet the current building code requirements. The project was a collaboration between NRC and Public Works and Government Services Canada (PWGSC) which owns the building. The objective was to determine whether all the required upgrades were necessary. The results showed that one of the required upgrades, closing the stair vents, was not necessary, meaning a saving of $37,000 (Canadian).

KEYWORDS: risk, cost, assessment model, fire safety, office building

INTRODUCTION

To permit flexibility and cost-effectiveness in fire safety designs, many countries in the world, notably New Zealand, the U.K. and Australia, are moving towards performance-based building regulations, and away from the present restrictive, prescription-based regulations. Canada is also planning to introduce performance-based requirements in the National Building Code of Canada (NBCC) in the year 2001. Unlike prescription-based regulations, performance-based regulations permit flexibility in design which often leads to lower construction costs. Similar to other engineering practices, performance-based regulations allow designers and regulatory officials the freedom to apply engineering principles to identify fire safety designs that meet the fire safety performance required but at lower costs.

The introduction of such performance-based building regulations, however, depends on the successful development of engineering tools that can be used to design the various fire safety systems in a building, as well as risk assessment tools that can be used to assess the overall fire safety performance of a building. To support the introduction of performance-based building regulations in Canada, the National Research Council of Canada (NRC) is developing a computer fire risk-cost assessment model that can be used to assess both the expected risk to life to the occupants and the expected costs of fire protection and fire losses in a building. The basic concept of the model is being developed in collaboration with the Victoria University of Technology (VUT) in Australia [1,2], and with funding support from Public Works and Government Services Canada (PWGSC) and the Canadian Department of National Defence (DND). The computer model that is being developed at NRC is called FiRECAM™ (Fire Risk Evaluation and Cost Assessment Model). In 1994, FiRECAM™ was used successfully to obtain changes to the Building Code of Australia (BCA) to permit the construction of 3-storey wood-frame apartment buildings [3].

FiRECAM™ assesses the expected risk to life to the occupants in a building as a result of all probable fire scenarios over the life of the building. As well, the model assesses the costs of fire protection and expected fire losses. By comparison to the performance required in a performance-based code, or the implied performance of a code-compliant design as specified in a prescription-based code, the model can assess whether a proposed design meets the performance requirements, or is equivalent in life risk performance to the code-compliant design. In addition, the model can assess the fire costs to see whether this proposed design has the lowest fire costs of all acceptable designs and, hence, is a cost-effective design. At present, the model being developed can be applied to both apartment and office buildings. In the future, other versions will be developed for other building applications.

This paper provides a brief description of the modelling concepts of FiRECAM™ and the results of its application to a six-storey Canadian federal government office building where the existing fire protection systems were being re-evaluated to see how they could be upgraded to meet the current building code requirements. The project was a collaboration between NRC and PWGSC, which owns the building. The objective of this study was to evaluate possible alternative fire safety designs for such a heritage building that could provide the occupants with the same, or better, level of safety as required by the current building code. Some of the alternative fire safety designs could be more cost effective than those prescribed by the building code requirements.

MODELLING CONCEPTS AND LIMITATIONS

FiRECAM™ uses both statistical data to predict the probability of occurrence of fire scenarios, such as the type of fire that may occur or the reliability of fire detectors, and mathematical models to predict the time-dependent development of fire scenarios, such as the development and spread of a fire and the evacuation of the occupants in a building. The life hazard to the occupants from one scenario is calculated based on the speed of fire development and the speed of evacuation of the occupants in that scenario. The life hazard from one scenario multiplied by the probability of that scenario gives the risk to life from that scenario. The overall expected risk to life to the occupants is the cumulative sum of all risks from all probable fire scenarios in a building. Similarly, the overall expected fire cost is the sum of fire protection costs (both capital and maintenance) and the cumulative sum of all fire losses from all probable fire scenarios in a building.

In FiRECAM™, due to the complexity of fire phenomena and human behaviour, certain conservative assumptions and approximations are made in the mathematical modelling. In addition, not all aspects of the model have been fully verified by full-scale fire experiments or actual fire experience. Only some of the sub-models have been verified by experiments or statistical data [4,5]. As a result, the predictions made by the model at the present time can only be considered as conservative and approximate. Until the model is fully verified, the model is not suitable for absolute assessment of life risks and protection costs. For comparative assessment of life risks and protection costs, however, the model is considered to be adequate.

As in many computer models, the model uses certain input parameters to describe the characteristics of various fire safety designs. These include the fire resistance ratings of boundary elements, the reliability of alarms and sprinklers, the probability of a door being open or closed and the response time of fire departments. The sensitivity of these parameters on the predicted risks have been checked and found to be reasonable [6].

FiRECAM™

A brief description of the system model and the submodels of FiRECAM™ is given in this section. FiRECAM™ is a newer version of the NRC risk-cost assessment model which was described in previous publications [1-3]. The objective here is to show what each submodel does and how the submodels are linked together. Details of some submodels have been published previously [6-9]; the rest will be published in the near future.

FiRECAM™ assesses the fire safety performance of a fire safety design in terms of two decision-making parameters: the expected risk to life (ERL) and the fire cost expectation (FCE). The ERL is the expected number of deaths per year. The FCE is the expected total fire cost which includes the capital cost for the passive and active fire protection systems, the maintenance cost for the active fire protection systems and the expected losses resulting from all probable fires in the building. The ERL is a quantitative measure of the risk to life from all probable fires in a building, whereas the FCE quantifies the fire cost associated with a particular fire safety design.

The separation of life risks and protection costs in FiRECAM™ avoids the difficulty of assigning a monetary value to human life and allows the comparison of risks and costs separately. The ERL value can be used for performance requirements' compliance (performance-based codes) or code equivalency consideration (prescription-based codes), whereas the FCE value can be used for cost-effectiveness considerations.

To calculate the ERL and FCE values, FiRECAM™ considers the dynamic interaction (time-dependent calculation) among fire growth, fire spread, smoke movement, human behaviour and fire department response. These calculations are performed by a number of submodels interacting with each other as shown in Fig. 1. The computer model includes two optional submodels that can be run if the building fire characteristics and fire department response are not considered typical. The model also has two submodels that are run only once to obtain the failure probability values of boundary elements and the capital and maintenance costs of fire protection systems; and ten submodels that are run repeatedly in a loop to obtain the expected risk to life values and the expected fire losses from all probable fire scenarios.

Building and Risk Evaluation Model

This is an optional model that can be run to evaluate the fire characteristics of a building if the building is considered to be not a typical building where normal fire statistics can be applied. Based on the type and quantity of combustibles in the building, the separation of the combustibles from potential ignition sources and the maintenance of fire suppression systems, if they are installed, the model calculates the factors that can be used to correct the statistical values of the probability of fire starts, the probability of various design fires that may develop and the reliability of the fire suppression systems. These factors are used later in the Design Fire Model to correct the normal statistical values.

Fire Department Response Model

This is an optional model that can be run to evaluate the fire department response characteristics to a design building if the fire department is not considered to be a typical one where normal response statistics can be applied. Based on the characteristics of the fire department and the distance to the design building, the model calculates the response time to the design building. The response time is used later in the Fire Department Effectiveness Model instead of the normal statistical value.

Boundary Element Failure Model

This model calculates the probability of failure of the boundary elements (such as walls, floors and doors) in the building when exposed to a design flashover fire that could occur in the building. The characteristics of the design flashover fire are obtained from the Fire Growth Model which is also used later to calculate the characteristics of other design fires that could occur in the building. The failure probability values are used later in the Fire Spread Model to calculate the probability of fire spread from the compartment of fire origin to every location in the building.

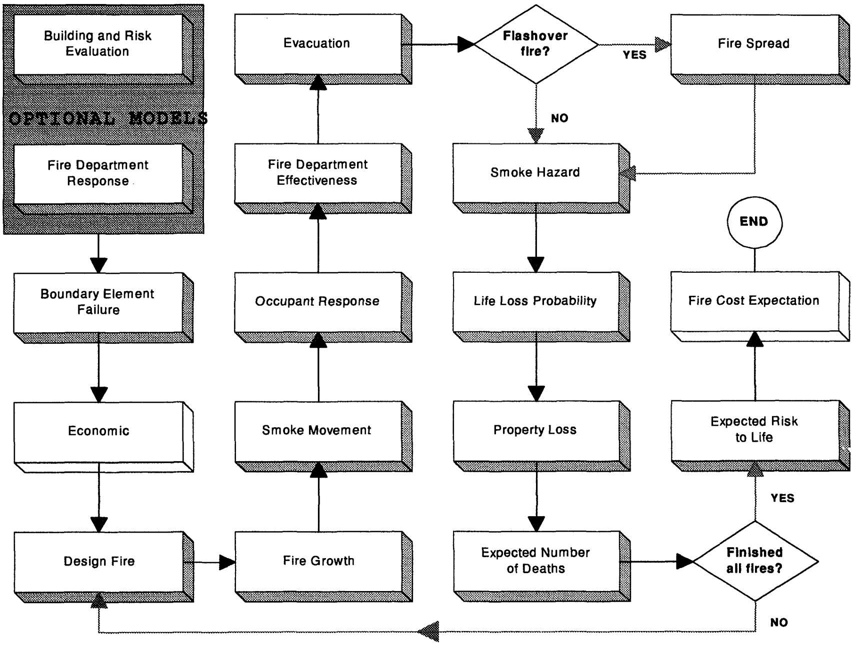


FIGURE 1. FiRECAM™ Flowchart

Economic Model

This model calculates the building construction cost and the capital and maintenance costs of the fire protection systems. It also calculates the replacement costs of building contents and the restoration costs of building elements as a result of smoke, fire and water damage. These costs are used later in the Property Loss Model to calculate the expected fire losses for each fire scenario, and in the Fire Cost Expectation Model to calculate the total fire cost expectation.

Design Fire Model

FiRECAM™ uses six design fires in the compartment of fire origin, and the subsequent fire and smoke spread, to evaluate life risks and protection costs for apartment and office buildings. The six design fires, representing the wide spectrum of possible fire types, 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 occurrence of each design fire is based on statistical data. For example, in Canada, statistics show that the probability of fire starts in office buildings is 7.68×10^{-6} per m^2 [10]. Of these fires, 24% reach flashover and become fully-developed fires, 54% are flaming fires that do not reach flashover and the remaining 22% are smouldering fires that do not reach the flaming stage [10]. If sprinklers are installed, the model assumes that some of the flashover and non-flashover fires, depending on the reliability and effectiveness of the sprinkler system, are suppressed [6].

FiRECAM™ evaluates the cumulative effect of all probable fire scenarios which could occur in the building during the life of the building. For example, in an office building, a fire scenario could be one resulting from one design fire in any one of the office units in the building. The number of fire scenarios, therefore, is the product of the number of design fires and the number of office units in the building.

Fire Growth Model

The fire growth model predicts the development of the 6 design fires in the compartment of fire origin. Details of this model for apartment buildings are described in a previous paper [7]. The model calculates the burning rate, room temperature and the production and concentration of toxic gases as a function of time. With these calculations, the model determines the time of occurrence of five important events: (1) time of fire cue, (2) time of smoke detector activation, (3) time of heat detector or sprinkler activation, (4) time of flashover, and (5) time of fire burnout. The first three detection times are used later in the Occupant Response and Evacuation Models to calculate the response and evacuation of the occupants from the building. The flashover time is used in the Fire Department Effectiveness Model to calculate the effectiveness of fire fighting and rescue efforts, whereas the burnout time is used in the Smoke Hazard Model to calculate the maximum smoke hazard to which the occupants could be subjected. The model also calculates the mass flow rate, the temperature and the concentrations of CO and CO_2 in the hot gases leaving the fire compartment. This latter information is used in the Smoke Movement Model to calculate the spread of smoke to different parts of the building as a function of time.

Smoke Movement Model

The smoke movement model calculates the spread of smoke and toxic gases to different parts of the building as a function of time. Details of this model are described in a previous publication [8]. The model also calculates the critical time at which the stairs become untenable. This is the time at which the remaining occupants, who have not evacuated the building, cannot use the stairs to evacuate and are considered trapped in the building. This critical time is used later in the Evacuation Model to calculate the time available for evacuation.

Occupant Response Model

This model calculates the probability of occupant response at different locations in the building and at the 3 detection times (fire cue, smoke detector, heat detector/sprinkler activation). Details of this model are described in a previous publication [9]. The probability of response is calculated based on warnings received from fire cues, local alarms, central alarms, voice alarms, warnings from others and from fire fighters. The response probability values are used later in the Evacuation Model to calculate the percentage of the occupants who would respond and evacuate at the 3 different detection times.

Fire Department Effectiveness Model

This model calculates the effectiveness of fire fighting and rescue efforts, based on the time of arrival of the fire department, the time of flashover from the Fire Growth Model and the fire fighting resources that have arrived on the scene. The effectiveness values are used later in the Evacuation Model to reduce the number of occupants who are trapped and in the Fire Spread Model to reduce the probability of fire spread. The time of arrival is also used later in the Smoke Hazard Model to evaluate the smoke hazard conditions to the occupants at the time of arrival of the fire department.

Evacuation Model

This is a time-dependent, deterministic model that calculates the egress of the occupants at the three detection times. Based on the probability of response at these three different times from the Occupant Response Model and the critical time in the stairways from the Smoke Movement Model, the model calculates the number of occupants who can evacuate the building and those who are considered trapped in the building. The number of occupants who are trapped in the building is reduced by the effectiveness of the rescue efforts of the fire department. The residual population in every location of the building is used later in the Expected Number of Deaths Model to calculate the expected number of deaths.

Smoke Hazard Model

This model calculates the smoke hazard at every location in the building at the time of arrival of the fire department, obtained from the Fire Department Effectiveness Model. If there is no fire department response, this model calculates the smoke hazard at the time of burnout in the compartment of fire origin, obtained from the Fire Growth Model. The smoke hazard is based on the dosage and temperature of the toxic gases to which the occupants are exposed [8]. The smoke hazard values are used later in the Life Loss Probability Model to evaluate the probability of life loss at every location in the building, and in the Property Loss Model to evaluate the replacement costs of building contents for smoke damage.

Fire Spread Model

Based on the probability of failure of the boundary elements, obtained from the Boundary Element Failure Model, and the fire fighting effectiveness, obtained from the Fire Department Effectiveness Model, this model calculates the probability of fire spread to every location in the building. The model is a non-time-dependent one where the probability of fire spread to every location in a building is assumed to occur at the time of fire burnout in the compartment of fire origin. This is a conservative approach since fire spread to all locations in a building is usually a slow process; much slower than the time it takes for the fire to burn out in the compartment of fire origin. The fire spread probability values are used later in the Life Loss Probability Model to evaluate the probability of life loss at every location in the building, and in the Property Loss Model to evaluate the replacement costs of building contents and restoration costs of building elements.

Life Loss Probability Model

This model calculates the probability of life loss in every location in the building, based on the smoke hazard values obtained from the Smoke Hazard Model and the fire spread values obtained from the Fire Spread Model. In this model, the probability of life loss is reduced if there is a refuge area nearby, such as a balcony, which the occupants can use to avoid the hazard. The life loss probability values are used later in the Expected Number of Deaths Model to calculate the expected number of deaths.

Property Loss Model

This model calculates the replacement costs of building contents and restoration costs of building elements for the fire scenario being considered, based on smoke spread values from the Smoke Hazard Model, fire spread values from the Fire Spread Model and replacement and restoration unit costs from the Economic Model. The fire losses are used later in the Fire Cost Expectation Model to calculate the total expected fire cost.

Expected Number of Deaths Model

This model calculates the expected number of deaths for the fire scenario being considered, based on the residual population obtained from the Evacuation Model and the life loss probability values obtained from the Life Loss Probability Model. The expected number of deaths is used in the Expected Risk to Life Model to calculate the total expected risk to life.

Expected Risk to Life Model

This model calculates the overall expected risk to life (ERL) by using the expected number of deaths in the building for each fire scenario, obtained from the Expected Number of Deaths Model, and the probability of occurrence of each scenario, obtained from the Design Fire Model. ERL, as defined earlier, is the expected number of deaths per year.

Fire Cost Expectation Model

This model calculates the total fire cost expectation (FCE) by using the capital and maintenance costs for the fire protection systems, obtained from the Economic Model, the expected fire losses for each fire scenario, obtained from the Property Loss Model and the probability of occurrence of each scenario, obtained from the Design Fire Model. FCE, as defined earlier, is the expected total fire cost which includes the capital cost for the passive and active fire protection systems, the maintenance costs for the active fire protection systems and the expected losses resulting from all probable fires in the building.

APPLICATION TO A SIX-STOREY GOVERNMENT OFFICE BUILDING

As an example of how FiRECAM™ can be used, the results of its recent application to a six-storey Canadian federal government office building, where the existing fire protection systems were being re-evaluated to see how they could be upgraded to meet the current building code requirements, are discussed here [11]. One of the difficulties with this building, built in the 1930's, is that it is designated a heritage building. With the heritage designation, no renovation to the building is permitted unless such renovation will not cause any change to the building's unique architectural characteristics. The objective of this study was to identify possible alternative cost-effective fire safety designs for such a heritage building that could provide the occupants with an equivalent level of safety to that required by the 1990 edition of the National Building Code of Canada.

The building is a six-storey concrete building with three staircases, two passenger elevators and two service elevators. A typical floor layout is shown in Fig. 2. The average usable area on each floor is about 1,000 m^2. On each floor, there are both closed offices and an open area where work spaces are defined by shoulder-height partitions. The building is currently occupied by various government departments as well as a post office on the main floor. It has a day-time population of approximately 180 people and a night-time population of mainly a few security personnel.

Currently, the building has no sprinklers, except in the basement. It has a central alarm system, but no voice communication system. In the stair shafts, there are a few closed-door closets that have vents connected to the floor side above the suspended ceiling that could leak smoke from the floor into the stair shafts. The current building code requires that the vents to the closets in the stair shafts be closed. The code does not require a voice communication system nor sprinkler protection. However, since this is a heritage building, PWGSC wants to install sprinklers throughout the building to protect its value. The code also permits a higher population density of one person per 9.3 m^2, or 110 persons per floor in this building, whereas the PWGSC's practice is to limit the population density to a lower value: one person per 12 m^2, or 85 persons per floor in this building. As mentioned earlier, the current population density in this building is very low, about 30 per floor.

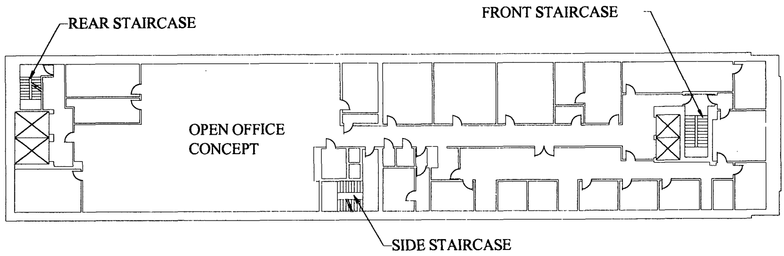


FIGURE 2. Typical Floor Layout

To compare the safety levels provided to the occupants, 16 fire safety design options were considered: with sprinklers and no sprinklers, voice alarm vs regular alarm, close the vents to the closets in the stair shafts or not, and a lower population density vs a higher population density. Table 1 shows the 8 options that were to be considered in conjunction with sprinklering and not sprinklering. The first option is the reference option that is code-compliant plus sprinkler protection.

RESULTS

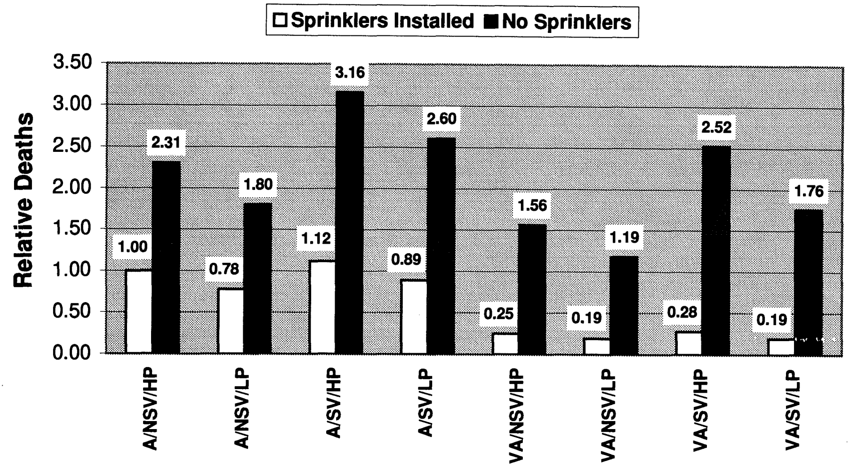
FiRECAM™ was used to determine the expected number of deaths for the 16 fire safety options shown in Table 1. The results are plotted in Fig. 3, where the expected number of deaths for each option is compared to the first option, the reference option which has a relative deaths value of 1. The reference option is the one that has sprinklers, a central alarm, no vents to the stair shafts, and a higher population density. The option that represents the current situation before upgrades is the non-sprinkler option that has a central alarm, vents to the closets in the stair shafts and a lower population density (A/SV/LP without sprinklers), which has a relative deaths value of 2.60. In this study, no calculations of the potential fire losses were performed because there was no reliable restoration cost data available for such a heritage building. However, the capital costs of providing some of the fire safety options, which were actual estimates from contractors, are addressed.

Figure 3 shows that all 8 options with sprinklers have a much lower expected number of deaths value when compared to similar options without sprinklers. This is expected since sprinklers suppress most of the flashover and non-flashover fires. With or without sprinklers, the results show that a lower population density has a lower expected number of deaths value. This is reasonable since a lower population would usually lead to less crowding in stairways, a quicker evacuation and therefore a lower number of occupants that could be trapped in the building. The results also show that closing the vents to the closets in the stair shafts gives a lower expected deaths value. This is again reasonable since closing the vents would lead to a lower possibility of smoke spread to the stairs and upper floors. Finally, Fig. 3 shows that adding a voice alarm results in a lower expected deaths value. This is again expected since a voice alarm is known to cause a faster evacuation response from the occupants [12].

Figure 3 also shows that some of the sprinkler options can provide equivalent life safety, or better, whereas none of the non-sprinkler options can provide equivalent life safety, when compared to the reference option (the first option). One cost-effective sprinkler option is the one that has the central alarm, but does not close the vents to the closets in the stair shafts and has a lower population density (A/SV/LP with sprinklers). This option has a lower relative deaths value of 0.89. The lower population density compensates for the slightly higher smoke spread through the stair vents. The saving in not having to close the stair vents allows this option to have a capital cost of about $37,000 (Canadian) less than that of the reference option.

Table 1. Fire Protection Options to be Considered with the Sprinklering and Not Sprinklering Options for a Total of 16 Options

Design Option	Add Voice Alarm	Close StairVent	Population Per Floor
A/NSV/HP (reference)	No	Yes	110
A/NSV/LP	No	Yes	85
A/SV/HP	No	No	110
A/SV/LP (current)	No	No	85
VA/NSV/HP	Yes	Yes	110
VA/NSV/LP	Yes	Yes	85
VA/SV/HP	Yes	No	110
VA/SV/LP	Yes	No	85



A = Alarm
NSV = No Stair Vent
HP = High Population Density
VA = Voice Alarm
SV = Stair Vent Present
LP = Low Population Density

FIGURE 3. Relative Expected Deaths for 16 Design Options Shown in Table 1

Before arriving at the final expected number of deaths values, certain intermediate calculations were checked to see whether the calculations were reasonable. Using the reference design as an example, the intermediate results are shown in Fig. 4. The intermediate results show the impact of the various fire scenarios on the risk to life. Figure 4(a) shows the expected number of deaths for the various fire scenarios, without considering the probability of occurrence of these fire scenarios. This figure, therefore, shows the number of deaths for each fire scenario by itself, assuming that all fires occurring in the building follow that particular fire scenario only. As expected, Fig. 4(a) shows that more deaths occur when the door of the compartment of fire origin is open and that flashover fires are more dangerous than other fires. It is noted that the figure also shows that smouldering fires (door open) have a higher number of deaths than that of non-flashover fires (also door open). This is because smouldering fires usually last longer than non-flashover fires, thus producing more smoke and toxic gases over time. In Fig. 4(b), the number of deaths for the various fire scenarios have been multiplied by the probabilities of occurrence of these fire scenarios (see discussions under Design Fire Model) and are shown as a percent contribution to the expected deaths. This figure gives the relative significance of the various fire scenarios. As expected, fire scenarios with the door of the fire compartment being open are the ones that cause most of the deaths (the probability value of the door being open is difficult to obtain, but was assumed conservatively in the model to be 99% to give this severe fire scenario a high probability of happening). Because of sprinklers, however, the most dangerous fire now is the smouldering fire, not the flashover or non-flashover flaming fires which have been suppressed by the sprinklers (see discussions under Design Fire Model). The above intermediate results for the reference option show that the model predictions of life hazards for the individual fire scenarios and the contributions to the overall risk to life are reasonable.

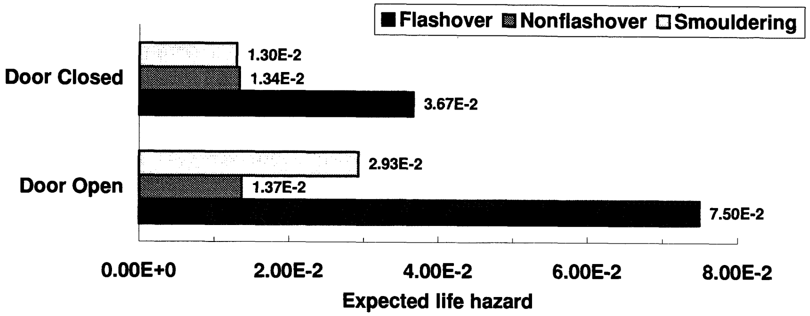


FIGURE 4(a). Intermediate Calculations for the Reference Option: Number of Deaths for Various Fire Scenarios if all Fires Occur in the Building Follow that Particular Fire Scenario

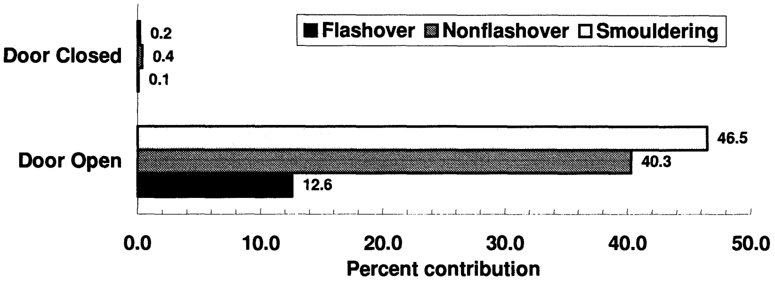


FIGURE 4(b). Intermediate Calculations for the Reference Option: Percent Contribution of the Various Fire Scenarios to the Expected Number of Deaths after the Probabilities of Fire Type and Door Condition have been Considered

SUMMARY

In this paper, the modelling concepts of the NRC risk-cost assessment model FiRECAM™ and its submodels were described. As an example of how the model can be used, the results of its recent application to a six-storey Canadian federal government building, where the existing fire protection systems were being re-evaluated to see how they could be upgraded to meet the current building code requirements, were also discussed.

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