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A DESCRIPTION OF THE PROBABILISTIC AND DETERMINISTIC MODELLING USED IN FIRECAM™

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ABSTRACT

To support the introduction of performance-based building regulations in Canada in the year 2003, 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 gives a brief description of the probabilistic and deterministic modelling concepts that are used in FiRECAM™. In addition, the paper shows 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 in a cost-effective manner to meet the current building code requirements.

1. INTRODUCTION

To permit flexibility and cost-effectiveness in fire safety designs, many countries in the world, notably New Zealand, Japan, the U.K. and Australia, are moving towards performance-based building regulations, and away from the current restrictive, prescription-based regulations. Canada is also planning to introduce objective/ performance-based requirements in the National Building Code of Canada (NBCC) in the year 2003. Unlike prescription-based regulations, performance-based regulations permit greater 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 required fire safety performance.

The introduction of 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 objective/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.

FiRECAM™ assesses the expected risk to life to
the occupants in a building as a result of all probable fire scenarios over the design 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 determine whether the 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 probabilistic and deterministic modelling concepts that are used in FiRECAM™. Probabilistic modelling is used to determine the probability of occurrence of a fire scenario, whereas deterministic modelling is used to determine the consequence of a fire scenario. In addition, the paper describes the results of its recent application to a six-storey Canadian federal government office building. This example shows how the model can be used to obtain cost-effective fire safety designs. The objective of this study was to evaluate alternative fire safety designs for such a building that could provide the occupants with the same, or better, level of safety as that required by the current prescriptive building code but at lower costs.

2. FiRECAM™

A description of FiRECAM™ and its submodels can be found in previous publications [1-9] and is not repeated here. The model was developed in collaboration with the Victoria University of Technology in Australia [3-4] and in partnership with Public Works and Government Services Canada (PWGSC) and the Canadian Department of National Defence (DND).

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 compliance with performance requirements (performance-based codes) or code equivalency considerations (prescription-based codes). The FCE value can be used to assess cost-effectiveness of various design options.

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. Two other submodels are run only once to obtain the failure probability values of boundary elements and the capital and maintenance costs of fire protection systems. The remaining ten submodels are run repeatedly in a loop to obtain the expected risk to life values and the expected fire losses from all probable fire scenarios.

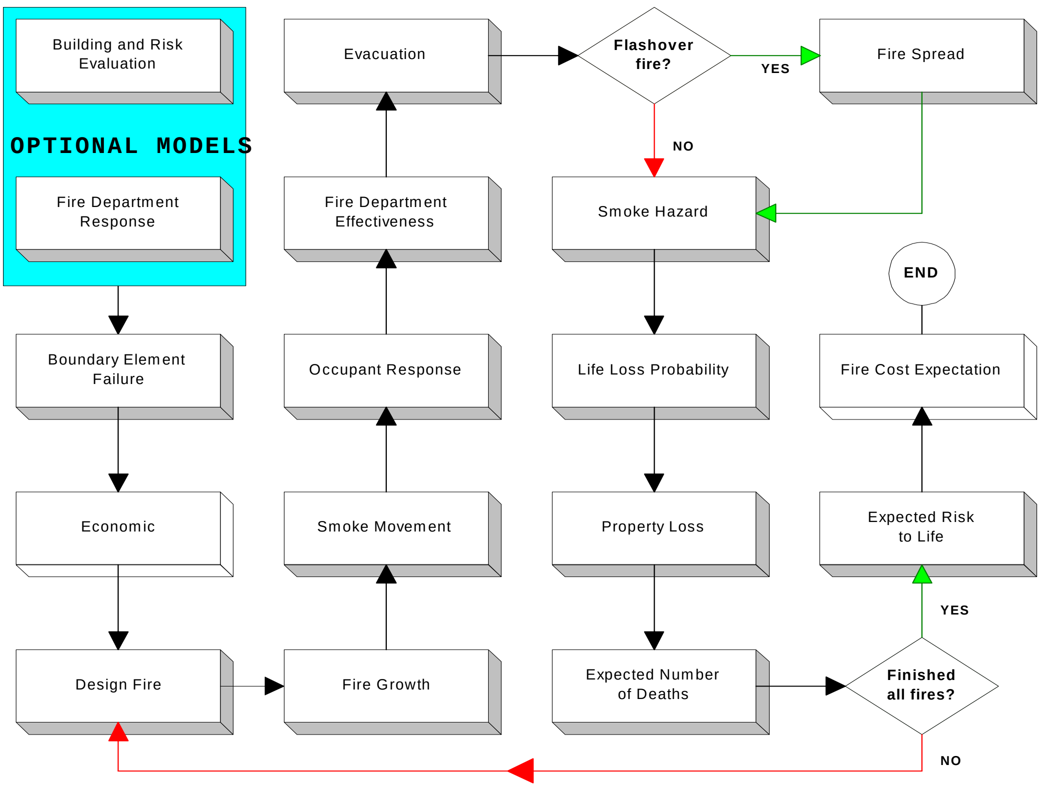


Fig. 1: FiRECAM™ flowchart

3. MODELLING CONCEPTS USED IN FiRECAM™

FiRECAM™ uses 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. Mathematical models are used 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 posed by a fire scenario is calculated based on how quickly the fire develops and how quickly the occupants evacuate the building in that scenario. The life hazard calculated for a 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.

The expected risk to life is expressed as

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

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

A fire scenario is a description of the conditions of the controlling parameters that would govern the outcome of the fire development and the evacuation of the occupants. For example, controlling parameters and their possible conditions include: (1) the location of the fire in a building; (2) whether the type of fire that has occurred in the compartment of fire origin is a smouldering fire, a small flaming fire or a flashover fire; (3) whether the door to the compartment of fire origin is open or closed; (4) whether smoke detectors, if installed, are operational or not; (5) whether sprinklers, if installed, are operational or not; etc. The probability of a controlling parameter in a particular condition 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 can often be obtained from expert opinion. The probability of a fire scenario is the product of the probabilities of its controlling parameters.

For each fire scenario, FiRECAM™ uses time-dependent deterministic models to calculate the life hazard to the occupants and fire losses. These models include fire growth, smoke spread and occupant evacuation. In the following sections, the fire growth and occupant evacuation models are described as examples of NRC's ongoing efforts to develop and validate these deterministic models by experiments. The validation of the smoke spread model has been described previously [5].

3.1 Design Fires and Fire Growth 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 a 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 [10] show that the probability of fire starts in office buildings is 7.68×10^{-6} per m^2. 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 rendered non-lethal [6].

The fire growth model predicts the development of the six design fires in the compartment of fire origin using representative fuels, such as polyurethane slabs for residential furniture and wood cribs for office furniture. Details of this model 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 (that can be detected by human senses), (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 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. The output of the fire growth model is used by other submodels in FiRECAM™ to calculate the spread of smoke to other parts of the building, the response and evacuation of the occupants as well as the response and effectiveness of the fire department.

Experiments have been conducted at VUT [11] in Australia as well as at NRC [12] to validate the fire growth model. Fig. 2 shows the results of a recent full-scale fire experiment at NRC [12], where a fire was started in a work space representative of that found in a large open office environment, as well as the model predictions. In this figure, the experimental results and the model predictions of the temperature, mass flowrate, CO and CO_2 concentrations are shown to be in reasonably good agreement.

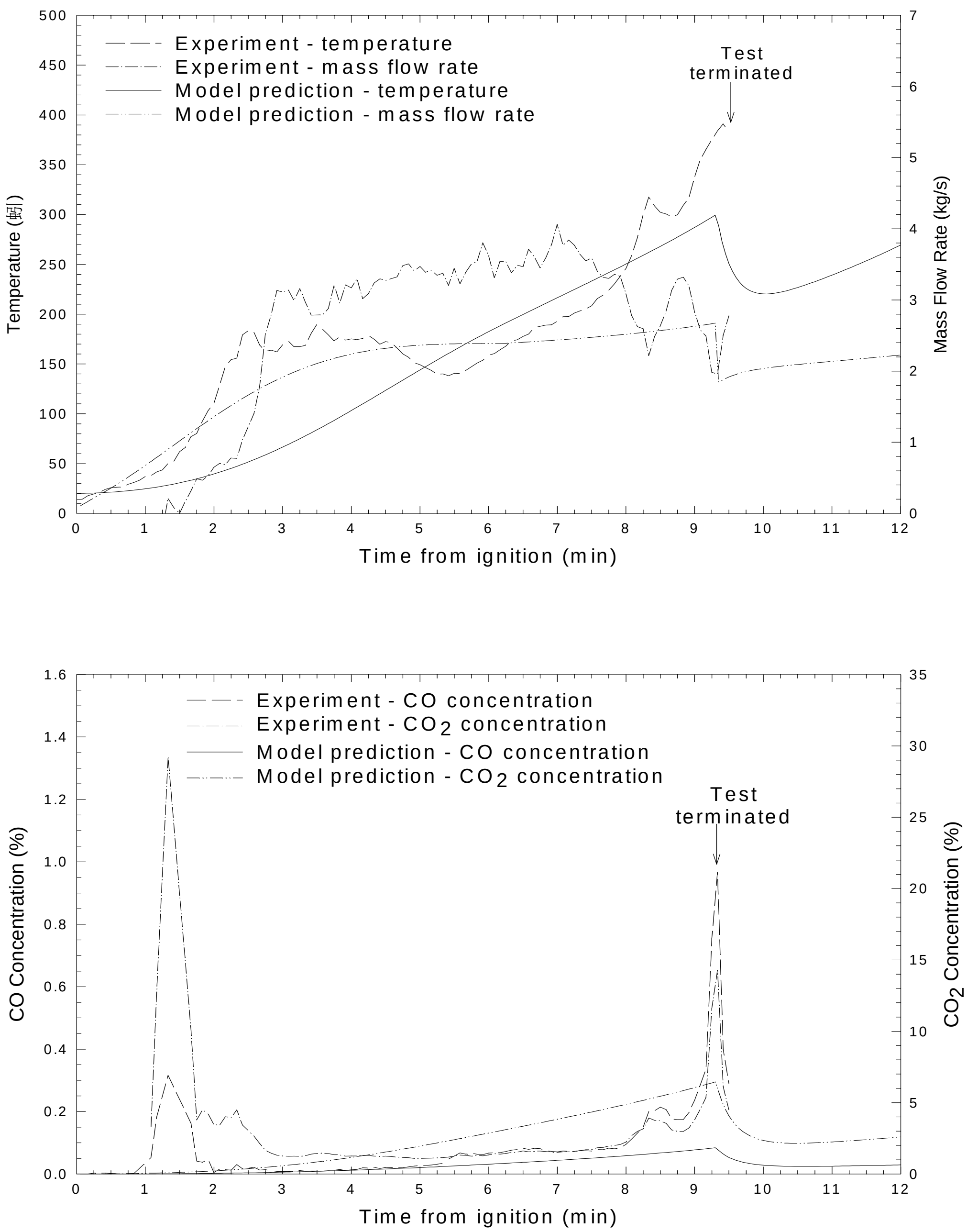


Fig. 2: Comparison of experimental results with model predictions in an open office arrangement

where work spaces are defined by 1.6 m high partitions

Other experiments are being conducted at VUT and NRC, including those using enclosed offices and residential rooms. The results will be used to improve the fire growth model.

3.2 Occupant Evacuation Model

When a fire starts on a specific floor, the Occupant Evacuation Model computes the movement of occupants from their original locations through corridors, stairwells and out of the building. The evacuation procedure involves selecting appropriate paths and evaluating queuing at doorways and stairwells. A network modelling approach, suitable for solving complex evacuation problems, is used.

The evacuation paths are generated on the basis of the assumption that occupants will use preferred routes to evacuate. This method relies on a network description of the building and the locations of occupants to solve the problem. A network model is a graphic representation of paths or routes by which persons can move from one point to another. Network nodes representing the compartment doors, corridors, stairwells and exits are used to define travel paths. The initial positions of occupants are assumed to be uniformly distributed in compartments or in open areas, which are also represented by network nodes.

The stairwell network is generated assuming that all stairwells have the same dimensions and structural layout. The network nodes specify the turn points in a stairwell.

There are two types of nodes in the network that can be weighted by a numerical value; namely, the source nodes and the destination nodes. The source nodes represent nodes of danger, such as the compartment of fire origin and stair exits blocked by smoke. These nodes are weighted by a negative value. The destination nodes represent nodes of safety, such as the exit stairs and building exits. They are weighted by a positive value.

Evacuation paths are generated for each occupant by solving the Poisson's equation. The preferred path is towards the node with a higher value. Based on the weights pre-defined for stairs, exits and the compartment of fire origin, the program calculates the appropriate path for each occupant. The higher the weighting of the destination node, the higher its attraction for occupants.

To evaluate the predictability of the model, its predictions are compared to results from evacuation drills in apartment and office buildings [13] and are shown in Figs. 3 and 4, respectively. As can be seen from Fig. 3, the evacuation curves for four apartment buildings are quite different. This is mainly attributed to the type of fire protection systems used in the buildings and the conditions of the alarms, including the loudness and audibility of alarm bells [14]. Fig. 3 shows that the model prediction for the case with a central alarm and occupants awake is in good agreement with the results of evacuation drills in Buildings 2 and 3, which had poor central alarm systems. The model prediction, therefore, is on the conservative side when compared to what was observed in evacuation drills.

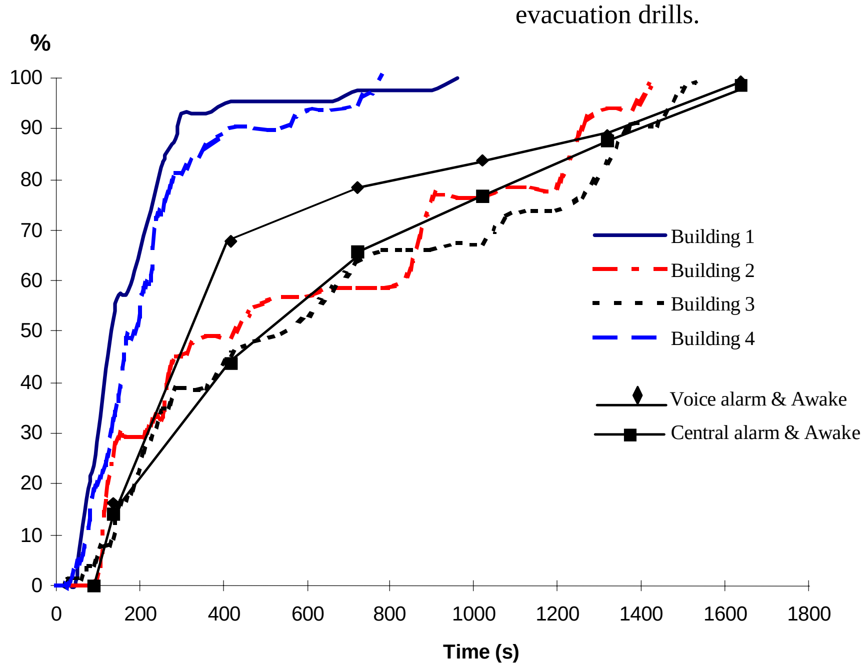


Fig. 3: Comparison of model predictions with results of fire drills in

apartment buildings

The results for office buildings are shown in Fig. 4, where the percentage of occupants who have evacuated is plotted as a function of time for both model predictions and fire drills. For the central alarm option (CA), two different building populations were used in the model predictions. As expected, the evacuation process for the case with a lower population is shown to be faster than that of the case with a higher population. The voice alarm option is shown to give better evacuation results than the other two options without voice communication. Fig. 4 also shows the model predictions of evacuation to be slightly slower than what was observed in the fire drills. However, the fire wardens and the occupants in the two buildings used for evacuation drills had received regular fire drill training [15]. These factors, which could have significant impact on evacuation, have not yet been considered in the current Occupant Response Model [9]. The Occupant Response Model calculates the probability of response and the delay time before evacuation. The present Occupant Response and Evacuation Models, therefore, give conservative predictions for building evacuation, which in turn allow FiRECAM™ to provide conservative assessments of fire safety designs.

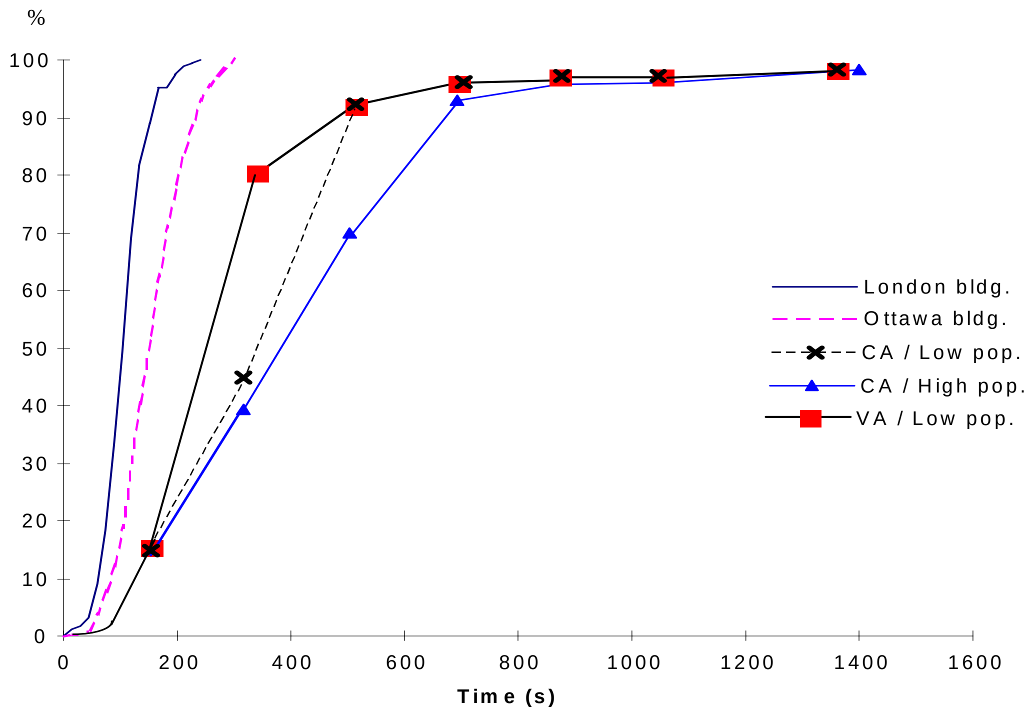


Fig. 4: Comparison of model predictions with results of fire drills in office buildings

4. APPLICATION OF FiRECAM™ TO A 6-STOREY OFFICE BUILDING

FiRECAM™ was applied to a six-storey Canadian federal government office building, located in London, Ontario. The existing fire protection systems of this building were being re-evaluated to see how they could be upgraded to meet the current building code requirements. One of the difficulties with this building was that it was designated a heritage building. The building was constructed in the 1930's and has unique architectural features. With the heritage designation, no renovation to the building would be permitted unless such renovation would 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 building that could provide the occupants with an equivalent level of safety to that required by the current building code.

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. 5. 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 1.6 m high 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 one security person.

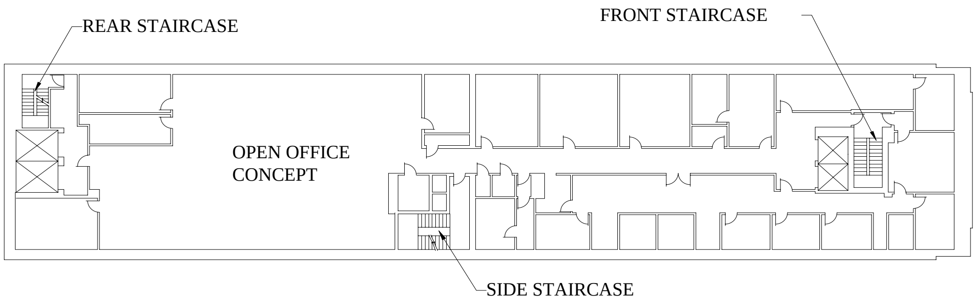


Fig. 5: Typical floor layout

Currently, the building has no sprinklers installed, except in the basement. It has a central alarm system, but no voice communication system. In the stair shafts, there are closed-door closets that have vents connected to the occupied floor side above the suspended ceiling. These vents 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, which owns the building, 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 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. The current population density in this building is very low, about 30 per floor.

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	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

To compare the safety levels provided to the occupants, 16 fire safety options were considered involving the following : with sprinklers or 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 considered in conjunction with sprinklering and not sprinklering. The first option is the reference option. It is code-compliant with the addition of sprinkler protection. A code-conforming building of this size does not require sprinklers.

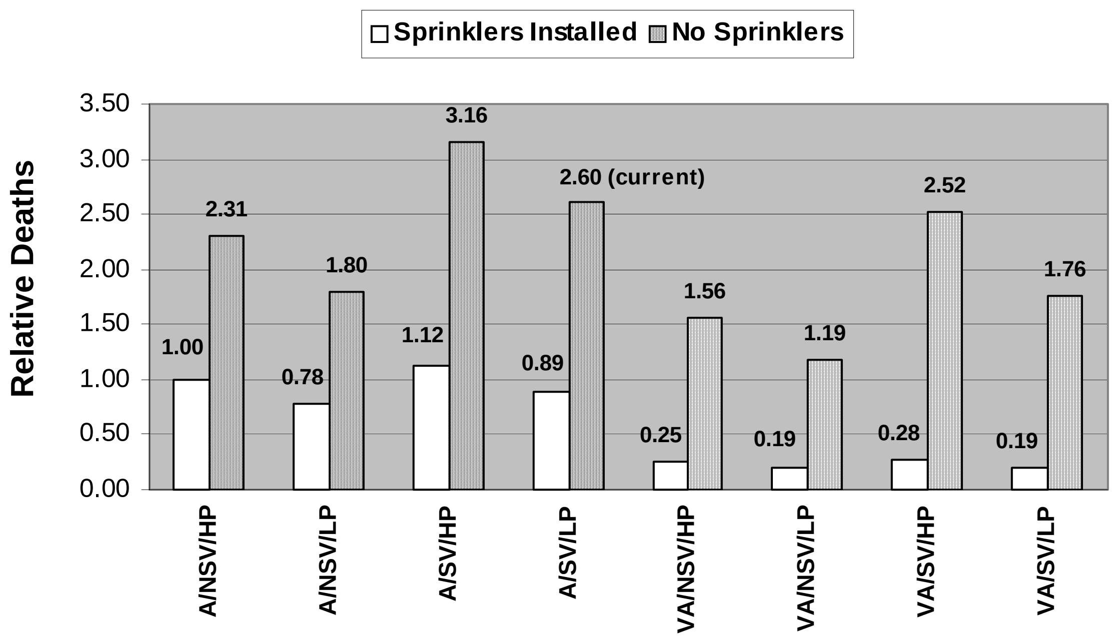
5. RESULTS

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. 6, 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 has sprinklers, a central alarm, no vents to the stair shafts, and a population density of 110 persons per floor. 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 suitable restoration cost data available for heritage buildings. However, the capital costs of providing some of the fire safety options, which were actual estimates from contractors, are addressed.

Fig. 6 shows that all 8 options with sprinklers have a much lower expected number of deaths 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 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. 6 shows that adding a voice alarm results in a lower expected deaths value. This is again expected since voice alarm is known to cause a faster response from the occupants because it provides information on both the fire and the direction to get to a safe area.

The results in Fig. 6 show that some of the sprinkler options can provide equivalent life safety, or better, when compared to the reference option (the first option). One such sprinkler option, that can provide better safety but with a lower capital cost, 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 higher smoke spread through the stair vents. The saving in not having to close the stair vents is about $37,000 when compared with the reference option.

Fig. 6 also shows that none of the non-sprinkler options can provide equivalent life safety to the reference option. However, one non-sprinkler option is very close to the reference option : the one that has voice alarms, closes the stair vents and has a lower population density (VA/NSV/LP without sprinklers). This option has a higher relative deaths value of 1.19 when compared to the reference option. But when compared to the 2.60 that represents the current level of risk before upgrades (A/SV/LP without sprinklers), it achieves almost the same reduction in risk as intended by the reference design : from 2.60 to 1.19 rather than 2.60 to 1. The use of voice alarms plus a lower population density allows this option to achieve almost the same result as the reference option with sprinklers but with a higher population density. The cost of installing sprinklers was estimated to be $575,000, whereas the cost of installing voice alarms was only $73,000. If funding to install the sprinklers is a problem, this option could be an attractive one to consider as a possible solution that could achieve most of the intended reduction in life risk, but with a capital cost of about $500,000 less. However, no consideration for property loss is included in this comparison which could be an important factor for heritage buildings.



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

Fig. 6: Relative expected deaths for 16 design options shown in Table 1

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