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Case Study: The Use of FiRECAM™ to Identify Cost-Effective Fire Safety Design Options for a Large 40-Storey Office Building

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ABSTRACT

The computer fire risk-cost assessment model that is being developed at the National Research Council of Canada, FiRECAM™, was used to identify cost-effective fire safety design options for a 40-storey office building specified by the conference organizers. FiRECAM™ (Fire Risk Evaluation and Cost Assessment Model) is a computer model that evaluates both the expected risk to life to the occupants and the fire costs in a building.

In this paper, a brief description of the conceptual design of the 40-storey office building is first given. The requirements of the National Building Code of Canada relevant to this building are then described. Five design options, including the code-compliant design and 4 alternative designs, are proposed and described. A brief description of FiRECAM™ is given and the results of its application to the five design options are then discussed. Two of the alternative design options are found to be cost-effective. These options provide the same or better level of safety as intended by the code-compliant design and also provide cost benefits to the owner.

INTRODUCTION

The present case study was carried out at the invitation of the 2nd International Conference on Performance-Based Codes and Fire Safety Design Methods. The objective of the study is to demonstrate the fire safety design method that the National Research Council of Canada (NRC) would use to identify cost-effective fire safety design options for a conference-specified 40-storey office building. The building is assumed to be located in Canada (specified by the conference organizers). A similar exercise for a 4-storey office building was carried out and presented at the 1st International Conference on Performance-Based Codes and Fire Safety Design Methods[1].

In this study, the computer fire risk-cost assessment model that is being developed at NRC was applied to the 40-storey office building. The NRC model, called FiRECAM™ (Fire Risk Evaluation and Cost Assessment Model), 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 fire protection costs (capital and maintenance) and expected fire losses. By comparison to the performance required in a performance-based code, or the implied performance of a reference design as specified in a prescriptive-based code, the model can assess whether a proposed design meets the performance requirements, or is equivalent in life risk performance, to the reference 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.

The basic concept of the model is being developed in collaboration with the Victoria University of Technology (VUT) in Australia[2], and in partnership with Public Works and Government Services Canada and the Canadian Department of National Defence. In 1994, FiRECAM™ was used successfully to obtain code changes to the Building Code of Australia to permit the construction of 3-storey wood-frame apartment buildings[3].

In this paper, a brief description of the conceptual design of the 40-storey office building is first given. The use of the centre core design for the elevator, stair and service shafts was chosen to provide the owner with: (1) the more profitable use of the perimeter and window area of the building for office space, (2) a simple floor layout that can be easily compartmentized and fire separated for different tenants, and (3) the provision of a refuge area in the centre core to act as a temporary safe place for disabled occupants and those who cannot evacuate. The requirements of the National Building Code of Canada (NBCC) relevant to this building are then described. Currently, the requirements are prescriptive-based, but Canada plans to introduce an objective-based code with performance requirements by the year 2001. Five design options, including the code-compliant design and 4 alternative designs, are proposed and described. A brief description of FiRECAM™ is given and the results of its application to the five design options are then discussed. Two of the alternative design options are found to be cost-effective. These options meet the safety level implied by the NBCC but provide the owner with cost and business benefits.

BUILDING DESCRIPTION

The building to be considered is a 40-storey office building with two basement levels. For this study, the building is assumed to be steel-framed, 60 m long by 50 m wide. The conceptual layout of the floors is shown in Fig. 1, with the elevator, stair and service shafts all located in a centre core. The centre core arrangement permits more profitable use of the perimeter and window area of the building for office space, and offers the potential of a refuge area in the core area (see Fig. 1) as a temporary safe area for people with disabilities who cannot walk down the stairs in an emergency.

The ground floor has a restaurant, a lobby area at the main entrance, and three side exits with one connected directly to the stairs via a protected corridor. The rest of the ground floor is occupied by various retail stores. Floors 2 to 40 are divided into four company-sized spaces, each of which is suitable for use by one professional company, such as a law office, an accounting firm or an insurance company. One of the spaces has been divided into smaller offices to show, as an example, how such a space could be utilized by a company. Each space can have two means of egress to the centre core area. Also, the spaces can be combined into larger space for larger companies. The first basement level, not shown, is used for meeting rooms and building staff offices. The second basement, also not shown, is used for storage and mechanical equipment. The basement levels have separate stairs for access to the lobby on the main floor. Only the service elevator goes down to the second basement level.

Occupant Characteristics

Since the building is an office building, the occupants are mainly office workers with the exception of a few working in the restaurant and in the stores on the ground floor. If there are occupants on the upper floors whose mobility is impaired, they are assumed, in case of

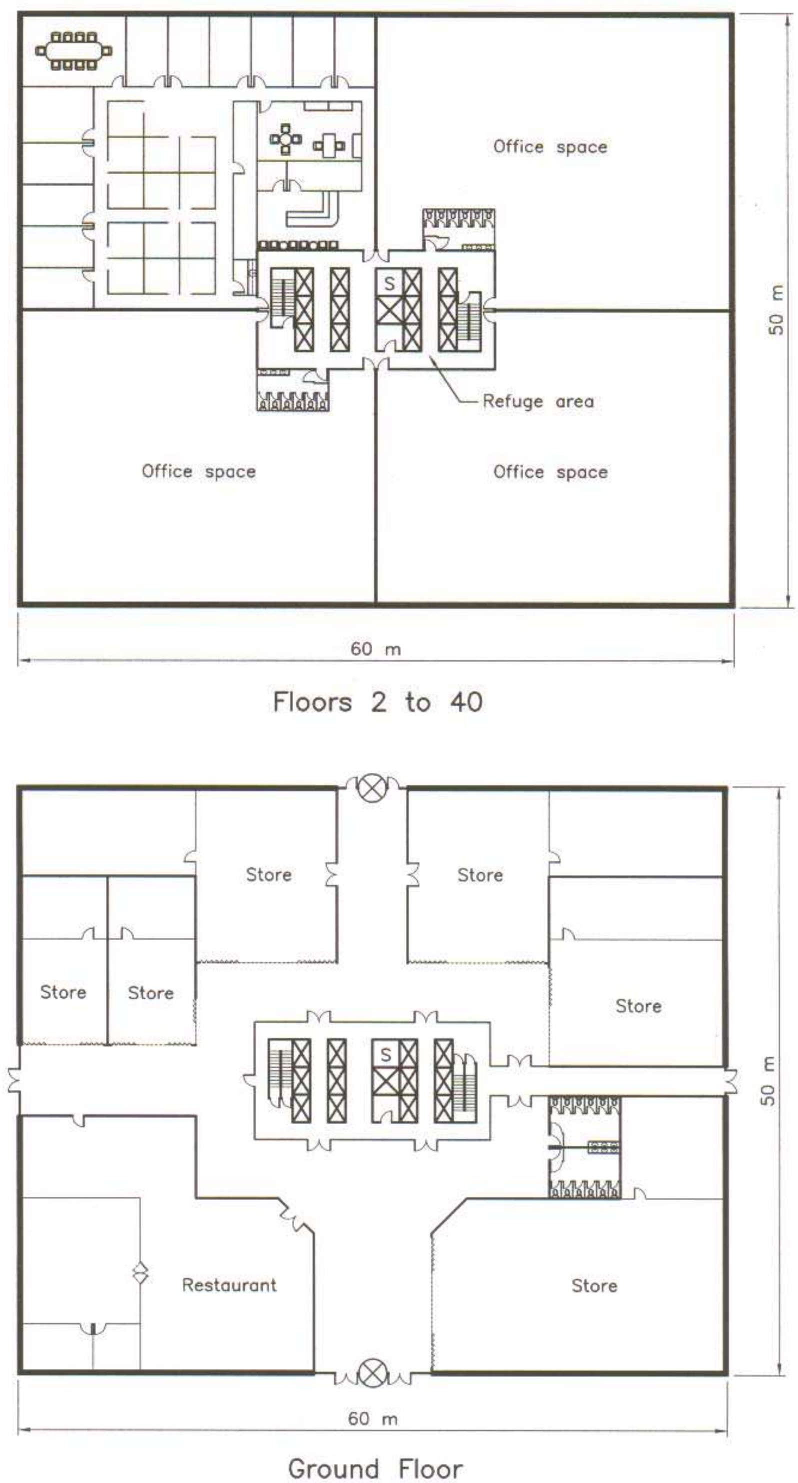

Fig. 1. Floor plans.

fire emergency, to wait in the refuge area in the centre core and to be guided to safety on the ground level by co-workers or to be rescued by the firefighters when they arrive. The number of occupants per floor is assumed to be 300, or one occupant per 9.3 m^2 usable space (assuming 93% of the total floor area is usable). The refuge area in Fig. 1 can accommodate 300 people, based on the NBCC requirement of 0.3 m^2 per person. Since the two basement levels are used mainly for meeting rooms and storage and therefore have very few regular workers, the total number of occupants in the building is 12,000.

CANADIAN BUILDING CODE REQUIREMENTS

The current National Building Code of Canada (NBCC 1995)[4] is a prescriptive-based code. However, as mentioned previously, the Canadian Commission on Building and Fire Codes plans to introduce an objective-based code with performance requirements by the year 2001. In the meantime, equivalency is permitted if an alternative design can be demonstrated to provide the same level of safety as implied by the prescriptive requirements.

Prescriptive Requirements

For the 40-storey building being considered, the relevant prescriptive requirements of the NBCC are as follows:

Fire Separation The building is required to be of non-combustible construction with major structural elements having a fire resistance rating (FRR) of not less than 2 h. On each floor, the FRR of partition walls between tenant suites can range from 15 min (between office suites) to 2 h (from restaurant to retail store). The cost of providing a higher FRR partition wall may be offset by improved fire containment and therefore lower fire losses. Every door in a fire separation is required to be fire rated and equipped with a self-closing device, designed to return the door to the closed position after each use.

Exit Stairs Two exit stairs are required, and must be located so that the travel distance to at least one is not more than 40 m. The present layout of the building meets this requirement.

Occupant Load The building is required to have no more than one occupant per 9.3 m^2 of usable space. The present building is assumed to have this occupant load.

Detectors and Alarms The building is required to have a fire alarm system and a voice communication system. Manual pull stations are required near principal entrances and exits. Smoke detectors are required in stairshafts.

Automatic Sprinklers Sprinkler protection is required for this building.

Stairwell Pressurization Pressurization is required for stairwells serving below ground level. However, pressurization is not required for stairwells serving above ground level if they are naturally vented, which is assumed for the present building.

Performance Requirements

The current NBCC is a prescriptive-based, not performance-based, code. For the present case study, the implied safety level provided by the prescriptive requirements is used to determine whether an alternative design meets the performance requirements.

OWNER'S FIRE SAFETY AND BUSINESS GOALS

The main goals of the building owner are: (1) to provide the occupants with a level of fire safety that meets the building code requirements, (2) to provide a safe area for occupants with disabilities, and (3) to minimize the potential for fire and smoke damage so as to minimize business losses to tenants. The owner also wants to minimize the cost of fire protection and expected fire losses. To achieve that, the owner wants to consider alternative design options that provide the occupants with the same level of fire safety as required by the building code but have lower fire protection costs and expected fire losses. Since the NBCC does not have performance requirements, the only way to do this is to consider alternative design options that could provide the occupants with the same level of fire safety as implied by the prescriptive requirements of the NBCC. This can be accomplished by using FiRECAM™ to assess the expected fire risk of a design that meets the prescriptive requirements and then those of alternative designs; these are compared to see if the alternative designs can provide equivalent safety. An alternative design that can provide equivalent life safety but has the lowest fire protection cost and expected fire losses is the most cost-effective design to the owner.

FiRECAM™

The modelling concept of FiRECAM™ is briefly described in this section. Details of FiRECAM™ were described in previous publications[1-2, 5-9]. The modelling of the occupant response and evacuation is also being presented at this conference[10].

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 over the design life of a building, divided by the total population of the building and the design life of the building. 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 compliance (performance-based codes) or code equivalency consideration (prescriptive-based codes), whereas the FCE value can be used for cost-effectiveness considerations.

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. The life hazard to the occupants from a scenario is calculated based on the speed of the fire development and the speed of the 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.

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 considering all probable fire scenarios that may occur in a building. The number of fire scenarios depends on a number of factors. These include the many types of fire that may occur in the compartment of fire origin and the many compartments in the building where a fire may start. What follows is a brief description of the types of fires to be considered (design fires), the fire growth characteristics of a flashover fire, the smoke movement in the stairshafts and the occupant evacuation profile. Other features of FiRECAM™ are described in previous publications[1-2, 5-9].

Design Fires

FiRECAM™ uses six design fires in the compartment of fire origin, with subsequent fire and smoke spread, to evaluate life risks and protection costs for 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[11] 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[11]. 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[9].

Fire Growth

The fire growth model predicts the development of the six design fires in the compartment of fire origin using representative fuels, such as wood cribs for office furniture. Details of this model are described in a previous paper[6]. 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. Figure 2 shows the model prediction of a flashover fire in a large office space within a company, with the entrance door open and a fire load of 10 kg/m^2. The figure shows the temperature and mass flowrate of combustion gases generated as well as the concentrations of CO and CO_2.

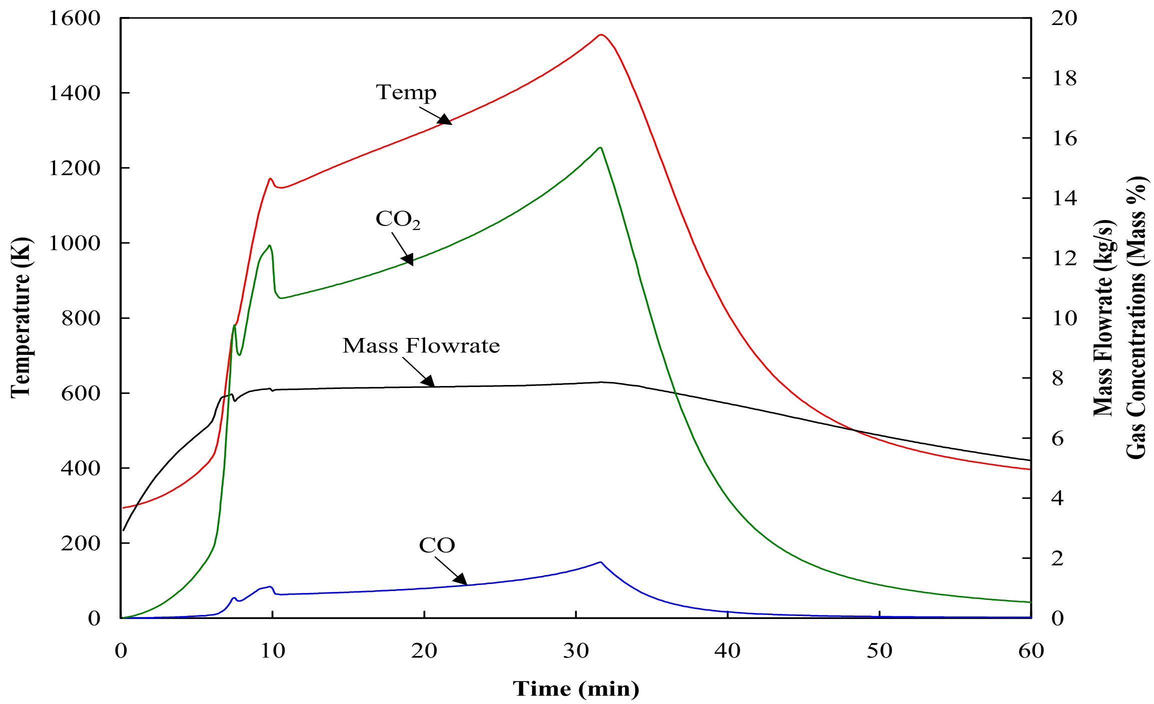

Fig. 2. Flashover fire with entrance door open.

Smoke Movement and Occupant Evacuation

The combustion gases, generated by the fire growth model, are used by the smoke movement model in FiRECAM™ to calculate the spread of the toxic gases through the corridor to other locations on the same floor, as well as through the stairshafts to other floors. Figure 3 shows the prediction of the temperature and CO concentration in the stairshafts as a result of a flashover fire on the first floor. Figure 3 also shows the evacuation of the occupants and the critical time at which the stairs become untenable. At this critical time, those occupants who have not evacuated are considered to be trapped and are then subject to the assault of fire and smoke spread until the arrival of the fire department. It should be noted that the evacuation curve in Fig. 3 is continued, after the stairs have become untenable, to show how the evacuation would have progressed if conditions were tenable. As can be seen in Fig. 3, a large number of occupants could be easily trapped in a highrise building. In this case, the use of a refuge area in the centre core would be invaluable as a temporary safe area for those who cannot evacuate.

ASSUMPTIONS AND LIMITATIONS

FiRECAM™ currently can only handle highrise buildings up to 30 storeys high. The present 40-storey building was modelled as a 30-storey building. However, both the floor population and the probability of fire starts were increased by a factor of 4/3. These allow the 30-storey building to have the same number of occupants and fire starts as in a 40-storey building.

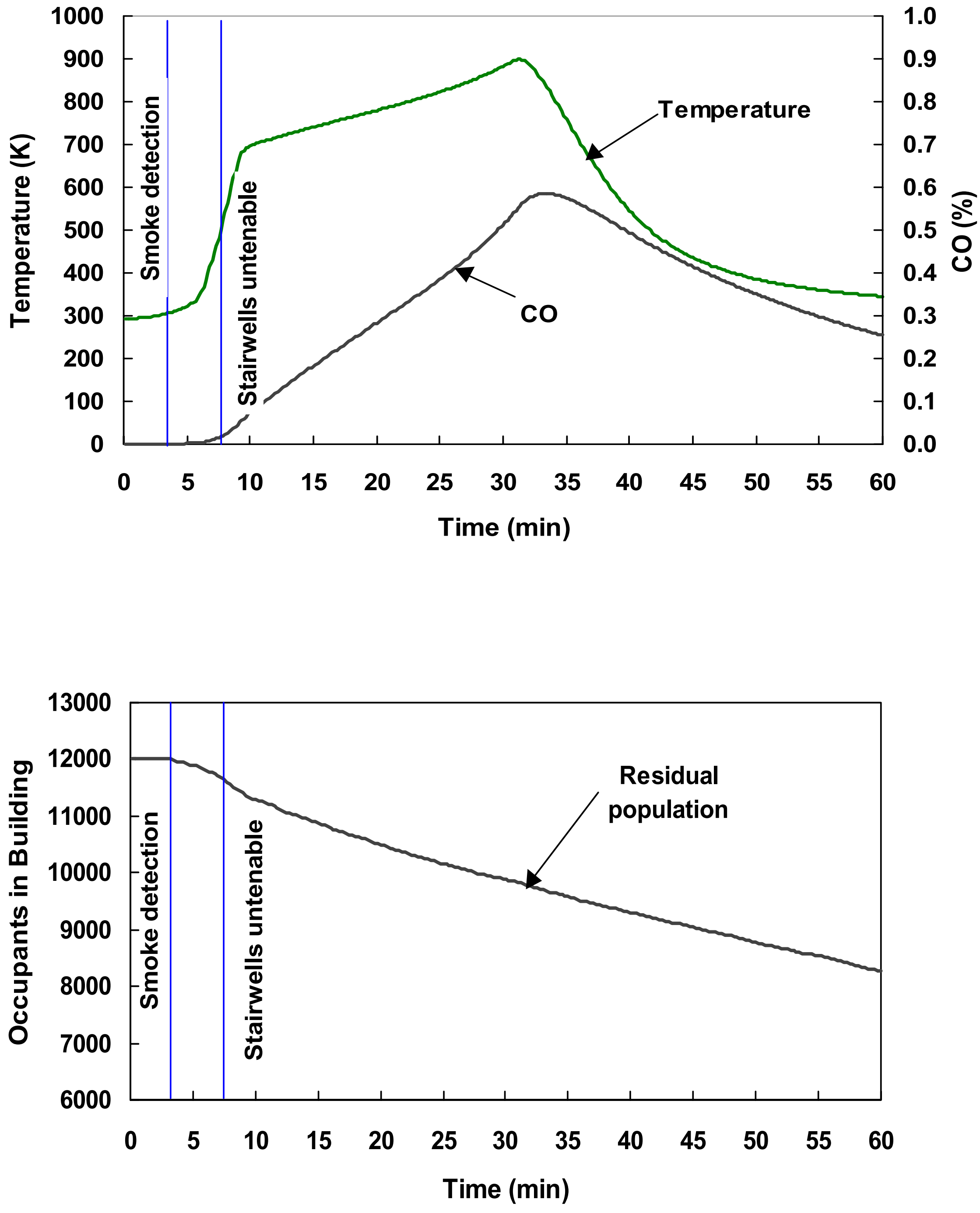

Fig. 3. The build-up of smoke and heat in the stairwell and the evacuation of occupants as a function of time for a flashover fire on the first floor with the entrance door to the fire compartment open.

FiRECAM™ currently does not contain a refuge area feature. A refuge area is an area protected from fire and smoke where occupants can go to in a fire emergency. For the present case study, smoke control was used in FiRECAM™ to simulate the effect of a refuge area. Smoke control reduces the smoke concentration everywhere in the building, thus reducing the smoke hazard to the occupants who are trapped. These occupants are still subject to the hazard of fire spread. Thus, the temporary use of only smoke control in FiRECAM™ to simulate the refuge area will provide conservative results.

For the present study, the two basement levels were assumed to be protected by sprinklers. The two stairwells for the basement levels only reach the ground floor and were assumed to be protected by stairwell pressurization. The elevators are protected by vestibules. Also, there are no regular workers in these levels. The risk to life to the occupants on the upper floors, from fires that may occur in the basement levels, is assumed to be small. Therefore, the calculation of various fire scenarios did not include these areas.

DESIGN OPTIONS

The number of options considered is shown in Table 1. Option 1 is the code-compliant option which is used as the reference option: with a fire resistance rating (FRR) of 2 h, sprinkler protection (assumed to have a nominal 95% reliability), but without a refuge area. Option 1 also includes a central alarm with voice communication, as described in the Code Requirements section. Option 2 is the same as Option 1 but with a slightly lower FRR of 90 min. This option was used to check what the reduction in protection cost, and the corresponding increase in risk, would be. Option 3 is the same as Option 2 but with a refuge area to help reduce risk. Option 4 is the same as Option 2 but with a higher sprinkler system reliability of 99% to help reduce risk. Option 5 is the same as Option 2 but without sprinkler protection. This option was used to check what the risk would be without sprinklers.

Table 1. Fire protection options to be considered

Design Option	Fire Resistance Rating (min)	Refuge Area	Sprinklers (% reliability)
1 (Ref)	120	No	95
2	90	No	95
3	90	Yes	95
4	90	No	99
5	90	No	No

RESULTS

The results obtained by FiRECAM™ for the five design options are shown in Figs. 4 and 5. In Fig. 4, the expected risk to life (ERL) of each option is compared to the reference option, which has a relative ERL of 1. In Fig. 5, the fire cost expectation (FCE) of each option is shown, which includes the capital costs of passive and active fire protection systems, the present worth of the annual maintenance cost of the active fire protection system and the present worth of annual fire losses (building restoration cost) as a result of damage from fire and smoke spread. In the cost calculations, the design life of the building was assumed to be 25 years and the discount rate for calculating the present worth of annual costs was assumed to be 3%.

Option 2 has the same fire protection as the reference option, except with a lower FRR of 90 min. The results show Option 2 has the same relative ERL of 1.0 (actual numerical value is slightly higher, at 1.04), but has a lower FCE. This is expected since a slightly lower FRR would increase the risk slightly due to fire spread and a correspondingly lower fire protection cost. Notice also the slightly lower FRR does not increase the fire losses significantly.

Option 3 is the same as Option 2, except with an added refuge area on each floor. Option 3 is shown to have a lower relative ERL of 0.5 and a lower FCE, when compared to the Reference Option. This is possible since the refuge area protects the large number of trapped occupants who may not be able to evacuate for some of the flashover fires. The FCE is lower because of the lower FRR. The active protection cost is slightly higher (not obvious in Fig. 5) because of the use of a smoke control system, but the property loss is lower because smoke control reduces smoke damage.

Option 4 is the same as Option 2, except with a higher reliability sprinkler. This option is shown to have a slightly lower relative ERL of 0.9 and a lower FCE, when compared to the Reference Option. In FiRECAM™, sprinkler protection is assumed to have a significant impact on flashover fires, limited impact on non-flashover fires and no impact on smouldering fires. The reduction in risk is mainly due to the reduction in the probability of flashover fires.

Option 5 is the one without sprinkler protection. As expected, both the relative ERL and the fire losses increase significantly, although the active protection cost is reduced.

COST-EFFECTIVE OPTIONS

The results indicate two cost-effective options. The first is Option 3 which uses a refuge area where smoke control was used to protect the occupants. This option has a relative ERL of 0.5 when compared to the Reference option, and an FCE of approximately $6.5 million, which is much lower than the $8.8 million for the Reference option. The second option is the one that uses a higher reliability sprinkler system (Option 4), where higher maintenance is implied. This option has a relative ERL of 0.9 and an FCE of approximately $6.5 million.

Both options have lower expected fire losses which should minimize business down time. Option 3 would be considered the better of the two because it provides safety for occupants with disabilities and has an overall lower ERL.

It should be noted that the assessment of property loss in the present case study may not be accurate because of the difficulty of assessing both the probability of fire spread and the cost of restoration. In FiRECAM™, conservative modelling is used in the assessment of the probability of fire spread and the cost of restoration after a fire. The assessment of the property loss, therefore, may be on the high side.

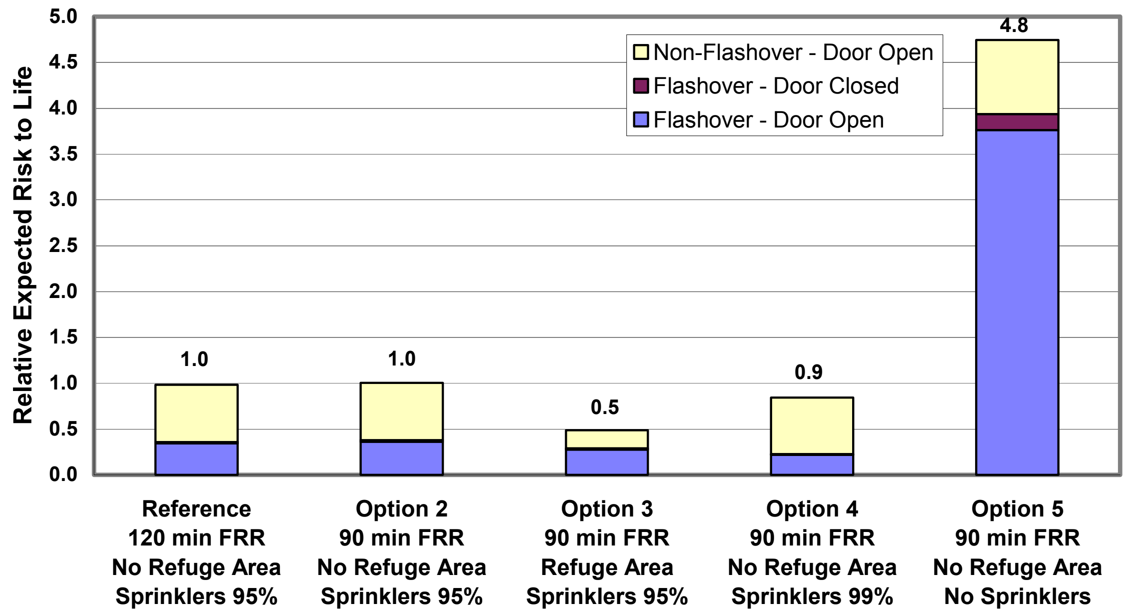

Fig. 4. Relative expected risk to life for 5 design options shown in Table 1.

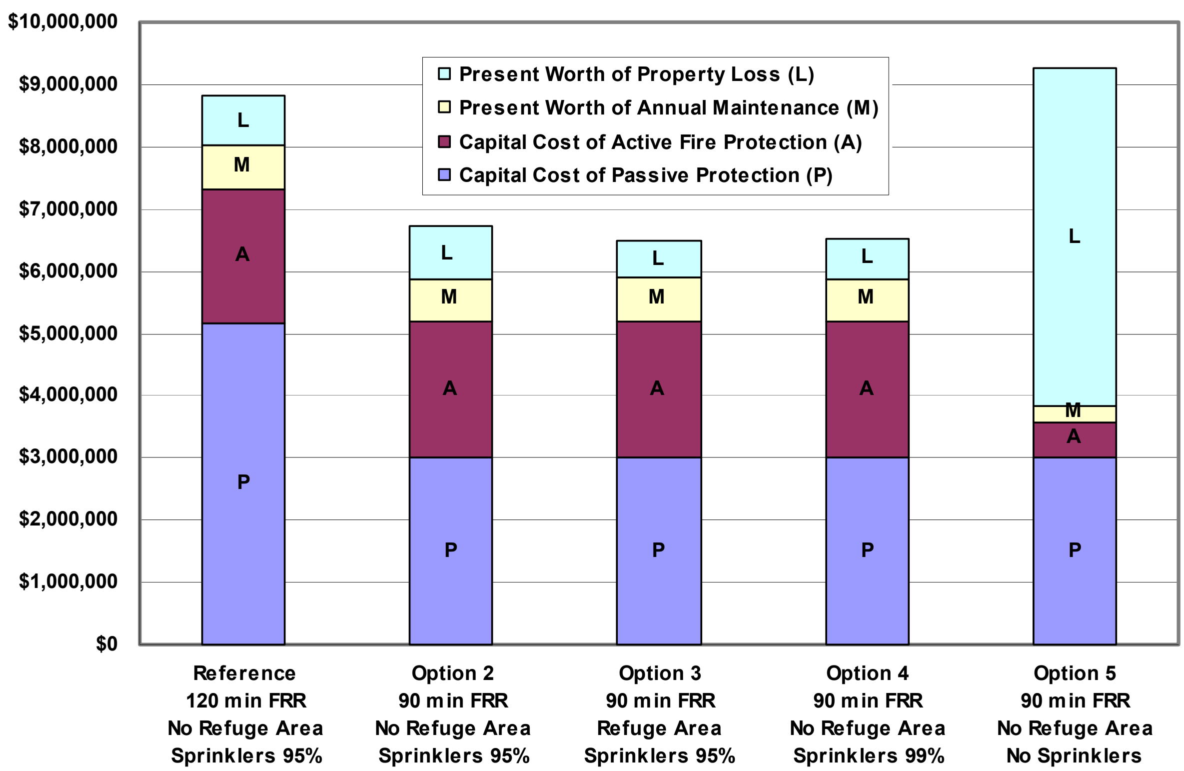

Fig. 5. Fire cost expectation for 5 design options shown in Table 1.

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