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FIERASYSTEM: A FIRE RISK ASSESSMENT TOOL TO EVALUATE FIRE SAFETY IN INDUSTRIAL BUILDINGS AND LARGE SPACES

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ABSTRACT

FIERAsystem is a computer model for evaluating fire protection systems in industrial buildings. The model has been developed as a tool to assist fire protection engineers, building officials, fire service personnel and researchers in performing fire safety engineering calculations, and can be used to conduct hazard and risk analyses, as well as to evaluate whether a selected design satisfies established fire safety objectives. While the model is primarily designed for use in warehouses and aircraft hangars, it can be modified for application to other industrial buildings. This paper describes the framework for FIERAsystem, along with its capabilities and flexibility. Individual models used to perform calculations are discussed, particularly those that calculate fire development and life hazard. A hazard analysis of an aircraft hangar is then described in detail, as an example of the types of calculations this model can perform. Methods used by the model to conduct risk assessments are also briefly described.

Key Words: Assessment, buildings, fire, large spaces, model, risk, computer tools

INTRODUCTION

As Canada and other countries move from prescriptive-based building codes to performance/objective-based codes, new design tools are needed to demonstrate that

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compliance with these new codes has been achieved. One such tool is FiRECAM™, a computer model that has been developed over the past decade by the Fire Research Program of the Institute for Research in Construction at the National Research Council of Canada (NRC) to evaluate fire protection systems in apartment and office buildings. Details of FiRECAM™ can be found in Yung et al. [1] along with an example of its use in evaluating possible upgrades to a six-storey Canadian federal government office building.

To extend the risk assessment concepts developed in FiRECAM™ to other occupancies, a new computer model, called FIERAsystem (**F**ire **E**valuation and **R**isk **A**ssessment system), has been developed to evaluate fire protection systems in industrial buildings, with a primary focus on warehouses and aircraft hangars. FIERAsystem uses time-dependent deterministic and probabilistic models to evaluate the impact of selected fire scenarios on life, property and business interruption. In order to demonstrate the utility of FIERAsystem, case studies were recently performed to evaluate fire protection systems in defense facilities.

This paper first discusses the design issues considered in the development of FIERAsystem, and then describes the framework of the FIERAsystem model. The main models included in FIERAsystem are also briefly described. The paper then describes how the framework and individual models were used to conduct a fire hazard analysis of an aircraft hangar. Procedures used for other calculations that can be performed using FIERAsystem, such as determinations of compliance with fire safety objectives and risk assessments, are also presented.

DEVELOPMENT OF FIERAsystem

FIERAsystem has been designed as a tool that can be used to support performance-based fire protection engineering design. The system is intended to be used by qualified individuals, who receive appropriate training in the use of the software. The individual models included in the overall system are based on accepted fire protection engineering practice and were chosen to give an appropriate level of sophistication, and still result in a system that can be run in a reasonable length of time on a desktop personal computer. This would allow for use of the system by all of the intended parties, and facilitate the examination of multiple fire scenarios and fire protection engineering options. The individual

models chosen and the overall system model are described in subsequent sections in this paper.

FRAMEWORK OF FIERAsystem MODEL

The FIERAsystem model allows the user to perform a number of fire protection engineering calculations in order to evaluate fire protection systems in industrial buildings. At startup, FIERAsystem provides several calculation options, which allow the user to:

- use standard engineering correlations,
- run individual models,
- conduct a hazard analysis, or
- conduct a risk analysis.

The standard engineering correlations model (FIERAscor) [2] is a collection of relatively simple equations that can be used to quickly perform simple fire protection engineering calculations. The current version of FIERAscor contains procedures for calculations in the general areas of fire development, plume dynamics, smoke movement, egress, fire severity and ignition of adjacent objects. The individual models included in FIERAsystem are described in the next section. The emphasis of this paper is on the hazard analysis option, which will then be described. After a discussion of the framework, which FIERAsystem uses to conduct a hazard analysis, an example of a hazard analysis of an aircraft hangar is then described. The process used to conduct a risk analysis will be discussed briefly later in the paper.

FIERAsystem can also be used to evaluate whether a fire protection system for a building will satisfy specific fire safety objectives. This can be done using individual models, or through a hazard or risk analysis. For example, individual models in FIERAsystem can be used to evaluate single components of a fire safety design, such as the time of activation of heat detectors or sprinklers, the time to flashover and the time of failure of construction elements. An example of the use of FIERAsystem in evaluating compliance with fire safety objectives can be found in Reference [3].

FIERAsystem MODELS

The main FIERAsystem models are described in this section. More detailed information on each of these models can be found in separate publications (e.g., [4,5]).

Fire Development

Models are currently available in FIERASystem for the following fire scenarios:

- liquid pool fires,
- storage rack fires, and
- t^2 fires (i.e., the heat release rate is assumed to be proportional to the square of the elapsed time, which is often used to simulate fires).

Each of the Fire Development Models calculates the quantities, which characterize the fire (heat release rate, temperature and thermal radiation heat fluxes) as functions of time. Currently, the equations used are standard engineering correlations, such as those found in the SFPE Handbook of Fire Protection Engineering [6]. As an example, a confined, enclosed pool fire was chosen as one of the fire scenarios in the case studies, described later in this paper. The heat release rate at any time is calculated by assuming that the pool fire can be described as an ultrafast t^2 fire, using the following equation [7]:

$$Q(t) = \alpha t^2 \quad (1)$$

Where

Q = the heat release rate of the fire at any time (kW),

α = the fire growth coefficient (kW/s²)

= 0.1876 kW/s², and

t = the time (s).

This heat release rate is limited to the maximum heat release rate possible based on either the amount of fuel in the compartment or the oxygen that can be supplied to the fire from the compartment and through ventilation openings. The duration of a confined pool fire is calculated using the volume of fuel burned, the dike area and the burning rate of the fuel, which are specified by the user. The model assumes that the diameter of a pool fire increases linearly with time to the maximum diameter, $D_{\max}$, entered by the user. This maximum diameter of the pool fire is assumed to be its equilibrium diameter (the spill rate equals the burning rate). The time required to reach this maximum diameter, $t_{\max}$, is given by the following equation [8]:

$$t_{\max} = 0.564 \frac{D_{\max}}{(g v_f D_{\max})^{1/3}} \quad (2)$$

Where

v_f = the burning (regression) rate of the fuel (m/s), and

g = the acceleration due to gravity (m^2/s).

The thermal radiation heat fluxes from the pool fire to a point located 1 m from the ground at various distances are calculated using the solid flame model of Mudan and Croce [8]. A height of 1 m was chosen so as to be representative of the mid-section of a person. The following equation is used to calculate thermal radiation heat fluxes at a distance from the fire:

$$q''(t) = q_e'' F(t) \tau SF \quad (3)$$

Where

q_e'' = the emissive power of the pool fire (kW/m^2),

$F(t)$ = the view factor from the pool fire to the point, calculated using the height and diameter of the flame ($0 \leq F \leq 1$),

τ = atmospheric transmissivity (assumed to be 1.0, because of the relatively short distances considered), and

SF = a safety factor.

The emissive power of the flame is calculated using the following equation:

$$q_e'' = E_f e^{-SD} + E_s (1 - e^{-SD}) \quad (4)$$

Where

E_f = the maximum emissive power of the visible portions of the fire (kW/m^2),
= $140 kW/m^2$,

E_s = the maximum emissive power of the smoky portions of the fire (kW/m^2),
= $20 kW/m^2$,

S = an experimentally determined parameter (m^{-1}),
= $0.12 m^{-1}$, and

D = the pool diameter (m).

The Fire Development Model provides the heat fluxes from the pool fire to the Life Hazard Model to calculate the probability of death from exposure to high heat fluxes. The Fire Development Model also supplies the Building Element Failure Model with information to calculate the convective and radiative heat fluxes from the fire to the boundaries of the compartment. The ceiling impingement gas temperature (T_{ce}) [9] and the effective plume temperature (T_{ep}) used to evaluate the time to failure of ceilings and walls of the compartment, respectively, are given by the following equations:

$$T_{ce}(t) = T_{amb} + 0.22 \frac{(k Q(t))^{2/3}}{H^{5/3}} \quad (5)$$

Where

T_{ce} = ceiling impingement gas temperature (K),

T_{amb} = the ambient temperature ($^{\circ}\text{C}$),

k = a factor to take into account the effect of the compartment walls on the temperature of the hot plume gases,

= 1 (if no walls are nearby),

= 2 (if the fire is close to one wall – default value),

= 4 (if the fire is in a corner),

Q = the heat release rate of the fire at any time (W), and

H = the distance or height between the top of the fuel and the ceiling (m).

$$\frac{H_f(t)}{H_c} T_f^4(t) + \left(1 - \frac{H_f(t)}{H_c}\right) T_{ce}^4(t) = T_{ep}^4(t) \quad (6)$$

Where

$H_f(t)$ = the height of the flame given in Equation (7) below
from the correlation [9] (m),

H_c = the height of the compartment (m),

T_f = flame temperature (K), and

T_{ep} = effective plume temperature (K).

$$H_f(t) = 0.011 (k Q(t))^{2/5} \quad (7)$$

Alpert and Ward [9] state that Equation (5) is derived from empirical data and is not valid when the flames are either very close to the ceiling or very far away from the ceiling; therefore, it cannot predict temperatures greater than 825°C accurately. In addition, the temperature at the centreline of the visible portion of the flame (T_f) is evaluated to be 980°C. This temperature value is calculated based on the thermal radiation heat flux of 140 kW/m² assumed earlier for the visible portion of the flame [8], an emissivity of 1 and a view factor of 1. The assumed value of 140 kW/m² and calculated temperature of 980°C are valid for pool fires only. For other types of fires, other values need to be used.

Smoke Production and Movement

FIERAsmoke is a two-zone model for calculating smoke production and spread through the compartments in a building. For each of the two zones, differential equations based on mass, energy and species conservation are solved, subject to boundary and initial conditions based on user input. These equations consider the combustion process, vent flows, plume entrainment, and conduction, convection and radiation heat transfer. The output of this model provides information on the temperature and thickness of smoke layers and species concentrations throughout the building. Thermal radiation heat fluxes from the smoke layer in each compartment are also calculated by the model. More details on this model can be found in Fu and Hadjisophocleous [4].

Fire Detection

Activation times of heat detectors, smoke detectors and sprinkler heads are determined using the Fire Detection Model. When the model is run on its own, the user is asked to specify the location of the fire source and the locations and types of any detectors or sprinklers. In an automated hazard analysis, the fire source is assumed to be centered between the detectors or sprinklers, resulting in the largest possible distance from these devices. The time-dependent heat release rate and effective diameter of the fire source are also input. Standard engineering correlations are used to predict the temperatures and velocities at different locations within the fire plume, ceiling jet and smoke layer [10].

The preceding information is then used to calculate the temperatures of all detection elements in the space with time. The time-dependent temperature of each detection element (or rate of temperature increase, for rate of rise detectors) can then be used to determine the activation time of each heat detector and sprinkler head in the space.

Information on the smoke layer is used to predict the activation time of smoke detectors in the space. Activation times for detectors and sprinklers can be used to determine the notification time, which helps in determining the occupant response time and the fire department response time.

Building Element Failure

The times to failure for the structural elements and barriers in the building are estimated using the Building Element Failure Model. Presently, the program can do calculations for steel beams and columns, concrete slabs, wooden beams and columns, and lightweight frame walls and floors. The user can choose to perform calculations based on standard fire protection engineering correlations, or use numerical techniques, such as finite difference heat transfer models, for some structural elements. The output of these models consists of the predicted time of failure (based on criteria specified in standards, ASTM E119 [11] or CAN/ULC-S101 [12]) of the structural element or barrier. Alternatively, the user can specify failure times, based on fire resistance ratings or other information.

Suppression Effectiveness

The Suppression Effectiveness Model calculates the effect of candidate automatic suppression systems on fires in the building. The model requires the user to input a suppression effectiveness value (η) from 0 to 1.0, which quantifies the ability of the automatic suppression devices to control the fire scenarios being considered. This value is then used to modify the fire heat release rate, diameter, thermal radiation heat fluxes and plume temperature

The heat release rate curve ($Q(t)$) from the Fire Development Model or another source is input to the Suppression Effectiveness Model. The suppression effectiveness value is used to produce a modified heat release rate curve ($Q_m(t)$) as shown in Figure 1. If the suppression system effectiveness is 1.0, the fire is controlled so that the heat release rate remains at its value at the time of automatic suppression system activation (i.e., $Q_m = Q_{act}$). If the effectiveness is 0, the original heat release rate curve (Q_o) will not be modified (i.e., $Q_m = Q_o$). If the effectiveness is between 0 and 1.0, the modified heat release rate will be calculated at each time step using the following equation:

$$Q_m(t) = (1.0 - \eta) \times (Q_o(t) - Q_{act}(t)) + Q_{act}(t) \quad (8)$$

Where subscripts are defined as

m = modified by the Suppression Effectiveness Model,

o = the original value of the parameter input to the Suppression Effectiveness Model, and

act = the heat release at time of suppression activation.

In the case where heat release rate values decay, any value of $Q(t)$, which is below Q_{act} , is not modified in any way. This helps ensure that the Suppression Effectiveness Model does not increase the value of $Q(t)$ in this situation. Heat fluxes and temperatures calculated using Equations (3) to (7) are then corrected using the modified heat release rate data.

Fire Department Response and Effectiveness

The Fire Department Response Model is used to determine the expected fire department response and intervention times, which are calculated using the times estimated for notification, dispatch and preparation, travel and set-up (see Figure 2). These calculations are based on factors such as the fire scenarios selected by the user and activation times for the detectors in the building. The presence of fire alarms in the building, their direct connection to the fire department (some buildings may be linked to a dispatch station through an alarm that will directly notify the fire department in case of fire), the occupant response to fire cues or other warning signals, the location of the building relative to the fire department, preplanning, traffic volume, and street arrangement are also considered in the calculations. More information on the model can be found in [13].

Once the fire department activities begin, the effectiveness of these activities is estimated by the Fire Department Effectiveness Model according to information on the fire development at the time suppression commences and the resources (e.g., equipment, water and human resources) available to the fire department. Factors such as the nature of the fire department (e.g., professional, volunteer or a combination of both), firefighter experience and training are also considered in this calculation, see [13].

Occupant Response and Evacuation

The Occupant Response and Evacuation Models are used to track the movement of occupants in the building during the selected fire scenarios, based on the occupant characteristics entered by the user. The characteristics include the location of the occupant

and their age [14]. Calculations take into account the processes of perception (occupants become aware of fire by means of direct perception of fire cues, warning by alarm or others, etc.), interpretation (occupants make a decision to respond), and action (e.g., occupants call the fire department, pull the alarm, begin to evacuate, etc.). This is different from most occupant evacuation models, which assume that the occupants respond immediately to a fire alarm, or cue, which is not the case in occupant evacuation field studies or in real life [15]. Once the occupants respond to the fire, the model then calculates their movement, taking into account their characteristics, fire development and smoke movement.

Life Hazard Model

The subject of life safety in fire has been studied by a number of researchers and the information has been produced in the SFPE Handbook [6], ISO [16,17] and NFPA [18]. SFPE provides technical guidance on the subject of life safety. ISO has published a technical specification document and a standard (ISO/TS 13571 [16] and ISO/DIS 13344 [17]), to provide the necessary requirements and the technical guidance to evaluate life safety in fire. The NFPA life safety code handbook also provides details on the life safety requirements and guidance to achieve these requirements. The information in these documents is valuable and some of it helped in the formulation of the FIERAsystem Life Hazard Model.

The FIERAsystem Life Hazard Model [5] calculates the time-dependent probability of death for occupants in a compartment due to the effects of being exposed to high heat fluxes and hot and/or toxic gases. The Life Hazard Model uses input from other FIERAsystem models that describe the heat fluxes (Fire Development and Smoke Movement Models) in the compartment, and the temperature and chemical composition of hot gases (Smoke Movement Model).

The time-dependent probability of death from exposure to high thermal radiation heat fluxes, P_{TR} , at a given location in the compartment, is calculated using the sum of the heat fluxes from the fire (calculated by Fire Development models) and from the hot smoke layer (calculated by the Smoke Movement Model). The revised vulnerability model of Tsao and Perry [19] is used to calculate the probability of death from the heat flux data. This model uses the following probit equation:

$$Y = -12.8 + 2.56 \ln V \quad (9)$$

Where

Y = the probit function, and

V = the thermal dose $((\text{kW/m}^2)^{4/3} \cdot \text{s})$.

The thermal dose, V, is calculated using the following equation [20]:

$$V(t) = \int_0^t (q''(t))^{4/3} dt \quad (10)$$

Where

q'' = the incident heat flux (kW/m^2), and

t = the exposure duration (s)

For a square wave heat flux (i.e., a constant value), Equation (10) reduces to the following equation:

$$V(t) = (q'')^{4/3} \cdot t \quad (11)$$

The probit function, Y, is then used to determine the probability of death due to thermal radiation heat fluxes:

$$P_{TR}(t) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{Y-5} e^{-\xi^2/2} d\xi \quad (12)$$

The probability of death due to breathing toxic gases, P_{TG} , is calculated using the same techniques originally developed for FiRECAM™ [21]. The FIERAsystem Life Hazard Model only considers the toxic effects of CO and CO₂, because in most practical fire situations, the effects of CO are the most important. CO₂ will affect the rate of breathing and hence will affect the intake of CO. The fractional incapacitating dose due to CO (FID_{CO}) is calculated using the following equation and the concentration of CO at a specified height in the compartment of interest:

$$FID_{CO}(t) = \int_0^t \frac{8.2925 \times 10^{-4} (CO(t))^{1.036}}{30} dt \quad (13)$$

Where

$FID_{CO}(t)$ = the fractional incapacitating dose of CO, and

$CO(t)$ = the concentration of CO at time t (ppm).

The FID is defined such that the dose will be lethal when $FID = 1$. The default height for these calculations is 1.5 m. While it can be argued that all individuals can crawl under a smoke layer at this height, this height was chosen so as to be conservative. The user can also specify other heights for this calculation, depending on the occupancy.

The concentration of CO_2 is used to calculate a factor, VCO_2 , which is used to increase the FID_{CO} to incorporate the increase in the breathing rate due to CO_2 :

$$VCO_2(t) = \frac{\exp((0.2496 \times \%CO_2(t)) + 1.9086)}{6.8} \quad (14)$$

Where

$VCO_2(t)$ = the multiplication factor for CO_2 -induced hyperventilation, and

$\%CO_2(t)$ = the percentage of CO_2 (by weight) in the compartment of interest.

The total fractional incapacitating dose for toxic gases is calculated using the following equation:

$$FID_{TG}(t) = FID_{CO}(t) \times VCO_2(t) \quad (15)$$

This FID is then used as the probability of death due to breathing toxic gases (i.e., $P_{TG} = FID_{TG}$).

The FIERAsystem Life Hazard Model also considers the probability of death due to breathing or being exposed to hot gases, P_{HG} . This probability is equal to the FID for exposure to hot gases, calculated using the following equation [22]:

$$FID_{HG}(t) = \int_0^t \frac{1}{60 \times \exp(5.1849 - 0.0273 T_s(t))} dt \quad (16)$$

Where

$T_s(t)$ = the temperature of the hot gases at a height of 1.5 m in the compartment of interest ($^{\circ}\text{C}$).

Equation (16) is based on data from the literature for human tolerance times in experimental exposures to dry and humid air at elevated temperatures. An FID_{HG} of 1.0 is said to represent the point where a person would become incapacitated by the exposure to the hot gases because of heat stroke, skin burns and/or respiratory tract burns.

The total probability of death, $P_D(t)$, at a given location in the compartment is calculated using the union of the individual probabilities of death from being exposed to high thermal radiation heat fluxes, and breathing hot or toxic gases:

$$P_D(t) = P_{TR}(t) \cup P_{TG}(t) \cup P_{HG}(t) \quad (17)$$

In order to calculate the total probability of death in any compartment using the FIERAsystem Life Hazard Model, the compartment is first divided into a number of rings from the fire (see reference [5]). Equation (17) is used to calculate the total probability of death within each of the rings. The total probability of death for the compartment is then calculated using a weighted sum of the probabilities of death in each of the rings:

$$P_{D-C}(t) = \sum_i \frac{P_{D-i}(t) A_i}{A_C} \quad (18)$$

Where

$P_{D-C}(t)$ = the total probability of death for compartment C,
 $P_{D-i}(t)$ = the probability of death for ring i,
 A_i = the area contained inside ring i, and
 A_C = the total area of compartment C.

Expected Number of Deaths

The Expected Number of Deaths Model calculates the number of occupants expected to die in each compartment with time. This calculation is based on the residual population in each

compartment computed by the Occupant Evacuation Model and the probability of death in that compartment computed by the Life Hazard Model. At each time step, the expected number of deaths are computed by multiplying the probability of death at that time with the residual live population at that time:

$$END(t) = \sum_C P_{D-C}(t) \times POP_{resid-C}(t) \quad (19)$$

Where

END(t) = the expected number of deaths in the building at time t,
 $P_{D-C}(t)$ = the probability of death for compartment C at time t, and
 $POP_{RESID-C}(t)$ = the residual live population in compartment C at time t.

Economic Model

The Economic Model calculates the costs of the building, fire protection systems, and contents based on information provided by the user. The sensitivity of the different parts of the building and contents to heat, smoke and water are also input by the user. Damage to the building and contents are then estimated for the fire scenarios selected by the user based on information from the Fire Development and Smoke Movement Models and the sensitivities of the building and contents. These damage estimates can then be used along with the cost information to estimate the value of the property loss to the building and its contents. More detail on the model can be in found in reference [23] and guidance on how to perform a cost analysis can be found in reference [24].

Downtime Model

The Downtime Model calculates the amount of time that operations in a building will be shut down after a fire. The user inputs information on the expected downtime for various levels of fire damage. This information is then compared with estimates of damages to the building and contents for the fire scenarios selected by the user based on information from the Fire Development and Smoke Movement Models and the sensitivities of the building and contents. Based on this comparison, an expected downtime for operations in the building is calculated. More detail on the model can be in found in reference [25].

HAZARD ANALYSIS PROCEDURE

Hazard analysis calculates the consequences of a specific fire scenario beginning in a specific compartment in the building. In FIERAsystem, the results of hazard analysis are the expected number of deaths, the expected cost of property damage and the expected interruption of business operations. The steps involved in hazard analysis for a multi-compartment building (e.g., Figure 3) are shown in Table 1 along with the models involved and their outputs.

The user first specifies the compartment of fire origin and the fire scenarios that would occur in each compartment. In order to make hazard analysis calculations manageable, FIERAsystem only considers the fire spread to adjacent compartments. For example, in Figure 3, where the compartment of fire origin is Compartment A, only the fire spread to Compartments B and C would be considered. The fire spread to Compartment D would be ignored. The Fire Development Models then calculate quantities that characterize fires, such as heat release rates, temperatures, and heat fluxes, as functions of time. In addition, this would involve simulating Scenarios 1, 2 and 3 in Compartments A, B and C. The process then continues as per Table 1 with the end result for each scenario being the expected number of deaths, the expected fire losses and the expected interruption of business operations.

HAZARD ANALYSIS OF AN AIRCRAFT HANGAR

To demonstrate the use of FIERAsystem, a hazard analysis of an aircraft hangar, Hangar 7, was performed. This study included an analysis of fire and smoke spread in the building, and the evacuation of occupants.

Hangar 7 includes two hangars and two office areas. The office areas have two levels. The presence of fire and barrier walls allows the hangar to be modelled using only a portion of the building. Figure 4 shows the floor plan and elevation of the compartments being modelled. The area modelled consists of five compartments on the ground level office area (escape systems storage room, welding shop, fabric shop, main workshop and paint workshop) and the large hangar. The office compartments have a total floor area of 572 m² and the large hangar has a floor area of 3443 m². The large hangar has a dome-shaped roof, and is modelled using an equivalent roof height. The equivalent roof height is calculated by equating the volume of the dome-shaped roof compartment to the volume of a

flat roof compartment. Using the same floor area, the equivalent roof height is calculated. All internal doors are assumed open and all external doors are assumed closed. The doors are standard size except for the 3 m wide by 2.75 m high roller doors. There is a wet-pipe sprinkler system installed throughout the building, but there are no smoke detectors. The building is of concrete construction.

One possible location for a fire is the paint workshop, where there is a fuel source of approximately 300 L of paint supplies, of which the main chemical is kerosene. The paint workshop dimensions are 8.1 m long, 6.7 m wide, and 4.0 m high. From the paint workshop, one door leads to the main workshop. Another standard door and a roller door lead to the large hangar.

Fire Scenarios

Two potential pool fire scenarios were chosen as design fires for the paint workshop. The first fire occurs when the paint fuel is limited to spilling within a dike diameter of 2.7 m. This fire is estimated to reach a maximum heat release rate of 10 MW. The second fire occurs when the paint fuel is limited to spilling within a dike diameter of 4.0 m. This fire is estimated to reach a maximum heat release rate of 20 MW.

Detailed results will only be shown in this paper for the 20 MW fire. Results for the 10 MW fire will be briefly discussed later in the paper. For the purpose of this case study, the fires are evaluated using the hazard analysis outlined in Table 1.

Fire Development

Figure 5 shows the heat release rate curve for the paint workshop, predicted by the Fire Development Model. The fire is estimated to reach flashover at 221 s, and the maximum heat release rate of 20 MW at 330 s, when the fire runs out of fuel.

Detection and Suppression

The fire is assumed to be located in the middle of the paint workshop and centered between four sprinklers. There are no heat or smoke detectors in the paint workshop. The sprinklers act as detectors and are assumed to have a response time index or RTI of $80 \text{ m}^{1/2}\text{s}^{1/2}$, and an activation temperature of 85°C. The sprinklers in the paint workshop are calculated to

activate at 46 s. Although the sprinklers activate, they are assumed to have no effect on a fire of this magnitude, because of the nature of the fuel.

There is a series of sprinklers located along the dome-shaped roof in the large hangar. Activation times are calculated by combining the time at which the smoke interface (as defined by the Smoke Movement Model) falls below the roller door and the time for the sprinkler to activate, as calculated by the Detection Model. This activation time is based on the heat release rate in the compartment of fire origin and an assumed fire area equivalent to the door width by 0.5 m. The height of the sprinklers is defined by the arc length along the dome, continuing down to the floor. The lowest sprinkler is considered to be located at 9.4 m along the wall, and the highest at 31.9 m along the wall. The lowest sprinkler in the hangar is predicted to activate at 108 s, and the highest is predicted to activate at 300 s.

Fire Department Response and Effectiveness

The fire department is notified by an automatic alarm that sounds with the activation of the sprinklers. The fire department is located on the military base, 1 km away from Hangar 7. The fire department is predicted to intervene within 10 minutes of being notified. The Fire Department Response Model calculates the dispatch, preparation, and travel time to be 10 s, 46 s, and 109 s, respectively (Figure 2). When these times are added to the notification time of 46 s, determined by the sprinkler activation, it is predicted that the fire department will respond at 211 s.

The fire department effectiveness is not considered because the predicted intervention time (646 s) is longer than the times at which flashover and the peak heat release rate are reached (221 and 330 s, respectively). In addition, the fire in the compartment of fire origin starts to decay after 330 s because all fuel is consumed.

Occupant Response

As shown in Figure 6, all occupants in the compartment of fire origin are predicted to take action in approximately 135 s, and all occupants in the remaining compartments are predicted to take action in approximately 260 s. The time the fire department would be notified by an occupant is compared with the time that the fire department is notified due to the activation of the sprinkler. Notification by an occupant is predicted to occur at 67 s. As it was calculated earlier that the fire department is automatically notified when the sprinkler

system activates at 46 s, the notification time calculated by the Occupant Response Model is not used in these calculations.

Building Element Failure

Using the time and temperature data calculated by the Fire Development Model, the 150 mm thick concrete walls of the paint workshop are predicted to fail after 155 minutes. The failure time is based on the absence of fire department action because the fire runs out of fuel and starts to decay after 330 s.

Smoke Movement Model

The Smoke Movement Model is run using the six compartments described above. The ventilation system is assumed closed which represents the worst-case scenario. Figure 7 shows the temperature and depth of the hot layer, and CO₂ production with time predicted by the Smoke Movement Model for the paint workshop, large hangar and the main workshop. Since kerosene is assumed as the fuel source, the Smoke Movement Model predicts no CO production. Predictions of CO₂ concentrations in the paint workshop indicate a gradual increase, reaching 15% after 330 s. CO₂ concentrations in the large hangar and the main workshop reach much lower concentrations of 1% and 4%, respectively. In the paint workshop, the temperature increases rapidly for 320 s up to about 830°C. Temperatures in the large hangar, and the main workshop are much lower because of the larger room volumes. The hot gas layer in the paint workshop descends from 4.0 m (the ceiling), at ambient temperature, to 0.5 m above the floor at 320 s. The hot gas layer falls to a height of 1.5 m above the floor at about 130 s, which is assumed to represent untenable conditions for occupants in the paint workshop. The hot gas layers in the large hangar and the main workshop do not drop below a height of 1.5 m above the floor.

Occupant Evacuation

The occupant load for each compartment is selected based on the National Building Code of Canada [26], which defines the maximum number of persons per unit area. The total number of occupants in the modelled portion of the building is 169. Table 2 shows the distribution of this occupant load and the exit distance for each compartment. The Occupant Evacuation Model assumes that all occupants can exit the building with the same travel speed, because the majority of occupants are trained military personnel.

As shown in Figure 8, it is predicted that all of the occupants in the compartment of fire origin will evacuate in approximately 140 s. All the other occupants are predicted to evacuate the building within approximately 275 s.

Life Hazard

The Life Hazard Model uses the fire development and the smoke movement data to determine the probability of death. As shown in Figure 9, the cumulative probability of death for occupants in the compartment of fire origin reaches 100% at 168 s, and the predicted probability of death for all other occupants is 0%.

Expected Number of Deaths

As shown in Figure 10, the Expected Number of Deaths Model predicts that all occupants will evacuate the building.

Economics and Downtime

The Economic and Downtime Models were not run for Hangar 7, as the information necessary for these models was not available.

Summary of Case Study Results

Table 3 shows a summary of the results of the analyses for the 20 MW fire described above, as well as for the 10 MW fire.

The 10 MW confined pool fire, which has a maximum diameter of 2.7 m, is estimated to reach 10 MW after 227 s, and continue to burn until 720 s. It is predicted that the fire will be detected at 49 s, flashover will occur at 221 s, and sprinklers in the large hangar will activate at 114 s. The Occupant Evacuation Model predicts that complete evacuation of the six compartments occurs at 290 s. The fire department is estimated to intervene after 649 s, and the Expected Number of Deaths Model predicts that no occupants will die.

The results for the 20 MW confined pool fire, which has a maximum diameter of 4.0 m, are similar to the results of the 10 MW fire. The fire is predicted to reach 20 MW after 330 s. It is estimated that the fire will be detected after 46 s, and flashover will occur at 221 s. Foam sprinklers in the large hangar are calculated to activate after 108 s, and will create a large amount of debris in this area. The Occupant Evacuation Model predicts that complete

evacuation of the six compartments occurs at 275 s. The fire department is estimated to intervene after 646 s, and the Expected Number of Deaths Model predicts that no occupants will die.

RISK ANALYSIS

The overall result of a FIERAsystem hazard analysis for each scenario is the expected number of deaths and the expected property losses. If information on the probabilities of different fire scenarios occurring is available and the reliabilities of fire protection systems are known, then a full risk assessment can be conducted using information from the hazard analyses of all of the possible fire scenarios. This information is currently being gathered for industrial buildings.

CONCLUSIONS AND FUTURE WORK

The development of FIERAsystem, a new computer model to evaluate fire protection systems in industrial buildings, has been described. The model provides information on the safety and cost of candidate fire protection systems. The development of this model is expected to assist engineers and building officials in evaluating, in a clear and concise manner, fire protection systems in a building and to determine whether a selected design satisfies the established objectives for the building. This type of model will also facilitate the introduction and use of performance/objective-based codes.

In this study, FIERAsystem was used to assess different fire scenarios in an aircraft hangar. Two different design fires in a paint workshop adjacent to the main hangar were considered. Complete evacuation of the building, with no occupant deaths, was predicted for both scenarios. Information on costs and reliabilities of fire protection systems, and estimates of downtime for various levels of fire damage are being gathered, which will allow a complete risk analysis to be performed for this and other buildings.

While this model has been specifically developed for the design of aircraft hangars and warehouses, further development of the model is planned. For example, the Life Hazard Model is being modified in order to utilize models for predicting probabilities of death from high thermal radiation heat fluxes based on human skin burn predictions [27].

NOMENCLATURE

A	area (m^2)
CO	concentration of carbon monoxide (ppm)
D	diameter (m)
E	emissive power (kW/m^2)
END	expected number of deaths
F	radiation view factor (dimensionless)
FID	fractional incapacitating dose (dimensionless)
g	acceleration due to gravity (m/s^2)
H	height (m)
k	factor to account for effect of compartment walls (dimensionless)
P	probability (dimensionless)
POP	population
Q	heat release rate (kW)
q"	heat flux (kW/m^2)
S	experimental parameter (m^{-1})
SF	safety factor (dimensionless)
T	temperature ($^{\circ}\text{C}$, K)
t	time (s)
V	thermal dose ($(\text{kW}/\text{m}^2)^{4/3} \cdot \text{s}$)
v	burning rate (m/s)
VCO ₂	multiplication factor for CO ₂ -induced hyperventilation (dimensionless)
Y	probit function (dimensionless)
%CO ₂	concentration of carbon dioxide (percentage)

Greek Letters

α	fire growth coefficient (kW/s^2)
η	suppression effectiveness value (dimensionless)
τ	atmospheric transmissivity
ξ	dummy variable for integration

Subscripts

act	at time of activation
amb	ambient
C	compartment

ce	gas at ceiling impingement
CO	carbon monoxide
D	death
e	emissive
ep	effective plume
f	fire, flame, fuel
HG	hot gases
i	index
m	modified
max	maximum
resid	residual
S	hot gas layer
s	smoke
TG	toxic gases
TR	thermal radiation
0	value with no automatic suppression system

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Figure 1 Modification of Heat Release Rate Using Suppression Effectiveness Value, η

Figure 2 Quantities Used to Calculate Fire Department Response and Intervention Times

Figure 3 Example of Fire Spread in a Multi-Compartment Building

All dimensions are in metres.

Figure 4 Six Compartments Modelled in Hangar 7

Figure 5. Predicted Heat Release Curve for the 20 MW Fire in the Paint Workshop

Figure 6 Predicted Occupant Response

Figure 7 Predicted Build-up of Smoke and Heat in Different Compartments

Figure 8 Predicted Occupant Evacuation

Figure 9 Predicted Life Hazard

Figure 10 Predicted Residual Population

Table 1. Procedure for FIERAsystem Hazard Analysis

Step	Model	Output(s)
1	Project definition	<ul style="list-style-type: none">• building and occupant characteristics
2	Fire development	<ul style="list-style-type: none">• heat release rates, temperatures and heat fluxes
3	Fire detection	<ul style="list-style-type: none">• detector activation time, sprinkler activation time, and times to fire cues
4	Suppression effectiveness (sprinkler operation)	<ul style="list-style-type: none">• modified heat release rates, modified temperatures and modified heat fluxes
5	Fire department response	<ul style="list-style-type: none">• fire department response time
6	Occupant response	<ul style="list-style-type: none">• probability of occupants commencing evacuation• time and probability of fire department notification
7	Fire department effectiveness (fire department operations)	<ul style="list-style-type: none">• modified heat release rates, modified temperatures and modified heat fluxes
8	Building element failure	<ul style="list-style-type: none">• time to failure of building elements in compartment of fire origin
9	Smoke movement	<ul style="list-style-type: none">• hot gas layer temperatures and height, and concentrations of CO and CO₂
10	Fire spread	<ul style="list-style-type: none">• time of fire spread to adjacent compartments• heat release rates, temperatures and heat fluxes in adjacent compartments
12	Occupant evacuation	<ul style="list-style-type: none">• residual population with time
13	Life hazard	<ul style="list-style-type: none">• probability of death with time
14	Expected number of deaths	<ul style="list-style-type: none">• expected number of deaths
15	Economic	<ul style="list-style-type: none">• expected property losses
16	Downtime	<ul style="list-style-type: none">• expected interruption to operations

Table 2 Compartment Characteristics

Compartment	Number of Occupants	Exit Distance (m)
Escape Systems Storage	2	15
Welding Shop	9	11
Fabric Shop	10	23
Paint Workshop	11	22
Main Workshop	61	30
Large Hangar	76	34

Table 3. Results of Hangar 7 Analysis

	10 MW fire	20 MW fire
Detection time / sprinkler activation in paint workshop	49 s	46 s
Earliest sprinkler activation time in the large hangar	114 s	108 s
Time to flashover in paint workshop	221 s	221 s
Onset of decay phase	720 s	330 s
Fire department response	214 s	211 s
Fire department intervention	649 s	646 s
Time required for all occupants to respond	270 s	260 s
Time required for all occupants to evacuate	290 s	275 s
Expected number of deaths	0	0

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