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Publisher's version / Version de l'éditeur:
https://doi.org/10.4224/20331209
Internal Report (National Research Council of Canada. Institute for Research in Construction), 2000-06-01

National Research Council Canada
Conseil national de recherches Canada

NRC·CNRC

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Internal Report 787

June 2000

Published by
Institute for Research in Construction
IRC

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June 16, 2000

Abstract

The Suppression Effectiveness Model of FIERAsystem modifies the heat release rate, temperature and heat flux data from the FIERAsystem Fire Development Models to account for the effects of sprinklers that activate. This calculation uses a single suppression effectiveness value, which is input by the user. Information from the Suppression Effectiveness Model is used to calculate the fire spread and life hazard in the building.

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Notation

D	diameter (m)
f	radiative fraction (dimensionless)
H	height (m)
h	convective heat transfer coefficient ($W/m^2 \cdot °C$)
k	factor (dimensionless)
Q	heat release rate (W)
q"	heat flux (W/m^2)
r	distance (m)
T	temperature (°C)
t	time (s)

Greek Letters

ε	emissivity (dimensionless)
η	suppression effectiveness value (dimensionless)
σ	Stefan Boltzmann constant ($5.67(10)^{-8}$ $W/m^2 \cdot K^4$)

Subscripts

act	at time of activation
amb	ambient
c	compartment
eq	equivalent
f	flame
fo	flashover
m	modified value considering automatic suppression system
o	value with no automatic suppression system
p	plume
sc	ceiling surface
T	total

1.0 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 compliance with these new codes has been achieved. One such tool is the computer model FiRECAM™, which has been developed over the past decade by the Fire Risk Management Program of the Institute for Research in Construction at the National Research Council of Canada (NRC). FiRECAM™ is a computer model for evaluating fire protection systems in residential and office buildings and can be used to compare the expected safety and cost of candidate fire protection options.

To evaluate fire protection systems in light industrial buildings, a new computer model has been developed. This model, whose current focus is aircraft hangars and warehouses, is based on a framework that allows designers to establish objectives, select fire scenarios which may occur in the building and evaluate the impact of each of the selected scenarios on life safety, property protection and business interruption. The new computer model is called FIERAsystem, which stands for **Fi**re **E**valuation and **R**isk **A**ssessment system.

FIERAsystem uses time-dependent deterministic and probabilistic models to evaluate the impact of selected fire scenarios on life, property and business interruption. The main FIERAsystem submodels calculate fire development, smoke movement through a building, time of failure of building elements and occupant response and evacuation. In addition, there are submodels dealing with the effectiveness of fire suppression systems and the response of fire departments. In this paper, the model used to calculate suppression effectiveness will be described.

The Suppression Effectiveness Model of FIERAsystem modifies the heat release rate, temperature and heat flux data from the FIERAsystem Fire Development Models (e.g., [1]) to account for the effects of sprinklers that activate. This calculation uses a single suppression effectiveness value, which is input by the user. Information from the Suppression Effectiveness Model is used to calculate the fire spread [2] and life hazard [3] in the building.

In this report, the theory underlying the equations used for each of the calculations in the Suppression Effectiveness Model is described. Particular emphasis is placed on the assumptions inherent in the equations used in the model. These assumptions must be kept in mind when considering any results of the FIERAsystem Suppression Effectiveness Model.

2.0 Suppression Effectiveness Value

The Suppression Effectiveness 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 extinguish 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. Work is ongoing to identify the factors that can be used to calculate this suppression effectiveness

value. The calculation of the suppression effectiveness value will be incorporated in future versions of the Suppression Effectiveness Model.

3.0 Modified Heat Release Rate

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 ($Q_m(t)$) (Figure 1). It is assumed that 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., $Q_m = Q_{act}$). This assumption is conservative, as the sprinkler may in fact extinguish the fire. 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:

$$Q_m(t) = (1.0-\eta)*(Q_o(t) - Q_{act}(t)) + Q_{act}(t) \quad (1)$$

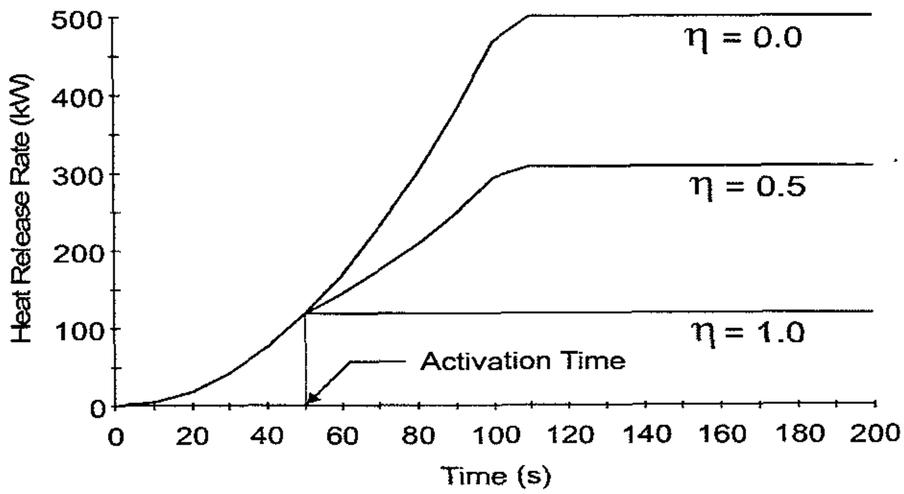
Where

m = modifed by the Suppression Effectiveness Model, and

• = the original value of the parameter input to the Suppression Effectiveness Model

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.

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



4.0 Modified Diameter of the Fire

The diameter of the fire, entered by the user or from one of the FIERAsystem Fire Development Models, is assumed to remain unchanged due to suppression. Suppression is assumed to only affect the height of the flames. Therefore, the diameter is not modified by the Suppression Effectiveness Model (i.e., $D_m = D_o$).

5.0 Modified Thermal Radiation Heat Fluxes

The thermal radiation heat fluxes (q"(t)) at a distance (r) from a fire of heat release rate (Q(t)) can be calculated, assuming a point source model, using the following equation [4]:

$$q''(t) = \frac{fQ(t)}{4\pi r^2} \qquad (2)$$

Where:

f = the fraction of the total heat release rate that is considered to be radiative.

In Equation (2), the thermal radiation heat flux is proportional to Q(t). Therefore, the Suppression Effectiveness model modifies the thermal radiation heat fluxes using the following equation:

$$q''_m(t) = \frac{Q_m(t)}{Q_o(t)} q''_o(t) \qquad (3)$$

The assumption that heat flux values are proportional to heat release rate is used for all heat flux modifications, even though the Enclosed Pool Fire Development Model [1] uses a different two-zone approach to calculate heat fluxes.

6.0 Modified Fire Plume Temperature

The temperature of the plume near the ceiling (T_p) at any time is calculated using the following equation in the FIERAsystem Fire Development Models [4].

$$T_p(t) = T_{amb} + 0.22\frac{(kQ(t))^{2/3}}{H_c^{5/3}} \qquad (4)$$

Where:

T_{amb} = the ambient temperature (°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); and

H_c = the compartment height (m).

In Equation (4), the difference between the plume and ambient temperature is proportional to $Q^{2/3}$. Therefore, the modified plume temperature ($T_{p-o}(t)$) is determined using the following equation:

$$\frac{T_{p-m}(t) - T_{amb}}{T_{p-o}(t) - T_{amb}} = \left(\frac{Q_m(t)}{Q_o(t)}\right)^{2/3} \qquad (5)$$

The ambient temperature (T_{amb}) in Equation (6) is assumed to be 20°C.

7.0 Flame Temperature

The flame temperature (T_f) is assumed to be 1000°C by the Suppression Effectiveness Model. If an emissivity of 1.0 is also assumed, this corresponds to a thermal radiation heat flux of approximately 150 kW/m^2. These temperatures and heat flux values are consistent with estimates of these quantities reported in the literature (e.g., [4], [5]).

8.0 Heat Flux Boundary Conditions and Modified Equivalent Temperature

The heat flux boundary conditions in the FIERAsystem Boundary Element Failure Model use the plume temperature and an equivalent temperature [7]. In the case of the ceiling, the plume temperature is used to calculate the heat transfer to the compartment boundary. The equations used to calculate this plume temperature are dependent on the heat release rate (e.g., see Equation (4)). As discussed earlier, the FIERAsystem Suppression Effectiveness Model is able to take into account the effect of suppression systems on heat transfer to the ceiling by recalculating the plume temperature using the modified heat release rate (Equation (5)).

The walls of the compartment will be subjected to convective and radiative heat fluxes from both the flame and the plume gases. The FIERAsystem Boundary Element Failure Model [7] uses only a single temperature to represent the effects of the fire on the walls (e.g., the hot gas temperature in a fire resistant test furnace). Therefore, the FIERAsystem Fire Development Models (e.g., [1]) calculate an equivalent temperature (T_{eq}) to account for heat transfer from both the flames and fire plume to the walls using the following equation:

$$\frac{H_f(t)}{H_c} T_f^4(t) + \left(1 - \frac{H_f(t)}{H_c}\right) T_p^4(t) = T_{eq}^4(t) \qquad (6)$$

The original equivalent ($T_{eq\text{-}o}(t)$) and plume temperature ($T_{p\text{-}o}(t)$) are input to the Suppression Effectiveness Model for each time step. First, the original ratio of the flame to compartment height is calculated from Equation (7) using the original equivalent and plume temperature and an assumed flame temperature of 1000°C (discussed earlier in Section 7.0).

The Suppression Effectiveness Model then modifies the ratio of the flame to compartment height. The height of the flames above a fire can be calculated using Heskestad's correlation [4]:

$$H_f(t) = 0.011(kQ(t))^{0.4} \qquad (7)$$

Where:

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); and

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

From Equation (7), the flame height is proportional to $Q^{0.4}$. Therefore, the Suppression Effectiveness Model modifies the ratio of the flame to compartment height using the following equation:

$$\frac{H_{f-m}(t)}{H_c} = \frac{H_{f-o}(t)}{H_c}\left(\frac{Q_m(t)}{Q_o(t)}\right)^{0.4} \qquad (8)$$

The modified flame to compartment height ratio ($H_{f-m}(t)$) and plume temperature ($T_{p-m}(t)$ in Equation (5)) are then used along with the assumed flame temperature of 1000 °C to calculate the modified equivalent temperature using the following equation:

$$\frac{H_{f-m}(t)}{H_c}T_f^4(t) + \left(1 - \frac{H_{f-m}(t)}{H_c}\right)T_{p-m}^4(t) = T_{eq-m}^4(t) \qquad (9)$$

Equivalent temperatures based on the flame and plume temperatures are then output to the FIERAsystem Boundary Element Failure Model [7] in order to determine the heat transfer to the boundaries and the time of failure of these boundaries.

9.0 Modified Time to Flashover

The Occupant Response and Evacuation Models, and the Life Hazard Model require a critical time, which is the time after which occupants will be unable to evacuate the compartment. As one of the possible values of this critical time, the fire development model calculates the time required for flashover to occur, using Thomas' flashover correlation [8].

$$Q_{fo} = 7.8A_T + 378A_o\sqrt{H_e} \qquad (10)$$

Where:

Q_{fo} = heat release rate at flashover (kW);

A_T = total surface area of the compartment (m^2);

A_o = total area of openings (m^2); and

H_e = equivalent height of openings (m).

The original time to flashover is input to the Suppression Effectiveness Model. Using the original heat release rate data ($Q_o(t)$), the heat release rate at flashover (Q_{fo}) is determined. The modified time to flashover is then determined by comparing the modified, time-dependent heat release rate data ($Q_m(t)$) calculated earlier by the Suppression Effectiveness Model using Equation (1) with the heat release rate necessary for flashover.

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