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FIERAsystem Radiation to Adjacent Buildings Model (RABM): Theory Report

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Nomenclature

L	overall length of the building
W	width of the building
H	height of the building
N	number of floors above ground
d_a	distance to adjacent buildings on each of the four sides
u	fraction of unprotected openings on each of the four sides
FRR	fire resistance rating of each of the four exterior walls
q''_{cr}	critical heat flux for each of the exposed walls of adjacent buildings
q_o''	equivalent heat flux at any unprotected openings in the burning building
q_{in}''	total incident heat flux
d_f	flame projection distance from the unprotected openings of the building
d	"effective" distance between the burning and adjacent buildings
d_a	actual distance between the buildings
d_b	distance between assumed location of flames on roof and the adjacent building
F_u	view factor for the unprotected openings
t_{ign}	time required for ignition
k	thermal conductivity of the exterior wall material
ρ	density of the exterior wall material
c	specific heat of the exterior wall material
T_{ign}	ignition temperature for the exterior wall material
T_0	initial temperature for the exterior wall material
L_o	wall thickness
α	thermal diffusivity
Z	characteristic parameter

1. INTRODUCTION

As Canada and other countries move from prescriptive-based building codes to performance/objective-based codes, new design tools are needed to aid in demonstrating 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 Research 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 that 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 is being 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 that 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 [1], 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 sub-models calculate fire development, smoke movement through a building, time of failure of building elements and occupant response and evacuation. In addition, there are sub-models dealing with the effectiveness of fire suppression systems and the response of fire departments.

The Radiation to Adjacent Buildings Model (RABM) of FIERAsystem calculates the time-dependent heat fluxes from a burning building to specified distances on each side of the building. It also estimates the time to ignition of adjacent buildings based on thermal properties specified by the user. Results from RABM can be used to evaluate compliance with objectives related to preventing the spread of fire to adjacent buildings [2]. These results can also be used by the FIERAsystem Water Requirements Model [3] to evaluate the water flow rate required to prevent ignition of adjacent buildings.

In this report, the theory behind the equations used in RABM 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 results of this model.

2. INCIDENT HEAT FLUXES TO ADJACENT BUILDINGS

The spread of fire from one building to an adjacent building may occur due to one or more mechanisms. For instance, the spread may be a result of flying brands, convective heat transfer, or/and radiative heat transfer. The incident heat flux to adjacent buildings is calculated using the techniques discussed in this section. It should be noted that only thermal radiation heat transfer between the buildings is considered. Absorption and scattering of thermal radiation by the smoke and air between the burning and adjacent buildings are neglected. Convection heat transfer between the two buildings is also neglected, which should be minor, especially at larger distances. Ignition of adjacent buildings due to flying brands is also neglected.

2.1 Required Information on Burning Building

The RABM requires the following information as input:

- Overall length (L), width (W) and height (H) of the building and number of floors above ground (N),
- Distance to adjacent buildings (d_a) on each of the four sides,
- Fraction of unprotected openings (u) on each of the four sides,
- Fire resistance rating (FRR) of each of the four exterior walls,
- Critical heat flux (q''_{cr}) for each of the exposed walls of adjacent buildings,
- Whether or not the building has a combustible roof, and
- Flame projection distance from the unprotected openings of the building (d_f).

2.2 Equivalent Heat Flux from Burning Building

The incident heat flux on exposed buildings is calculated as follows. First, the user selects the equivalent heat flux at any unprotected openings in the burning building, q_o''. While the user can input any equivalent heat flux value, one of two suggested values may also be selected:

- 180 kW/m^2 for an occupancy of "normal" hazard, or
- 360 kW/m^2 for an occupancy of "severe" hazard.

These values form the basis for the Tables for spatial separation and exposure protection in the 1995 National Building Code of Canada (NBC) [4]. McGuire [5], examining data from the St. Lawrence Burns, noted that these heat flux levels were not exceeded for at least 16 minutes after any of these fire tests began. Sixteen minutes was thought to be greater than the length of time it normally takes a fire department to reach a burning building. However, heat fluxes up to five times these values were recorded after 16 minutes in these tests. Therefore, for buildings where fire departments may take a longer time to respond, it may be appropriate to specify a larger equivalent heat flux value when using RABM.

2.3 Radiation View Factor

Once the equivalent heat flux value is selected, the model calculates the radiation view factor between the unprotected openings and a point on the face of the adjacent building based on the information provided by the user. A view factor is defined as the ratio of the radiant intensity at the receiving surface to that at the radiating surface. A view factor is calculated solely from the relative geometry of the radiating and receiving surfaces. Several assumptions are implicit in the used formulae and they are:

- Significant thermal radiation is only emitted from unprotected openings. A time-dependent fraction of unprotected openings is calculated for each of the four exterior walls using the following equation:

$$\begin{aligned} u &= u \qquad t < FRR \\ u &= 1.0 \qquad t \geq FRR \end{aligned} \tag{1}$$

  Where u is the fraction of unprotected openings ($0 \leq u \leq 1$)

  In other words, the model assumes that once the fire resistant rating is exceeded, thermal radiation is emitted from the entire exterior wall.

- The gray radiator concept is used to treat the unprotected openings [6,7]. This technique assumes that the unprotected openings can be treated as one large unprotected opening with the same area as the total of all the unprotected openings. The emissivity for the burning building is then assumed to be the fraction of the exposing facade that is unprotected openings. While this assumption is generally valid and produces conservative results, it is not always correct for buildings that have a low percentage of unprotected openings [7]. Techniques for treating these cases can be found in Williams-Leir [7].

The view factor, F_u, for the unprotected openings, is calculated using the following formula [6]:

$$F_u = \frac{2u}{\pi}\left[\sqrt{\frac{C/S}{C/S+4}}\, arctan\sqrt{\frac{CS}{C/S+4}} + \sqrt{\frac{CS}{CS+4}}\, arctan\sqrt{\frac{C/S}{CS+4}}\right] \tag{2}$$

Where:

$$C = \frac{HW}{d^2} \tag{3}$$

H	height of face of the burning building (m)
W	width of the face of the burning building (m)
d	"effective" distance between the burning and adjacent buildings (m)

$$S = \frac{H}{W}\left(or\, \frac{W}{H}\, if\ W > H\right) \text{ (S > 1)}$$

(4)

The effective distance, d, is the actual distance between the buildings (d_a in Figure 1) minus the assumed distance that flames may project horizontally outside of the windows of the burning building, d_f.

$$d = d_a - d_f \tag{5}$$

One value of d_f that may be used is 2.0 m, based on observations made during the St. Lawrence Burns [6].

2.4 Treatment of Combustible Roof

If the burning building has a combustible roof, then an adjustment is also made to account for the fact that the burning roof may also emit significant amounts of thermal radiation to adjacent buildings once its fire resistance rating is exceeded. In the preparation of NFPA 80A [8], photographs from thousands of fires were analysed in order to see how high flames projected above the roofs of burning buildings. Using the information in this standard, this method assumes that any roof on fire becomes an additional unprotected opening of area equal to the width of the exterior wall of the building, W, multiplied by an estimated flame height, h_{eff}.

$$h_{eff} = nH \tag{6}$$

Where n is factor depends on the number of floors above the ground of the burning building as follows:

Number of Floors Above Ground in Burning Building	n
1	1.4
2	0.9
3	0.73
4	0.65
5	0.58
6	0.52

The distance, d_b, between this extra assumed "unprotected opening" and the same point on the face of the exposed building used to calculate F_u, is calculated as follows (Figure 1).

$$d_b = \sqrt{{d_a}^2 + \left(\frac{H}{2}(1+n)\right)^2} \tag{7}$$

This distance, d_b, is used along with h_{eff} and the width (or length) of the building to calculate the view factor, F_{ri}, using Equation 2, setting $u = 1.0$.

2.5 Incident Heat Fluxes to Adjacent Buildings

Once the view factors, F_{ui} and F_{ri}, have been calculated, the incident heat fluxes at the face of the exposed building, q_{fi}'' and q_{ri}'', can be found using:

$$q_{ui}'' = F_{ui} q_o'' \tag{8}$$

$$q_{ri}'' = F_{ri} q_o'' \tag{9}$$

The total incident heat flux is the sum of these two heat fluxes

$$q_{in}'' = q_{ui''} + q_{ri}'' \tag{10}$$

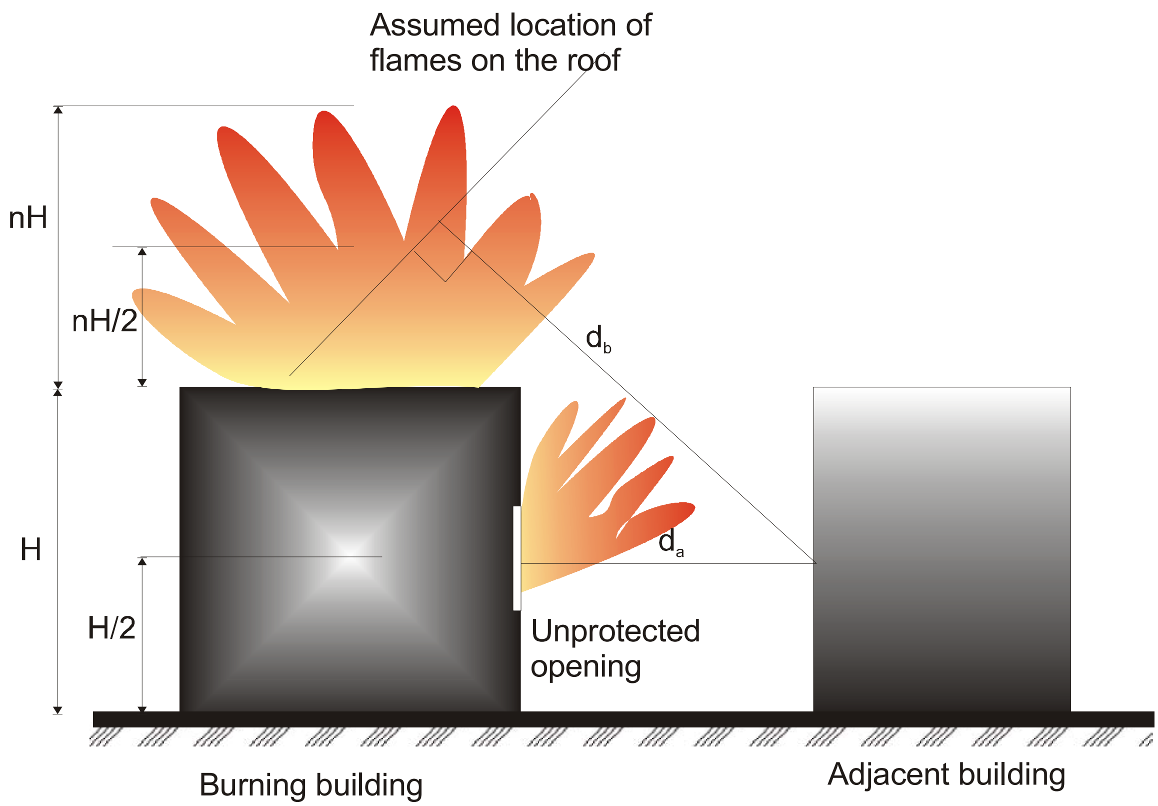

Figure 1 Quantities used for calculating view factor for flames in RABM

3. ESTIMATING IGNITION TIMES OF ADJACENT BUILDINGS

Once the heat flux to the adjacent building has been calculated, the model estimates the time required for pilot ignition, t_{ign}, using the equations developed by Mikkola and Wichman [9]. In their derivation, Mikkola and Wichman [9] only considered simple thermal ignition problems in which the gas and solid phases are highly idealized. Thus, they ignored temperature dependency of thermal properties and energies associated with thermo-chemical reactions.

They have examined two ignition models, namely, linearized and integral models to produce a functional relationship between the ignition time and the incident heat flux. The linearized model offered a simple mathematical derivation of exact formulas. However, they have indicated that results produced by this model required careful interpretation. The second model produced correlations by solving the exact integral energy balance of the problem at hand. Mikkola and Wichman [9] commented that the integral method was less precise since the numerical constants were left completely unspecified.

The RABM uses the correlations based on the linearized model. It should be noted that the material properties used in these correlations should all be taken from the same source of data, as the quantities are dependent on each other, and are often determined experimentally. Depending on the thickness of the exterior material, the procedure to calculate time for ignition will be shown in the following paragraphs. A characteristic parameter, Z, is used to determine whether the wall is to be considered as a thick or thin wall. The characteristic parameter is defined as the ratio of the wall thickness, L_o, to the charateristic conduction length as follows:

$$Z = \frac{L_o}{\sqrt{\alpha \, t_{ign}}} \tag{11}$$

Where:

t_{ign} = time required for ignition (s)
L_o = wall thickness (m)
α = thermal diffusivity

$$\alpha = \frac{k}{\rho \, c} \tag{12}$$

k = thermal conductivity of the exterior wall material (W/m·°C)
ρ = density of the exterior wall material (kg/m^3)
c = specific heat of the exterior wall material (J/kg·°C)

3.1 Thermally thick materials:

The criterion for thermally thick materials is:

$$Z \geq 4 \tag{13}$$

In this case the time for ignition is calculated from:

$$t_{ign} = \frac{\pi}{4} k\rho c \frac{(T_{ign} - T_o)^2}{(q"_{in} - q"_{cr})^2} \tag{14}$$

Where:

T_{ign} = ignition temperature for the exterior wall material (°C)
T_0 = initial temperature for the exterior wall material (°C)
$q"_{in}$ = incident heat flux on the exterior wall material (W/m^2)
$q"_{cr}$ = estimated heat losses from the exterior wall material (W/m^2)
= critical heat flux for exterior wall material
= ignition heat flux for $t_{ign} = \infty$

3.2 Thermally thin materials:

$$t_{ign} = \rho c L_o \frac{(T_{ign} - T_o)}{(q"_{in} - q"_{cr})} \tag{15}$$

The following equation is used as the criterion for thermally thin materials:

$$\frac{L_o}{\sqrt{\alpha t_{ign}}} \le 0.4 \tag{16}$$

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