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SIMPLIFIED FIRE GROWTH MODELS FOR RISK-COST ASSESSMENT IN APARTMENT BUILDINGS

by

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SUMMARY

A simplified compartment fire growth model is described. The model is a one-zone model that runs on PCs with a CPU time shorter than those of other two-zone models. Included in the model are the characteristics of fires under vitiated oxygen conditions and a combustion efficiency that is dependent on the compartment size. The model is shown to compare favourably with the "FIRST" and "FAST"models developed at NIST. The model is also shown to predict more conservative, but realistic, CO and CO_2 concentrations than the other two models. The present fire growth model can be used to predict the fire growth characteristics of various fire scenarios for the risk-cost assessment model which is being developed for the evaluation of life risks and protection costs in apartment buildings.

INTRODUCTION

The National Research Council of Canada (NRCC) is presently developing a risk-cost assessment model for evaluating the fire risks and protection costs in apartment buildings.[1] The computer model evaluates the life risks and fire costs over the lifetime of a building by assessing the characteristics of fire growth, fire and smoke spread, detection and suppression systems and human response in the building. One of the models being developed as part of this risk-cost assessment model is the fire growth model. The fire growth model is used to characterize the growth of various fire scenarios, the production of smoke and toxic gases, the actuation times of smoke detectors and sprinklers and the time allowed for evacuation. Three different fire growth scenarios ("design" fires) are considered in the risk-cost assessment model. They are the flashover, non-flashover flaming, and smouldering fires. With the large number of calculations required in the risk-cost assessment model in order to assess the lifetime performance of a building, the fire growth model needs to be relatively simple. The computer run time must be sufficiently short so that the program can be used as an interactive tool for design.

Over the past two decades, a number of compartment fire models have been developed by various researchers.[2-4] Two of the models that are more sophisticated and easily accessible are the zone models "FAST" and "FIRST" which were developed at the National Institute of Standards and Technology.[3,4] These two models, however, contain a number of aspects which make them less desirable for use in the risk-cost assessment model. For example, as an input, the "FAST" model requires the time-dependent burning rate and the generation rates for CO and other toxic gases. Such input information, however, is not easily available because the values depend on many factors including the compartment size, ventilation openings, and wall materials. Providing the wrong input information can easily lead to erroneous results. The "FIRST" model calculates the burning rate and the generation rates of CO, CO2 and smoke, but the predictions of CO concentrations are much lower than those obtained in full-scale experiments.[5-7]

In addition to the above, in the modelling of burning characteristics, the "FAST" and "FIRST" models have other deficiencies.[7] One of the deficiencies is that these models predict a relatively hazard-free environment if the compartment door is closed. This is due, in part, to the modelling approach used as these models are not intended for fires in closed compartments. The "FIRST" model assumes that when the hot layer drops to the level of the fuel surface, it will suffocate the fire completely. The "FAST" model requires the burning rate as an input and, in the present study, is assumed to have the same burning rate as generated by "FIRST". In the closed-door situation where the hot layer comes down relatively quickly to the fuel surface, the modelling assumption used in "FIRST" has the effect of suppressing the fire prematurely. This is not necessarily the case in real-world fires where fires could continue to burn under vitiated oxygen conditions and could still create a hazardous environment. These models also take considerable computer time to run, which may not be suitable for the risk assessments of the lifetime performance of a building where large numbers of fire scenarios have to be iterated.

In this paper, a new simplified compartment fire growth model, using a one-zone approach, is developed for the risk-cost assessment model for apartment buildings. This fire growth model assumes that a fire compartment can be treated as a single reactor, which allows the calculation of the typical energy and mass balances much quicker with fewer iterations required. This model also includes a new treatment of the burning rate under vitiated oxygen conditions, which allows more realistic modelling of the development of fires in a compartment when the door is closed. Finally, this model includes a better representation of the burning characteristics and a combustion efficiency that is dependent on the size of the compartment. In this paper, the model is compared with both "FIRST" and "FAST" and is used to predict the characteristics of the three design fires.

COMPARTMENT FIRE GROWTH MODEL

Basic Equations

The basic equations of the one-zone, compartment fire growth model consists of the following conservation of energy equation:

$$C_p \, \rho \, V \left(\frac{dT_g}{dT} \right) = Q_c - Q_w - Q_v - Q_o - Q_r \quad (1)$$

with

$$\begin{cases} Q_c = \Delta H_c \, R \, \gamma \, \mu \text{ (fuel controlled fire)} \\ Q_c = \Delta H_c \, m_a \, \mu \text{ (ventilation controlled fire)} \end{cases} \quad (2)$$

$$Q_w = \varepsilon \, \sigma \left(T_g^4 - T_{wi}^4 \right) S + h_i \left(T_g - T_{wi} \right) S \quad (3)$$

$$Q_v = C_p \left[m_a \left(T_g - T_o \right) + R \left(T_g - T_s \right) \right] \quad (4)$$

$$Q_o = \left[\varepsilon \, \sigma \, T_g^4 + \left(1 - \varepsilon \right) \sigma \, T_{wi}^4 - T_o^4 \right] A \quad (5)$$

$$Q_r = R \, \Delta H_v \quad (6)$$

In Equations 1-6, Q_c is the heat release rate in the compartment, Q_w is the heat loss rate through the compartment walls, Q_v is the heat loss rate by ventilation through the compartment opening, Q_o is the radiative heat loss rate through the compartment opening and Q_r is the heat loss rate to the burning object in vaporization. The other terms are defined in the Nomenclature.

Flame Spread Formulation

The flame spread rate on a burning object in a compartment is governed by the combustion properties of the burning object and by external factors. The main external factors are the radiative heat flux from the hot ceiling layer and the oxygen concentration in the compartment. In the present fire growth model, both of these factors are taken into consideration.

In the apartment risk-cost assessment model, flexible polyurethane foam is considered as a typical burning material. The flame spread rate on flexible polyurethane foam under thermal exposure from an external heat source was measured by Quintiere[8] using a vertical radiant panel. The results showed the following relationship between the lateral flame spread rate V_{fo} and the external radiative heat flux q:

$$V_{fo} = \frac{6.13}{\left(9.31 - q \right)^2} \quad (7a)$$

The above relationship and the experimental data are also shown in Figure 1. In the present fire growth model, Equation 7a is used to describe the flame spread rate on the flexible polyurethane foam as a function of the radiative heat fluxes from the hot gases and the compartment walls:

$$q = \varepsilon\sigma T_g^4 + \left(1-\varepsilon\right)\sigma T_{wi}^4 - \sigma T_s^4 \qquad (7b)$$

where the surface emissivity of the compartment walls and the burning object is assumed to be 1.

The flame spread rate is also affected by the oxygen concentration in the compartment. According to a study by Tewarson and Pion[9], the burning rate decreases with decreasing oxygen concentration and flaming combustion ceases when the oxygen concentration is lower than 11% regardless of what the external heat flux may be. Based on the Tewarson and Pion study, the following flame spread formulation is used in the present fire growth model:

$$\begin{cases} V_f = V_{fo}\left\{\dfrac{Y_{O_2R} - 11.0}{12.0}\right\}^{0.5} & for\ Y_{O_2R} > 11.0 \\ V_f = 0.0 & for\ Y_{O_2R} < 11.0\ or\ A_v = A_{v,\,max} \end{cases} \qquad (8)$$

where V_f is the flame spread rate on the flexible polyurethane foam and Y_{O_2R} is the oxygen concentration in the gas mixture before combustion

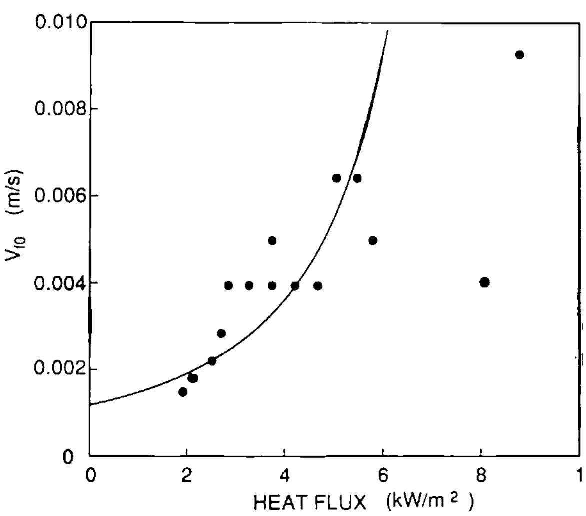

Figure 1. Quintiere correlation and experimental data of flame spread rate V_{fo} as a function of heat flux q for polyurethane flexible foam

(percent by weight). The above formulation ensures that there is no flame spread when the oxygen concentration is below 11% or when the burning surface reaches its maximum area.

Mass Burning Rate

Based on the study by Tewarson and Pion[9], the mass burning rate of flexible polyurethane foam can be written as:

$$R = \left[\left(\frac{\xi}{\Delta H_v}\right)N_{O_2} + \Delta r\right]A_v \qquad (9)$$

where ξ is a constant and is equal to 11.3 (MJ/m^2 · min) for polyurethane foam, N_{O_2} is the oxygen mole fraction based on Y_{O_2R} and A_v is the burning surface area. The burning surface area is described by the following simple integral:

$$A_v = \pi\left[\left(A_{vo}/\pi\right)^{0.5} + \int V_f dt\right]^2 \qquad (10)$$

where A_{vo} is the initial burning area. Equation 10 assumes that the flame spreads radially on the burning object with a speed V_f. Also in Equation 9, Δr is the enhancement of the mass burning rate as a result of the radiative heat fluxes received from the hot gasses and from the compartment walls:

$$\Delta r = \frac{\varepsilon\,\sigma\,T_g^4 + \left(1-\varepsilon\right)\sigma\,T_{wi}^4 - \sigma\,T_s^4}{\Delta H_v} \qquad (11)$$

where the surface emissivity of the compartment walls and the burning object is assumed to be 1.

Oxygen Vitiated Fire

The burning characteristics of fires under low oxygen concentrations are not well understood. The study by Tewarson and Pion[9] showed that a flaming fire on a PMMA slab extinguishes when the oxygen concentration is below 11% (percent by weight) under any level of external heat flux. Another study[10] showed that even a smouldering fire on polyurethane foam extinguishes when the oxygen concentration is below approximately 12%. The critical value should depend on the burning material but is probably not less than 10% for flexible polyurethane foam. In this study, the critical value of oxygen concentration below which a fire is considered to be extinguished is conservatively assumed to be 10%.

The oxygen concentration in the gas mixture before combustion, Y_{O_2R}, is obtained using the following mass-balance equation:

$$Y_{O_2R} = \frac{Y^*_{O_2}\rho V + 23.0\, m_a\, \delta t}{\rho V + \left(m_a + R\right)\delta t} \quad (12)$$

where Y^*_{O2} is the oxygen concentration in the product gas after combustion at time = $t - \delta t$, and δt is the time step.

When the oxygen concentration Y_{O_2R} drops below 16%, a different calculation scheme is used in the present fire growth model to ensure that the oxygen concentration does not drop too fast and thus cause the fire to be extinguished prematurely. The following asymptotic equation, rather than Equation 12, is used to calculate the oxygen concentration when it is below 16%.

$$Y_{O_2R} = 10.0 + \left(16.0 - 10.0\right)\exp\left(\frac{k\left(t - t_{16}\right)}{16.0 - 10.0}\right) \quad (13)$$

where

$$k = \left(\frac{dY_{O_2R}}{dt}\right) \text{ at } Y_{O_2R} = 16.0 \quad (14)$$

and t_{16} is the time when Y_{O_2R} reaches 16.

Equation 13 ensures that Y_{O_2R} approaches the 10% asymptotically and provides a better simulation of a real-world fire under low oxygen concentrations. The value of 16% was chosen for the present fire modelling as the transition point from normal burning to burning under low oxygen concentrations.

Wall Heat Loss

The heat loss rate through the compartment walls is obtained using the following one-dimensional heat conduction equation:

$$\left(\frac{\partial T_w}{\partial t}\right) = \kappa\left(\frac{\partial^2 T_w}{\partial x^2}\right) \quad (15)$$

with the following boundary conditions:

$$-K\left(\frac{\partial T_w}{\partial x}\right)_i = \varepsilon\sigma\left(T_g^4 - T_{wi}^4\right) + h_i\left(T_g - T_{wi}\right) \quad (16)$$

$$-K\left(\frac{\partial T_w}{\partial x}\right)_o = \sigma\left(T_{wo}^4 - T_o^4\right) + h_o\left(T_{wo} - T_o\right) \quad (17)$$

In the above equations, κ is the thermal diffusivity of the wall, K is the thermal conductivity of the wall, T_w is the internal temperature of the wall, T_{wi} is the wall surface temperature inside the compartment, T_{wo} is the wall surface temperature outside the compartment, hi and ho are the heat transfer coefficients at the inside wall surface and outer wall surface, respectively. Also ε is the gas emissivity which depends on the gas volume and concentration as:

$$\varepsilon = 1.0 - \exp\left(-k_g L\right) \quad (18)$$

where L is the characteristic length of the compartment and k_g is the gas absorption coefficient. The gas absorption coefficient in turn depends on the product concentration and, in this paper, is assumed to have the following simple relationship:

$$k_g = k_{go} Y_{PRO} \quad (19)$$

where Y_{PRO} is the product gas concentration and k_{go} is a proportionality derived from experiments.[1] The wall conduction equation with non-linear boundary conditions is solved numerically in the present fire model using the Crank-Nicolson method[11] and the Newton-Raphson iterative scheme.

Air Ventilation Rate

The air ventilation rate through the compartment opening is calculated using the following empirical equations[12,13] which include a correction factor to take into account the effect of compartment size.

$$m_a = \frac{2}{3}\sqrt{2g}\, C_D\, \rho\, A\sqrt{H} \left(\left(\frac{T_o}{T_g}\right)\left(1 - \frac{T_o}{T_g}\right)\right)^{0.5}\left(1 - \frac{n}{H}\right)^{1.5} F \quad (20)$$

where

$$F = \frac{\left(1 - B\right)\left(T_g - 273\right)}{1000} + B \quad (21)$$

and

$$B + \frac{H}{2L} \quad (22)$$

In the above equations, C_D is the orifice coefficient, g is the gravitational constant, H is the height of the compartment opening, n is the height of the neutral plane at the opening, and

F is the correction factor. The correction factor F, derived from experimental data[14], is plotted in Figure 2 as a function of the room temperature and for various values of the compartment size factor B. Full-scale experimental data by Quintiere[14] are also plotted in Figure 2. The comparison in Figure 2 shows that Equation 21 is an appropriate correction factor to use.

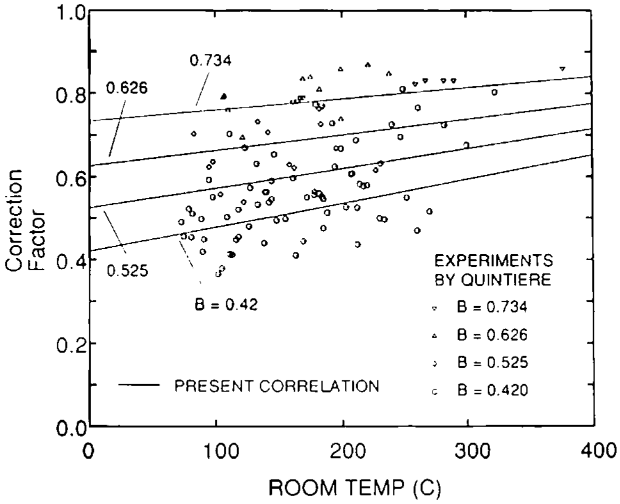

Figure 2. Correlation of air flowrate correction factor F as a function of compartment temperature and for various compartment size factor B.

Product Gas Concentration (after combustion)

The product gas concentration after combustion in a fuel-controlled fire is determined using the following mass balance equation:

$$Y_{PRO} = \frac{Y^*_{PRO}\,\rho V + \left(100 + 23\gamma\right)\mu\, R\,\delta t}{\rho V + \left(m_a + R\right)\delta t} \quad (23)$$

In the case of a ventilation-controlled fire, the equation is:

$$Y_{PRO} = \frac{Y^*_{PRO}\,\rho V + \left(23 + 100/\gamma\right)\mu\, m_a\,\delta t}{\rho V + \left(m_a + R\right)\delta t} \quad (24)$$

In the above equations, δt is the time step, Y^*_{PRO} is the product gas concentration at time $t = t - \delta t$, and μ is the combustion efficiency. The combustion efficiency is calculated using the Takeda model[15] where the combustion efficiency is found to be a function of L, A_v, ρ and R:

$$\mu = f\left(\frac{LA_v\,\rho}{R}\right) \quad (25)$$

The CO and CO_2 concentrations are obtained using the following equations. First, the amount of CO and CO_2 produced are calculated using the following stoichiometric equation:

$$CH_{1.91}\,O_{0.263}\,N_{0.055} \rightarrow a\;CO + b\;CO_2 + 0.955\;H_2O \quad (26)$$

where

$$a + b = 1.0 \quad (27)$$

Then, based on experimental data[6], the mass ratio of CO_2 to CO is assumed to have the following linear dependence on the oxygen concentration Y_{O_2} as:

$$\frac{44\,b}{28\,a} = \frac{60Y_{O_2}}{23} \quad (28)$$

Equations 27 and 28 provide the two equations needed to solve for the values of a and b. The concentrations for CO and CO_2 are then obtained using the following two equations derived from Equation 26:

$$\frac{Y_{CO}}{Y_{PRO}} = \frac{28\,a}{28\,a + 44\,b + 17.19} \quad (29)$$

$$\frac{Y_{CO_2}}{Y_{PRO}} = \frac{44\,b}{28\,a + 44\,b + 17.19} \quad (30)$$

Finally, the oxygen concentration in the product gas after combustion is obtained using the following mass balance equation:

$$Y_{O_2} = \frac{Y^*_{O_2}\,\rho V + 23\left(m_a - R\,\gamma\,\mu\right)\delta t}{\rho V + \left(m_a + R\right)\delta t} \quad (31)$$

Where $Y^*_{O_2}$ is the oxygen concentration at time $t = t - \delta t$. In the present fire growth model, the fire is assumed to be extinguished when Y_{O_2} reaches 5%.

Smouldering Fire

The present fire growth model includes a smouldering fire model. The burning rate for the smouldering fire is determined using the following equation:

$$R = 0.1t + 0.0185t^2 \quad (32)$$

This empirical relationship was derived by Quintiere[16] based on his smouldering fire experiments. The validity of this equation was also confirmed[7] by comparison with Bill and Kung's full-scale experimental data.[17]

The CO and CO_2 concentrations are calculated using the following correlations for the smouldering fire:

$$Y_{CO} = 0.05 Y_{PRO} \tag{33}$$

$$Y_{CO_2} = 0.56 Y_{PRO} \tag{34}$$

Computation Algorithm

The computation algorithm for the present fire growth model is shown in Figure 3. The initial burning rate is calculated using the initial burning radius which is given. The heat release rate is then calculated and then the room temperature is calculated. With the room temperature, the compartment wall temperature and the air ventilation rate are determined. Then the radiative heat fluxes from the hot gases and from the compartment walls are determined. Next, the flame spread rate is calculated based on both the heat flux and the oxygen concentration which is obtained from the exhaust gas concentration. Finally, the burning rate is recalculated, and the whole calculation procedure repeats itself for the next time step.

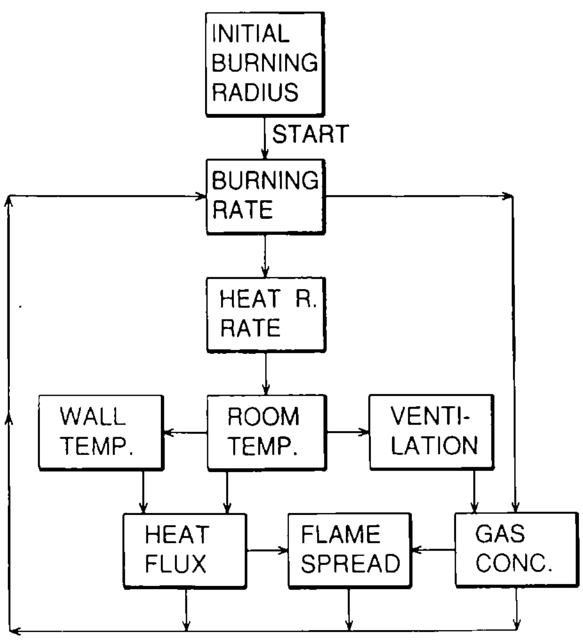

Figure 3. Computation algorithm of the "NRCC" fire growth model.

At the beginning of the run, the user can specify the following: the type of fire whether flaming or smouldering, the size of the room and the door opening, whether the door is open or closed, the size and material of the burning object, wall material, wall thickness, calculation time, etc. Optional burning materials include polyurethane, PMMA, and wood; optional wall materials include gypsum board and koawool. The combustion, chemical and thermal properties of these materials are stored in the computer program's data files. Depending on the quantity and size of burning material chosen, the fire may end up as a flashover fire or a non-flashover flaming fire. Details on how to use the program are described in the User's Guide.[18]

The present fire growth model is a simple one-zone model with a shorter computer run time (CPU time) than those of other two-zone models. The CPU time depends, obviously, on the length of the simulation time for fire growth, the time step and the machine environment. For a simulation time of 6 minutes, the present fire growth model has a CPU time of about 20 seconds running on a 486 computer (20 MHz). The time chosen was 0.02 min (default value) based on the consideration of numerical sensitivity and the total running time.

RESULTS

Comparisons of "FIRST", "FAST" and "NRCC" for A Fire in A Single Room

To check the validity of the present fire growth model ("NRCC") against two other zone models ("FIRST" and "FAST"), comparative runs were made of the three models. For these runs, the same default input data of "FIRST" were used as the input for all three models. The room size was 2.44 m x 3.66 m x 2.44 m high; the door opening was 0.76 m wide x 2.03 m high; and the amount of fuel (polyurethane) was 6.85 kg. In these calculations, the second burning object in the "FIRST" model was treated as an inert object. Also for these comparisons, two door conditions were used: open and closed.

Door Open

The results of the three models for the case where the door is open are shown in Figures 4-6. Figure 4 shows the results of the "FIRST" model. The predicted burning rate R, the oxygen concentration and the height of the hot gas layer seem quite reasonable, except that the CO concentration is quite low (when compared with experimental data[5,6] which are not shown).

Figure 5 shows the results of the "FAST" model, Version 17. The "FAST" model requires the burning rates at different times as an input, in the form of an array. In these calculations, the burning rates obtained from the "FIRST" model were used as the input to the "FAST" model. Table 1 shows the input data used in the running of the "FAST" model, where FMASS is the input burning rate at different times. The results in Figure 5 show that the CO and CO_2 concentrations are very close to those of the "FIRST" model. The room temperature, however, is much higher than that of "FIRST". The big difference in temperature between these two models is remarkable. The "FAST" model does not predict the oxygen concentration and therefore cannot be compared with that of "FIRST".

Figure 6 shows the results of the "NRCC" model. As it can be seen, the "NRCC" model compares quite well with the other two models. The burning rate is slightly lower than that of "FIRST", while the room temperature is slightly higher. The oxygen concentration is similar to that of "FIRST". The major difference is in the prediction of the CO concentration. The "NRCC" model predicts a higher CO concentration than "FIRST" and "FAST". The "NRCC" prediction, however, is closer to experimental observations[5,6].

As was mentioned earlier in this paper, the CPU time of the "NRCC" model is considerably faster than those of the other two models. For these runs, the CPU time was 28.3 sec for the "NRCC" model, 120.0 sec for "FIRST" and 320.0 sec for "FAST".

Door Closed

The results of the three models for the case where the door is closed are shown in Figures 7-

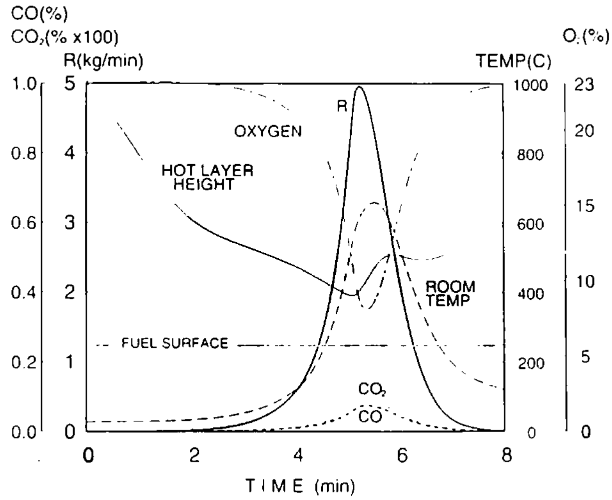

Figure 4. Calculated results of the "FIRST" model for a fire in a single room with the door open.

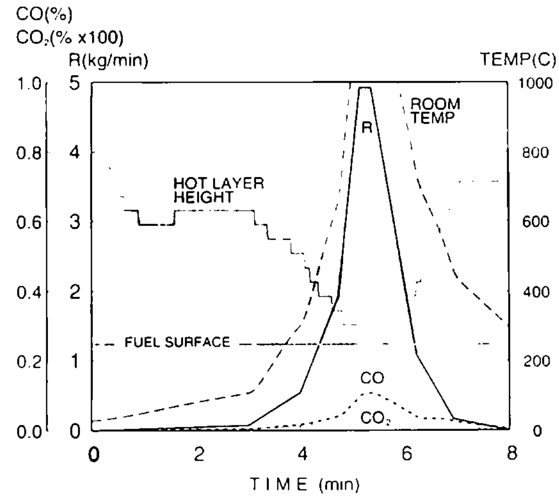

Figure 5. Calculated results of the "FAST" model for a fire in a single room with the door open.

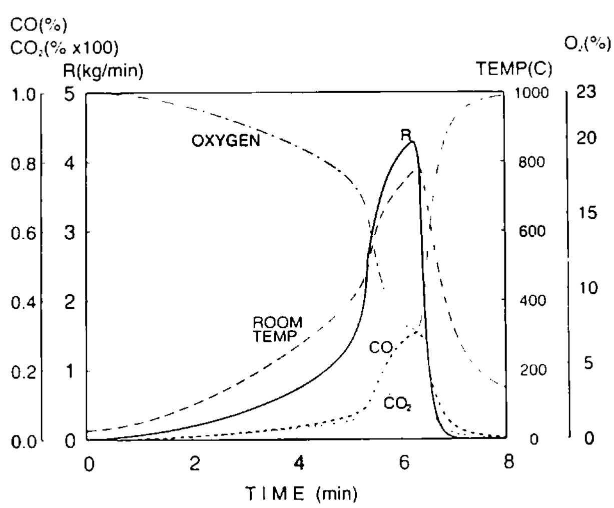

Figure 6. Calculated results of the "NRCC" model for a fire in a single room with the door open.

Table 1.

"FAST" INPUT DATA

```
VERSN 017 BUILDING FIRST-DEFAULT DATA
TIMES 480 6 0
NROOM 1
NMXOP 1
TAMB 300
NI/F 0.0
WIDTH 2.44
DEPTH 3.66
HEIGH 2.44
HVENT 1 2 0.762 2.032 0.0
CEILI
COND .000134
SPHT  1.062
DNSTY 800.
THICK .0254
EMISS 0.9
WALLS
COND .000134
SPHT 1.062
DNSTY 800.
THICK .0254
EMISS 0.9
FLOOR
COND .000134
SPHT 1.062
DNSTY 800.
THICK .0254
EMISS 0.9
LFBO 1 ROOM OF FIRE ORIGIN
LFBT 1 TYPE OF FIRE (SPECIFIED FIRE)
LFPOS 1 FIRE POSITION (CENTER)
CHEMI 1.0 0.0 0.0 0.0 0.0 28700 300
LFMAX 10 NUMBER OF INTERVALS OF FIRE GROWTH
FMAS 0 .00126 .009 .032 .082 .082 .018 .00273 0
FHEIGH 0.61 0.61 0.61 0.61 0.61 0.61 0.61 0.61 0.61
FTIME 180 60 45 25 13 51 42 64
CO .013 .013 .013 .013 .013 .013 .013 .013 .013
OD .02 .02 .02 .02 .02 .02 .02 .02 .02
CO2 1.51 1.51 1.51 1.51 1.51 1.51 1.51 1.51 1.51
CT 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0
```

9. In these calculations, it is assumed that when the door is closed, there is still a small gap of 2.5 cm at the bottom of the door. It is recognized that the "FIRST" and "FAST" models are not intended for closed compartments. They are compared here mainly to show that the "NRCC" model is the only suitable model for closed compartments.

The results of the "FIRST" model are shown in Figure 7. The results show that the burning rate, room temperature and CO concentration

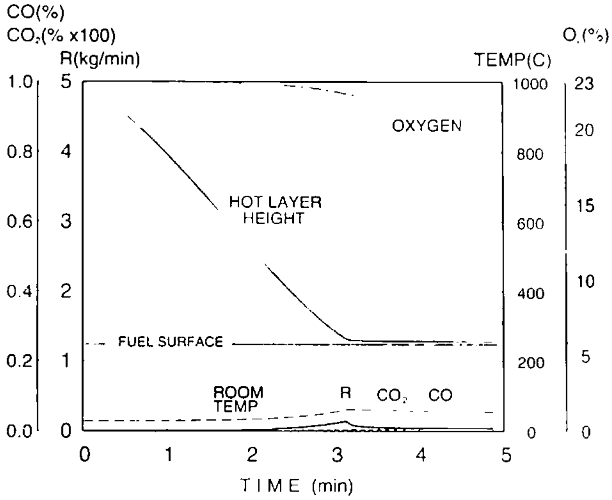

Figure 7. Calculated results of the "FIRST" model for a fire in a single room with the door closed.

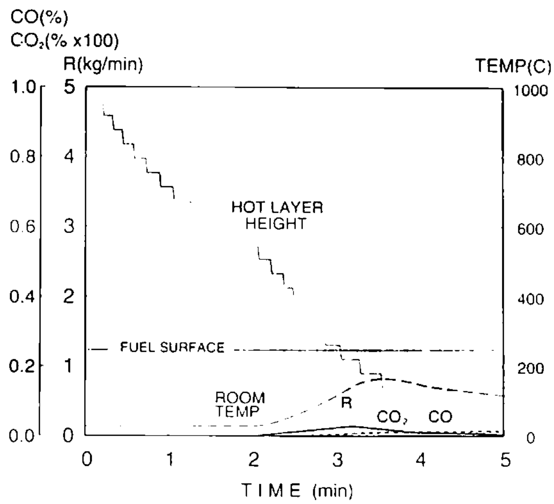

Figure 8. Calculated results of the "FAST" model for a fire in a single room with the door closed.

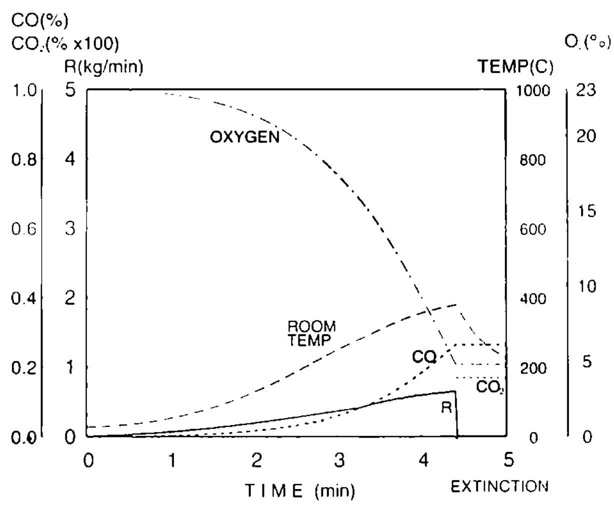

Figure 9. Calculated results of the "NRCC" model for a fire in a single room with the door closed.

are all quite low and that the oxygen concentration stays high. These results imply that such a room fire with the door closed is not hazardous. This is not necessarily the case in real-world fires where a fire in a room with the door closed can still produce a hazardous environment. As mentioned earlier, part of the reason for this relatively hazard-free result is due to the modelling approach used in the "FIRST" model which is not intended for closed compartments. The "FIRST" model assumes that when the hot layer drops to the fuel surface, it suffocates the fire completely. In a closed-door situation where the hot layer drops relatively quickly to the fuel surface, such a modelling assumption has the effect of suppressing the fire prematurely.

The results of the "FAST" model are shown in Figure 8. The results are almost the same as those of the "FIRST" model, except for the room temperature and the hot gas layer height. The room temperature is slightly higher than that from the "FIRST" simulation, and the hot gas layer drops, for some unknown reason, below the fuel surface. In these calculations, as in the open door case, the burning rate obtained from the "FIRST" model was input into the "FAST" model.

The results of the "NRCC" model are shown in Figure 9. The results are quite different from those of the other two models. The burning rate increases more rapidly, and then the fire extinguishes at about 4.3 min as a result of low oxygen concentration. Associated with this higher burning rate, the room temperature is higher, reaching about 400°C, and the CO and CO_2 concentrations are also much higher than those of the other two models. These results are in better agreement with experimental observations[19] that show that a room fire with the door closed can still be hazardous, even though it does not reach flashover.

As in the door open case, the CPU time of the "NRCC" model is much faster than those of the other two models. For these runs, the CPU time was 18.3 sec for the "NRCC" model, 415.0 sec for "FIRST" and 210.0 sec for "FAST". These calculations were carried out up to a time limit of 5.0 min only rather than 8.0 min as in the door open case. This was because the CPU time of "FIRST" for this case would exceed one hour if the calculations were to continue to a time limit of 8.0 min.

The above comparisons show that the "NRCC" model is a reasonable model even though it is a simple one-zone model. For the door open case, the "NRCC" predictions are comparable to those of the other two models. For the door closed case, the "NRCC" model predicts a more realistic and more severe fire. Coupled with its fast CPU time, the "NRCC" model is considered to be a more suitable model for use in the risk-cost assessment model.

Apartment Fire Models for Risk-Cost Assessments

As was mentioned earlier in this paper, the present fire growth model is used to determine the fire growth characteristics of three design fires: flashover fire, non-flashover flaming fire and smouldering fire. These design fires are used in the apartment risk-cost assessment model to characterize the growth of various fires, the production of smoke and toxic gases, the actuation times of smoke detectors and sprinklers and the time allowed for evacuation.

In the modelling of the three design fires, the compartment is considered to be 7 m x 7 m x 2.44 m high. This compartment size represents roughly the combined space of the living, dining and kitchen areas in a typical Canadian apartment. In the present fire growth model, the bedroom doors are assumed closed. Hence, the bedroom area is not contributing to the fire growth. Also, the main entrance door to the apartment is assumed to be 0.8 m x 2.0 m high. If the door is closed, a gap of 2.5 cm is also assumed at the bottom of the door. The walls are assumed to be of standard construction with the assembly consisting of 12.7 mm thick gypsum board on wood frame studs with fibreglass insulation[20] in the cavities. The burning object is assumed to be flexible polyurethane foam with a maximum burning radius of 1 m. Other input data are the same as those in the previous calculations.

Flashover Fire

A flashover fire is a fire that has sufficient fuel and burning area to reach flashover (temperature equal to 600°C) if there is a sufficient supply of fresh air. For the present calculations, the fuel load is assumed to be 200 kg of flexible polyurethane foam. Two door conditions are considered: open and closed. A window, having the same area as the door opening, is assumed to be located in the wall opposite the door opening. The window glass is assumed to be broken when the room temperature reaches 300°C, providing additional fresh air. For the door open case, the results are shown in Figure 10. The results show that the window glass is broken at about 8 min, the fire reaches flashover at about 14 min and that it becomes a ventilation controlled fire soon afterwards. The results also show that the room temperature exceeds 800°C in about 30 min, the CO concentration reaches about 0.2%, CO_2 concentration reaches about 10% and the oxygen concentration drops to about 10%.

For the case when the door is closed, Figure 11 shows that the window glass is broken slightly sooner, at about 7.5 min. The burning rate is about half that for the door open case and the room reaches flashover at approximately 20 min. The CO and CO_2 concentrations are slightly higher than those of the door open case. These results show that a fire in a closed compartment can also reach flashover if the window is broken.

Non-Flashover Fire

A non-flashover flaming fire is a fire that does not have sufficient fuel and burning area to reach flashover even if there is a sufficient supply of fresh air. For the present example, the fuel load is assumed to be 34.3 kg of polyurethane flexible foam. Two door conditions are again considered: open and closed. No window is considered in this case because the fresh air supply does not significantly affect the fire. For the door open case, the results are shown in Figure 12. The results show that the burning object is almost consumed in about 20 min and that the maximum temperature reached is about 600°C. The results also show that both the CO and CO_2 concentrations are about the same as those of a flashover fire (Figure 10) and that they drop slowly to zero once the fuel is consumed.

For the case when the door is closed, the results

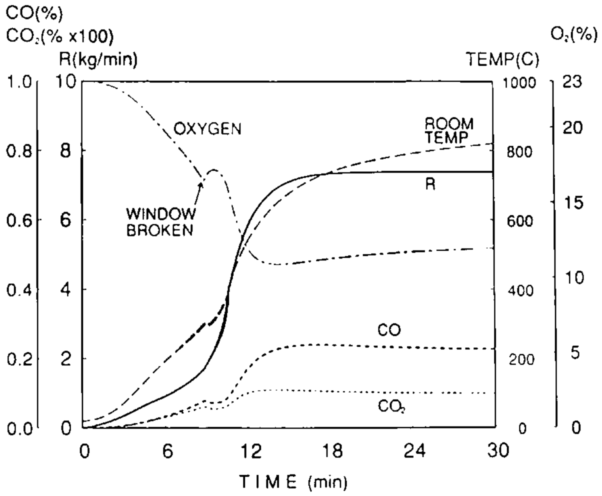

Figure 10. Calculated results of the "NRCC" model for a flashover fire in an apartment with the door open.

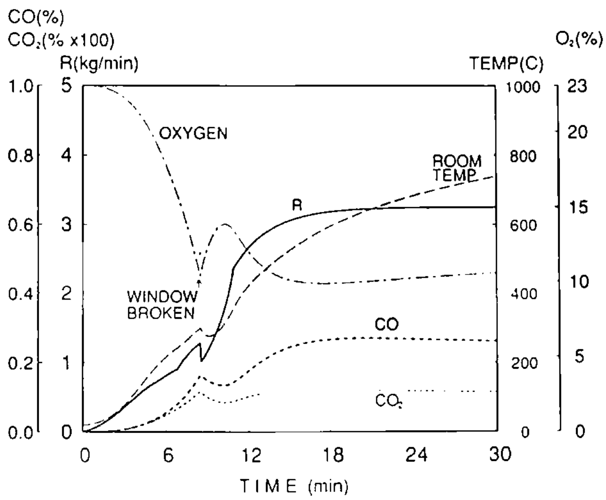

Figure 11. Calculated results of the "NRCC" model for a flashover fire in an apartment with the door closed.

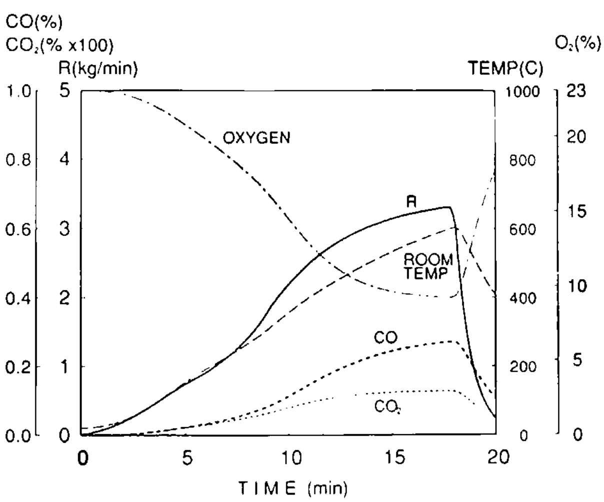

Figure 12. Calculated results of the "NRCC" model for a non-flashover flaming fire in an apartment with the door open.

are shown in Figure 13. The results show that oxygen in this case is consumed rapidly, and the fire is extinguished in about 10 min. After the fire is extinguished, the chemical reaction continues to produce CO and CO_2 utilizing the small amount of air coming through the gap at the bottom of the door. Figure 13 shows that a fire in a closed compartment is still hazardous even after the fire is extinguished. These results are reasonable when compared with closed-door fire experience.

Smouldering Fire

A smouldering fire is a non-flaming, slow fire. The results of a smouldering fire in an apartment with the door closed are shown in Figure 14. The results show that the burning rate, room temper-

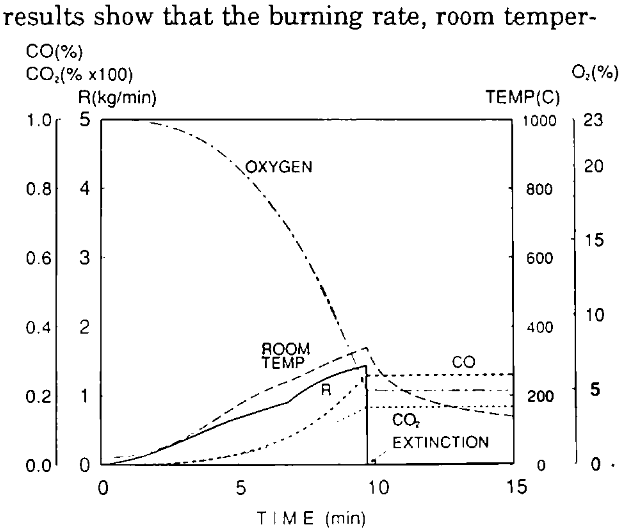

Figure 13. Calculated results of the "NRCC" model for a non-flashover flaming fire in an apartment with the door closed.

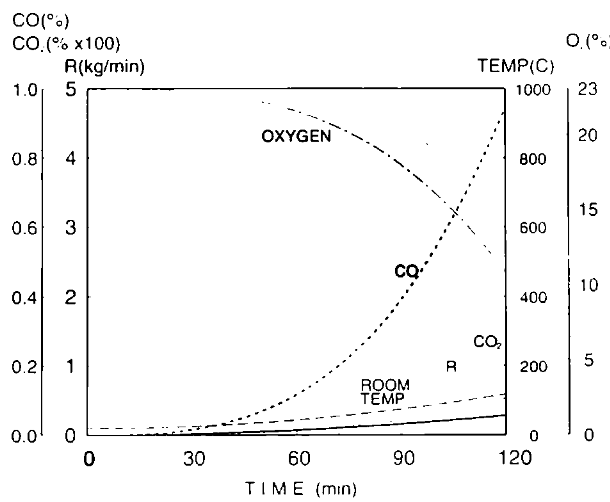

Figure 14. Calculated results of the "NRCC" model for a smouldering fire in an apartment with the door closed.

ature and CO concentrations are all very low and that the oxygen concentration stays high in the first 30 min. However, after 120 min, the CO concentration reaches 1%. Based on these results, a smouldering fire is not shown to be hazardous if it is detected early; but it is still dangerous if it is allowed to continue for a long time.

CONCLUSIONS

A simple compartment fire growth model, called the "NRCC" model, has been developed. The model is a simple, one-zone model that runs on PCs with a CPU time much faster than those of other two-zone models which have been considered. Included in the model are the characteristics of fires under vitiated oxygen conditions and a combustion efficiency that is dependent on the compartment size. The "NRCC" model can be used to predict the fire growth characteristics of various fire scenarios in an apartment. Predictions include the burning rate, room temperature, oxygen concentration and the production of smoke and toxic gases. The "NRCC" model is also suitable for use in the apartment risk-cost assessment model, which is being developed for the evaluation of the life risks and protection costs in apartment buildings.

The "NRCC" model was compared with the "FIRST" and "FAST" models, developed at the National Institute of Standards and Technology. For the open door case, the predictions were comparable, except for CO concentration where the "NRCC" model predicts higher values. The higher values, however, are in better agreement with experimental observations. For the closed door case, the "NRCC" model predicts high values for both CO and CO_2 concentrations, whereas the other two models predict a basically hazard-free environment. Again, the "NRCC" predictions are in better agreement with experimental observations which show that a fire in a closed-door compartment can still be hazardous. The CPU time of the "NRCC" model was also shown to be faster than those of the other two models.

NOMENCLATURE

A door opening area (m^2)

A_v burning surface area (m^2)

B compartment size factor

C_p average specific heat of gases (J/(kg·K))

C_D orifice constant

g gravitational constant (m/min^2)

H door opening height (m)

h heat transfer coefficient (J/(m^2·K·min))

ΔH_c heat of combustion (J/kg)

ΔH_v heat of vaporization (J/kg)

K thermal conductivity of wall (J/m·K·min)

k_g gas absorption coefficient (1/m)

L characteristic compartment length (m)

m_a air ventilation rate (kg/min), defined in Equation 20

n height of the neutral plane (m)

R mass burning rate (kg/min)

Δr enhancement of mass burning rate (kg/min)

S surface area of compartment walls and ceiling (m^2)

t time (min)

T_0 ambient temperature (K)

T_g average gas temperature (K)

T_w wall temperature (K)

T_{wi} wall temperature inside compartment (K)

T_s surface temperature of burning object (K)

V compartment volume (m^3)

V_f flame spread rate (m/min)

Y_{CO} CO concentration (weight %)

Y_{CO_2} CO_2 concentration (weight %)

Y_{PRO} product gas concentration (weight %)

Greek Letters

ε average gas emissivity

γ stiochiometric air to fuel mass ratio

μ combustion efficiency

κ thermal diffusivity (m^2/min)

ρ average gas density (kg/m^3)

σ Stefan-Boltzmann constant (J/m^2·K^4·min)

REFERENCES

1. Yung, D., and Beck, V.R., "A Risk-Cost Assessment Model for Evaluating Fire Risks and Protection Costs in Apartment Buildings," *Proceedings of the Int. Symp. on Fire Engineering for Building Structures and Safety*, Melbourne, Australia, November 14-15, 1989, p. 15.

2. Walton, W.D., ASET-B, *A Room Fire Program for Personal Computers*, NBSIR 85-3144, National Institute for Standards and Technology, Gaithersburg, Maryland, 1985.

3. Walton, W.D., Baer, S.R., and Jones, W.W., *User's Guide for FAST*, NBSIR 85-3284, National Institute of Standards and Technology, Gaithersburg, Maryland, December 1985.

4. Mitler, H.E., and Rockett, J.A., *User's Guide to FIRST, A Comprehensive Single-Room Fire Model*, NBSIR 87-3595, National Institute of Standards and Technology, Gaithersburg, Maryland, September 1987.

5. Morikawa, T., Yanai, E., and Nishina, T., "Toxicity Evaluation of Fire Effluent Gases from Experimental Fires in A Building," *Journal of Fire Sciences*, **5** (1987) 248.

6 Woolley, W.D., and Fardell, P.J., "Basic Aspects of Combustion Toxicology," *Fire Safety Journal*, **5** (1982) 29.

7. Takeda, H., and Yung, D., "Simplified Fire Growth Models for Risk-Cost Analysis," *Fourth CIB Workshop on Fire Modeling*, National Institute of Standards and Technology, Gaithersburg, Maryland, February 12-14, 1990.

8. Quintiere, J.G., and Harkleroad, M., *New Concepts for Measuring Flame Spread Properties*, NBSIR 84-2943, National Institute of Standards and Technology, Gaithersburg, Maryland, 1984.

9. Tewarson, A., and Pion, R.F., "Flammability of Plastics - I. Burning Intensity," *Combustion and Flame*, **26** (1976) 85.

10. Rogers, F.E., and Ohlemiller, T.J., "Smolder Characteristics of Flexible Polyurethane Foams," *Journal of Fire and Flammability*, **11** (1980) 32.

11. Crank, J., and Nicolson, P., "A Practical Method for Numerical Evaluation of Solutions of P.D.E. of the Heat Conduction Type," *Proc. Cambridge Phil. Soc.*, **43** (1947) 50.

12. Steckler, K.D., Quintiere, J.G., and Rinkinen, W.J., *Flow Induced by Fire in A Compartment*, NBSIR-82-2520, National Bureau of Standards, Gaithersburg, MD, 1982.

13. Prahl, J., and Emmons, H.W., "Fire Induced Flows Through an Opening, *Combustion and Flame*, **25** (1975) 369.

14. Quintiere, J.G., Steckler, K.D., and Corley, D., "An Assessment of Fire Induced Flows in Compartments," *Fire Science and Technology*, **4** (1984) 1.

15. Takeda, H., "Mixing Effect and Combustion Efficiency in Compartment Fires," *Fire Safety Hournal*, **5** (1983) 199.

16. Quintiere, J.G., Birky, M., Macdonald, F., and Smith, G., "An Analysis of Smoldering Fires in Closed Compartments and Their Hazard Due to Carbon Monoxide," *Fire and Materials*, **6** (1982) 99.

17. Bill, R.G., and Kung, H., "Evaluation of an Extended Coverage Sidewall Sprinkler and Smoke Detectors in A Hotel Occupancy," *J. of Fire Protection Engineering*, **1** (1989) 77.

18. Takeda, H., *User's Guide for the NRCC Fire Growth Model*, in preparation.

19. Kim, A.K., "Full-scale Fire Tests on FRP Furniture," SFPE Technology Report, 88-2 (1988) 1.

20. ASHRAE Handbook, 1981 Fundamentals, ASHRAE, Atlanta, GA, p. 23.21.