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Radiative Heat Transfer From Products of Combustion in Building Corridor Fires

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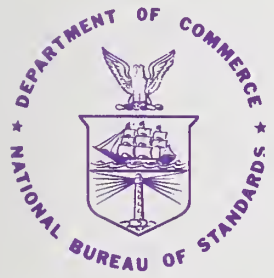

U.S. DEPARTMENT OF COMMERCE
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The contribution of radiative heat transfer from hot combustion products to corridor floors is examined. Data from full-scale corridor fire experiments is used to calculate emissivity and absorptivity of the combustion products. An empirical model based on attenuation by absorption is used to specify the absorption coefficient due to particulates in the products. In these experiments it is shown that radiation from the combustion products is just as significant as radiation from convectively heated walls and ceiling of the corridor. Calculations show that the ratio of radiant heat transfer to the floor due to ceiling emission to that by combustion product emission ranges from about 0.2 to 0.7. Also, molecular gas radiation and particulate radiation can both be significant for the combustion products. Calculations show that the emissivity of the gaseous combustion products alone would be about 0.3, but the inclusion of soot particles yields an emissivity for the total combustion product mixture of as high as 0.73, based on the experimental data considered.

Key words: Combustion products; full-scale fire; radiative heat transfer.

1. INTRODUCTION

Radiative transfer is an important mechanism in the spread of fires in buildings. As a flame spreads over the surface of a material, its rate of spread will depend on the radiant flux received by the material. Also, as a fire grows in size within a compartment, the magnitude of radiant flux falling on the combustible contents will increase. This heating can lead to increased burning rates for items involved in the fire and spontaneous ignition for the remaining combustible items. Thus, radiant heat transfer can initiate the rapid involvement in fire (flashover) of the contents of a room.

In the growth of a fire within a building compartment, several sources of radiant energy do arise. As a flame grows in size, radiation emitted by it becomes significant. This direct flame radiation will depend on the concentration and nature of particles in the flame, as well as the temperature. Another source of radiation in fires is from the heated surfaces. Hot combustion products will convectively heat the

ceiling and upper walls of a compartment. Although the temperature of these heated surfaces will be much less than flame temperatures, resulting radiation to the floor can be significant because large areas of the walls and ceiling are heated and the emissivity of these surfaces (which will become coated with soot) is generally high. Finally, a third source of radiation is the products of combustion which fill the upper region of a compartment. As for radiation from flames, this source of radiation depends on particulate concentration, gas composition, thickness of the combustion product cloud, and temperature.

It is the purpose of this study to determine the significance of the combustion product layer along the ceiling on radiative energy transfer to the floor. This layer can emit radiant energy to the floor and can attenuate radiant energy emitted from the ceiling. The relative contribution of ceiling versus radiant transfer to the floor by ceiling and combustion products was investigated by analyzing data from NBS corridor fire experiments. In these experiments [1,2][1] hot combustion products from a fully-involved room fire flow out along a corridor. These hot combustion products heat the upper surfaces of the corridor, and radiant energy, originating from these products directly or from the heated surfaces, is received by the corridor floor. In these experiments, it has been found that radiant energy transfer is essential for sustained flame spread over a combustible floor covering. Based on data from these experiments, an attempt will be made to discriminate between the role of the combustion products and the heated surfaces as a source of radiation.

2. CORRIDOR FIRE EXPERIMENTS

Data from two corridor fire experiments will be examined. One experiment (348)[2] had a nylon carpet as the floor covering; the other experiment (349) had an unvarnished red oak floor in the corridor and a portion of the burn room. Temperature, gas composition, and smoke measurements were made in these experiments and will be used to estimate the combustion product radiation.

The smoke and gas composition data were taken from three measuring stations as shown in figure 1. The concentration measurements of CO_2, CO, and O_2 were continuous (Birky [3]).

[1]Numbers in brackets correspond with the literature references listed at the end of this paper.

[2]The numbers, 348 and 349, identify two experiments in a series of NBS corridor fire experiments which were conducted to investigate the fire hazards of floor covering materials.

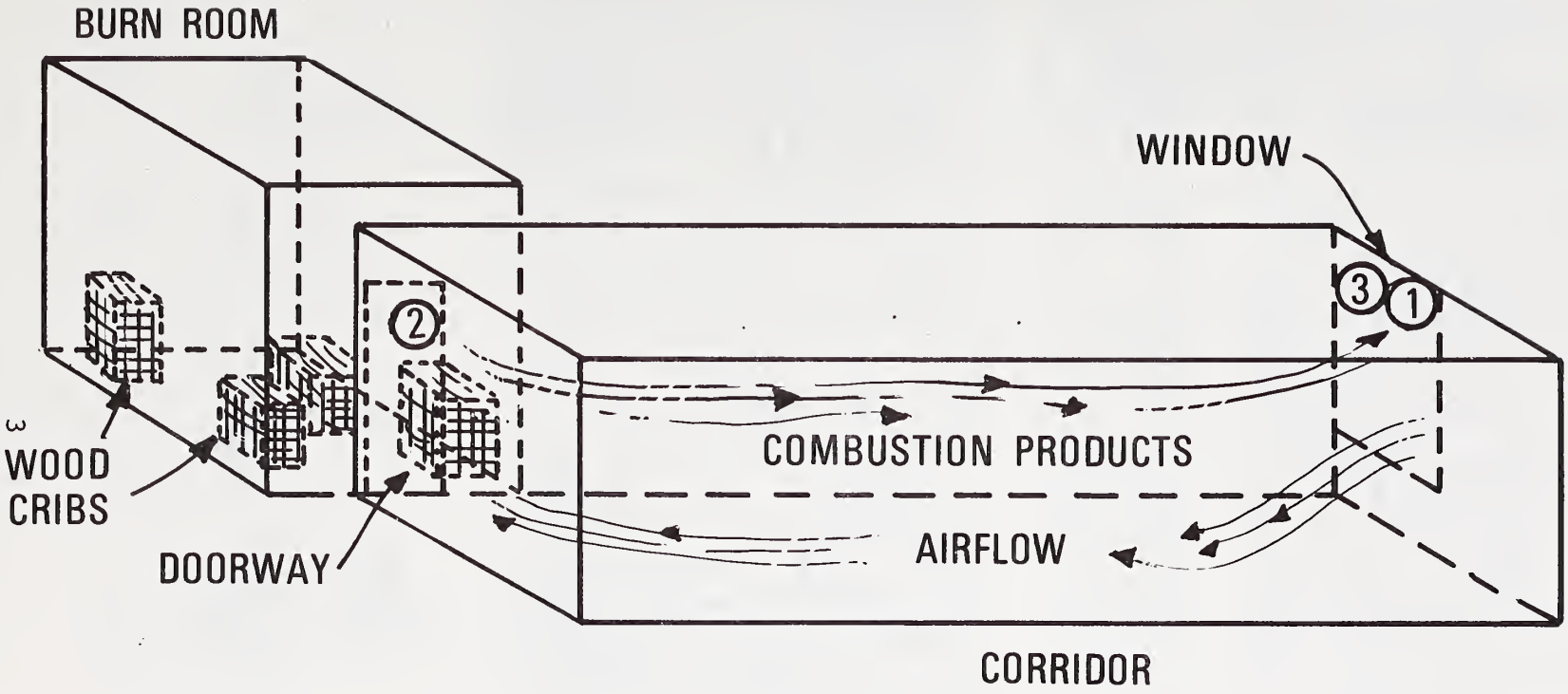


Figure 1. Smoke and gas measuring stations in the NBS corridor fire facility (1) CO_2, O_2, CO in test 348, (2) CO_2 O_2, CO in test 349 (3) smoke transmission and H_2O.

Smoke measurements taken at the exit corridor included light obscuration and particulate measurements. The obscuration apparatus continuously recorded the attenuation of light by a photo-detector at a wavelength of approximately 0.52μm. This device has an optical path length of 7.6 cm (3 in). The particulate measurements were made by sampling the combustion products at several times during the experiment for a duration of about one minute each. Over each sampling period either solid particulate concentration was measured or condensables in the combustion products were collected. The solid particulates were collected on a filter maintained at 150°C. The condensables were collected by a cold trap at -50°C and approximately ninety percent was estimated to be water. The smoke data were summarized in table 1.

Two time periods should be distinguished in these experiments. They are before and after rapid flame spread occurs over the floor covering in the corridor. Rapid flame spread occurs at 430 s in test 348 and 620 s in test 349. The effect on gas temperature is shown in figure 2 for test 348.

Some measurements were examined in test 348 in order to assess the source of radiant energy to the floor. Radiant flux to the floor (measured with a sapphire window radiometer) at 8 ft and combustion product and ceiling temperature at 10 ft were compared, along with attenuation by smoke, in figure 3. The sharp peak in radiation at 300 s appears to follow the combustion product temperature and smoke attenuation. (It should be remarked that the recording lag between the radiometer and temperature measurements is within 8 seconds.) The smoke measurement lags behind these other data by about 5 to 10 seconds, the time for gas to flow from the 10 ft station to the window. This indicates that, at least at 300 s, radiant transfer to the floor is primarily due to combustion product radiation rather than ceiling radiation. This is further confirmed by comparing the ratio of floor radiation at 300 and 360 s with the fourth power of the gas temperature ratio at these times.

This gives

$$\frac{\dot{q}''_{(300)}}{\dot{q}''_{(360)}} = \frac{1.85}{0.95} = 1.95$$

and

$$\left(\frac{T_{(300)}}{T_{(360)}}\right)^4 = \left(\frac{890°K}{789°K}\right)^4 = 1.72$$

Table 1. Results of Smoke Measurements at the Window in the Corridor Fire Experiments[a]

Test	Sampling Time (s)	Concentration of Solids (mg/liter)	Concentration of Condensables (mg/liter)	Optical Transmission (%)	k_o ($\mu m(cm)^{-1}(mg/\ell)^{-1}$)
	300-360	1.6	--	57	0.024
348	360-420	--	40	60	--
	480-535	7.4	--	13	0.018
	370-420	0.2	--	90	0.032
	435-495	--	40	91	--
349	550-610	0.3	--	91	0.020
	690-740	--	13	~40	--
	780-830	0.5	--	83	0.025

[a]Data from Tom Lee, National Bureau of Standards.

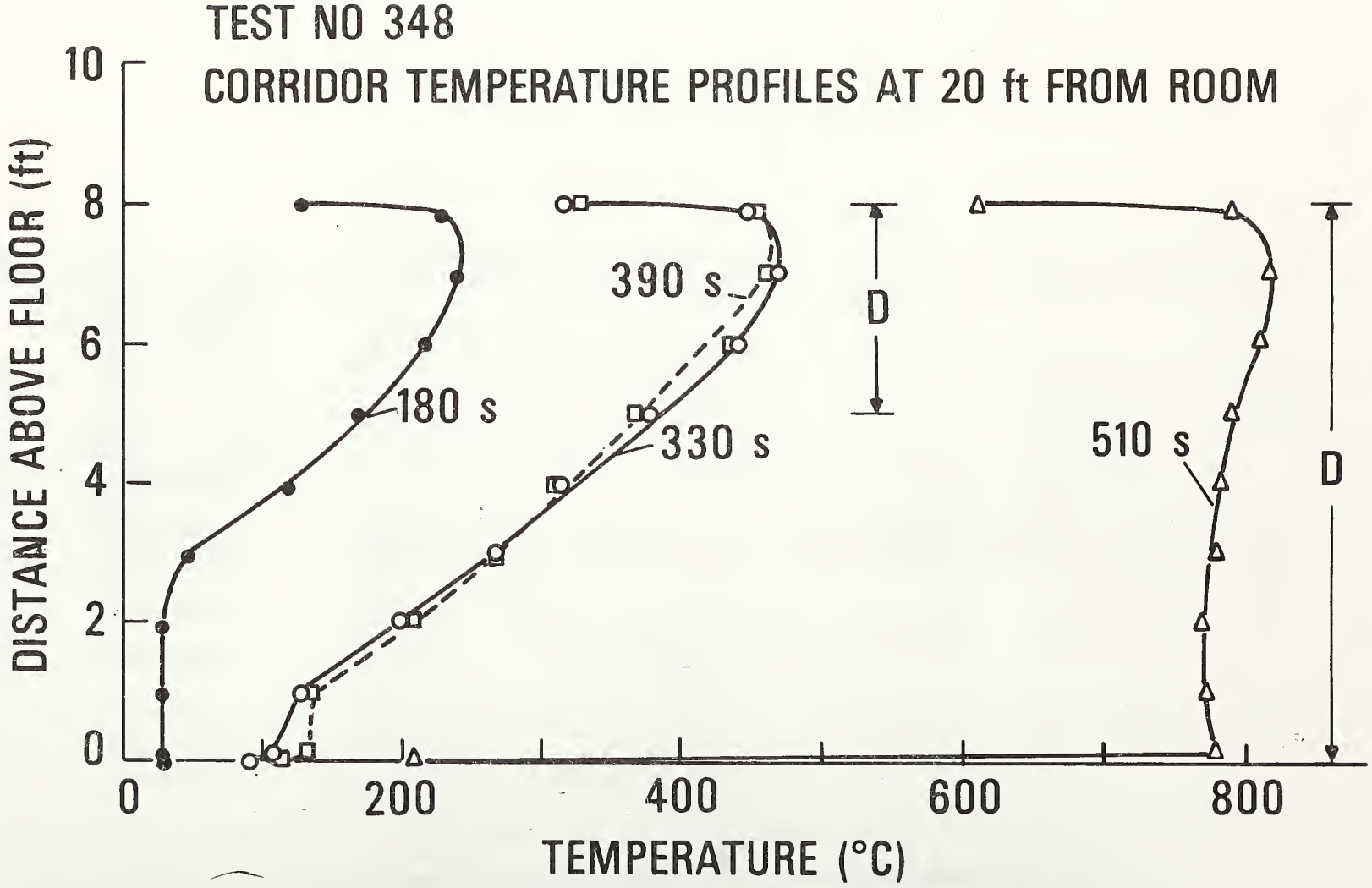


Figure 2. Corridor temperature profiles at 20 ft from room for test 348.

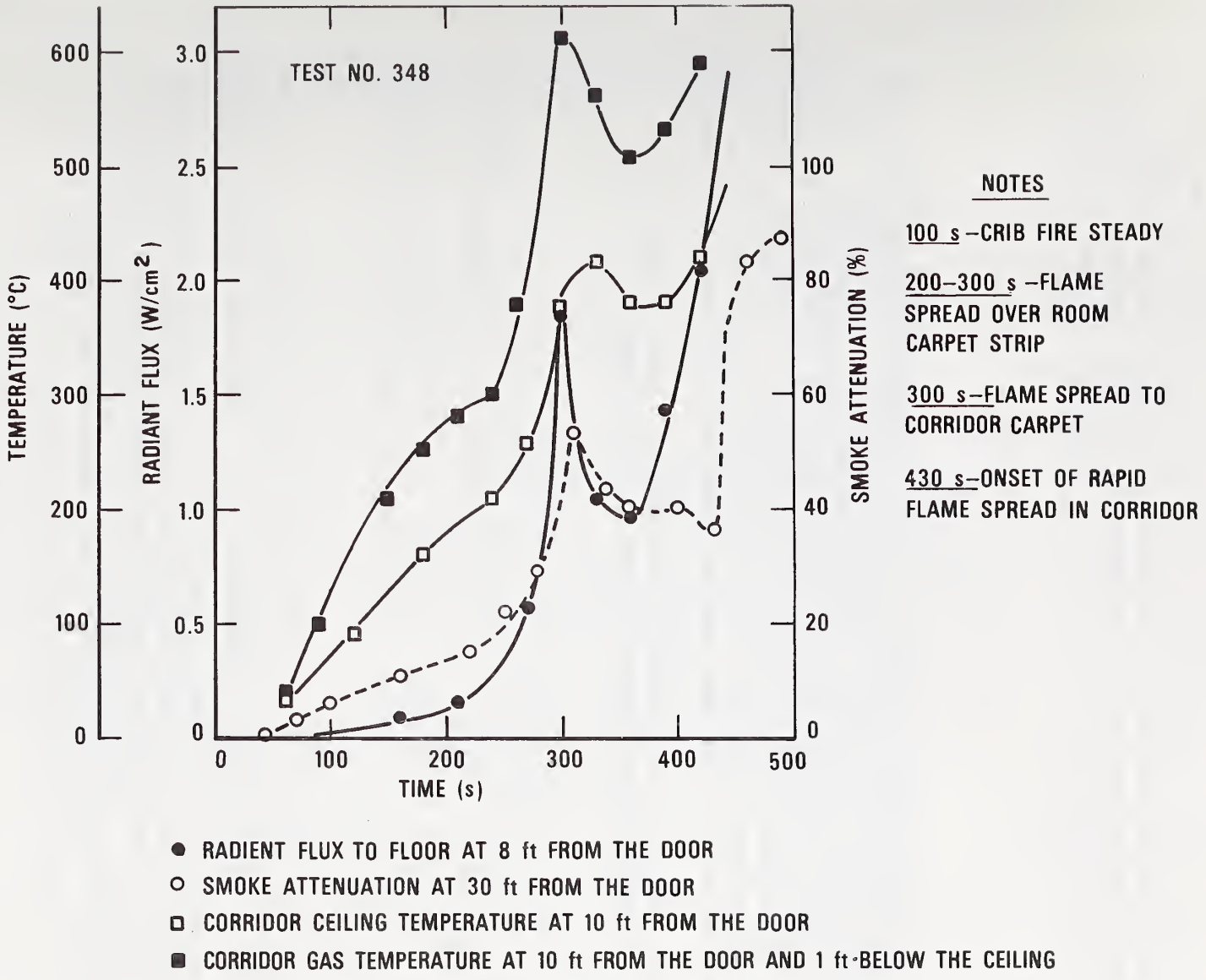


Figure 3. Temperature, radiant flux at floor, and smoke attenuation as a function of time in test 348.

whereas the ratio of corresponding ceiling temperatures is essentially one. This implies that the gas is the primary source of radiation since the energy radiated is proportional to the fourth power of the temperature of the radiator. In the following analysis this will be examined further by determining the emissivity and absorptivity of the combustion products.

3. ANALYSIS

An attempt will be made to use the smoke and gas data to calculate the emissivity of the combustion products and their absorptivity with respect to ceiling emitted radiation. In order to do this, the gas compositions, the nature of the particulate matter in the smoke, and the temperature of gas mixture all must be determined. This information is limited in these fire experiments. However, with some reasonable estimates and assumptions, calculations can be made to yield realistic results.

In general, the spectral absorptivity of a combustion product layer of mean beam length, L, is given by

$$\alpha_\lambda = 1-\exp(K_{g,\lambda} + K_{p,\lambda})L \qquad (1)$$

where $K_{g,\lambda}$ is the absorption coefficient due to molecular gas radiation,

and $K_{p,\lambda}$ is the absorption coefficient due to particulate radiation.

The spectral absorption coefficient associated with gas specie radiation depends on gas temperature, specie concentration, and pressure. For particle absorption, $K_{p,\lambda}$ depends on the particle complex index of refraction [$m = n(1 - \kappa i)$], size, shape, and distribution. If scattering also occurs, then eq (1) must be modified to account for transmittance and reflectance due to scattering [4]. When scattering is negligible, eq (1) can be used along with a knowledge of the spectral variation of $K_{g,\lambda}$ and $K_{p,\lambda}$ to obtain the total absorptivity

$$\alpha = \frac{1}{\sigma T_S^4} \int_0^\infty \alpha_\lambda e_{b,\lambda}(T_S)\,d\lambda \qquad (2)$$

where $e_{b,\lambda}$ is the spectral blackbody emissive power and T_S is the source temperature.

The total emissivity of the mixture is determined from eq (2) by replacing the source temperature with the mixture temperature (T), i.e.

$$\varepsilon = \frac{1}{\sigma T^4} \int_0^\infty \alpha_\lambda e_{b,\lambda}(T) d\lambda \qquad (3)$$

It has been implicit in these formulations for emissivity and absorptivity that an isothermal gas of temperature T is being considered. In order to apply this to the corridor experiments, some idealizations have been made. The combustion product layer will be represented by an isothermal (T) infinite slab bounded by a hot surface (T_c) representative of the ceiling and a cold surface (T_f) representative of the cooler lower half of the corridor. It is assumed that the gas in the lower half space and floor are at the same temperature, and that this gas is totally transparent. Uniform composition is also assumed for the slab. The thickness of the slab is estimated by the visible smoke layer and the temperature distribution. This thickness, D, is indicated in figure 2 for all of the cases to be analyzed. It is obvious that its selection is somewhat arbitrary. Visual inspection of photographs of the corridor suggests that its thickness is about 3 ft. Figure 4 illustrates the idealized model describing the radiative transfer process in the corridor. If the floor and ceiling surfaces are taken as blackbodies, then it can be shown [5] that the net heat flux to the floor is given by

$$\dot{q}''_f = \sigma[1-\alpha(T,T_c)]T_c^4 + \varepsilon(T)\sigma T^4 - \sigma T_f^4 \qquad (4)$$

where α and ε are evaluated at the mean beam length L = 1.8D (for an infinite slab). The first term on the left represents the energy transmitted by the ceiling through the gas layer to the floor, the second term represents the energy emitted from the gas to floor, and σT_f^4 represents the energy emitted by the floor. It will be useful to employ the ratio

$$\frac{\dot{q}''_{c,f}}{\dot{q}''_{g,f}} = \frac{(1-\alpha)T_c^4}{\varepsilon T^4} \qquad (5)$$

in order to assess the relative importance of the energy radiated from the gas to the floor compared with that received from the ceiling.

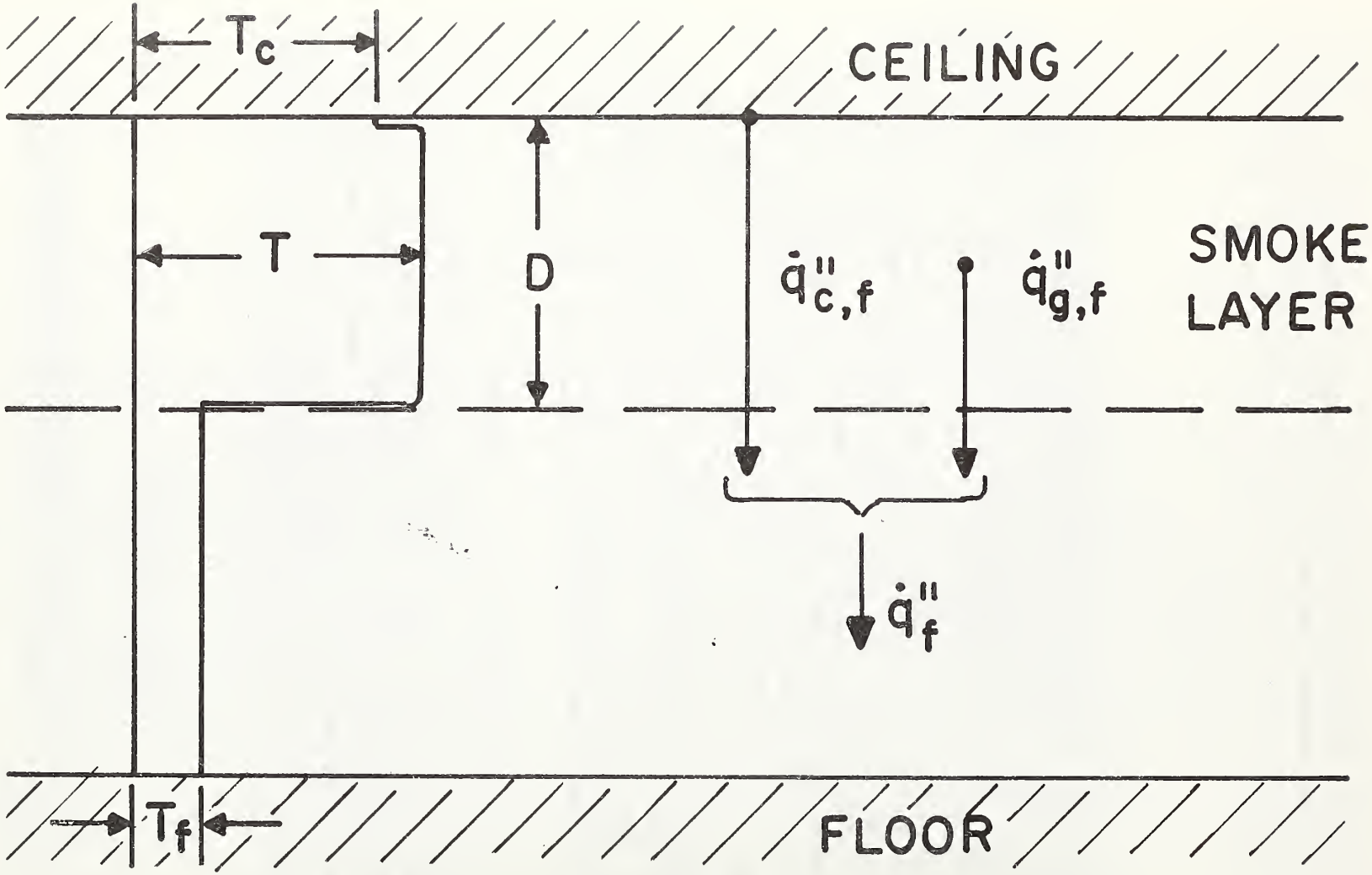


Figure 4. Idealized corridor model of radiative transfer.

In order to calculate α_λ for the mixture it is convenient to consider

$$1-\alpha_\lambda = (1-\alpha_{\lambda,p}) \cdot \prod_{i=1}^{N} (1-\alpha_{\lambda,i}) \qquad (6)$$

which follows from eq (1). In eq (6), $\alpha_{\lambda,p}$ is the spectral absorptivity of the particulate matter and $\alpha_{\lambda,i}$ is the spectral absorptivity of the ith gas specie. The important wavelength range for fire situations can be assessed from figure 5 which shows the locus of wavelengths above and below which 10 percent of blackbody radiation is distributed. Particulate matter attenuates and emits radiation as a smoothly continuous function of wavelength. On the other hand, the gases radiate over discrete wavelength bands. For example, the important combustion products have major emission bands at 2.7 and 6.3μm for H_2O, 2.7, 4.3, and 15μm for CO_2, and 4.7μm for CO.

The work of Edwards and Balakrishnan [6] has been used to determine the spectral absorptivities and emissivities of a mixture of gases. They use a wide band absorption model in their analysis and describe a computer routine (TOTAL) for calculating total absorptivity and emissivity. This computer program was used in this present study, and it is described in the Appendix.

In order to determine the contribution of the particulate matter, it is necessary to digress to the theory of attenuation by particles [4,5,7]. For simplicity, spherical particles of uniform size and distribution will be considered. In the large particle limit, i.e., $2\pi r/\lambda > 5$ (r = particle radius):

$$K_a = \frac{3}{4} \varepsilon \frac{f_v}{r} \qquad (7)$$

is the absorption coefficient, and

$$K_s = \frac{3}{4} \rho \frac{f_v}{r} \qquad (8)$$

is the scattering coefficient with

ε = particle emissivity,

ρ = particle reflectivity,

and f_v = volume concentration of particles. (The p and wavelength, λ, subscripts have been dropped here for convenience.)

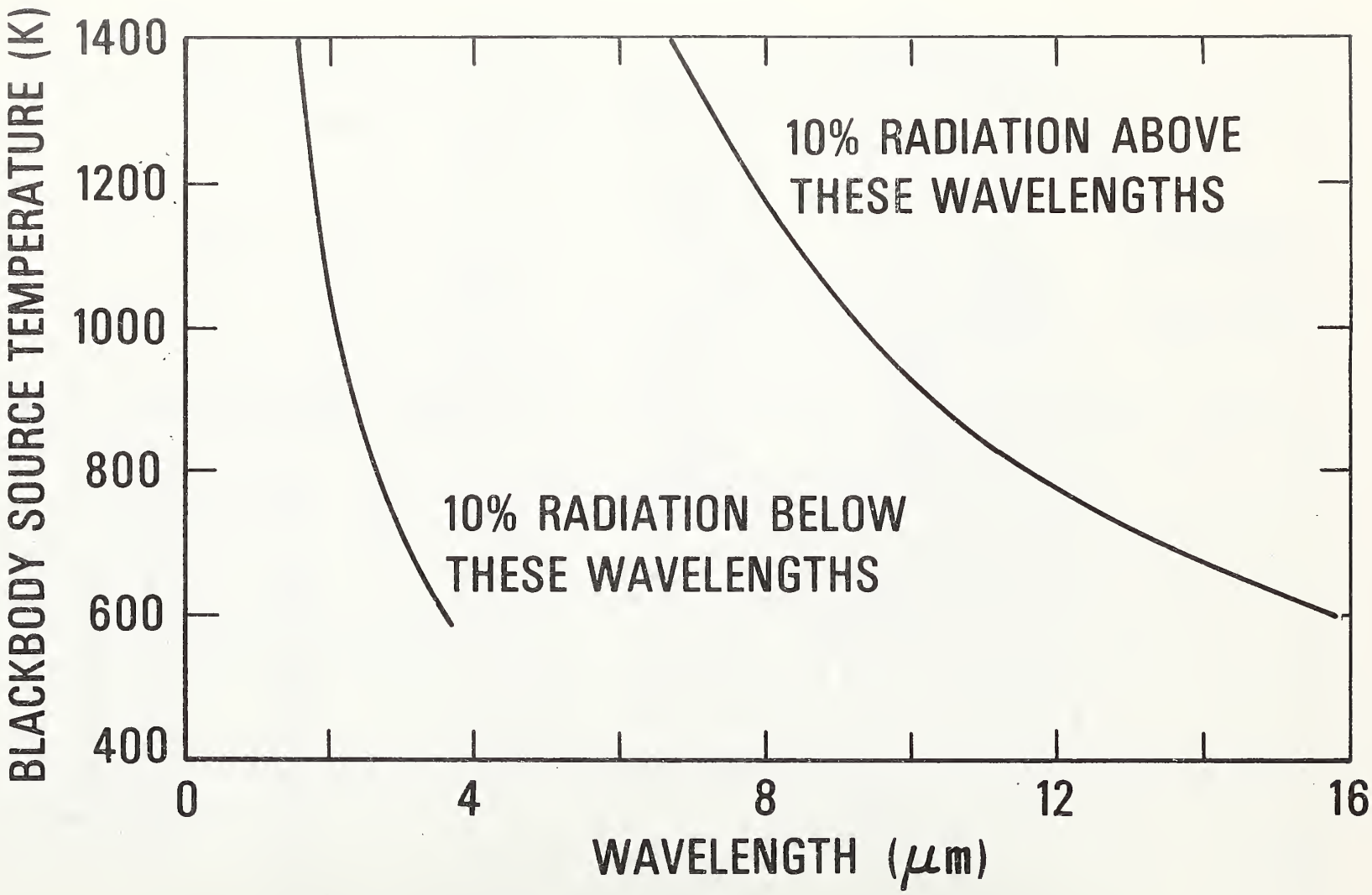


Figure 5. Locus of wavelengths having 10% blackbody radiation above and below.

In the small particle limit, i.e., $2\pi r/\lambda < 0.6$;

$$K_a = - \frac{6\pi}{\lambda} \text{Im} \frac{m^2-1}{m^2+1} f_v \tag{9}$$

and

$$K_s = \frac{24\pi}{\lambda 4} \left| \frac{m^2-1}{m^2+1} \right|^2 \left(\frac{4}{3} \pi r^3\right) \cdot f_v \tag{10}$$

with

$$m = n(1-\kappa i) \tag{11}$$

The terms containing m can be evaluated if the nature of the particle is known. If $\kappa = 0$, only scattering can occur for the particles. Since smoke can vary in particulate composition, it is difficult to predict accurately the attenuation by smoke without measuring the refractive index (n) and the absorption index ($n\kappa$) for the smoke. For example, Foster found that wood smoke generated from heated sawdust was found to be tarry spherical droplets with $m = 1.5 - 0.0015\ i$ ($\lambda = 0.5\mu m$) which indicates nearly pure scattering [8]. Yet, King found that wood smoke from flaming combustion consists of both liquid and solid particles, implying the possibility of attenuation by both scattering and absorption [9]. Carbon particles (soot) are mainly responsible for radiation from flames and will also be present in smoke. For soot, $n = 1.57$ and $\kappa = 0.348$ at $\lambda = 0.55$ m, and $n = 2.04$ and $\kappa = 0.56$ at $\lambda = 2.5\mu m$ [5]. In general, smokes of obvious color suggest that absorption becomes important [10]. In the fire experiments examined in this study, the smoke varies in color from grey to black.

Equations (7) and (9) will be examined together with the smoke data in table 1 in order to develop an empirical relationship for the absorption coefficient for smoke in these corridor experiments. The transmission of smoke recorded in table 1 is given by

$$\tau = \exp(-K_e \ell) \tag{12}$$

at $0.52\mu m$ where K_e ($= K_a + K_s$) is the extinction coefficient. As a representative case, test 348 at 300-360 s is examined. This yields $K_e = 0.074\ cm^{-1}$. If the large particle limit is assumed to be applicable, an average particle radius can be determined from eq (7). If the particles are characterized as soot with a density of $2\ g/cm^3$ and an emissivity of 1,

then $f_v = 0.8 \times 10^{-6}$ and $r = 0.08\mu$ and correspondingly, $\frac{2\pi r}{\lambda} = 0.97$. The large particle limit is not applicable because it requires that $\frac{2\pi r}{\lambda} > 5$. Hence, eq (9) would appear more suitable. In this case, eq (9) becomes

$$K_a = 4.64\ f_v/\lambda\ (cm^{-1}) \qquad (13)$$

where λ is in cm.

It will be useful to compare the measured value of the extinction coefficient: $K_e = 0.074\ cm^{-1}$ at $\lambda = 0.52$ m, with the value predicted by eq (13) at 0.52μm: $K_a = .07/cm^{-1}$. This implies that scattering is negligible for the case of test 348 at 300-350 s. On the other hand, calculations based on the wood flooring test (349) for time 370-420 s yield a value of $K_e = 0.014\ cm^{-1}$ and a value of $K_a = 0.009\ cm^{-1}$. This implies that scattering is significant for this case. Observations of the fire development indicated the presence of grey smoke within the corridor, which suggests a scattering medium. Yet, at a later time (550-610 s), observations show a black smoke layer, suggesting the dominance of absorption. Similar calculations, for this time, yield $K_e = 0.012\ cm^{-1}$ and $K_a = 0.013\ cm^{-1}$ which indicates negligible scattering.

The assumption of smoke composed of soot particulates coupled with the small particle limit as expressed in eq (13) appears to give a reasonable prediction of K_a in the visible. This is implied from the fact that the above calculations indicate that K_a is approximately equal to or less than the measured extinction coefficient, K_e. The apparent lack of a scattering medium also makes eq (13) a good estimate of K_e. However, the implication from the theory that the scattering component may be small is subject to question, since the theory relies on the physical nature of the particulate matter and the absence of liquid aerosols in the smoke.

Nevertheless, it is still reasonable to assume that $K_a >> K_s$ in the infrared region. Since K_a is proportional to $1/\lambda$ and K_s is proportional to $1/\lambda^4$, K_s becomes completely insignificant in the infrared, the wavelength range of interest in fires (see fig. 5). Thus, eq (9) represents all the attenuation in the infrared region.

For $\lambda = 2.5\mu$ (the infrared) eq (9) becomes

$$K_a = 5.85\ f_v/\lambda \tag{14}$$

which is only about 25% higher than eq (13). The variation is due to the change of n and κ with wavelength. As a result of the above discussion, it is reasonable to use

$$K_{p,\lambda} = k_o \rho_p f_v/\lambda \tag{15}$$

(ρ_p is the particle density)

as an empirical relationship for the coefficient of absorption due to particles. This expression is consistent with eqs (13) and (14) above. The selection of the quantity K_o was based on the data from the corridor fire experiments.

A more complete analysis for carbon smokes has been reported by Tien, et al [11]. They develop approximate analytical expressions for K_a based on Mie scattering theory. Unfortunately, the lack of measurements of particle size distribution and refractive index of smokes precludes the use of such exact expressions for K_a. In fact, they point out that particle size can vary from 0.005μm for soot in flames to 100μm for oil flames in industrial furnaces. Also, the agglomeration of particles in smoke will increase particle size after combustion. For soot in flames, various investigators report experimental correlations of the form

$$K_a = k_1 f_v/\lambda^a \tag{16}$$

where a is dependent on λ and can vary from 0.45 to 1.75μm [11], but generally is nearly 1 over the range, 1 to 7μm [5]. It should be noted that eq (15), used in the program TOTAL, is really eq (16), with a = 1, and $k_1 = k_o \rho_p$.

Combining eq (15) with eq (12) and using the smoke data in table 1 (where $\rho_p f_v$ is the mass concentration of the solids), k_o can be determined (for λ 0.52μm). Since there is no information in regard to any possible wavelength-dependence of k_o, it was assumed to be constant. Values of k_o are tabulated in table 1. As discussed above, scattering is suspected to be significant in test 349 (370-420 s) and consequently its value of k_o is overestimated for use in eq (15). In fact, this value of k_o is greater than the other values where absorption is believed to be the dominant mechanism of attenuation in the visible.

Ideally, the procedure should be to determine which portion of the attenuation in the visible was due to absorption in order to calculate the value of k_o. This value of k_o would be the most appropriate for the determination of $k_{p,\lambda}$ in the infrared regions. In practice, however, it was not feasible to isolate the scattering component, and, therefore, it was assumed to be zero (based on the previous observations). Therefore, the average value of all the k_o values was employed.

Equation (15) was used to modify the computer program TOTAL [6] given in the Appendix. TOTAL calculates α and ε by use of eqs (1,2,3 and 6).

4. RESULTS AND DISCUSSIONS

Table 2 represents a compilation of data necessary to make the calculations for α, ε, and $\dot{q}''_f$. Only times before flameover are considered. A mean time is used and average values are used for gas concentration and temperatures over the sampling times given in table 1. Where possible, H_2O concentration was determined by assuming 90 percent of the condensables to be water. Where the condensable data was not available, the H_2O concentration was estimated by calculation. This was done by using an approximate pyrolysis model for wood [12],

$$CH_{1.5}O_{0.5} \cdot xH_2O \rightarrow xH_2O + 0.7CH_2O + 0.3CH_{0.33}$$

where x was taken as 0.13 which is representative of the approximately 10% moisture content of the wood cribs burned in these fire experiments. Combustion of the volatiles CH_2O result in

$$\text{Combustion Products} \rightarrow wO_2 + yCO + zCO_2 + 0.83H_2O + 3.76(z + w + y/2)N_2$$

It can be shown that the volume concentrations (χ_i) of the measured components are related to H_2O by

$$\chi_{H_2O} = 1-[2.88\chi_{CO} + 4.76(\chi_{CO_2} + \chi_{O_2})]. \qquad (17)$$

The constant k_o of eq (15) was determined from the data (table 1) with an average value of

$$k_o = 0.024\,\mu m(cm)^{-1}(mg/\ell)^{-1}$$

which is within 30 percent of all values. In table 2 one value of particulate concentration was interpolated between two measured values, while another value was estimated by using eqs (12) and (15) and the value of k_o. For a particle density of 2g/cm^3 (soot), this k_o corresponds to a k_1 [eq (16)] of 4.8, which compares favorably to that coefficient given in eq (13) for carbon smoke.

With the program TOTAL, α and ϵ were calculated in the manner previously described. Using eqs (4) and (5), $\dot{q}''_f$, the net flux to the floor and $\dot{q}''_{c,f}/\dot{q}''_{g,f}$, the ratio of the ceiling flux to the gas flux, were calculated. These values are presented in table 3.

Figure 6 shows the spectral emission of the particles and gas during test 349 at t = 468 seconds. The continuous emission due to particles alone is represented by the dotted line labeled 0.25mg/ℓ. The emissivity of this particulate cloud alone (neglecting the molecular gas contribution) is 0.15. If the concentration is increased by a factor of 10 the emissivity rises to 0.74. For illustration, the spectral emission from a 2.5 mg/liter particulate cloud is also shown in figure 6. The significant gas bands consist of CO_2 and H_2O and are located at 2.7μm, 4.3μm and 6.3μm. The widths (calculated by TOTAL) are nearly directly proportional to the gas volume fractions. With the addition of the gas absorption to the particulate absorption ($\rho_p f_v$ = 0.24mg/ℓ), the total emissivity for the mixture is 0.48. Thus, in this case of low particulate concentration, the gas contributes more than the particles to the total emissivity.

An examination of figure 7 shows the dependence of total emissivity on particulate concentration for three different cases. Curve 1 employs the gas and temperature data from test 348, t = 330 seconds and varies the particulate concentration. The modified program TOTAL was used to generate curve 1. Three basic regions are discerned: low, intermediate and high concentration. For the low concentrations, as seen before in test 349, the gas contributes primarily, while at high concentration, the particulate matter is the primary source of emissivity. In the intermediate range, the total emissivity has significant contributions from both.

Curves 2 and 3 employ the same gas and temperature data, but are generated by two different procedures. Curve 2 is derived from the results of Felske and Tien [13] for emissivity as a function of soot volume concentration. A soot density of 2 g/cm^3 was assumed to convert their volume concentration to mass concentration. Curve 3 was generated by TOTAL.

Table 2. Summary of Corridor Data
Required For Radiation Calculations

Test	Mean Time (s)	Volume Fractions (%)				Particulates (mg/ℓ)	D (m)	T (K)	T_c (K)	T_f (K)
		H_2O	CO	CO_2	O_2					
348	330	14.0[a]	0.8	9.7	7.0	1.6	0.9	720	640	410
348	390	10.8 or 9.5[a]	0.6	9.0	9.6	1.4[b]	0.9	720	625	420
349	468	17.7	0.2	15.2	6.1	0.25[c]	0.9	650	590	365

[a] calculated
[b] estimated
[c] interpolated

Table 3. Radiative Properties
of the Combustion Products in Tests 348 and 349

Test	Mean Time (s)	ε -	α -	$\dot{q}''_{c,f}/\dot{q}''_{g,f}$ -	$\dot{q}''_f$ (W/cm^2)
348	330	.781	.765	0.19	1.26
348	390	.741	.720	0.22	1.20
349	468	.484	.490	0.72	0.74

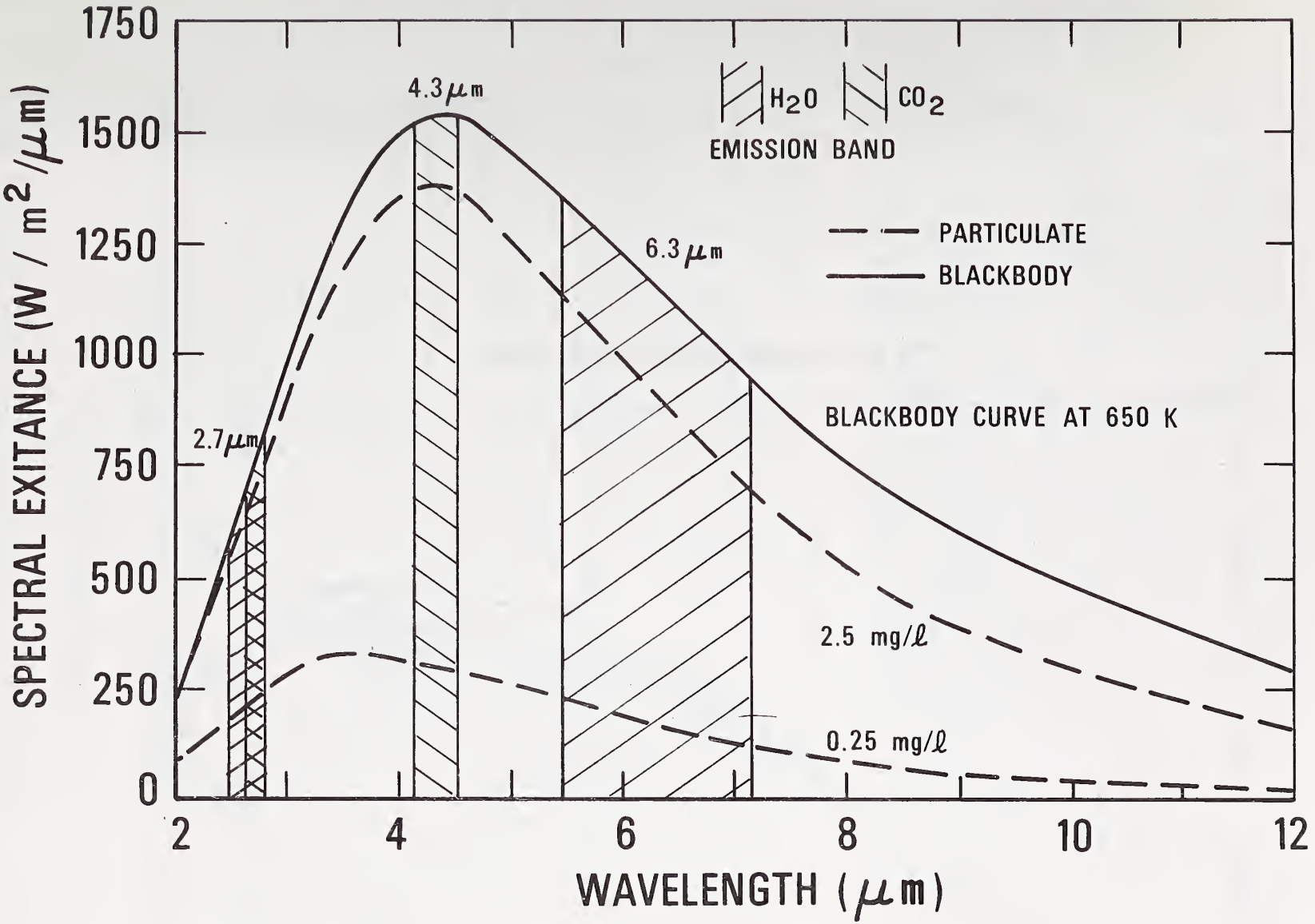
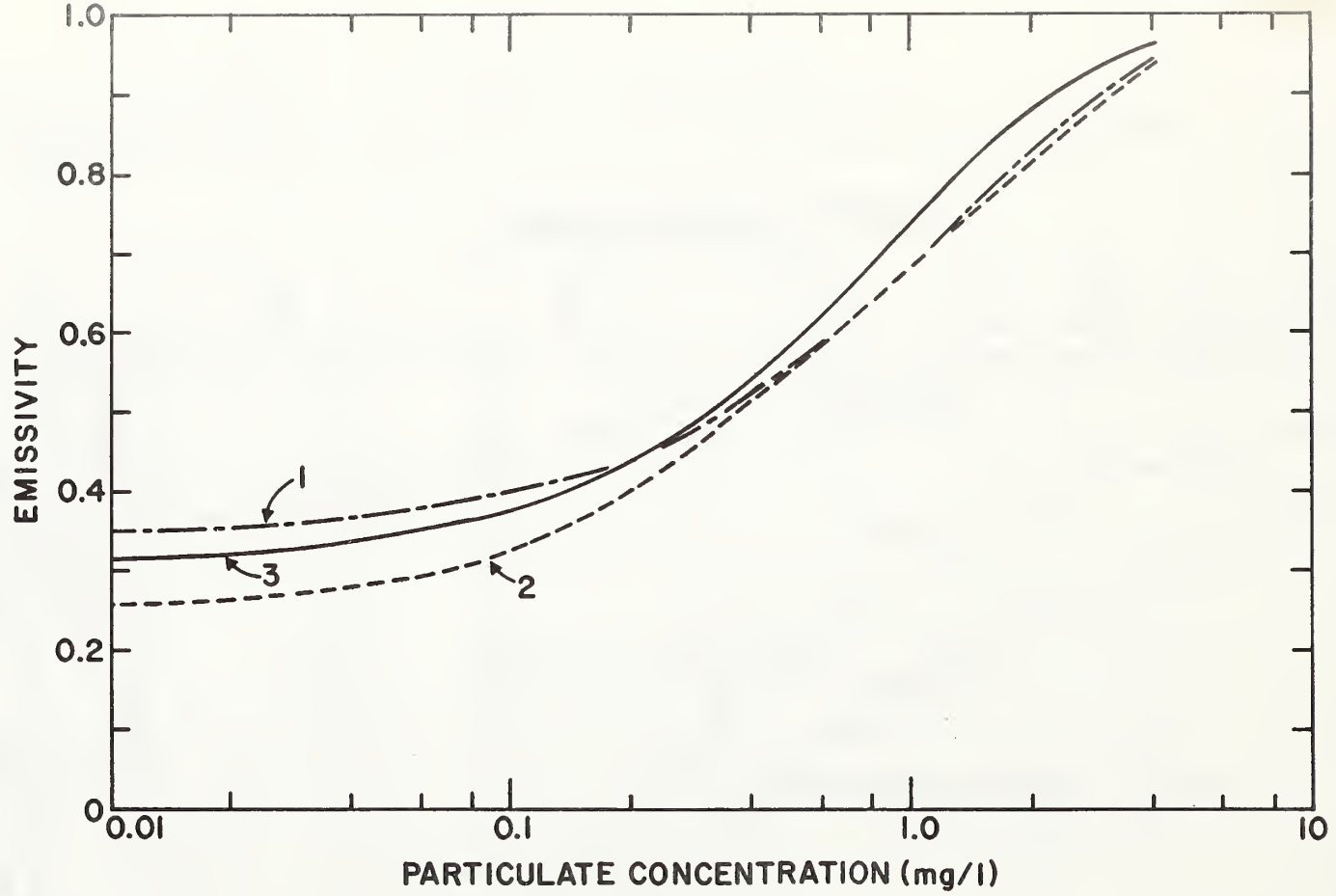


Figure 6. Spectral emission characteristics of particulate matter and gas for test 348 at t = 368 s. (17.7% H_2O, 15.2% CO_2, 0.2% CO, L = 160 cm, T = 650°K).



Curve	Procedure	Vol. Conc. (%) H_2O	CO_2	CO	T(K)	L(cm)
1	Total	14	9.7	0.8	720	160
2	Ref. 13	13	12	0	1000	160
3	Total	13	12	0	1000	160

Figure 7. Emissivity as a function of particulate concentration.

Figure 8 shows how the radiant heat fluxes in the corridor vary with particulate concentration based on a fixed gas composition. As expected, the ratio is a strong function of soot density. The gas radiation is predominant for particulate concentrations above 0.8 mg/liter. However, at the same time, the net flux to the floor is a fairly weak function of the concentration. This results since the hot combustion products which heat the ceiling are slightly higher in temperature than the ceiling. Hence, if the gas is totally transparent, the floor receives ceiling emitted radiation σT_c^4; yet, if the gas is opaque ($\varepsilon = 1$), it radiates to the floor as σT^4. Moreover, the view factor between the floor and the ceiling and upper walls is nearly identical to the view factor between the floor and the hot combustion products. Unless one could spectrally discriminate, a radiometer measurement of the floor flux would not necessarily reveal the source of radiation.

5. CONCLUSIONS

The role of combustion products on radiative transfer has been examined by analysis of data from corridor fire experiments. Although the data were not necessarily complete, reasonable assumptions were introduced in order to permit the determination of emissivity and absorptivity of the hot combustion products. Measurements (fig. 3) have shown that under some circumstances radiation due to particulates in the combustion products can be significant. Analysis suggested that attenuation of radiation by the particulates in these experiments was due to absorption, with scattering as a negligible factor. Based on this and on the theory of radiative attenuation by particles, an empirical model was introduced to describe the attenuation by the particulates. The results of these calculations displayed the relative contribution of both molecular gas radiation and particulate emission in these corridor fire experiments. The assumptions used in these calculations have been to simplify the analysis and were necessary because more detailed data were not available. The effect of non-uniform temperature and concentrations on radiative heat transfer in the combustion products can have a substantial influence on the results. Moreover, the effect of scattering has not really been dealt with to any conclusive end in this paper. In the least, this paper demonstrates that one can not ignore the radiative transfer effects of the combustion products in compartment fires.

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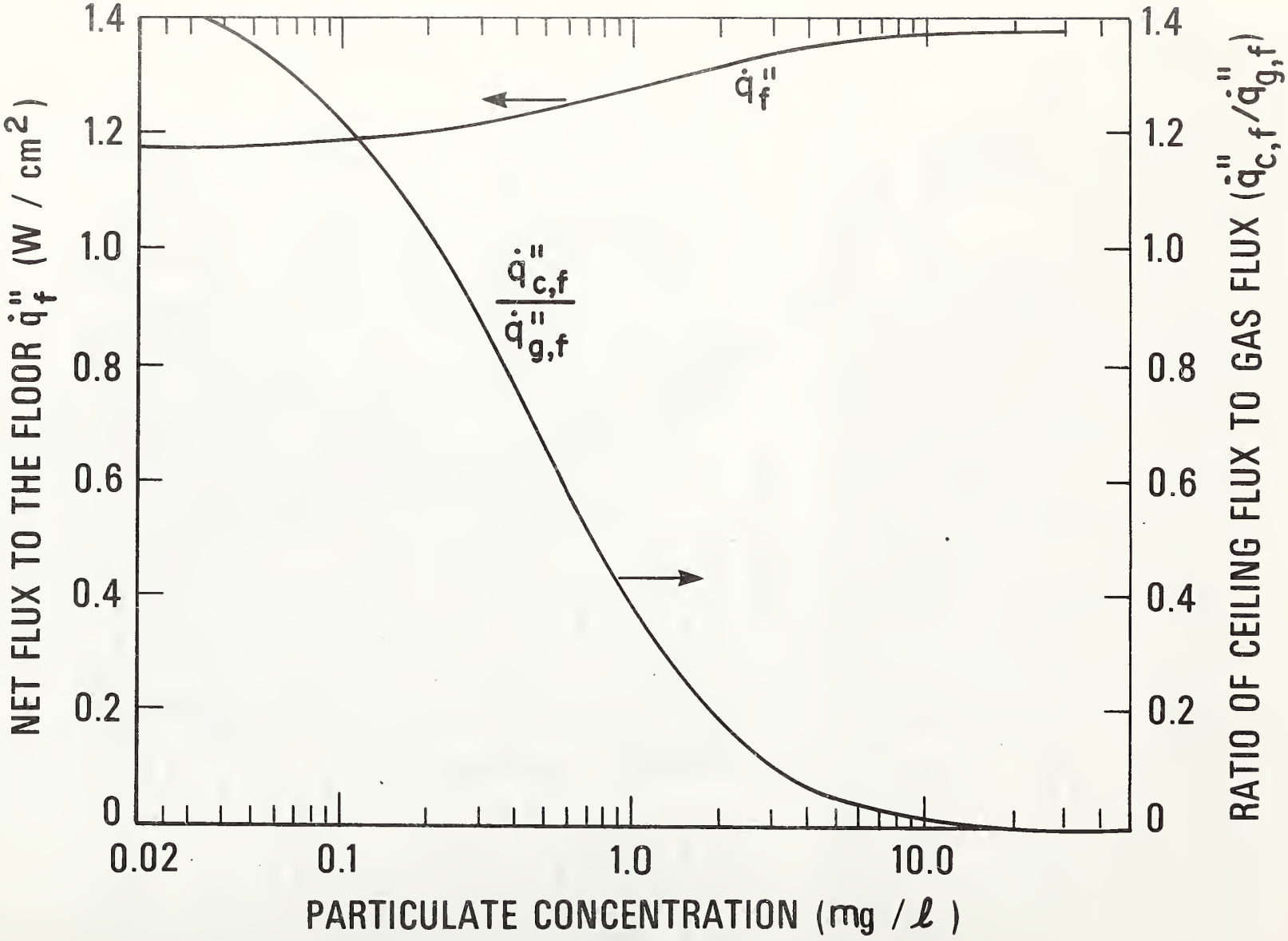

Figure 8. Ratio of ceiling flux to gas flux and net flux to the floor as a function of particulate concentration (14% H_2O, 0.8%CO, 9.7%CO_2, L = 160cm, T_c = 684°K, T_f = 408°K).

D. K. Edwards and A. Balakrishnan for sending us a copy of their program, TOTAL.

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Appendix

Emissivity and absorptivity of a multicomponent gas mixture can be calculated by using the wide band absorption model of Edwards and Balakrishnan [6]. They formulate a computer program TOTAL to compute the above values. In order to do the calculation for a gas-soot mixture, an additional term for the soot transmissivity is necessary. From TOTAL, the spectral gas transmissivity is given by

$$\exp(-K_{g,\lambda}L) = \prod_{i=1}^{M} \prod_{j=1}^{N} (1-\alpha_{\lambda,i,j}) \qquad \text{(A-1)}$$

where $\alpha_{\lambda,i,j}$ is the absorptivity of the ith gas specie and jth wavelength band. Substitution of eq (A-1) into eq (1) yields the spectral mixture absorptivity,

$$\alpha_{\lambda} = 1-\exp(-K_{p,\lambda}L) \cdot \prod_{i=1}^{M} \prod_{j=1}^{N} (1-\alpha_{\lambda,i,j}). \qquad \text{(A-2)}$$

$K_{p,\lambda}$ is given by eq (15) and the $\alpha_{\lambda,i,j}$ are determined by the procedure presented in reference 6 and executed in TOTAL. The total absorptivity is calculated by a spectral integration of eq (A-2) over the wave-number range of 0 to 8,500 cm^{-1} using the trapezoidal rule.

$$(T,T_s,\chi_i,L,p) = \frac{1}{\sigma T^4} \int_0^{\infty} \alpha_{\lambda}(T,\chi_i,L,p) e_{b,\lambda}(T_s) d\lambda \qquad \text{(A-3)}$$

$e_{b,\lambda}$ = spectral blackbody emissive power

σ = Stefan-Boltzmann constant

χ_i = mole fraction of ith gas species

T = gas temperature

T_s = surface temperature (ceiling in this case)

p = total pressure of mixture

Emissivity is calculated by replacing T_s with T

$$\varepsilon(T,\chi_i,L,p) = \frac{1}{\sigma T^4} \int_0^{\infty} \varepsilon_{\lambda}(T,\chi_i,L,p) e_{b,\lambda}(T) d\lambda \qquad \text{(A-4)}$$

Nomenclature

a	constant
D	thickness of combustion product layer
$e_{b,\lambda}$	spectral blackbody emissive power
f_v	volume concentration of particles
k_o, k_1	constants
K_a	absorption coefficient (particle)
K_e	extinction coefficient
$K_{g,\lambda}$	gas spectral absorption coefficient
$K_{p,\lambda}$	particulate spectral absorption coefficient
K_s	scattering coefficient (particle)
ℓ	photometer path length
L	mean beam length
m	complex index of refraction, $n(1-\kappa i)$
n	real part of index of refraction
p	total pressure of gas mixture
$\dot{q}''_{c,f}$	flux from ceiling to floor
$\dot{q}''_f$	net flux to the floor
$\dot{q}''_{g,f}$	flux from gas to floor
r	particle radius
T	temperature of the gas
T_c	temperature of the ceiling
T_f	temperature of the floor
T_s	temperature of the source

χ_i gas volume concentration

α total absorptivity

α_λ spectral absorptivity

$\alpha_{\lambda,p}$ spectral absorptivity of the particulate matter

$\alpha_{\lambda,i}$ spectral absorptivity of the ith gas specie

ε total emissivity, or particle emissivity

κ absorption index/n

λ wavelength

ρ particle reflectivity

ρ_p particle density

σ Stefan-Boltzmann constant

τ transmissivity, or transmission

Subscripts

b blackbody

c ceiling

f floor

g gas mixture

i gas specie

j gas band

λ spectral

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16. ABSTRACT (*A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.*)

The contribution of radiative heat transfer from hot combustion products to corridor floors is examined. Data from full-scale corridor fire experiments is used to calculate emissivity and absorptivity of the combustion products. An empirical model based on attenuation by absorption is used to specify the absorption coefficient due to particulates in the products. In these experiments it is shown that radiation from the combustion products is just as significant as radiation from convectively heated walls and ceiling of the corridor. Calculations show that the ratio of radiant heat transfer to the floor due to ceiling emission to that by combustion product emission ranges from about 0.2 to 0.7. Also, molecular gas radiation and particulate radiation can both be significant for the combustion products. Calculations show that the emissivity of the gaseous combustion products alone would be about 0.3, but the inclusion of soot particles yields an emissivity for the total combustion product mixture of as high as 0.73, based on the experimental data considered.

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Combustion products; full-scale fire; radiative heat transfer.

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