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SMOKE EMISSION AND BURNING RATES FOR URBAN STRUCTURES*

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Abstract—Cribs, ordered arrays of sticks, were burned to mimic post-nuclear building fires. As the packing density of the cribs was increased to simulate blast damage, the smoke yield increased and the smoke changed from strongly light absorbing to whitish in color. A ventilation parameter proportional to the ratio of the crib vent area to the total fuel surface area correlated the burning rate and smoke yield data for both large (3.81 cm stick thickness) and small (0.64 cm stick thickness) scale cribs. The globally averaged smoke optical depth inferred from the burning of the wood cribs is in the low range of Penner's (1986, *Nature* **324**, 222–226) estimate. The smoke yield for freely burning cribs containing wood, gypsum, and plastic can be accounted for based on the high sooting yield of the plastic by itself.

Key word index: Smoke emissions, burning rates, urban fires, nuclear winter, smoke generation, crib burning, scale effects, wood, ABS plastics, gypsum.

INTRODUCTION

Crutzen and Birks (1982) and Turco *et al.* (1983) first proposed that the smoke aerosol produced by post-nuclear fires could cause subfreezing temperatures in the summer over much of America, Europe and Russia. This temperature reduction or 'nuclear winter' would result from the attenuation of the solar radiation by the global smoke cloud. Three-dimensional global climate simulations by Thompson *et al.* (1986) indicated a less severe climate effect although intermittent freezing was still predicted over large interior regions of North American and Eurasian continents.

In these predictions much of the smoke would be generated by urban areas where residential structures and other buildings would be ignited by the nuclear exchange. The original smoke yields were estimated from small scale experiments which ignited flat pieces of wood or plastic, 10 cm diameter × 1–5 cm thick (Tewarson, 1982) and 8 cm × 8 cm × 1 cm thick (Bankston *et al.*, 1981). While burning flat, homogeneous samples provided useful first order estimates, Penner (1986) pointed out that such data are of limited use for making a quantitative estimate of the smoke emission for realistic scale structures. Real structures are three-dimensional and contain heterogeneous mixtures of wood, plastic, inert, and asphalt (shingles and tile) with large internal void spaces. There are no data at any scale on smoke emission for mixed fuels such as found in a building. The burning rate and smoke production are also expected to be strongly affected by the ventilation to the interior of the structure. The ventilation rate will be relatively high for a free standing building with broken windows caused by the nuclear blast, while the ventilation rate will be low for the same building collapsed as a result of the blast.

To simulate the effects of scale, fuel composition, and ventilation rate on smoke emission and heat release rate, we have burned ordered arrays of sticks, referred to as cribs. Burning cribs which incorporate internal void spaces and mix of fuels will better simulate an urban structure fire than igniting a flat homogeneous fuel sample. The fire research community has extensively studied the burning of wood cribs as a model system for building fires. Gross (1962) and Block (1971) have obtained a universal correlation between the burning rate and the ventilation rate, which is valid for stick thicknesses varying from as small as 0.16 cm, tooth pick size, up to as large as 9 cm. The present study extended the approach of Gross and Block to include the key aspects of smoke production and optical properties. We have examined the effect of fuel composition on smoke emission by burning cribs of all wood, wood and gypsum, and of wood, gypsum, and acrylonitrile butadiene styrene (ABS) plastic. The percentages of wood, gypsum, and ABS simulate fractions of wood, inert, and petrochemicals (plastics, asphalt shingles and tiles) found in a house (Ransohoff *et al.*, 1987). The crib porosity has been varied from 18 to 68% to simulate the ventilation differences among various structures intact and in various states of blast damage. The scale effect has been studied by burning geometrically similar cribs (i.e. same length to thickness ratio) with stick thicknesses of 0.64 cm and of 3.81 cm.

FABRICATION OF CRIBS

Large and small cribs of all wood, wood and inert, and wood, inert, and plastic were assembled in four different porosities (ratio of void volume to total volume), which were selected to include ventilation limited and free combustion regimes of burning. Douglas fir was selected to represent the framing lumber, plywood and wood siding which accounts for about 50% of the mass of a typical house (Ransohoff *et al.*, 1987). Gypsum drywall ($CaSO_4 \cdot 2H_2O$) was chosen to simulate the non-combustibles, approximately 40% of the typical house mass. Acrylonitrile butadiene styrene (ABS) plastic was selected to represent the asphaltic roofing, carpeting, polyurethane furnishings, vinyl tile, and other plastic components of the combustibles, about 10% of the total house mass. In addition to the 50% wood–40% inert–10% plastic (mass basis) cribs, all wood cribs and 55% wood–45% inert cribs were also burned to examine the effect of fuel/inert mix.

The cribs consisted of N layers, with each layer containing n sticks of b square cross-section and each successive layer laid crosswise to the previous layer (Fig. 1). These cribs are similar in design to the wood cribs burned by Gross and Block. Each crib was identified as $b \times N \times n$, thickness of each stick, number of layers, and number of sticks per layer. For example, a crib designated $3.81 \times 10 \times 7$, would contain 3.81×3.81 cm sticks, 10 layers with seven sticks per layer. The length of each stick was 14.7 times the stick thickness. More details of the crib construction are contained in Appendix A.

After construction, each crib was stored under controlled temperature (23°C) and controlled humidity (50% r.h.) resulting in a moisture content after conditioning which ranged from 6 to 8%. The density of the Douglas fir, gypsum, and ABS averaged about 0.55, 0.68, and 1.06 $g\,cm^{-3}$, respectively. The initial weight of the large cribs averaged about 35 kg, while the small cribs averaged about 200 g.

TEST FACILITY

After conditioning, the large cribs were burned under a 2.4×2.4 m collection hood (Fig. 1) with an exhaust rate of about 2 $m^3\,s^{-1}$ (70 $ft^3\,s^{-1}$). The ignition method (Block, 1971) consisted of burning acetone in a square fuel pan ($61 \times 61 \times 1.3$ cm) centered at the stick distance b below the crib. The amount of acetone used varied from 500 ml for the most porous fuel bed to 1500 ml for the most compact. The acetone averaged about 3% of the initial mass of the crib. The

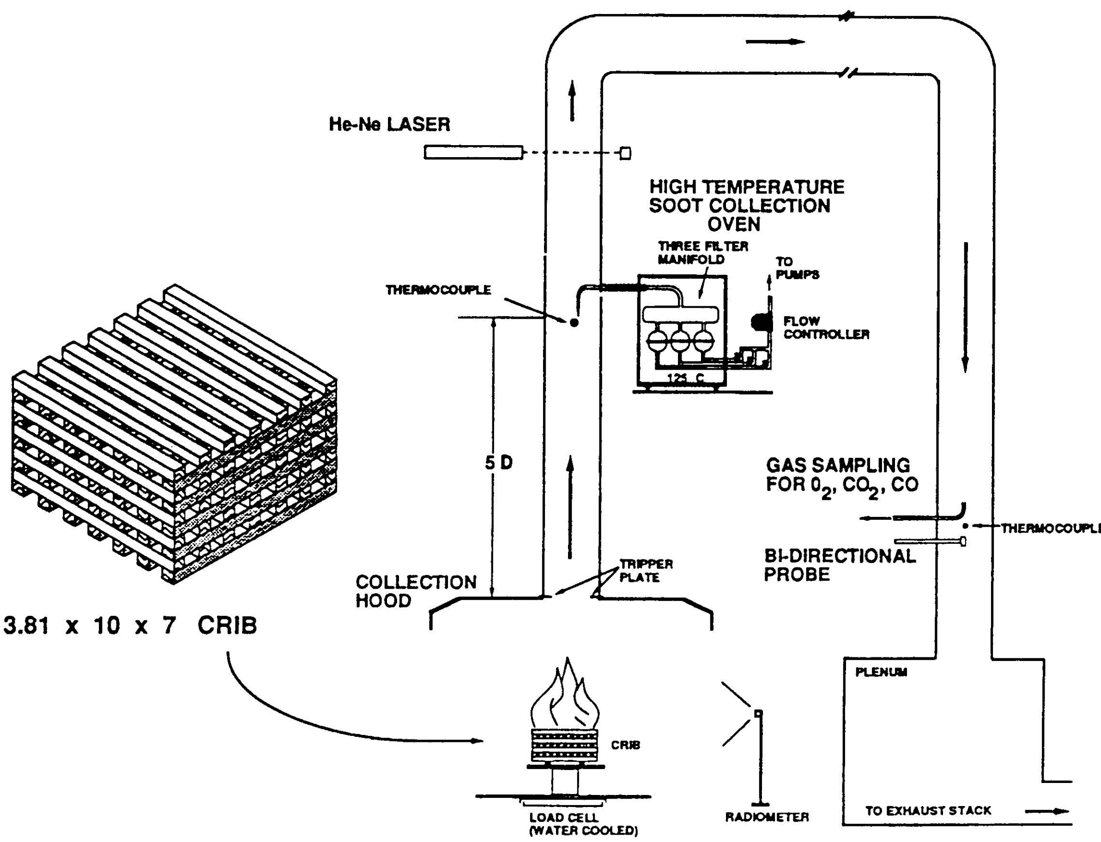

Fig. 1. Large scale burn facility and $3.81 \times 10 \times 7$ crib.

four quantities measured in this facility, which has been described in more detail by Mulholland *et al.* (1989), were the mass loss rate of the fuel, the heat release rate of the fuel, the smoke yield defined as grams of smoke aerosol produced per gram of fuel consumed, and the specific extinction area of smoke. The mass loss rate of the burning fuel was monitored with a water cooled load cell with a sensitivity of about 3 g. The heat release rate was determined via oxygen consumption calorimetry (Huggett, 1980, Parker, 1984), which involves measuring the oxygen concentration, the flow velocity, and the temperature in the exhaust duct. The filter collection system contained three filter holders allowing continuous collection of smoke aerosol throughout a crib burn. Each burn was continued until the fire went out or a substantial amount of the burning crib fell off the load cell.

The smoke yield ε was obtained from measurements of the smoke collected on the filter, m_s; the mass loss of the sample, m_f; and from the ratio of the mass flow of air through the exhaust duct to the mass flow through the filter sampler, ϕ, using the formula

$$\varepsilon = (m_s/m_f)\phi. \qquad (1)$$

The specific extinction area, σ_f, was determined from the light transmittance, I/I_0, through the 0.48 m duct, the mass loss rate of the fuel, $\dot{m}_f$, and the volumetric flow rate, $\dot{V}$, of the combustion products through the exhaust duct via the formula

$$\sigma_f = -\ln(I/I_0)\,\dot{V}/(L\dot{m}_f). \qquad (2)$$

The light extinction measurement was based on a He–Ne laser beam (633 nm) with one detector monitoring the initial laser intensity and a second monitoring the intensity of the transmitted beam.

For the small crib burns a bench scale version of this apparatus, termed the Cone Calorimeter, was used (Babrauskas, 1982; Mulholland *et al.*, 1989). The ignition method was the same as for the large scale tests although the relative amount of acetone was larger, about 10% of the crib mass for the small scale tests compared to about 3% for the large scale tests. We were unable to obtain sustained burning for the small cribs with 12 sticks per layer, and only in the case of all wood construction were we able to get sustained combustion at 10 sticks per layer. As the spacing between the sticks decreases (12 sticks per layer corresponds to an 0.15 cm spacing), the heat loss increases, probably resulting in the flame extinction. It is known in flame studies (Lewis and von Elbe, 1987) that heat loss to a surface can reduce the flame temperature to the point where the production rate of chain propagating free radicals is too low to maintain a flame.

RESULTS

For the high porosity cribs the burning is intense with flames rising a meter above the cribs, while for the low porosity cribs the flame is confined within the crib for much of the burn (Figs 2a and 2b). The corresponding peak mass loss rate is seen in Fig. 3 to decrease from 21 g s^{-1} for the most porous structure to 6 g s^{-1} for the most compact structures. The relative mass loss rate of the wood crib is about factor of two faster than for the wood and gypsum crib (Fig. 4) as a result of the reduced radiation feedback from the gypsum sticks compared to all wood sticks. The temperature of the gypsum ($CaSO_4 \cdot 2H_2O$) remains below 230°C until the water of hydration (21% of the mass of gypsum is water) is removed. The time required to vaporize the water of hydration accounts for the longer time to reach the peak mass loss rate for the wood and gypsum cribs. The much higher mass loss rate of the

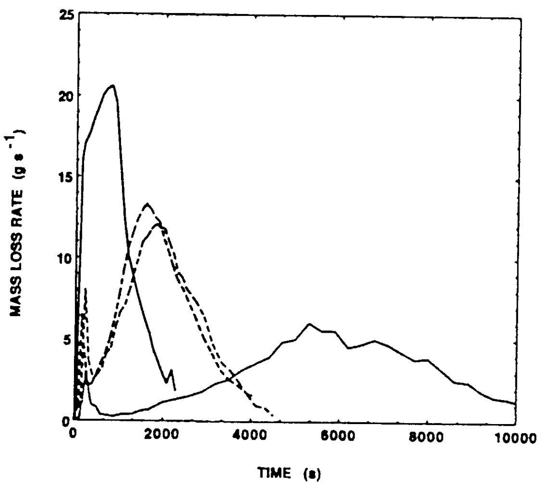

Fig. 3. The effect of porosity on the mass loss rate of large ($b = 3.81$ cm) cribs constructed of wood, gypsum and plastic (10 × 7 —— 7 × 10 — — — 6 × 12- - -). Cribs designated by $b \times N \times n$, where b = stick thickness, N = number of layers per crib, and n = number of sticks per layer.

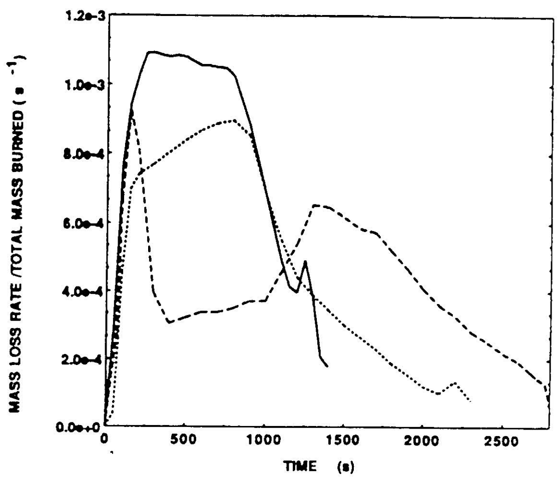

Fig. 4. The effect of fuel composition on the mass loss rate on large ($b = 3.81$ cm) all wood 10 × 7 crib (——), wood and gypsum 10 × 7 crib (— — —), and wood, gypsum and plastic 10 × 7 crib (· · · ·).

ABS together with its high thermal radiation compensates for the presence of gypsum so that the relative mass loss curve for wood, gypsum, and ABS is similar to that observed for wood by itself.

Gross (1962) and Block (1971) were able to correlate wood crib burns for a range of stick thicknesses and fuel porosities by using a reduced mass loss rate plotted as a function of a ventilation parameter. The reduced mass loss rate, $\dot{m}_r$, is defined by

$$\dot{m}_r = \dot{m}_{peak}/(A_s * b^{0.5}) \quad (3)$$

where $\dot{m}_{peak}$ is the peak mass loss rate, A_s is the exposed surface area of the fuel, and b is the stick thickness. This correlation is based on the empirical observation that for large spacings between sticks, the burning rate per unit area is proportional to $b^{0.5}$; thus the reduced mass rate defined above is expected to approach a constant value for large stick spacings or high ventilation rates. The ventilation parameter ψ, which differs just slightly from the parameter used by Gross (by $b^{0.1}$), is defined by

$$\psi = (bh)^{0.5} A_v/A_s \quad (4)$$

where h is the height of the crib and A_v is the open area of the vertical shafts. We use this empirically determined ventilation parameter rather than the expression derived by Block based on the flow and heat transfer in a crib, because Block's parameter is difficult to evaluate and because his analysis does not apply to fuel mixtures.

The results of all the large and small scale experiments (Table 1) are summarized in the correlation

Table 1. Burning and emission properties of large and small cribs

Crib configuration	Crib material§	Burn time T_{50}* (s)	Mass loss total (kg)	Mass loss rate, T_{50}† (g s^{-1})	Pk. heat release rate, T_{50}‡ (kW)	Extinction area avg. (m^2 g^{-1})	Smoke yield (g smoke per g fuel burned)
Large cribs‖ $b = 3.81$ cm							
10 × 7	W	630	26.1	27.7	300	0.012	0.0029
10 × 7	W	570	25.8	31.9	410	0.014	0.0016
7 × 10	W	1180	29.7	20.8	260	0.031	0.0012
7 × 10	W	1190	27.9	19.0	200	0.009	0.0006
6 × 12	W	3095	30.6	9.7	120	0.085	0.0027
6 × 12	W	2700	31.1	10.4	170	0.096	0.0026
10 × 7	WG	1380	18.8	9.3		0.002	0.0002
10 × 7	WG	1420	18.7	10.3	110	0.003	0.0009
7 × 10	WG	1900	22.2	9.1	120	0.020	0.0020
7 × 10	WG	2230	24.0	9.4	100	0.025	0.0014
6 × 12	WG	5200	23.5	4.5	110	0.012	0.0060
6 × 12	WG	4055	23.8	4.5	42	0.012	0.019¶
10 × 7	WGP	790	23.0	19.7	330	0.21	0.023
10 × 7	WGP	850	20.6	17.6	260	0.24	0.025
7 × 10	WGP	1820	25.1	10.7	140	0.13	0.012
7 × 10	WGP	1985	24.9	11.9	180	0.13	0.012
6 × 12	WGP	5810	26.4	4.8	110	0.27	0.020
6 × 12	WGP	11080	27.0	2.9	60	0.24	0.020
Small cribs‖ $b = 0.64$ cm							
14 × 5	W	100	0.166	1.10	15	0.0030	0.0013
14 × 5	W	105	0.166	1.09	15	0.0020	0.0013
14 × 5	W	85	0.166	1.10	16	0.0030	0.0026
10 × 7	W	155	0.117	0.49	9.1		0.0058
10 × 7	W	155	0.151	0.68	8.6	0.0020	0.0009
10 × 7	W	165	0.152	0.62	9.0	0.0030	0.0041
7 × 10	W	250	0.103	0.23	3.7	0.0050	0.0022
7 × 10	W	460	0.166	0.20	3.3	0.0050	0.0045
14 × 5	WG	90	0.135	0.85	10	0.0020	0.0016
14 × 5	WG	100	0.127	0.76	8.4	0.0010	0.0055
10 × 7	WG	230	0.135	0.34	3.9	0.21	0.047
10 × 7	WG	160	0.135	0.47	6.0	0.058	0.0092
14 × 5	WGP	100	0.144	0.72	8.2	0.074	0.026
14 × 5	WGP	100	0.132	0.81	10	0.047	0.0097
10 × 7	WGP	220	0.148	0.37	4.1	0.28	0.057
10 × 7	WGP	220	0.143	0.36	4.5	0.36	0.036

* T_{50} = time over most rapid 50% of burning.
† Mass loss rate averaged over most rapid 50% of burning.
‡ Heat release rate peak over most rapid 50% of burning.
§ W = all wood, WG = wood and gypsum, WGP = wood, gypsum and plastic.
‖ $b \times N \times n$, where b = stick thickness, N = number of layers, and n = sticks per layer.
¶ Glass filter support plate shattered, glass shards on filter.

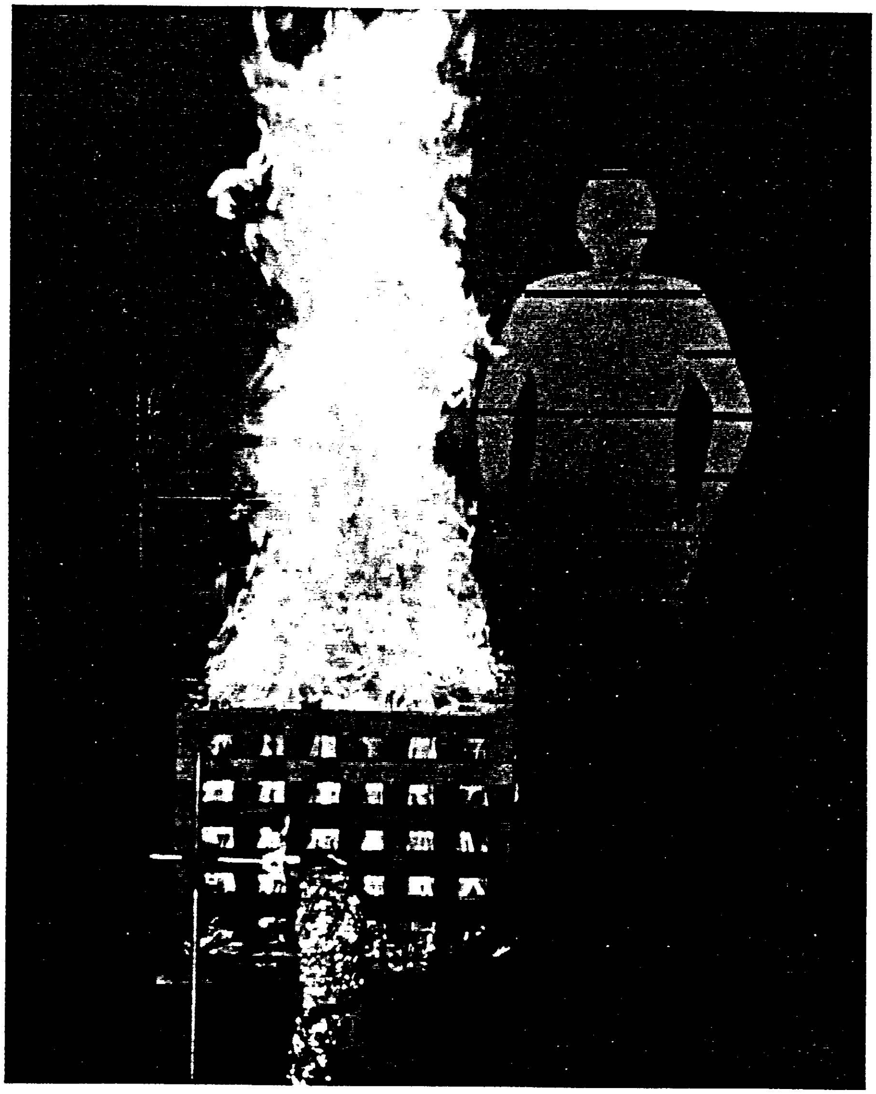

Fig. 2a. Free-burning of high porosity crib.

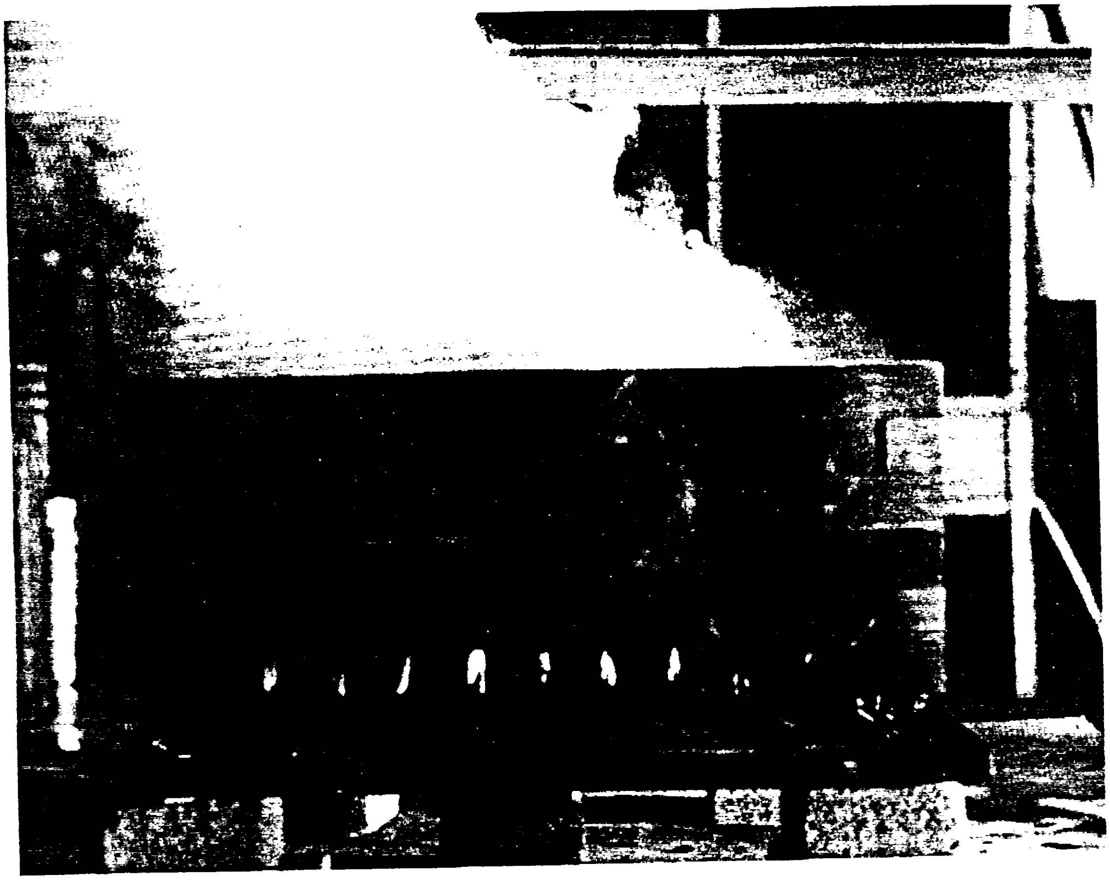

Fig. 2b. Ventilation controlled burning with internal flamelets of low porosity crib.

plotted in Fig. 5. The peak mass loss is determined based on 50% of the mass loss during the most rapid burning. It is seen in Fig. 5 that the ventilation limited burning regime corresponds to the ventilation parameter ψ less than 0.1 cm and that the free combustion regime, for which the reduced burning rate is independent of ψ, corresponds to ψ greater than 0.1 cm. The small scale data all fall within the ventilation limited regime and over this range of ψ both the large and small scale data for the reduced burning rate are well correlated with the ventilation parameter for each fuel array. The most significant effect of the fuel composition is the lower specific burning rate for the wood and gypsum cribs. For the large and small cribs, there is better correlation for reduced mass loss rates than for smoke yield or average extinction area.

The period of peak mass loss rate of fuel is also the period of peak heat release rate and peak smoke emission in the high ventilation limit. However, at low ventilation the specific extinction area of the smoke is greatest before the peak mass loss rate as illustrated in Fig. 6. The peak in the specific extinction area occurs as a result of very intense white smoke produced by small flames within the crib. Based on sampling with a filter at ambient temperature, we estimate that as much as half of this white smoke evaporates from the heated filter. Later in the burn the flames envelop the crib, the pyrolysis products (white smoke) are being burned out, and the smoke becomes darker because of the high sooting tendency of the ABS during flaming combustion.

The dependence of smoke yield, ε, and specific extinction area, σ_f, on the ventilation parameter ψ is shown in Figs 7 and 8 for the three different fuel mixtures. The smoke yield based on filter collection for the ABS containing cribs is about 0.02, independent of the ventilation rate. On the other hand, for the cribs without ABS the smoke yield and the specific

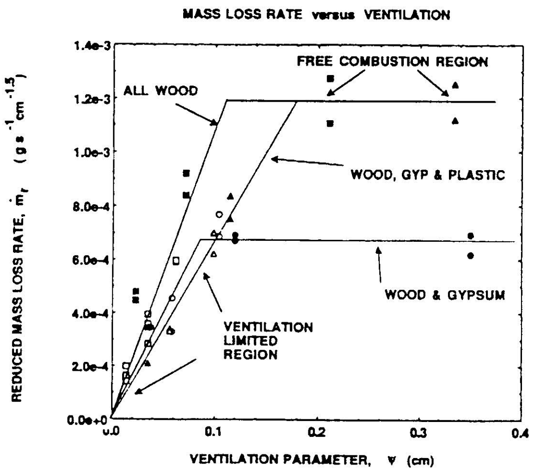

Fig. 5. The effect of ventilation on the reduced mass loss rate for large all wood cribs (■), small all wood cribs (□), large wood and gypsum cribs (●), small wood and gypsum cribs (○), large wood, gypsum and plastic cribs (▲), small wood, gypsum and plastic cribs (△).

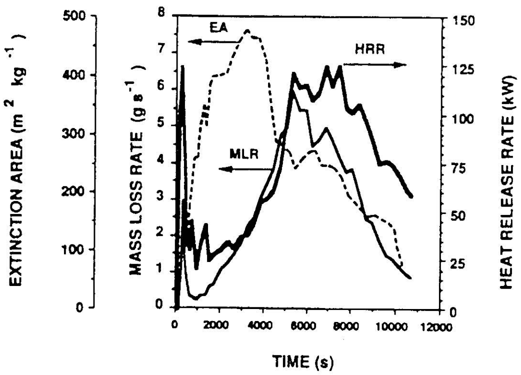

Fig. 6. Extinction area, mass loss rate, and heat release rate as a function of time for a large ($b = 3.81$ cm) 6 × 12 wood, gypsum and plastic crib.

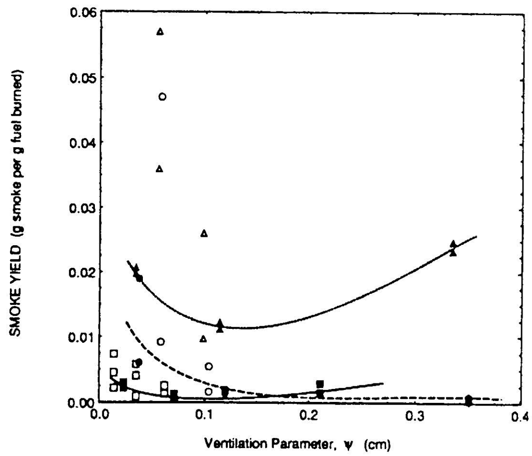

Fig. 7. The effect of ventilation on the smoke yield for large all wood cribs (■), small all wood cribs (□), large wood and gypsum cribs (●), small wood and gypsum cribs (○), large wood, gypsum and plastic cribs (▲), small wood, gypsum and plastic cribs (△).

extinction area increase about a factor of five as the ventilation is decreased about a factor of 10 from 0.3 to 0.03 cm. The maximum value of σ_f is 0.25 m^2 g^{-1} for the ABS containing crib, about 0.125 m^2 g^{-1} for the wood and gypsum crib, and about 0.080 m^2 g^{-1} for the all wood cribs. The large scale tests have better precision because of the larger sample collected on the filter and because of the five times longer path length for the extinction measurement. The curves in Figs 7 and 8 are drawn through the large scale data points. There is a discrepancy in the specific extinction area results between the small and large scale results. This may be a real scale effect or it could be caused by a lack of measurement sensitivity in the small scale experiment.

DISCUSSION

Effects of fuel composition and ventilation on smoke yield

While the effects of fuel additives upon soot formation in a flame (Gill and Olson, 1984; Hamins and

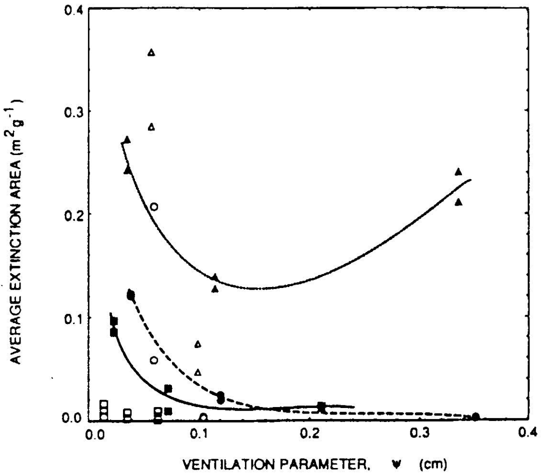

Fig. 8. The effect of ventilation on the average extinction area for large all wood cribs (■), small all wood cribs (□), large wood and gypsum cribs (●), small wood and gypsum cribs (○), large wood, gypsum and plastic cribs (▲), small wood, gypsum and plastic cribs (△).

Miller, 1991) is an active area of research, there is not a general theory for predicting smoke emission for fuel mixtures. Lacking this capability, we use the simple approach of estimating the smoke yield for the fuel mixture as the mass weighted average of the values for the individual fuels. This is equivalent to treating the fire as two independent burns. The validity of this method can be tested for the high ventilation wood, gypsum, and ABS crib, since there are cone calorimeter data for the individual fuel components as free burning fuels (ε equals 0.004 for wood and 0.053 for ABS and σ_f equals 0.040 $m^2 g^{-1}$ for wood and 1.12 $m^2 g^{-1}$ for the ABS with 50 $kW m^{-2}$ radiant exposure on the sample). The mass weighted estimate of the overall yield is 0.011 compared to the large crib result of 0.025, and the mass weighted estimate of the specific extinction area is 0.19 $m^2 g^{-1}$ compared to the large crib result of 0.23 $m^2 g^{-1}$. The experimental results lie closer to the mass weighted estimates than to the values of either pure fuel.

As the ventilation rate decreases, there is no longer adequate oxygen for complete combustion within the crib. Using Block's thoery (1971), we estimate that the amount of fuel pyrolyzed in the crib with 12 sticks per layer is a factor of 6 greater than the amount needed for stoichiometric combustion of the air entering the crib. Fuel rich combustion is ideal for high soot formation. The quantities ε and σ_f increase by about a factor of 5 as the ventilation rate is decreased for the all wood and the wood and gypsum cribs; however, the character of the smoke changes. The smoke produced during free burning is primarily soot (graphitic carbon), while the smoke produced during reduced ventilation is whitish indicating a high fraction of condensed pyrolysis products. As indicated in Fig. 2b, small flamelets appear low in the crib. The heating of the wood surface produces the pyrolysis products, but the heat loss caused by the pyrolysis apparently reduces the flame temperature to the point where the pyrolysis products are not converted to soot.

The way in which the ventilation is limited has a large effect on the type of smoke produced. Dod *et al.* (1989) reported a tenfold increase in smoke yield from burning wood cribs as the ventilation was reduced. The cribs used by Dod *et al.* had high porosity and burned freely in the open. The reduced ventilation in that case resulted from burning three wood cribs in an enclosed room with a single window. The inflow of air was not adequate for burning all the pyrolysis products, and some of the pyrolysis products were converted to soot in the fuel rich portion of the flame. In that case, the flame was primarily above the crib so its temperature was not as much affected by heat loss to the crib as in the case of the small, internal flamelets described above. In the study by Dod *et al.*, the smoke was primarily soot (graphitic carbon) both in the free burn configuration, which involved the burning of three cribs under a canopy hood, as well as in the ventilation limited case.

COMPARISON WITH PREVIOUS SMOKE TERM ESTIMATES

A convenient measure of the combined effects of the amount of smoke produced and its optical properties is the average optical depth that would result if the smoke were distributed over half the Northern Hemisphere (Penner, 1986). The extinction optical depth τ_e is defined by

$$\tau_e = (k_a + k_s)\, \varepsilon F (1 - f_r)/A, \qquad (5)$$

where k_s and k_a are the scattering and absorption cross-sections of the smoke (in $m^2 g^{-1}$), F is the amount of fuel burned, f_r is the fraction of smoke promptly removed by precipitation, and A is the area blocked by the smoke cloud (taken as half the area in the Northern Hemisphere or 1.28×10^{14} m^2). In Table 2, estimates of extinction optical depth, τ_e, and the absorption optical depth, τ_a, are given for urban wood smoke. The values of F and f_r are fixed in this comparison. The values of τ_e in parentheses are computed based on the measured values of σ_f, which is given by

$$\sigma_f = (k_a + k_s) \cdot \varepsilon. \qquad (6)$$

Table 2 includes the cases of free burning wood, a mixture of 75% free burning and 25% ventilation limited as a result of structural collapse, and a mixture of 70% free burning, 15% ventilation limited by collapse (white smoke), and 15% ventilation limited as fire spreads through an intact structure (black smoke). The choice of 70–75% free burning is based on expected ignition of at least as large an area with window breakage and slight damage (0.5–3.0 psi overpressure, Glasstone and Dolan, 1977) compared to the

Table 2. Comparison of average optical depths for urban wood smoke: previous study and crib fire estimates*

Reference	k_a ($m^2 g^{-1}$)	k_e ($m^2 g^{-1}$)	ε (g^{-1})	τ_a	τ_e
High†	3.3	6.8	0.03	1.6	3.3
Low	1.3	4.0	0.015	0.3	1.0
Crib burns					
Free burn	7.0‡	10.5‡	0.002	0.2	0.3 (0.2)††
Vent. limited§	1.3	4.0	0.02	0.4	1.3 (1.5)‡‡
Vent. limited‖	7.0	10.5	0.02	2.3	3.4
75%–25%¶				0.3	0.6 (0.5)
70%–15%–15%**				0.6	0.9 (0.9)

* All estimates for computing τ using Equation (5) are based on $F = 4130$ Tg and the scavenging fraction, $f_r = 0.5$.

† The high/low estimates for k_a, k_e, and ε are from Penner (1986).

‡ Crutzen *et al.* (1984), value for elemental carbon.

§ Ventilation limited by high packing density of crib.

‖ Ventilation limited by window.

¶ 75% free burn and 25% ventilation limited by crib.

** 70% free burn, 15% ventilation limited by crib, and 15% ventilation limited by window.

†† τ_e calculated using the measured extinction area of 0.013 for the large 10 × 7 all wood crib burns.

‡‡ τ_e calculated using the measured extinction area of 0.090 for the large 6 × 12 all wood crib burns.

area ignited with localized structural collapse (3.0–15 psi overpressure). As can be seen from Table 2, these estimates for τ_e range from 0.2 to 0.9, which are comparable to or less than the low value of 1.0, based on Penner's (1986) lower estimates for k_e and ε. The primary reason for the lower values of τ in our estimates compared to the high value from previous studies is the low value of the smoke yield during free burning (ε equal about 0.002) obtained in this study as well as obtained by Mulholland *et al.* (1989) and by Dod *et al.* (1989). Small's inventory (1989) for urban wood in the U.S. indicates that the estimate for F used in Table 2 may be a factor of 3 or more high. Reducing F by a factor of 3 would reduce all the estimated optical depths in Table 2 by a factor of 3.

While the crib burns provide the best quantitative information on smoke from urban structures, they still fall short in regard to the scale effect. That is, we cannot rule out the possibility that at the scale of an actual house for even a free burn the smoke emission could increase perhaps as a result of thermal radiation trapping by the hot smoke leading to an increased flame temperature. Also the nature of the smoke produced under ventilation limited conditions is dependent on the details of the fuel configuration in regard to heat loss and on how much of the smoke is burned out as it leaves the structure.

CONCLUSIONS

Crib structures have been shown to provide a useful framework for estimating the effects of ventilation, fuel composition, and scale on smoke emission and optical properties. A new type of ventilation limited burning involving the production of white rather than black smoke was observed. This study found that a small amount of plastic (10% mass basis) dominated the smoke emission. Based on our measurements of smoke yield and specific extinction area, we estimate an average optical depth for wood smoke to be in the low range of Penner's estimate (1986). We found that mass weighting the smoke yields of individual components of a mixture provides a reasonable first order estimate of the measured smoke yield of the mixture.

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APPENDIX A

Each stick was cut or machined to a square cross-section and to a length, L, equal to 14.67 times the width, b. The large cribs utilized 3.81 × 3.81 × 55.88 cm sticks and the small cribs used 0.64 × 0.64 × 9.4 cm sticks. The wood sticks were sawed from kiln-dried, grade D, Douglas fir 2 × 8 ins, 2 × 10 ins and 2 × 12 ins. Rounded corners, wany surfaces, painted ends or large knots (> 1 cm diam.) caused a stick to be discarded. For the large cribs, gypsum was cut from 20 pieces of 1.27 × 122 × 244 cm gypsum drywall. This necessitated stacking three pieces of 1.27 × 3.81 cm gypsum to form the square 3.81 × 3.81 cm inert stick. For the wood and inert and the wood, inert and plastic cribs, each layer of sticks began and ended with a wood stick, generally with gypsum sticks alternating with wood sticks. To account for the large fraction of the petroleum derived fuels in the form of asphaltic shingles, two of the four ABS sticks were positioned on the top layer. For the small cribs, all the inert sticks were cut from a single piece of 0.64 × 122 × 244 cm drywall and stacking was not necessary. The plastic sticks were cut from 3.81 cm thick ABS and 0.64 cm thick ABS for the large and small cribs. The large cribs were assembled using 12 penny common bright nails, while the small cribs were held together with straight pins. While the number of nails in each large cribs was almost identical from crib to crib, the number of pins in each cribs was less uniform and probably contributed to the variability of the mass of the small crib. Each 14 × 5, 10 × 7, and 7 × 10 wood and gypsum crib contained 70 sticks, 42 wood, and 28 gypsum. Each 6 × 12 wood and gypsum crib contained 72 sticks, 43 wood, and 29 gypsum. Each 14 × 5, 10 × 7, and 7 × 10 wood, gypsum and plastic crib contained 70 sticks, 40 wood, 26 gypsum, and 4 ABS. Each 6 × 12 wood, gypsum and plastic crib contained 72 sticks, 41 wood, 26 gypsum, and 5 ABS.