SMOKE EMISSION AND BURNING RATES FOR URBAN STRUCTURES*

NELSON P. BRYNER and GEORGE W. MULHOLLAND
National Institute of Standards and Technology (Formerly National Bureau of Standards), Gaithersburg, MD 20899, U.S.A.

(First received 3 November 1989 and in final form 29 June 1990)

Abstract—Crib, 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 extends 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.

* Contribution of National Institute of Standards and Technology not subject to copyright in the U.S.
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 (CaSO₄·2H₂O) 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 \( 3.81 \times 3.81 \) 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 × 61 × 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

![Diagram of the test facility](image_url)

Fig. 1. Large scale burn facility and 3.81 × 10 × 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 \( \varepsilon \) was obtained from measurements of the smoke collected on the filter, \( m_s \); the mass loss of the sample, \( m_i \); and from the ratio of the mass flow of air through the exhaust duct to the mass flow through the filter sampler, \( \phi \), using the formula

\[
\varepsilon = \frac{m_s}{m_i} \phi.
\]

(1)

The specific extinction area, \( \sigma_i \), 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

\[
\sigma_i = -\ln\left(\frac{I}{I_0}\right) \frac{\dot{V}}{(L \dot{m}_f)}.
\]

(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 for 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\(_4\cdot2\)H\(_2\)O) 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

\[
\dot{m}_r = \frac{\dot{m}_{\text{peak}}}{(A_r \cdot b^{0.5})}
\]

where \( \dot{m}_{\text{peak}} \) is the peak mass loss rate, \( A_r \) 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 \( \psi \), which differs just slightly from the parameter used by Gross (by \( b^{0.1} \)), is defined by

\[
\psi = (bh)^{0.5} \frac{A_r}{A_s}
\]

where \( h \) is the height of the crib and \( A_s \) 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>
<thead>
<tr>
<th>Crib configuration</th>
<th>Crib material</th>
<th>Burn time ( T_{50} ) (s)</th>
<th>Mass loss total (kg)</th>
<th>Mass loss rate average ( \dot{m}_{\text{avg}} ) (g s(^{-1}))</th>
<th>Pk. heat release rate average ( T_{30} ) (kW)</th>
<th>Extinction area avg. (m(^2) g(^{-1}))</th>
<th>Smoke yield (g smoke per g fuel burned)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Large cribs</strong></td>
<td>( b \approx 3.81 ) cm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10 \times 7</td>
<td>W</td>
<td>630</td>
<td>26.1</td>
<td>27.7</td>
<td>300</td>
<td>0.012</td>
<td>0.0029</td>
</tr>
<tr>
<td>10 \times 7</td>
<td>W</td>
<td>570</td>
<td>25.8</td>
<td>31.9</td>
<td>410</td>
<td>0.014</td>
<td>0.0016</td>
</tr>
<tr>
<td>7 \times 10</td>
<td>W</td>
<td>1100</td>
<td>29.7</td>
<td>20.8</td>
<td>260</td>
<td>0.031</td>
<td>0.0012</td>
</tr>
<tr>
<td>7 \times 10</td>
<td>W</td>
<td>1190</td>
<td>27.9</td>
<td>19.0</td>
<td>200</td>
<td>0.009</td>
<td>0.0006</td>
</tr>
<tr>
<td>6 \times 12</td>
<td>W</td>
<td>3095</td>
<td>30.6</td>
<td>9.7</td>
<td>120</td>
<td>0.085</td>
<td>0.0027</td>
</tr>
<tr>
<td>6 \times 12</td>
<td>W</td>
<td>2700</td>
<td>31.1</td>
<td>10.4</td>
<td>170</td>
<td>0.096</td>
<td>0.0026</td>
</tr>
<tr>
<td>10 \times 7</td>
<td>WG</td>
<td>1380</td>
<td>18.8</td>
<td>9.3</td>
<td>110</td>
<td>0.003</td>
<td>0.0009</td>
</tr>
<tr>
<td>7 \times 10</td>
<td>WG</td>
<td>1420</td>
<td>18.7</td>
<td>10.3</td>
<td>110</td>
<td>0.003</td>
<td>0.0009</td>
</tr>
<tr>
<td>7 \times 10</td>
<td>WG</td>
<td>1900</td>
<td>22.2</td>
<td>9.1</td>
<td>120</td>
<td>0.020</td>
<td>0.0020</td>
</tr>
<tr>
<td>7 \times 10</td>
<td>WG</td>
<td>2230</td>
<td>24.0</td>
<td>9.4</td>
<td>100</td>
<td>0.025</td>
<td>0.0014</td>
</tr>
<tr>
<td>6 \times 12</td>
<td>WG</td>
<td>5200</td>
<td>23.5</td>
<td>4.5</td>
<td>110</td>
<td>0.012</td>
<td>0.0060</td>
</tr>
<tr>
<td>6 \times 12</td>
<td>WG</td>
<td>4055</td>
<td>23.8</td>
<td>4.5</td>
<td>42</td>
<td>0.012</td>
<td>0.0199</td>
</tr>
<tr>
<td>10 \times 7</td>
<td>WGP</td>
<td>790</td>
<td>23.0</td>
<td>19.7</td>
<td>330</td>
<td>0.21</td>
<td>0.023</td>
</tr>
<tr>
<td>10 \times 7</td>
<td>WGP</td>
<td>850</td>
<td>20.6</td>
<td>17.6</td>
<td>260</td>
<td>0.24</td>
<td>0.025</td>
</tr>
<tr>
<td>7 \times 10</td>
<td>WGP</td>
<td>1820</td>
<td>25.1</td>
<td>10.7</td>
<td>140</td>
<td>0.13</td>
<td>0.012</td>
</tr>
<tr>
<td>7 \times 10</td>
<td>WGP</td>
<td>1985</td>
<td>24.9</td>
<td>11.9</td>
<td>180</td>
<td>0.13</td>
<td>0.012</td>
</tr>
<tr>
<td>6 \times 12</td>
<td>WGP</td>
<td>3810</td>
<td>26.4</td>
<td>4.8</td>
<td>110</td>
<td>0.27</td>
<td>0.020</td>
</tr>
<tr>
<td>6 \times 12</td>
<td>WGP</td>
<td>11080</td>
<td>27.0</td>
<td>2.9</td>
<td>60</td>
<td>0.24</td>
<td>0.020</td>
</tr>
<tr>
<td><strong>Small cribs</strong></td>
<td>( b \approx 0.64 ) cm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14 \times 5</td>
<td>W</td>
<td>100</td>
<td>0.166</td>
<td>1.10</td>
<td>15</td>
<td>0.0030</td>
<td>0.0013</td>
</tr>
<tr>
<td>14 \times 5</td>
<td>W</td>
<td>105</td>
<td>0.166</td>
<td>1.09</td>
<td>15</td>
<td>0.0020</td>
<td>0.0013</td>
</tr>
<tr>
<td>14 \times 5</td>
<td>W</td>
<td>85</td>
<td>0.166</td>
<td>1.10</td>
<td>16</td>
<td>0.0030</td>
<td>0.0026</td>
</tr>
<tr>
<td>10 \times 7</td>
<td>W</td>
<td>155</td>
<td>0.117</td>
<td>0.49</td>
<td>9.1</td>
<td>0.0058</td>
<td></td>
</tr>
<tr>
<td>10 \times 7</td>
<td>W</td>
<td>155</td>
<td>0.151</td>
<td>0.68</td>
<td>8.6</td>
<td>0.0020</td>
<td>0.0009</td>
</tr>
<tr>
<td>10 \times 7</td>
<td>W</td>
<td>165</td>
<td>0.152</td>
<td>0.62</td>
<td>9.0</td>
<td>0.0030</td>
<td>0.0041</td>
</tr>
<tr>
<td>7 \times 10</td>
<td>W</td>
<td>250</td>
<td>0.103</td>
<td>0.23</td>
<td>3.7</td>
<td>0.0050</td>
<td>0.0022</td>
</tr>
<tr>
<td>7 \times 10</td>
<td>W</td>
<td>460</td>
<td>0.166</td>
<td>0.20</td>
<td>3.3</td>
<td>0.0050</td>
<td>0.0045</td>
</tr>
<tr>
<td>14 \times 5</td>
<td>WG</td>
<td>90</td>
<td>0.125</td>
<td>0.85</td>
<td>10</td>
<td>0.0020</td>
<td>0.0016</td>
</tr>
<tr>
<td>14 \times 5</td>
<td>WG</td>
<td>100</td>
<td>0.127</td>
<td>0.76</td>
<td>8.4</td>
<td>0.0010</td>
<td>0.0055</td>
</tr>
<tr>
<td>10 \times 7</td>
<td>WGP</td>
<td>230</td>
<td>0.135</td>
<td>0.34</td>
<td>3.9</td>
<td>0.21</td>
<td>0.047</td>
</tr>
<tr>
<td>10 \times 7</td>
<td>WGP</td>
<td>160</td>
<td>0.135</td>
<td>0.47</td>
<td>6.0</td>
<td>0.058</td>
<td>0.0092</td>
</tr>
<tr>
<td>14 \times 5</td>
<td>WGP</td>
<td>100</td>
<td>0.144</td>
<td>0.72</td>
<td>8.2</td>
<td>0.074</td>
<td>0.026</td>
</tr>
<tr>
<td>14 \times 5</td>
<td>WGP</td>
<td>100</td>
<td>0.132</td>
<td>0.81</td>
<td>10</td>
<td>0.047</td>
<td>0.0097</td>
</tr>
<tr>
<td>10 \times 7</td>
<td>WGP</td>
<td>220</td>
<td>0.148</td>
<td>0.37</td>
<td>4.1</td>
<td>0.28</td>
<td>0.057</td>
</tr>
<tr>
<td>10 \times 7</td>
<td>WGP</td>
<td>220</td>
<td>0.143</td>
<td>0.36</td>
<td>4.5</td>
<td>0.36</td>
<td>0.036</td>
</tr>
</tbody>
</table>

* \( T_{50} \): 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_t, 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 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_t is 0.25 m² g⁻¹ for the ABS containing crib, about 0.125 m² g⁻¹ for the wood and gypsum crib, and about 0.080 m² 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...
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 calorim-
eter data for the individual fuel components as free
burning fuels (ε equals 0.004 for wood and 0.053 for
ABS and σε equals 0.040 m² g⁻¹ for wood and
1.12 m² 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 m² g⁻¹ compared to the
large crib result of 0.23 m² 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 theory (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 σε 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 ventila-
tion 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 pro-
ducts, and some of the pyrolysis products were conver-
ted 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 Hemi-
sphere (Penner, 1986). The extinction optical depth τs
is defined by

\[
τ_s = (k_s + k_a) ε F (1 - f_s) / A,
\]

(5)

where \(k_s\) and \(k_a\) are the scattering and absorption
cross-sections of the smoke (in m² g⁻¹), \(F\) is the
amount of fuel burned, \(f_s\) 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 × 10¹⁴ m²). In
Table 2, estimates of extinction optical depth, \(τ_s\),
and the absorption optical depth, \(τ_a\), are given for urban
wood smoke. The values of \(F\) and \(f_s\) are fixed in this
comparison. The values of \(τ_s\), in parentheses are com-
pared based on the measured values of \(σ_s\), which is
given by

\[
σ_s = (k_s + k_a) ε.
\]

(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 over-
pressure, Glassstone and Dolan, 1977) compared to the
Smoke emission and burning rates

<table>
<thead>
<tr>
<th>Reference</th>
<th>$k_1$ (m² g⁻¹)</th>
<th>$k_2$ (m³ g⁻¹)</th>
<th>$ε$ (g⁻¹)</th>
<th>$τ_a$</th>
<th>$τ_s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>High†</td>
<td>3.3</td>
<td>6.8</td>
<td>0.03</td>
<td>1.6</td>
<td>3.3</td>
</tr>
<tr>
<td>Low</td>
<td>1.3</td>
<td>4.0</td>
<td>0.015</td>
<td>0.3</td>
<td>1.0</td>
</tr>
<tr>
<td>Crib burns</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Free burn</td>
<td>7.0*</td>
<td>10.5*</td>
<td>0.002</td>
<td>0.2</td>
<td>0.3 (0.2)††</td>
</tr>
<tr>
<td>Vent. limited§</td>
<td>1.3</td>
<td>4.0</td>
<td>0.02</td>
<td>0.4</td>
<td>1.3 (1.5)‡‡</td>
</tr>
<tr>
<td>Vent. limited‖</td>
<td>7.0</td>
<td>10.5</td>
<td>0.02</td>
<td>2.3</td>
<td>3.4</td>
</tr>
<tr>
<td>75%–25%§§</td>
<td>0.3</td>
<td>0.6 (0.5)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>70%–15%–15%**</td>
<td>0.6</td>
<td>0.9 (0.9)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* All estimates for computing $τ$ using Equation (5) are based on $F = 4130$ Tg and the scavenging fraction, $f_s = 0.5$.
† The high/low estimates for $k_1$, $k_2$, 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.
†† $τ_a$ calculated using the measured extinction area of 0.013 for the large 10 × 7 all wood crib burns.
‡‡ $τ_a$ 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 $τ_s$ 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 $k_1$ 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.

Acknowledgements—This work was funded by a grant from the Defense Nuclear Agency and monitored by Dr Mark Flohr and Maj. Richard Hartley. Essential support in assembling the cribs, maintaining the burn facilities, and collecting the data was provided by R. Zile, R. McLane, G. Roadarmel, J. Shields and C. Brooks.

REFERENCES

Babrauskas V. (1982) Development of the cone calorimeter—a bench scale heat release apparatus based on oxygen consumption, NBSIR 82-2611, National Institute of Standards and Technology (formerly the National Bureau of Standards) available as NBSIR 82-2611 from NTIS, Springfield, VA.


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 \( 3.81 \times 3.81 \times 55.88 \) cm sticks and the small cribs used \( 0.64 \times 0.64 \times 9.4 \) cm sticks. The wood sticks were sawed from kiln-dried, grade D, Douglas fir 2 x 8 ins, 2 x 10 ins and 2 x 12 ins. Rounded corners, wavy 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 \( 1.27 \times 122 \times 244 \) cm gypsum drywall. This necessitated stacking three pieces of \( 1.27 \times 3.81 \) cm gypsum to form the square \( 3.81 \times 3.81 \) 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 \( 0.64 \times 122 \times 244 \) 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 \( 14 \times 5, 10 \times 7, \) and \( 7 \times 10 \) wood and gypsum crib contained 70 sticks, 42 wood, and 28 gypsum. Each \( 6 \times 12 \) wood and gypsum crib contained 72 sticks, 43 wood, and 29 gypsum. Each \( 14 \times 5, 10 \times 7, \) and \( 7 \times 10 \) wood, gypsum and plastic crib contained 70 sticks, 40 wood, 26 gypsum, and 4 ABS. Each \( 6 \times 12 \) wood, gypsum and plastic crib contained 72 sticks, 41 wood, 26 gypsum, and 5 ABS.