Journal of the Air Pollution Control Association

ISSN: 0002-2470 (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/uawm16

# A Study of Wood Stove Particulate Emissions

Samuel S. Butcher & Edmund M. Sorenson

**To cite this article:** Samuel S. Butcher & Edmund M. Sorenson (1979) A Study of Wood Stove Particulate Emissions, Journal of the Air Pollution Control Association, 29:7, 724-728, DOI: 10.1080/00022470.1979.10470854

**To link to this article:** https://doi.org/10.1080/00022470.1979.10470854

Published online: 13 Mar 2012.

# A Study of Wood Stove Particulate Emissions

**Samuel S. Butcher and Edmund M. Sorenson**
Bowdoin College
Brunswick, Maine

**Particulate emission factors for two wood stove models have been determined for two types of fuel and a range of operating conditions. The emission factors range from 1 g/kg (fuel) to 24 g/kg. A model is presented which represents the emission factor as a simple function of the ratio of fuel load to combustion rate, or the length of time between refueling. This model is felt to be appropriate for evaluating the impact of wood-based residential space heating on ambient air concentrations of particulate matter if certain assumptions can be made about stove operating conditions. An application of the emission factor model to a typical community suggests that the contribution of wood stoves to ambient particulate levels might reach 100 $\mu g/m^3$ if the entire heating load were carried by wood.**

***Preliminary analyses of the particulate matter indicate that benzene* extractables range from 42% of the total particulate mass at short refuel times to 67% at longer refuel times. About 45% of the mass of benzene extractables appeared in the neutral fraction of acid base extractions. Polycyclic aromatic hydrocarbons are expected to be included in this neutral fraction.**

Recent surveys have shown that substantial amounts of indigenous fuel wood are being used to supplement conventional energy sources (oil or electricity) for residential space heating in northern New England. These surveys indicate that 11, 28, and 37 million Btu equivalents of wood per residence were used in the winters of 1975–76,[1] 1976–77,[2] and 1977–78,[3,4] respectively. The Btu equivalent of fuel oil required to maintain the entire heating load for this area is about 170 million Btu per residence year.[1,5] These surveys also point out that the most common wood heating unit is a small stove, rather than a fireplace or a wood-fired furnace. Although small stoves differ considerably in size (less than 20,000 to more than 100,000 Btu/hr), and design of the combustion chamber (baffled or not, firebrick lined or not, single or multiple drafts, etc.), most of them have a passive draft system. The combustion air intake in these stoves is driven solely by the buoyancy of the hot flue gases and the rate of combustion is generally controlled by limiting the air supply. This method of controlling the combustion rate may lead to incomplete combustion at low firing rates as a result of inadequate air or temperatures which are too low.

Our preliminary study[6] showed that particulate emission factors increased as draft settings were reduced. These studies have been extended with further measurements and a simple model is proposed to represent the emission factor for particulate matter as a function of stove operating parameters. The results of preliminary chemical analyses of the particulate matter are also included.

**Figure 1.** The Jotul Model 602 wood stove.

## Experimental Methods

A Jotul #602 stove and a Riteway #2000 stove* were used in these studies, see Figures 1 and 2. The sampling method used in this work is a slight modification of that used in our earlier work.[6] The flue system consisted of about 3 meters of 15 cm diameter steel stovepipe connected to a tile-lined chimney with an inside dimension 20 × 20 cm and a length above the stovepipe of about 2.5 m. No flue damper was used.

* *Mention of a trade name should not imply a recommendation by the authors or the organizations with which they are associated.*

The sampling method consisted of collecting all stack emissions for measured time intervals with a high volume sampler. The smoke from the chimney was drawn through a 1 m section of 15 cm stovepipe to the high volume sampler. The collecting section of stovepipe was supported just above the chimney and no effect of the sampling system on the combustion rate could be observed. The flow rate of air through the sampler started out at about 110 $ft^3$/min for each sampler run and decreased as the filter became loaded with particulate matter. The flow rate remained above 90 $ft^3$/min for most filter samples and very seldom dropped as low as 70 $ft^3$/min. The flow rate of gas through the chimney at a fuel combustion rate of 3.4 kg/hr and 50% excess air is about 13 $ft^3$/min, substantially less than the high volume sampler flow rate.

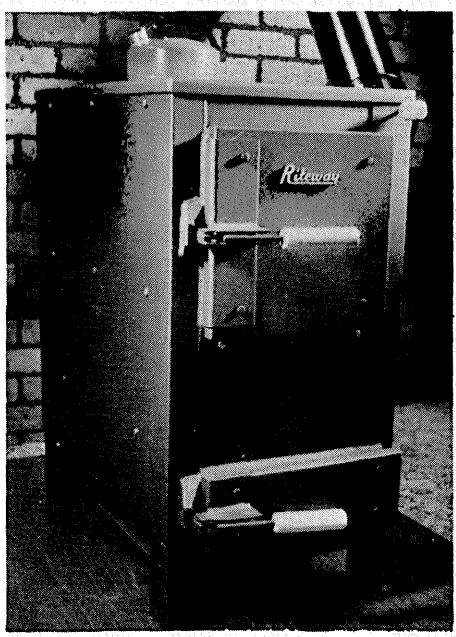


**Figure 2.** The Riteway Model 2000 wood stove.

The temperature of the flue gas at the point of sampling was not monitored. The temperature in the stovepipe near the masonry flue was recorded. This temperature reached 250°C in some of the burns at full draft, but was generally less than 120°C. The temperature at the top of the chimney was judged to have been less than 100°C for most runs and the dilution air in the collection system would have further reduced the flue gas temperature.

Each burn was conducted by adding a weighed charge of wood (as 3–5 pieces of wood) to a bed of live coals from a previous burn. The draft setting (or the thermostat control in the case of the Riteway #2000) remained constant throughout the burn with two exceptions: The door was opened briefly a few times during each burn to judge the amount of fuel remaining. The end of the burn was the point at which the amount of live coals remaining in the stove was judged to be similar to that at the start of the burn.

The particulate matter samples were collected on a series of 8 × 10 in. glass fiber filters. The sampling times for individual filters ranged from 30 seconds to 6 minutes with most of the sampling time falling in the 1–2 min range. Typically, 10 to 20 filters were used for each burn.

The filters were dried in a desiccator for 24 hr and reweighed. The emission rate was determined as the amount of particulate matter on a filter divided by the sampling interval for that filter. The dependence of emission rate on time during a typical burn is shown in Figure 3. The total amount of particulate matter emitted during the burn was determined by integrating the emission rate over the time of the burn by the

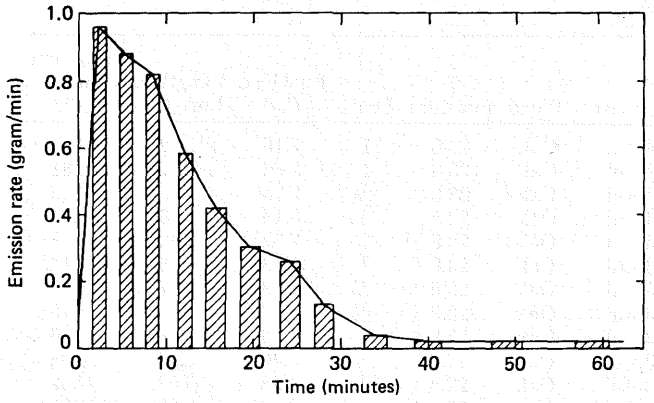


**Figure 3.** Emission during the combustion of 2.27 kg of oak.

trapezoidal method. The sources of error involved in the determination of the emission factors have been discussed in the preliminary study.[6] Errors in the measurement of particulate emissions amount to about 25% of the emission factor. The measurement of the length of the burn is uncertain by about 10 min; this affects the determination of the combustion rate more than the emission factor.

Eastern white pine and red oak were used in these experiments. The moisture content of the fuel was determined by drying at 105°C to constant weight (usually two days). It is reported here as the percentage of weight loss relative to the pre-dried weight.

Selected filters were extracted with 350 ml of benzene in a Soxhlet extractor for 24 hr. The solvent was then removed at 25°C with a rotary evaporator and the extracts evaporated to constant weight at room temperature. The filters were reweighed to determine the weight loss and in some cases the extract was weighed. The agreement between the weights obtained by the two methods was generally quite good for these purposes (10 to 15% difference at most). The change in filter weight is used for further calculations in this section. This is referred to as the benzene-extractable weight.

Selected benzene extracts were subjected to the following acid-base extraction scheme: 1) a bicarbonate extraction to remove carboxylic acids and compounds with similar acid-base properties; 2) a sodium hydroxide extraction to remove phenols and similar compounds; and 3) a hydrochloric acid extraction to remove organic bases. The residue from this series of extractions was termed the neutral fraction and would be expected to contain the aromatic hydrocarbons and other compounds lacking marked acidic or basic properties.

### A Particulate Emission Model

The results for 26 burns with oak and pine are collected in Table I. The draft setting for the Jotul stove is defined as the fraction of the distance between the fully closed and wide open position of the rotating sector draft control. The fuel load is the amount of wood added at the start of the burn. The emission factor is represented as the grams of particulate matter collected per kilogram of fuel. For those burns recorded as <1/4 draft, the draft was varied between 1/4 draft and 1/8 draft in order to maintain a stable fire.

It may be seen that there is considerable variation in the emission factor even in a series of burns which have the same draft setting and similar fuel loads. It seems likely that much of this variation results from differences in fuel geometry and whether or not ignition occurs quickly following addition of the fuel. It is also likely that the same variations occur in residential heating units.

A number of attempts have been made to relate the emission factor, E, to easily determined parameters which define the manner in which the stove is operated. The parameters chosen here are the initial fuel load, $m$ (wet weight in kg); and

**Table I.** Total particulate emission factors.

| Stove | Wood | % moisture | Draft | Fuel load (kg) | Length of burn (hr) | Emission factor (g/kg) |
|---|---|---|---|---|---|---|
| Jotul | Oak | 23.8 | 1 | 2.15 | 1.72 | 13.31 |
| Jotul | Oak | 23.8 | 1 | 2.66 | 0.67 | 2.31 |
| Jotul | Oak | 23.8 | 1/2 | 2.75 | 1.55 | 9.40 |
| Jotul | Oak | 23.8 | 1/2 | 3.18 | 1.56 | 5.21 |
| Jotul | Oak | 23.8 | 1/4 | 2.32 | 1.42 | 10.39 |
| Jotul | Oak | 23.8 | 1/4 | 2.69 | 1.23 | 10.14 |
| Jotul | Oak | 23.8 | 1/4 | 2.69 | 1.77 | 8.24 |
| Jotul | Oak | 23.8 | 1/4 | 2.27 | 1.05 | 6.75 |
| Jotul | Oak | 22.8 | 1/4 | 1.42 | 0.48 | 2.46 |
| Jotul | Oak | 22.8 | 1/4 | 3.40 | 1.38 | 3.36 |
| Jotul | Oak | 22.8 | 1/4 | 1.28 | 0.62 | 2.52 |
| Jotul | Oak | 19.8 | 1/4 | 0.49[a] | 0.26[a] | 1.82[a] |
| Jotul | Oak | 8.7 | 1/4 | 2.69 | 0.87 | 4.85 |
| Jotul | Oak | 8.7 | 1/4 | 1.22 | 0.65 | 4.90 |
| Jotul | Oak | 8.7 | 1/4 | 1.05 | 0.45 | 1.27 |
| Jotul | Oak | 8.7 | 1/4 | 2.72 | 1.10 | 10.87 |
| Jotul | Oak | 23.8 | <1/4 | 2.07 | 1.70 | 15.72 |
| Jotul | Oak | 23.8 | <1/4 | 2.01 | 1.95 | 24.35 |
| Jotul | Oak | 23.8 | <1/4 | 1.67 | 1.80 | 12.82 |
| Jotul | Pine | 42.4 | 1/4 | 2.04 | 0.98 | 10.37 |
| Jotul | Pine | 42.4 | 1/4 | 3.23 | 1.40 | 10.79 |
| Jotul | Pine | 42.4 | <1/4 | 1.67 | 1.33 | 18.52 |
| Jotul | Pine | 42.4 | <1/4 | 1.50 | 1.52 | 15.33 |
| Jotul | Pine | 42.4 | <1/4 | 1.39 | 0.73 | 9.60 |
| Riteway | Oak | 22.8 | [b] | 5.23 | 1.52 | 11.85 |
| Riteway | Pine | 42.4 | [c] | 4.10 | 1.20 | 13.26 |

[a] These figures are averages for a burn in which 3.94 kg of fuel, divided into eight portions, was burned in 2.05 hours.
[b] These figures are averages for a burn in which the thermostat setting remained fixed and 15.71 kg of fuel, in three portions, was burned in 4.58 hours.
[c] These figures are averages for a burn in which the thermostat setting remained fixed and 12.30 kg of fuel, in three portions, was burned in 3.59 hours.

the average combustion rate, $q$ (Btu/hr). The combustion rate is defined here as the heat of combustion of the load of fuel (the low value, corrected for moisture) divided by the length of the burn. The heat of combustion is taken to be $17{,}970 - 203 \times P$ in Btu/kg, where $P$ is the percentage moisture.

The simple relationship $E = A + B(m/q)$ accounts for much of the variation of the emission factor with fuel load and draft setting. The least square line for the data in Table I is shown in Figure 4. The points in this figure are coded so the relationships of oak to pine and Jotul to Riteway stove may be compared. The negative value for A should amplify the importance of not using this model outside the range represented by the data. In this regard it should be noted that the regression line was obtained by assigning unit weights to the points for the 0.49 kg load in the Jotul and the two burns for the Riteway stove even though these points represent averages for more than one charge of wood. In particular, increasing the weight of the 0.49 kg load point (which has the lowest value of $m/q$ in Figure 4) brings the value of $A$ closer to zero. It may be seen that the model represents fairly well the emission factor for oak and pine; dry and wet wood; Jotul and Riteway stove. The data from the preliminary study are also consistent with this model.

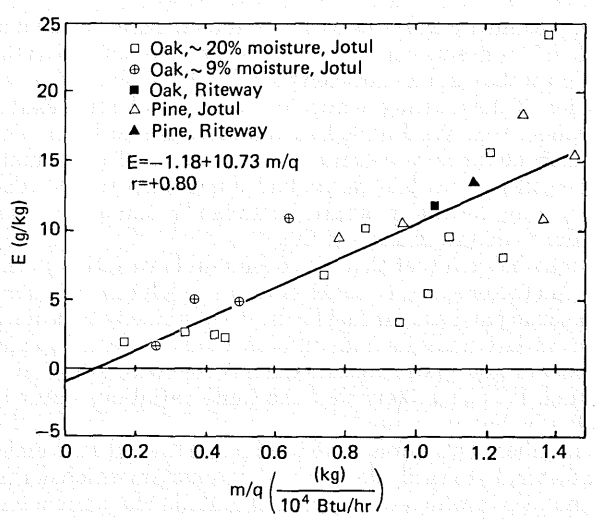


**Figure 4.** Emission factor as a function of $m/q$.

The variable $m/q$ was chosen as the independent variable in the regression analysis because it should be related to the inverse of the bulk fuel temperature. The emission factor was also regressed against several other functions of $m$ and $q$. These analyses yielded correlation coefficients similar to or less than the value obtained for the $m/q$ regression, +0.80. The regression of $E$ against $1/q$ gave a correlation coefficient of +0.78 when only the Jotul stove data were used but these results did not accommodate the data from the larger Riteway stove nearly as well as the $m/q$ regression. $m/q$ is directly related to the length of the burn, for a given fuel moisture content, and the uncertainty in this parameter is the same as the uncertainty in the length of the burn.

The data from this study and the earlier work were also segregated by fuel type (pine and oak) and treated by separate regression analyses. These gave the following results: $E(\text{pine}) = 4.18 + 6.88(m/q)$, $r = 0.53$ ($N = 17$); $E(\text{oak}) = -2.21 + 11.41(m/q)$, $r = 0.83$ ($N = 47$). The dimensions of $m$ and $q$ are the same here as in Figure 4: kg and $10^4$Btu/hr. The difference between oak and pine is not large and must be checked by further measurements.

**Table II.** Benzene-extractable particulate matter.

| Burn # | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| Fuel | Oak | Oak | Oak | Oak | Pine |
| % $H_2O$ | 23.8 | 23.8 | 8.7 | 23.8 | 42.4 |
| Draft | Full D | 1/2 D | 1/4 D | 1/4 D | 1/4 D |
| Fuel charge (kg) | 2.66 | 3.18 | 1.22 | 2.01 | 2.04 |
| Total particulate matter (g) | 6.16 | 16.5 | 5.97 | 49.0 | 21.2 |
| Benzene-extractable particulate matter (g) | 2.91 | 9.28 | 2.51 | 32.6 | 12.8 |

The data from this work and our earlier work indicates that the combustion of very dry wood at low draft settings occasionally leads to higher-than-expected emission factors. This is consistent with observations by Shelton[7] of reduced combustion efficiencies when very dry wood is burned in small stoves.

## Benzene Extracts

Over 50 filters from 5 burns in a Jotul #602 stove which covered a range of burning conditions and fuel types were selected for extraction with benzene. Using the weight of material extracted from the filters, the rate of emission of benzene extractables was determined as a function of time during the burn. This rate of emission of extractables was then integrated over the period of the burn in the same manner as has been done for the total particulate mass. This gave the total amount of benzene-extractables emitted during the burn, which could be compared with the total mass emitted and to the amount of fuel burned. These numbers are collected in Table II for the 5 burns analyzed here.

As may be seen in Table II, there is a tendency for the burns with larger emission factors to also have a larger fraction of benzene-extractables. This may result from the increased

importance of pyrolysis for the slower, air-poor burns. Also, the only run with very dry fuel yielded the lowest value for percentage of benzene-extractables.

In order to examine the role of pyrolysis further, the fraction of benzene extractable material was examined during the course of each of these 5 burns. These numbers are collected in Table III as a function of the approximate time into the burn. (Although a more exact time was used in all calculations of emission factors, an approximate time is used in this table to permit a simple tabulation of the data.) It may be seen that there is a general trend for the fraction of the extractables to decrease during the course of a burn. Burn #4, which is the most air-poor of these burns, is a notable exception; the fraction of benzene-extractables is quite high and fairly constant for this burn.

**Table III.** Percentage benzene-extractable of total emissions.

| Approximate time (min) | Burn 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| 2 | 54.1 | 59.9 | 41.0 | 67.9 | 63.6 |
| 5 | 52.5 | 65.5 | 44.3 | 69.1 | 62.8 |
| 8 | 50.5 | 61.5 | 47.5 | | 64.9 |
| 10 | 30.4 | | 38.9 | 69.8 | 64.2 |
| 13 | 40.5 | 62.5 | | | |
| 16 | 36.5 | 64.2 | 33.5 | | 62.7 |
| 20 | 38.5 | 59.4 | | 68.0 | 56.4 |
| 25 | 30.3 | 57.4 | 29.6 | 67.4 | 49.4 |
| 30 | 30.7 | 56.8 | 17.8 | 70.2 | 51.3 |
| 35 | End | 54.0 | End | 67.6 | |
| 40 | | | | | 50.8 |
| 45 | | 40.6 | | 68.0 | |
| 50 | | | | | 55.4 |
| 55 | | 28.3 | | 53.8 | End |
| 65 | | 22.4 | | 59.8 | |
| 80 | | 31.5 | | 65.8 | |
| 90 | | 22.6 | | 66.9 | |
| 100 | | End | | 68.5 | |
| 110 | | | | 72.5 | |

The benzene extracts from the four burns with oak were placed into groups according to whether they were collected early in the burn (near the maximum of the emission rate), late in the burn (where mostly coals remained), or were collected at an intermediate time. Composite samples were then formed from these extracts and subjected to acid-base extractions.

No significant variation of the relative amounts of the four fractions from the acid-base extractions were seen when comparing the four burns or when comparing different phases of a single burn. The averages for all acid base extractions are shown in Table IV. The percentages are the ratio of each acid base fraction to the sum of weights of all acid base fractions. The figure may misrepresent the composition if the small transfer losses were not distributed proportionately over the four fractions.

**Table IV.** Average composition of the acid-base fractions of the benzene extractables.

| | |
|---|---|
| Carboxylic acid fraction | 15% |
| Phenol fraction | 40% |
| Neutral fraction | 45% |
| Organic base fraction | ~1% |

## Discussion

The near-zero value of the intercept in the emission factor model means that the emission factor is approximately inversely related to the combustion rate for a constant fuel load. Sandberg[8] obtained a similar result for the emission factors of carbon monoxide, gaseous hydrocarbons, and particulate matter resulting from the combustion of pine needles under open burning conditions. Prakash and Murray[9] demonstrated that emissions of carbon monoxide, hydrocarbons, and particulate matter from the controlled combustion of wood waste were strongly temperature-dependent for combustion zone temperatures less than 600°C.

The estimation of the worst case ambient particulate matter contribution from wood smoke is subject to several uncertainties which can only be resolved by examining how stoves are used. First, emission rates may not be obtained from a casual use of emission factors and fuel use rates. Rather, the rates depend on whether the stove operator refuels frequently with small loads (operating at smaller values of $m/q$) or enjoys the convenience of longer refuel times (larger fuel charges and larger values of $m/q$). Emission rates will also depend on the fuel moisture content (a higher moisture content will increase $m/q$ for a given draft setting). As a second major area of uncertainty, there is little data available on the way in which wood displaces oil and what the potential for wood use might be. It has been assumed here that displacement of oil by wood occurs on a Btu equivalent basis (with a small correction for differences in combustion efficiencies), but there are at least two reasons why homeowners may get by with fewer wood Btu equivalents. The stand-by requirements for oil-fired furnaces are usually larger than those for wood stoves and small wood stoves may also be more efficient in delivering heat to the point of need.

The observation that $E$ is nearly proportional to $m/q$, given certain other assumptions, leads to an interesting conclusion about emission rates. If the stove user maintains a constant value of m and varies q with the heating demand by controlling the draft, the emission rate will be nearly independent of the heating demand. During times of high demand the fuel use rate will be high and the emission factor low; during times of low demand the emission factor will be high and the fuel use rate low.

An estimate of worst case ambient particulate concentrations was made using meteorological factors similar to those used earlier.[6] (Wind speed was taken to be 1.6 m/s; the wind direction was uniformly distributed over a 90° sector; atmospheric stability was distributed as 15 hr of F stability and 9 hr of C stability.) The emission data were 4.72 kg/hr/residence of 20% moisture oak with a refuel time of 1 hr. This gave an emission rate of 7.9 mg/s/residence. It may be shown that worst case 24 hr average ambient concentrations of up to 100

$\mu g/m^3$ may be expected for wood smoke particulates for a housing density of 400–500 residences/$km^2$ spread over 4 $km^2$ or more if the entire heating load is carried by wood.

Qualitative analyses of the chemical constituents of wood smoke have been the subject of many studies by others because of its importance to food processing.[10] Most of these studies produce wood smoke by heating sawdust in controlled smoke generators and are not felt to be directly applicable to wood stove emissions. Gerstle and Kemnitz[11] reported that 65% of the mass of particulate matter from the open burning of lawn and tree trimmings was soluble in benzene, a result consistent with the range 42–67% reported here. Further work is needed to resolve the chemical species present in the particulate matter. Polycyclic aromatic hydrocarbons may be expected to occur in the neutral fraction of the benzene extractables. The present data suggest that emission factors for these compounds will increase as $m/q$ increases.

## References


1. "Use of Wood and Other Fuels for Home Heating in Bangor, Old Town, and Milford," Dept. of Agriculture and Resource Economics, Univ. of Maine, Orono, ME, 1977.
2. M. M. Dalton, O. B. Durgin, J. H. Herrington, and R. A. Andrews, "Household Fuel Wood Use and Procurement in New Hampshire," Research Report #59, New Hampshire Agricultural Experiment Station, University of New Hampshire, Durham, NH, 1977.
3. E. Swain, Maine Audubon Society, Falmouth, ME, private communication, 1978.
4. C. Stuart, "Household Fuelwood Use and Procurement in Franklin County," Franklin County Community Action Corp., Turners Falls, MA, 1978.
5. G. L. Hobart, Hines Oil Co., Topsham, Maine, private communication, 1977.
6. S. S. Butcher and D. I. Buckley, "A preliminary study of particulate emissions from small wood stoves," *J. Air Poll. Control Assoc.* **27:** 346 (1977).
7. J. Shelton, "Preliminary Results on the Effects of Some Fuel and Operator Variables on Stove Efficiencies," Wood Heating Seminar II, Wood Energy Institute, Camden, ME, 1977.
8. D. V. Sandberg, "Slash Fire Intensity and Smoke Emissions," Third National Conference on Fire and Forest Meteorology of the American Meteorological Society and the Society of American Forestors, Lake Tahoe, CA, 1974.
9. C. B. Prakash and F. E. Murray, "Studies on air emissions from the combustion of wood waste," *Combustion Sci. Technol.* **6:** 81 (1972).
10. D. E. Hruza, M. van Praag, and H. Heinsohn, "Isolation and identification of the components of the tar of hickory wood smoke," *J. Agr. Food Chem.* **22:** 123 (1974).
11. R. W. Gerstle and D. A. Kemnitz, "Atmospheric emissions from open burning," *J. Air Poll. Control Assoc.* **17:** 324 (1967).



Dr. Butcher is Professor of Chemistry and Mr. Sorenson is a Teaching Fellow at Bowdoin College, Brunswick, Maine 04011.


This work was supported in part by a contract from the Maine Department of Environmental Protection.