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Project Summary

Characterization of Emissions from the Combustion of Wood and Alternative Fuels in a Residential Woodstove

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This study was undertaken to compare the emissions from the combustion of alternative fuels to those from wood in a residential woodstove, and to check the effects of woodstove operating parameters on combustion emissions. Overall, oak wood is the best fuel tested, considering both emissions and stove operation. Compressed wood logs with binders and bituminous coal produce the highest emissions of SO_2, particulate, and NO_x. Compressed wood logs without binders and treated lumber produce the highest PAH emissions. Important parameters affecting CO emission levels are fuel structure and, to a lesser degree, combustion air flow. SO_2 emission levels are related directly to fuel sulfur content. NO_x emissions are controlled by fuel nitrogen content and combustion air flow rate. Organic emissions are affected by fuel consumption rate, fuel structure, and amount of air through the stove. PAH formation is affected by combustion air flow, firebox temperature, and fuel structure. Bioassay results indicate the presence of both mutagens and promutagens in the organic extracts of flue gas samples from both wood and coal combustion tests.

This Project Summary was developed by EPA's Industrial Environmental Research Laboratory, Research Triangle Park, NC, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

The purpose of this study is to measure the emissions from the residential combustion of alternative fuels to wood, including coal, in a conventional woodstove. Fuels tested include compressed wood, treated wood, newspapers, commercially available paper logs, and peat, in addition to untreated oak wood and bituminous coal. Pollutants including particulates, SO_x, NO_x, CO, PAH, organics, and benzo(a)pyrene were measured during the course of this study for the alternative fuels tested, and their emission levels are compared to those from wood combustion. The effects of the stove operation parameters on emission levels of these pollutants are also considered. This information should be useful in estimating the overall effect of these emissions from residential solid fuel units on ambient air quality.

Procedure

During the planning phase of this project, eight fuels were chosen as likely alternatives to wood for use in residential combustion units. Dry oak wood was also tested so that emissions from alternative fuels could be compared to it. The alternative fuels chosen were coal (both bituminous and anthracite), peat, newspaper logs, cardboard logs, compressed woodchip logs (both with and without binders),

and pine lumber pressure-treated with copper compounds to retard rot.

The woodstove used in this study was free-standing and air-jacketed, with a simple open firebox. Originally designed as a fireplace insert, this type of stove is being installed in increasing numbers of new homes. The stove utilizes forced air circulation through the air jacket to convect heat into the room.

Two successful runs were performed for each fuel except for anthracite coal, which was not successfully burned in the stove chosen for this study. Two tests were also carried out using split and round dry oak. These tests were used as a baseline for comparison to tests with other fuels.

Temperature was measured during each run by several thermocouples: in the firebox and the stack, at the air jacket blower inputs and outputs, and in the test room (ambient). Temperature data and certain gas data were automatically recorded by the online DEC PDP-1100 computer. An RTI-designed turbine meter (vane anemometer) was used for continuous flow measurements of the stack flow during each test.

Stack gas composition was continuously monitored during the tests. Carbon monoxide, carbon dioxide, and methane were analyzed using infrared detectors. Nitrogen oxides (NO_x) were measured using a photoluminescent detector. Sulfur dioxide (SO_2) was measured using a photometric detector. In addition to continuous gas analysis, gas bulb samples were also taken and analyzed by gas chromatography for total organic carbon.

A whole-test-integrated sample of polycyclic organic matter and other organic emissions was collected by a modified Method 5 sampling train similar to the one described in the trial protocol. The train was assembled and checked out according to a test protocol developed to meet RTI's situation as well as to incorporate the trial protocol. Mass emissions were collected over a 45 to 120 minute interval depending on the volume of sample required for analysis.

Modified Method 5 samples which were analyzed for organics include: probe wash (CH_2Cl_2 + CH_2OH), filter, condenser and XAD module wash (CH_2Cl_2), XAD-2 adsorbent, condensate catch, and impinger water. These samples were extracted using an EPA procedure. Each test produced two samples: one was the concentrated extract of the XAD and particulate; and the other was the extract of the aqueous impinger solutions and the aqueous condensate.

Organics analyses were performed separately on the two types of concentrated samples. Total organics with a boiling point of 100 to 300°C were determined by total chromatographable organics (TCO). Organics with a boiling point above 300°C were determined by a gravimetric technique.

Glass capillary gas chromatography (GC^2) was used to determine PAH concentrations in the modified Method 5 sample extracts. PAH analyses were performed separately on the two samples described previously. PAH-spiked samples were used to identify PAHs in the unspiked samples. PAH concentrations were quantified using an internal standard. GC/MS was used to confirm GC^2 identifications for selected samples.

In addition to GC^2 analysis, a PAH sensitized fluorescence spot test was used to screen the XAD extract, condenser and probe wash, and in the methylene chloride extract from the aqueous impingers and condensate samples for the presence of PAHs. Both original and concentrated extracts were tested.

To properly compare the emissions of the alternative fuels tested, it was necessary to sample only at steady-state stove operating conditions. Start-up and shutdown conditions were too variable for reproducible testing. Steady-state conditions were chosen to approximate conditions the typical stove owner would achieve for most of the stove's operation.

Results and Discussion

Comparisons of the emission factors of the fuels tested are given a figure for each pollutant. Emission rates in grams per hour and emission factors in grams per kilogram of fuel consumed are graphed in each figure.

Particulate—Particulate emission results for the eight fuels successfully tested are given in Figure 1. This figure shows that the fuels may be ranked by particulate emissions as follows (highest to lowest):

1. Compressed wood-chip logs with binders (CWB)
2. Bituminous coal (BC)
3. Newspaper logs (N)
4. Treated Lumber (TW)
5. Peat (P)
6. Compressed wood-chip logs (no binders) (CW)
7. Cardboard logs (C)
8. Wood (W)

Sulfur Dioxide (SO_2)—Figure 2 gives SO_2 emission factors for the fuels tested. The eight fuels ranked as follows with regard to sulfur emissions (highest to lowest):

1. Bituminous coal
2. Compressed wood-chip logs with binders
3. Peat

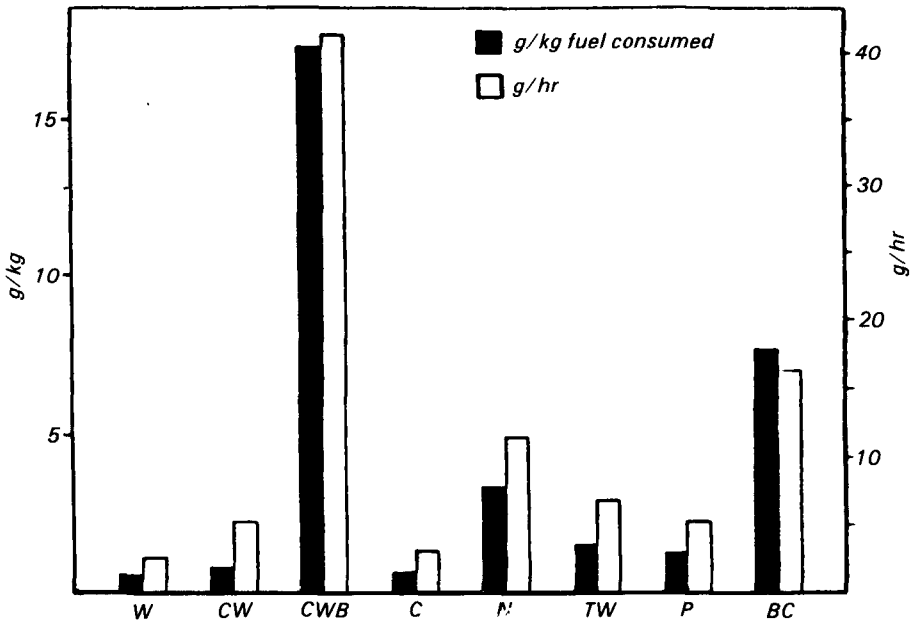
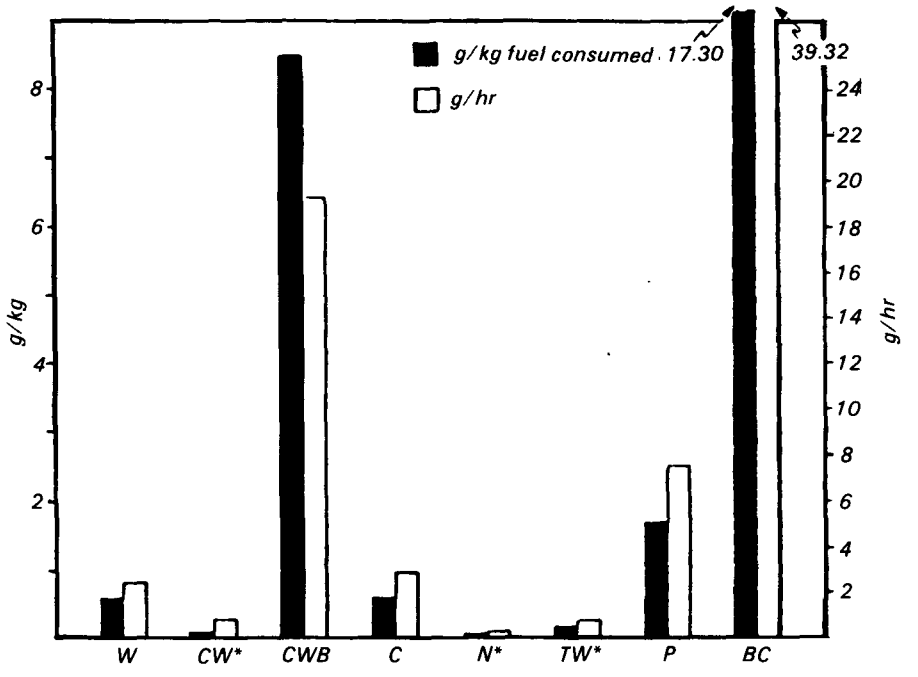


Figure 1. Emission factors: particulate.



*Factors based on single test.

Figure 2. Emission factors: SO_2.

4. Cardboard logs
5. Wood
6. Compressed wood-chip logs (no binders)
7. Treated lumber
8. Newspaper logs

SO_2 emissions varied directly with fuel sulfur content.

Nitrogen Oxides (NO_x)—NO_x emission factors are shown in Figure 3. Two rankings of fuel by NO_x emissions are possible. First, considering NO_x emission rates (g/hr), the fuels may be ranked as follows (highest to lowest):

1. Peat
2. Compressed wood-chip logs with binders
3. Bituminous coal
4. Wood
5. Compressed wood-chip logs (no binders)
6. Cardboard logs
7. Newspaper logs
8. Treated logs

Considering NO_x emission factors (g/kg fuel consumed), the fuels may be ranked as follows (highest to lowest):

1. Compressed wood-chip logs with binders
2. Bituminous coal
3. Peat
4. Wood
5. Newspaper logs
6. Cardboard logs
7a. Treated wood (same level as 7b)
7b. Compressed wood-chip logs (no binders)

The difference in ranking between g/hr and g/kg emission factors is due to difference in fuel consumption rates. Higher heating value fuels (BC and CWB) have low fuel consumption rates because less fuel has to be burned to produce a unit heat output. Two factors were found to influence NO_x emission magnitude: fuel nitrogen content and stack gas flow rate. Fuel nitrogen content was judged to be the most important factor affecting NO_x emissions from the combustion of these fuels.

Carbon Monoxide (CO)—CO emission factors are given in Figure 4. CO emissions for the various fuels tested did not vary as much as with the previously discussed pollutants. The ranking of fuels according to CO emission factors (g/kg fuel consumed) is as follows (highest to lowest):

1. Newspaper logs
2. Compressed wood-chip logs with binders
3. Peat
4. Bituminous coal
5. Cardboard logs
6. Compressed wood-chip logs (no binders)

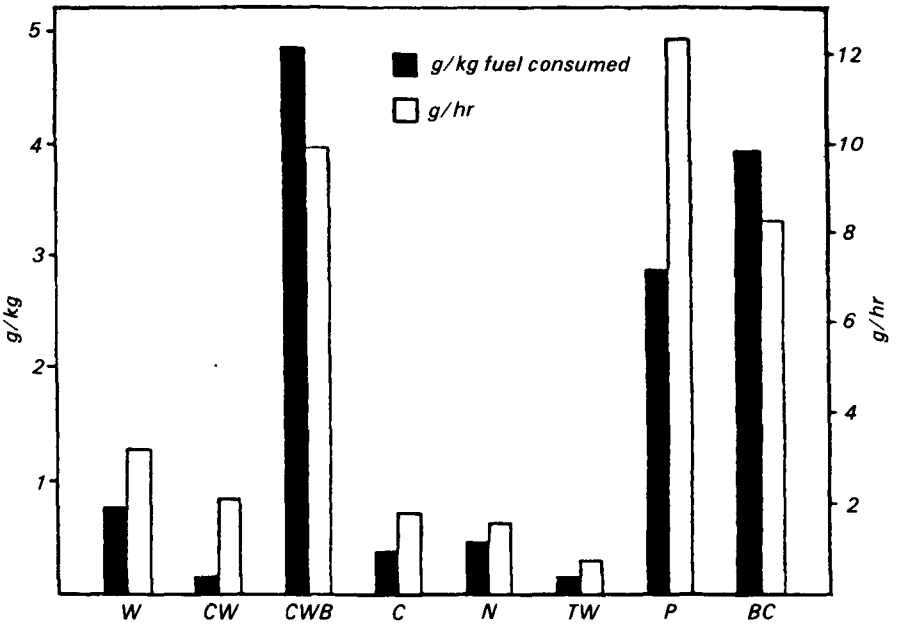


Figure 3. Emission factors: NO_x.

7. Treated lumber
8. Wood

Ranking of fuels according to CO emission rates (g/hr) is as follows (highest to lowest):

1. Newspaper logs
2. Compressed wood-chip logs (no binders)
3. Peat
4. Cardboard logs
5. Compressed wood-chip logs with binders
6. Treated lumber
7. Wood
8. Bituminous coal

Reasons for the change in ranking between emission factors (g/kg) and emission rates (g/hr) are related to fuel consumption rates and fuel heating values as discussed earlier for NO_x emissions.

CO emission levels could not be successfully correlated with stove operating parameters, including stack flow rates, firebox temperatures, stack temperatures, fuel consumption rate, and heat output. The physical structure of the fuels tested probably is the major factor affecting CO emissions: compressed man-made fuels have higher CO emissions than the naturally formed fuels (wood and coal). Results from duplicate tests for each fuel suggest that combustion air flow also affects CO emissions: reduced air flow leads to increased emissions.

Organics—Results from total chromatographical organics and gravimetric analyses indicated that total organic emissions in the flue gas were similar for all fuels except N and P, which had higher organic emission factors. This is somewhat surprising since N had the lowest PAH emission factors. BC, with organic emissions comparable to most other fuels, had the highest proportional contribution of heavy organics.

Polynuclear Aromatic Hydrocarbons (PAH)—PAH formation was affected by combustion air flow, firebox temperature, and fuel structure. Composite structured fuels had higher PAH formation except for N which, in contrast to high total organic emissions, had very low emissions of heavier PAHs. It was concluded that, during the tests with N, firebox temperatures were too low for extensive cyclization reactions leading to PAH formation. Other composite fuels had relatively high PAH production rates:

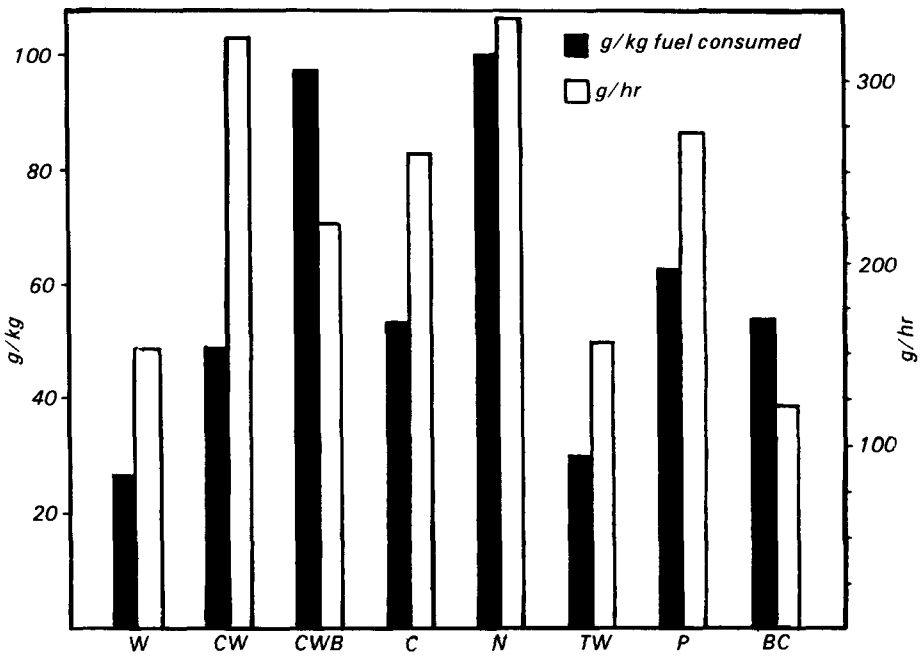


Figure 4. *Emission factors: CO.*

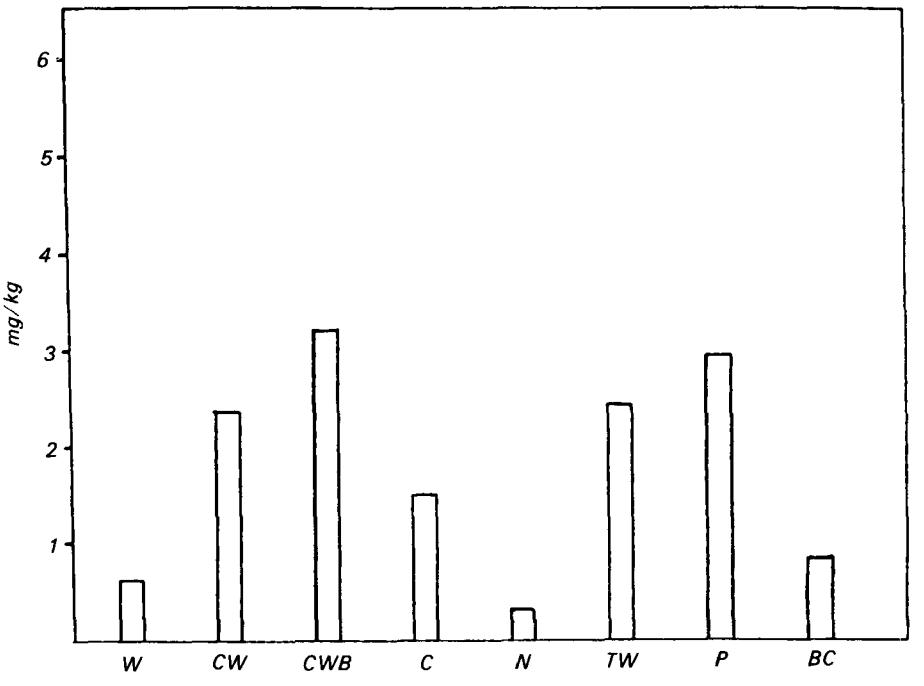


Figure 5. *Emission factors. benz(a)pyrene*

attributed to their structure, which limits the availability of air during combustion and creates starved air conditions favorable to PAH production. Tests with TW also had relatively high levels of PAHs in the flue gas effluent stream: attributed to low air flow through the stove during these tests. W and BC had similar PAH emissions: BC emitted less PAHs than wood. PAH emissions from BC could possibly be pyrolysis products from the coal itself. Figure 5, a comparison of benz(a)pyrene (BaP) emission factors for eight fuels tested, shows that BaP emis-

sion factors are lowest for N. W and BC have similar levels. Other fuels had higher BaP emission factors probably due to burning characteristics which reduce air to the fuel (particulate fuels) or to very low air flow through the stove (TW).

Bioassay—Method 5 sample extracts from one W combustion (W1) and one BC combustion test (BC1) were subjected to an Ames *Salmonella* mutagenicity assay to measure their mutagenic potential. The results of bioassay analysis suggest the presence of frameshift and base pair substitution mutagens in both samples. Both samples were highly mutagenic with TA98 and moderately mutagenic with TA100. Both samples demonstrated an increase in mutagenic activity with the addition of S9, a metabolic activator of promutagen compounds. Therefore, both samples contain direct-acting mutagens and promutagens.

The BC combustion sample was more mutagenic than the W combustion sample, based on the slope of the dose/response curves in units of revertants/mg of sample. Putting bioassay results on a revertants/kg of fuel consumed basis, the BC extract is more mutagenic than the W extract by a factor of two. Since emission factors (g/kg) for the PAHs analyzed in this report are only slightly higher for BC1 than for W1, this suggests that compounds other than the 24 PAHs analyzed in this report may be contributing to the mutagenicity of these samples.

Conclusions

1. Overall oak wood (W) was the best fuel, considering both emissions and stove operation. Cardboard logs (C) were almost as good as W. Although they did emit more CO and PAHs than W, levels of these pollutants were lower than for most other fuels, and stove operation was easier with C than with other fuels.
2. Compressed wood logs with binders (CWB) and bituminous coal (BC) produced the highest emissions (g/kg fuel consumed) of SO_2, particulate, and NO_x. In addition, CWB emissions were high in CO and PAHs.
3. Compressed wood logs without binders (CW) were determined to be unsuitable for stove use on safety grounds. CW also emitted large amounts of CO and had the highest PAH emission rates of all fuels.
4. Treated wood (TW) should not be burned under any circumstances because of the presence of arsenic compounds which probably volatilize during combustion. Other studies have shown that, in the combustion of chlorophenol-treated wood products, polychlorinated dibenzo-p-dioxins (PCDD) and polychlorinated dibenzofurans (PCDF) are emitted.
5. Peat (P) emissions had relatively high levels of NO_x, SO_2, CO, and PAHs.
6. Particulate matter from BC and CWB combustion was sooty and sticky. These fuels produced the highest particulate emission by far. Composite fuels (CW, C, P, newspaper (N)) produced particulate emissions higher than those of W. High particulate levels for N and TW were largely attributable to condensed organics.
7. Important parameters affecting CO emission levels were fuel structure and, to a lesser degree, combustion air flow. Fuels with a man-made, compressed particulate structure (CW, CWB, C, P) and N had high CO emissions because their structure inhibited air flow to the combustion zone. W, TW, and BC had the lowest CO emissions: these fuels would shrink and crack when burned, permitting sufficient air to reach the burning fuel. Results from duplicate tests for each fuel suggest that air flow through the stove is also a factor affecting CO emissions: reduced air flow leads to increased emissions.
8. SO_2 emission levels could be related to fuel sulfur content: higher fuel sulfur content causes higher SO_2 emissions. SO_2 emissions were at levels of environmental concern only for P, BC, and CWB.
9. NO_x emissions were controlled by fuel nitrogen content and combustion air flow rate. High nitrogen content fuels (P and BC) had highest NO_x emissions. Increased air flow through the stove also led to increased NO_x emissions. NO_x levels, generally low, were not as much of a concern as other pollutants.
10. Organic emission levels were comparable for all fuels except P and N, which had high levels of organics in the flue gas effluent stream. Organic emissions were affected by fuel consumption rate, fuel structure, and amount of air through the stove. Higher fuel consumption sometimes led to increased organics. Lowering air flow through the stove increased organic emissions. N had high organic emissions because of their physical structure, which inhibited air from reaching the combustion zone leading to increased pyrolysis products.
11. PAH formation was affected by combustion air flow, firebox temperature, and fuel structure. Composite structured fuels had higher PAH formation except for N which, in contrast to high total organic emissions, had very low emissions of heavier PAHs. It was concluded that, during the tests with N, firebox temperatures were too low for extensive reactions leading to PAH formation. Other composite fuels had relatively high PAH production rates: attributed to their structure, which limits the availability of air during combustion and creates starved air conditions favorable to PAH production. Tests with TW also had relatively high levels of PAHs in the flue gas effluent stream: attributed to low air flow through the stove during these tests. W and BC had similar PAH emissions, with BC emitting less PAHs than wood. PAH emissions from BC could possibly be pyrolysis products from the coal itself.
12. Bioassays on organic extracts from one W test and one BC test demonstrated the presence of both mutagens and promutagens in the sample extracts. Organics from BC combustion were about twice as mutagenic as those from W combustion on a mutagenicity per unit mass of fuel consumed basis.

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The complete report, entitled "Characterization of Emissions from the Combustion of Wood and Alternative Fuels in a Residential Woodstove," (Order No. PB 85-105 336; Cost: $14.50, subject to change) will be available only from:
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