EFFECTS OF BURNRATE, WOOD SPECIES, ALTITUDE, AND STOVE TYPE ON WOODSTOVE EMISSIONS

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During the winter of 1986–87, the U.S. Environmental Protection Agency (EPA) conducted an emission measurement program in Boise, ID, as part of the Integrated Air Cancer Project (IACP). This program was designed to identify the potential mutagenic impact of residential wood burning on ambient and indoor air. One facet of this field sampling effort involved obtaining emission samples from chimneys serving wood burning appliances in Boise. As a companion to the field source sampling, a parallel project was undertaken in an instrumented woodstove test laboratory to quantify woodstove emissions during operations typical of Boise usage.

Two woodstoves were operated in a test laboratory over a range of burnrates, burning either eastern oak or white pine from the Boise, ID, area. A conventional stove, manufactured in the Boise area, was tested at altitudes of 90 and 825 m. A catalytic stove was tested only at the high altitude facility. All emission tests were started with kindling a fire in a cold stove using black and white newsprint. Emissions were collected using the wood stove dilution sampling system (WSDSS) for a continuous period of about 8 hours, encompassing start-up and several wood additions. The results showed wide variability probably due primarily to the difficulty in duplicating conditions during start-up. Total WSDSS emissions showed the expected inverse correlations with burnrate for the conventional stove and nearly flat for the catalytic stove. While there appeared to be little or no correlation

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of total WSDSS emissions with altitude, the sum of the 16 polynuclear aromatic hydrocarbons (PAHs) quantified showed an inverse correlation with altitude: higher PAH emissions at the lower altitude.

INTRODUCTION

During the winter of 1986–87, the U.S. Environmental Protection Agency (EPA) conducted an emission measurement program in Boise, ID, as part of the Integrated Air Cancer Project (IACP). This program was designed to identify the potential mutagenic impact of residential wood burning on ambient and indoor air. One facet of this field sampling effort involved obtaining emission samples from chimneys serving wood burning appliances in Boise. As a companion to the field source sampling, a parallel project was undertaken in an instrumented woodstove test laboratory to quantify woodstove emissions during operations typical of Boise usage. The results from these laboratory source tests are the subject of this paper.

EXPERIMENTAL DESIGN

Nearly all of the woodstove data in the literature have been obtained in a laboratory setting with the start of an emission test occurring after the fire was lit and the appliance brought up to operating temperature. In many cases, these tests also used dimensional lumber as fuel as specified in various regulatory procedures (40 CFR Part 60, Oregon, and Colorado). In a moderate winter climate such as found in Boise, ID, it is common practice for woodstove users to kindle a new fire in a cold stove in the morning. This fire is often allowed to die out during the day when heating demand falls. A new fire is kindled during the early evening which is then stoked for the night and, oftentimes, burns out before the residents rise the next morning. Since the objective of this work was to obtain emission samples under operating conditions similar to those observed in Boise, ID, it was decided that each emission test would start with lighting a fire in a cold stove.

To limit the number of tests required to obtain statistically valid results, the number of operating variables to be investigated was limited to four: fuel type (wood species), burnrate, stove type, and altitude. Each of these variables was investigated at two levels.

Fuel .....eastern oak and white pine from Boise, ID, area
Burnrate.....high and low values
Stove type.....conventional airtight stove manufactured in Boise, ID, area and a catalytic stove
Altitude.....90 and 825 m

Easter oak was burned at the 90 m elevation to provide a tie to earlier IACP source laboratory tests (Leese and McCrillis, 1986). The tests at 825 m were to provide data at an altitude equivalent to the residential area studies in Boise, ID. Tests on the catalytic stove were included to gain some understanding of the changes to be expected in source emissions as low emission technology stoves become more common because of recent EPA regulations (40 CFR Part 60).

To prepare for an emission test, the stove and flue pipe were brushed and vacuumed clean. A pretest fire was then lit and burned for several hours at the conditions of wood species and burnrate planned for the next test. The pretest fire was allowed to burn out, and the stove cooled to room temperature. To start a test, several newspaper balls and kindling wood were placed in the stove. All sampling equipment was started when the paper was ignited. The stove loading door was left open for 5–10 minutes until a good fire was established. At this time additional wood was loaded into the stove and the door closed. Each emission test lasted for about 8 hours; wood was added periodically as needed to maintain the desired overall burnrate for the test.

All emission samples were collected with the wood stove dilution sampling system (WSDSS). This system, described in detail elsewhere (Merrill and Harris, 1987), removes a sample directly from the flue exit and dilutes the sample with cleaned ambient air simulating plume formation. The cooled and diluted sample then passes through a Teflon coated filter and XAD-2 adsorbent resin. During the tests, the filter was changed anytime the pressure drop across it became excessive. In all of the tests it was necessary to change the filter several times over the course of an 8 hour burn. Excessive pressure drop was usually encountered within a short time after the addition of fresh fuel to the stove.

The WSDSS samples recovered at the end of each test consisted of the filter(s), XAD-2, and probe wash. The probe wash consisted of separate dichloromethane and methanol rinses. Representative samples of the wood burned and the ash were also collected for elemental analysis. The WSDSS filters were weighed and then extracted with dichloromethane. The XAD-2 was similarly extracted. These separate extracts and the dichloromethane probe wash were analyzed separately for total organic mass in two steps. The semivolatile mass was quantified by gas chromatography, and the condensible mass, gravimetrically. The methanol probe wash was analyzed gravimetrically. Selected PAHs were quantified by high pressure liquid chromatography (40 CFR Part 136).

A 1 l/min slipstream of the diluted sample was removed from the WSDSS upstream of the filter for aldehydes analysis. A 5 l/min slipstream was removed between the filter and XAD-2 cartridge for hydrocarbon analysis.

RESULTS

The following discussion summarizes the results of analyses completed to date on the WSDSS samples. Still to be completed are the bioassays. These and other

data collected, such as the hydrocarbon and elemental analyses, will be reported later. The aldehyde samples did not comply with quality assurance requirements and will not be reported.

Figure 1 presents WSDSS emission results for all valid test burns. Each bar is composed of three parts: the semivolatile, condensible, and nonextractable fractions. For most of the test burns the nonextractable fraction is larger than usually seen in woodstove samples. This may be largely due to the cold stove start employed in these tests, whereas previous data were taken during hot start tests only. During start-up, draft is much higher than at other times which may have carried more ash particles (including bits of newspaper) up the flue. The ratio of semivolatile to condensible fraction ranged from 0.13 to 2.2 with an average value of 0.35 which is in general agreement with earlier results (Merrill and Harris, 1987, and McCrillis and Merrill, 1985). Note the small variability between some replicate burns (SOLL-1 and SOLL-2) compared to the large variability between others (SOLH-1 and SOLH-2). As noted previously, this variability was anticipated (but certainly not welcomed!) as a result of the cold start feature of the test program.

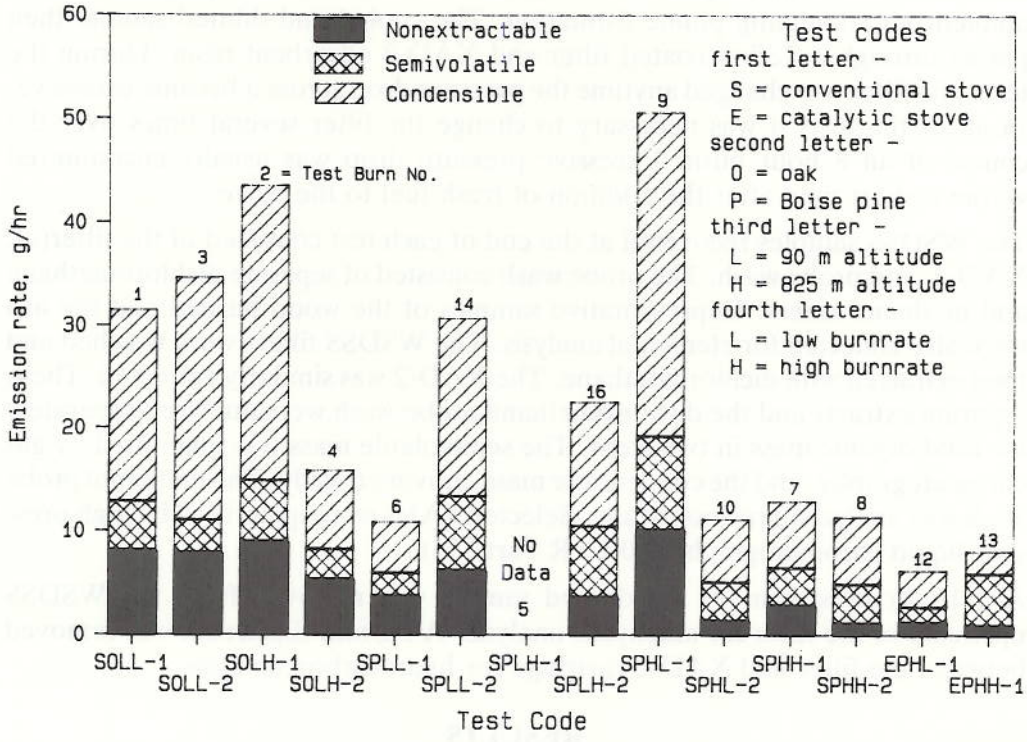

FIGURE 1. Boise source laboratory emission test results showing total dilution sampler emission rates for nonextractable, semivolatile, and condensible fractions.

Figure 2 presents the same WSDSS emission results as a function of burnrate. There are three data points for each burn plotted at the same burnrate. The circumscribed numbers are the total train emission values. The diamonds present the condensible emissions, while the crosses are the semivolatile emissions. The total minus the semivolatile and condensible fractions equals the nonextractable emission rate. With exception of Burn 2, the conventional stove data show the expected trend: high emissions at low burnrates decreasing rapidly and leveling out at high burnrates. It is of interest to note that the condensible fraction emission rate trend is similar; however, the semivolatile emission rate is relatively constant with burnrate. Burn 2 is an anomaly because the test was terminated early due to an electrical power failure. It may be that, if carried to a more typical conclusion, the average burnrate would have been lower, producing a result more in agreement with other tests. With the limited data available, it appears that the catalytic stove emission characteristics are similar to those for other models of this technology; i.e., an increasing emission rate with burnrate.

Figures 3 and 4 illustrate the relationship between the PAH emission rates and the burnrate. The sum of the 16 PAHs and naphthalene showed some correlation (r^2 = 0.48 and 0.58, respectively). The correlation coefficients for pyrene and

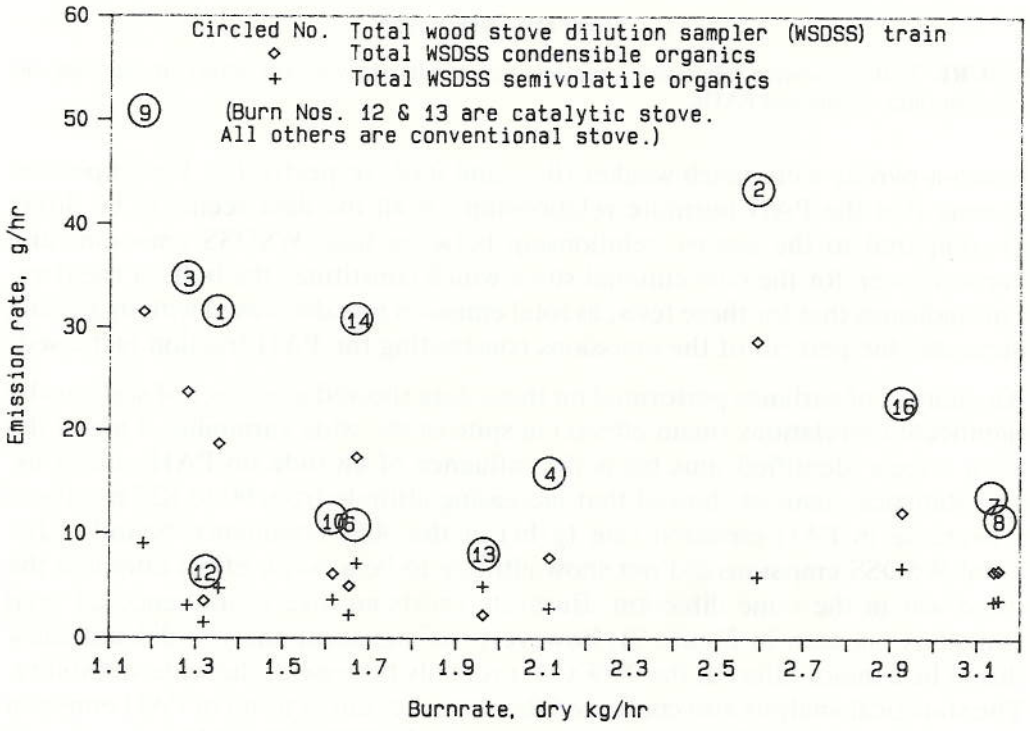

FIGURE 2. Boise source laboratory emission test results showing the effect of burnrate on total smoke emissions.

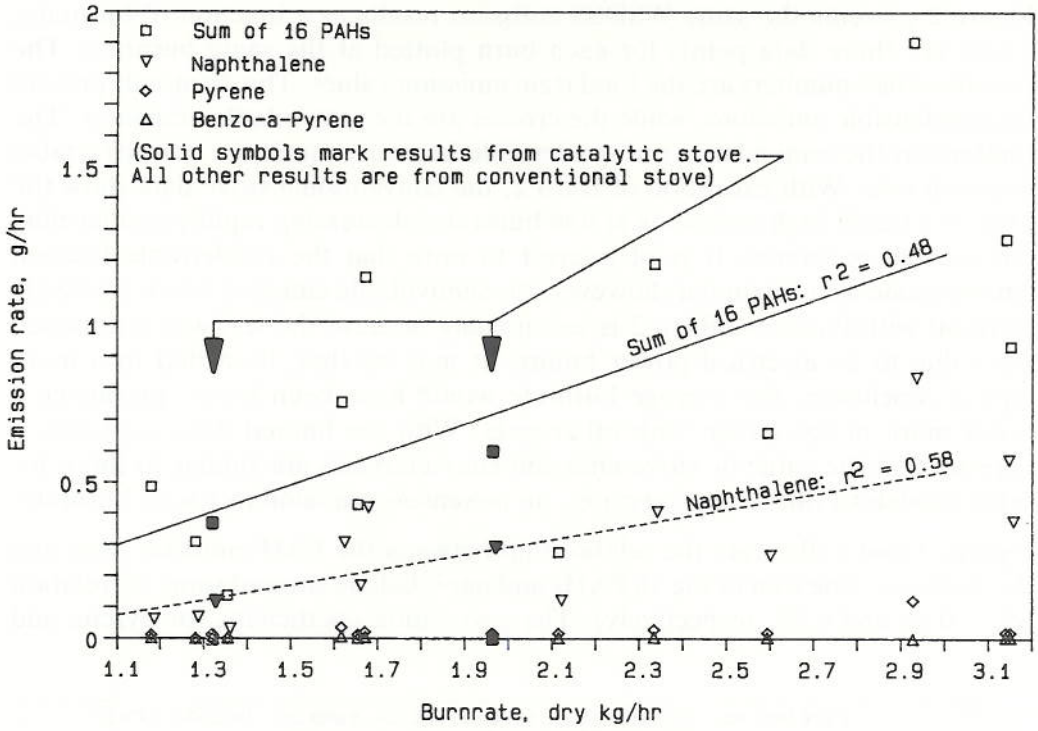

FIGURE 3. Boise source laboratory emission test results showing the effect of burnrate on emission rates of selected PAHs.

benzo-a-pyrene were much weaker (0.23 and 0.04, respectively). It is important to note that the PAH burnrate relationship for all the data seems to be direct as compared to the inverse relationship between total WSDSS emissions and burnrate seen for the conventional stove which constitutes the bulk of the data. This indicates that for these tests, as total emission rate decreased with increasing burnrate, the percent of the emissions constituting the PAH fraction increased.

An analysis of variance performed on these data showed a number of statistically significant correlations (main effects) in spite of the wide variability. One of the main effects identified thus far is the influence of altitude on PAH emissions. The statistical analysis showed that increasing altitude from 90 to 825 m caused a decrease in PAH emission rate (g/hr) at the 90% confidence bound (CB). Total WSDSS emissions did not show altitude to be a major effect although the trend was in the same direction. Burnrate exerts an inverse influence on total emissions (as seen in Figure 2); however, the statistical analysis did not show this to be a major effect at the 90% CB, probably because of the wide variability. The statistical analysis also confirmed the opposite, direct trend of PAH emission rate versus burnrate showing a major effect at the 90% CB. PAH emission rate also showed a correlation significant at the 99% CB on wood species, pine

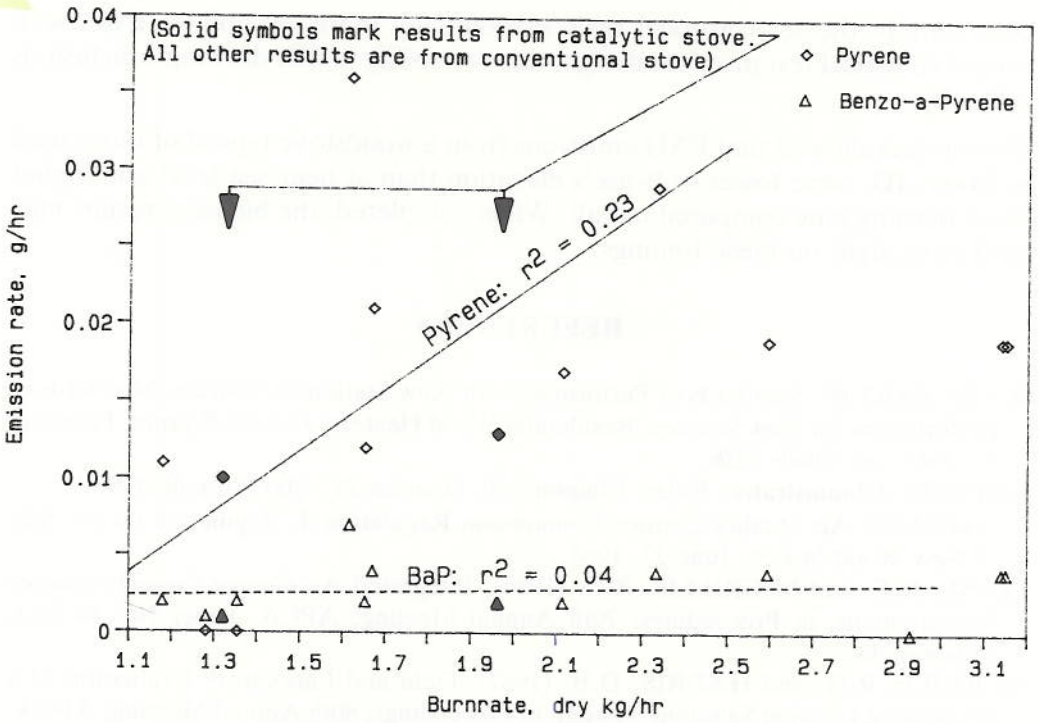

FIGURE 4. Boise source laboratory emission test results showing the effect of burnrate on emission rates of pyrene and benzo-a-pyrene (BaP).

producing a higher PAH emission rate than oak. Stove type showed an effect significant at the 90% CB on PAH emission rate, the conventional stove showing a higher rate. Another major effect was the direct relationship between stack flow rate (normal m^3/hr) and burnrate. On the other hand, increasing altitude seemed to result in reducing stack flow rate.

CONCLUSIONS

In the IACP field studies, emission tests on residential sources such as woodstoves are necessary. However, some variables, such as burnrate, are nearly impossible to measure over short time frames of a few hours without causing a major disruption to the residents. The parallel testing of such residential combustion sources under controlled conditions in a laboratory offers the advantage of allowing measurement of all parameters under simulated field conditions. Together, the field and laboratory data provide the means of adequately characterizing these sources.

Combustion in woodstoves is an inherently variable process because of the non-homogeneity of the fuel and the batch nature of the fueling procedure. Including

cold start in the test protocol adds substantially more variability. Even with proper statistical test program design, this variability makes drawing conclusions difficult.

This project showed that PAH emissions from a woodstove typical of those used in Boise, ID, were lower at Boise's elevation than at near sea level and higher when burning pine compared to oak. When completed, the bioassay results may shed more light on these findings.

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