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83-5 Chap 4
Ref 6

CHARACTERIZATION OF EMISSIONS OF PAH'S
FROM RESIDENTIAL COAL-FIRED SPACE HEATERS

AP42 Section 1.2
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Reference 14

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Introduction:

A joint emissions testing and analysis program was conducted by the U.S. Environmental Protection Agency and the State of Vermont to determine PAH, particulate, sulfur dioxide and carbon monoxide emissions from two coal-fired residential space heaters. Testing was conducted in October, 1982 at a test facility in Barre, Vermont. One space heater had a magazine type feed system while the other was a batch loader. Anthracite and bituminous coal were burnt in each stove at burning rates felt to be representative of normal homeowner usage. A modified EPA Method 5 train (utilizing a XAD-2 resin trap) was used to collect PAH and particulate samples. A total of six particulate tests were run (three each for bituminous and anthracite). The field samples were submitted to Battelle-Columbus Laboratories for both quantification and qualification of the PAH emissions as well as particulate emissions, extractable organics and volatiles.

Analysis included fixed combustion gases, condensible organics, Method 5 particulates, principal volatile compound screening by gas mass spectrometry (GMS), and polynuclear aromatic hydrocarbon (PAH) analysis by high resolution gas chromatograph/mass spectrometry (GC/MS).

Experimental Methods:

The two stoves were started up and operated in a manner dictated by the stove design and type of fuel being used. These procedures are described in detail in the latter part of this section. Each stove was tested with bituminous and anthracite coal to evaluate the effect of the two fuels on emissions. Stove B was tested at both a high and low burn rate while Stove C was tested at a moderate burn rate.

The stove to be tested was placed on a set of beam scales, such that the weight of fuel used during the test period could be accurately determined. Each stove is designed to operate with a six inch diameter round flue pipe. The flue pipe extended vertically up into a seven inch diameter elbow, which was four feet from the chimney. The 1/2" space around the vertical flue pipe allowed the stove to be weighed without being effected by the weight of the remaining flue pipe and testing equipment. During actual sampling the 1/2" gap was sealed with an aluminum foil collar.

All flue gas samples for Orsat analysis were taken upstream of this loose connection. Gas samples for particulate and SO₂ analysis were taken in the horizontal 7" pipe. Draft temperature measurements were taken downstream of the sampling probes.

Stove Design and Operating Specifics

Stove B (Coal Stove)

This stove was a magazine style stove, designed to burn "pea" sized anthracite or "nut" bituminous coal. The only fuel that was actually burning was the fuel which was on the grates. When burning anthracite, the stove was

designed such that the exhaust gases passed out of the combustion chamber at both ends of the grates, and did not pass through the magazine of fuel. In order to burn bituminous coal in this stove, a different magazine was required. With the bituminous magazine in use, the exhaust gases still exited at either end of the grates, but some of the gases first passed through the magazine of fuel. This allowed the volatiles to be released at a slower rate, and as they were released from the stored fuel, to be brought into the firebox where they should be combusted.

Primary air was controlled by an automatic damper system. No secondary combustion air was supplied when burning anthracite, while for bituminous coal secondary combustion air was supplied along the front edge of the grates.

A coal fire was started and the magazine filled (with 30-50 pounds of coal) approximately two to three hours prior to the start of emission testing. This allowed the stove to reach a normal operating temperature and the fire to stabilize. The tests for each fuel were conducted under both a "high" burn rate (approximately 1.4 kg/hour for bituminous and 1.9 kg/hr for anthracite) and a "low" burn rate (0.75 kg/hour for bituminous and 0.67 kg/hr for anthracite). Each test was conducted over approximately a two hour period. Table I contains a summary of the test parameters for each test.

Stove C ("Wood" Stove)

This was designed as a batch feed type stove, with manual control for the secondary air, and automatic controls (bi-metallic strip) for the primary air inlet. The firebox will hold approximately 15-20 pounds of either "pea sized" anthracite or "stoker sized" bituminous coal. The secondary air is partially preheated (approximately 400 degrees F) before it enters the firebox along the back wall.

The primary air damper must always be open at least half way in order to insure that a sufficient amount of air is available for combustion. The secondary air inlet was left in the fully open position for all testing.

This stove can also be used as a wood stove by removing the coal grates and replacing them with the wood grates.

As with Stove B, a fire was started in the stove 2-3 hours prior to the start of testing. A new charge of coal was added to the firebox immediately prior to the start of each test.

The stove was operated at what was considered a "moderate" burn rate (0.9 kg/hr for anthracite and 1.2 kg/hr for bituminous). See Table I for a summary of test parameters.

During the combustion of bituminous coal, the volatile matter from the new charge of coal (when placed on an established bed) was burnt/driven off fairly rapidly (within one half hour).

Table I. Stove and Sampling Parameters

Stove Parameters	Bituminous Coal Stove High Burn Rate	Stove B		Stove C	
		Anthracite Coal Stove High Burn Rate	Bituminous Coal Stove Low Burn Rate	Bituminous "Wood" Stove Low Burn Rate	Anthracite "Wood" Stove Low Burn Rate
Burn Rate, kg/hr (lb/hr) (1)	1.2 (2.8)	1.9 (4.2)	0.8 (1.9)	1.2 (2.7)	0.9 (2.0)
Mean Stack Tem- perature, C (F) (2)	270 (520)	250 (480)	220 (420)	160 (315)	140 (280)
Sampling Time, min.	120	120	150	155	155
Stack Water, percent	1.8	3.5	1.8	1.9	2.3
Stack Oxygen, per- cent (3)	13	10	17	14	13
Stack Carbon Dioxide, percent (3)	6	10	4	6	7
Stack Carbon Monoxide, percent (3)	0.6	0.6	0.2	0.4	0.4
Method 5 Volume (dry), SCM (SCF)	1.8 (64)	1.9 (68)	2.0 (70)	2.3 (8.1)	2.5 (87)
Total Stack Discharge, Q, SCM (SCF)	64 (2,300)	58 (2,050)	72 (2,500)	67 (2,400)	44 (1,600)

(1) Averaged over total test.

(2) At Method 5 probe.

(3) Values determined by ORSAT technique.

Sampling Procedures

Sulfur Dioxide

For each particulate test conducted, at least one sulfur dioxide test was conducted simultaneously using EPA reference Method 6. The SO₂ test was conducted over a 20 minute period with the average sample size being 1.0 DSCF of flue gas. The test train used a solution of 3% hydrogen peroxide to absorb the SO₂, preceded by an impinger packed with glass wool and 80% isopropyl alcohol to trap any sulfuric acid.

At the conclusion of the test the glassware following the isopropyl alcohol filled impinger was rinsed with distilled water, and the rinse placed in a sample bottle along with the peroxide solution. This sample was then diluted to a volume of 100 ml and titrated with barium perchlorate to determine the SO₂ concentration.

An additional sample was also collected using an evacuated sample bulb (See description under volatile organics).

Volatile Organics

Samples were collected for fixed gas and volatile organics analysis using evacuated glass bulbs. Three liter glass sampling bulbs were prepared at Battelle by evacuating to approximately .000001 torr pressure and heated to drive off residual moisture. After preparation, the sample bulbs were wrapped with foam insulation and shipped to the experimental site in Vermont. The gas samples were taken by inserting a stainless steel probe through a sample port. A sample was collected by opening the stopcock on the evacuated sample bulb during steady state combustion.

Flue Gas

An integrated sample of flue gas was collected over the duration of the particulate test. At the completion of the test the gas sample was analyzed using an Orsat analyzer for percent CO₂, O₂ and CO. Additionally, 15 minutes into the test an evacuated flask was used to collect a single grab sample of the flue gas. (Description of sampling flasks is contained under volatile organics sampling procedures)

Particulates and PAH

All testing for particulates was done using a modified EPA reference Method 5 sample train. Three determinations were made on the Modified Method 5 sample; condensible organics, particulate matter, and PAH. The Method 5 sampling train separates the sample into a particulate fraction in the heated probe and filter section, and a semivolatile organics fraction which collects on the resin. The XAD-2 resin material was extracted along with the particulate-laden filter in a Soxhlet extractor

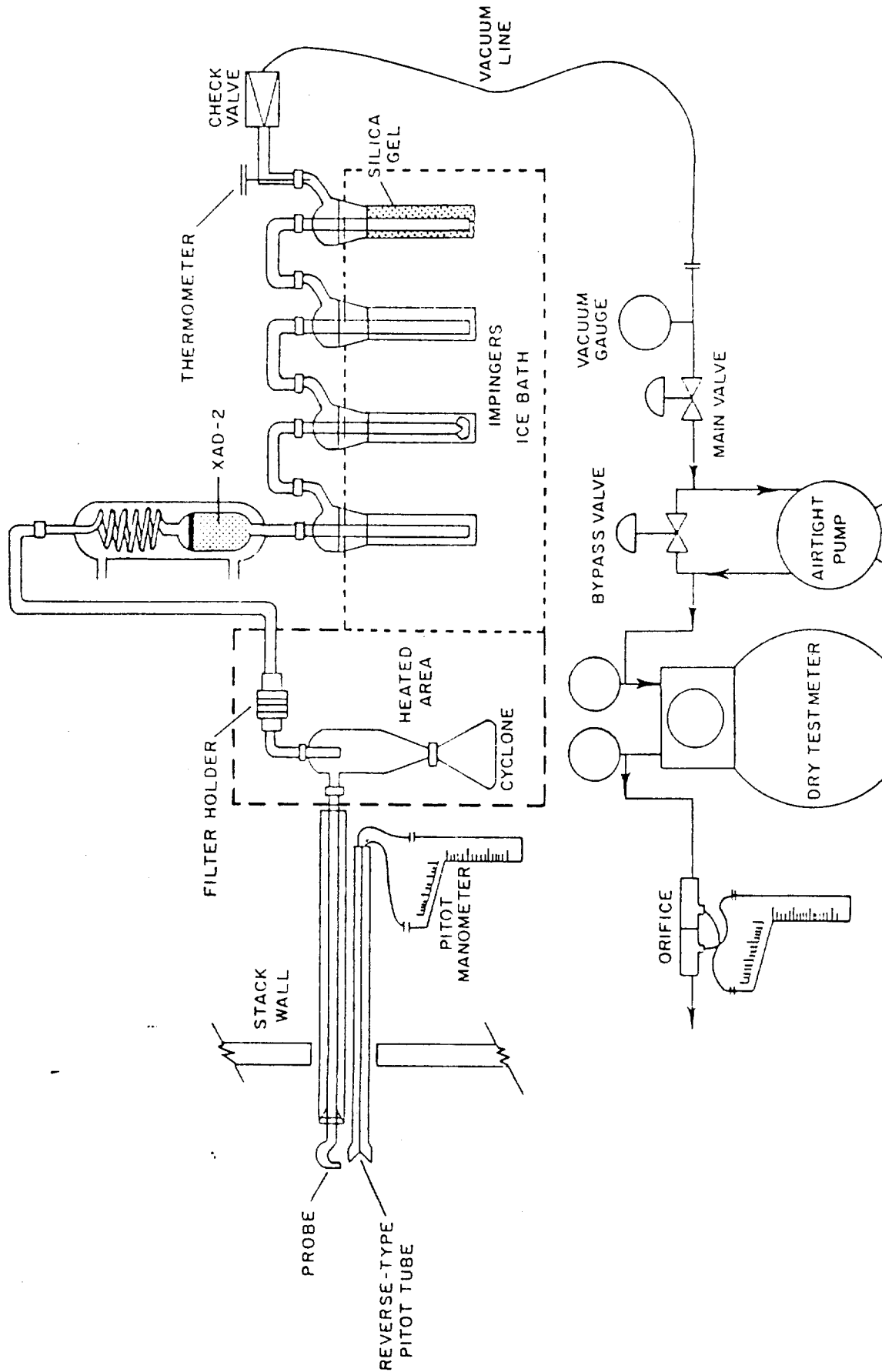


Figure 1. Particulate Sampling Train - Modified Method 5

using methylene chloride. The filter was re-extracted separately with benzene to remove PAH compounds not extracted by methylene chloride. The resin-filter extracts were combined with the extracted aqueous impinger samples to produce a combined organics sample. The combined extract was analyzed by gas chromatography and gravimetry to determine condensible organics. This extract was also used for PAH analyses.

ANALYTICAL PROCEDURES

Fuel Analysis:

An analysis of the fuel used in this study is contained in Table II. Due to the low values reported for percent oxygen and sulfur on both of the anthracite coal samples, parts of the analysis were redone and the low values were confirmed.

TABLE II. FUEL PARAMETERS

Ultimate Analyses	Anthracite (Pea)	Bituminous (Nut)	Bituminous (Stoker)
Carbon, percent	85.8	79.1	80.6
Hydrogen, percent	1.9	5.2	5.3
Nitrogen, percent	0.7	1.5	1.6
Oxygen, percent	0.1	6.9	4.9
Sulfur, percent	0.4	0.8	0.8
Ash, percent	8.9	3.2	5.5
Proximate Analyses			
Fixed Carbon, percent	85.6	56.5	56.2
Volatiles, percent	3.3	37.0	37.0
Moisture, percent	2.2	3.3	1.3
Heating, value, dry basis, ash free, Btu/lb	14,900	15,100	14,400

The bituminous coal, which was used, can be classified as high volatile, Class A, low ash and low sulfur. The anthracite is low sulfur with an averaging amount of ash. Although the anthracite has a higher ash content than the bituminous, it has a much lower volatile content. Due to the low flue gas velocity, very little if any ash is carried out

of the firebox of residential coal stoves by the flue gases, thus the volatile content is of more concern than the ash content when coal is used in residential space heaters. Unburnt volatile matter may represent a significant portion of the particulate emissions, making a low volatile coal the more desirable fuel.

Gas Analyses

Fixed gas analyses were performed on the glass bulb samples. Samples were analyzed using a combination of mass spectrometry and three gas chromatographic techniques. A Consolidated Electrodynamics Corporation, Model 21-620, mass spectrometer was used for a general analysis from mass 2 to 100. Since the mass spectrometer does not separate carbon monoxide and nitrogen, the carbon monoxide was determined using an Aerograph, Model 202, gas chromatograph with a molecular sieve column and a thermal conductivity detector.

Low molecular weight hydrocarbons and sulfur gases were determined using a Varian, Model 3700, gas chromatograph. The hydrocarbon analysis employed a Poropak Q column and flame ionization detector, and the sulfur gases were separated on a Supelco S column and detected with a flame photometric detector.

Condensible Organics Analyses

Condensible organics were measured by extracting the Method 5 particulates and the XAD-2 resin bed with methylene chloride and performing a gravimetric analysis (GRAV) on the extracts. This procedure is described in EPA's Level 1 manual for characterization of source discharges⁽¹⁾. The gravimetric analysis measures the mass of extracted material. This analysis does not measure volatile species, in fact most volatiles are lost by the Method 5 sampling train. The evacuated gas bulbs are useful in estimating principal volatile organics.

PAH Analyses

The filter/resin extraction yielded two extracts: a methylene chloride extract which contained most of the organic burden, and a benzene extract which contained much of the PAH. The combined extracts were reduced to a convenient volume by a Kuderna-Danish concentrator. The PAH compounds were then isolated by liquid chromatography using silica gel to remove interfering species. The column was packed (methylene chloride slurry) with 10 g of 100-200 mesh silica gel and washed with 40 ml of petroleum ether. A 25 ml fraction of petroleum ether were collected and discarded. The PAH were eluted with 75 ml of 20 percent methylene chloride in petroleum ether, followed by 30 ml of 50 percent methylene chloride in petroleum ether. The volume of the PAH fraction was reduced to about 1 ml by use of a Kuderna-Danish concentrator and to a final 0.5 ml by directing a gentle stream of nitrogen across the top of the sample. An internal standard (9-phenyl-

anthracene) was spiked into the extract at this point.

The analytical scheme involved a glass capillary GC/MS procedure which separates many of the PAH isomers (including benzo(a)pyrene and benzo(e)pyrene) with only one chromatographic run. A 30 m SE-52 capillary column was directly coupled to the mass spectrometer via a glass capillary transfer line. The gas chromatograph was equipped with a Grob-type injector enabling splitless injections. The column was temperature programmed from 160-320 degrees C at 4 degrees C/minute. Injector temperature was 300 degrees C while the transfer line was held at 315 degrees C.

Compounds such as coronene and dibenzopyrenes with boiling points above 520 degrees C are eluted as sharp peaks. Close to baseline separation is achieved for isomeric compounds such as phenanthrene/anthracene, benzo(a)anthracene/chrysene and benzo(a)pyrene/benzo(e)pyrene.

In the GC/MS analysis, sensitivity was improved by the use of single ion monitoring. The molecular ions of up to three compounds of interest were simultaneously monitored. Quantification was achieved by ratioing the ion current of the molecular ion of interest to that of the differences in ionization efficiencies of the compound and the internal standard. The use of single ion monitoring minimized interferences from fragmentation of extraneous compounds which may not have been removed during the liquid chromatographic cleanup. Since the coal extracts were heavily loaded with organics, the silica gel cleanup and use of single ion monitoring was necessary.

Results

The stove operation data shows that burn rates varied between 0.7-1.9 kg/hr and typical gas discharge volumes varied between 44-80 cubic meters as shown in Table I, which gives general test and stove operating parameters. The stoker grade bituminous coal was only used to test Stove C, the modified "wood" stove. Nut grade bituminous and pea grade anthracite were used in all other tests.

The effect of fuel type is clearly seen in the particulate discharge levels and condensible organics concentrations shown in Table III. In every case the bituminous coal gave much higher emission levels than anthracite. This is expected from the two coal types but the magnitude of the differences in emission levels between the two coals is surprising.

In all cases the particulate and extractable organic emissions were higher for the combustion of bituminous coal than for anthracite coal. Based on additional emission testing conducted by the Vermont Agency of Environmental Conservation, it has been found that particulate emissions from the combustion of anthracite coal are not dependant upon the burn rate nor the burn cycle. For bituminous coal the particulate and extractable organic emissions are dependant upon the burn cycle, which in turn is a factor of the stove design, fuel loading techniques and the volatile content of the coal. The volatile matter from the bituminous coal is driven off as new fuel comes in contact

with the burning bed. This stage creates a high emission rate, which drops off rapidly as the volatiles are released. For the latter portion of the burn cycle where only the fixed carbon remains the particulate emissions are as low as those from anthracite coal.

Testing conducted for this program encompassed an entire bituminous burn cycle for each test.

TABLE III. PARTICULATE AND EXTRACTABLE ORGANIC EMISSIONS

Stove	Coal	Burn Rate, kg/hr	Method 5 ^(a) Particulates g/kg (mg/SCM)	Extractable ^(b) Organics g/kg (mg/SCM)	Carbon Monoxide g/kg (mg/SCM)
B-Coal	Bituminous	High (1.2)	10.7 (458)	2.2 (96)	166.7 (7135)
B-Coal	Anthracite	High (1.9)	0.1 (8)	0.05 (3)	122.0 (9760)
B-Coal	Bituminous	Low (0.8)	7.0 (176)	5.1 (128)	93.7 (2356)
B-Coal	Anthracite	Low (0.7)	0.3 (6)	0.1 (2)	59.5 (1190)
C-Modified Wood	Bituminous	Moderate (1.2)	4.9 (197)	1.6 (66)	116.8 (4696)
C-Modified Wood	Anthracite	Low (0.9)	0.2 (8)	0.2 (8)	227.8 (9112)

(a) Blank value determined, 0.0000 +/- 0.2 ng.

(b) GRAV only on XAD-2 extract.

Condensable organics are measured by extracting both the Method 5 filterable particulates and the XAD-2 resin bed with methylene chloride then performing a total chromatographable organics (TCO) analysis followed by a gravimetric analysis (GRAV) on the extracts. These two procedures are described in EPA's Level 1 manual for characterization of source discharges (1). TCO is performed by summing the estimated responses of organic compounds with boiling points between 100 and 300 degrees C. The gravimetric analysis measures the mass of extracted material with boiling points above 300 degrees C. This analysis does not measure volatile species, in fact most volatiles are lost by the Method 5 sampling train. The evacuated gas bulbs are useful in estimating principal volatile organics. The results of the volatiles analyses are shown in Table IV. For most compounds the sensitivity of gas mass spectrometry and gas chromatography with selective detectors is about 1-50 ppm (V/V).

The results of anthracite tests show that Stove C, the modified "wood"

stove had higher methane emissions than Stove B, the coal stove. Stove B, the coal stove generated much higher S02 levels than the "wood" stove, by a factor of ten, when burning anthracite. It has been determined from other S02 tests conducted on coal stoves by the Agency of Environmental Conservation that the S02 emissions are dependant upon stove type, burn rate, and the point in the burn cycle that the test was taken. Long term testing on both of these stoves has shown the emission of S02 from the combustion of anthracite coal to be very similar (5.2 g/kg for Stove B, and 5.7 g/kg for Stove C).

In tests with bituminous fuel Stove B, the coal stove, had much higher levels of methane and ethene than Stove C, the modified multifuel stove designed primarily for wood burning. The "wood" stove had higher levels of S02. Comparing the sulfur oxide data from this study with results of earlier EPA coal stove tests is very interesting. The industrial coal stoker boiler study firing bituminous coal⁽²⁾ reported SOx levels of 90-490 g/kg fuel-dry basis (180-970 lb/ton) with a mean of 227 g/kg (450 lb/ton) for 11 stokers tested, with 21 coal/fuel combinations.

Table IV. Principal Volatile Emissions, ppm (V/V)

	Stove B - Coal Stoves				Stove C	
	High Burn		Low Burn		"Wood" Stove	
	Anthracite	Bituminous	Anthracite	Bituminous	Anthracite	Bituminous
Methane	100	210	100	90	630	95
Ethene	1	722	0.2	1000	0.8	61
Ethane	1	2	--	--	2	--
Propane	--	2	--	--	--	0.4
Propane	--	--	--	--	2	--
p-Butene	--	--	--	3	--	--
S02	350	208	290	300	25	430
COS	--	--	--	3	23	1
CS2	--	--	0.2	--	--	0.3
H2S	--	--	--	--	6	--
NOx	--	--	--	--	100	160

During tests of stoker fed residential units,⁽³⁾ SOx was measured at 3-15 g/kg (6-30 lb/ton) for ten tests with a mean of 9.5 g/kg (19 lb/ton). Bituminous coal was used in both studies and each study showed a linear

relationship between available fuel sulfur and SOx emissions. In this study the three bituminous tests yielded values of 13 g/kg (fuel basis-dry-ash free) for Stove B, the high burn rate coal stove, 32 g/kg for the companion low burn rate test, and 29 g/kg for Stove C, the modified "wood" stove burning bituminous coal. Thus the residential units tend to produce lower SOx levels than larger industrial units. This is probably caused by the higher grate heat and more efficient combustion which is effective in releasing fuel bound sulfur and oxidizing it to volatile oxides in the industrial stoker boilers. Analysis of the coal ash from this study is being conducted by EPA to verify that they did in fact remain with the ash.

Polynuclear aromatic hydrocarbon emissions from coal combustion sources were summarized in 1967 in a classical paper by Hangebrauck, von Lemden, and Meeker.⁽⁴⁾ These researchers graphically illustrated relative PAH emissions from several sources by using BaP as a key indicator compound. They reported BaP concentrations as a function of gross heat input to the furnace. Thus, large utility furnaces with very high grate temperatures, secondary air and sufficient excess air, produce far less BaP per unit of fuel burned than residential units. Even though Hangebrauck et al summarized data from the 1960s, the relationship of PAH emissions to combustion efficiency is still valid and has been verified many times. The Vermont study provided an opportunity to measure specific PAH compounds including BaP with modern analytical techniques and good quality control procedures.

The emission data for a representative series of PAH compounds are given in Table V. The magnitude of PAH emissions can be compared between sources by using consistent units. One Electric Power Research Institute study has suggested using $\text{ng/J} \times 10^{-5}$ as a standard unit for coal combustion.⁽⁵⁾ Several sources including coal and wood-fired residential units are compared in Table VI using this unit as a basis for comparison. Residential coal combustion (using bituminous coal) shows the highest emissions of BaP relative to other coal-burning combustion systems compared. This observation is consistent with the Hangebrauck curve. Anthracite fuel was found to generate far lower BaP emissions than bituminous coal in equivalent appliances. BaP levels firing anthracite average lower by about $700 \text{ ng/J} \times 10^{-5}$ less than in bituminous tests and about $16,000 \text{ ng/J} \times 10^{-5}$ less than reported wood combustion tests having the EPRI comparison unit. Higher BaP emission levels than found for residential bituminous-fired space heating have been reported, e.g., coal gasification;⁽⁶⁾ however, the magnitude of the discharges found in the Vermont study together with high particulates and SOx cause concern about the widespread use of bituminous coal for residential space heating.

In other tests conducted by the Agency of Environmental Conservation on these two stoves, it has been found that the emission rate of CO is significantly higher for anthracite coal than bituminous coal, although this was not the case in the limited testing done for this study. Also, no correlation has been found between burn rate and CO emissions. It has also become apparent that CO emissions are dependant upon the stove design. Whereby a stove with a large grate area will have lower CO emissions than one with a smaller grate area.

Jaasma⁽⁸⁾ concluded that CO emissions are dependant on the loading and

Table V. Polynuclear Aromatic Hydrocarbon Emissions, ug/SCM

	Stove B				Stove C	
	Coal Stove High Burn Rate Ant.	Coal Stove Burn Rate Bit.	Coal Stove Low Burn Rate Ant.	Coal Stove Burn Rate Bit.	"Wood" Stove Moderate Burn Rate Ant.	"Wood" Stove Burn Rate Bit.
Naphthalene	5.3	830	0.08	210	14.*	>330*
Acenaphthene	0.94	120	0.12	19	0.82	70
Acenaphthylene	0.99	1100	0.12	16	6.3	>330*
Fluorene	0.89	210	0.08	90	1.2	210
Phenanthrene	11.	780	0.81	180	9.0	>330*
Anthracene	1.2	210	0.08	100	0.9	160
Fluoranthene	8.7	360	0.85	76	4.7	270
Pyrene	6.3	210	0.48	69	3.7	190
Benzo(a)anthra- cene	5.4	130	0.12	46	1.1	170
Chrysene	5.9	150	0.20	37	1.5	140
Benzo(k) fluoranthene	0.68	190	0.12	92	1.3	280
Benzo(e)pyrene	0.16	100	0.04	38	0.30	85
Benzo(a)pyrene	0.10	110	0.08	52	0.17	120
Perylene	0.02	13	0.02	5	0.04	16
Indeno(123-cd) perylene	0.37	14	0.04	36	0.17	150
Benzo(g,h,i) perylene	0.31	49	0.04	24	0.09	72
Anthanthrene	0.005	4	0.01	7	0.02	27
Coronene	0.21	60	0.01	9	0.13	42

the stage of the burn cycle. He found that as the fuel (bituminous coal) agglomerated and swelled, the air flow through the bed decreased, causing an increase in CO emissions. All tests in the Jaasma study were done with a high volatile bituminous coals that had a medium to high free swelling index.

This trend of increasing CO concentrations has not been observed during extensive tests on stoves B & C. In fact the emissions appear to decrease over time. Nor does the above theory explain why the CO emissions are higher for anthracite (which does not swell or agglomerate appreciably) than bituminous.

One difference between the two fuels was that the anthracite coal used was of a higher ash content than the bituminous. Secondly, the anthracite ash does not fall away from the remaining coal as easily as the bituminous ash does. So even though the anthracite does not swell, it is possible that it is the ash that causes a restriction in the air supply to the bed, causing higher CO concentrations.

Table VI. Benzo(a)pyrene Emissions, 10^{-5} ng/J

Wood	Residential Stoves	Anthracite (This Study)	Industrial Units Bituminous-Fired	Utilities Oil-Fired
	Bituminous (This Study)			
1.8×10^5	7.6×10^3	11	(5,A) 7 (7,B) 2	(5,C) 0.04

(A) Reference 5, Table 3-1, page 3-3, power plants.

(B) Bituminous-fired industrial stoker boilers.

(C) Reference 5, Table 3-5, page 3-9.

Summary:

In conclusion it was found that emissions of particulates, extractable organics, PAH and volatiles were higher for bituminous coal than anthracite. The style of the stove, type of fuel and burn rate all effect the emissions. Thus when comparing overall emissions from the two stove styles, it is not clear which stove was less polluting (i.e. more efficient). Sulfur dioxide emissions are dependant upon both the firebox temperature and the alkalinity of the ash and are therefore expected to vary accordingly from test to test and stove to stove.

It should be noted that the values reported in this study represent a very small data base, thus this work should be considered a contribution to the literature in the field instead of a comprehensive evaluation of these combustion systems.

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