United States
Environmental Protection
Agency

Air and Energy Engineering
Research Laboratory
Research Triangle Park NC 27711

Research and Development

EPA/600/S7-87/010 May 1987

EPA

Project Summary

Environmental Assessment of a Wood-Waste-Fired Industrial Firetube Boiler

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This report gives emission results from field tests of a wood-waste-fired industrial firetube boiler. Emission measurements included: continuous monitoring of flue gas emissions; source assessment sampling system (SASS) sampling of the flue gas with subsequent laboratory analysis of samples to give total flue gas organics in two boiling point ranges, compound category information within these ranges, specific quantitation of the semivolatile organic priority pollutants, and flue gas concentrations of 65 trace elements; Method 5 sampling for particulates; controlled condensation system (CCS) sampling for SO_2 and SO_3; and grab sampling of boiler bottom ash for trace element content determinations.

Flue gas CO emissions were quite variable during the tests, and often quite high. Emissions ranged from about 100 to almost 10,000 ppm (dry, 3% O_2). The high emission levels were attributed to the high excess air level at which the unit operated, approximately 160%. NO_x emissions, at about 300 ppm (3%, O_2), were relatively high for a wood-fired boiler, although the fuel nitrogen content (0.18%) was relatively high for a wood fuel. SO_2 and SO_3 emissions were less than 10 ppm, in keeping with the low sulfur content of the wood-waste fuel. Total organic emissions from the boiler were 5.7 mg/dscm (3.4 ng/J heat input or 65 mg/kg fuel); about 90% of these consisted of volatile (boiling point less than 100°C) compounds. Emission levels of five polycyclic organic matter (POM) species and phenol were quantitated. Except for naphthalene, all species were emitted at concentrations less than 0.4 μg/dscm; naphthalene emissions were 3.3 μg/dscm.

Trace element composition data show selective concentration of several elements in emitted coarse fraction (>3 μm) particulate over boiler bottom ash. However, further concentration to fine fraction (<3 μm) particulate did not seem evident.

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

Introduction

In recent years wood has experienced a revival as a primary or alternate source of energy for steam raising in industrial boilers as well as space heating in the commercial and residential sectors. As an indirect consequence, emissions from wood combustion and associated air quality impacts have become of interest since recent studies have suggested that wood combustion can produce significant emissions of potentially hazardous organic pollutants. The report describes the results of comprehensive emissions testing of an industrial firetube boiler designed to burn wood waste from a furniture manufacturing plant. The flue gas was analyzed for criteria pollutants as well as total organic and several organic and inorganic species. The tests were conducted in conjunction with an independent test program by the North

Carolina Department of Natural Resources and Community Development (DNR) to measure POM species emissions from this boiler and other wood-fired boilers in North Carolina.

The tests were performed on a McBurney horizontal return tube, firetube boiler designed to fire wood waste. The boiler has a three-pass design with flyash reinjection. Rated capacity is 3.15 kg/s saturated steam (25,000 lb/hr) at 1.0 MPa (150 psig). The unit normally burns a mixture of pine, oak, hickory, glue, and ground masonite blown in by a pair of wood-feeder blowers. After combustion, the flue gas proceeds through three heat exchanger passes. Before entering the stack, the flue gas passes through a cyclone which separates the larger flyash particles for reinjection.

Summary and Conclusions

Boiler Operation

Table 1 summarizes the operating conditions for the tests performed. The fuel analysis is given in Table 2. The tests were conducted over a 6-hr period with no unusual operating difficulties. However, because of the relatively high average excess air level over the test period (160%), boiler efficiency was a modest 64.5%, based on the ASME heat loss calculation method. The wood waste flowrate noted in Table 1 is not a measured value: it was calculated based on measured stack gas flowrate (Method 5) and O_2 level, and the fuel analysis. This value should be treated with caution. If the expected steam flowrate is calculated based on the fuel flowrate and heating value and the boiler efficiency noted in Table 1, a value of 2.4 kg/s (19,400 lb/hr) results. This contrasts with the control panel steam meter reading of 1.7 kg/s (13,600 lb/hr). The calculated value is more likely to be nearly correct.

Emission Measurements and Results

The sampling and analysis procedures used in this test program conformed to a modified EPA Level 1 protocol. The flue gas measurements included:

- Continuous monitors for O_2, CO, and NO_x
- SASS
- CCS for SO_2 and SO_3
- EPA Method 5 for particulate
- Grab sample for onsite C_1–C_6 hydrocarbon analysis

Table 1. *Boiler Operating Conditions*

Steam flow, kg/s (10^3 lb/hr)	*1.71 (13.6)*
Drum pressure, MPa (psig)	*0.841 (122)*
Feed water pressure, MPa (psig)	*1.09 (158)*
Furnace outlet pressure, kPa (in. H_2O)	*0.25 (1.0)*
Collector pressure, kPa (in. H_2O)	*0.54 (2.10)*
Stack temperature, °C (°F)	*343 (650)*
Ambient air, °C (°F)	*25 (77)*
Wood flowrate kg/s (lb/hr)[a]	*0.514 (4,070)*
Excess air, percent[b]	*160*
Boiler efficiency, percent[c]	*64.5*

[a]As fired, calculated from stack gas flow, O_2, and fuel analysis.
[b]Calculated from the O_2 measurement and fuel analysis.
[c]Based on heat loss method.

Table 2. *Ultimate fuel Analysis (Percent by Weight)[a]*

Carbon, C	*47.60*
Hydrogen, H	*5.75*
Nitrogen, N	*0.18*
Sulfur, S	*0.04*
Oxygen, O (by difference)	*45.93*
Ash	*0.50*
Moisture[b]	*5.66*
Higher heating value, kJ/kg (Btu/lb)	*20,060 (8,630)*

[a]Dry basis, except as noted.
[b]As received.

In addition, samples of the boiler bottom ash and the wood fuel fired were collected for analysis.

The analysis protocol included:

- Analyzing the fuel, SASS train samples, and the mechanical collector hopper ash for 65 trace elements using spark source mass spectrometry (SSMS), supplemented by atomic absorption spectrometry (AAS)
- Analyzing SASS train samples for total organic content in two boiling point ranges: 100°C to 300°C by total chromatographable organics (TCO) analysis and >300°C by gravimetry (GRAV)
- Analyzing the SASS train sorbent module extract for 58 semivolatile organic species including many of the POM compounds
- Infrared (IR) spectrometry analysis of organic sample extracts
- Determining the alpha and beta radiometric activity of particulate and mechanical collector hopper ash samples
- Performing several mutagenicity and toxicity health effects bioassays and several aquatic toxicity ecological effects bioassays of SASS samples and the bottom ash

Table 3 summarizes exhaust gas emissions measured in the test program. Emissions are presented both as nanograms per Joule (ng/J) of heat input and micrograms per dry standard cubic meter (μg/dscm) of flue gas. CO emissions are presented as a range because CO concentrations exhibited too large a variation to allow defining a meaningful average.

As a measure of the relative potentia significance of the emissions, an occupational exposure guideline for eacr species is also noted in Table 3. The guideline noted is the time-weightec average Threshold Limit Value (TLV) These are noted only to aid in rankin the potential significance of pollutan species emissions. Conclusions regarding the absolute risk associated witl emission levels ocmpared to occupational exposure guidelines are not, an should not be, drawn. With respect t ranking, however, species emitted a levels several orders of magnitude highe than their occupational exposure guidelines might warrant further considera tion. Species emitted at levels signifi cantly lower than their occupation exposure guidelines could be considere of little potential concern. Only specie emitted at levels exceeding 100% of the occupational exposure guidelines ar noted in the table.

Table 3 shows that several trac elements were emitted at levels betwee 0.1 and 2 times their respective guid lines. For comparison, CO emissior ranged up to almost 50 times its occ pational exposure guideline; average N(emissions (as NO_2) were over 40 tim its guideline.

Table 3. Summary of Flue Gas Emissions

Criteria Pollutants and Other Vapor Species	Emissions: ng/J Heat Input	Emissions: µg/dscm	Occupational Exposure Guideline[a] (µg/m³)
CO	26 to 1,580	4.4×10^4 to 2.53×10^6	55,000
NO_x (as NO_2)	154	2.56×10^5	6,000
Particulate			
SASS	114	1.90×10^5	--
Method 5: solid	108	1.80×10^5	--
Method 5: condensible	1.1	1,900	--
DNR Method 5[b]: solid	127	2.00×10^5	--
Total gravimetric organics (GRAV) (C_{16+})	0.42	700	--
Total chromatographable organics (TCO) (C_7 to C_{16})	<0.006	<10	--
Total volatile organics (C_1 to C_6)	3.0	5,000	--
Trace Elements			
Nickel, Ni	0.11	190	100
Phosphorus, P	>0.072	>120	100
Barium, Ba	>0.11	>190	500
Lead, Pb	0.027	45	150
Chromium, Cr	0.0090	15	50
Potassium, K	>0.24	>400	2,000
Silver, Ag	0.0011	1.9	10
Copper, Cu	0.019	32	200
Iron, Fe	>0.084	>140	1,000

[a]Threshold Limit Value.
[b]North Carolina Department of Natural Resources and Community Development.

Emissions of sulfur oxides (SO_2 and SO_3) were sampled but not detected above a detection limit of 10 ppm in the flue gas. This is not entirely surprising since total conversion of the sulfur in the wood to SO_2 would have resulted in, at most, 26 ppm stack emissions.

Table 4 shows the emitted particle size distribution as determined by the SASS train. The preponderance of less than 1 µm particulate (51% by weight) agrees with expectations. Flyash reinjection should cause emitted particulate to be relatively fine.

Table 4. Particulate Size Distributions

Particle Size Cut	Emissions: ng/J	Emissions: mg/dscm	Emissions: Percent of Total Particulate
>10 µm (10 µm cyclone plus probe wash)	26	44	23.1
3 to 10 µm (3 µm cyclone)	18	29	15.5
1 to 3 µm (1 µm cyclone)	12	20	10.5
<1 µm (filter)	58	97	50.9
Total	114	190	100.0

Table 5 summarizes the organic emission results for this test. Most of the organics (88%) consist of species in the nominal C_1–C_6 boiling point range. No organics were present above the protocol detection limits in the nominal C_7–C_{16} boiling point range of 100°–300°C. The remaining 12% of the organics were in the nominal C_{16+} boiling point range of greater than 300°C. The semivolatile analysis result (nominally C_7–C_{16} organics with boiling points in the 100°–300°C range) is compromised somewhat because the XAD-2 sorbent resin used

Table 5. *Summary of Total Organic Emissions*

	mg/dscm	ng/J	mg/kg Fuel as Fired
Volatile organic gases analyzed in the field by gas chromatography:			
C_1	1.2	0.72	14
C_2	0.5	0.30	5.7
C_3	2.8	1.68	32
C_4	0.5	0.30	5.7
C_5	ND	ND	ND
C_6	ND	ND	ND
Total C_1–C_6	5.0	3.0	57
Semivolatile organics analyzed by TCO:			
XAD-2 cartridge	<0.01	<0.006	<0.11
Organic module condensate	<0.003	<0.002	<0.03
Total C_7–C_{16}	<0.01	<0.006	<0.01
Nonvolatile organics analyzed by gravimetry:			
Probe wash	<0.2	<0.12	<2.3
10 + 3 μm cyclones	<0.2	<0.12	<2.3
Filter + 1 μm cyclone	0.4	0.24	4.5
XAD-2 cartridge	0.3	0.18	3.4
Organic module condensate	<0.1	<0.06	<1.1
Total C_{16+}	0.7	0.42	7.9
Total organics	5.7	3.4	65

ND—Not detected.

in this test had been inadvertently contaminated with acetone, resulting in high analysis values both in the sample extract and field blank. Gas chromatography/mass spectrometry (GC/MS) analyses were performed to identify and quantify specific contaminant species, thereby allowing corrected sample and blank results to be defined. The resulting data are defensible, although still compromised to some degree.

Results of the GC/MS analysis of the XAD-2 resin extract for the semivolatile organic priority pollutants are shown in Table 6. All species present, except phenol in the organic model condensate, were detected only in concentrations above the detection limits in the XAD-2 extract. Naphthalene was the POM compound emitted in the greatest quantity. Results from the DNR POM emissions tests are also shown in Table 6, and indicate relatively good agreement among findings.

Bioassays were performed on the bottom ash, a composite particulate sample, and the XAD-2 extract. The various health effects assays performed were the Ames mutagenicity assay, the CHO cytotoxicity assay, the rabbit alveolar macrophage (RAM) cytotoxicity assay, and the whole animal acute toxicity (WAT) test in live rodents. The results of these assays are summarized in Table 7.

Bottom ash samples were also tested in ecological effects assays for acute toxicity to freshwater invertebrates (*Daphnia magna*), freshwater fish (fatheat minnow, *Pimephales promelas*), and freshwater algae (*Selenastrum capricornutum*). Table 8 summarizes the results of these tests. Results in the tables suggest that the composite particulate and the bottom ash were of nondetectable mutagenicity and of nondetectable to low toxicity, while the XAD-2 extract was of moderate toxicity and mutagenicity.

Conclusions

Emissions tests of a wood-waste-fired industrial firetube boiler suggest that emissions of potential concern can arise from inefficient (high excess air) operation of the unit. In the tests performed, CO emissions varied from under 200 ppm (corrected to 3% O_2) with flue gas O_2 under 12%, to almost 10,000 ppm (3% O_2) with flue gas O_2 almost 17%. Total organic emissions at 3.4 ng/J heat input were relatively low for a wood-fired boiler. POM emissions (less than 0.4 μg/dscm for most species, 3.3 μg/dscm for napththalene) were at the high end of the range typical for coal-fired industrial boilers.

Table 6. *POM and Other Organic Species Emission Summary*

Compound	This Study		DNR 1[a]		DNR 2[a]	
	μg/dscm	μg/kg fuel[b]	μg/dscm	μg/kg fuel[b]	μg/dscm	μg/kg fuel[b]
Acenaphthylene	0.30	3.4	NA	NA	NA	NA
Fluoranthene	0.08	0.9	ND	ND	ND	ND
Naphthalene	3.3	37.5	6.34	83.2	0.85	12.1
Phenanthrene	0.30	3.4	ND	ND	ND	ND
Pyrene	0.20	2.3	ND	ND	0.30	4.3
Phenol	0.38[c]	4.3	NA	NA	NA	NA
Detection limit	0.04	0.5	0.12	1.6	0.08	1.2

NA—Compound not analyzed.
ND—Compound not detected above detection limit.
[a]North Carolina Department of Natural Resources and Community Development.
[b]Dry basis.
[c]60 percent of phenol noted detected in the organic module condensate; all other results from XAD-2 extract only.

Table 7. *Health Effects Bioassay Results*

Sample	Bioassay			
	Ames[a]	CHO[b]	RAM[b]	WAT[b]
Bottom ash	ND	NP	L/ND	ND
Composite particulate	ND	NP	L	NP
XAD-2 extract	M	M	NP	NP

ND—Nondetectable
L—Low.
M—Moderate.
NP—Assay not performed.

[a]Mutagenicity test.
[b]Toxicity test.

Table 8. *Ecological Effects Bioassay Results for the Boiler Bottom Ash*

Algae	Daphnia	Freshwater Fish
L	L/ND	ND

L—Low toxicity.
ND—Nondetectable toxicity.

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The complete report consists of two volumes, entitled "Environmental Assessment of a Wood-Waste-Fired Industrial Firetube Boiler:
"Volume I. Technical Results," (Order No. PB 87-176 285/AS; Cost: $13.95)
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