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HAZARDOUS AIR EMISSIONS POTENTIAL FROM A WOOD-FIRED FURNACE

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ABSTRACT

During the first week of April, 1991 the Wisconsin Department of Natural Resources (WDNR) conducted a series of air emissions tests of a small industrial wood-fired boiler in northern Wisconsin. The boiler was firing a virgin hogged wood/wood waste fuel with a moisture content of about 35 percent. The pollutants measured were particulates, nitrogen oxides (NO_x), carbon monoxide (CO), total hydrocarbons (THC), benzene, formaldehyde (CHOH), polycyclic organic matter (POM, e.g. benzo (a) pyrene), aldehydes, and trace metals (As, Ba, Cu, Pb, Mn, Ni, K, Se, Na, and Zn).

For two and a half days continuous emissions data were recorded by laboratory-certified continuous emissions monitors for CO, NO_x, O_2, THC, and CO_2 while the EPA reference method stack tests were being conducted by a stack testing firm for the pollutants mentioned in the first paragraph. In addition, a WDNR test team measured CO, O_2, and flue gas temperature with a Rosemount portable combustion analyzer for several hours over the course of those two and a half days.

The principal purpose behind the study was to evaluate the hazardous air emissions potential of a small industrial furnace firing a virgin wood fuel. To that end, it was hoped that a surrogate pollutant could be identified which would represent the levels of hazardous air emissions (e.g., benzene) present in the wood-fired furnace flue gases. If a readily monitorable pollutant could be identified, then a regulatory strategy of measuring one representative pollutant could be put in place to continually assess the hazardous emissions potential of virgin wood combustion.

HAZARDOUS AIR EMISSIONS POTENTIAL FROM A WOOD-FIRED FURNACE

INTRODUCTION

On October 1, 1988 the State of Wisconsin Department of Natural Resources promulgated a rule regulating hazardous air pollutants. This rule, which appears as chapter NR 445, Wisconsin Administrative Code, regulates new as well as existing sources of air pollution in Wisconsin. Consequently, all permits to operate an air pollution source in Wisconsin must address the hazardous air emissions potential of the source.

Especially in the northern areas, Wisconsin has a significant population of wood-fired boilers. Wood is a convenient source of energy in Wisconsin and has appeal if for no other reason than it is renewable. While widely perceived as a clean-burning fuel, wood is often burned in a manner which clearly results in significant emissions of very hazardous air pollutants. Residential wood stoves, for example, emit approximately 0.5 pound of formaldehyde per ton of wood fired according to U.S. EPA (1). But wood stoves are not industrial furnaces, so the question for air pollution engineers is "What is the hazardous air pollution potential of industrial wood combustion?"

This paper presents the results of the wood combustion study conducted by the Wisconsin Department of Natural Resources (DNR) at Birchwood Lumber & Veneer during the first week of April, 1991. The new wood-fired boiler at Birchwood Lumber & Veneer represents a common size and type of boiler for northern Wisconsin which is why we selected this unit for study.

The pollutants selected for measurement were particulates, nitrogen oxides (NO_x), carbon monoxide (CO), total hydrocarbons (THC), benzene, formaldehyde (CHOH), polycyclic organic matter (POM, e.g. benzo (a) pyrene), aldehydes, and trace metals (As, Ba, Cu, Pb, Mn, Ni, K, Se, Na, and Zn). Of particular interest to Wisconsin DNR were (and are) the emissions of benzene, CHOH, POM, arsenic, and nickel from wood combustion, because all of these substances are known to cause or suspected of causing cancers in humans. Since very little data are available for the emissions of these substances from the combustion of "virgin" wood, we have taken it upon ourselves to contribute something to the understanding of the hazardous air emissions potential of wood-fired furnaces.

DESCRIPTION OF EMISSIONS TESTING

The emissions tests were conducted at Birchwood Lumber & Veneer Company (B L & V) in Birchwood, WI. This site was selected for the study because it offers both a new wood-fired boiler and an old wood-fired boiler (circa 1918) retrofitted with a modern sawdust firing system. While the new boiler fires a hogged wood with a spreader stoker and the older boiler fires a sawdust/sanderdust mixture with a pneumatic feeder, at least the wood species (red oak and some aspen) is common between the two units. Thus, one site was able to provide opportunities to quantify emissions from two fuels and two firing systems, all of which are in common use in Wisconsin.

Equipment Description: New Spreader Stoker Boiler

On August 9, 1990 the Wisconsin DNR issued a permit to construct and operate a 20.01 million BTU per hour (MMBTU/hr) wood-fired boiler to Birchwood Lumber & Veneer Co. Construction of the boiler was completed by January of 1991 and an initial operation period culminated with initial emissions performance testing on April 5, 1991.

The new boiler at B L & V is a 400 HP two-pass wood waste boiler manufactured by Industrial Boiler Company, Inc. of Thomasville, GA, Model No. Modul - Pak II - 400. Figure 1 is a sectional view of the boiler. The boiler system uses a screw auger-fed spreader stoker configuration and employs fly ash reinjection. The furnace, shown at the lower left in the figure, is equipped with overfire air ports located at an elevation about one quarter of the distance from the grate to the furnace exit. The overfire air ports are represented in Figure 1 by a horizontal pipe which penetrates the boiler wall at the lower right of the furnace section. Underfire air, represented by the manifold across the bottom of the furnace section in Figure 1, serves as both a source of combustion air as well as a fuel fluidizing mechanism.

A multiple-cyclone particulate emissions control system, IBC Model No. MU 12/10, treats the flue gases prior to atmospheric discharge. The operating pressure drop of the control device is approximately 3.5 inches water gauge. The estimated control efficiency (for particulates) of the multiple-cyclone is 75 percent.

Equipment Description: Existing Auger-Type Stoker Boiler

Boiler No. 2 at B L & V is a 100 HP horizontal return tube (HRT) wood waste-fired boiler manufactured by Kewaunee Boiler Corporation in 1918. The boiler system uses a recently-retrofitted G & S Automatic Stoker manufactured by The G & S Mill, Inc. of Northborough, MA to meter the two fuels for the boiler (sawdust and sanderdust) into the

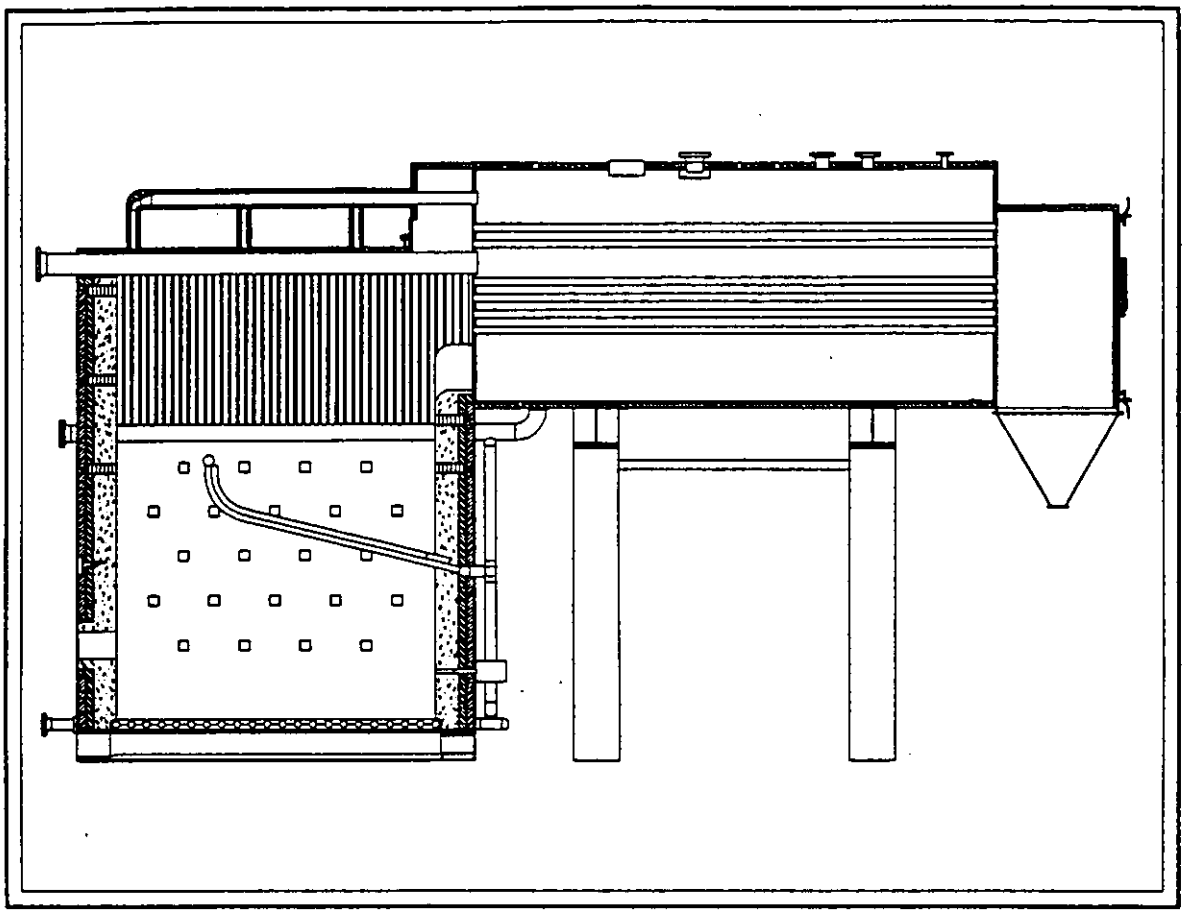

Figure 1. SECTIONAL VIEW OF FURNACE AND CONVECTIVE PASSES OF BOILER NO. 3 AT BIRCHWOOD LUMBER & VENEER

furnace. Figure 2 shows a typical G & S Mill furnace retrofit for a HRT boiler, much like the one for Boiler No. 2 at Birchwood Lumber & Veneer.

A corrosion-resistant fuel bin incorporates an auger feed mechanism with dual vibrators to prevent bridging of the fuel. The main screw auger is powered by a 5 HP auger drive which drops fuel into a firebox screw auger powered by a 2 HP auger drive. The physical break between the two screw augers is intended for firebreak protection. In addition, the firebox auger has an extended on-cycle to purge itself of fuel after each feed sequence.

The combination bin/stoker accurately meters the pulverized wood fuel to the furnace on a timed, rhythmic sequence. Through initial adjustment of the combustion air volume and fuel feed rate, a proper balance of the two is maintained within the firebox. To satisfy the demand for high fire or low fire operation, the combustion air and fuel feed rates are automatically increased or decreased in proportion. The control panel at the upper right of Figure 2 represents this combustion control.

The Automatic Stoker rear-feeds the combustion chamber, with fuel being pushed forward over the force-drafted horizontal grates. Overfire air ports are carefully located and are used to aerodynamically control the flame front within the furnace. The remaining combustion air completes the tuning of the furnace for optimal operation.

There is no air pollution control equipment associated with Boiler No. 2.

Description of Testing Strategy

One of the goals of the study was to investigate the role of overfire air in the quality of wood combustion. Boiler No. 3, the IBC boiler, is equipped with dampered overfire and underfire air headers. This flexibility is useful for tuning the furnace in terms of combustion air and it provided an opportunity for studying the hazardous emissions potential for wood combustion as a function of combustion air configuration. Consequently, the emissions testing program, which extended over four full days, included a wide range of overfire and underfire air settings.

A second goal of the study was to investigate the correlation between the carbon monoxide (CO) concentration in the flue gas and levels of hazardous air pollutants. Since carbon monoxide is a product of incomplete combustion, its presence in a flue gas represents a departure from ideal combustion conditions. If it could be shown that CO concentration is well correlated with levels of hazardous air contaminants during the combustion of wood, then CO

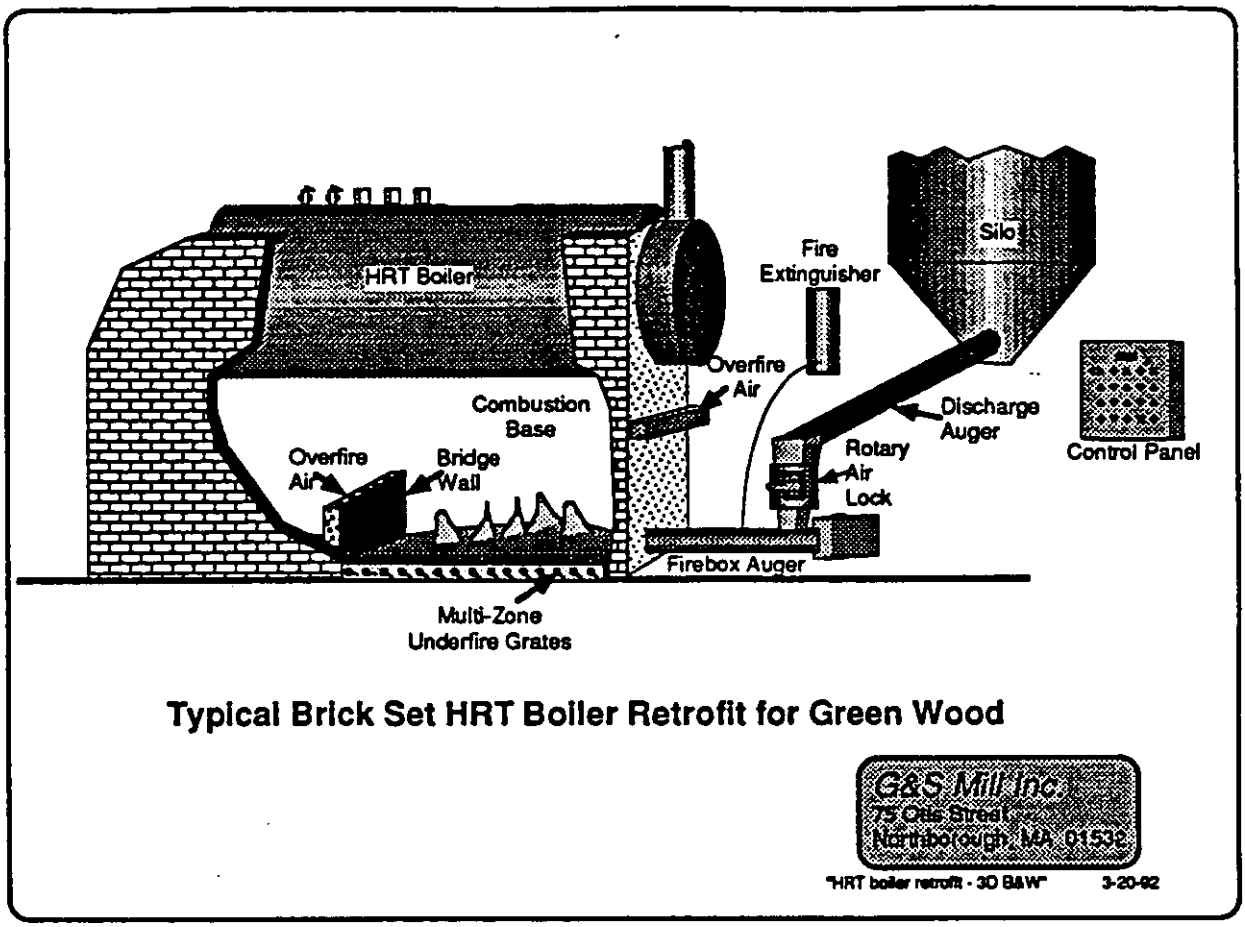

Figure 2. SCHEMATIC DIAGRAM OF BOILER NO. 1 AT BIRCHWOOD LUMBER & VENEER

would indicate the hazardous emissions potential of wood combustion.

The third major goal of the study was to measure the levels of hazardous air pollutants from the combustion of ordinary wood. Other investigators have measured emissions from various fuels derived from wood, including railroad ties, plywood, particleboard, and various other waste materials containing wood. Such waste fuels are burned in Wisconsin, but a great many industrial facilities burn only "virgin" wood. So the question for Wisconsin's air pollution regulatory agency has been, "How can we quantify the levels of hazardous air contaminants resulting from the combustion of ordinary wood?" In the absence of anything else, we have been forced to use emissions data which may not be entirely appropriate for virgin wood burning. The emissions data presented in this paper begin to fill this void.

Description of Emissions Test Methods

The Wisconsin Department of Natural Resources hired Interpoll Laboratories, Inc. of Circle Pines, MN to perform the emission measurements. All of the flue gas samples were taken from the boiler stacks and analyzed according to test methods and procedures accepted by U.S. EPA and Wisconsin DNR. In addition, Interpoll's mobile laboratory was used to continuously monitor carbon dioxide (CO_2), oxygen (O_2), carbon monoxide (CO), nitrogen oxides (NO_x), and total hydrocarbons (THC) during the first three days of the pollutant determinations. Interpoll also measured and recorded the furnace exit temperature every ten minutes during each test condition using an optical pyrometer.

Testing on Boiler No. 3 was conducted using a set of four test ports oriented at 90 degrees on the stack. These test ports are located 4.5 stack diameters downstream of the nearest flow disturbance and 5.8 stack diameters upstream of the stack exit. A 24-point traverse was used to isokinetically collect representative particulate, trace metals, and modified Method 5 samples; each traverse point was sampled for 2.5 minutes to give a total sampling time of 60 minutes per run. A three-point traverse was used to collect formaldehyde samples; each traverse point was sampled for 10 minutes to result in a total of 30 minutes per run. Benzene sampling was conducted using a single-point traverse; three one-hour runs were performed for each test condition.

Particulates and Trace Metals. Particulate and trace metals evaluations were performed in accordance with EPA Draft Procedure "Methodology for the Determination of Trace Metal Emissions in Exhaust Gases from Stationary Source Combustion Processes". This methodology provides for front-half particulate emission measurement by performing a

gravimetric analysis of the acetone rinses of the probe and filter assembly and of the quartz filter catch. A preliminary determination of the gas linear velocity profile was made before the first particulate and trace metals determination to allow selection of the appropriate nozzle diameter required for isokinetic sampling.

The standard multi-metal modified Method 5 sampling train was used to isokinetically collect solid and vapor phase trace metals from the exhaust gas stream. The aerosol or solid phase trace metal samples were collected on Pallflex Type 2500 QAT ultra pure filters. The vapor phase trace metals were collected in an all-glass impinger train. The first and second impingers each contained 100 cc of a mixture of 5 percent HNO_3 and 10 percent H_2O_2. The third impinger was empty and served as a trap.

The recovered three-part trace metal samples were combined, solubilized in acid and analyzed by inductively-coupled argon plasma emission spectrometry (ICP) except for arsenic and selenium which were determined by graphite furnace atomic absorption spectrometry (GF/AA). A field-biased blank was collected and recovered at the test site and analyzed with the field samples.

Formaldehyde and Benzene. Formaldehyde determinations were conducted according to Draft EPA Method 0011. The samples were analyzed in accordance with EPA Method 8315. Acidic 2,4,dintrophenylhydrazine is used for collection. Analysis of the aldehydehydrazone reaction products is accomplished by high performance liquid chromatography (HPLC) with ultraviolet detection at 360 nanometers.

Benzene sampling was performed in accordance with EPA Method 18, Section 7.4, using 800/200 mg charcoal tubes with an upstream silica gel desiccant tube to dry the gas stream. The samples were analyzed by the gas chromatograph-flame ionization detection (GC/FID) method required under NIOSH Method 1501.

An integrated flue gas sample was extracted simultaneously with each of the formaldehyde and benzene sampling trains using a specially designed gas sampling system. Integrated flue gas samples were collected in 44-liter Tedlar bags housed in a protective aluminum container. After sampling was complete, the bags were sealed and returned to the laboratory for Orsat analysis. Prior to sampling, the Tedlar bags are leak-checked at 15 inches of mercury (vacuum) with an in-line rotameter. Bags with any detectable inleakage are discarded.

Polycyclic Organic Matter and Phenols. The semi-volatile compounds were extracted from the stack in accordance with the EPA Method 0010 SW846 Modified Method 5 sampling procedure for the EPA List of Hazardous Substances

to include POMs (polycyclic organic matter) and phenols. The four-part sample and field blank were extracted, concentrated to 1000 microliters and cleaned prior to final concentration and analysis according to Interpoll Labs Method II 8904-2. The samples were analyzed in accordance with EPA Method 8270 by HRCG/LRMS using electron impact (EI) with total ion monitoring (TIM). Quantification was performed using the six standard M-8270 internal standards. In order to document collection efficiency and sample recovery, each XAD-2 resin cartridge was field-spiked with d_{10}-fluoroanthene prior to the beginning of each test run.

Continuous Emissions Monitoring. The instrumental monitoring was conducted according to EPA Methods 3A, 7E, 10, and 25A, 40 CFR Part 60, Appendix A (as revised July 1, 1990). A slipstream of exhaust gas was drawn from the flue gas stream using a test port provided by the plant. The sample gas was filtered hot and transported via a heat-traced teflon line from the filter holder outlet to the dryer. This dry, particulate-free gas sample then entered the CO_2, O_2, CO, and NO_x analyzers. A small slipstream of the flue gas sample was drawn off upstream of the dryer for the total hydrocarbon analysis.

NO_x concentrations were measured by a chemiluminescent analyzer. CO concentrations were measured with nondispersive infrared (NDIR) spectrophotometry. THC concentrations were determined with a Ratfisch Model RS55 heated flame ionization detector (HFID). Oxygen and carbon dioxide concentrations were measured with paramagnetic and NDIR analyzers, respectively. Each analyzer was calibrated against commercially-obtained standard gases. The analog output of each analyzer was monitored with a multi-point stripchart recorder. The charts were manually processed to derive one-hour averages for each measured gas.

RESULTS OF EMISSIONS TESTING

The results of the emissions testing program are presented in a series of tables and plots. Several trends emerge, although further study would be required to establish clear linkages between the combustion parameters and the emissions of interest. In addition, a summary of non-criteria pollutant emission factors for wood combustion appears in the paper and represents a significant contribution to the scientific understanding of the nature of wood combustion.

It is apparent from the testing at Birchwood that the furnace CO and oxygen levels are inversely related. Figure 3, which illustrates the carbon monoxide and oxygen levels measured during normal operation of Boiler No. 3, suggests that a properly operating wood-fired furnace can sustain a relatively steady combustion condition even with oxygen

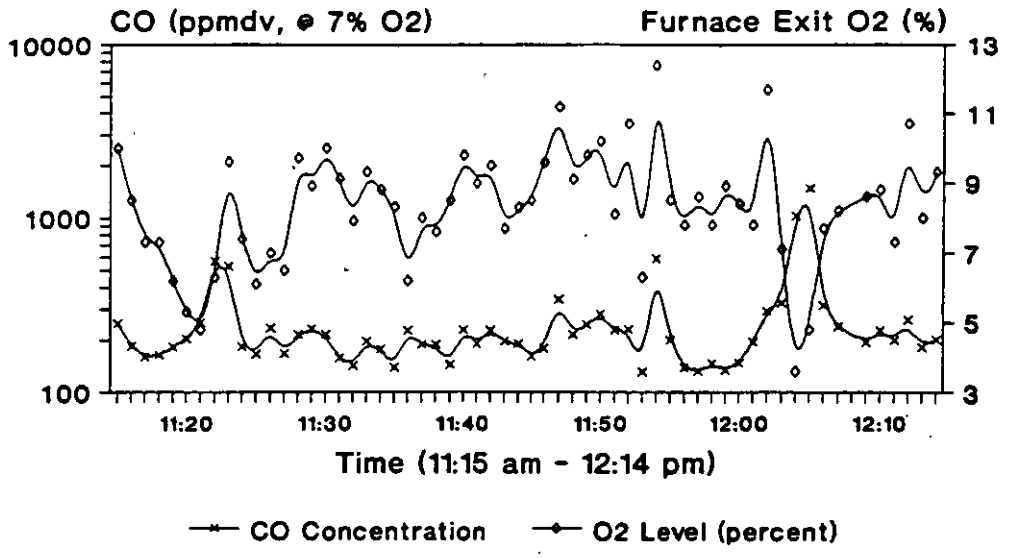

Figure 3. CARBON MONOXIDE AND OXYGEN TRENDS DURING NORMAL OPERATION OF BOILER NO. 3

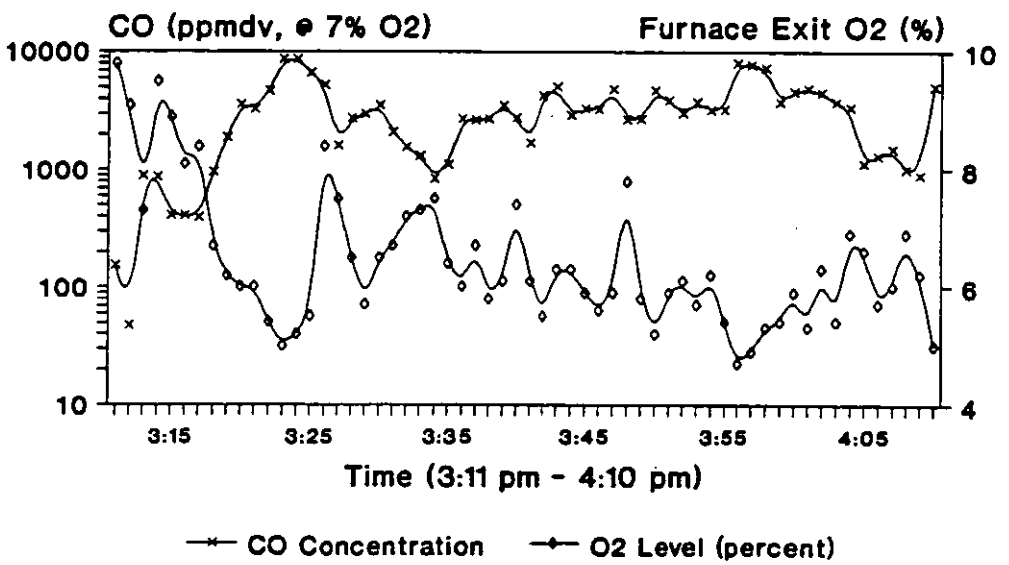

Figure 4. CARBON MONOXIDE AND OXYGEN TRENDS DURING POOR COMBUSTION CONDITIONS FOR BOILER NO. 3

fluctuations. It is also apparent from Figure 3 that when this boiler's oxygen level decreased substantially, a moment or two later the furnace CO concentration increased dramatically.

The testing at Birchwood also showed that the CO concentration within a wood-fired furnace can vary over nearly three orders of magnitude, as Figure 4 demonstrates. This is significant because the results of this study also suggest that the emissions of products of incomplete combustion, such as benzene and polycyclic organic matter, tend to follow CO concentration.

Tables 1, 2, 3 and 4 examine the correlation between the oxygen (O_2), carbon monoxide (CO), and total hydrocarbon (THC) concentrations in the flue gas, and furnace temperature and levels of hazardous air pollutants. All of the emissions data for benzene, formaldehyde, and polycyclic organic matter measured during the testing of Boiler No. 3 (the new boiler) are contained within these tables. Notice that the carbon monoxide measurement is often preceded by a "greater than" sign. This means that the true value of the hourly average CO concentration is somewhat higher than the reported value. The reason for this is that the span of the CO monitor was set at 1000 ppm before the tests began in anticipation of 1000 ppm being the maximum measurement. As we discovered during the study, the new boiler at Birchwood can easily have a flue gas CO concentration of 2000 ppm.

For polycyclic organic matter, there are two sets of emissions reported. The State of Wisconsin DNR regulates only the ten POMs with clear carcinogenic potential in Chapter NR 445, Wis. Adm. Code, Control of Hazardous Pollutants. U.S. EPA places a great many more POMs on its hazardous substance list, so this result represents a broader view of the POM emission potential. Thus, Table 3 compares the aforementioned combustion parameters with the measured emissions of the Wisconsin-listed polycyclic organic matter, whereas Table 4 compares these combustion parameters with the measured emissions of the EPA-listed polycyclic organic matter.

When the benzene, formaldehyde, and POM emissions data are plotted versus combustion air ratio (see Figure 5), a <u>family</u> of concave upwards curves results. In other words, Boiler No. 3 apparently may be set up with a combustion air configuration which <u>minimizes hazardous air pollution</u>. A close look at Figure 5 reveals that this result is especially true for benzene and POM emissions. If the balance of combustion air heavily favors underfire air, there is apparently insufficient combustion air in the upper furnace to complete the combustion of the products of incomplete combustion (PICs) which are formed during the early stages of combustion. Conversely, with excessive overfire air, the flame quenching effect of too much

Table 1. A COMPARISON OF BENZENE EMISSIONS WITH FLUE GAS OXYGEN, CARBON MONOXIDE AND TOTAL HYDROCARBON CONCENTRATION, AND FURNACE TEMPERATURE

Emissions (lb/ton)	O_2 (%)	CO (@ 7% O_2)	THC	Furnace Temp. (°F)
0.00127	8.70	191	1.0	2238
0.00773	5.00	>652	36	2425
0.00385	8.50	>516	2.7	2301
0.02178	5.80	>441	99	2503
0.00315	5.97	>524	87	2443
0.00252	11.67	218	0	2256

Table 2. A COMPARISON OF FORMALDEHYDE EMISSIONS (NEW BOILER) WITH FLUE GAS OXYGEN, CARBON MONOXIDE AND TOTAL HYDROCARBON CONCENTRATION, AND FURNACE TEMPERATURE

Emissions (lb/ton)	O_2 (%)	CO (@ 7% O_2)	THC	Furnace Temp. (°F)
0.00126	6.90	>515	27	2468
0.00179	6.13	>480	210	NM
0.01209	7.77	>524	30	NM
0.00231	8.39	>627	36	2207
0.00268	8.39	>627	36	2207
0.00291	9.82	>479	24	2171
0.00137	9.82	>479	24	2171
0.00412	9.82	>479	24	2171
0.00234	NM	NM	NM	NM

NM = No Measurement

Table 3. A COMPARISON OF POLYCYCLIC ORGANIC MATTER EMISSIONS (WISCONSIN LIST) WITH FLUE GAS OXYGEN, CARBON MONOXIDE AND TOTAL HYDROCARBON CONCENTRATION, AND FURNACE TEMPERATURE

Emissions (lb/ton)	O_2 (%)	CO (@ 7% O_2)	THC	Furnace Temp. (°F)
0	8.70	191	1.0	2238
0	5.00	>652	36	2425
0	8.50	>516	2.7	2301
1.87×10^{-5}	5.80	>441	99	2503
0.41×10^{-5}	5.97	>524	87	2443
0.54×10^{-5}	11.67	218	0	2256
0	12.63	486	0	1919
0	8.39	>627	36	2207
0	9.82	>479	24	2171

Table 4. A COMPARISON OF POLYCYCLIC ORGANIC MATTER EMISSIONS (U.S. EPA LIST) WITH FLUE GAS OXYGEN, CARBON MONOXIDE AND TOTAL HYDROCARBON CONCENTRATION, AND FURNACE TEMPERATURE

Emissions (lb/ton)	O_2 (%)	CO (@ 7% O_2)	THC	Furnace Temp. (°F)
0.00060	8.70	191	1.0	2238
0.00212	5.00	>652	36	2425
0.00356	8.50	>516	2.7	2301
0.00461	5.80	>441	99	2503
0.00075	5.97	>524	87	2443
0.00218	11.67	218	0	2256
0.00112	12.63	486	0	1919
0.00065	8.39	>627	36	2207
0.00244	9.82	>479	24	2171

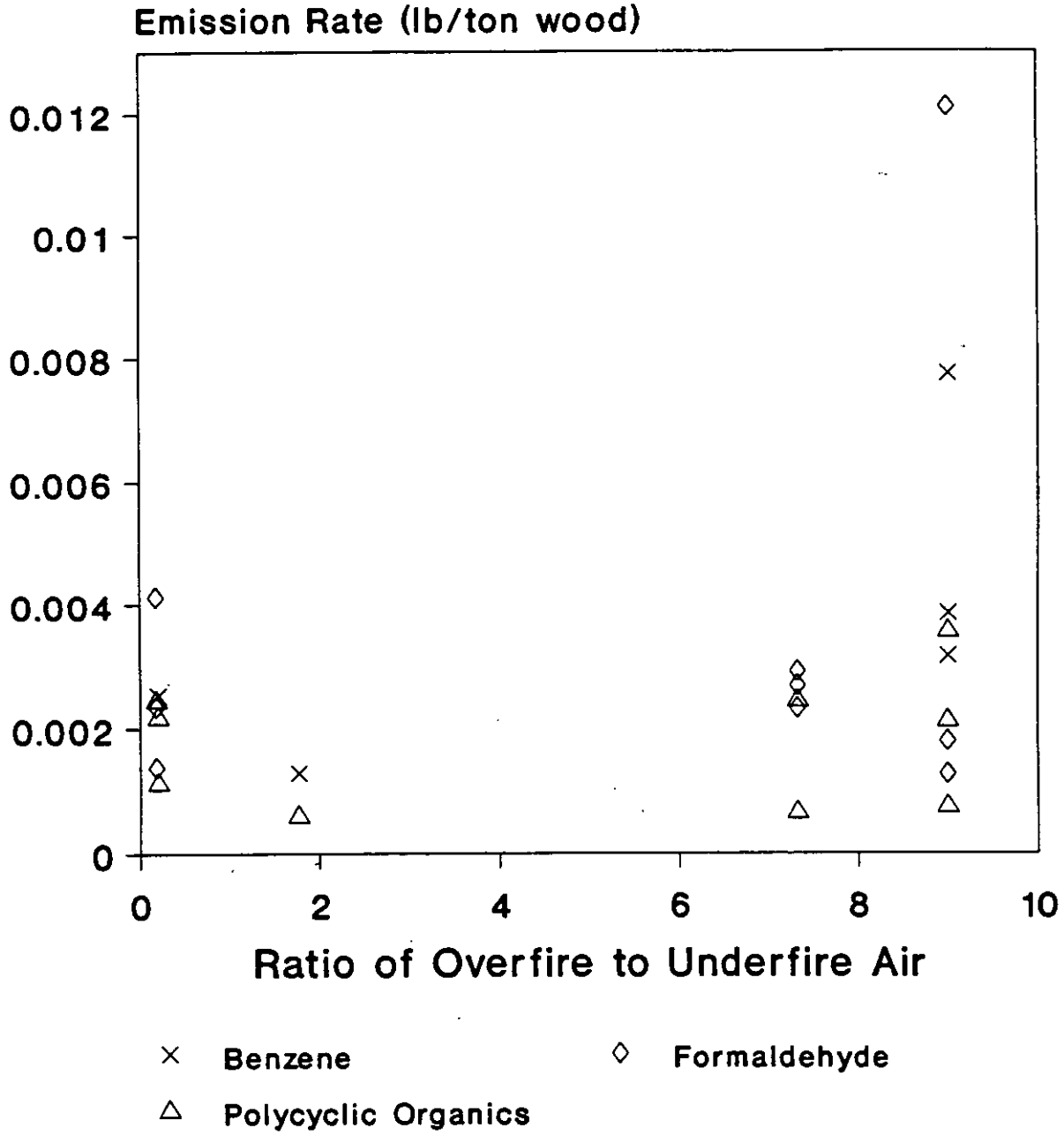

Figure 5. HAZARDOUS EMISSIONS FROM BOILER NO. 3 VS. COMBUSTION AIR RATIO

combustion air in the upper furnace appears to suppress the combustion of the PICs at that stage of the combustion process. In addition, PIC formation may have been exacerbated by the relatively starved combustion conditions at the fuel bed resulting from the shift of combustion air from the lower furnace to the overfire air ports.

The hazardous air pollution-minimizing behavior shown in Figure 5 is generally not exhibited by trace metal emissions. Figure 6 presents the relationships between arsenic, lead, manganese, and nickel emissions and combustion air ratio. While the plot of lead emissions versus combustion air ratio is clearly concave upwards, lead represents the exception rather than the rule for trace metal emissions. Of course this trend is not surprising, since trace metal emissions are not products of incomplete combustion and as such are not affected by combustion air configuration.

On the other hand, one might suspect that a very high proportion of underfire air might enhance the emission of trace metals due to a shearing of metals from the fuel which might otherwise remain with the bottom ash. However, this supposition is not borne out by the results of this study. Considering all of the trace metal emissions data, there appears to be no relationship whatsoever between these emissions and combustion air configuration.

Figures 7, 8 and 9 investigate the dependence of hazardous emissions on carbon monoxide (CO) levels. That carbon monoxide concentration indicates the hazardous emission potential of wood combustion is well illustrated by the plot of benzene emission rate as a function of CO (Figure 7). This correlation is less evident in Figures 8 and 9, which present formaldehyde and POM emissions as a function of CO concentration.

While formaldehyde emissions from the old boiler were also evaluated, those tests did not include continuous emission monitoring for oxygen, carbon monoxide, or total hydrocarbons. Nevertheless, Figure 8 compares the formaldehyde emissions from the old and new boilers. It is evident that the older boiler emitted formaldehyde at a significantly higher rate.

Part of this higher emission rate may be explained by the presence of formaldehyde-based resins in the sawdust and sanderdust which fuel the old boiler. These fine fuels are generated by various veneer mill operations including resin hot press stations. However, the quantity of resin that is actually used, coupled with the amount of such material that would be sanded or sawed from the veneered pieces is so small that only a slight contribution to boiler formaldehyde emissions should result from the mill's resin use. Perhaps boundary layer effects associated with low-flow regions

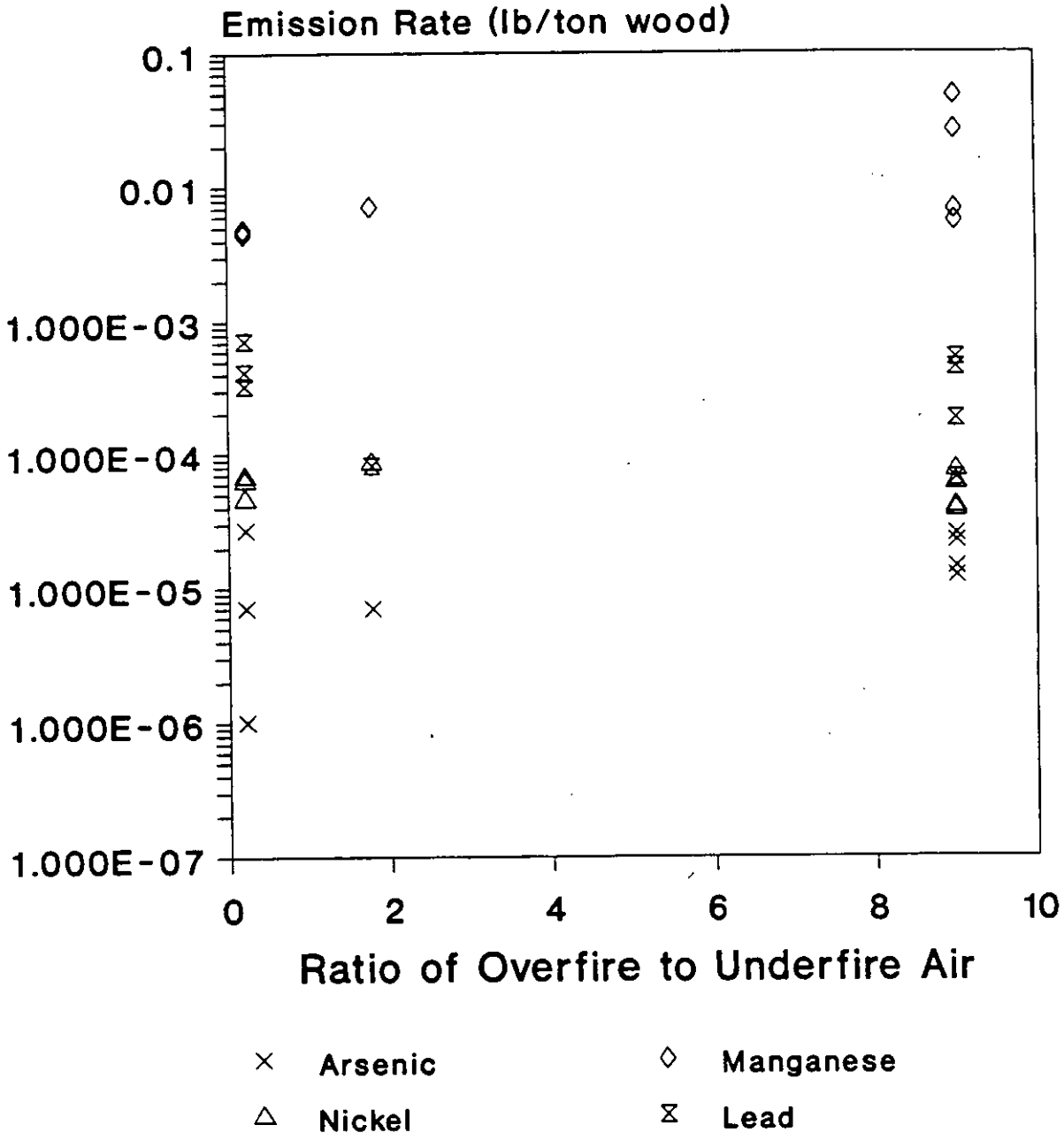

Figure 6. TRACE METAL EMISSIONS FROM BOILER NO. 3 VS. COMBUSTION AIR RATIO

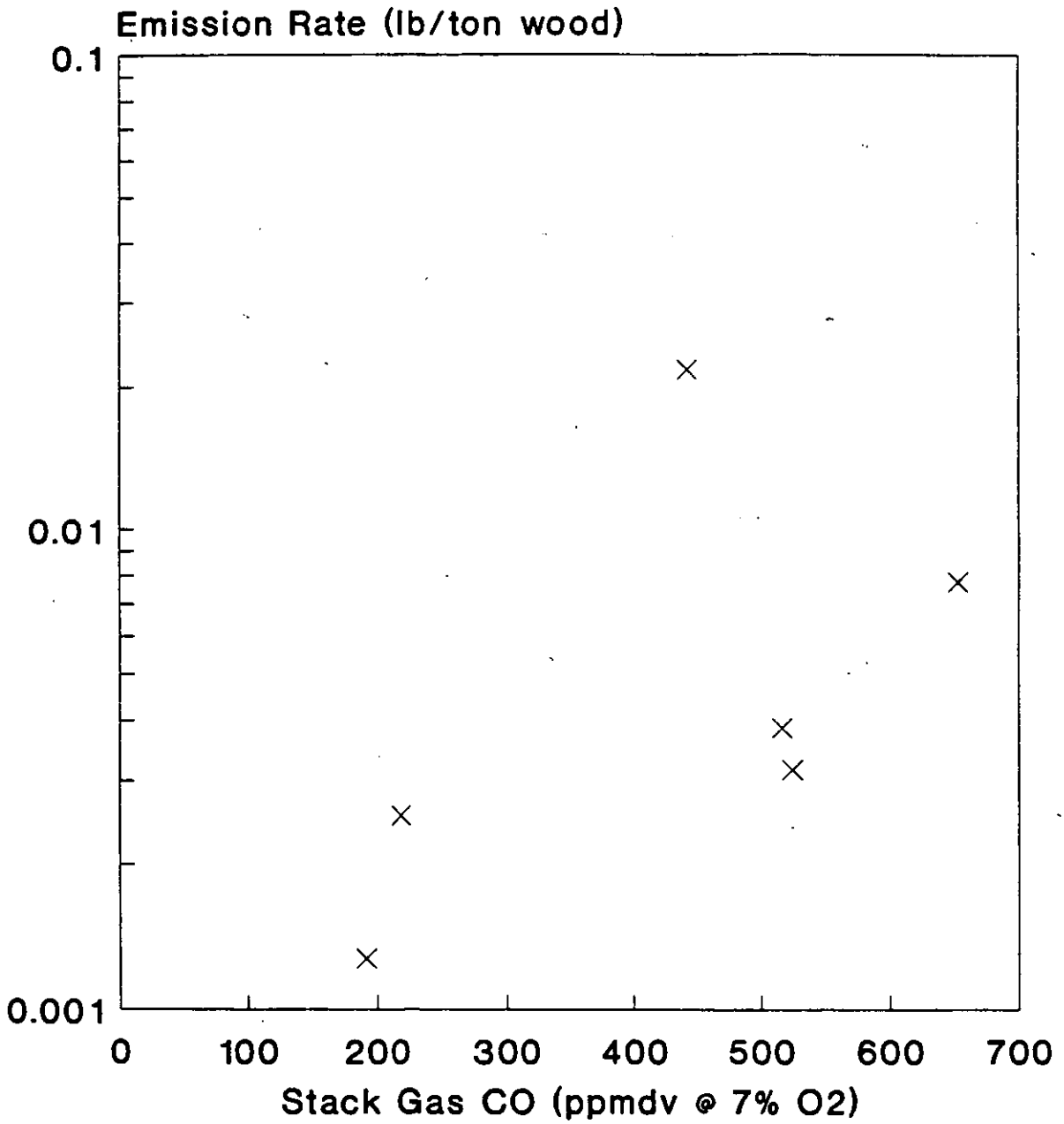

Figure 7. BENZENE EMISSIONS VS. CARBON MONOXIDE (CO) CONCENTRATION AT BIRCHWOOD LUMBER & VENEER

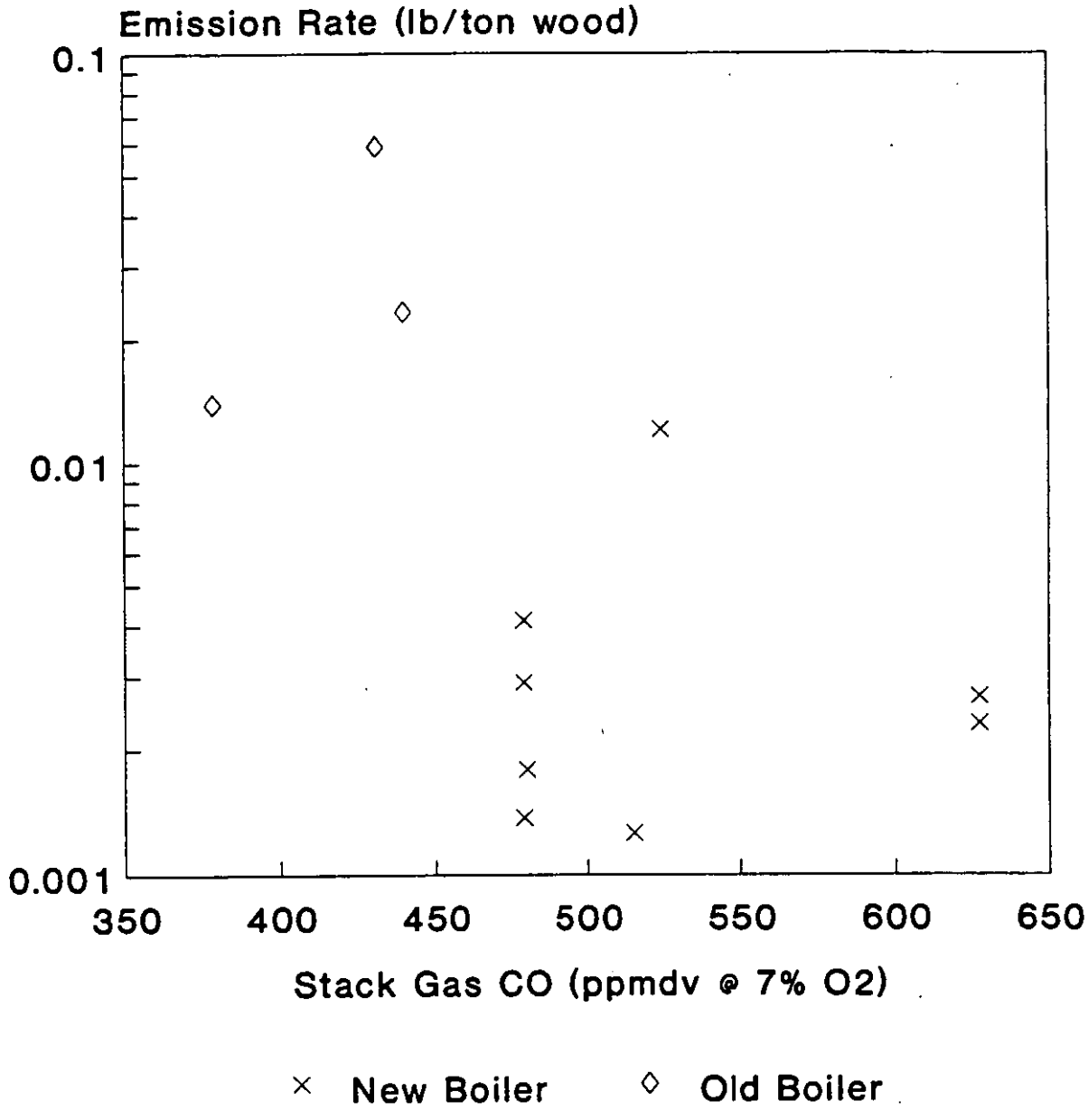

Figure 8. FORMALDEHYDE EMISSIONS VS. CARBON MONOXIDE (CO) CONCENTRATION AT BIRCHWOOD LUMBER & VENEER

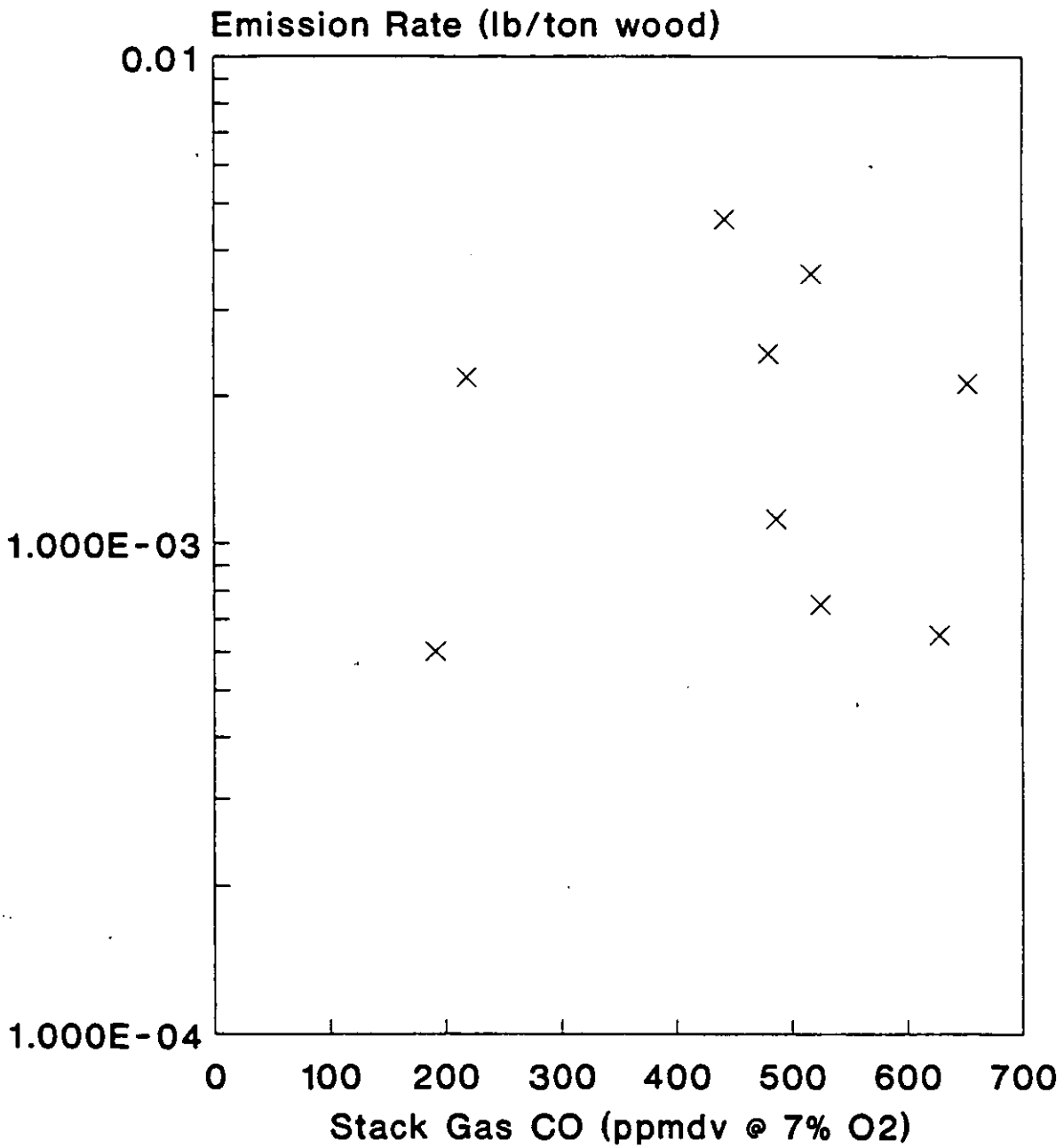

Figure 9. POLYCYCLIC ORGANIC MATTER EMISSIONS VS. CARBON MONOXIDE (CO) CONCENTRATION @ BIRCHWOOD LUMBER & VENEER

within the old boiler's furnace permit localized poor combustion conditions leading to a "slippage" of products of incomplete combustion, such as formaldehyde, through the furnace. Whatever the reason, the general trend of increasing formaldehyde emissions with increasing CO concentration is exhibited by both boilers.

Table 5 summarizes the relationships between flue gas carbon monoxide concentration and trace metal emissions. Figures 10, 11, 12 and 13 investigate the dependence of trace metal emissions on carbon monoxide (CO) levels. Arsenic (Figure 10) and lead (Figure 11) emissions are especially well correlated with CO. For the other two trace metal emission rates plotted as a function of CO concentration, manganese (Figure 12) and nickel (Figure 13), the correlation is very weak. But then, as implied earlier, one does not expect trace metal emission levels to be as affected by poor combustion conditions as are levels of CO and other products of incomplete combustion.

As shown in Figure 14, the emissions of front-half particulate matter were found to correlate fairly well with carbon monoxide concentration. Here one would expect the quality of combustion, as evidenced by CO levels, to have a direct bearing on the emission rate of non-condensible (i.e., the EPA Reference Method 5 "front-half", or filter, catch) particulates.

Table 6 is a summary of the non-criteria pollutant emission factors for wood combustion derived from the wood combustion study. In this table, the emission factors under the heading "Good Combustion Value" represent the arithmetic average of the measured emission rates when the boiler was operating normally. When the boiler was in an upset or unsteady condition, the quality of the combustion was poor, resulting in excessive emissions. This peak value for a given pollutant represents the emission potential for that pollutant measured during the study.

A comparison of the potential emissions of hazardous pollutants from the combustion of virgin wood with the rules regulating such emissions in Wisconsin is found in Table 7. Chapter NR 445 of the Wisconsin Administrative Code regulates hazardous pollutants in various ways, but only if the potential emissions (before controls are applied) exceed particular de minimus emission rates. For example, if a wood-fired furnace emits more than 300 pounds of benzene in a year, the furnace must control those benzene emissions to the extent consistent with "lowest achievable emission rate" (LAER). Thus, Table 7 presents a summary of the minimum furnace size, in terms of million BTU per hour heat input, which would emit each of the pollutants of interest at its de minimus emission rate. The calculations are based on the emission factors presented in Table 6.

Table 5. SUMMARY OF TRACE METAL EMISSIONS

Emission Factor (10^{-6} pound per ton wood fired)

Test No.	1	2	3	4
CO (7% O_2)	191	>652	>516	>441
Arsenic	7	11.7	14.0	21.9
Barium	299	3120	7710	759
Copper	851	796	1250	1750
Lead	81.8	436	515	178
Manganese	7070	26,000	47,000	5470
Nickel	87.0	37.9	59.5	40.2
Potassium	618,000	464,000	884,000	643,000
Selenium	20.1	10	6	26.2
Sodium	12,000	10,000	17,000	21,000
Zinc	17,000	13,000	24,000	31,000

Emission Factor (10^{-6} pound per ton wood fired)

Test No.	5	6	7	8
CO (7% O_2)	>524	218	486	>994
Arsenic	25.4	6.6	1	27.3
Barium	384	6440	7750	9000
Copper	1880	771	863	1420
Lead	63.9	411	324	710
Manganese	6650	4460	4810	4760
Nickel	74.3	45.9	67.8	63.4
Potassium	1,345,000	623,000	708,000	979,000
Selenium	25.4	24.1	10.9	16.4
Sodium	35,000	17,000	13,000	20,000
Zinc	31,000	18,000	25,000	28,000

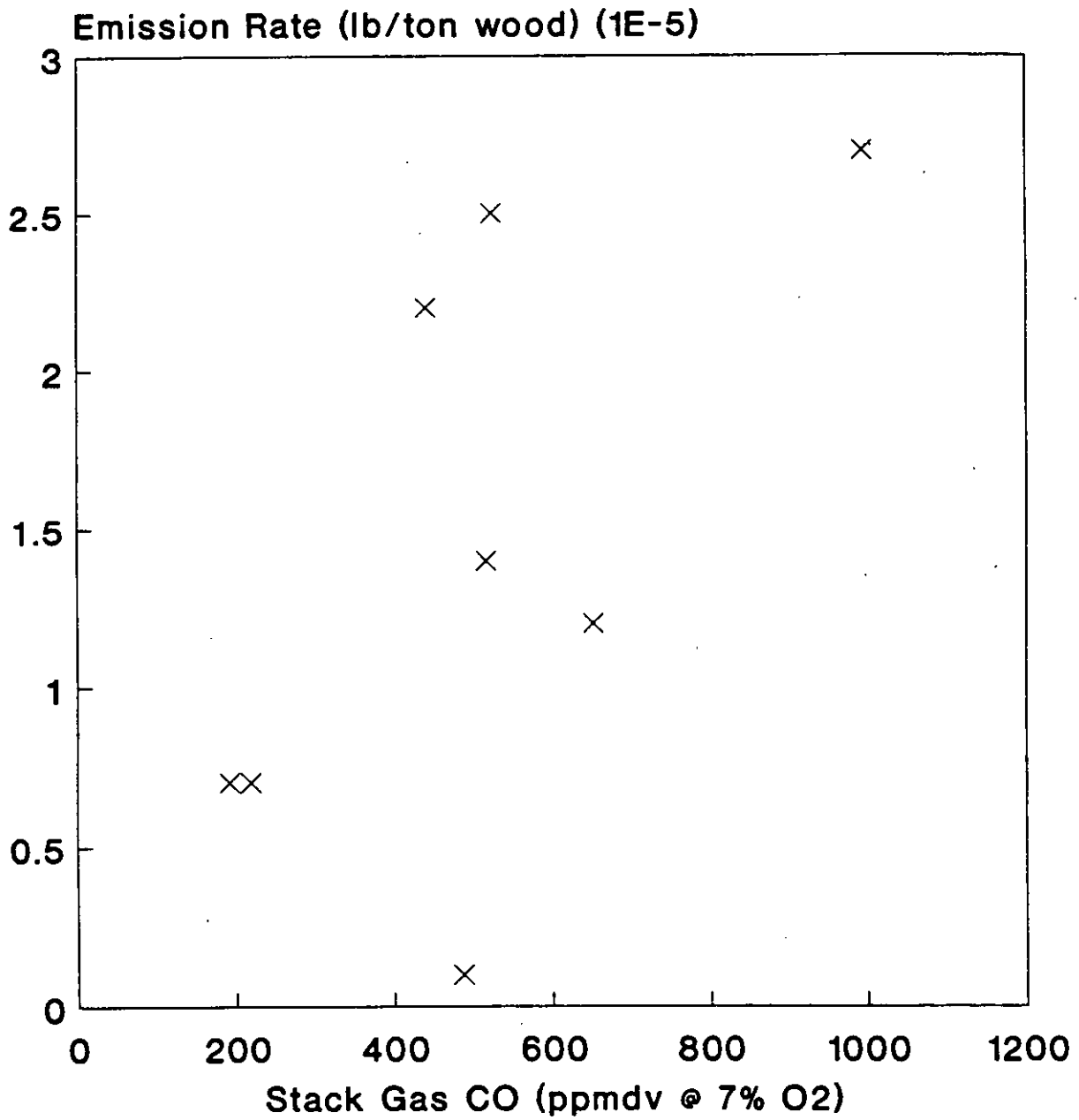

Figure 10. ARSENIC EMISSIONS VS. CARBON MONOXIDE (CO) CONCENTRATION AT BIRCHWOOD LUMBER & VENEER

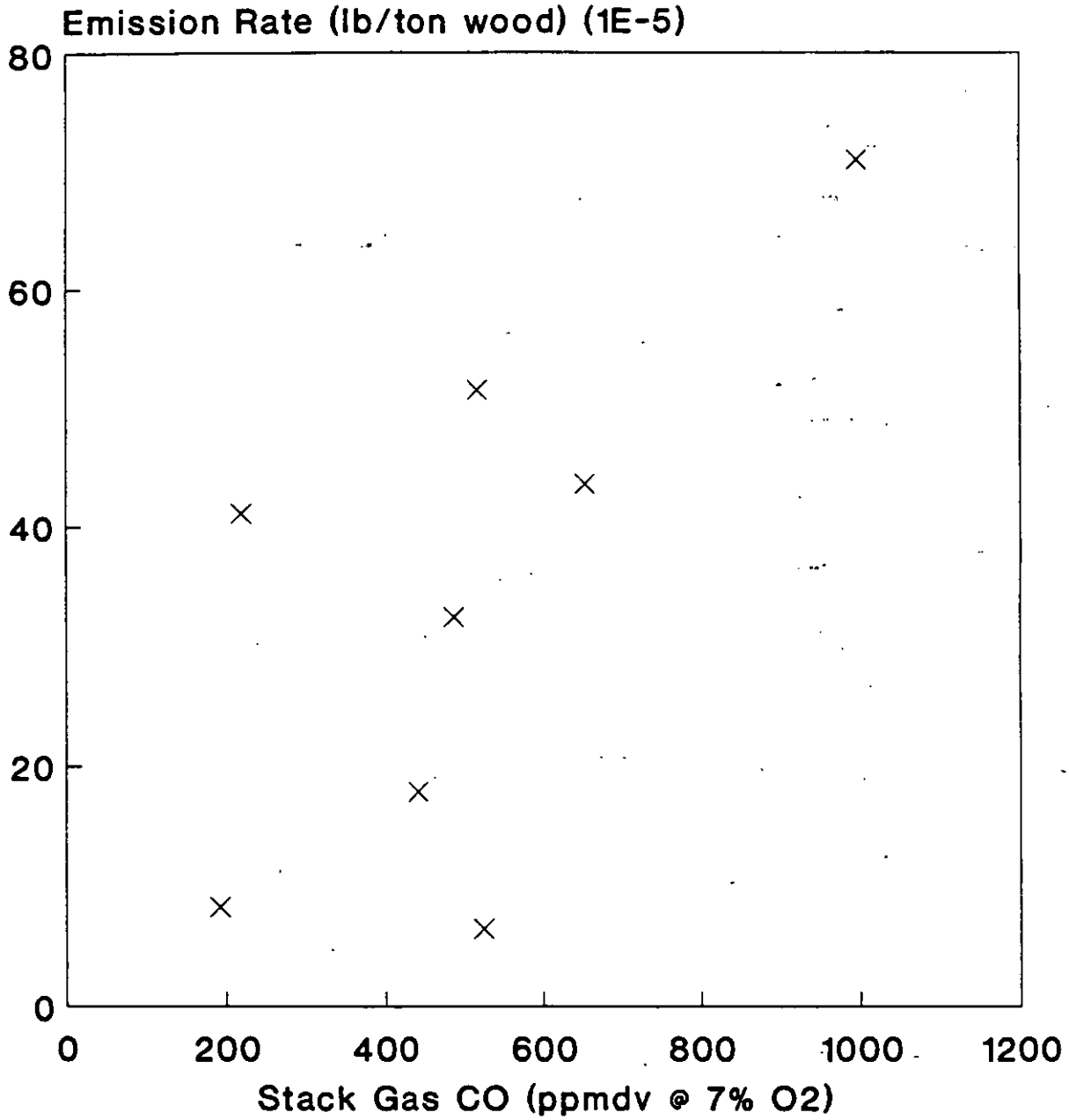

Figure 11. LEAD EMISSIONS VS. CARBON MONOXIDE (CO) CONCENTRATION AT BIRCHWOOD LUMBER & VENEER

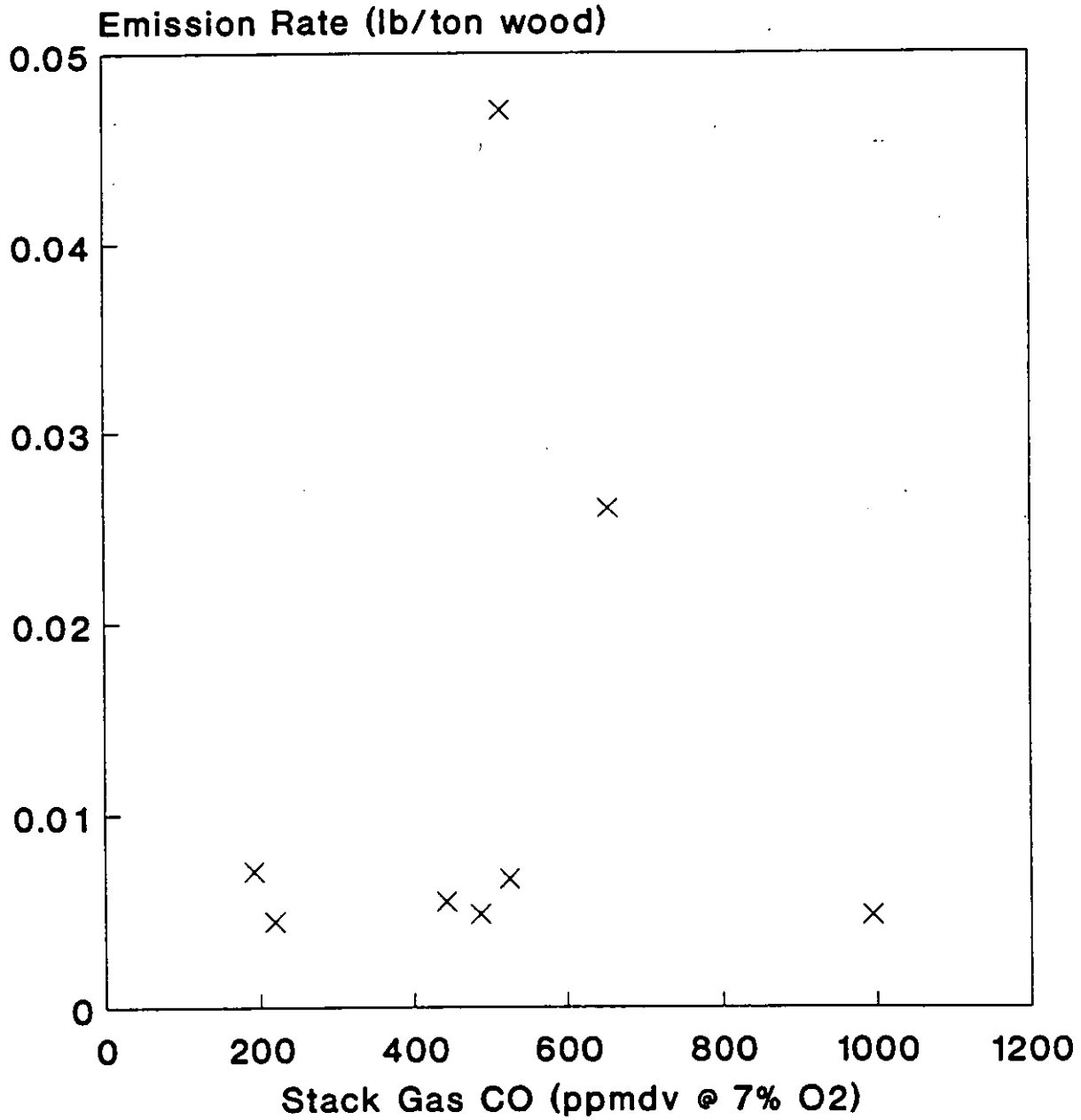

Figure 12. MANGANESE EMISSIONS VS. CARBON MONOXIDE (CO) CONCENTRATION AT BIRCHWOOD LUMBER & VENEER

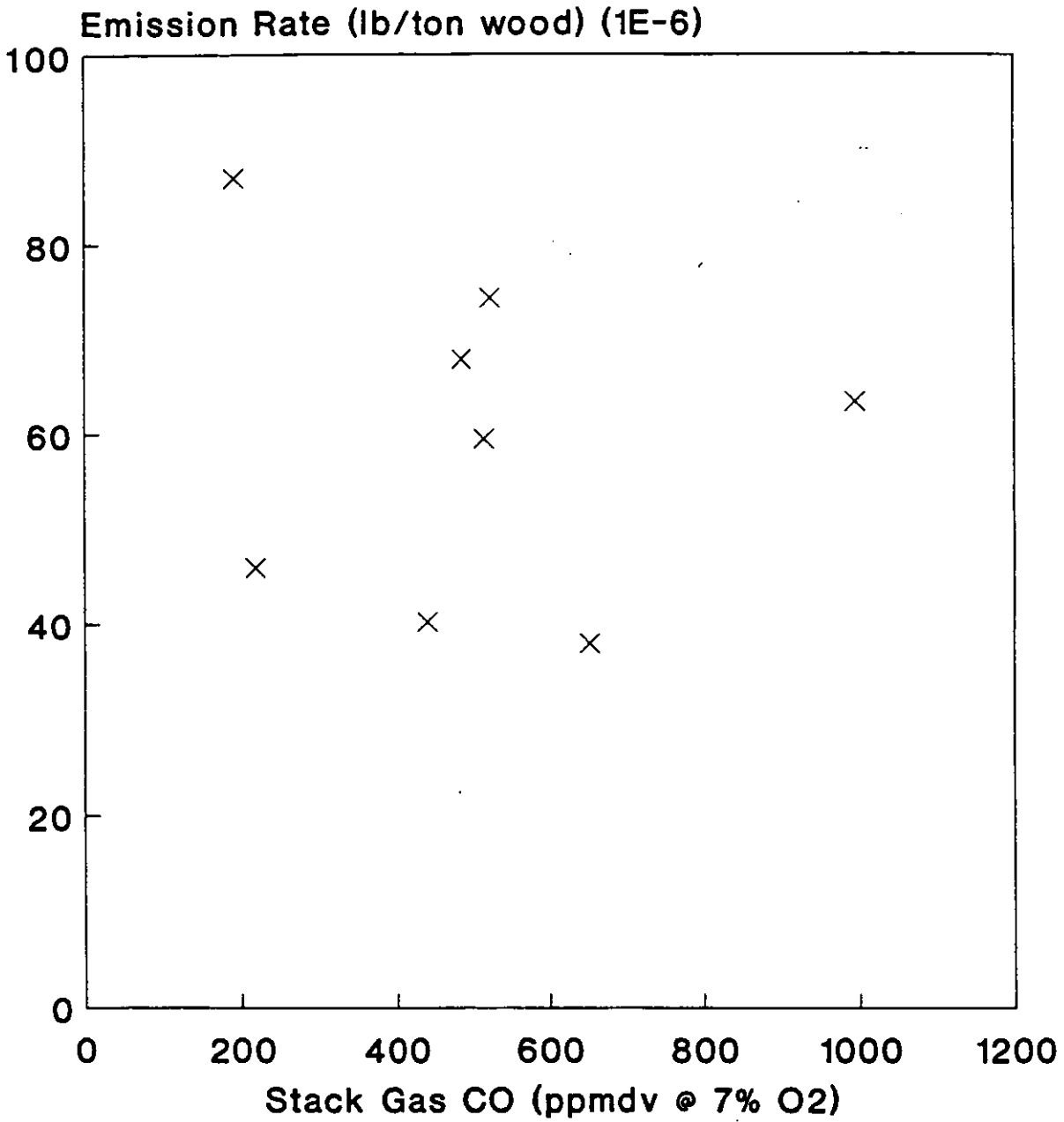

Figure 13. NICKEL EMISSIONS VS. CARBON MONOXIDE (CO) CONCENTRATION AT BIRCHWOOD LUMBER & VENEER

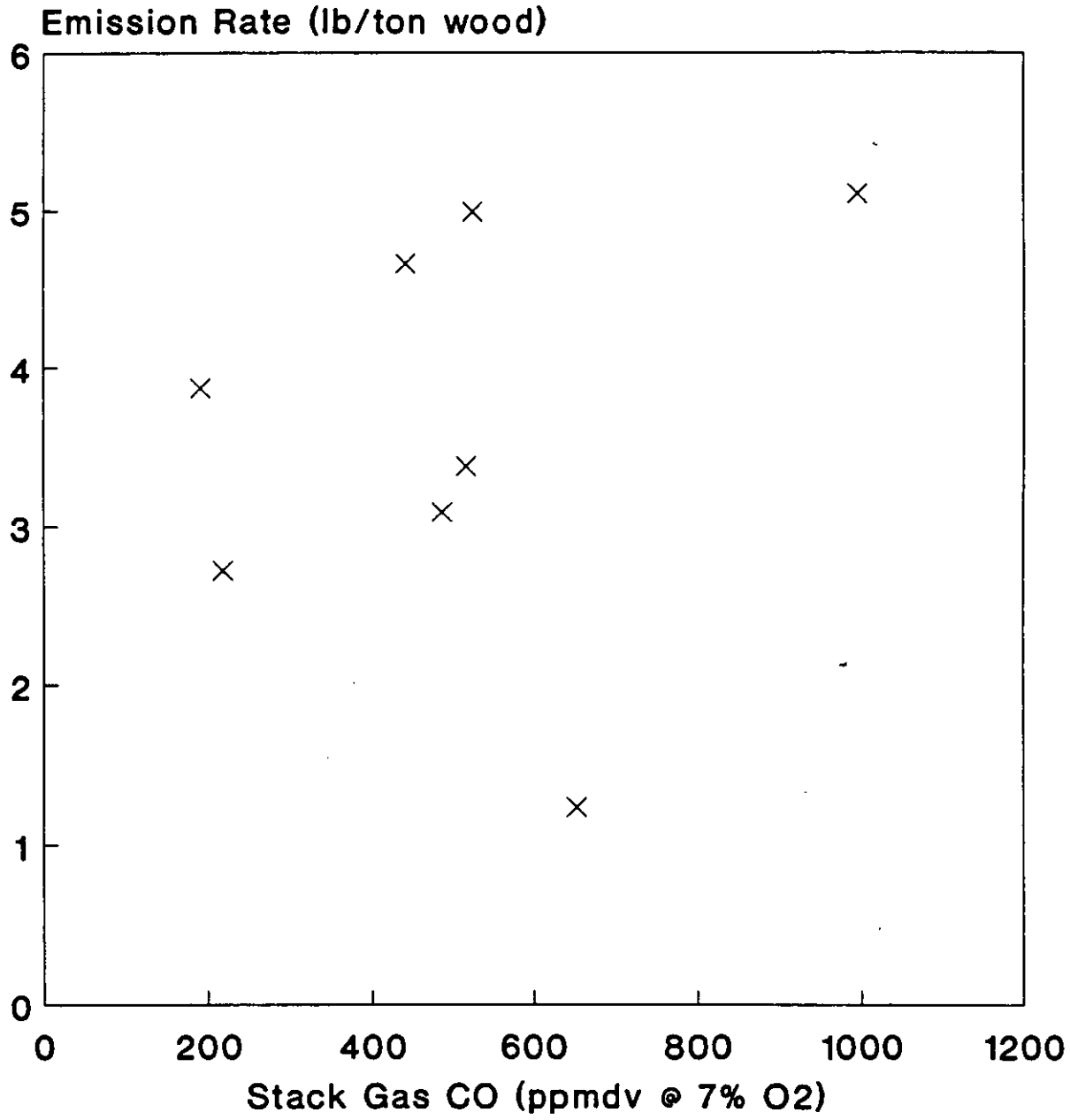

Figure 14. FRONT-HALF PARTICULATES VS. CARBON MONOXIDE (CO) CONCENTRATION AT BIRCHWOOD LUMBER & VENEER

Table 6. NON-CRITERIA POLLUTANT EMISSION FACTORS FOR WOOD DERIVED FROM THE WOOD COMBUSTION STUDY AT BIRCHWOOD LUMBER & VENEER

Pollutant	Good Combustion Value (pound per ton wood)	Emission Potential (pound per ton wood)
Benzene	0.00270	0.02178
POM		
NR 445	0.48×10^{-5}	1.87×10^{-5}
EPA List	0.00161	0.00461
Aldehydes		
Formaldehyde	0.00235	0.01209
Acetaldehyde	0.000061	0.001775
Acrolein	0.000004	0.000024
Salicylaldehyde	0.000023	0.000161
Benzaldehyde	0.000012	0.000081
Total Aldehydes	0.00245	0.01413
Arsenic	14.4×10^{-6}	27.3×10^{-6}
Barium	4.43×10^{-3}	9.00×10^{-3}
Copper	1.20×10^{-3}	1.88×10^{-3}
Lead	340×10^{-6}	710×10^{-6}
Manganese	13.3×10^{-3}	47×10^{-3}
Nickel	59.5×10^{-6}	87.0×10^{-6}
Potassium	0.783	1.345
Selenium	17.4×10^{-6}	26.2×10^{-6}
Sodium	0.018	0.035
Zinc	0.023	0.031

Note: The wood fired during these tests had 34.3 percent moisture and 5555 BTU per pound. The emission factors are derived on a "per ton of wood fired" basis.

Table 7. MINIMUM WOOD-FIRED FURNACE SIZE TO BE REGULATED UNDER THE HAZARDOUS AIR POLLUTANT RULES IN WISCONSIN

Pollutant	ch. NR 445 de minimus Emission	With Good Combustion (MMBTU/hr)	With Poor Combustion (MMBTU/hr)
Benzene	300 lbs/yr	141	18
POM	250 lbs/yr	66,055	16,955
Aldehydes			
Formaldehyde	250 lbs/yr	135	26
Acetaldehyde	62.95 lbs/hr	11×10^6	394,030
Acrolein	0.086 lb/hr	239,980	39,996
Arsenic	25 lbs/yr	2202	1161
Barium	0.17 lb/hr	427	210
Copper	0.34 lb/hr	3111	1986
Manganese	0.98 lb/hr	822	233
Nickel	250 lbs/yr	5329	3644
Selenium	0.07 lb/hr	42,908	28,496

Table 8 offers a comparison of published hazardous air pollutant emission factors for industrial wood combustion (1) with the emission factors derived from the Birchwood study. Notice that in almost every case the published emission factor is based on data from woodstoves. The results of the Birchwood study show that such woodstove data generally overestimate the hazardous emission potential of industrial wood combustion. In some cases, the difference spans several orders of magnitude.

CONCLUSIONS

There are seven principal conclusions to draw from this investigation.

1. The ratio of overfire to underfire air appears to play a very important role in the hazardous emission potential of wood firing, especially for emissions of benzene and polycyclic organic matter (POM).

2. Carbon monoxide flue gas concentration is well correlated with benzene, arsenic, lead, and front-half particulate emissions, and reasonably well with most of the other hazardous emissions measured.

3. A set of emission factors to predict non-criteria pollutant emission levels from virgin wood fired under good combustion conditions is available from this study.

4. A set of emission factors to predict non-criteria pollutant emission levels from virgin wood fired under poor combustion conditions is available from this study.

5. The benzene and formaldehyde emission rates under good firing conditions are an order of magnitude lower than the benzene and formaldehyde emission rates under poor firing conditions.

6. For polycyclic organic matter and trace metal emissions, the difference between the emission rates under good and poor firing conditions is a factor of two to five.

7. Under the hazardous air pollution rules in Wisconsin, and based on the emission factors derived from this investigation, a wood-fired boiler with a maximum continuous heat input of less than 18 million BTU per hour represents an insignificant source of hazardous air contaminants.

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REFERENCES CITED

1. United States Environmental Protection Agency Document EPA-450/2-88-006a, Toxic Air Pollutant Emission Factors - A Compilation for Selected Air Toxic Compounds and Sources, Office of Air Quality Planning and Standards, Research Triangle Park, October 1988.

Table 8. COMPARISON OF PUBLISHED HAZARDOUS AIR POLLUTANT EMISSION FACTORS FOR INDUSTRIAL WOOD COMBUSTION AND EMISSION FACTORS DERIVED FROM THE BIRCHWOOD STUDY

Pollutant	U.S. EPA Emission Factor (lb/ton dry)	Good Combustion Value (lb/ton wet)	Factor for Emission Potential (lb/ton wet)
Benzene	0.1356 - 2.6*	0.00270	0.02178
POM (EPA List)	4×10^{-7} - 0.006	0.00161	0.00461
Aldehydes			
Formaldehyde	0.48*	0.00235	0.01209
Acetaldehyde	0.0288 - 2.0*	0.000061	0.001775
Acrolein	0.08*	0.000004	0.000024
Arsenic	260×10^{-6}*	14.4×10^{-6}	27.3×10^{-6}
Barium	400×10^{-6}*	4.43×10^{-3}	9.00×10^{-3}
Copper	340×10^{-6}*	1.20×10^{-3}	1.88×10^{-3}
Manganese	1.0*	13.3×10^{-3}	47×10^{-3}
Nickel	3400×10^{-6}*	59.5×10^{-6}	87.0×10^{-6}
Selenium	260×10^{-6}*	17.4×10^{-6}	26.2×10^{-6}

* emission factor based on residential woodstoves