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STATE OF CALIFORNIA
AIR RESOURCES BOARD

Stationary Source Control Division

ENGINEERING EVALUATION BRANCH

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Emissions From Residential Fireplaces

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State of California

AIR RESOURCES BOARD

Emissions from Residential Fireplaces

I. SUMMARY

Fireplaces and metal wood-burning stoves are popular with homeowners concerned about fuel shortages. They are also suspected of contributing a large portion of the air pollution in some residential and rural areas. **Tests show that fireplace and wood stove emissions are highly variable.**

Although fireplace and stove emissions have been tested by several organizations, detailed test data have not been widely publicized. Emission factors published by EPA for residential fireplaces are based on limited data and are in some cases estimates. Results of tests by ARB and other organizations were analyzed and compared to evaluate the cause of emissions variations and to assess reliability of published emission factors, particularly at high altitudes in mountainous areas. Tests on which EPA published emission factors are based were included in the analysis. Findings are indicative rather than conclusive due to difficulties in comparing tests of diverse methodologies.

A major finding is that emission factors, except for NO_X, increase with increasing excess air and decreasing stack temperatures. NO_X emission factors show no clear trend. The normal range of fireplace and woodstove excess air ratios is 500% and above, **and stack gas analyses show no indications of air starvation in wood stoves.**

Pete [illegible] temperatures [illegible]
incomplete combustion . . . [illegible]
of air, per se.

Primary control of excess air is by damper adjustment and regulation of fire size. Large fires and restricted draft favor clean burning. The higher firebox temperatures which accompany clean burning at lowered excess air make it compatible with fuel economy in residential heating. Severe draft restrictions may reduce fire size and increase excess air, causing

deterioration of fuel efficiency and higher emission factors.

Emission factors presented by EPA in Publication AP-42 for carbon monoxide (120 lb/ton of fuel) and sulfur oxides (negligible emissions) seem fairly compatible with averages found in all test programs. The NO_x emission factor in AP-42 seems to be too low and a value of 5 lb/ton of fuel is considered more reasonable. An emission factor for hydrocarbons of 30 lb/ton of fuel is considered preferable to the figure given by AP-42. Most data support the AP-42 figure for particulate matter; ARB's higher findings in particulate tests above 6,000 ft. elevation are not considered conclusive.

Suggested operational procedures were developed that will enable the user to minimize emissions from fireplace and wood stoves. If only moderately followed, these procedures could result in up to 50% reduction of particulate emissions and would provide a higher thermal efficiency for the user. The effects of fireplace design, draft control and firing methods are sufficiently clear to establish guidelines for fireplace usage. It would be effective to have such guidelines distributed to the APCDs and to the public and architectural design firms. A significant reduction in emissions can be obtained at very minimal expense.

II. INTRODUCTION

This report discusses factors important to fireplace and metal stove emissions, describes ARB tests done in 1977, interprets the apparent causes of test result variations and compares ARB results to data from other organizations. Tables and figures illustrate ARB results at the end of the report. Data from other organizations, with illustrative tables and figures, are included in appendices.

III. BACKGROUND DISCUSSION

GENERAL

Fireplaces are a familiar and traditional source of heat, cheer and smoke. Particulate matter is the most readily noticed fireplace pollutant because of its visibility. Organic compounds are the cause of the familiar odor and condense to form much of the visible material. Considerable amounts of carbon monoxide, odorless and invisible, are also emitted.

Metal stoves are attractive to homeowners interested in auxiliary or emergency heating equipment. Accessories to improve heating efficiency of brick fireplaces are also popular. Installation of metal stoves and fireplaces is regulated under the Uniform Building Code (UBC) by building inspection departments in most California localities. The UBC refers to metal stoves as "factory built fireplaces."

Pollutant emissions from stoves and fireplaces are influenced by factors of design, operation and fuel which are discussed in the following sections.

DESIGN OF STOVES AND FIREPLACES

Brick fireplace design is influenced heavily by esthetics. Combustion efficiency and fuel economy are usually secondary to considerations of appearance and safety requirements. Accessories are available for improving the performance of brick fireplaces, including glass doors. Glass doors can protect against escaping sparks, limit loss of warm indoor air up the chimney, and provide a means of regulating intake air to a certain extent. The brick fireplace tested by ARB was equipped with such doors. Brick or stone fireplaces provide a large mass for heat storage. They are usually located on an outside wall, wasting most stored heat.

Metal stove designs are proliferating because of current energy concerns. Many new designs feature improvements in control of intake air and other innovations advertised as improving efficiency in residential heating applications. Virtually all metal stoves, including the Franklin stove which dates back to the American Revolution, have some form of intake air control. Heat transfer through metal stove walls is vastly superior to that in a brick fireplace. Stoves are generally equipped with doors. They provide little mass for heat storage.

Grate and chimney designs influence combustion. Grates affect combustion air flow patterns. Flue height and cross section affect friction, resisting the flow of combustion products. Mass and thermal inertia of the chimney may cause cooling of the stack gas while a fire is growing and, later, heating of gases from a dying fire. This will affect the buoyant force which opposes friction in flue passages and partially closed dampers.

Firebox materials have varying insulating properties. Excessive heat loss to the surface on which fuel rests can retard or extinguish combustion. Contact with surfaces of the firebox or flue can also cool burning gases and prevent complete combustion. Ashes, the air gap provided by a grate, or insulating brick can isolate fuel from the supporting surface. Isolation of burning gases is determined by firebox geometry.

In some residences the supply of combustion air may be restricted by tight weather stripping installed for energy conservation. Fireplace draft is affected when doors or windows are opened in any residence.

FIREPLACE AND STOVE OPERATING PRACTICE

Operation of fireplaces and stoves is a matter of personal taste and opinion. There are no strict rules. Generally, addition of fuel is the most common means of regulating a fire. Adjustments may be made to an existing fire with a poker. Less frequently, a hand bellows may be used. Flue dampers are rarely adjusted. Those in brick fireplace chimneys are usually left wide open, while stovepipe dampers are most commonly partially closed off. Inlet air dampers on metal stoves are sometimes closed off to slow combustion but in other cases stove doors may be opened wide for esthetic reasons.

The consequences of the fireplace "control procedures" above are various.

Addition of fuel affects the fuel combustion rate. Large fires raise temperatures in the firebox and flue. This affects flue and inlet air velocities. Stack velocity rises with higher temperatures but friction increases rapidly as the square of velocity, limiting the velocity change. Because velocity changes little, a large fire's combustion products form a larger fraction of stack gas and the excess air ratio measurable in the is lower.

Closing inlet air dampers can reduce the excess air, raising flue gas temperatures. Reduction of the fuel combustion rate may result if inlet air flow is severely reduced. Characteristics of the individual fireplace determine the minimum stable excess air which can be achieved by damper adjustment.

The effects of flue damper adjustment are similar to those of inlet air damper adjustment except that smoke may backup into the residence at restricted damper settings. Flow resistance caused by dampers generally overshadows friction in flue passages.

Higher combustion gas temperatures cause more of the fuel's energy to be transferred through stove walls. Large fires and low excess air ratios therefore improve fuel economy.

FIREPLACE FUEL CHARACTERISTICS

Wood is the traditional fuel burned in stoves and fireplaces. Dry hardwood logs are most often recommended. Fireplaces are, however, a convenient place to dispose of combustible household refuse. In residential heating, the most economical fuel available is usually preferred.

Fuels commonly burned in fireplaces (wood, paper, cardboard, etc.) are similar in chemical composition. All contain roughly 50% carbon, 6% hydrogen and 40% oxygen by weight. Roughly 70% is volatile, burning in gas phase. Fixed carbon which may burn as glowing coals is typically around 10% of the fuel weight. Ash content is most variable. It is about 5% for paper but typically less than 1% for wood.

Coal, not a common fireplace fuel, differs from wood in that it typically has less than 35% volatile content and much more fixed carbon. It's ash content is higher than paper or wood. Coal may contain as much as 1 or 2% sulfur while paper and wood rarely have more than 0.2%.

Differences between wood species are less than the difference between wood and paper and insignificant when comparing wood to coal. Some woods contain more resinous sap which may volatilize rapidly in a fire. Ash content of hardwoods and softwoods is not consistently different. Density of hardwoods is usually higher.

Dimensional and moisture variations in wood and paper products overshadow differences in composition. Paper and small kindling have much more exposed surface area than large logs. This greater surface area allows rapid heating and volatilization in a fire, leading to high combustion rates. Moisture contained in wet or green wood can exceed the oven-dry weight of the fuel. Fuel energy needed to vaporize moisture is not available to volatilize unburned fuel or heat the residence. Wet material may burn fitfully, allowing uncombusted organic compounds to be drawn up the chimney.

Dimensional properties of fuel are frequently modified by chopping wood into kindling or crumpling paper. Moisture content is less readily modified by the fireplace owner. Chemical composition is fixed by the choice of fuel.

IV. EXPERIMENTAL PROCEDURES

Tests were conducted on three (3) fireplaces: a metal Franklin stove, a metal Fisher stove, and a brick fireplace fitted with glass doors. Three fuels, oak, pine and coal, were burned. Tests were run in duplicate, two tests for each combination of fireplace and fuel fired.

These ARB tests were performed in 1977 at which time a preliminary report was prepared. A summary of ARB test results is presented in Table 2.

The Franklin stove which was tested was installed in a private home at South Lake Tahoe. The stove was tested with its doors ajar rather than completely closed. Oak (2 tests) and pine (2 tests) were fired in this stove. Testing was conducted on May 24, 1977.

The Fisher stove which was tested was moved from one test site (the Fisher stove works at Tahoe Vista on the north shore of Lake Tahoe) to a second site (Caltrans facility at Kingvale on Interstate 80, west of Lake Tahoe) after the first pair of tests. The metal flue of the stove passed through the roof of high-ceiling industrial-type buildings in both cases, and both sites were at approximately the same altitude, approximately 6,000 feet. The Fisher stove was tested at the first site, burning oak, on May 25, 1977. Tests at the second site were conducted August 2, burning pine, and August 3, burning coal.

The brick fireplace which was tested was equipped with glass doors which provided some draft control. It was tested using oak as fuel, with the doors closed and also with the doors open, on June 14, 1977.

Oak used as fuel was obtained in a single large lot. This supply was used for all oak fires. Pine was obtained from separate sources for use in tests May 24 and August 2. Coal, in bags, was obtained in a single lot.

In all cases, fires were started at least twenty minutes before testing and were burning vigorously during testing. Fires were maintained by addition of fuel during testing. No strict regime for draft adjustment, "poking", or other fireside activities was followed. Stack temperature was used as a loose guide in maintaining stable fires.

EPA Method 5 was used to measure the concentration and mass emission rate of particulate matter in each test. Combustion gas was sampled (duplicate or triplicate samples) in mylar bags. EPA Method 7 was used to sample for oxides of nitrogen. EPA Method 8 was used to sample for sulfur oxides in tests conducted August 2 and 3, (pine and coal fires). Sampling for organic acids was attempted, but the sampling procedure used was not effective. Samples to be analyzed for aldehydes were obtained in 2 liter flasks.

Samples were transported to the state Air and Industrial Hygiene Laboratory (AIHL) in Berkeley for analysis. Some bag samples were lost due to bag deflation. Those not lost were analyzed by gas chromatography. Some Method 7 samples were erroneously discarded. All samples were logged in and assigned a laboratory number when received by AIHL. Results of analyses were identified by field number and AIHL laboratory number when reported. AIHL's date of receipt was used as a check against field identification numbers of samples.

Fuel consumption rates and excess air ratios shown in Table 2 were calculated by a carbon balance method from combustion gas analyses and measured stack gas flows. The method used cancels stack velocity measurement errors in emission factor calculations but is dependent on precise combustion gas analyses. Low velocities typical in fireplace flues and chimneys are difficult to measure, making accuracy of stack gas flow rates suspect. Gas chromatograph analyses were used in calculation of fuel consumption rates and excess air; Orsat analyses, considered less precise, were disregarded. Calculation notes are included in Appendix B together with tabulations of intermediate calculated values and analytical results reported by AIHL.

V. INTERPRETATION OF TEST RESULTS

Original objectives of ARB testing were to identify the effects of fuel type, fireplace type and altitude on emissions. In testing, emissions were found to vary widely from fireplace to fireplace, from fuel to fuel, between similar fires and even during the course of the same fire. Variability of emissions during the course of individual fires was so large that the effects of fuel and fireplace type were masked. Similar problems have been encountered in studies of fireplace emissions by other organizations.

Data from fireplace tests by several organizations are available for comparison to ARB results. Particulate emissions were measured in all cases, but not all tests measured gaseous pollutants. Direct comparison is somewhat difficult because of test method differences. Comparison, however, provides additional perspective on ARB results.

Tests on a brick fireplace were performed for EPA by Valentine, Fisher and Tomlinson of Seattle (VFT) in 1974. Results were reported in an EPA publication, Source Sampling Residential Fireplaces for Emission Factor Development (EPA-450/3-76-010) dated November 1975. Appendix C contains a retabulation of VFT data in units compatible with ARB results including estimated excess air ratios (not calculated by VFT).

Tests on several brick fireplaces were conducted by the Bay Area Air Quality Management District (BAAQMD) of San Francisco and summarized in an internal memo in 1968. Appendix D contains a retabulation of BAAQMD data with estimated excess air (again, excess air was not calculated in conjunction with tests).

Tests on metal stoves have been done by Bowdoin College of Brunswick, Maine and reported in two articles in the Journal of the Air Pollution Control Association. Test data in the articles were insufficient for estimation of excess air ratios but additional information was furnished by Dr. S. Butcher of Bowdoin College. Excess air ratios estimated for Bowdoin tests are higher than indicated in the published articles; they are included in a retabulation of some Bowdoin results in Appendix E.

Average values of emission factors from ARB tests are compared in Table 1 to average emission factors found by other organizations. Emissions factors for equipment other than fireplaces are included in Table 1 for additional perspective.

Let us consider ARB test results in detail before discussing Table 1.

Emissions were found to vary more with fireplace type than with fuel type in preliminary analysis of ARB results. A major difference between fireplaces tested by ARB was in their draft control provisions. Notably, potential effects of high excess air on emissions were mentioned in the report on VFT testing. Since excess air is influenced by draft controls, variation of emissions with excess air in ARB tests was investigated.

Figures 1 and 2 illustrate that calculated excess air for ARB tests is a reasonable indicator of test conditions despite variations which occurred during each test. Stack temperature shows a distinct relationship to excess air in Figure 1, decreasing for higher excess air ratios as would be expected. Figure 2 indicates that higher fuel burning rates correspond to lower excess air ratios in 6 out of 7 pairs of tests.

Figure 3 shows that particulate matter emission factors increase at higher excess air in ARB tests. Particulate matter was segregated into several fractions in ARB testing and Figure 4 shows different components plotted against excess air individually. While "back half" material trapped by impingers downstream of the filter follows a strong trend with excess air in Figure 4, little pattern is apparent in the plot of "front half" material, trapped by the probe and filter, against excess air. Figure 5, however, shows front half material for different fuel types and indicates that both fuel type and excess air ratio may be influential in determining "front half" emission factors. Oak, pine and coal have progressively higher ash contents and show progressively steeper trends of front half material with excess air in Figure 5.

Plots of emission factors for gaseous pollutants measured in ARB tests show, for increasing excess air, general tendencies toward increasing emission factors for volatile hydrocarbons (Figures 6 and 7), and carbon monoxide (Figure 8). Nitrogen oxide emission factors (Figure 9) show little relation to excess air. ARB tests confirm that emissions of sulfur oxides are very low when burning wood.

It should be carefully noted that excess air ratios indicated by ARB tests are quite high. There is no indication of air starvation in any of the tests. Rather, a huge surplus of unneeded air is typical.

Now, let us compare ARB test results to results from other test programs. First, consider particulate matter emission factors from the different test programs.

ARB results for particulate matter are higher than results from other test programs. Stack temperatures were higher and excess air lower in ARB tests and this may be related to differences in results for particulate matter.

The test programs of ARB, VFT BAAQMD and Bowdoin College all show lower particulate matter emission factors at higher stack temperatures. Particulate matter also tends to decrease with decreasing excess air in each test program. Extrapolation of trends in different test programs, however, indicates that differences in stack temperatures and excess air ratios do not account for ARB's higher particulate matter results. Barring test error, ARB tests may reflect a different regime of operation in which larger quantities of particulate matter are emitted.

Tentatively, high stack temperatures in ARB tests may have caused material which would otherwise have been deposited inside flues to instead appear as emissions of particulate matter. Two potential explanations exist, barring test error, for the higher stack temperatures and lower excess air ratios found in ARB tests. First, ARB tests were conducted at high altitude where lower atmospheric density can inhibit fireplace draft. Second, fuel consumption rates in ARB tests were relatively high in accord with ARB policy of conducting source tests with equipment operating at maximum capacity. Recalling that stack temperature was used as a loose guide to stove operation in ARB testing, higher emissions found by ARB at high elevations are far from conclusive.

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The AP42 emission factor for particulate matter, 20 lbs per ton of fuel, is compatible with the majority of test results but may be questionable at elevations above 6,000 ft.

Turn now to comparison of gaseous emission factors found in different test programs.

Carbon monoxide emission factors found in ARB testing correspond well to the results of VFT and BAAQMD as indicated in Table 1. Results from the three programs are in remarkably close agreement and support the AP42 emission factor of 120 lb/ton of fuel.

Emission factors for nitrogen oxides found by ARB and BAAQMD are in fairly good agreement. The AP42 figure of 1 lb per ton of fuel is an estimate only, and results from ARB and BAAQMD indicate that 5 lb per ton of fuel would be a more reasonable figure.

Comparison of emission factors for volatile organic compounds is difficult because of the divergent test methodologies involved. There is also some possibility that all test programs show some compounds both as volatile organics and as particulate matter since all programs found particulate matter to consist largely of condensed organic compounds. Comparison of VFT results to results from ARB and BAAQMD, however, indicates that VFT results are unusually low. The figures of 5 lb per ton of fuel given by AP42 for hydrocarbons is based on VFT testing. ARB and BAAQMD results indicate that 30 lbs per ton of fuel would be a more reasonable figure.

Next, consider the range of excess air ratios found in the several test programs in the light of stove behavior found in practice.

Reduction of inlet air supply is a well proven means of reducing fuel consumption rates and heat output in metal stove operation. The intuitive explanation for the observed reduction of the fuel consumption rate is that air starvation occurs. Stack gas analyses, however, do not reflect air starvation; since no other mechanism is apparent, assume that air starvation does in fact occur. Large amounts of apparently "excess" air found in the stack, then, must be considered as "dilution" air. It would seem that when inlet air is reduced a smaller fraction of entering air is available for combustion. Since the flames of a small fire may extend into only a small fraction of the firebox, air can readily bypass the combustion zone. Momentum and turbulence reductions at low inlet air rates are presumably instrumental in reducing the effective air supply in the combustion zone. When flow resistance of the inlet air damper is small in comparison to friction in the flue, inlet air damper closure may increase momentum and turbulence. Progressive closure, however would increase damper friction and eventually begin to reduce momentum and turbulence.

The behavior hypothesized above accounts for high excess air ratios found at severe damper restrictions in Bowdoin College tests and for lower excess air ratios achieved in stoves with superior inlet air control in ARB testing. It would seem, in summary, that inlet air reduction can achieve a reduction of the excess air ratio but that excessively severe reduction of inlet air may have the opposite effect and increase the stack excess air, simultaneously reducing the size of the fire.

Finally, since emissions seem to be dependent on how the fire is tended, it is reasonable to consider what advice might be given a homeowner interested in reducing smoke from his fireplace or woodstove. This advice must be conditioned on the homeowner's needs. Home heating and disposal of refuse will require that an unavoidable minimum weight of fuel be burned. If the objective is esthetic enjoyment of the fire, on the other hand, then the homeowner can be advised to burn less fuel.

When a certain weight of fuel <u>must</u> be burned, the homeowner should be advised to build a large, fast burning fire and reduce inlet air to lower the stack excess air but not so severely that the size of the fire is impaired. If stack excess air is effectively minimized, 50 percent of worst-case emissions of particulate matter, carbon monoxide and volatile hydrocarbons may be eliminated.

When esthetic enjoyment is the objective of building a fire, excess air can not be reduced unless the fireplace or stove has glass doors. The homeowner should be advised to keep such fires small in order to minimize the pollution emitted.

DATA SOURCE	EMISSION FACTORS LB/TON-OF-FUEL						
	Particulate						
	Total	Front Half	Back Half	CO	NO_x	THC	SO_2
Air Resources Board Tests							
2 Metal Fireplaces(Stoves)	24.5 g/kg 49	13	36	104	8.5	15	0
1 Brick Fireplace with Glass Doors	66	10	56	178	3.3	56	-
Overall Average	55	13	42	129	6.4	31	0
EPA (Valentine, Fisher & Tomlinson) Tests							
1 Brick Fireplace	24	8	16	116	-	5	-
Bay Area Air Quality Management District Tests							
4 Brick Fireplaces	-	21	-	136	4.4	(36)	0
Bowdoin College Tests							
Metal Fireplace (Stove)	16	-	-	-	-	-	-
Compilation of Air Pollution Emission Factors (AP 42) 3rd Edition, August 1977							
Residential Fireplaces	20	-	-	120	1	5	0
Domestic Incinerator (No Aux. Burner)	35	-	-	300	1	100	0.5
Wood in Trench Fire	13	-	-	-	4	-	0.1
Open Burning of Forest Residues	4-17	-	-	90-195	-	-	-
Wood in Conical Burners	20	-	-	130	1	11	0.1
Wood and Bark Waste in Boiler	30	-	-	2-60	10	2-70	1.5

Table 1

COMPARISON OF EMISSION FACTORS FOR WOOD COMBUSTION

RUN NO.	DATE	LOCATION	FIREPLACE	FUEL TYPE	FUEL LB/HR	STACK CONDITIONS TEMP. °F	FLOW DSCFM	VEL. FPS	H_2O %	EXCESS AIR %	EMISSION FACTORS LB/TON-OF-FUEL PART.	CO	THC	NO_x	SO_2	SO_3
1	5/24/77	S. Lake Tahoe	Franklin Stove	Oak	6.57	384	120.7	12.02	2.60	1236	45.66	95.5	20.53	14.10	-	-
2	5/24/77	Same	Same	Oak	6.31	429	129.0	13.58	2.69	1290	56.06	294.5	32.98	13.42	-	-
3	5/24/77	Same	Same	Pine	4.17	498	72.6	8.32	13.69	919	90.72	102.1	9.26	6.50	-	-
4	5/24/77	Same	Same	Pine	4.53	354	103.9	10.11	13.62	1365	78.23	106.1	18.38	5.40	-	-
5	5/25/77	Tahoe Vista	Fisher Stove	Oak	8.69	608	52.8	12.57	8.21	306	15.16	72.4	5.99	-	-	-
6	5/25/77	Same	Same	Oak	7.00	502	38.9	9.43	11.27	638	25.72	20.4	0.49	-	-	-
7	8/2/77	Kingvale	Same	Pine	10.53	632	34.3	8.37	10.24	129	29.03	79.3	-	3.20	0.00	0.10
8	8/2/77	Same	Same	Pine	2.70	645	36.7	8.90	8.56	928	53.35	65.0	-	8.64	0.00	0.45
9	8/3/77	Same	Same	Coal	5.86	586	30.3	7.66	16.78	150	21.80	8.7	-	10.41	24.89	0.30
10	8/3/77	Same	Same	Coal	5.25	606	35.2	8.79	14.14	276	29.88	51.0	-	14.54	29.88	0.89
11	6/14/77	Homewood	Brick Fireplace Glass Doors Shut	Oak	46.71	524	508.6	23.52	4.79	830	34.46	155.1	73.06	4.61	-	-
12	6/14/77	Same	Same	Oak	26.57	432	420.6	17.78	5.60	1171	46.13	240.9	96.94	3.36	-	-
13	6/14/77	Same	Brick Fireplace Glass Doors Open	Oak	32.22	300	669.7	23.82	4.55	1306	57.00	189.5	37.31	3.14	-	-
14	6/14/77	Same	Same	Oak	31.73	294	712.4	24.78	2.99	1633	126.99	124.4	15.27	2.06	-	-

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TABLE 2

AIR RESOURCES BOARD FIREPLACE TESTS - SUMMARY OF RESULTS

Fig 1.

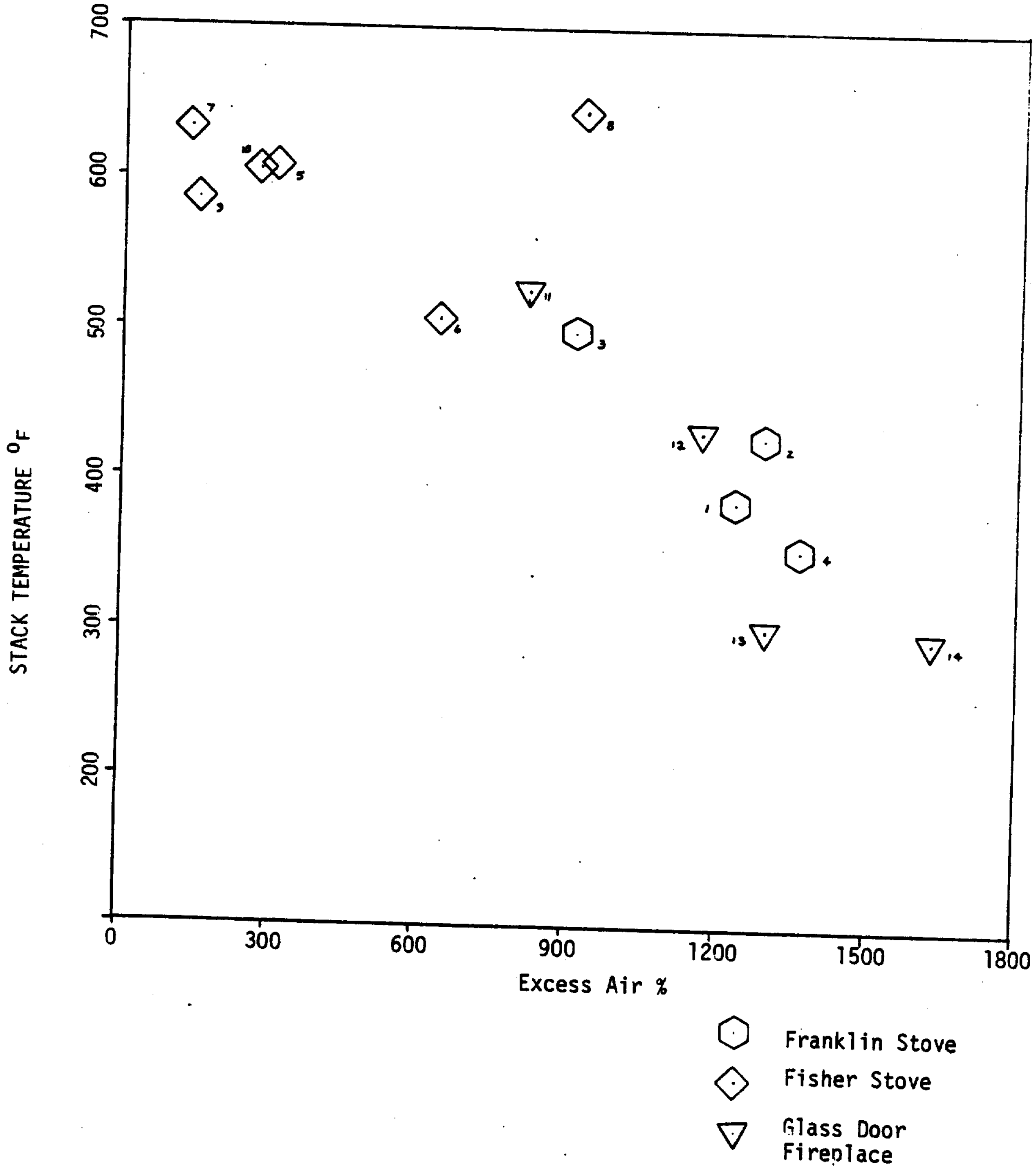
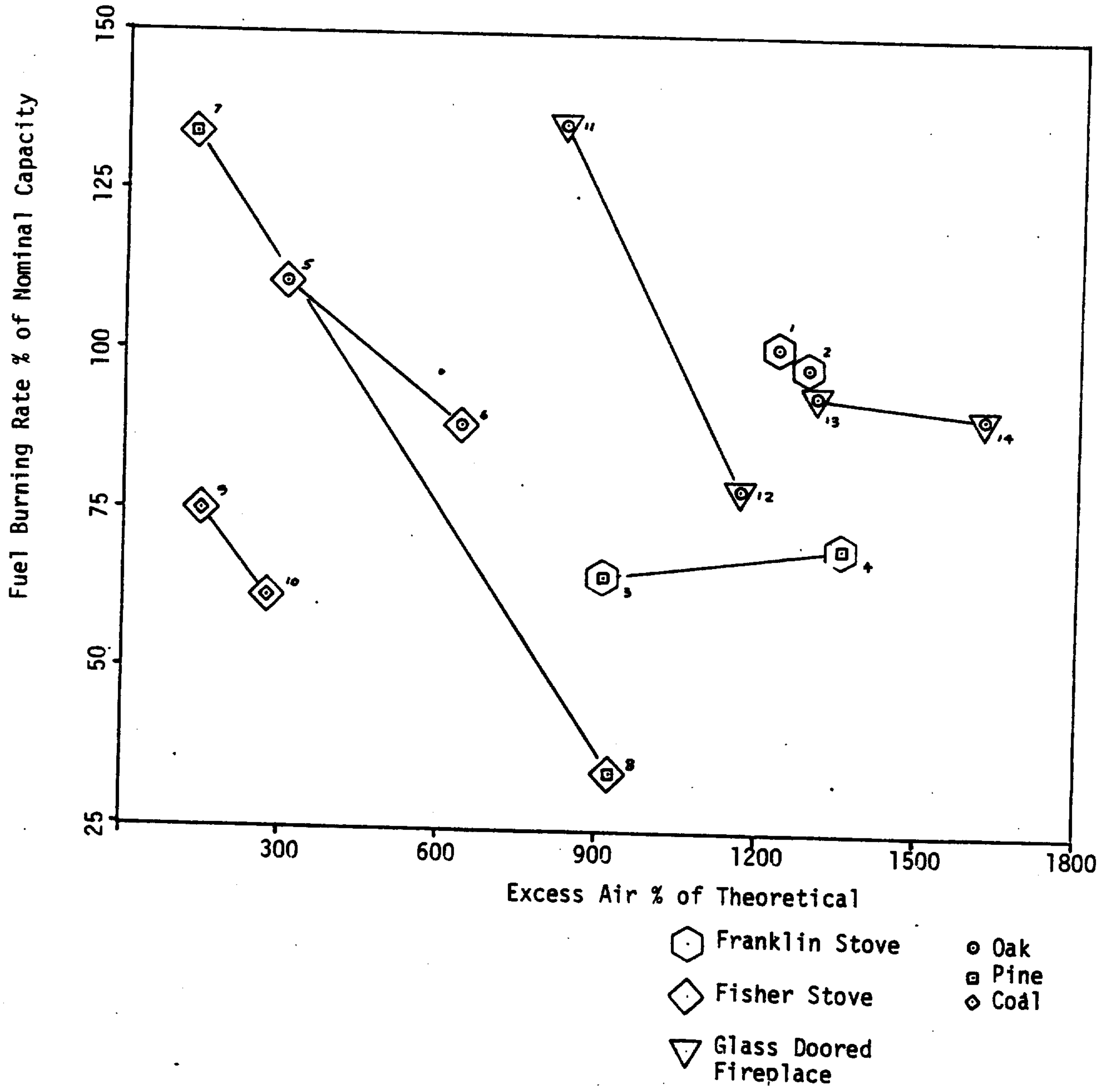


Figure 1. STACK TEMPERATURE VS EXCESS AIR

FIG 2



Connecting lines link same fireplace and fuel. Nominal capacity is taken as avg. fuel burning rate for oak.

Figure 2. Fuel Burning Rate vs Excess Air

FIG 3

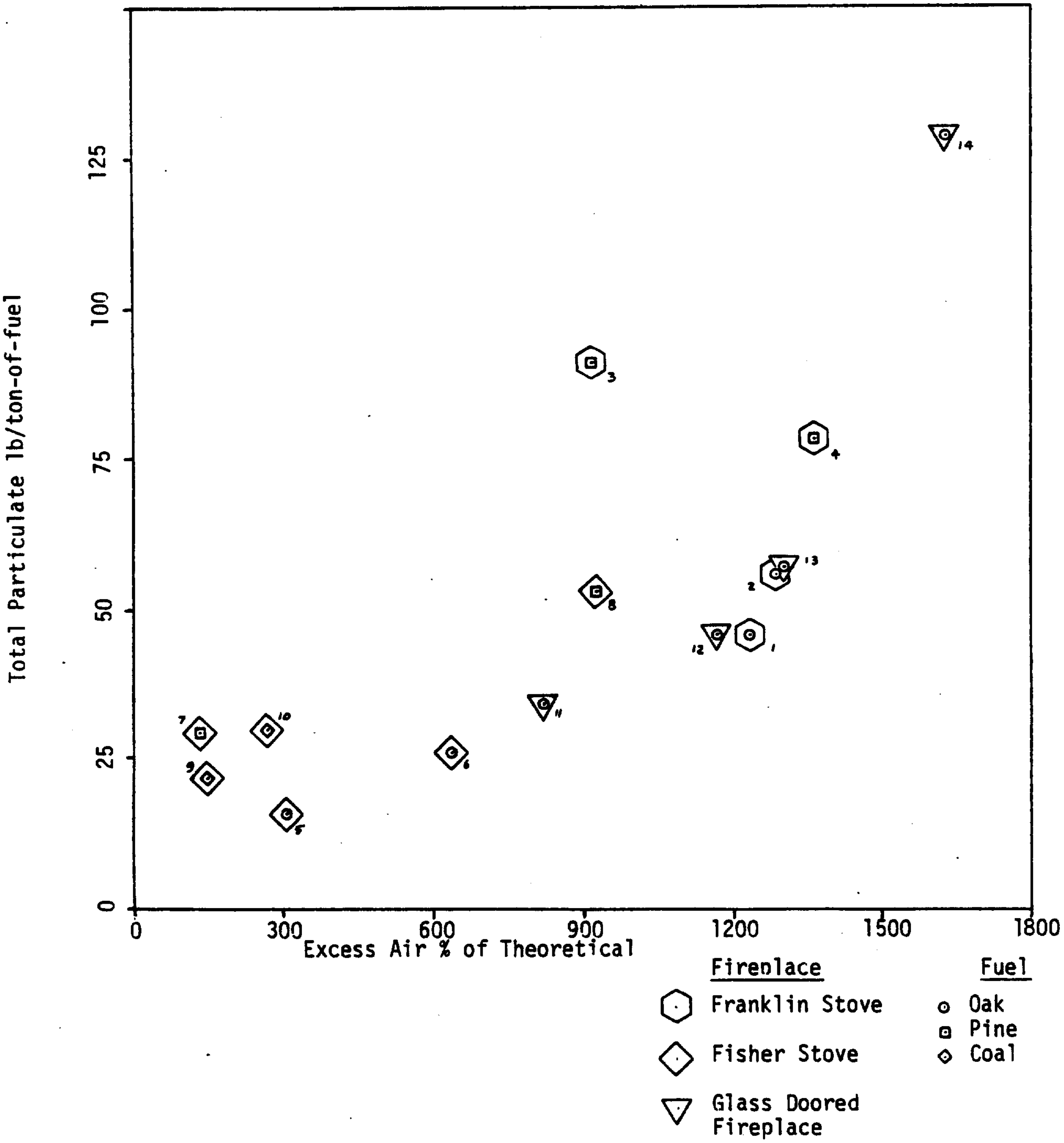


Figure 3. Total Particulate vs Excess Air

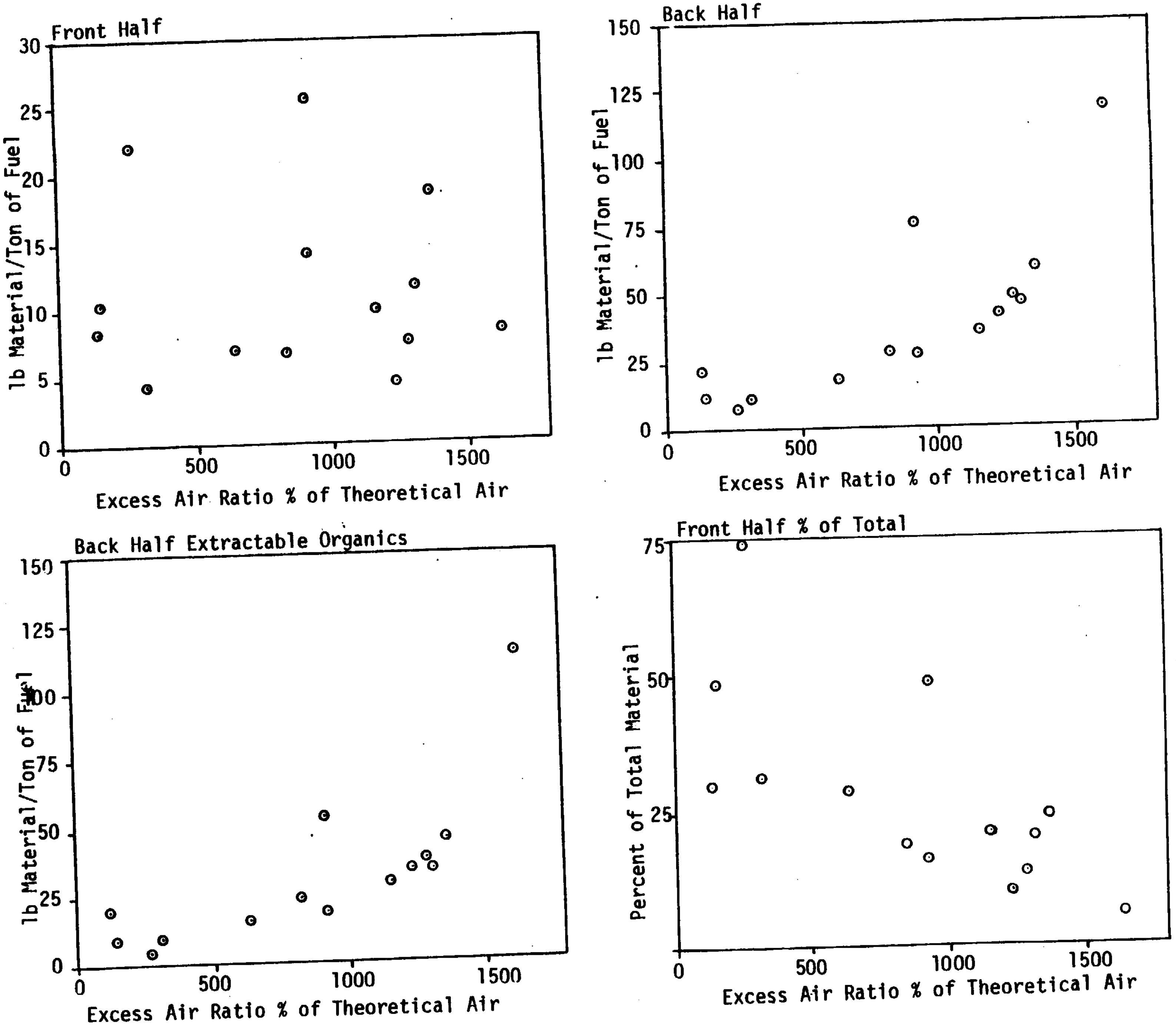


Figure 4, Distribution of Particulate Matter

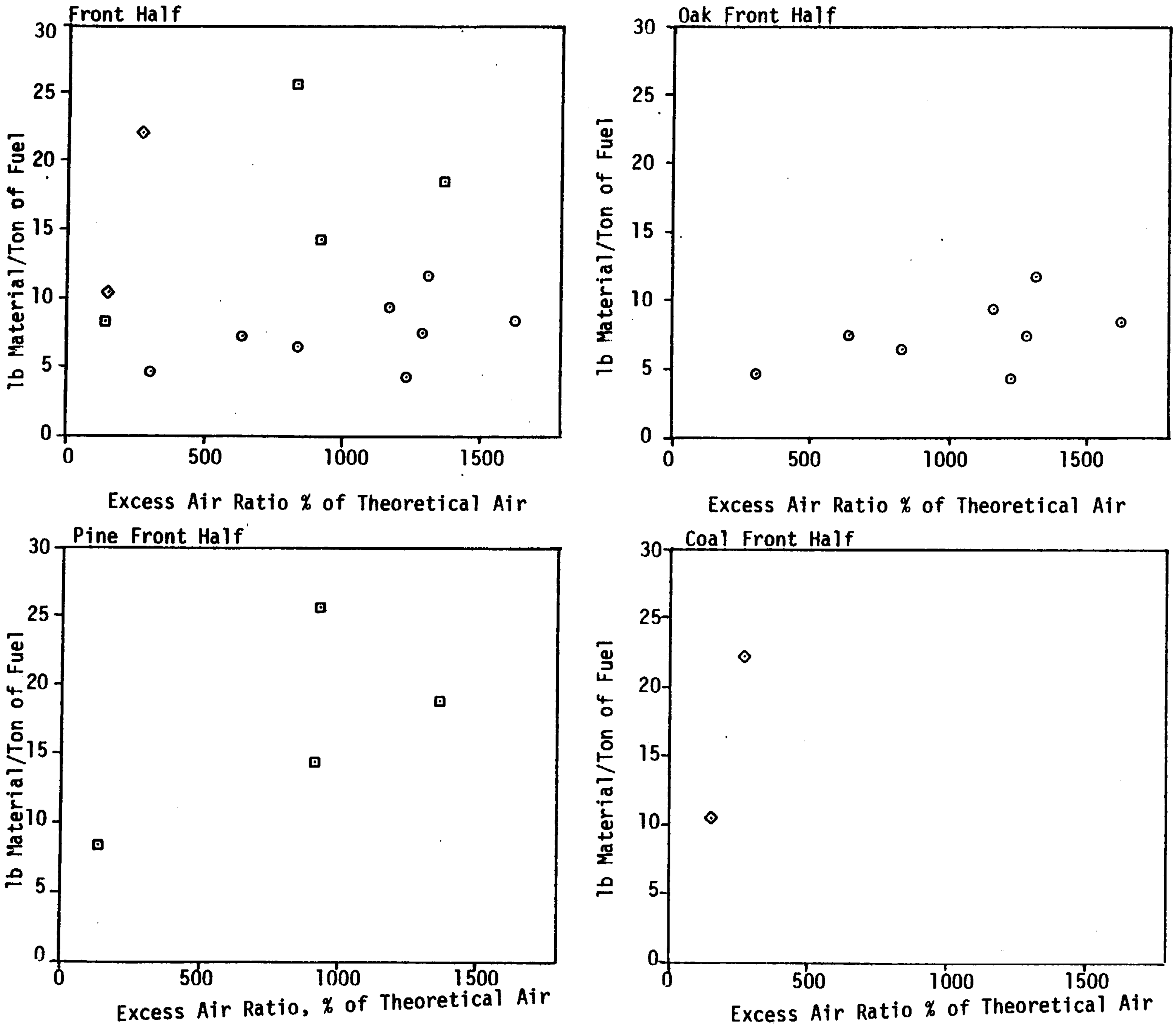
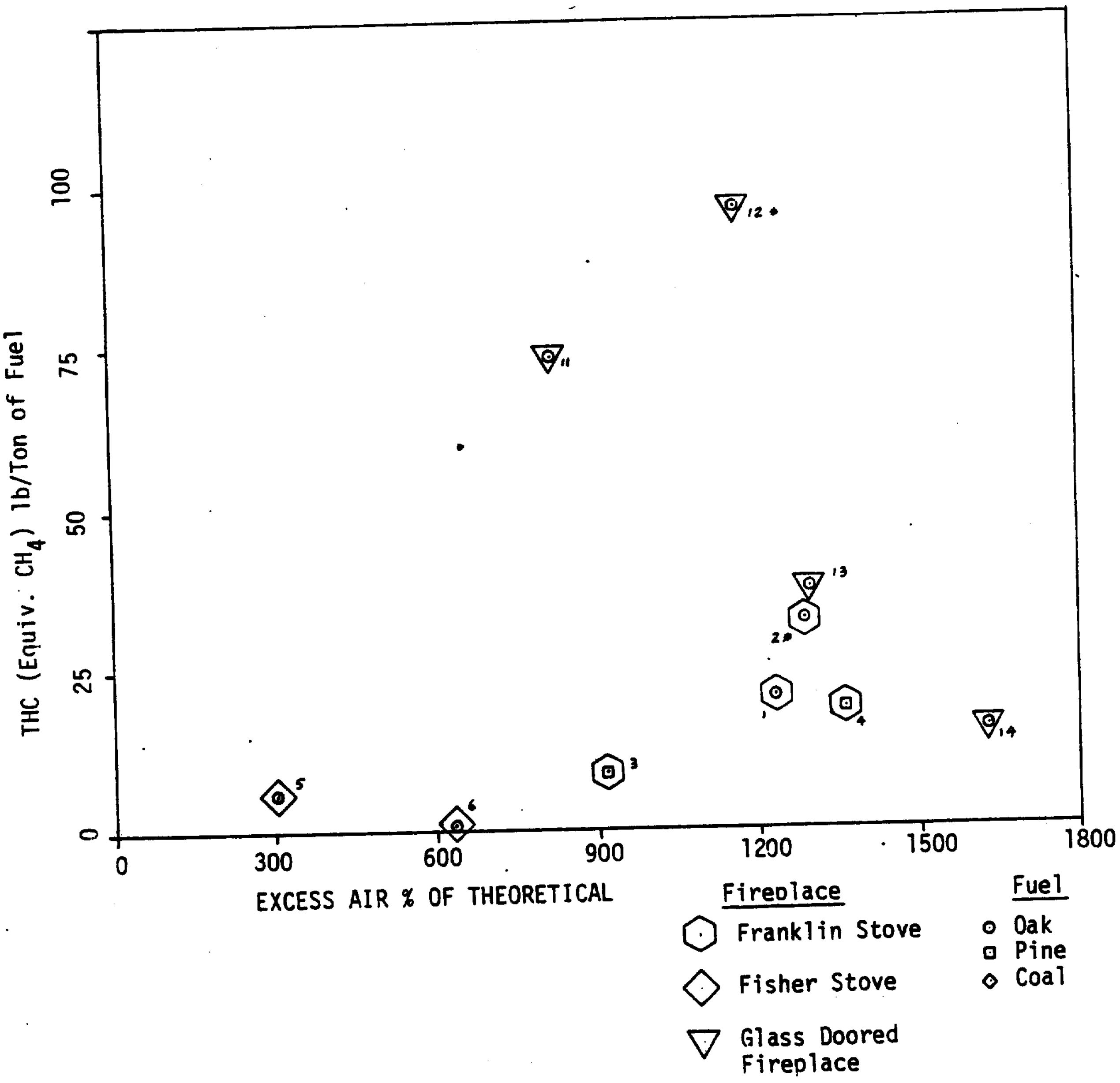
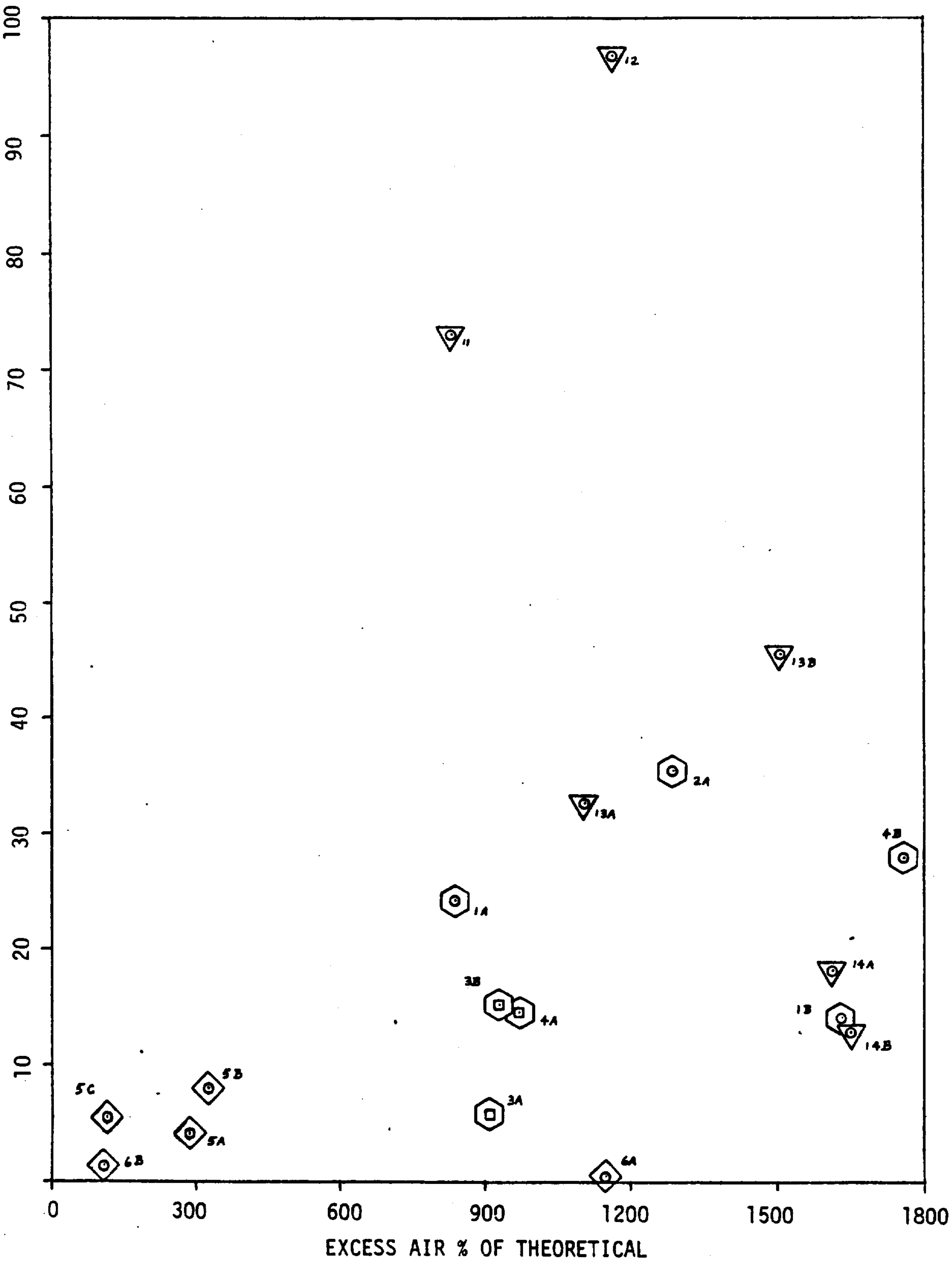


Figure 5. Effects of Fuel Type



*Indicates no duplicate THC analysis available - single analysis plotted.

Figure 6. THC vs Excess Air, Averages of Duplicated Samples



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for legend

Figure 7. THC vs Excess Air, Individual Analyses

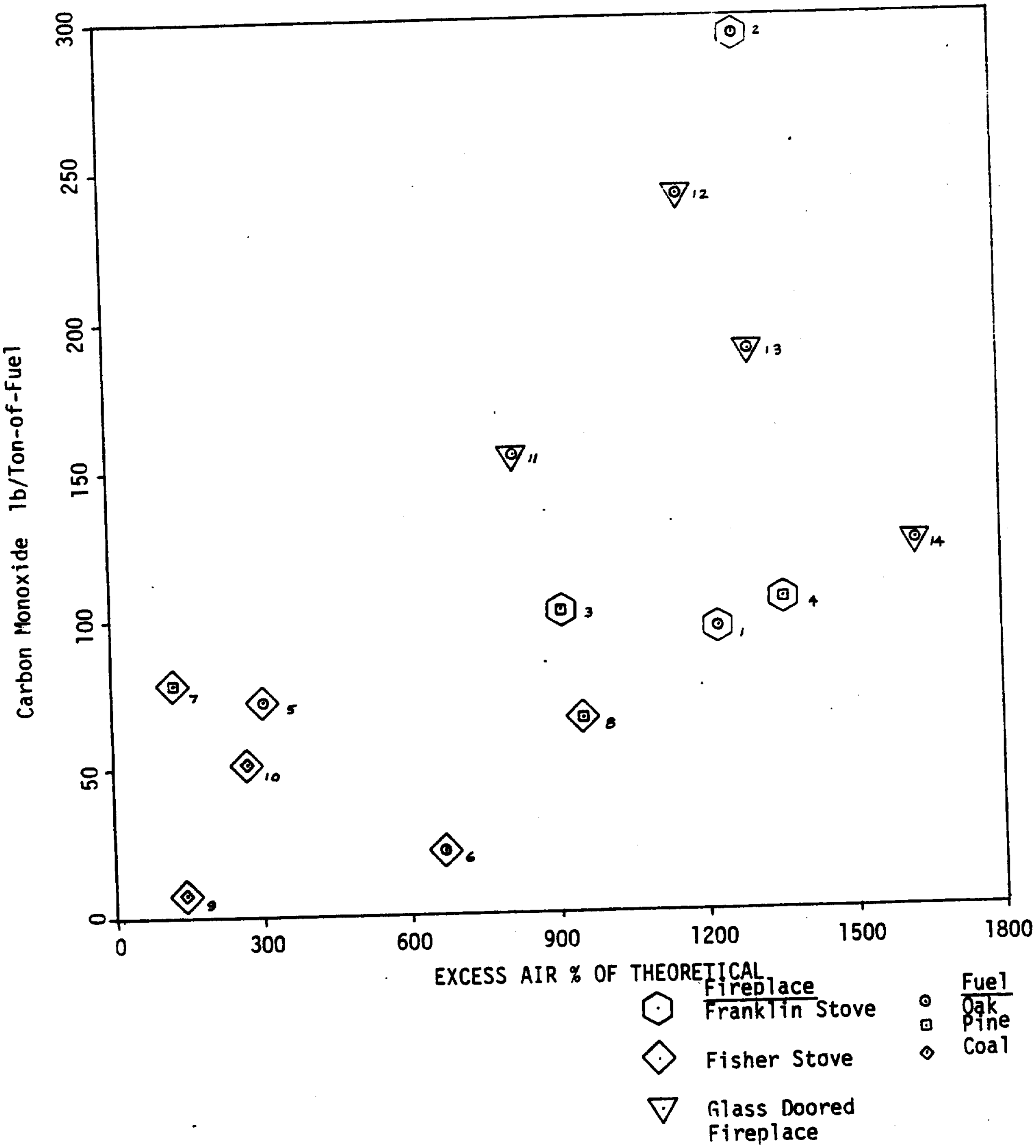

Figure 8. Carbon Monoxide vs Excess Air

FIG 8

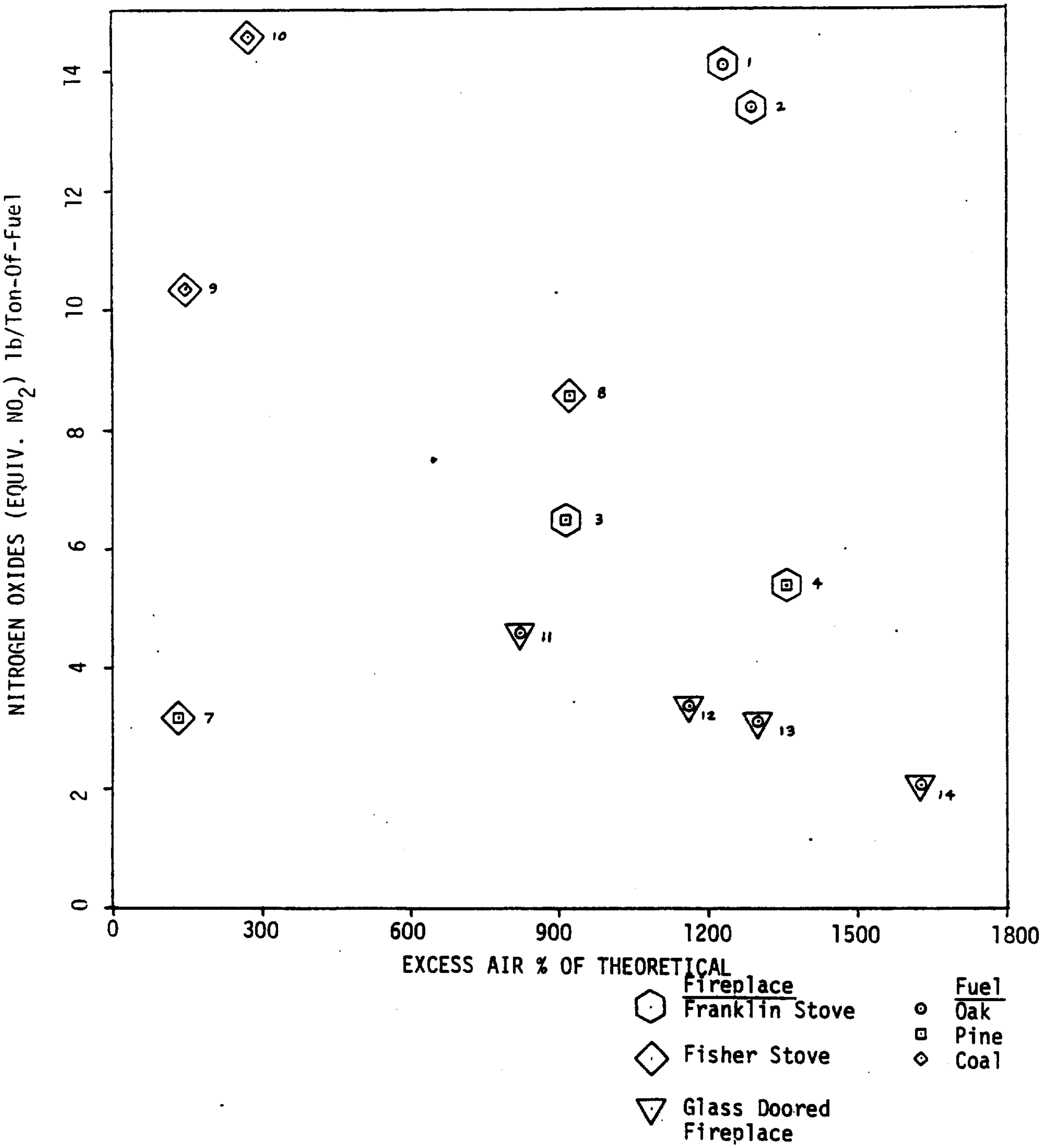

Figure 9. NO_x vs Excess Air

APPENDIX A

GUIDELINES FOR RESIDENTIAL FIREPLACES

GUIDELINES FOR RESIDENTIAL FIREPLACES

Tests indicate that metal fireplace stoves with tight fitting doors can emit less smoke as well as providing the superior home heating performance for which they are traditionally valued. Combustion of one ton of wood, about a cord, can cause 50 to 100 lbs of particulate (smoke) emissions from a metal stove with doors open or from a brick fireplace. This can be reduced to 15 to 30 lbs. if the same amount of wood is burned in a metal fireplace stove with the doors closed and air inlets reduced as far as possible without reducing fire size. The higher temperatures in stove and flue with this type of operation will result in superior fuel economy.

Fires built in open front fireplaces simply to be enjoyed will emit less smoke overall if they are kept small. Again, this type of operation will provide superior fuel economy in achieving the purpose intended. Less fuel means less smoke even though large fires burn slightly cleaner.

Fires built simply for the disposal of paper or trash will produce less smoke overall if they are built large and hot within the limits of reason and safety.

APPENDIX B

CALCULATION NOTES

	Total	Front Half	Back Half	Organic Extract	All Mat'l Not Extracted	% as Front Half	Extract % of Total	% of Back Half Extractable
①	45.66	4.56	41.10	34.38	11.28	10	75	84
②	56.06	7.49	48.57	38.84	17.22	13	69	80
③	90.72	14.24	76.48	54.41	36.31	16	60	71
④	78.23	18.74	59.49	46.15	32.08	24	59	78
⑤	15.16	4.68	10.48	8.75	6.41	31	58	83
⑥	25.72	7.17	18.55	16.52	9.20	28	64	89
⑦	29.03	8.38	20.65	19.31	9.72	29	67	94
⑧	53.05	25.48	27.57	18.89	34.16	48	36	69
⑨	21.80	10.47	11.33	7.73	14.07	48	35	68
⑩	29.88	22.01	7.87	4.46	25.42	74	15	57
⑪	34.46	6.25	28.21	23.69	10.77	18	69	84
⑫	46.13	9.35	36.78	29.76	13.40	20	69	81
⑬	57.00	11.7	45.83	33.62	23.38	20	59	73
⑭	126.99	8.23	118.76	114.35	12.64	6	90	96

Particulate Matter Emission Factors by component

EMISSION FACTOR CALCULATIONS

1. $\text{EMISSION FACTOR}\left(\frac{\text{LB}}{\text{TON}}\right)$ FOR CO $= 60 \times \text{SCFM} \times \frac{\text{PPMV CO}}{10^6} \times \frac{28\ \text{LB/MOLE}}{379.7\ \text{FT}^3/\text{MOLE}} \times \frac{1}{\text{LB FUEL/HR}} \times \frac{2000\ \text{LB}}{\text{TON}}$

$= \text{SCFM}_{\text{STACK}} \times \text{PPMV CO} \times \frac{1}{\text{LB FUEL/HR}} \times 8.849 \times 10^{-3}$

2. $\text{EMISSION FACTOR}\left(\frac{\text{LB}}{\text{TON}}\right)$ FOR THC $= 60 \times \text{SCFM}_{\text{STACK}} \times \frac{\text{PPMV THC}}{10^6} \times \frac{16\ \text{LB/MOLE}}{379.7\ \text{FT}^3/\text{MOLE}} \times \frac{1}{\text{LB FUEL/HR}} \times \frac{2000\ \text{LB}}{\text{TON}}$

$= \text{SCFM}_{\text{STACK}} \times \text{PPMV THC} \times \frac{1}{\text{LB FUEL/HR}} \times 5.057 \times 10^{-3}$

NOTE: "THC" IS EQUIVALENT METHANE MEASURED BY GAS CHROMATOGRAPH WITH FLAME IONIZATION DETECTOR.

3. EMISSION FACTOR FOR $\text{NO}_x = 60 \times \text{SCFM}_{\text{STACK}} \times \frac{\text{PPMV NO}_x}{10^6} \times \frac{46\ \text{LB/MOLE}}{379.7\ \text{FT}^3/\text{MOLE}} \times \frac{1}{\text{LB FUEL/HR}} \times \frac{2000\ \text{LB}}{\text{TON}}$

$= \text{SCFM}_{\text{STACK}} \times \text{PPMV NO}_x \times \frac{1}{\text{LB FUEL/HR}} \times 1.454 \times 10^{-2}$

NOTE: NO_x IS NITROGEN OXIDES AS EQUIVALENT NO_2

4. EMISSION FACTOR FOR $\text{SO}_2 = 60 \times \text{SCFM}_{\text{STACK}} \times \frac{\text{PPMV SO}_2}{10^6} \times \frac{64\ \text{LB/MOLE}}{379.7\ \text{FT}^3/\text{MOLE}} \times \frac{1}{\text{LB FUEL/HR}} \times \frac{2000\ \text{LB}}{\text{TON}}$

$= \text{SCFM} \times \text{PPMV SO}_2 \times \frac{1}{\text{LB FUEL/HR}} \times 2.023 \times 10^{-2}$

NOTE: SO_3 IS TABULATED SEPARATELY AND IS NOT INCLUDED WITH SO_2 BECAUSE SO_3 VALUES ARE CONSIDERED POTENTIALLY SPURIOUS.

5. $\text{EMISSION FACTOR}\left(\frac{\text{LB}}{\text{TON}}\right)$ FOR PARTICULATE $= \frac{\text{GRAINS PARTICULATE}}{\text{FT}^3} \times \frac{1\ \text{LB}}{7000\ \text{GRAINS}} \times \text{SCFM}_{\text{STACK}} \times \frac{1}{\text{LB FUEL/HR}} \times \frac{2000\ \text{LB}}{\text{TON}} \times 60$

$= \frac{\text{GRAINS PARTICULATE}}{\text{FT}^3} \times \text{SCFM}_{\text{STACK}} \times \frac{1}{\text{LB FUEL/HR}} \times 17.14$

6. $\text{EMISSION FACTOR}\left(\frac{\text{LB}}{\text{TON}}\right)$ FOR $\text{SO}_3 = 60 \times \text{SCFM}_{\text{STACK}} \times \frac{\text{PPMV SO}_3}{10^6} \times \frac{80\ \text{LB/MOLE}}{379.7\ \text{FT}^3/\text{MOLE}}\ \frac{1}{\text{LB FUEL/HR}} \times \frac{2000\ \text{LB}}{\text{TON}}$

$= \text{SCFM}_{\text{STACK}} \times \text{PPMV SO}_3 \times \frac{1}{\text{LB FUEL/HR}} \times 2.528 \times 10^{-2}$

Fuel Burning Rates and Excess Air Derived from Combustion Gas Analyses

Run No.	Stack DSCFM	Carbon Lb/Hr	Fuel	Fuel Lb/Hr	Theoretical Air Ft³/Hr	Excess Air Ft³/Hr	Excess Air %
①	120.7	4.14 2.30 3.22 Avg.	Oak	8.45 4.69 6.57 Avg.	662.0 367.4 514.7 Avg.	5552.2 6000.5 5776.4 Avg.	839 1633 1236 Avg.
②	129.0	3.09	Oak	6.31	494.4	6376.3	1290
③	72.6	2.25 2.16 2.21 Avg.	Pine	4.25 4.08 4.17 Avg.	379.0 363.9 371.9 Avg.	3443.3 3381.1 3412.2 Avg.	909 929 919 Avg.
④	103.9	3.03 1.77 2.40 Avg.	Pine	5.72 3.34 4.53 Avg.	510.1 297.9 404.0 Avg.	4927.8 5254.4 5091.1 Avg.	966 1764 1365 Avg.
⑤	52.8	4.41 3.99 4.38 4.26 Avg.	Oak	9.00 8.14 8.94 8.69 Avg.	705.1 637.7 700.4 680.8 Avg.	2021.5 2127.1 2081.8 2076.9 Avg.	287 334 297 306 Avg.
⑥	38.9	5.79 1.07 3.43 Avg.	Oak	11.85 2.18 7.00 Avg.	926.0 170.8 548.4 Avg.	1089.2 1978.3 1533.8 Avg.	118 1158 638 Avg.
⑦	34.3	6.04 6.31 4.39 5.58 Avg.	Pine	11.40 11.91 8.28 10.53 Avg.	1016.7 1062.1 738.4 939.1 Avg.	1136.8 1029.0 1323.0 1163.3 Avg.	112 97 179 129 Avg.
⑧	36.7	1.83 1.03 1.43 Avg.	Pine	3.45 1.94 2.70 Avg.	307.7 173.0 240.8 Avg.	1981.8 2097.1 2039.5 Avg.	644 1212 928 Avg.
⑨	30.3	4.44 4.49 4.46 Avg.	Coal	5.83 5.90 5.86 Avg.	668.7 676.7 672.1 Avg.	995.6 1021.5 1008.6 Avg.	149 151 150 Avg.
⑩	35.2	5.50 2.63 3.86 4.00 Avg.	Coal	7.23 3.46 5.07 5.25 Avg.	829.2 396.8 581.5 602.1 Avg.	1206.9 1770.1 1377.8 1451.5 Avg.	146 446 237 276 Avg.
⑪ ⑫ ⑬	508.6 420.6 669.7	22.89 13.02 17.20 14.38 15.79 Avg.	Oak Oak Oak	46.71 26.57 35.10 29.35 32.22 Avg.	3659.5 2081.6 2749.9 2299.4 2524.3 Avg.	30370.7 24377.4 30423.5 34633.1 32528.3 Avg.	830 1171 1106 1506 1306 Avg.
⑭	712.4	15.30 15.80 15.55 Avg.	Oak	31.22 32.24 31.73 Avg.	2445.9 2525.8 2485.9 Avg.	39487.3 41726.3 40606.8 Avg.	1614 1652 1633 Avg.

Stack total flow is assumed constant at the average flow found during particulate testing. Carbon contribution of hydrocarbons is assumed zero in tests where hydrocarbons were not determined.

FUEL & EXCESS AIR RATES

CALCULATIONS NOTES

1. $$\text{LB/HR CARBON} = \text{SCFM}_{\text{TEST}} \times 60\,\frac{\text{MIN}}{\text{HR}} \times \frac{1\text{ MOLE}}{379.7\text{ FT}^3} \times \frac{12\text{ LB}}{\text{MOLE}} \times \left(\frac{\%CO_2}{100} + \frac{\%CO}{100} + \frac{\text{PPM THC}}{10^6}\right)$$

$$= 1.896\,\frac{\text{LB/HR CARBON}}{\text{SCFM}} \times \left(\frac{\%CO_2}{100} + \frac{\%CO}{100} + \frac{\text{PPM THC}}{10^6}\right) \times \text{SCFM}_{\text{STACK}}$$

2. $$\text{LB/HR FUEL} = \text{LB/HR CARBON} \times \frac{100}{\%\text{ CARBON IN FUEL}}$$

% CARBON IN FUELS IS: OAK, 49 % ; PINE, 53 % ; COAL 76.12 %

3. $$\text{FT}^3\text{/HR THEORETICAL AIR} = 379.7\,\frac{\text{FT}^3}{\text{MOLE}} \times 4.76\,\frac{\text{FT}^3\text{ AIR}}{\text{FT}^3\ O_2} \times \left(\frac{\text{MOLES } O_2 \text{ TO BURN}}{100\text{ LB OF FUEL}}\right) \cdot \frac{\text{FUEL LB/HR}}{100\text{ LB}}$$

MOLES O_2 TO BURN 100 LB FUEL IS: OAK, 4.333 ; PINE, 4.9323 ; COAL 6.3433

4. $$\text{FT}^3\text{/HR DILUTION AIR} = \%O_2 \times \frac{1}{100\%} \times \text{SCFM}_{\text{STACK}} \times 4.76\,\frac{\text{FT}^3\text{ AIR}}{\text{FT}^3\ O_2} \times \frac{60\text{ MIN}}{\text{HR}}$$

5. $$\%\text{ EXCESS AIR} = 100\% \times \left(\text{FT}^3\text{/HR EXCESS AIR}\right) / \left(\text{FT}^3\text{/HR THEOR. AIR}\right)$$

THEORETICAL COMBUSTION REACTIONS

OAK FUEL COMPOSITION*: 49% "C" 6.5% "H", 44% "O", 0.5% ASH

100 LB OAK + 4.333 LBMOLE O_2 → 4.0833 LB MOLE CO_2 + 3.25 LBMOLE H_2O

% CO_2 IN DRY COMBUSTION GASES $= \frac{4.0833}{4.0833 + 3.76(4.333)} = 20\%$ (BY VOLUME)

$\frac{\text{STOICHIOMETRIC } O_2 \text{ VOLUME}}{CO_2 \text{ VOLUME}} = \frac{4.333}{4.0833} = 1.0612 \; \frac{\%}{\%}$

PINE FUEL COMPOSITION* 53% "C", 7% "H", 39.5% "O", 0.5% ASH

100 LB PINE + 4.9323 LBMOLE O_2 → 4.4167 LBMOLE CO_2 + 3.50 LBMOLE H_2O

% CO_2 IN DRY COMBUSTION GASES $= \frac{4.4167}{4.4167 + 3.76(4.9323} = 19.2\%$

$\frac{\text{STOICHIOMETRIC } O_2 \text{ VOL.}}{CO_2 \text{ VOL.}} = \frac{4.9323}{4.4167} = 1.1167$

COAL

FUEL COMPOSITION* 76.12% "C", 5.31% "H", 11.95% "O", 0.33% "S", 1.31% "N", 4.98% ASH

100 LB COAL + 7.2974 LBMOLE O_2 → 6.3433 LBMOLE CO_2 + 2.655 LBMOLE H_2O + .33 LB "S" + 1.31 LB "N"

% CO_2 IN DRY COMBUSTION GASES $= \frac{6.3433}{6.3433 + 3.76(7.2974)} = 18.78\%$

$\frac{\text{STOICH, } O_2 \text{ VOL.}}{CO_2 \text{ VOL.}} = \frac{7.2974}{6.3433} = 1.1504$

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* (FUEL COMPOSITIONS ARE NOMINAL WEIGHT %.)

RESULTS OF ANALYSIS OF INDIVIDUAL SAMPLES BY AIHL (SHEET 2 OF 2)

Run No.	NO_x PPMV	SO_2 PPMV	SO_3 PPMV	ALDEHYDES (EQUIV. CH_2O) PPMV	ORGANIC ACIDS (EQUIV. CH_3COOH) PPMV
①	33.6 72.0 (52.8)	—	—	38.1 66.5 (52.8)	1225
②	55.8 34.5 (45.15)	—	—	19.0 38.1 (28.5)	1255
③	32.4 19.0 (25.70)	—	—	18.2 18.2 (18.2)	900
④	20.8 11.6 16.20	—	—	18.2 18.2 (18.2)	149
⑤	—	—	—	18.5 18.5 (18.5)	167.7
⑥	—	—	—	18.5 18.5 (18.5)	142.0
⑦	70.4 64.8 (67.60)	0	1.22	83.5 83.5 (83.5)	1.31
⑧	0 ? 43.7	0	1.30	0? 76.8	1.04
⑨	148.7 128.0 (138.4)	238	2.30	60.2 60.2 (60.2)	0.08
⑩	150.5 147.9 (149.2)	219	1.85	41.8 41.8 (41.8)	0.06
⑪	27.1 31.2 (29.15)	—	—	38.0 38.0 38.0	25.5
⑫	14.6 14.6 (14.6)	—	—	(30.5) 7.6 (19.0)	25.7
⑬	12.5 8.3 (10.40)	—	—	29.9 37.4 (33.6)	83.4
⑭	6.3 6.3 (6.3)	—	—	82.3 113.6 (98.0)	61.9

NOTE: RESULTS FOR ORGANIC ACIDS AND FOR ALDEHYDES ARE CONSIDERED SUSPECT.

RESULTS OF ANALYSIS OF INDIVIDUAL SAMPLES BY AIHL (SHEET 1 OF 2)

RUN NO.	PARTICULATE, MG.						COMBUSTION GAS BY G.C.				
	FILTER CATCH	PROBE CATCH	IMPINGER RESIDUE	IMPINGER EXTRACT	POST-IMPINGER FILTER	TOTAL	OXYGEN %	CARBON DIOXIDE %	CARBON MONOXIDE PPMV	VOLATILE HYDROCARB. PPMV EQUIV. CH₄	TRUE CH₄ PPMV
①	36.1	14.7	74.8	382.8	—	508.4	16.1 17.4 (16.75)	1.67 0.98 (1.325)	1053 122 (588)	335 107 (221)	150 20.8 (85.4)
②	49.5	15.9	84.9	339.1	—	489.4	17.3	1.07	1628	319	163
③	58.2	6.9	100.9	248.7	—	414.7	16.6 16.3 (16.45)	1.58 1.47 (1.525)	450 877 (663)	70.3 140 (105.1)	30.4 69.1 (49.75)
④	95.5	24.2	85.2	294.8	—	499.7	16.6 17.7 (17.15)	1.47 0.83 (1.150)	533 512 (522)	134 183 (158.5)	60.0 78.0 (69.0)
⑤	36.4	29.0	24.2	122.3	—	211.9	13.4 14.1 13.8 (13.77)	4.29 3.80 4.21 (4.100)	1046 1580 1417 (1347)	136 262 187 (195.0)	70.8 147 91 (102.9)
⑥	65.5	42.4	30.7	248.7	—	387.2	9.8 17.8 (13.80)	7.77 1.45 (4.61)	781 50.5 (415.7)	20.6 14.5 (17.55)	7.6 3.6 (5.6)
⑦	198.6	114.7	49.8	721.7	—	1084.8	11.6 10.5 13.5 (11.87)	9.1 9.1 6.7 (8.3)	1800 6000 450 2750	— — — —	— — — —
⑧	188.2	75.7	64.6	181.6	—	510.1	18.9 20.0 (19.45)	2.6 1.4 (2.00)	280 800 (540)	— — —	— — —
⑨	179.4	59.9	82.2	176.7	—	498.2	11.5 11.8 (11.65)	7.7 7.8 (7.75)	260 120 (190)	— — —	— — —
⑩	246.1	176.0	65.4	85.5	—	573.0	12.0 17.6 13.7 (14.43)	8.1 3.9 5.7 (5.90)	1400 410 770 860	— — — —	— — — —
⑪	85.6	25.2	78.3	420.0	1.9	611.0	20.9	2.08	1610	1327	98.5
⑫	68.8	21.9	42.0	308.7	6.3	447.7	20.3	1.34	1720	1211	138
⑬	52.7	21.1	80.0	222.1	0.5	376.6	15.9 18.1 (17.00)	1.22 0.99 (1.105)	1009 1052 (1030)	338 372 (355)	98 136 (117.0)
⑭	38.1	14.5	27.5	730.8	0.7	811.6	19.4 20.5 (19.95)	1.05 1.10 (1.075)	667 585 (626)	156 113 (134.5)	60.7 47.7 (54.2)

( ) INDICATES AVERAGE

APPENDIX C

VFT TEST RESULTS

"VFT" FIREPLACE TESTS (EPA 450/3-75-010, NOVEMBER 1975)

RETABULATION OF DATA IN UNITS COMPATIBLE WITH A.R.B. TESTS

						EMISSION FACTORS LB/TON-OF-FUEL				
			FUEL			PARTICULATE			CARBON MONOXIDE	VOLATILE HYDROCARBONS
RUN NO.	STACK TEMP. °F	STACK GAS DRYSCFM	TYPE	LB/HR	EXCESS AIR %	TOTAL	FRONT HALF	BACK HALF		
1	181	400	ALDER	10.6	3202	32.0	10.4	21.6	—	—
2	226	364	ALDER	17.2	1752	11.8	4.0	7.8	—	—
3	153	286	ALDER	4.2	5872	44.2	5.6	38.6	—	—
4	237	320	ALDER	23.8	1076	24.5	4.4	20.1	—	—
6	210	443	ALDER	13.7	2728	—	—	—	80.0	3.95
7	174	421	DOUG. FIR	12.6	2825	23.0	7.2	15.8	—	—
8	190	406	DOUG. FIR	9.0	3834	28.8	6.6	22.2	156.4	5.57
9	181	294	DOUG. FIR	8.3	1355	17.6	4.4	13.2	—	—
10	230	409	DOUG. FIR	14.8	2322	27.0	5.5	21.5	—	—
14	187	348	LOCUST	19.8	1434	19.0	6.2	12.8	—	—
15	198	395	LOCUST	13.7	2429	25.4	6.5	18.9	112.4	4.16
16	180	344	LOCUST	11.5	2520	23.2	—	—	—	—
18	198	440	LOCUST	12.1	3074	30.6	12.5	18.1	—	—
19	257	401	PINE	24.7	1322	14.4	9.2	5.2	—	—
20	228	381	PINE	30.9	979	19.0	4.6	8.4	—	—
22	277	365	PINE	24.5	951	27.2	17.8	9.4	—	—
23	221	294	PINE	20.1	1520	16.2	7.7	8.5	—	—

EPA 450/3-76-010 Tests

EXCESS AIR ESTIMATES FROM TABLE I DATA CALCULATIONS

1. Theor. Comb. Prod. $\frac{M^3}{hr}$ (dry) $= \frac{\text{kg Fuel}}{\text{hr}} \times 2.2\,\frac{\text{lb}}{\text{kg}} \times 69\,\frac{\text{scf (dry)}}{\text{lb fuel}} \times \frac{1\ M^3}{35.31\ ft^3}$

$$= \frac{\text{kg fuel}}{\text{hr}} \times 4.31 = \text{"C.P."}$$

NOTE: This is a nominal estimate using combustion calculations from Appendix "F" of the EPA report.

2. Excess Air $\frac{M^3}{hr}$ (dry) = (actual stack gas $\frac{M^3\text{(dry)}}{\text{min}} \times 60\ \frac{\text{min}}{\text{hr}}$) - "C.P."

3. Theor. Air $= \frac{70}{69} \times$ "C.P." $\frac{M^3}{hr.}$ (dry)

NOTE: Per Appendix "F" of EPA report, 70 scf air are theoretically required to burn 1 lb wood (fuel) and 69 scf combustion products (mostly CO_2 & unreacted N_2 from comb. air) are produced.

4. % Excess Air = (excess air $\frac{M^3}{hr}$ /Theor. Air $\frac{M^3}{hr}$) x 100

5. Combined Calculation:

Let F = fuel $\frac{kg}{hr}$

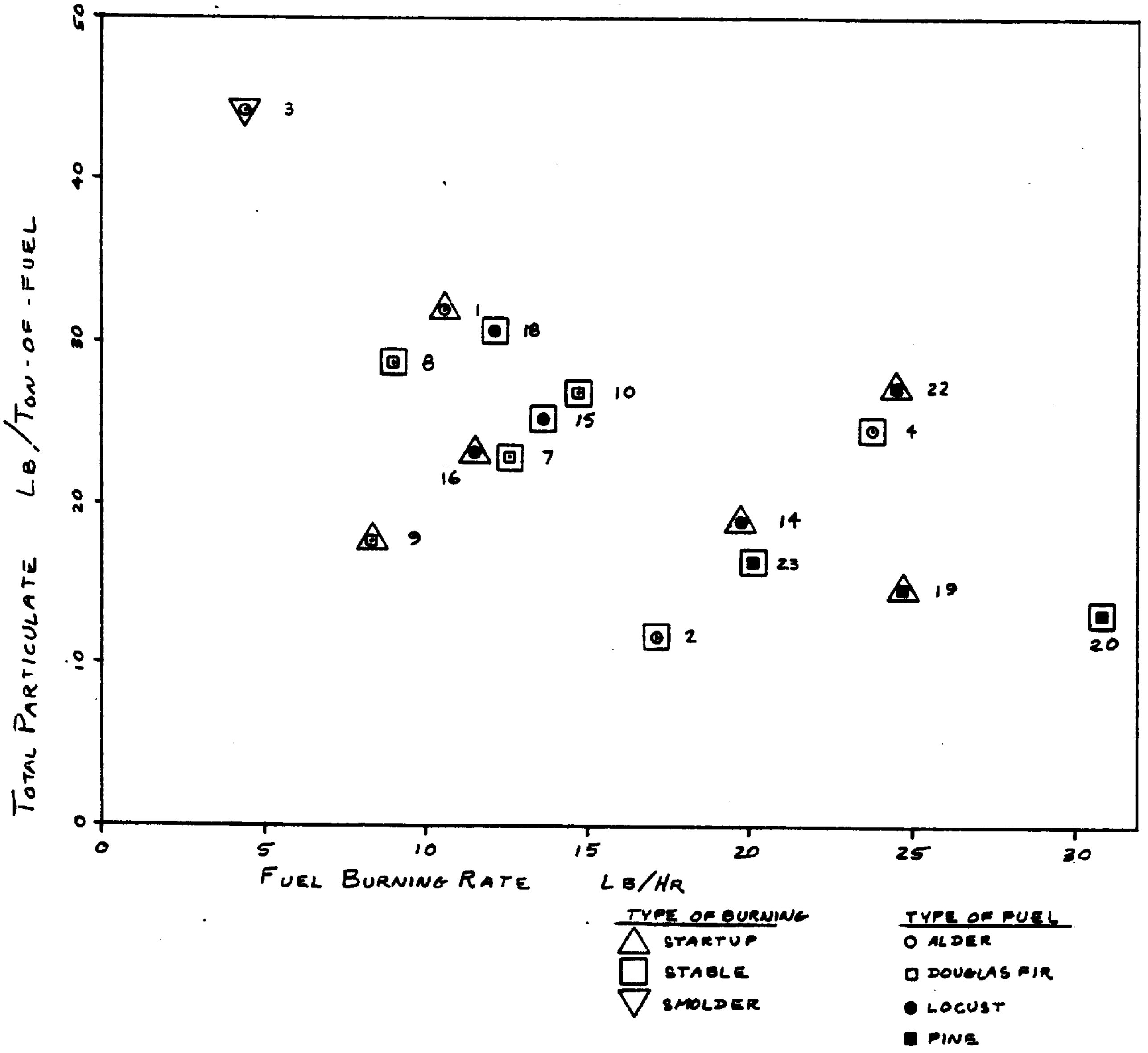
Q = stack gas $\frac{M^3}{min}$

E = % excess air

then . . .

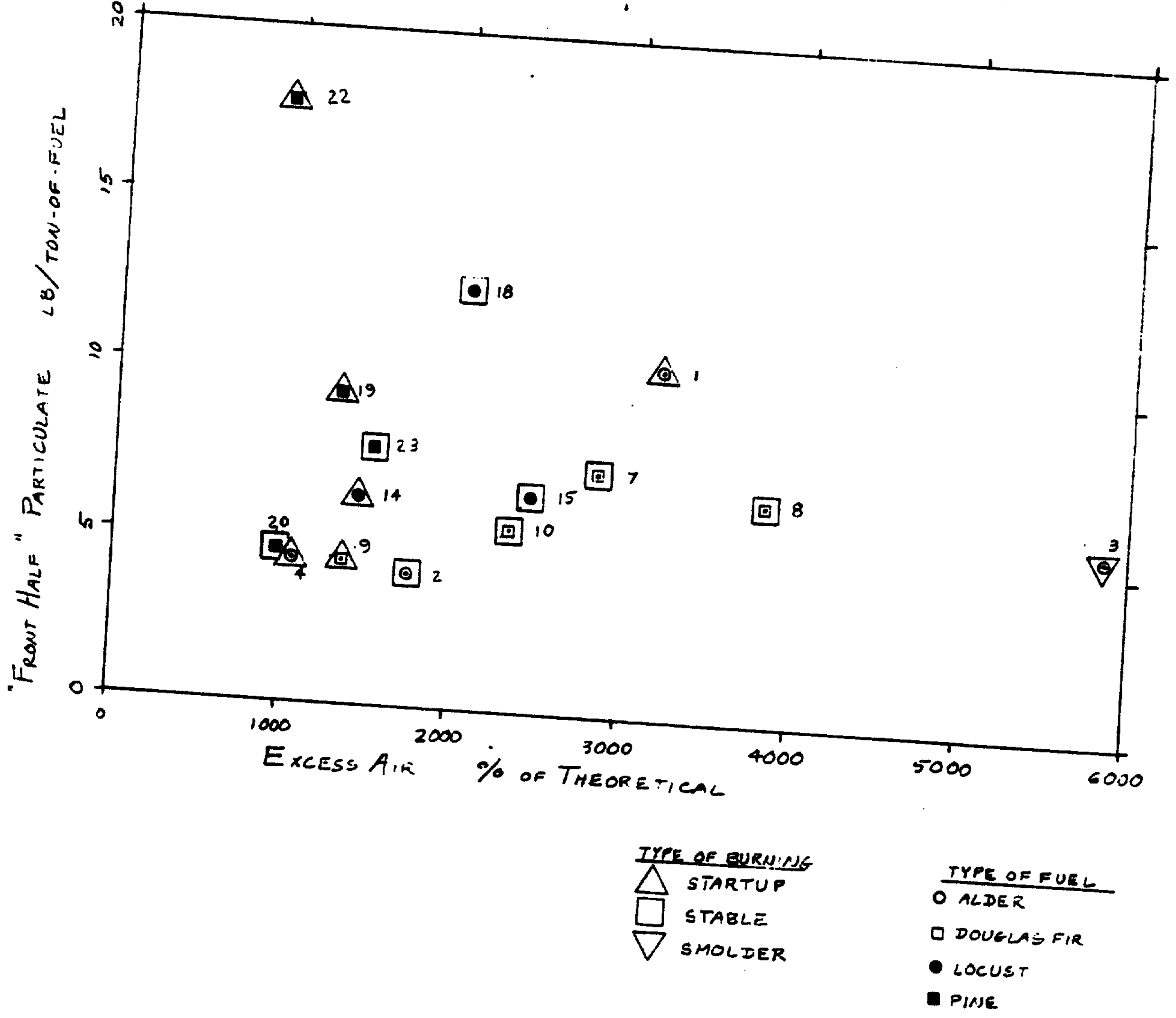
$$E \simeq [(60 \times Q) - (4.31 \times F)]/\left(\frac{70}{69} \times 4.31 \times F\right)] \times 100\%$$

VFT Fireplace Tests (EPA 450/3-75-010, November 1975)



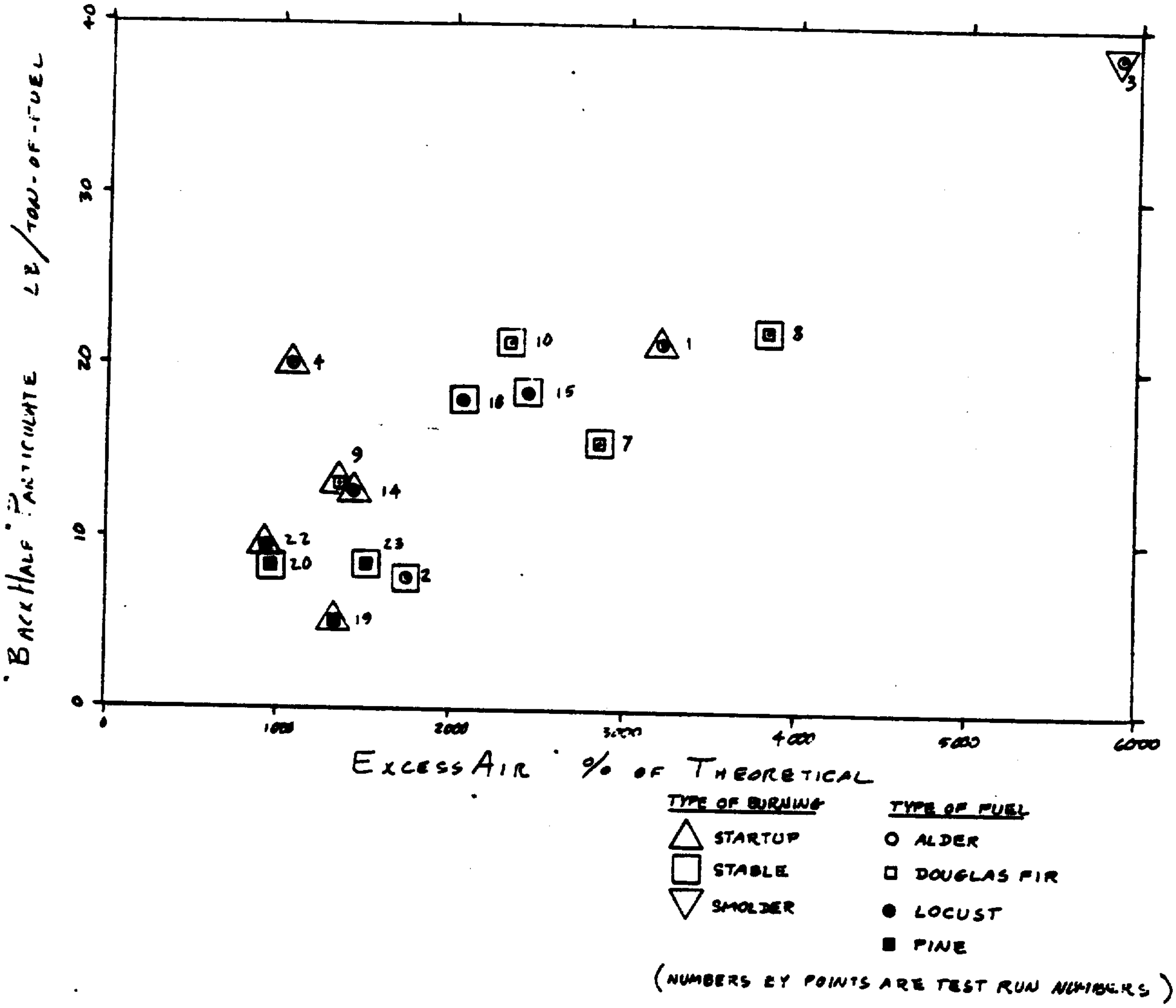
YFT Fireplace Tests (EPA 450/3-75-010, November 1975)

"Front Half" (Probe & Filter) Particulate vs Excess Air



VFT FIREPLACE TESTS (EPA 450/3-75-010, NOVEMBER 1975)

"BACK HALF" (DOWNSTREAM OF FILTER) PARTICULATE VS EXCESS AIR



FIREPLACE TESTS

TABLE I

Summary of Emissions and Burning Conditions

Fuel Type	Run	*Burning Conditions	Burning Rate Kg/hr (BR)	Stack Temp °C	Stack Gas Flow Rate Std.[a] m3/min	**Pollutant Mass Rate gm/hr (PMR)	**Concentration gm/std.m3	% CO2	**Concentration gm/std.m3 @12%CO2	Pollutant Mass Rate / Burning Rate (PMR/BR) gm/Kg
Alder	1	Start Up	4.8	83	11.538	76.6	.111	0.1	13.279	16.0
Alder	2	Stable	7.8	108	10.513	46.0	.073	0.6	1.389	5.9
Alder	3	Smolder	1.9	67	8.262	42.2	.085	0.1	10.211	22.2
Alder	4	Start Up	10.8	114	9.242	135.4	.244	0.6	4.690	12.5
Alder	5b	Stable	9.1	92	---b	---b	---b	---	---b	----b
Alder	6c	Stable	6.2	99	12.771	---c	---c	0.5	---c	-----c
Alder Average		Start Up	7.8	98	10.39	106	.178	0.4	8.984	14.2
Alder Average		Stable e	7.8e	108e	10.513e	46.0e	.073e	0.6e	1.389e	5.9e
Alder Average		All Conditions e	6.3e	93e	9.889e	75.0e	0.128e	0.4e	7.392e	14.15e
Douglas Fir	7	Stable	5.7	79	12.139	65.7	.090	0.2	5.414	11.5
Douglas Fir	8	Stable	4.1	88	11.715	58.9	.084	0.4	2.322	14.4
Douglas Fir	9	Start Up	8.3	83	8.787	72.7	.138	0.6	2.759	8.8
Douglas Fir	10	Stable	6.7	110	11.814	90.2	.127	0.4	3.817	13.5
Douglas Fir	11c	Stable	4.3	88	11.737	---c	---c	0.5	---c	----c
Douglas Fir Average		Start Up	8.3	83	8.787	72.7	.138	0.6	2.759	8.8
Douglas Fir Average		Stable	5.5e	92e	11.889e	71.6e	.104e	0.3e	3.851e	13.1e
Douglas Fir Average		All Conditions	6.2e	90e	11.114e	71.9e	.110e	0.4e	3.578e	12.05e
Locust	14	Start Up	9.0	86	10.046	85.2	.141	0.4	.430	9.5
Locust	15	Stable	6.2	92	11.414	78.7	.115	0.4	.397	12.7
Locust	16	Start Up	5.2	82	9.918	60.4	.102	0.6	2.150	11.6
Locust	17b	Stable	4.5	91	----b	---b	---b	---	---b	---b
Locust	18	Stable	5.5	91	12.709	84.2	.110	0.4	3.312	15.3
Locust Average		Start Up	7.1	84	9.982	72.8	.112	0.5	1.290	10.6
Locust Average		Stable	5.8d	92d	12.062d	81.4d	.112d	0.4d	1.854d	14.0d
Locust Average		All Conditions	6.5d	88d	11.022d	77.1d	.117d	0.4d	1.572d	12.3d
Pine	19	Start Up	11.2	125	11.857	80.5	.113	0.2	6.792	7.2
Pine	20	Stable	14.0	109	10.986	91.4	.139	0.2	8.323	6.5
Pine	21c	Stable	10.0	104	10.539	----c	----c	---c	----c	---
Pine	22f	Start Up	11.1	136	8.484	151.5	0.298	1.0f	3.572	13.6
Pine	23	Stable	9.1	105	10.727	73.9	.115	0.5	2.755	8.1
Pine	24b	Stable	13.6	97	----	----	----	---	----	---
Pine Average		Start Up	11.2e	125e	11.857e	80.5e	.113e	0.2e	6.792e	7.2e
Pine Average		Stable	11.6e	107e	10.856e	82.6e	.127e	0.4e	5.539e	7.3e
Pine Average		All Conditions	11.4e	113e	11.190e	81.9e	.122e	.3e	5.957e	7.3e
Coal	12	Start Up	2.3	80	11.290	69.8	.103	0.2	6.186	30.3
Coal	13	Stable	2.7	74	11.597	38.8	.056	0.3	2.231	14.4
Coal Average		All Conditions	2.5	77	11.444	54.3	.080	0.2	4.208	22.4
All Types h	Aver.	All Conditions	7.4	95	10.778	76.1	.119	0.4	4.536	***11.7

---

a) Standard - 76 cm Mercury 21.1°C and dry
b) Particle sizing - see particle sizing results
c) Sampling for polycyclic organic materials (POM) - See Table II
d) Particle sizing runs not included in average
e) POM; particle sizing, smolder and glass front, (if run) are not included in average
f) Glass fireplace screen was used for this run - note higher % CO2
g) POM runs are not included in average
h) Coal, POM, particle sizing and glass front runs are not included in average

* Start Up - Initial ignition of fire or fuel addition, increasing combustion rate.
Stable - Constant combustion rate.
Smolder - Tail end of combustion, decreasing combustion rate.

** All values reported from results of modified EPA Method 5; front half, back half impinger catch, and back-up filter.

***Statistically determined mean from individual values of PMR/BR. Division of mean PMR by mean BR is not equal to the mean of the individual PMR/BR values due to statistical procedure for obtaining mean values

TABLE III

Summary of Emission Constituents

					Parameters Obtained by Gas Chormatography and Mass Spectophotometry				[illegible] THC AS METHANE SEE PG 20
Fuel Type	Run	Burning Condition	Polycyclic Organic Materials a (ng)	Concentration Polycyclic Organic Materials ng/std. m3 b	% O2	% N2	PPM CO	PPM CO2	PPM NMVHc
Alder	6	Stable	166,000	5,746	20.2	79	280	6,300	4.5
Douglas Fir	8	Stable	---	---	20.0	79	405	7,900	4.7
Douglas Fir	11	Stable	220,000	7,444	---	--	---	---	---
Locust	15	Stable	---	---	20.2	79	440	6,500	5.3
Pine	21		162,000	7,647	---	--	---	---	---
All Average			183,000	6,946	20.1	79	375	6,900	4.8

a) See table V for quantification of specific materials
b) Standard - 76 cm. Mercury 21.1°C and dry
c) NMVH - Non Methane Volatile Hydrocarbons

~~APPENDIX B~~

Tabulation of Front Half to Back Half Ratios

This tabulation of the front half to the back half ratios in 18 runs show the significance of the back half particulate. Also, the back-up filter shows to be important in this type of sampling.

Run #	Ratio: BH particulate / FH particulate	Ratio: BU Filter particulate / F Filter particulate
1	2.07	0.463
2	1.93	0.542
3	0.688	0.289
4	4.36	1.020
5	—	—
6	—	—
7	2.18	0.540
8	3.35	1.32
9	2.99	1.37
10	3.93	1.79
11	—	—
12	0.509	.064
13	1.05	0.143
14	2.08	0.525
15	2.90	0.761
16	—	—
17	—	—
18	1.44	0.200
19	0.537	.028
20	1.92	1.07
21	—	—
22	0.528	.027
23	1.10	0.239
ave.	1.968	0.612

APPENDIX D

BAAQMD TEST RESULTS

BAY AREA AIR QUALITY MANAGEMENT DISTRICT (SAN FRANCISCO BAY) DATA SUMMARY

Run No.	Stack Temp. °F	Stack SCFM (Dry)	Fuel		Emission Factors lb/ton-of-fuel				Excess Air %
			Type	LB/Hr	Carbon Monoxide	NO_x	"Total Organics"	Particulate	
A1	300	315	Eucalyptus	22	87	2.50	41	13.2	1114
A2	204	230	Euc. & Oak	69	25	1.70	5.4	—	188
A3	238	240	Euc. & Oak	5	438	15.35	82.9	—	4072
A4	225	234	Oak	13	217	4.19	32.8	16.1	1464
A5	215	220	Garden Waste	27	140	—	24.3	3.4	607
B1	312	158	Presto Logs	18	47.8	—	14.6	7.7	662
B2	191	152	Oak	12	96.7	—	44.5	26.7	1000
C1	170	295	Oak	19	114	—	39.3	26.3	1249
C2	192	306	Oak	15	171	—	48.8	44.0	1672
C3	160	304	Madrone	10	168	—	66.3	48.0	2542
D1	242	283	Oak	25	55	1.81	11.9	10.4	883
D2	306	253	Oak	20	52	1.47	15.1	16.0	999
D2½	234	253	Oak (Burndown)	5	161	3.68	—	—	4299

EXCESS AIR ESTIMATION FOR BAAQMD DATA

REQUIRED AIR = 69 SCF (DRY) PER LB. FUEL

COMBUSTION PRODUCTS = 70 SCF (DRY) PER LB FUEL

FUEL CONSUMPTION RATE, LB/HR = "F"

STACK GAS FLOW, SCFM (DRY) = "Q"

EXCESS AIR RATIO, PERCENT = "E"

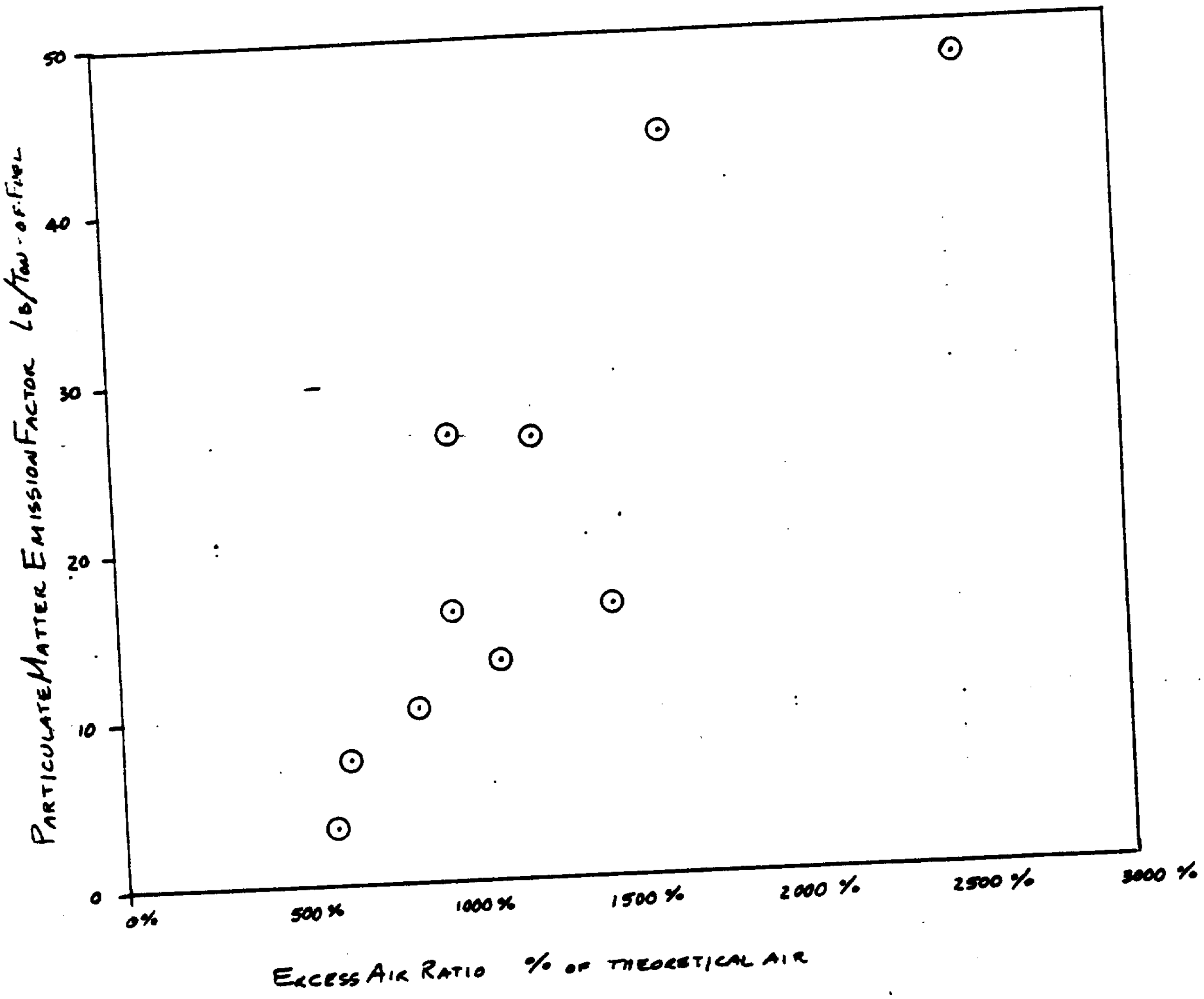
REQUIRED AIR PER HOUR = $69 \times F$

COMBUSTION PRODUCTS PER HOUR = $70 \times F$

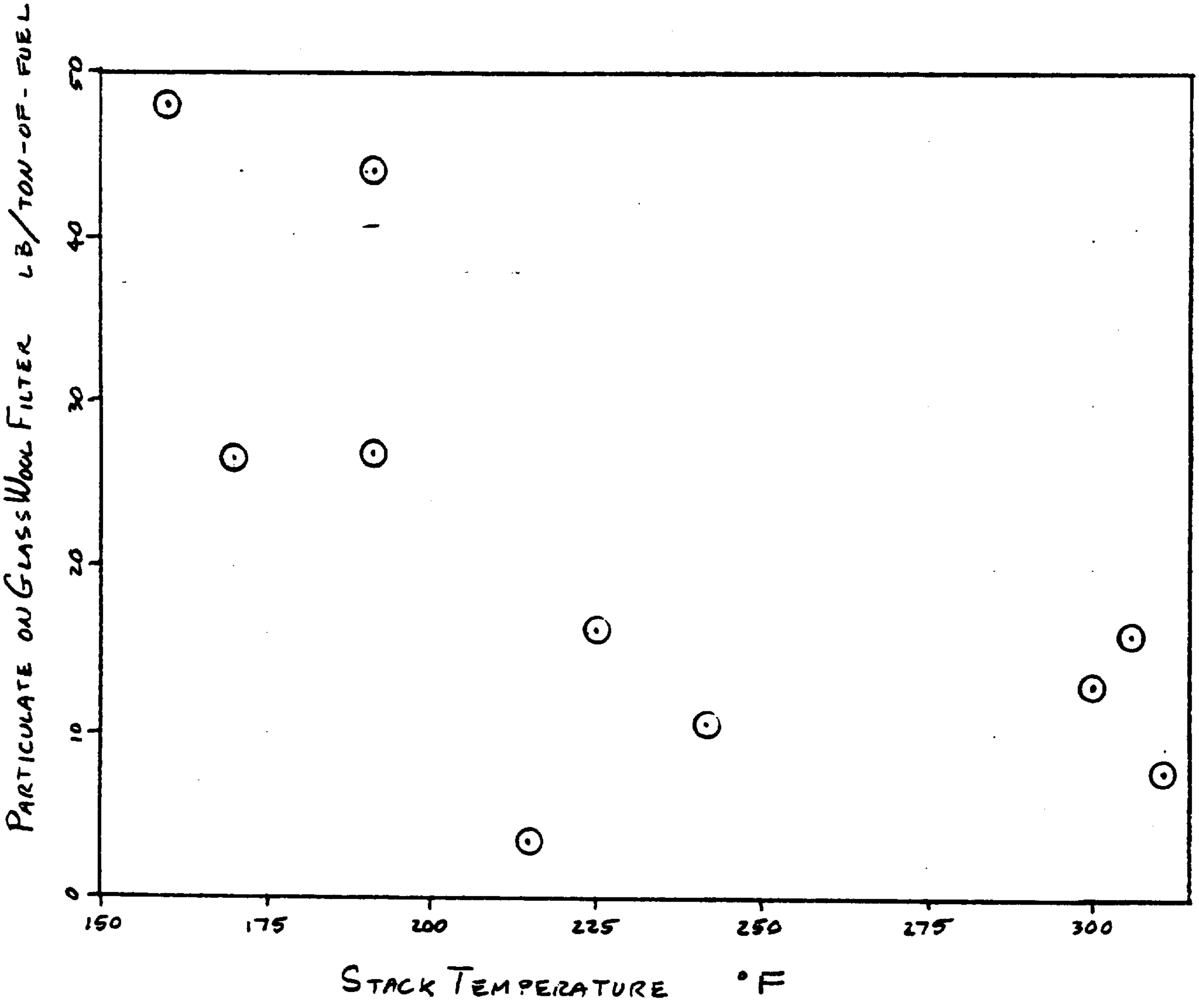
EXCESS AIR PER HOUR, SCF = $60Q - 70F$

$$\text{"E"} = \left[(60Q - 70F) / 69F\right] \times 100\%$$

BAAQMD DATA

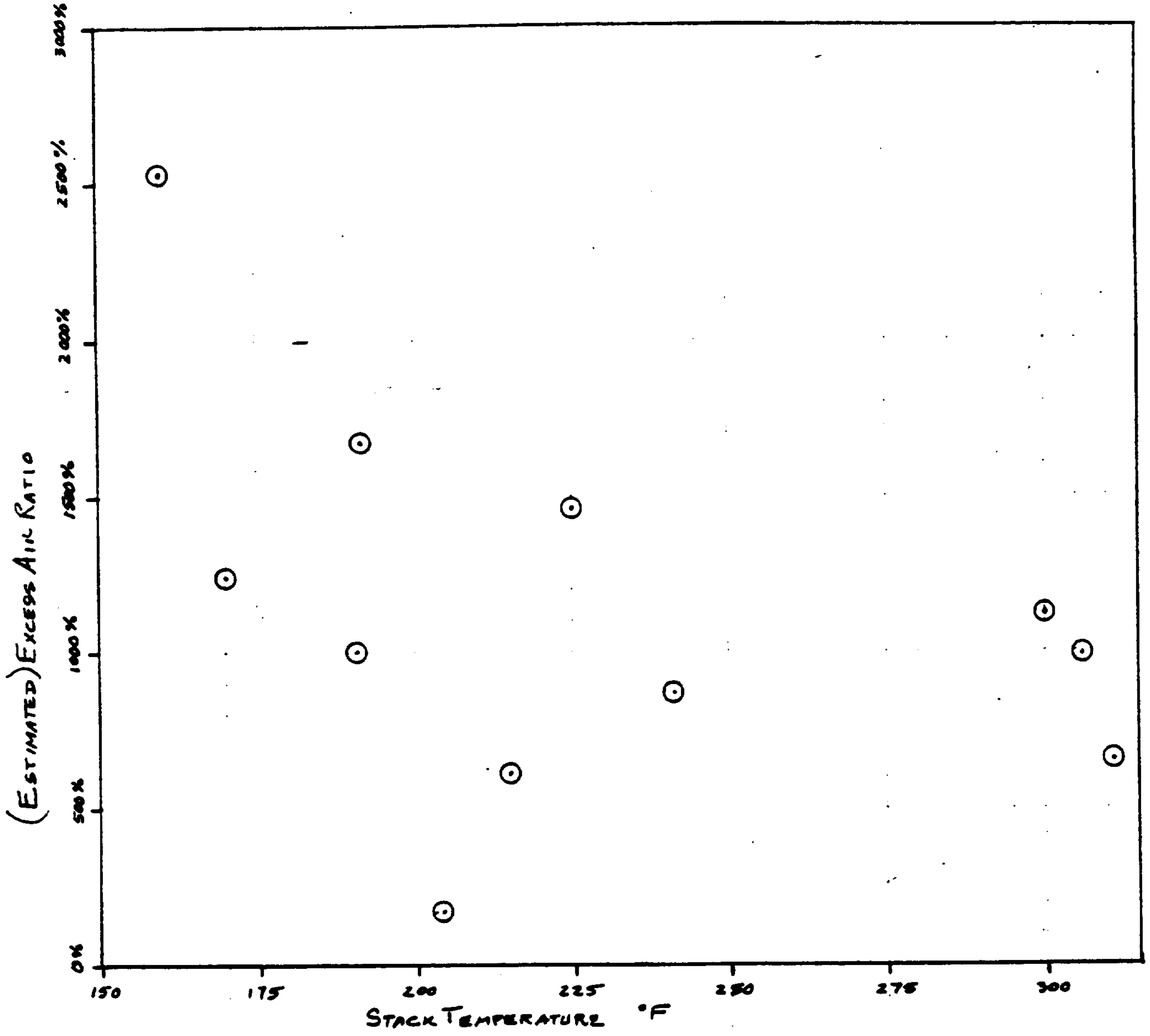

Particulate Matter Emission Factor LB/TON-OF-FUEL
50
40
30
20
10
0
0%
500%
1000%
1500%
2000%
2500%
3000%
Excess Air Ratio % of theoretical air

SF BAY DATA - PARTICULATE VS STACK TEMPERATURE



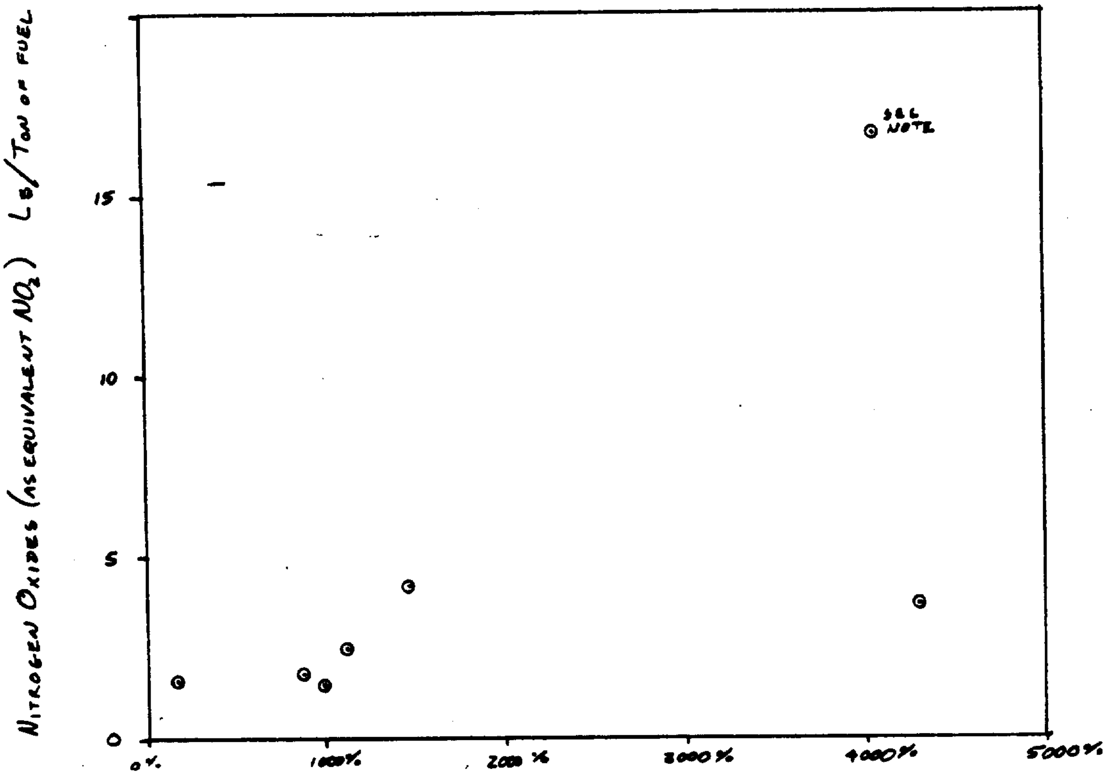
NOTE: EMISSION FACTORS ARE CONSIDERED ROUGHLY EQUIVALENT TO FRONT HALF FOUND BY EPA METHOD 5. PARTICULATE WAS FOUND USING A WADDED GLASS WOOL FILTER.

BAAQMD DATA



Note - differences in fireplaces and fuel moisture affect temperature at similar excess air ratios.

BAAQMD DATA



Note: Excess air ratio for point marked is questionable

January 31, 1968

TO: HERB JOHNSON

FROM: LEONARD CLAYTON LCC 2/5/68

SUBJECT: EMISSIONS FROM RESIDENTIAL TYPE FIREPLACES
(LOCATIONS OF UNITS ON FILE WITH SOURCE TEST DATA)

S.T. 24C67
S.T. 26C67
S.T. 29C67
S.T. 40C67
S.T. 41C67
S.T. 65C67
S.T. 66C67

District Personnel: L. Clayton, G. Karels and C. Ong (T. Ping, formerly with the staff, was also involved with these tests.)

Source tests were conducted on residential fireplaces in order to determine the type and nature of contaminants being emitted to the atmosphere from the normal use.

SUMMARY:

Seven source tests were conducted on fireplace emissions based on their normal use. Considerable time was spent on reporting the analysis of the results. As the results are rather lengthy and involved, it is not possible to summarize them in this summary. The reader is requested to refer to the "Tabulated Results."

DESCRIPTION OF PROCESS AND EQUIPMENT:

These fireplaces were all of the conventional type (residential) and similar in dimensions:

Unit	Firebox			Chimney	
	Height, in.	Width, in.	Depth, in.	Height, ft.	Area $ft.^2$
A	29	35	19	12 1/2	0.73
B	31	35	19	12	0.59
C	30	38	20	13 1/2	0.76
D	25	37	18	12 1/4	0.75

Each fire was started with a small amount of paper and kindling. As soon as the paper was burned, the tests were begun. No wood was added to the fire once it had started to burn. The burning logs were not moved or stoked unless it had appeared that the fire might not burn to completion. Unit D deviated from the design of the others in that both the front and one side were open. All of the other three were of the open front type. Each damper was left fully open during burning. Unit B was the only unit that smoked back considerably.

TEST PROCEDURES:

Gas Velocities: Bay Area Air Pollution Control District's Source Test Manual, Section 1-A; intermittant readings were taken at the midpoint of the cross-sectional area and the average velocity assumed to be 0.8 of this value.

NO_x: Method G

Total carbonyls, specific aldehydes: Method D;
Organic acids, phenols: Method F;
C_1 + hydrocarbons, including aromatics: Method E;
Particulates: Method B

DISCUSSION OF RESULTS:

Please refer to the "Tabulated Results." At least two tests were performed on each unit and ranged from 30 to 50 minutes each. In order to make it convenient to compare the results of these tests with emissions from other combustion operations, the values ppm, ppm at 6% O_2, lbs. emissions/ ton burned, total "carbon" and other Regulation 2 notations are shown.

As is the case with emissions from poor incinerators, there was some condensed oils on the glasswool probes used for particulate collection. As these probes were at or near emission temperature, they may not have collected all the condensing material.

sc

UNIT A

#/Ton Burned	Test #1	Test #2	Test #3	Test #4	Test #5
C_2-C_6 Sat	.5-1.0	.3	7.8	.92-.46	2.5
C_7 Sat	.09-.18	<.05	<.05	<.05	<.05
C_6H_6	.27	.3	1.5	<.03	.58
C_2H_2	.26-.09	.6	1.4	.6-.15	.50
CH_4	6.6-7.6	2.1	42.5	9.2-6.8	10.7
CO	64-111	25.8	438	268-166	140
Olefins, (<C_4)	1.7-1.9	1.1	11.6	3.5-1.5	3.8
Aromatics (Excl. C_6H_6)	.91-2.1	<.02	<.02	<.02	.71
Organic Acids, as HAc	20.2-16.2	<.03	<.03	~7.7	.03
Phenols	1.5-2.2	<.04	<.04	~4.6	<.04
Total Carbonyls as CHOH	9.1-8.0	1.01	18.1	6.2-3.1	5.5
CHOH	3.3-2.2	.27	4.3	1.4-1.2	.12
CH_3CHO	N.A.	.45	1.21	N.A.	2.4
Total Organics incl. CH_4	41-40	5.4	82.9	~32.8	24.3
)Particulate	~13.2	N.A.	N.A.	25.2-6.9	N.A.
Other Data					
H_2O,%	4.9-2.8	1.6	2.0	1.7-1.6	3.4
CO_2,%	1.4-1.0	1.0	1.1	.9	1.1
O_2,%	19.5-19.6	19.6	19.5	19.8-19.5	19.5
2)C_2-C_6, ppm @ 6% O_2	189-252	772	457	402-125	873
2)Total Carbonyls, ppm @ 6% O_2	663-662	350	409	465-147	720
Total "C" ppm, Excl. CH_4	198-195	278	142	191-40+	316
NO_x as NO_2, ppm	12	35	22	16	N.A.
Burning Rate, #/hr. and type	Eucalyptis, 22	Eucalyptus and Oak 69	Euc. and Oak, 5	Oak 13	Green den cu 27
Stack Temp. °F	300	204	238	220-230	215
Stack Flow, SDCFM	320-310	230	240	228-230	220

$V = 5.25$ ft/sec

P .078" H_2O

(1) Solids and Condensed Organics on Glasswool Filter
(2) Reg. #2 Notatio

UNIT B

#/Ton Burned	Test #1	Test #2
C_2-C_6 Sat.	.33	1.7
C_7 Sat	<.01	<.01
C_6H_6	<.02	<.02
C_2H_2	<.01	.50
CH_4	2.9	8.7
CO	47.8	96.7
Olefins ($<C_4$)	1.1	2.3
Aromatics (Excl. C_6H_6)	<.02	<.02
Organic Acids, as HAC	1.2	11.8
Phenols	.33	.83
Total Carbonyls, as CHOH	8.8	18.7
CHOH	3.9	10.5
CH_3CHO	N.A.	N.A.
Total Organics, incl. CH_4	14.6	44.5
Particulate (1)	7.7	26.7
Other Data		
H_2O,%	~2	~2
CO_2%	1.2	.5
O_2%	19.3	20.2
(2) C_2-C_6, ppm @ 6% O_2	145	837
(2) Total Carbonyls, ppm @ 6% O_2	957	3540
Total "C", ppm, Excel. CH_4	165	351
NO_x as NO_2	N.A.	N.A.
Burning Rate, #/hr, and type	18 Prestologs	12 ,Dry Oak
Stack Temp. , °F	312	191
Stack Flow, SDCFM	158	152

---

(1) Solids and Condensed Organics on Glass Wool Filter

(2) Reg. #2 Rotation

UNIT C

#/Ton Burned	Test #1	Test #2	Test#3
C_2-C_6 Sat.	1.2	2.5	3.9
C_7 Sat.	<.04	<.04	<.04
C_6H_6	.50	.81	.70
C_2H_2	<.02	<.02	<.02
CH_4	9.2	12.1	11.1
CO	114	171	168
Olefins, $(<C_4)$	4.9	5.3	4.9
Aromatics, (Excl. C_6H_6)	<.04	.42	.28
Organic Acids, as HAC	17.5	17.9	29.3
Phenols	1.6	2.8	4.8
Total Carbonyls, as CHOH	4.4	7.0	11.4
CHOH	1.2	1.5	3.2
CH_3CHO	1.3	1.9	2.5
Total Organics, incl. CH_4	39.3	48.8	66.3
Particulate (1)	26.3	44.0	48.0
Other Data			
H_2O, %	2.5	2.6	2.4
CO_2,%	1.1	1.0	.7
O_2,%	19.7	19.8	20.1
(2)C_2-C_6,ppm,@6% O_2	430	513	389
(2)Total Carbonyls,ppm,@6%O_2	358	467	665
Total "C", ppm	264	263	206
NO_x as NO_2, ppm	N.A.	N.A.	N.A.
Burning Rate, #/hr., andtype	19 Oak	15 Oak	10 Madrone
Stack Temp., °F	170	192	160
Stack Flow, SDCFM	295	306	304

6.56 fl

(1) Solids and Condensed Organics on Glasswool Filter
(2) Reg. #2 Notation

P= 0.098

UNIT D

#/Ton Burned	Test #1	Test #2	Burndown Following #2
C_2-C_6 Sat.	.25	.37	1.2
C_7 Sat.	<.04	<.04	<.04
C_6H_6	<.04	<.04	<.04
C_2H_2	<.02	<.02	<.02
CH_4	4.8	3.9	16.8
CO	55.1	52.6	161
Olefins, ($<C_4$)	.95	1.2	3.0
Aromatics (Excl. C_6H_6)	<.04	<.04	<.04
Organic Acids, as HAc	3.4	5.3	N.A.
Phenols	.20	.48	N.A.
Total Carbonyls, as CHOH	2.4	3.9	N.A.
CHOH	.59	1.03	N.A.
CH_3CHO	.36	.78	N.A.
Total Organics, Incl. CH_4	11.9	15.1	-
Particulate (1)	10.4	16.0	N.A.
Other Data			
H_2O, %	Approx. 2.4	Approx. 2.4	Approx. 2.4
CO_2,%	1.3	1.3	1.2
O_2,%	19.4	19.4	19.4
C_2-C_6, ppm, @ 6% O_2	118	119	84
Total Carbonyls, @ 6% O_2	216	295	N.A.
Total "C", ppm	87	112	-
NO_x as NO_2, ppm	11	8	5
Burning Rate,#/hr., and type	25 Oak	20 Oak	<5 (Burndown)
Stack Temp., °F	242	306	234
Stack Flow, SDCFM	283	253 V 5.62	253

(1) Solids and Condensed Organics on Glasswool Filter

Notes on S.F. Bay Fireplace Test Methodology

Mr. G. Karels of BAAQMD was contacted by telephone and provided the following information regarding the fireplace tests he participated in.

CO_2 and oxygen were determined by the Orsat method.

Hydrocarbons, including "C_2-C_6 Sat", "C_7 Sat", "C_6H_6", "C_2H_2", "CH_4", and "Olefins ($<C_4$)", and "CO" (carbon monoxide) were determined by gas chromatography of a sample obtained in a large steel tank, initially evacuated, into which stack gases were drawn continuously during an extended sampling period.

"Aromatics (Excl. C_6H_6)" were determined by G.C. analysis of a sample obtained using a silica gel sorbant trap.

"Organic acids" were determined by analysis of a sample which was obtained in wet impingers containing a weak basic solution. Phenols were determined from the same sample.

"Total Carbonyls as CHOH" were determined colorimetrically using a sample obtained with wet impingers containing Sodium Bisulfate solution. "CHOH" and "CH_3CHO" were found by G.C. analysis of the same sample.

Particulate was determined using glass wool wadding as a filter medium in an instack location where feasible; a heated probe was used in instances where instack location of the filter was impossible.

Nitrogen oxides were determined by a method comparable to EPA method 7.

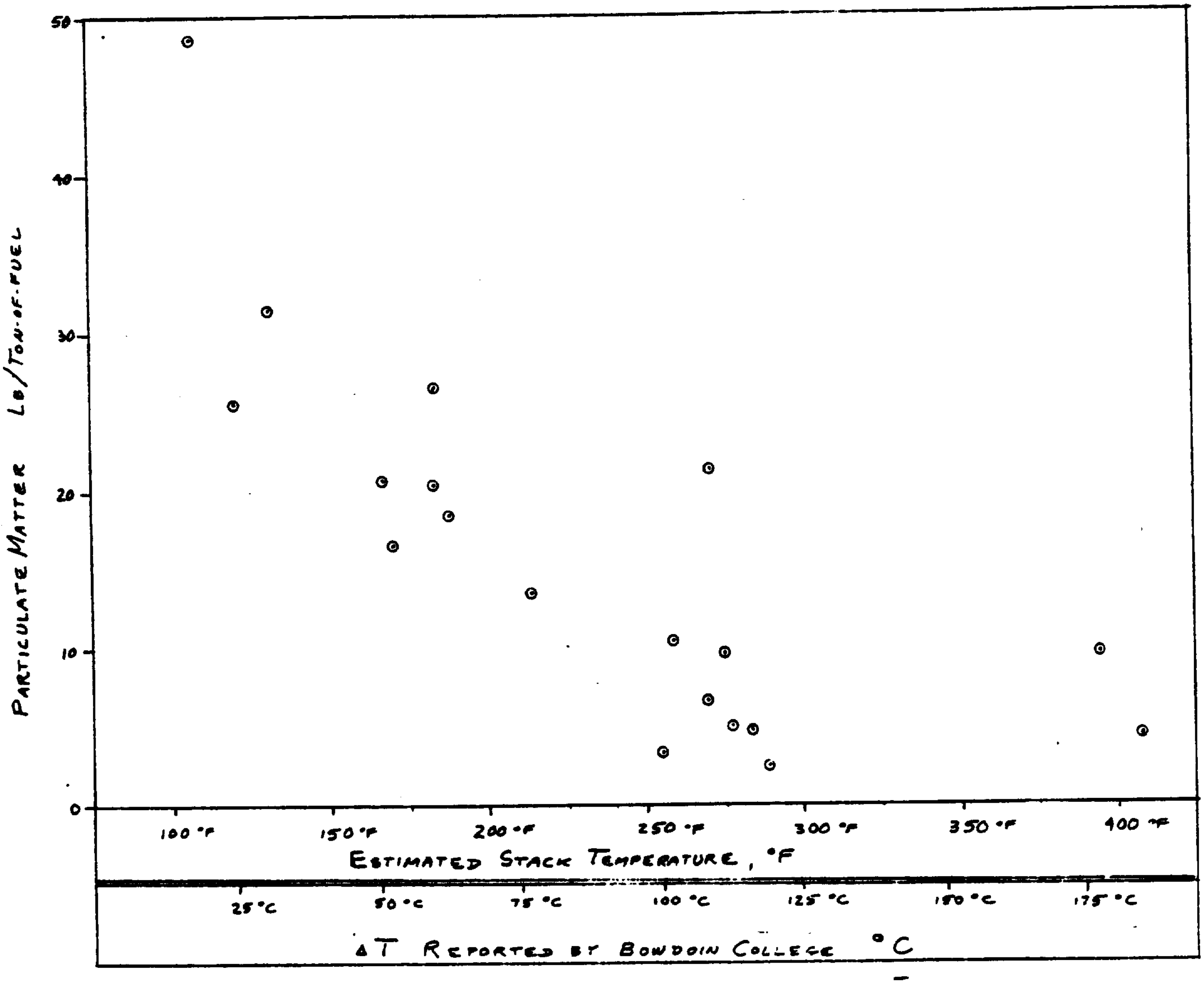
APPENDIX E

BOWDOIN COLLEGE TEST RESULTS

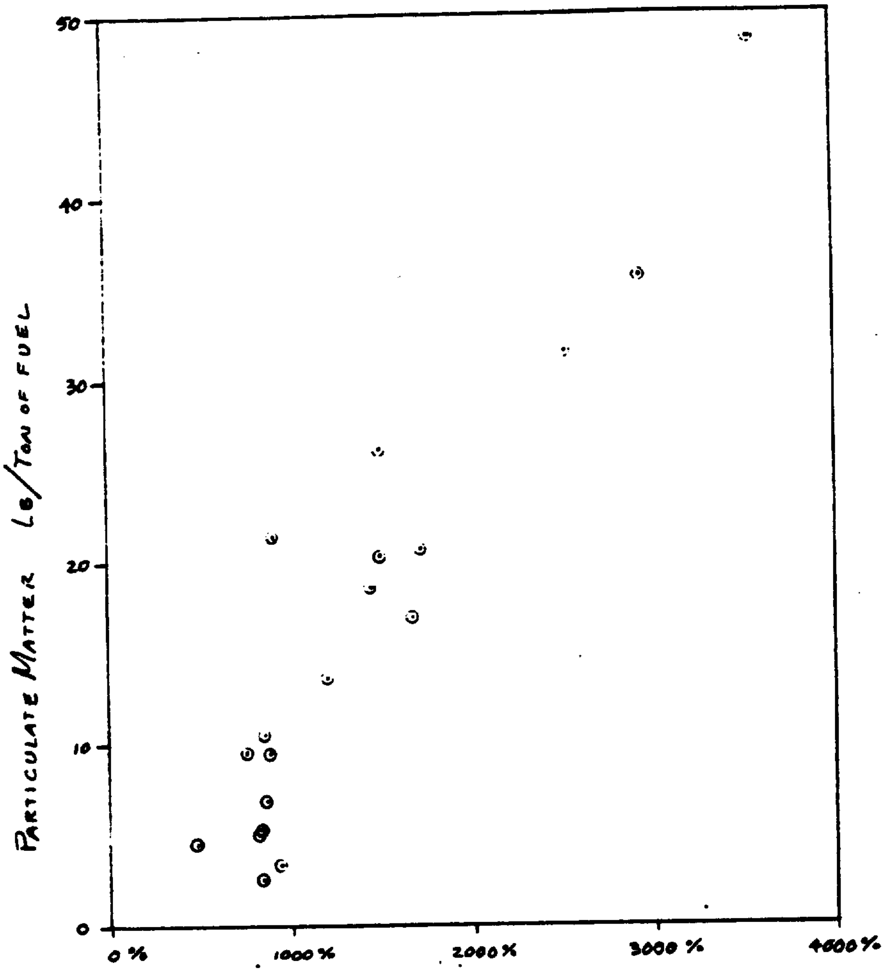
BOWDOIN COLLEGE TESTS ON JOTUL STOVE BURNING OAK - SUMMARY OF RESULTS

RUN NO	FUEL LB/HR	ESTIMATED STACK TEMP. °F	ESTIMATED EXCESS AIR %	PARTICULATE EMISSIONS $\frac{\text{LB}}{\text{TON OF FUEL}}$
a	2.76	183	1500	26.62
b	8.75	409	479	4.62
c	3.90	187	1459	18.40
d	4.50	259	916	10.42
e	3.59	167	1719	20.78
f	4.83	183	1500	20.28
g	3.35	170	1666	16.48
h	4.76	214	1200	13.50
i	6.53	284	806	4.92
j	5.42	269	867	6.72
k	4.54	277	836	5.04
l	3.97	255	944	3.64
m	6.81	395	755	9.70
n	4.14	275	873	9.80
o	5.14	289	815	2.54
p	5.45	271	891	21.54
q	2.69	131	2521	31.44
r	2.40	107	3567	48.70
s	2.05	120	2926	25.64

BOWDOIN DATA



BOWDOIN DATA



ESTIMATED EXCESS AIR RATIO BASED ON
ASSUMED 50% THERMAL EFFICIENCY AND
15°C ERROR IN REPORTED STACK TEMPERATURE

BOWDOIN DATA EXCESS AIR CALCULATION NOTES

PH. KOSEL '79

I HEATING VALUE (DRY OAK)

UNDIFFERENTIATED OAK: 7740 BTU/LB (ESTIMATED)
RED OAK: 7992 BTU/LB ; BLACK OAK 7524 BTU/LB

II HEATING VALUE (WET OAK)

(7730 - 87.1 P) BTU/LB WHERE P IS PERCENT H_2O. INCLUDES ALLOWANCE FOR 970.33 BTU/LB FOR VAPORIZATION OF H_2O AND REDUCTION OF COMBUSTIBLES: 1 LB WET WOOD CONTAINS (1 - P/100) LB COMBUSTIBLES AND P/100 LB OF WATER.

III COMPOSITION

49% C, 6.5% H, 44% O, ½% ASH

IV COMBUSTION REACTION (DRY OAK)

$$1 \text{ LB } \underline{\text{DRY}} \text{ OAK} + 5.953 \text{ LB } (78.27 \text{ SCF}) \text{ AIR} \rightarrow 1.797 \text{ LB } CO_2 + 0.585 \text{ LB } H_2O + 4.566 \text{ LB } N_2$$

V HEAT CAPACITY & HEAT CONTENT OF COMBUSTION GASES (DRY OAK)

HEAT CAPACITIES OF COMBUSTION GASES INDIVIDUALLY

ARE, AT	100°F	1000°F	2000°F
CO_2	.203	.280	.322
H_2O	.445	.51	.60
N_2	.248	.269	.298
AIR (EXCESS)	.240 $\frac{BTU}{LB}$	.262 $\frac{BTU}{LB}$	.286 $\frac{BTU}{LB}$

FOR COMBUSTION GASES FROM 1 LB OF DRY WOOD USING 1000°F HEAT CAPACITIES,

$$\text{HEAT CONTENT} = \Delta T \times [.280 \times 1.797 + .51 \times .585 + .269 \times 4.566] = \Delta T \times 2.03 \frac{BTU}{LB\ FUEL}.$$

AVERAGE HEAT CAPACITY OF 6.948 LB OF COMBUSTION PRODUCTS IS $2.03/6.948 = 0.292 \frac{BTU}{LB\ GAS}$

VI HEAT CONTENT OF COMBUSTION GASES FROM MOIST FUEL BURNED WITH EXCESS AIR

LET "E" BE THE PERCENT EXCESS AIR (AS A PERCENTAGE OF THE 5.953 LB OF AIR REQUIRED FOR EACH LB OF DRY FUEL).

- FOR COMBUSTION OF 1 LB OF MOIST FUEL, GASES FROM COMBUSTION WILL INCLUDE $[(1 - P/100)\, 6.948]$ LB OF ACTUAL DRY-FUEL COMBUSTION PRODUCTS, $(P/100)$ LB OF H_2O AND $[(1 - P/100)(E/100)(5.953)]$ LB OF AIR.

$$\text{HEAT CONTENT} = \Delta T \times \Big[[(0.292)(1 - P/100)(6.948)] + [(.51)(P/100)] + [(.286)(1 - P/100)(\tfrac{E}{100})(5.953)]\Big]$$

$$= \Delta T \times \left[2.03 + (1.703)\left(\frac{E}{100}\right) - \left(\frac{P}{100}\right)\left(1.52 + 1.703\left(\frac{E}{100}\right)\right)\right]$$

VII EXCESS AIR FOUND IF TEMPERATURE IS KNOWN

THE HEAT CONTENT SHOWN IN VI AS A FUNCTION OF ΔT MUST BE EQUAL TO THE HEATING VALUE SHOWN IN II. ASSUMING P (PERCENT MOISTURE) AND ΔT (DIFFERENCE BETWEEN AMBIENT AND COMBUSTION GAS TEMPERATURE) ARE KNOWN, E CAN BE FOUND AS

$$E = \left[\frac{7780 - 87.1\,P}{\Delta T} - 2.03 + \left(\frac{P}{100}\right)(1.52)\right] \frac{100}{1.703\left(1 - \frac{P}{100}\right)}$$

ΔT °C + 15 × 2 × ?

PH Kosal '79

[illegible] + 157 × ? ← Calculated [illegible] with [illegible] 50% [illegible]

a	270	23.8	1500	26.21	486	776
b	729	|	479	4.62	1302	209
c	277		1459	18.40	499	
d	421		916	10.41	758	
e	233		1719	20.73	428	
f	270		1500	20.78	486	
g	243	↓	1666	16.48	441	
h	331	23.8	1200	12.00	596	
i	472	22.8	806	4.92	850	
j	443	↓	867	6.72	797	
k	407	22.8	836	[illegible]	823	
l	414	9.8	944	[illegible]	715	
m	515	6.7	755	[illegible]	927	
n	439		873	[illegible]	817	
o	482	↓	815	[illegible]	868	
p	446	8.7	891	[illegible]	803	
q	166	23.8	2521	21.43	299	
r	119	|	3567	18.[illegible]	214	
s	144	↓	2926	[illegible]	259	

HP29C Calculator program

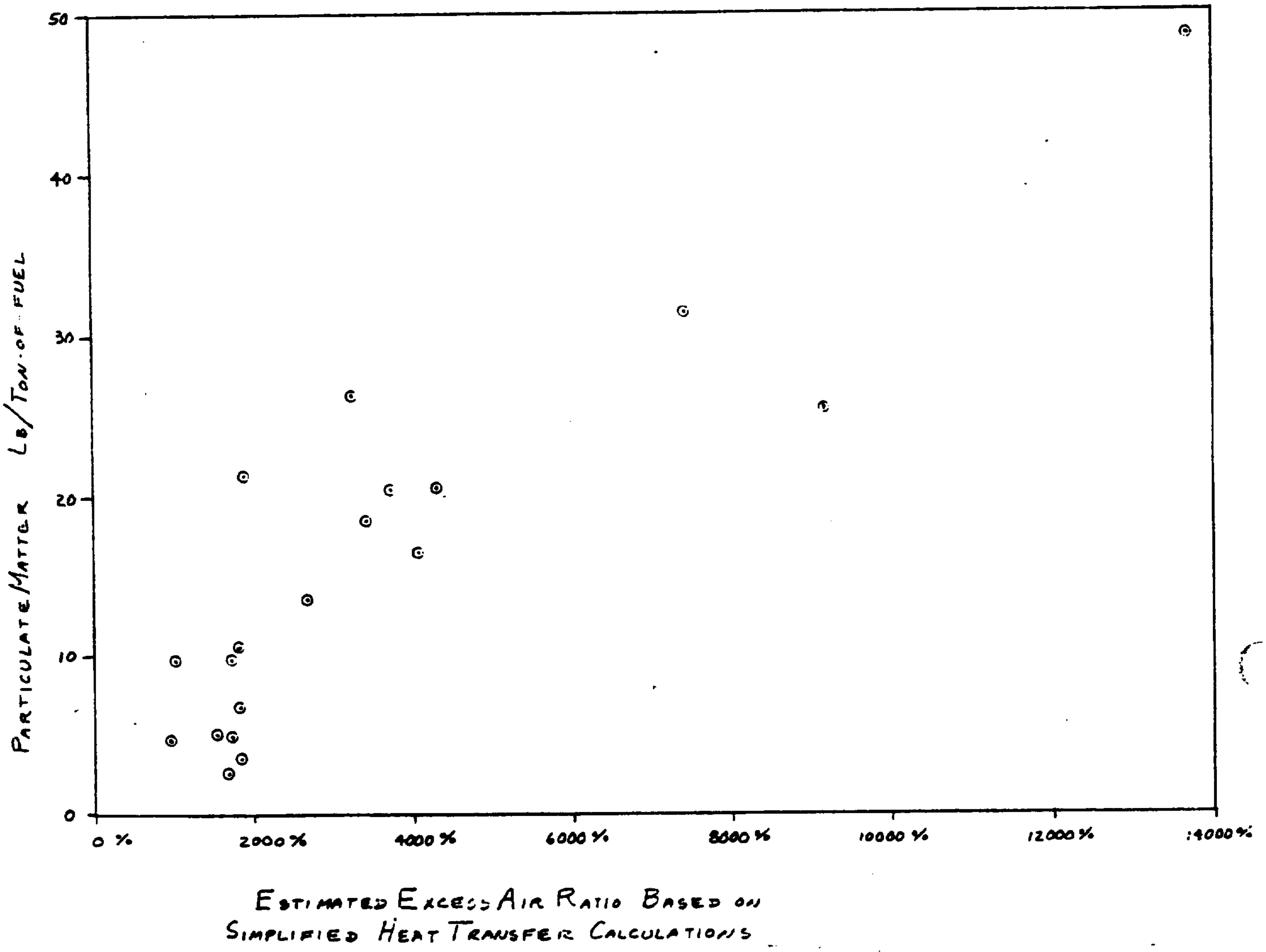
DATA ENTRY ΔT [illegible] 1/x

PROGRAM 2f [illegible] 1

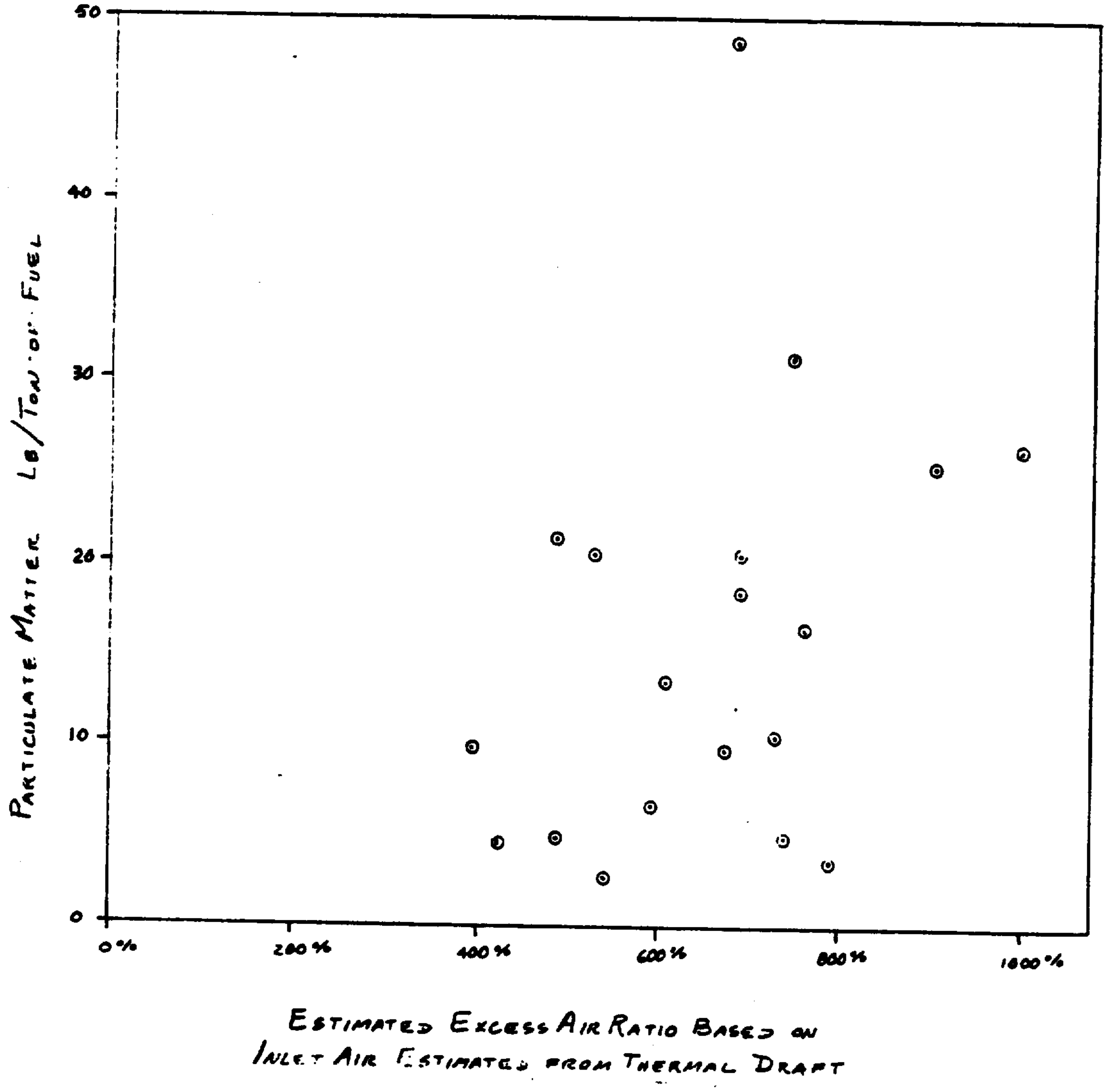
CONSTANTS		
	1	P
	2	ΔT °F
	3	7780
	4	87.1
	5	2.03
	6	.03
	7	1.52
	8	[illegible]

```
[illegible] rcl 4 × rcl 3 ⇄ −
⇄ sto 2 ÷ rcl 5 −
rcl 1 rcl 6 ÷ rcl 7 × +
rcl 6 × rcl 8 ÷ rcl 1 rcl 6 ÷
1 ⇄ − ÷
[illegible] gto 1
```

Bowson Data


50
40
30
20
10
0
Particulate Matter Lb/Ton of fuel
0 %
2000 %
4000 %
6000 %
8000 %
10000 %
12000 %
14000 %
Estimated Excess Air Ratio Based on
Simplified Heat Transfer Calculations

BOWDOIN DATA



BOWDOIN COLLEGE
DEPARTMENT OF CHEMISTRY
BRUNSWICK, MAINE 04011

17 September 1979

Mr. Peter Kosel
California Air Resources Board
1102 Q Street
Sacramento, CA 95814

Dear Mr. Kosel:

I have added the stack temperature figures to Table I of the enclosed reprint. These figures represent the average change in temperature, in degrees centrigrade, relative to room temperature, for each of the burns. The temperature ranges over 20°C in some of the burns and so the temperatures reported here are uncertain by at least 5°, mainly because of the uncertainties in the averaging process.

The New Mexico contact I mentioned to you over the phone was Harry M. Davidson; Air Resources Mgr.; Environmental Health Dept.; City of Albuquerque; Albuquerque, NM 87103.

I look forward to receiving descriptions of the work your department has done in this field.

Sincerely,

Samuel S. Butcher

SSB:pl

A Study of Wood Stove Particulate Emissions

Samuel S. Butcher and Edmund M. Sorenson
Bowdoin College
Brunswick, Maine

Particulate emission factors for two wood stove models have been determined for two types of fuel and a range of operating conditions. The emission factors range from 1 g/kg (fuel) to 24 g/kg. A model is presented which represents the emission factor as a simple function of the ratio of fuel load to combustion rate, or the length of time between refueling. This model is felt to be appropriate for evaluating the impact of wood-based residential space heating on ambient air concentrations of particulate matter if certain assumptions can be made about stove operating conditions. An application of the emission factor model to a typical community suggests that the contribution of wood stoves to ambient particulate levels might reach 100 $\mu g/m^3$ if the entire heating load were carried by wood.

Preliminary analyses of the particulate matter indicate that benzene extractables range from 42% of the total particulate mass at short refuel times to 67% at longer refuel times. About 45% of the mass of benzene extractables appeared in the neutral fraction of acid base extractions. Polycyclic aromatic hydrocarbons are expected to be included in this neutral fraction.

Recent surveys have shown that substantial amounts of indigenous fuel wood are being used to supplement conventional energy sources (oil or electricity) for residential space heating in northern New England. These surveys indicate that 11, 28, and 37 million Btu equivalents of wood per residence were used in the winters of 1975–76,[1] 1976–77,[2] and 1977–78,[3,4] respectively. The Btu equivalent of fuel oil required to maintain the entire heating load for this area is about 170 million Btu per residence year.[1,5] These surveys also point out that the most common wood heating unit is a small stove, rather than a fireplace or a wood-fired furnace. Although small stoves differ considerably in size (less than 20,000 to more than 100,000 Btu/hr), and design of the combustion chamber (baffled or not, firebrick lined or not, single or multiple drafts, etc.), most of them have a passive draft system. The combustion air intake in these stoves is driven solely by the buoyancy of the hot flue gases and the rate of combustion is generally controlled by limiting the air supply. This method of controlling the combustion rate may lead to incomplete combustion at low firing rates as a result of inadequate air or temperatures which are too low.

Our preliminary study[6] showed that particulate emission factors increased as draft settings were reduced. These studies have been extended with further measurements and a simple model is proposed to represent the emission factor for particulate matter as a function of stove operating parameters. The results of preliminary chemical analyses of the particulate matter are also included.

Figure 1. The Jotul Model 602 wood stove.

Experimental Methods

A Jotul #602 stove and a Riteway #2000 stove* were used in these studies, see Figures 1 and 2. The sampling method used in this work is a slight modification of that used in our earlier work.[6] The flue system consisted of about 3 meters of 15 cm diameter steel stovepipe connected to a tile-lined chimney with an inside dimension 20 × 20 cm and a length above the stovepipe of about 2.5 m. No flue damper was used.

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* Mention of a trade name should not imply a recommendation by the authors or the organizations with which they are associated.

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The sampling method consisted of collecting all stack emissions for measured time intervals with a high volume sampler. The smoke from the chimney was drawn through a 1 m section of 15 cm stovepipe to the high volume sampler. The collecting section of stovepipe was supported just above the chimney and no effect of the sampling system on the combustion rate could be observed. The flow rate of air through the sampler started out at about 110 ft^3/min for each sampler run and decreased as the filter became loaded with particulate matter. The flow rate remained above 90 ft^3/min for most filter samples and very seldom dropped as low as 70 ft^3/min. The flow rate of gas through the chimney at a fuel combustion rate of 3.4 kg/hr and 50% excess air is about 13 ft^3/min, substantially less than the high volume sampler flow rate.

Figure 2. The Riteway Model 2000 wood stove.

The temperature of the flue gas at the point of sampling was not monitored. The temperature in the stovepipe near the masonry flue was recorded. This temperature reached 250°C in some of the burns at full draft, but was generally less than 120°C. The temperature at the top of the chimney was judged to have been less than 100°C for most runs and the dilution air in the collection system would have further reduced the flue gas temperature.

Each burn was conducted by adding a weighed charge of wood (as 3–5 pieces of wood) to a bed of live coals from a previous burn. The draft setting (or the thermostat control in the case of the Riteway #2000) remained constant throughout the burn with two exceptions: The door was opened briefly a few times during each burn to judge the amount of fuel remaining. The end of the burn was the point at which the amount of live coals remaining in the stove was judged to be similar to that at the start of the burn.

The particulate matter samples were collected on a series of 8 × 10 in. glass fiber filters. The sampling times for individual filters ranged from 30 seconds to 6 minutes with most of the sampling time falling in the 1–2 min range. Typically, 10 to 20 filters were used for each burn.

The filters were dried in a desiccator for 24 hr and reweighed. The emission rate was determined as the amount of particulate matter on a filter divided by the sampling interval for that filter. The dependence of emission rate on time during a typical burn is shown in Figure 3. The total amount of particulate matter emitted during the burn was determined by integrating the emission rate over the time of the burn by the trapezoidal method. The sources of error involved in the determination of the emission factors have been discussed in the preliminary study.[6] Errors in the measurement of particulate emissions amount to about 25% of the emission factor. The measurement of the length of the burn is uncertain by about 10 min; this affects the determination of the combustion rate more than the emission factor.

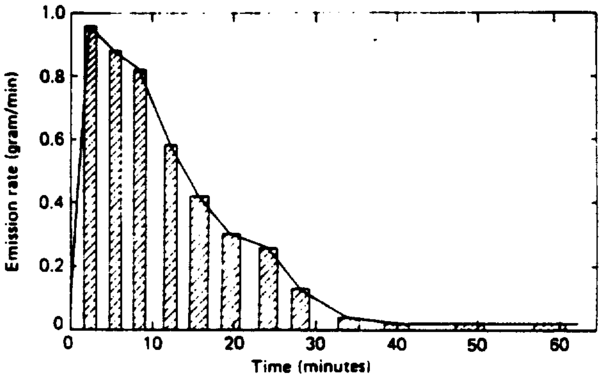

Figure 3. Emission during the combustion of 2.27 kg of oak.

Eastern white pine and red oak were used in these experiments. The moisture content of the fuel was determined by drying at 105°C to constant weight (usually two days). It is reported here as the percentage of weight loss relative to the pre-dried weight.

Selected filters were extracted with 350 ml of benzene in a Soxhlet extractor for 24 hr. The solvent was then removed at 25°C with a rotary evaporator and the extracts evaporated to constant weight at room temperature. The filters were reweighed to determine the weight loss and in some cases the extract was weighed. The agreement between the weights obtained by the two methods was generally quite good for these purposes (10 to 15% difference at most). The change in filter weight is used for further calculations in this section. This is referred to as the benzene-extractable weight.

Selected benzene extracts were subjected to the following acid-base extraction scheme: 1) a bicarbonate extraction to remove carboxylic acids and compounds with similar acid-base properties; 2) a sodium hydroxide extraction to remove phenols and similar compounds; and 3) a hydrochloric acid extraction to remove organic bases. The residue from this series of extractions was termed the neutral fraction and would be expected to contain the aromatic hydrocarbons and other compounds lacking marked acidic or basic properties.

A Particulate Emission Model

The results for 26 burns with oak and pine are collected in Table I. The draft setting for the Jotul stove is defined as the fraction of the distance between the fully closed and wide open position of the rotating sector draft control. The fuel load is the amount of wood added at the start of the burn. The emission factor is represented as the grams of particulate matter collected per kilogram of fuel. For those burns recorded as <¼ draft, the draft was varied between ¼ draft and ⅛ draft in order to maintain a stable fire.

It may be seen that there is considerable variation in the emission factor even in a series of burns which have the same draft setting and similar fuel loads. It seems likely that much of this variation results from differences in fuel geometry and whether or not ignition occurs quickly following addition of the fuel. It is also likely that the same variations occur in residential heating units.

A number of attempts have been made to relate the emission factor, E, to easily determined parameters which define the manner in which the stove is operated. The parameters chosen here are the initial fuel load, m (wet weight in kg); and

Table I. Total particulate emission factors.

	Stove	Wood	% moisture	Draft	Fuel load (kg)	Length of burn (hr)	Emission factor (g/kg)
80	Jotul	Oak	23.8	1	2.15	1.72	13.31
186	Jotul	Oak	23.8	1	2.66	0.67	2.31
62	Jotul	Oak	23.8	½	2.75	1.55	9.40
102	Jotul	Oak	23.8	½	3.18	1.56	5.21
51	Jotul	Oak	23.8	¼	2.32	1.42	10.39
60	Jotul	Oak	23.8	¼	2.69	1.23	10.14
53	Jotul	Oak	23.8	¼	2.69	1.77	8.24
77	Jotul	Oak	23.8	¼	2.27	1.05	6.75
116	Jotul	Oak	22.8	¼	1.42	0.48	2.46
108	Jotul	Oak	22.8	¼	3.40	1.38	3.36
112	Jotul	Oak	22.8	¼	1.28	0.62	2.52
100	Jotul	Oak	19.8	¼	0.49[a]	0.26[a]	1.82[a]
128	Jotul	Oak	8.7	¼	2.69	0.87	4.85
111	Jotul	Oak	8.7	¼	1.22	0.65	4.90
119	Jotul	Oak	8.7	¼	1.05	0.45	1.27
109	Jotul	Oak	8.7	¼	2.72	1.10	10.87
31	Jotul	Oak	23.8	<¼	2.07	1.70	15.72
18	Jotul	Oak	23.8	<¼	2.01	1.95	24.35
25	Jotul	Oak	23.8	<¼	1.67	1.80	12.82
67	Jotul	Pine	42.4	¼	2.04	0.98	10.37
71	Jotul	Pine	42.4	¼	3.23	1.40	10.79
38	Jotul	Pine	42.4	<¼	1.67	1.33	18.52
47	Jotul	Pine	42.4	<¼	1.50	1.52	15.33
61	Jotul	Pine	42.4	<¼	1.39	0.73	9.60
131	Riteway	Oak	22.8	b	5.23	1.52	11.85
130	Riteway	Pine	42.4	c	4.10	1.20	13.26

[a] These figures are averages for a burn in which 3.94 kg of fuel, divided into eight portions, was burned in 2.05 hours.

[b] These figures are averages for a burn in which the thermostat setting remained fixed and 15.71 kg of fuel, in three portions, was burned in 4.58 hours.

[c] These figures are averages for a burn in which the thermostat setting remained fixed and 12.30 kg of fuel, in three portions, was burned in 3.59 hours.

the average combustion rate, q (Btu/hr). The combustion rate is defined here as the heat of combustion of the load of fuel (the low value, corrected for moisture) divided by the length of the burn. The heat of combustion is taken to be $17{,}970 - 203 \times P$ in Btu/kg, where P is the percentage moisture.

The simple relationship $E = A + B(m/q)$ accounts for much of the variation of the emission factor with fuel load and draft setting. The least square line for the data in Table I is shown in Figure 4. The points in this figure are coded so the relationships of oak to pine and Jotul to Riteway stove may be compared. The negative value for A should amplify the importance of not using this model outside the range represented by the data. In this regard it should be noted that the regression line was obtained by assigning unit weights to the points for the 0.49 kg load in the Jotul and the two burns for the Riteway stove even though these points represent averages for more than one charge of wood. In particular, increasing the weight of the 0.49 kg load point (which has the lowest value of m/q in Figure 4) brings the value of A closer to zero. It may be seen that the model represents fairly well the emission factor for oak and pine; dry and wet wood; Jotul and Riteway stove. The data from the preliminary study are also consistent with this model.

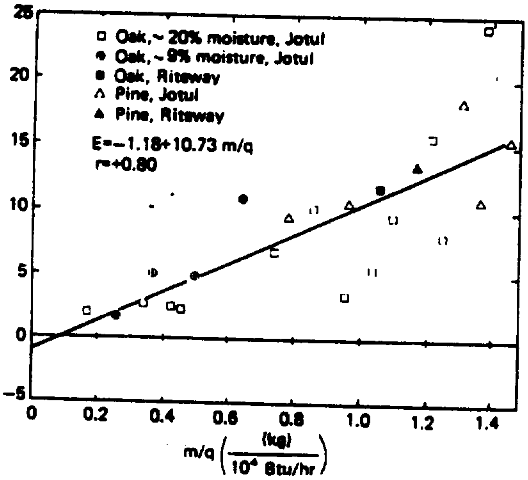

Figure 4. Emission factor as a function of m/q.

The variable m/q was chosen as the independent variable in the regression analysis because it should be related to the inverse of the bulk fuel temperature. The emission factor was also regressed against several other functions of m and q. These analyses yielded correlation coefficients similar to or less than the value obtained for the m/q regression, +0.80. The regression of E against $1/q$ gave a correlation coefficient of +0.78 when only the Jotul stove data were used but these results did not accommodate the data from the larger Riteway stove nearly as well as the m/q regression. m/q is directly related to the length of the burn, for a given fuel moisture content, and the uncertainty in this parameter is the same as the uncertainty in the length of the burn.

The data from this study and the earlier work were also segregated by fuel type (pine and oak) and treated by separate regression analyses. These gave the following results: $E(\text{pine}) = 4.18 + 6.88(m/q)$, $r = 0.53$ ($N = 17$); $E(\text{oak}) = -2.21 + 11.41(m/q)$, $r = 0.83$ ($N = 47$). The dimensions of m and q are the same here as in Figure 4: kg and 10^4Btu/hr. The difference between oak and pine is not large and must be checked by further measurements.

Table II. Benzene-extractable particulate matter.

Burn #	1	2	3	4	5
Fuel	Oak	Oak	Oak	Oak	Pine
% H_2O	23.8	23.8	8.7	23.8	42.4
Draft	Full D	½ D	¼ D	¼ D	¼ D
Fuel charge (kg)	2.66	3.18	1.22	2.01	2.04
Total particulate matter (g)	6.16	16.5	5.97	49.0	21.2
Benzene-extractable particulate matter (g)	2.91	9.28	2.51	32.6	12.8

The data from this work and our earlier work indicates that the combustion of very dry wood at low draft settings occasionally leads to higher-than-expected emission factors. This is consistent with observations by Shelton[7] of reduced combustion efficiencies when very dry wood is burned in small stoves.

Benzene Extracts

Over 50 filters from 5 burns in a Jotul #602 stove which covered a range of burning conditions and fuel types were selected for extraction with benzene. Using the weight of material extracted from the filters, the rate of emission of benzene extractables was determined as a function of time during the burn. This rate of emission of extractables was then integrated over the period of the burn in the same manner as has been done for the total particulate mass. This gave the total amount of benzene-extractables emitted during the burn, which could be compared with the total mass emitted and to the amount of fuel burned. These numbers are collected in Table II for the 5 burns analyzed here.

As may be seen in Table II, there is a tendency for the burns with larger emission factors to also have a larger fraction of benzene-extractables. This may result from the increased importance of pyrolysis for the slower, air-poor burns. Also, the only run with very dry fuel yielded the lowest value for percentage of benzene-extractables.

In order to examine the role of pyrolysis further, the fraction of benzene extractable material was examined during the course of each of these 5 burns. These numbers are collected in Table III as a function of the approximate time into the burn. (Although a more exact time was used in all calculations of emission factors, an approximate time is used in this table to permit a simple tabulation of the data.) It may be seen that there is a general trend for the fraction of the extractables to decrease during the course of a burn. Burn #4, which is the most air-poor of these burns, is a notable exception; the fraction of benzene-extractables is quite high and fairly constant for this burn.

Table III. Percentage benzene-extractable of total emissions.

Approximate time (min)	Burn 1	2	3	4	5
2	54.1	59.9	41.0	67.9	63.6
5	52.5	65.5	44.3	69.1	62.8
8	50.5	61.5	47.5		64.9
10	30.4		38.9	69.8	64.2
13	40.5	62.5			
16	36.5	64.2	33.5		62.7
20	38.5	59.4		68.0	56.4
25	30.3	57.4	29.6	67.4	49.4
30	30.7	56.8	17.8	70.2	51.3
35	End	54.0	End	67.6	
40					50.8
45		40.6		68.0	
50					55.4
55		28.3		53.8	End
65		22.4		59.8	
80		31.5		65.8	
90		22.6		66.9	
100		End		68.5	
110				72.5	

The benzene extracts from the four burns with oak were placed into groups according to whether they were collected early in the burn (near the maximum of the emission rate), late in the burn (where mostly coals remained), or were collected at an intermediate time. Composite samples were then formed from these extracts and subjected to acid-base extractions.

No significant variation of the relative amounts of the four fractions from the acid-base extractions were seen when comparing the four burns or when comparing different phases of a single burn. The averages for all acid base extractions are shown in Table IV. The percentages are the ratio of each acid base fraction to the sum of weights of all acid base fractions. The figure may misrepresent the composition if the small transfer losses were not distributed proportionately over the four fractions.

Table IV. Average composition of the acid-base fractions of the benzene extractables.

Carboxylic acid fraction	15%
Phenol fraction	40%
Neutral fraction	45%
Organic base fraction	~1%

Discussion

The near-zero value of the intercept in the emission factor model means that the emission factor is approximately inversely related to the combustion rate for a constant fuel load. Sandberg[8] obtained a similar result for the emission factors of carbon monoxide, gaseous hydrocarbons, and particulate matter resulting from the combustion of pine needles under open burning conditions. Prakash and Murray[9] demonstrated that emissions of carbon monoxide, hydrocarbons, and particulate matter from the controlled combustion of wood waste were strongly temperature-dependent for combustion zone temperatures less than 600°C.

The estimation of the worst case ambient particulate matter contribution from wood smoke is subject to several uncertainties which can only be resolved by examining how stoves are used. First, emission rates may not be obtained from a casual use of emission factors and fuel use rates. Rather, the rates depend on whether the stove operator refuels frequently with small loads (operating at smaller values of m/q) or enjoys the convenience of longer refuel times (larger fuel charges and larger values of m/q). Emission rates will also depend on the fuel moisture content (a higher moisture content will increase m/q for a given draft setting). As a second major area of uncertainty, there is little data available on the way in which wood displaces oil and what the potential for wood use might be. It has been assumed here that displacement of oil by wood occurs on a Btu equivalent basis (with a small correction for differences in combustion efficiencies), but there are at least two reasons why homeowners may get by with fewer wood Btu equivalents. The stand-by requirements for oil-fired furnaces are usually larger than those for wood stoves and small wood stoves may also be more efficient in delivering heat to the point of need.

The observation that E is nearly proportional to m/q, given certain other assumptions, leads to an interesting conclusion about emission rates. If the stove user maintains a constant value of m and varies q with the heating demand by controlling the draft, the emission rate will be nearly independent of the heating demand. During times of high demand the fuel use rate will be high and the emission factor low; during times of low demand the emission factor will be high and the fuel use rate low.

An estimate of worst case ambient particulate concentrations was made using meteorological factors similar to those used earlier.[6] (Wind speed was taken to be 1.6 m/s; the wind direction was uniformly distributed over a 90° sector; atmospheric stability was distributed as 15 hr of F stability and 9 hr of C stability.) The emission data were 4.72 kg/hr/residence of 20% moisture oak with a refuel time of 1 hr. This gave an emission rate of 7.9 mg/s/residence. It may be shown that worst case 24 hr average ambient concentrations of up to 100

$\mu g/m^3$ may be expected for wood smoke particulates for a housing density of 400–500 residences/km^2 spread over 4 km^2 or more if the entire heating load is carried by wood.

Qualitative analyses of the chemical constituents of wood smoke have been the subject of many studies by others because of its importance to food processing.[10] Most of these studies produce wood smoke by heating sawdust in controlled smoke generators and are not felt to be directly applicable to wood stove emissions. Gerstle and Kemnitz[11] reported that 65% of the mass of particulate matter from the open burning of lawn and tree trimmings was soluble in benzene, a result consistent with the range 42–67% reported here. Further work is needed to resolve the chemical species present in the particulate matter. Polycyclic aromatic hydrocarbons may be expected to occur in the neutral fraction of the benzene extractables. The present data suggest that emission factors for these compounds will increase as m/q increases.

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Dr. Butcher is Professor of Chemistry and Mr. Sorenson is a Teaching Fellow at Bowdoin College, Brunswick, Maine 04011. This work was supported in part by a contract from the Maine Department of Environmental Protection.

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A Preliminary Study of Particulate Emissions from Small Wood Stoves

Samuel S. Butcher and Douglas I. Buckley
Bowdoin College, Brunswick, Maine

Residential space heating in the northern New England states is largely obtained from the use of #2 fuel oil at the present time. The increasing cost of #2 oil coupled with the general availability of wood in this area has led many people to augment their oil heating systems with small wood stoves.

An attempt to survey the impact of wood combustion for space heating on ambient air quality indicated very few emission factors relevant to the types of heating systems in common use in northern New England.

This note reports on preliminary studies of particulate matter emission factors made on two types of stoves. These factors are then combined with simple models for fuel use and area source dispersion to obtain estimates for ambient levels of particulate matter under conditions of high heating demands.

Experimental Method

Two stoves were tested: a Model 602 Jotul, and a Model 2 Franklin. The Jotul is an air-tight cast iron stove manufactured in Norway. It has a flue gas baffle and draft regulator which are designed to achieve high combustion efficiencies while minimizing excess air. The Franklin stove is cast iron and made by the Portland Stove Foundry, Portland, ME. This stove has front doors which may be opened to simulate a fireplace or closed to reduce excess air and increase its heating efficiency. The Franklin stove was operated with the front doors closed for these experiments.

The flue system consisted of 22.7 ft of 6 in. steel stovepipe. The low flue gas velocities expected for wood-stoves would appear to make the determination of emission rates by conventional stack sampling techniques very difficult. The sampling method used for these studies consisted of collecting all stack emissions for selected time intervals with a high volume sampler. For this purpose a 4 ft diameter sheet metal cone, connected to the high volume sampler, was positioned over the flue in a way which minimized the effect of the high volume sampler on the operation of the stove while maximizing the collection of particulate matter. The high volume samplers were operated at flow rates ranging from 40–100 ft^3/min. The maximum volume flow rate through the flue was estimated to be 25 ft^3/min, assuming 50% excess air. Very little smoke loss was observed for the runs included in this report.

Each run was conducted by placing a weighed charge of wood (1–3 kg in 2–5 pieces) on a bed of coals. The particulate matter was then collected on a series of 8 × 10 in. glass fiber filters. The run was allowed to continue with a constant draft setting until the amount of coals remaining in the stove was judged to be equal to the amount at the start of the run. The sampling times for individual filters ranged from 30 sec to 5 min, with most of the sampling times falling in the 1–2 min range. An average of eight filters were used for each run.

The filters were left in a desiccator for 24 hr and then reweighed. The total amount of particulate matter emitted during the run was determined by integrating a graph of emission rate (g/min) as a function of time (min) by the trapezoidal method.

Three types of wood were used in this study: eastern white pine (*Pinus strobus*); red oak (*Quercus rubra*); and white birch (*Betula papyrifera*). Most of the wood used had been cut in 14 in. lengths, split, and stored outdoors for at least 6 months before it was brought into the building. The moisture content determined by cutting small blocks from this wood and drying at 100°C for 24 hr ranged from 7–11%. While this value is subject to large sampling errors, the wood used is felt to have a moisture content typical of that generally used for fuel.

Experimental Results

The emission factors g (particulate matter)/kg (wood) showed a great deal of variation from one run to another. It is quite likely that much of this scatter results from variations in burning conditions from one run to another, rather than random errors in measurement. In the only run not included in Table I, oak wood at full draft in the Jotul stove smoldered for 11 min before igniting. The emission rates were very large during the smoldering stage and the overall emission factor was 10.4 g/kg, nearly 10 times the values for the other two runs at this draft setting. It seems reasonable to expect that the same sort of variation in burning conditions occurs in home stoves and that the average of a significant number of runs will simulate emissions from a large number of stoves.

Table I. Summary of emission factors.

Stove	Wood	Draft setting	Number of runs	Emission factor (g/kg) Ave.	Std. Dev.	Range
Jotul	Pine	1/2 open	6	4.5	1.0	2.9–5.6
Jotul	Pine	1/4 open	5	10	8	4.5–25
Jotul	Oak	1/2 open	6	1.7	0.9	0.7–2.8
Jotul	Oak	Open	2	1.17	0.01	1.16–1.18
Jotul	Birch	1/2 open	2	2.3	1.7	1.1–3.5
Franklin	Oak	a	15	2.8	1.0	1.2–4.4
Franklin	v. dry Oak	a	3	1.02	0.10	0.91–1.08

[a] The small draft adjustments were altered for the Franklin stove, but no significant variations of the emission factor were observed as a function of the draft setting. This probably results from the large amount of air able to leak in around the doors of the Franklin stove independently of the draft setting.

The average emission factor, standard deviation of the sample, range of values, and number of runs are reported for each burning condition in Table I.

Sources of Error

The decision of just when the wood has burned down to an amount of coals equivalent to that present at the start of the burn can be uncertain by perhaps 10 min in a burn which lasts typically 40 min. The contribution of this uncertainty to the emission factor is probably very small, however, since only a small fraction of the total particulate matter emitted is released in the final 10 min of the burn. During the final stage of the burn only charcoal remains and the emission rate is typically 0.03 g/min, compared with 0.5 g/min during the open flame active pyrolysis stage. The relative error contributed by judging the end of the burn is estimated to be about 10%.

Particulate matter collected on a filter at a fairly low temperature close to the flue can be expected to include measurable amounts of condensible vapors which would not be present in the condensed state farther from the stack. The dirty filters in eleven of the runs in which oak was burned were dried at 50°C for 24 hours immediately after the post sampling weighing. The average weight loss for each run was 4.4% (range 1.1–12.5%) of the total particulate matter collected. This factor will contribute a small systematic error to the results in Table I, which were calculated without this extra drying.

Effect on Ambient Air Quality

In order to obtain an estimate of the effect of widespread wood burning on air quality, the meteorological and home heating factors outlined in Table II were used.

The oil consumption figure, 1050 gal/yr, is the average of 242 noncommercial and apparently nonseasonal customers of a local oil distributor. This figure includes a number of mobile homes and is less than the estimated requirement of 1200 gal/yr for the average single-family house.[1] The figures chosen for emission factors are felt to represent most closely actual operating stoves. Average temperature and wind speed were evaluated for the period 1 Oct 1975 to 30 Apr 1976. All fuel use was assumed to occur within this period.

Values of the dispersion parameter cu/Q, where c is the concentration in g/m^3, u the wind speed in m/sec, and Q the area emission rate in g/m^2-sec, range from 27 to 143 for neutral stability, depending on the dispersion model chosen. Turner's workbook[2] yields a value of 27 for cu/Q if one assumes a stack height of 10 m and an initial value for σ_z of 30 m. The model of Sharma[3] yields a value of 56 for cu/Q for neutral stability if a surface roughness of 1.0 m is used. The simple model proposed by Hanna[4] gives the value 143 for cu/Q for neutral stability.

The maximum concentration of particulate matter may be estimated for very cold days (average temperature 4°F) using the figures given above and assuming that wood completely replaces oil. The use of pine leads to a value of 101 $\mu g/m^3$, while that for oak is 19 $\mu g/m^3$. These figures represent expected maxima and not 24 hr averages.

Discussion

The figures for emission factors in Table I fall roughly in the range indicated by E.P.A.[5] for wood and bark waste combustion in boilers (2.5–7.5 g/kg) and are considerably below the figure of 15 g/kg cited by Feldstein[6] for fireplaces.

The dependence of the emission factor on draft setting shows an increase in the emission factor as the available air is reduced. It is likely that many people operate stoves with smaller draft settings than have been used in these studies and that emission factors of stoves in actual use will be greater than those in Table I.

The numbers presented here suggest that emission factors for wood stoves are large enough to lead to an air pollution problem in communities where wood may carry a substantial fraction of the space heating load. Much more research on the relationship between emission factor, stove design and operating mode, and wood type needs to be performed.

Acknowledgments

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Table II. Meteorological and home heating factors.

- Oil furnaces
  - Efficiency 65%
  - Oil consumption 1050 gal/yr
  - Heat of combustion 140,000 Btu/gal
- Wood stoves
  - Efficiency 50%
  - Heat of combustion[a]
    - Oak 7180 Btu/lb
    - Pine 7960 Btu/lb
  - Emission factor
    - Oak 1.7 g/kg
    - Pine 10 g/kg
- Community density and size
  - Density 2 units/acre (4.94 × 10^{-4} units/m^2)
  - Size 2 km by 2 km
- Climatic and dispersion factors
  - Average temperature[b] 34°F
  - Coldest 5% of the days ≤4°F
  - Dispersion parameter cu/Q = 70
  - Wind speed[b] 4 m/sec

[a] *Forestry Handbook*, ed. R. D. Forbes, Ronald Press, New York, 1961, Ch. 22, p. 18.

[b] "Local climatological data for Portland, Maine," NOAA Environmental Data Service, U.S. Dept. of Commerce.

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Pressure Loss in Venturi Scrubbers

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Venturi scrubbers are used extensively for the collection of small particles. The major limitation on their use is that they have high pressure drops which result in high operating costs. With a better understanding of the fundamentals of the operation of this type of scrubber, the pressure drop could be optimized for a given level of particle collection.

Nomenclature

C_D = drag coefficient, dimensionless
d = diameter, cm
g_c = conversion factor
l_t = throat length, cm
P = pressure, dyne/cm^2
Q = volumetric flow rate, cm^3/sec
u = velocity, cm/sec
x = $3l_tC_D\rho_G/16d_d\rho_L + 1$
z = axial coordinate, cm

Greek

σ = surface tension, dyne/cm
ρ = density, g/cm^3
μ = viscosity, poise

Subscripts

d = liquid drop
G = gas
L = liquid
1,2 = throat entrance and exit, respectively

Dimensionless numbers

N_{Re} = Reynolds number based on drop diameter

The pressure drop for gas flowing through a venturi scrubber is due to the friction loss along the wall of the scrubber and the acceleration of liquid drops. Friction loss depends largely upon the geometry of the scrubber. Acceleration losses, which are frequently predominant in the venturi scrubber pressure drop, are fairly insensitive to scrubber geometry and in most cases can be predicted theoretically.

Currently, there are several correlations available, both theoretical and experimental, for the prediction of pressure drop in a venturi scrubber. Correlations by Matrozov,[1] Yamauchi, *et al.*,[2] Volgin, *et al.*,[3] Gleason, *et al.*,[4] and Hesketh[5] are experimental correlations. Matrozov's correlations and Volgin's correlation were obtained mainly on small size venturi scrubbers. Yamauchi's correlation was based on experimental data taken from a venturi scrubber with high temperature gas flow (100°–900°C). Hesketh's correlation is an experimental correlation he obtained after he had evaluated data obtained from many fixed throat venturi scrubbers.

Equations proposed by Yoshida, *et al.*,[6,7] Calvert,[8] Tohata, *et al.*[9] Boll,[10] Behie and Beeckmans[11] are theoretical correlations. All of the equations were derived from the equations of motion and momentum balance. Geiseke's equation accounts for the mass transfer between liquid and gas. Boll's equation[10] is similar to that of Geiseke's except Boll had neglected the mass transfer between phases. Equations by Tohata, *et al.*,[9] Yoshida, *et al.*,[6,7] and Boll[10] contain terms attributed to wall friction. While Tohata, *et al.*,[9] and Yoshida, *et al.*,[6,7] have used different values for the friction factors in the convergent, throat and divergent sections, Boll[10] suggested a single value, 0.027, for all sections.

Of all the equations, Calvert's equation[8] is the easiest to apply. Calvert derived his equation by use of Newton's law and

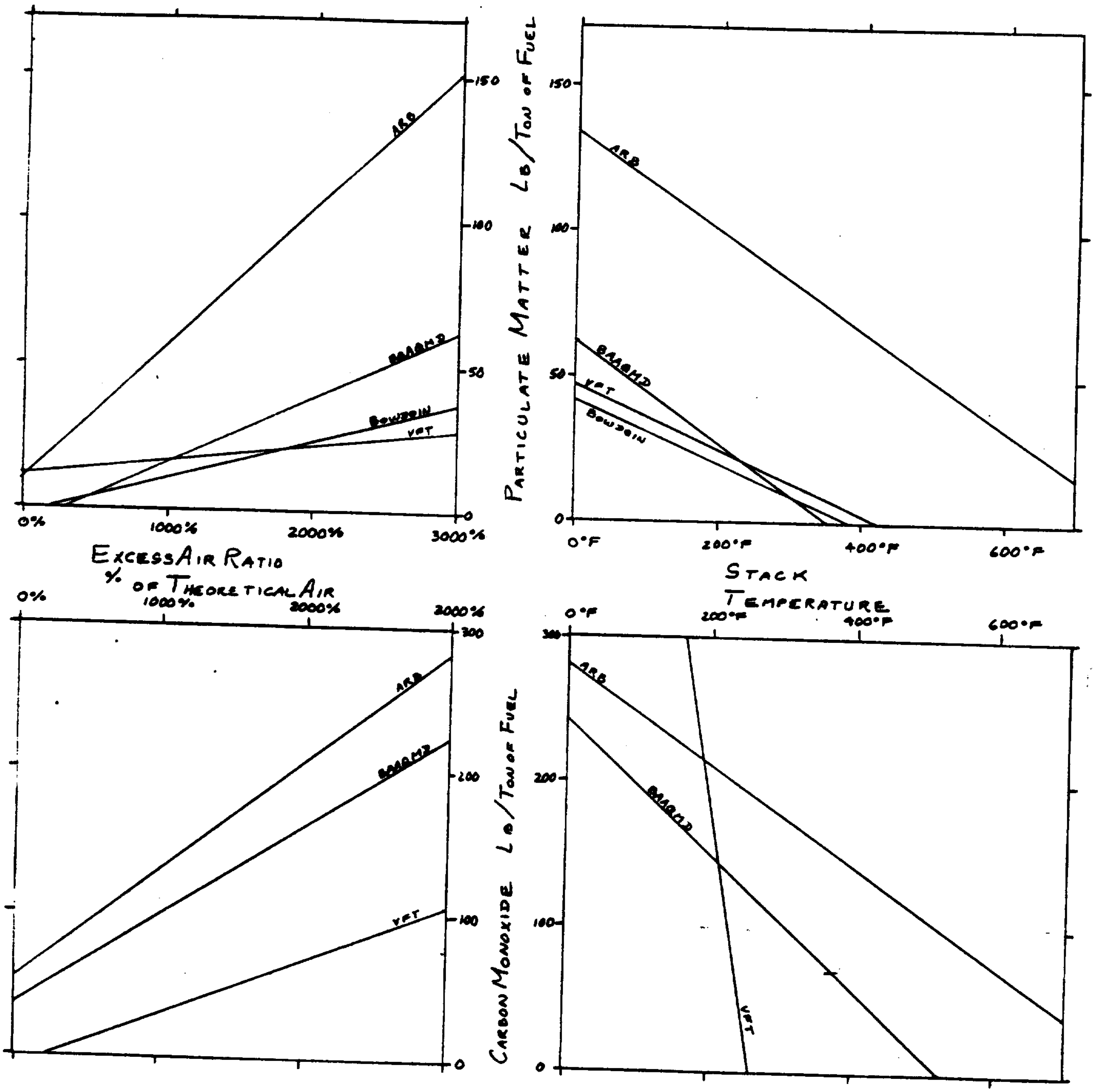
APPENDIX F

COMPARISON OF PARTICULATE TEST PROGRAMS

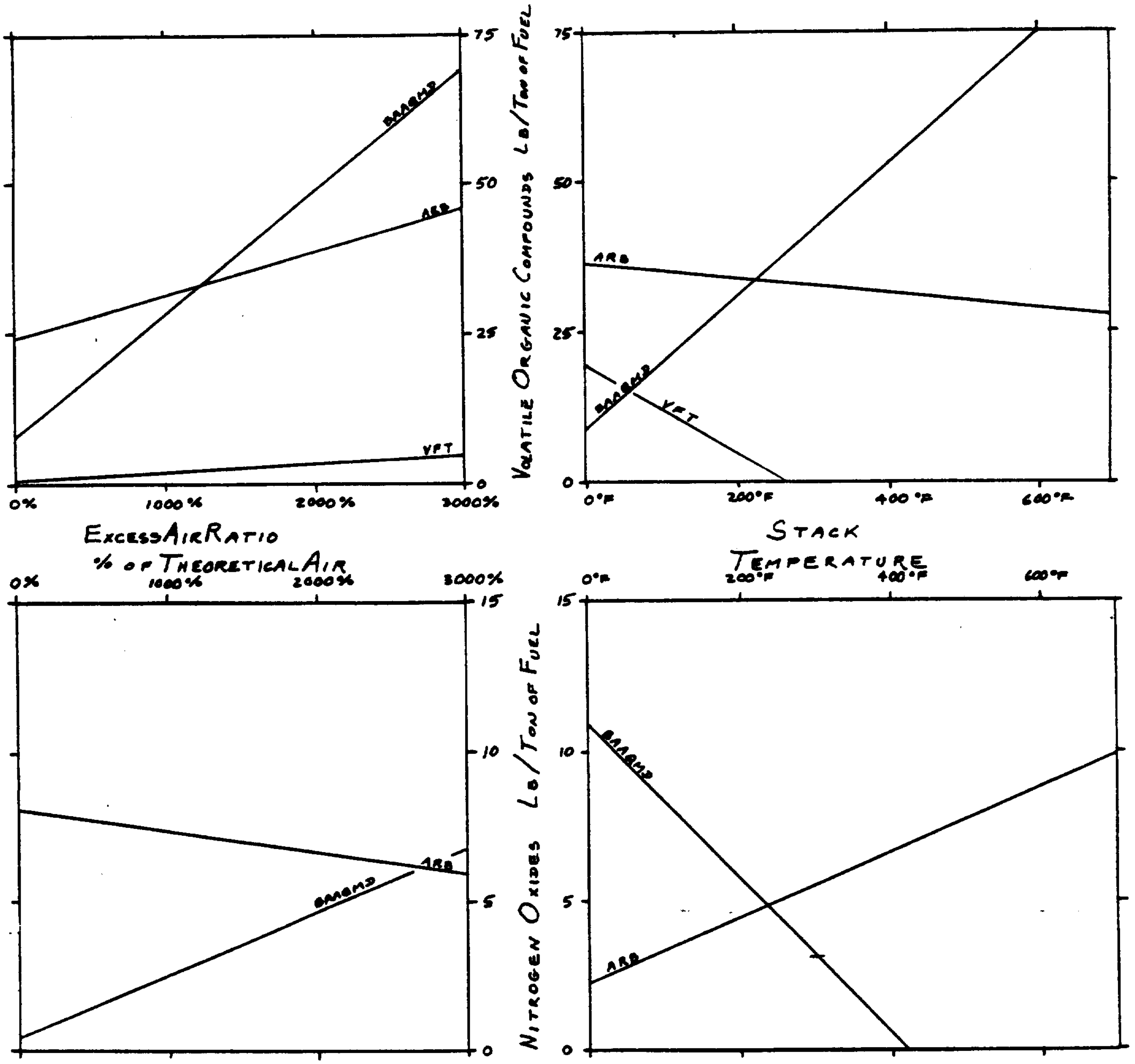
Testing Organization	ARB	VFT	BAAQMD	Bowdow Col.
Excess Air Ratio* % :				
Average	869.79	2279.19	1219.20	1381.05
Range	129 to 1633	951 to 5872	607 to 2542	479 to 3567
Sample Std Dev (s)	497.52	1302.06	569.75	818.23
Stack Temperature* °F :				
Average	491.71	207.38	231.30	233.95
Range	294 to 645	153 to 277	160 to 312	107 to 409
Sample Std. Dev. (s)	125.18	33.43	57.00	83.46
Particulate Matter $\frac{LB}{TON}$:				
Average	50.73	23.62	21.18	15.83
Range	15.16 to 126.99	11.8 to 44.2	3.4 to 48.0	2.54 to 48.7
Sample Std. Dev. (s)	30.62	8.36	15.01	11.78
Carbon Monoxide $\frac{LB}{TON}$:				
Average	114.64	116.27	136.35	(Not Tested)
Range	8.7 to 294.5	80.0 to 156.4	25 to 438	(Not Tested)
Sample Std. Dev. (s)	81.28	38.35	107.55	(Not Tested)
Nitrogen Oxides $\frac{LB}{TON}$:				
Average	7.45	(Not Tested)	4.39	(Not Tested)
Range	2.06 to 14.54	(Not Tested)	1.47 to 15.35	(Not Tested)
Sample Std. Dev. (s)	4.63	(Not Tested)	4.94	(Not Tested)
Volatile Organics (THC) $\frac{LB}{TON}$:				
Average	31.02	4.56	35.58	(Not Tested)
Range	0.49 to 96.94	3.95 to 5.57	5.4 to 82.9	(Not Tested)
Sample Std. Dev.	31.10	0.88	23.25	(Not Tested)

Notes: 1. Excess Air Ratio and Temperature statistics vary for each pollutant; values shown for Excess Air Ratio and Temperature statistics correspond to particulate matter tests.

2. High boiling and polar organic compounds may appear as particulate in ARB and VFT tests using EPA Method 5; material reported as volatile organics may include some material some material of this type.



PARTICULATE MATTER AND CARBON MONOXIDE TRENDS FOUND BY LINEAR REGRESSION



Nitrogen Oxides and Volatile Organics Trends found by Linear Regression