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EVALUATION OF LOW-EMISSION WOOD STOVES

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June 23, 1986

FINAL REPORT
CONTRACT A3-122-32

Prepared for
CALIFORNIA AIR RESOURCES BOARD
P.O. Box 2815
1102 Q Street
Sacramento, California 95812

Shelton Research, Inc. Research Report No. 1086

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Section 1

Summary and Conclusions

Emissions and efficiencies of five residential woodburning heaters were measured. Measured emissions included particulate matter (PM), carbon monoxide (CO), hydrocarbons (HC) polycyclic aromatic hydrocarbons (PAHs), benzene, oxides of nitrogen (NOx), total combustibles, elemental carbon, cyanide (CN⁻), ammonia (NH₃) and creosote. Three fuels were used, although not in all appliances -- dimensional Douglas fir lumber (as specified in the Oregon and Colorado emissions standards), seasoned oak logs and green oak logs. The appliances consisted of a conventional airtight stove, a catalytic stove, two non-catalytic advanced technology stoves, and a wood pellet stove.

The observed range of emission factors (dry basis) are given in Table 1-1.

Table 1-1: Ranges for Emissions

	Minimum (g/kg)	Mean (g/kg)	Maximum (g/kg)	Phase
PM	.10	8.8	61	Main loads
C O	1.6	86	307	Main loads
HC (as methane)	.23	14	47	Main loads
PAH	.004	.24	.55	Cold-to-cold
NOx (as NO)	.22	.51	1.1	Main loads
Benzene	< .02	.70	2.2	Cold-to-cold
Elemental Carbon	< .08	.67	2.2	Cold-to-cold
Cyanide			< .0005	Main loads
Ammonia	.001	.026	.10	Main loads
Creosote	.2	2	10	Cold-to-cold

Appliance effects were strong. All products of incomplete combustion (PM, C O, HC, benzene, PAH, elemental carbon, creosote and combustibles) were lowest for the pellet burner, next lowest for the catalytic stove, and highest for the conventional airtight stove. NOx emissions had the opposite trend, being highest for the pellet burner.

Fuel effects were largest for NO_x and elemental carbon. Both these emittants were highest for the green oak and lowest for the Douglas fir.

Some emittants were measured during each of the major burn phases -- kindling, main load, and charcoal. Generally, the contribution to total emissions from the kindling and charcoal phases was no larger than from the main loads. However, the one prominent exception was PM for the catalytic stove, wherein the kindling phase contributed up to five times more PM to the atmosphere than a main load. This is of possible significance since current wood stove emissions regulations are based on main load performance only, although the complexity of including the kindling phase in a test protocol may dictate against changing current protocols.

Burn rate had a dramatic effect on emissions. The catalytic stove's advantage in combustion efficiency was very pronounced at medium to low burn rates -- the burn rates most utilized in the field. However, at high burn rates the non-catalytic stoves performed nearly as well as the catalytic. The pellet burner's combustion efficiency remained high at all of its burn rates, but the burn rate range was relatively narrow.

Overall energy efficiencies generally correlated with clean combustion; the cleaner stoves generally consumed less fuel to produce the same amount of useful heat. However, an exception to this is the pellet burner. Although it had the highest combustion efficiency, its overall efficiency was not the highest. The system uses a relatively large amount of combustion air. This tends to carry more heat up the flue.

Creosote correlates well with particulate matter. Thus creosote will be reduced with stoves certified to have low PM emissions. By this mechanism regulation of emissions can improve safety of heating with wood.

The two most common test methods for wood stove PM correlate with each other but do not give the same result. Oregon Method 7 always yields a higher emission rate because it includes material which would be in vapor phase in the atmosphere. The dilution tunnel is a better measure of PM in the atmosphere but does not catch all of the organics that OM7 does.

Section 2

Recommendations

There is a large range of actions that can be taken to improve air quality in a geographical area with a significant amount of wood smoke. These range from prohibiting burning of wood to voluntary no-burn times. This project addressed the specific areas of appliance design, operation, and fuel. In these areas, the following recommendations follow from this project:

1. Appliance design can have a very large effect on organic emissions. Requiring catalytic and other equally effective designs is likely to reduce emissions by a substantial amount -- on the order of a factor of 10.
2. Recommending use of seasoned instead of green fuels will not substantially reduce emissions from stoves. However seasoned wood can reduce most emissions from open stoves and fireplaces by roughly a factor of two.
3. Catalytic and other low emitting chunk-wood stoves should be used according to the manufacturer's instructions; otherwise emissions may not be reduced. When operated with bypass dampers open or doors open, there is little benefit. For catalytic stoves steady burning at medium to low burn rate will usually result in lower emissions than burning the same amount of wood in shorter but higher-burn-rate periods. Each kindling phase from a cold start can contribute as much to emissions as an entire twenty-four hour day of steady use.

Section 3

Introduction

This project was undertaken to provide a broad database to assist the California Air Resources Board in assessing the impact of residential wood-burning on air quality in California. Many emissions and efficiencies were determined over all burn phases -- kindling, main load and charcoal phases -- and not limited to main load or cold-to-cold phases as has been the usual practice. Both standard fuel loads of milled Douglas fir and more realistic loads of green and seasoned California oak (tanbark oak) were used in a variety of stoves characteristic of California practice. In addition a very clean-burning pellet stove was tested to extend both emissions data and test methods comparisons into a region that has not been explored before.

Additional unique features of this project were determination of ammonia and cyanide in smoke. Creosote deposition in chimneys was quantified by direct gravimetric measurement and correlated with total particles. PAH and benzene emissions were studied over a wide range of conditions. The idea that catalytic stoves emit a relatively high amount of nitrogen oxide was investigated. The comparatively inexpensive dilution tunnel method of determining particulates has been further correlated with the OM7 (Oregon Method 7). Finally, a comparison of the Oregon flue loss efficiency method and DOE direct efficiencies has been made for the first time.

Previous Research

The study most similar in scope to the present one was done by the Tennessee Valley Authority.¹ In it emissions and efficiencies of five wood heaters were measured over a range of burn rates. The study was limited to a single fuel (red oak) and a single phase (main load).

There are several other studies that overlap with the present one in one or more respects:

-PAHs and other organics emitted by an airtight stove were studied by a group at Argonne National Laboratory.²

-Particulates, carbon monoxide, volatile hydrocarbons, oxides of nitrogen and elemental carbon from a fireplace were studied by Jean L. Muhlbaier at General Motors Research Laboratory.³

-PAHs and benzene were studied by a Norwegian team.⁴

-PAHs, particulates, carbon monoxide, oxides of nitrogen and efficiencies of a fireplace and two airtight stoves were studied by a group at Monsanto Research Corporation for the U.S. EPA.⁵

Comparisons with other studies will be made as appropriate in the body of the report.

Section 4

Appliance and Fuel Selection

Three guidelines were followed in selecting appliances and fuels for this project:

1. that they be common in California;
2. that a wide range of appliances and fuels be tested;
3. that they overlap as much as possible with testing done by the United States Environmental Protection Agency (EPA) and Oregon Department of Environmental Quality (DEQ) to help clarify correlations between measurement methods and the effect of altitude on emissions.

Telephone Survey

To obtain an overview of wood-burning practices in California, nineteen chimney sweeps and one dealer were contacted by telephone. Chimney sweeps were preferentially contacted because their work brings them in contact with a wide range of appliances. Those sweeps called were selected with a view to even geographical distribution from a list of members of the National Chimney Sweep Guild. The one dealer contacted was in Tahoe, an area without a sweep on the Guild list. A Reno sweep was included because of the lack of a Guild member in California to the east of the Sierra Mountains.

The data from the survey are presented from north to south in Table 4-1. Inspection shows a large difference between north and south. Airtight appliances (inserts or stoves) are the most common types of heaters in the north and fireplaces are most common in the south. North of Fresno, airtight appliances are most common (10 of 12 responses) south of Salinas, open fireplaces are most common (6 of 8 responses). The two exceptions (Big Bear Lake and Descanso) are in the mountains.

The most common fuelwoods north of Fresno are dense hardwood, either oak or eucalyptus in 9 out of 12 responses. South of Salinas, low density woods are more common (5 out of 8 responses).

There is a high degree of correlation between type of heater and burning regime. Of six towns where short, hot fires are the rule, five are also towns where fireplaces predominate.

Without being prompted, many of those interviewed offered the comment that more fireplace inserts are being installed than any other kind of heater.

On the basis of this survey, and in consultation with Robert Grant (the project manager) of the California Air Resources Board, it was decided to test the following appliances:

- * a conventional airtight stove,
- * an open fireplace stove,
- * a fireplace insert,
- * a catalytic stove,
- * a non-catalytic advanced technology stove,
- * a pellet burner.

To decide on stove makes, several stove dealers in California were contacted to find out which makes were most popular. The final selection included:

- * a conventional airtight stove that could also serve as a fireplace stove with its doors open.
- * the Lopi A6 as the fireplace insert,
- * the Blaze King as the catalytic stove, and
- * the Kent Tile Fire with emissions kit (a set of specially designed firebrick and stainless steel additions to the stove) as the advanced non-catalytic,
- * the Pellefier pellet stove.

The basic structure and airflow patterns of the stoves are illustrated in Figures 4-1 through 4-5. The fuels chosen were seasoned (16-20% moisture on a moist basis) and green (23-30% moisture on a moist basis) tanbark oak and seasoned Douglas fir dimensional lumber as prescribed in the Oregon DEQ test method. This fuel consists of 2x4 and/or 4x4 (nominal) dimensional Douglas fir lumber with a moisture content of between 16 and 20% (moist basis) and with spacers holding the pieces 1 1/2 inches apart.

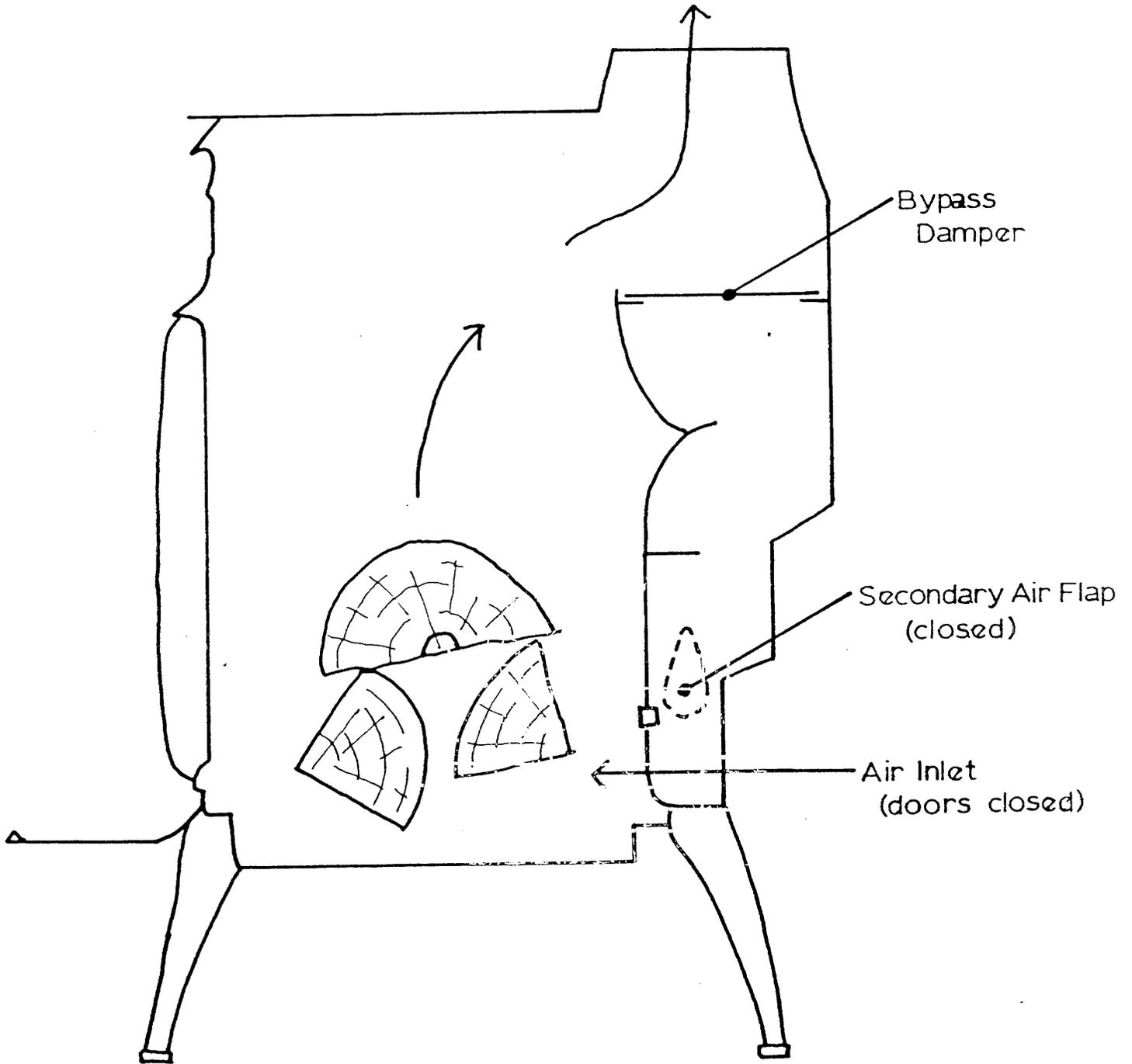
The final appliance and fuel matrix is shown in Table 4-2.

Table 4-1: California Wood Heater and Fuel Survey

Location	HEATERS		FUELWOOD		Burning Regime
	Most Common	Second	Most Common	Second	
Yreka	Fireplaces	Inserts	Red Fir	Cedar	SH
Lake Shastina	Stoves	Inserts	Pine	Oak	LS
Red Bluff	Inserts	Fireplaces	Oak	Softwood	LS
Chico	Inserts	Fireplaces	Oak	Almond	LS
Oroville	Inserts	No opinion	Oak	Almond	LS
Reno	Stoves	Fireplaces	Pine	Oak	LS
Tahoe	Stoves	Fireplaces	Oak	Tamarack	LS
Loomis	Stoves	Inserts	Oak	Madrone	LS
Mill Valley	Inserts	No opinion	Oak	Eucalyptus	LS
San Ramon	Fireplaces	Inserts	Oak	Almond	SH
Menlo Park	Inserts	Stoves	Oak	Madrone	SH
Salinas	Inserts	Fireplaces	Eucalyptus	Oak	LS
Fresno	Fireplaces	Inserts	Pine	Tamarack	LS
Santa Barbara	Fireplaces	Inserts	Oak	Eucalyptus	LS
Big Bear Lake	Inserts	No opinion	Softwoods	Oak	LS
Downey	Fireplaces	Inserts	Pine	Construction Waste	LS
Orange	Fireplaces	Non airtight Antique Stoves	Orange	Pine	SH
Hemet	Fireplaces	Stoves	Softwoods	Eucalyptus	SH
San Diego	Fireplaces	Inserts	Oak	Softwoods	SH
Descanso	Inserts	Stoves	Oak	Softwoods	LS

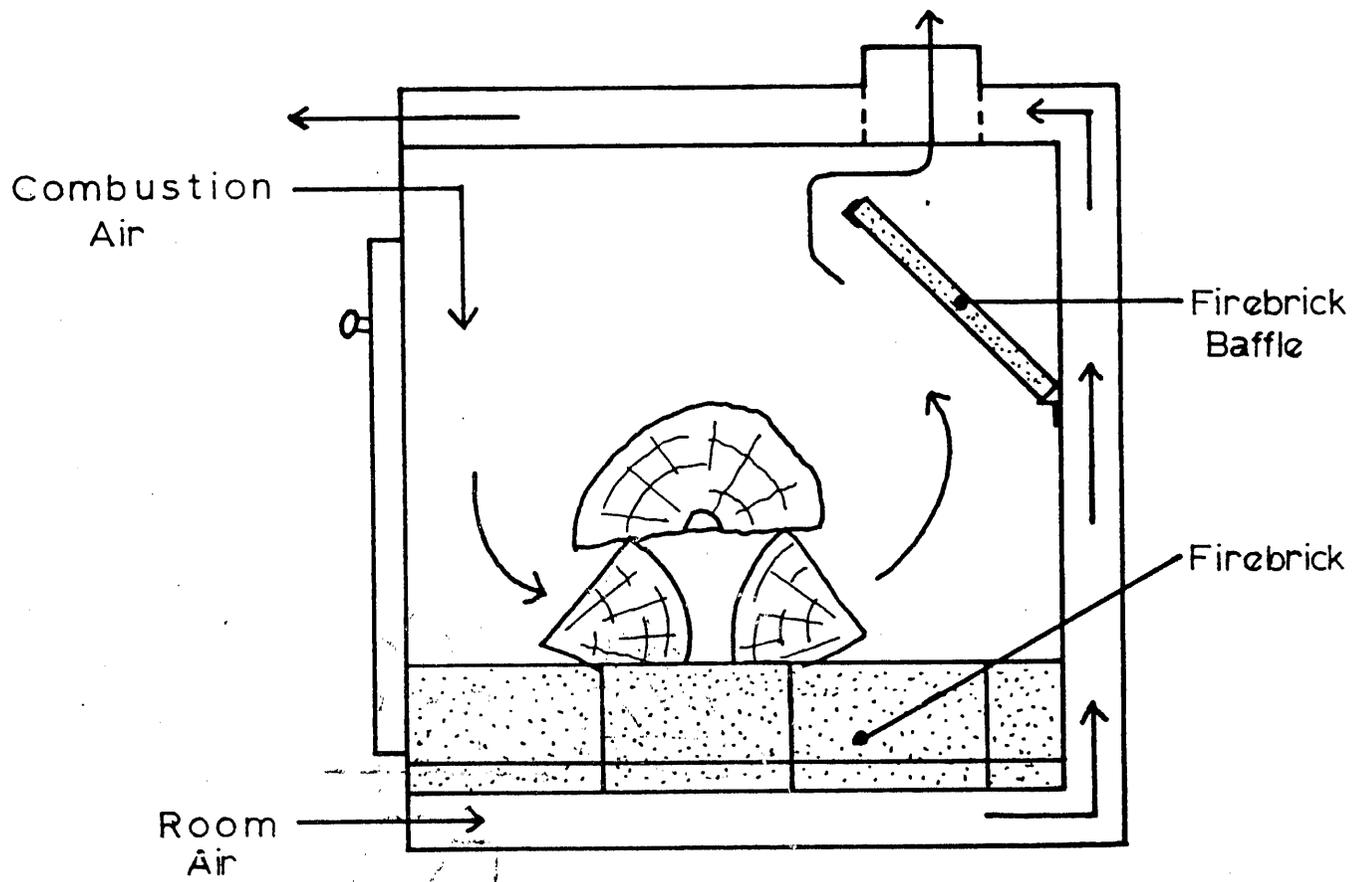
Fireplaces = all open appliances including open Franklins; Stoves = closed, airtight stoves; LS = long, smoldering burn; SH = short, hot burn

FIGURE 4-1



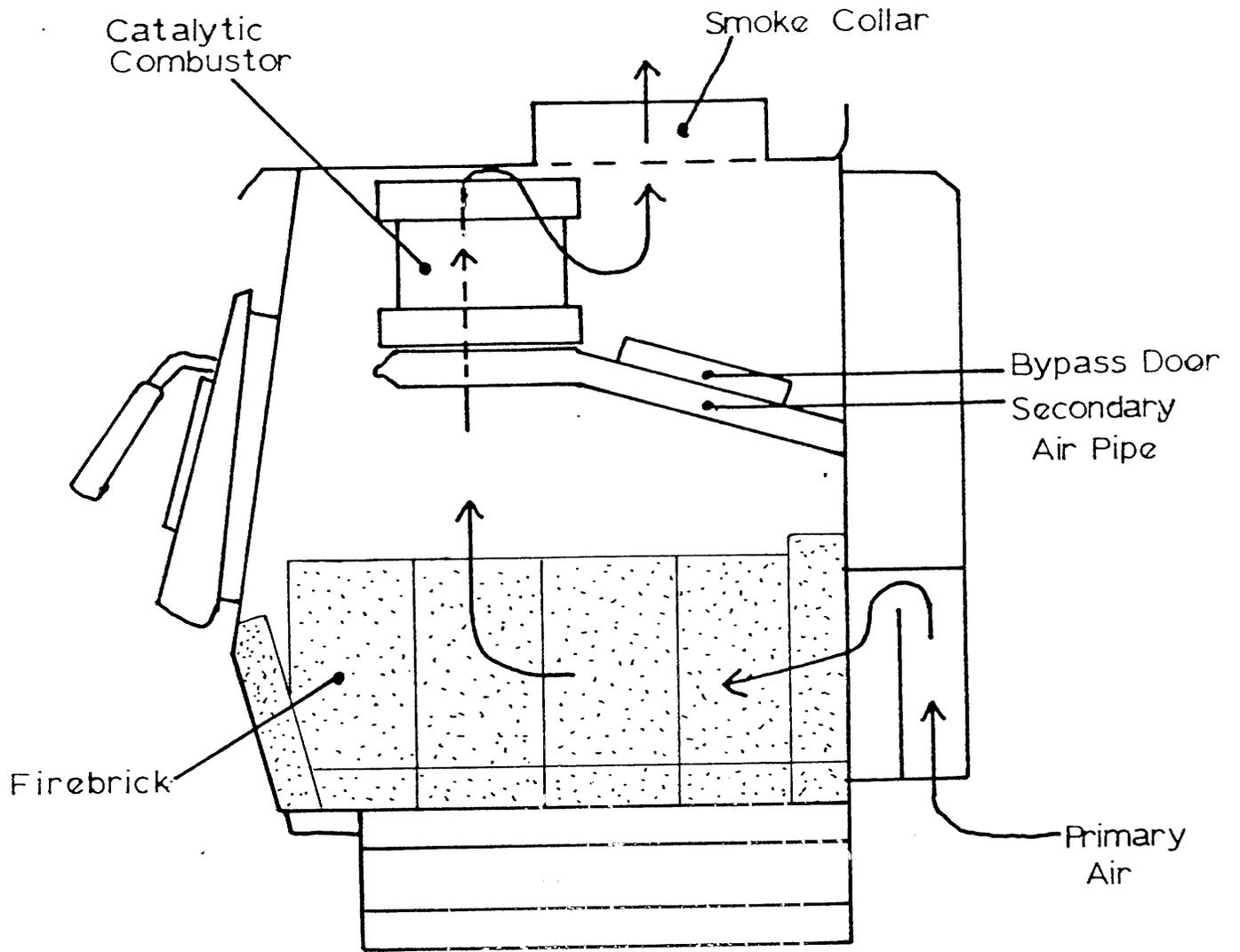
CONVENTIONAL AIRTIGHT STOVE

FIGURE 4-2



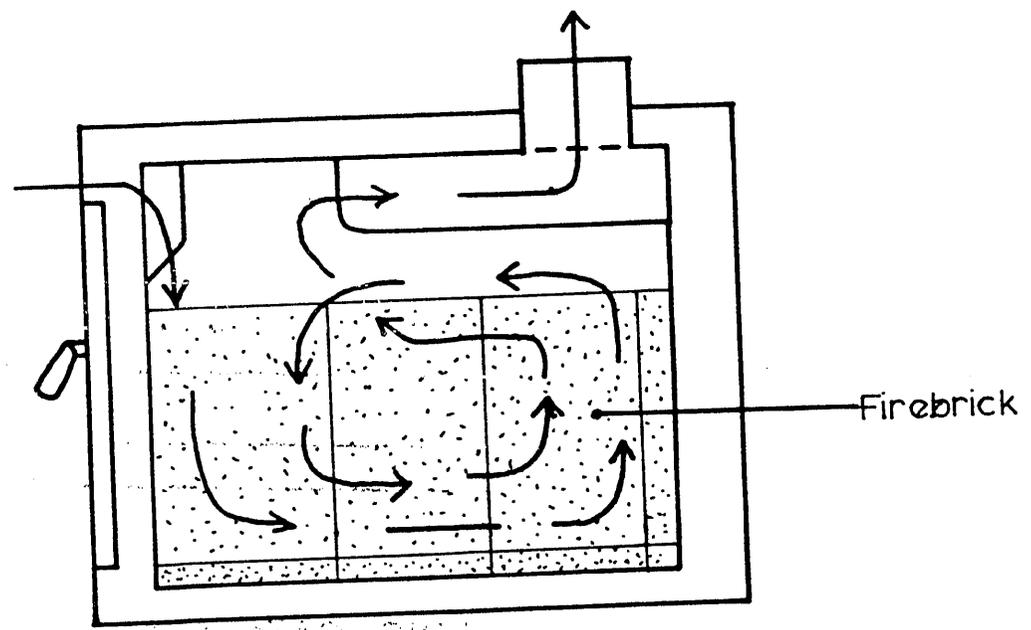
LOPI FIREPLACE INSERT

FIGURE 4-3



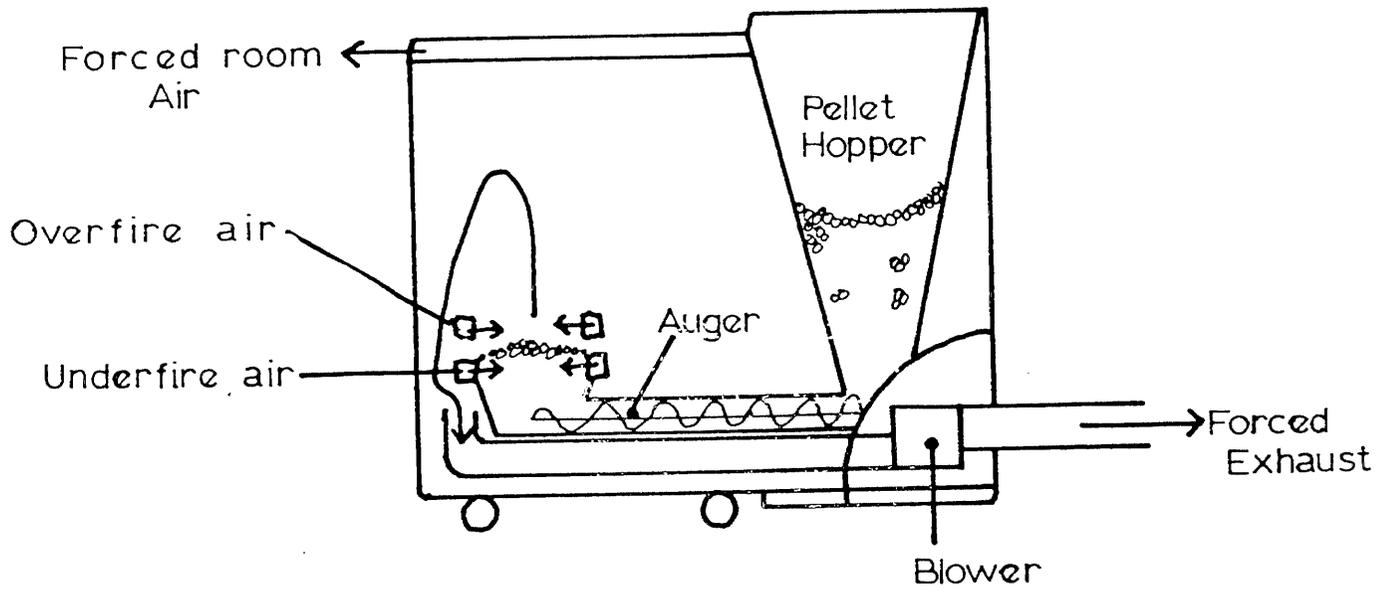
BLAZE KING CATALYTIC

FIGURE 4-4



Gas flow in the Kent Tile Fire

FIGURE 4-5



PELLEFIER PELLET BURNER

Table 4-2: Appliance and Fuel Matrix

	Oregon Fuel	Oak Logs 16-20% Moisture Content	Oak Logs 23-30% Moisture Content	Wood Pellets
Blaze King "King"	4	4	4	
Kent Tile Fire Mark II	4	2		
Conventional Closed Door		4	2	
Conventional Open Door		2		
Lopi A6 Insert	4			
Pellefier Pellet Burner				2

Table entries represent the number of cold-to-cold tests conducted over a range of burn rates.

The test matrix indicated in Table 4-2 provides overlap (appliance, fuel and particulate measurement method) with Oregon DEQ data for four appliances. This is significant for interlaboratory comparison of results. The four appliances were: the Blaze King "King", Kent Tile Fire Mark II, Lopi A3 insert, and Pellefier. The Lopi stove tested for Oregon DEQ was Model A3 without a convection blower. We are assured by the distributor that the A6 tested here differs from the A3 only in cosmetic aspects.

Section 5

Technical Approach

Test Cycles

The two objectives which influenced the choice of test cycles were 1) to generate data applicable to field use of wood stoves, and 2) to generate data which is directly comparable to that available from other laboratories (to facilitate interlaboratory comparisons).

The need for field-applicable data dictated the inclusion of kindling and final charcoal phases (as well as use of realistic fuels). The need for interlaboratory comparability required "conditioning" the stove and its charcoal bed before the addition of each main load to meet the requirements in the Oregon test method for stove surface temperature, charcoal bed weight and charcoal bed chemistry (degree of charcoalization).

Thus a typical test consisted of a kindling phase starting with a room-temperature stove, interphase no. 1, main load no.1, up to three more interphases plus main load pairs, and a final charcoal phase.

The interphases were of variable duration. During the interphase small amounts of fuel in relatively small pieces were added as necessary 1) to bring the initial stove surface temperature to the value anticipated to be close to the final surface temperature, 2) to have a fully charcoalized (by subjective judgment) charcoal bed, 3) to have a charcoal bed of the correct weight (20 to 25% of a main load weight) and 4) to allow time to change filters and other sampling train components for those sampling systems obtaining separate data for each main phase of the test.

Instruments acquiring data continuously (CO, NO_x, HC) were used throughout all phases, including the interphases. A number of sampling systems were integrating; these were tunnel PM, OM7 PM, PAH, benzene and elemental carbon. None of these sampling trains was run during the interphases. This was done since 1) interlaboratory comparability of PM results required sampling over main loads only, and 2) the duration of and fuel consumption during interphases were variable and unusually small.

For PAH and benzene, one integrated sample from all primary phases together (excluding only the interphases) was obtained; the sampling pumps were turned off during the interphases. Separate tunnel PM measurements were made over each primary phase (kindling, each main load, and charcoal). Filters were changed during the interphases. OM7 tunnel samples were collected over main loads only. (See Table 5-1 for a summary of measurements and the corresponding phases.)

The test cycle for the pellet burner was different because of its continuous fueling. Aside from a very small amount of newspaper, the kindling phase involved burning pellets and was considered over when steady state was achieved. During the short interphase (needed to change filters) the stove continued to burn pellets. There were no considerations of charcoal bed size or chemistry, or of stove surface temperature since the whole system was in steady state.

TABLE 5-1. MATRIX OF PRIMARY MEASUREMENTS AND RESULTS.

PARAMETER	SAMPLE SOURCE	METHOD	ENTIRE COLD TO COLD CYCLE	EACH PRIMARY PHASE (CHARCOAL, KINDLING, MAIN LOADS)	AVERAGE OF ALL PRIMARY PHASES	EACH MAIN LOAD
COMBUSTION EFF		DIRECT LOSS	X			X
COMBUSTION EFF		OREGON				X
HEAT TRANS EFF		DIRECT LOSS	X			X
HEAT TRANS EFF		OREGON				X
OVERALL EFF		DIRECT LOSS	X			X
OVERALL EFF		OREGON				X
NOX	TUNNEL	CHEMILUM.	X	X	X	X
HC	TUNNEL	FID	X	X	X	X
CO	TUNNEL	NDIR	X	X	X	X
CREOSOTE	FLUE	GRAVIMETRIC	X			
COMBUSTIBLES	TUNNEL	CO+HC+PM		X	X	X
PM	TUNNEL	FILTER		X	X	X
PM	FLUE	OM-7				X
PAH'S	TUNNEL	LIQ. CHROM.			X	
BENZENE	TUNNEL	GC			X	
ELEMENTAL CARBON	TUNNEL	SOLVENT EXTR.			X	
VOLATILE HC	TUNNEL	GC			(1)	
NH3 AND CYANIDE	TUNNEL	WET CHEMISTRY			(1)	
BURN RATE		SCALE		X	X	X
FLUE GAS FLOW		TRACER		X	X	X
FLUE GAS TEMP		THERMOCOUPLES		X	X	X
POWER OUTPUT		DIRECT LOSS				X
POWER OUTPUT		OREGON				X

1. DETERMINED OVER SELECTED INSTEAD OF ALL TESTS.

Installation

The test installation consisted of stove, flue, dilution tunnel and associated instrumentation (Figure 5-1).

Most emissions samples were taken from the dilution tunnel. An advantage of sampling from the dilution tunnel instead of the flue is that the flow in the tunnel is essentially constant. This is especially convenient for integrated samples (eg, PM, PAH, and benzene). Integrated samples must be drawn from the source (flue or tunnel) at a rate which is proportional to the source flow. Constant sampling from the tunnel is proportional sampling, because tunnel flow is constant.

The stove was elevated above the floor so that the OM7 particulate probe penetration -- required to be from 8 to 9 feet above the stove base -- was at a convenient level. All penetrations into the tunnel were far enough downstream to ensure sampling of thoroughly mixed smoke and air.

Stove Operation

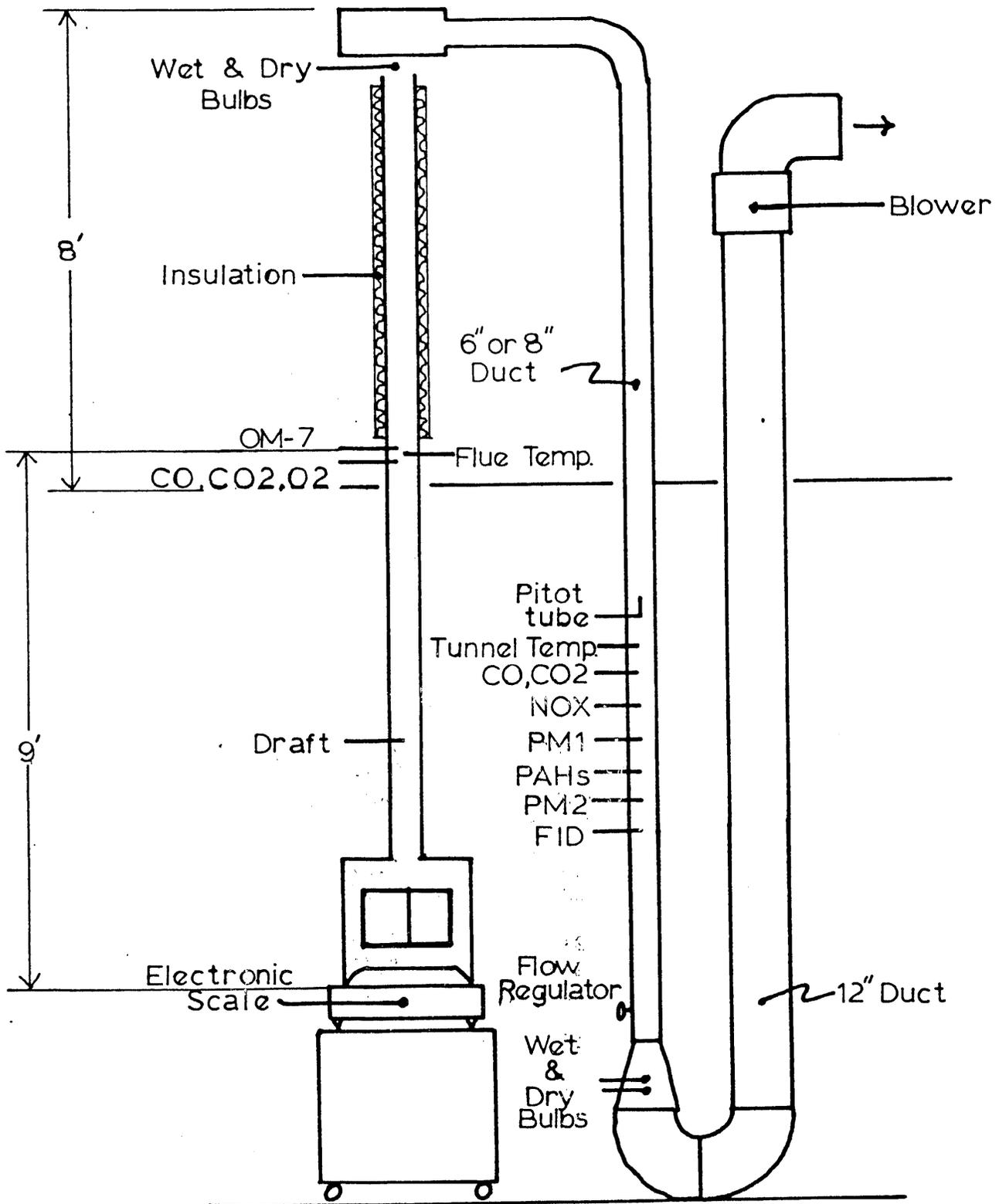
In general, stoves were operated in accordance with the manufacturer's instructions. However, some exceptions were necessary. In particular, the secondary air supply to the conventional airtight was closed and the secondary combustion system never engaged. The primary air supply was set manually once and for all at the beginning of a run and not controlled by the automatic thermostat built into the stove. These changes were made to make the operation of the stove more nearly like that of a "conventional airtight stove."

Kindling loads were always the same species as the main loads and about one-half the mass (See Table 5-2). Pieces were split to a size that facilitated easy kindling, typical of what a wood stove user would do. These were laid on six pieces of wadded newspaper in the firebox.

Table 5-2: Summary of Fuel Load Properties

Stove	Species	Average Moisture Content (% dry basis)	Avg. Piece Mass (kg)	Avg. Load Mass (kg)
Conventional Airtight	Oak	24	1.19	7.16
	Green oak	38	1.65	6.84
Blaze King	Douglas fir	21	2.35	14.11
	Oak	24	2.42	14.53
	Green oak	41	2.71	14.92
Lopi	Douglas fir	21	1.857	3.43
Kent	Douglas fir	21	1.15	4.60
	Oak	24	1.62	8.09
Fireplace Stove	Oak	21	1.13	6.78
	Green oak	41	1.15	6.91

FIGURE 5-1



TEST INSTALLATION

An exception was made in all tests of the Kent Stove with Douglas fir in which the first main fuel load was placed directly on top of the kindling which averaged 1.91 kg in mass. (Some pieces of kindling were inserted into the spaces between the larger pieces of the main load.) This departure from the general procedure was undertaken in consultation with OMNI Environmental Services and the manufacturer in an effort to more closely follow the testing procedure used in the Oregon-certified testing of the same stove (and hence enhancing the value of the interlaboratory comparison of results).

The end of the kindling phase was defined as the point when the weight of the remaining fuel was equal to 20% of the weight of the fuel to be used in the following main load. During the interphase between kindling and first main load finely split pieces of wood and/or charcoal were added to maintain a 20% charcoal bed. Whether to add wood or charcoal was a subjective judgement because of sometimes conflicting goals. A fully charcoaled bed was always desired, but sometimes wood was added to raise the temperature of the stove to the desired level. If these pieces of wood were split very fine, they would charcoalyze quickly and both goals could be met.

Typically, the amounts of fuel added during interphases were less than 1 kg, but sometimes greater, especially for the larger stoves at high burn rates.

For main loads the end of the phase was defined as the point when the fuel weights had decreased to the weight of the original charcoal bed, i.e., when a weight of fuel corresponding to that of the main load had been burned. There was no interphase between the last main load and the charcoal phase. The end of the charcoal phase was arbitrarily defined as that point where the concentration of stack CO_2 fell below 0.1% for at least five minutes. The rest of the test -- until the following morning when instruments were turned off -- was the cooldown phase.

Measurement Methods

Flue Gases CO , CO_2 , O_2

Concentrations of carbon monoxide and carbon dioxide in the flue were monitored continuously during every run using non-dispersive infrared analyzers (Horiba PIR-2000).

Oxygen in the flue was monitored continuously with a Beckman Model 755 paramagnetic analyzer.

All three analyzers were calibrated periodically during this project using calibration gases accurate to within 1%. Each analyzer was zeroed and spanned before and after each test.

The sample gas stream was conditioned by filtration and drying (with Drierite).

Flue Gas H₂O

Water vapor in the flue gas was determined from wet/dry bulb tables appropriate for high altitude. The wet and dry "bulbs" were thermocouple junctions located in the middle of the smoke stream at the top of the stack. The wet thermocouple was a sheathed thermocouple fastened to the end of a stainless steel tube. The whole assembly was covered with a wet bulb sock. It was kept wet by supplying water under pressure to the tube at a rate slightly greater than the loss rate by evaporation. Excess water drained back down the outside of the tube into a vessel outside the flue.

In addition, an integrated sample of flue gas water was collected in the impingers of the OM7 train for main loads when the OM7 train was running.

Tunnel CO and CO₂

Carbon monoxide and carbon dioxide in the tunnel were monitored using Horiba PIR-2000 infrared analyzers. Calibration procedures as well as spanning and zeroing procedures were the same as for the flue gas analyzers.

OM7 PM

For determination of particulate matter by Oregon Method 7 a stream of gas was drawn directly from the flue at a rate proportional to stack mass flow. This was accomplished automatically with a mass flow control valve (Datametrics Corp. Model No. 825) driven by the data acquisition system.

Particulate matter caught on the filters and in the cold traps of the sampling system was processed as prescribed by Oregon Method 7.⁶

No attempt was made in this project to gage the uncertainty of PM determination by the OM7 method. However, in a previous study⁷ it was found that the average differences in two OM7 trains operated simultaneously in 35 tests was 15% of the average catch value. The standard deviation for the same set was 12%.

Tunnel PM

Particulates in the dilution tunnel were measured using an ASTM proposed test method⁸ using two identical sampling trains for all phases of all tests. Each sampling train consisted of stainless steel probe, two filter holders, 1/4 inch teflon tubing, pump, flow stabilizing valve, rotameter, two pressure gages and exhaust tubing. Vacuum-side leak checks were conducted on every filter change. Pressure-side leak checks were made whenever a sampling system was altered.

Before use, glass filters (Gelman AE, 47mm) were desiccated and weighed twice. After use they were desiccated between 24 and 72 hours and then weighed once. Probes were weighed twice before use and immediately after use, the outside surface first having been cleaned with a tissue dampened with acetone. The particulate catch was taken as the sum of the mass gains of the primary filter, secondary filter, and probe.

Total particulate matter for each phase was calculated as the product of the catch and the ratio of the (nearly constant) mass flow in the tunnel and the mass flow in the sampling system. The average difference between the catches of the two sampling trains for main loads in this project was about 6% for 51 tests. (Pellefier main loads are excluded from this set because of small catches and correspondingly high weighing errors.) The standard deviation for the 51 main loads was less than 4%.

The scaling procedure for tunnel PM -- and other integrated samples taken from the tunnel, namely PAHs and benzene -- is based upon the following relationships:

$$\text{Total PM} = \int [\text{PM}] \cdot \dot{m}_T dt \cong \dot{m}_T \int [\text{PM}] dt$$

$$\text{PM Catch} = \int [\text{PM}] \cdot \dot{m}_{SS} dt \cong \dot{m}_{SS} \int [\text{PM}] dt$$

$$\text{Total PM} = (\dot{m}_T / \dot{m}_{SS}) \cdot \text{PM catch}$$

where \dot{m}_T / \dot{m}_{SS} is the ratio of mass flow in tunnel and sampling system and $[\text{PM}]$ is the mass-based concentration (mass fraction) of PM in the tunnel.

Elemental Carbon

The amount of elemental carbon in the ASTM particulate catch was determined by the extraction method of Williams and Chock.⁹ For this, a set of primary filters from each test was weighed, extracted with a gently boiling 4:1 benzene-ethanol solution in a Soxhlet apparatus until the extracting solution remained colorless, dried and reweighed to give the organic fraction of the catch. Any glass fibers or elemental carbon lost from the filters during extraction were reclaimed by washing the glassware and filtering through a Buchner funnel. The mass of elemental carbon in the catch was taken as the difference between original catch and weight loss on extraction.

Creosote

Creosote collected in the stack during a run was determined as the difference in stack mass before and after the run. In so far as possible, runs were scheduled so that hotter burns preceded cooler burns to avoid loss of stack weight due to pyrolysis of previously deposited creosote during a run. When this order was reversed, a short hot fire was used to pyrolyze chimney deposits between runs.

Determination of PAHs

Gas for PAH analysis was drawn at a constant rate from the tunnel. The first element in the sampling train was a filter holder containing a Gelman A/E glass fiber filter backed by a Gelman TE-1000 PIFE filter. This assembly was followed by two adsorption tubes (CRBO-43, Supelco, Inc.) at room temperature wrapped with black plastic.

A sampling rate of .3 to 1.0 l/min was maintained to ensure that the total volume sampled fell within the range specified in NIOSH (National Institute of Occupational Safety and Health) Method 5506 (200-1000 liters).¹⁰

ORBO-43 tubes are made of 6 mm (i.d.) glass tubing and contain two sections of a styrene-divinylbenzene copolymer similar to Amberlite XAD-2. The second section (50 mg) is used to detect compounds not fully retained in the first section (100 mg).

After each test the filters and tubes were refrigerated in darkness until four or five sets had accumulated. These were then packed in an insulating box along with a frozen U-Tek Refrigerant Pack (Polyfoam Packers Corp.) and shipped by overnight express to University Analytical Center (Tucson, Arizona). Analysis of the sixteen PAHs designated in EPA Method 610 was carried out using NIOSH Method 5506, a method utilizing high performance liquid chromatography.

Through test no. 13 both sections in both tubes and combined filters were analyzed separately. By then it was apparent that almost all the PAH material was on the filters and in the first ORBO tube. Thereafter extracts from the filters and first ORBO tube were combined and analyzed together. The extracts from both sections in the second tube continued to be analyzed separately to detect breakthrough.

Detection limits for the 16 PAHs are given in Table 5-3. The estimated uncertainty in the reported results is 50% of value at the detection limit and 10% of value when the value is an order of magnitude or more above the detection limit.

Table 5-3: PAH Detection Limits

	Detection Limit for Combined Glass and PIFE Filters* (ng)	Approximate Equivalent Emission Factor (mg/kg)
Naphthalene	200	.40
Acenaphthylene	300	.60
Acenaphthene	300	.60
Fluorene	165	.33
Phenanthrene	70	.14
Anthracene	14	.03
Fluoranthene	140	.28
Pyrene	55	.11
Benzo(a)anthracene	250	.50
Chrysene	20	.04
Benzo(b)fluoranthene	30	.06
Benzo(k)fluoranthene	12	.02
Benzo(a)pyrene	12	.18
Dibenzo(a,h)anthracene	280	.56
Benzo(ghi)perylene	90	.18
Indeno(1,2,3-cd)pyrene	25	.05

*Detection limits for CRBO adsorbent sections are one-half of the limits for the combined filters.

Volatile Hydrocarbons

A Gow-Mac 750 P gas chromatograph was used to continuously monitor total volatile hydrocarbons in the tunnel. For this purpose the manufacturer modified the instrument so that a sample stream could be fed directly to one of the two flame ionization detectors (FIDS) at a steady rate without passing through a separatory column. The detector was calibrated with 0.1004% ($\pm 2\%$) methane in air obtained from Scott Specialty Gases.

Benzene

Benzene was determined by gas chromatography (FID detector) at room temperature using integrated samples of gas collected in tedlar bags (SKC Inc., Eighty Four, PA) from the dilution tunnel. For most runs separation was on a 4' x 1/8" nonpolar packed column (5% OV-101 on Chrom-P-AW-DMCS) at room temperature, although a 10-foot column with a stronger adsorbent (20% SP-2100 and .1% Carbowax 1500 on Supelcoport) was used after test no. 32. In routine analyses the longer column was operated at 100 C, but in several instances it was operated at room temperature to corroborate peak identification by comparison of retention times. Further corroboration was by mass spectrometry (Hauser Laboratories, Boulder, CO).

In almost all analyses, the benzene peak appeared fully resolved on the short column, except for occasional shoulders at very low benzene levels. On the long column the benzene peak appeared to be fully resolved except for one instance -- a sample of smoke taken during the very first minutes of the kindling phase and therefore unrepresentative of the integrated samples reported here.

In the range 0-170 ppm the response of the FID was linear with benzene concentration. For runs up to no. 19 the calibration standard was made by spiking pure air in a tedlar bag with a small volume of air saturated with benzene. After run no. 19 calibration was by direct injection of a 10.6 ppm benzene-in-air standard ($\pm 2\%$) obtained from Scott Specialty Gases. Linearity was demonstrated for the lower range as well as the higher.

Analysis followed collection by no more than a few hours, since benzene is slowly lost from tedlar bags. The loss amounts to about 1% per hour at a benzene concentration of 10.6 ppm (Figure 5-2). All bags were purged with laboratory air and checked on the gas chromatograph for residual benzene before use.

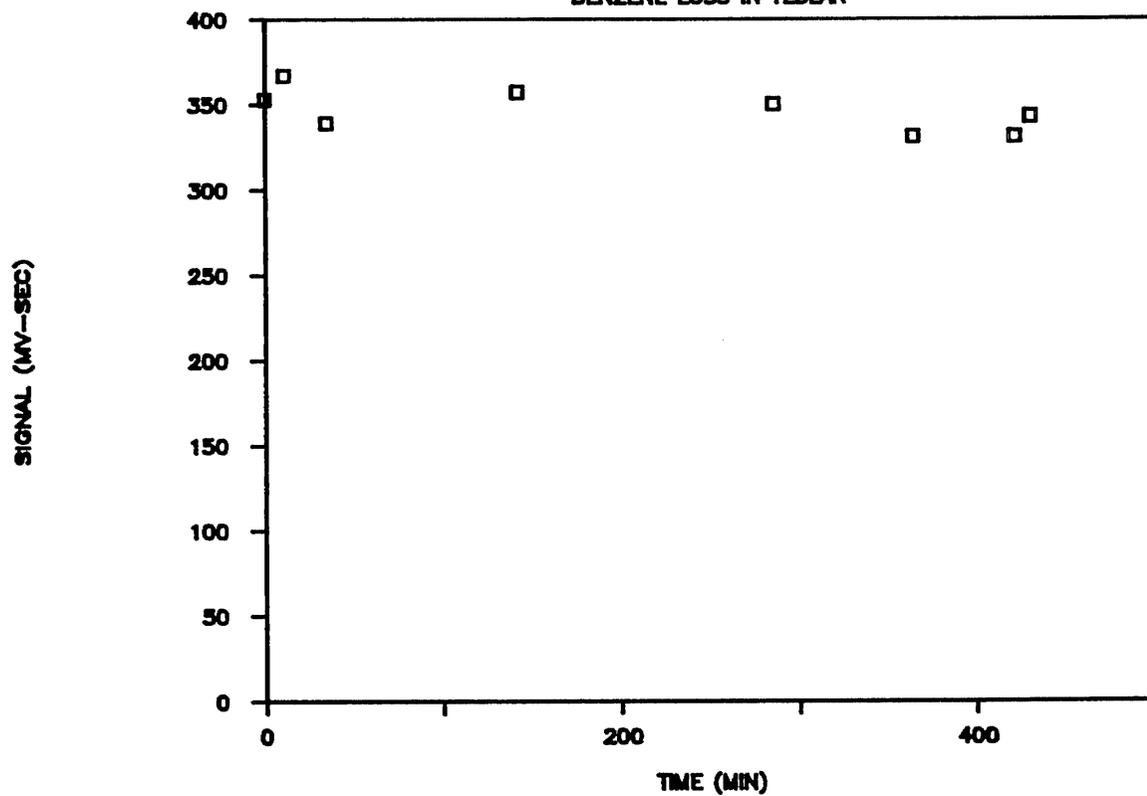
The volume of gas collected was calculated from sampling time and flow rate as measured by a calibrated rotameter. The total benzene catch was then calculated from the sample volume and concentration, and total benzene was calculated through multiplication by the appropriate scaling factor.

NO_x

Oxides of nitrogen in gas from the dilution tunnel were determined continuously using a Thermo-Electron 10AR chemiluminescent analyzer, operated most often on the 10 ppm range. The instrument was spanned with 945 ppm NO which was standardized against a primary standard ($\pm 1\%$) obtained from Scott Specialty Gases.

FIGURE 5-2

BENZENE LOSS IN TEDLAR



Ammonia

Ammonia was determined in selected runs using a wet chemical method -- the phenate method, standard method 417C.¹¹ Samples were taken from water collected in the first and second impingers in the OM7 train (25 ml out of approximately 380 ml). The method is based on the development of a dark blue compound, indophenol, whose intensity is measured in a spectrophotometer at 630 nm, in this case a Coleman Model 6/35. The sample was first clarified by distillation.

It proved impossible to eliminate all traces of ammonia from blanks subjected to the entire distillation and color-development procedure. Therefore, absorbance of the sample was corrected by subtracting absorbance of a blank put through the procedure immediately before the sample. The problem of variable background introduced a comparatively large uncertainty, estimated to be on the order of 50% of the reported values. The detection limit for this method was about 1 microgram/ml of OM7 water (flue concentration of about 1 ppm or emission factor of about 0.01 g/kg).

Cyanide

Standard method 412C.¹¹ as used for detection of cyanide. This method uses an indicator which gives a color change when cyanide is titrated with silver nitrate.

Samples were obtained by bubbling the effluent from the OM-7 train through 100ml of .1M NaOH. None of these samples showed any indication of cyanide. The detection limit corresponded to an emission factor of about 0.1 mg/kg.

Estimated Uncertainties for Gases

Sources of uncertainty in measured values were normal random error of measurement as well as systematic errors such as calibration errors and instrument drift. In the case of the CO and CO₂ analyzers, the dominant uncertainty was in the value of the span gas concentration (1% of value or 0.1% absolute, whichever was smaller).

For oxygen the dominant uncertainty was random and estimated by the root mean square deviation of points on a calibration curve or precision of repeated measurements.

For benzene the major uncertainty was introduced by interaction of benzene with tedlar.

For total volatile hydrocarbons and NO_x the major source of uncertainty was from changes in curvature of calibration curves and baseline drift, respectively. The values of these uncertainties, as well as detection limits, are summarized in Table 5-4.

For all these gases, calibration curves were fit to sets of points using the least-squares criterion. These curves were forced through zero to avoid very high relative errors at the low end of the calibration range.

Table 5-4: Estimated Maximum Errors of Measurement for Flue Gases

Analyzer	Span Gas Concentration (%)	Estimated Maximum Error * (%)
Flue CO	7.01	1
Flue CO2	21.1	0.1 absolute
Flue O2	20.95	0.1 absolute
Tunnel CO	0.821	1
Tunnel CO2	3.97	1
Total Volatile Hydrocarbons	0.1004 CH4	10
NOx	945 ppm	5
Benzene	10.6 ppm	5-10

* Percent of value unless otherwise specified.

The Direct Stack Loss Efficiency Method

Overall efficiency, as well as combustion and heat transfer efficiencies, can be determined by making direct measurements of all energy losses up the flue and comparing these losses to the wood energy input.

Conceptually, the three energy efficiencies are defined as follows:

$$\begin{aligned} \text{Overall energy efficiency} &= \frac{\text{heat output (into house)}}{\text{wood energy input}} \\ \text{Combustion efficiency} &= \frac{\text{heat generated in combustion}}{\text{wood energy input}} \\ \text{Heat transfer efficiency} &= \frac{\text{heat output (into house)}}{\text{heat generated in combustion}} \end{aligned}$$

It is traditional in North America to assess the wood energy on the higher heating value basis; this means that the latent heat of the water vapor generated (or evaporated) during combustion is included in the computed wood energy.

In the direct flue loss method, the three efficiencies are computed as follows:

$$\text{Overall efficiency (OE)} = \frac{W - SL - CL - LL}{W}$$

$$\text{Combustion efficiency (CE)} = \frac{W - CL}{W}$$

$$\text{Heat transfer efficiency (HT)} = \frac{W - SL - CL - LL}{W - CL}$$

where W = wood energy input
 SL = sensible heat loss
 CL = chemical energy loss
 LL = latent heat loss.

(note that OE = CE*HT)

In this project the following measurements, assumptions and calculations served as the basis for the direct loss method.

-The Sensible Heat Loss was computed as the integral of flue gas flow times the specific heat times temperature rise above ambient; i.e.,

$$SL = \int \dot{m}_{ST} \cdot C \cdot \Delta T \cdot dt$$

where \dot{m}_{ST} = mass flow of flue gases
 C = specific heat of flue gas
 ΔT = flue gas temperature minus ambient temperature.

The specific heat was computed as a function of flue gas composition and temperature.

-Latent Heat loss attributable to unrecondensed water was computed on the assumption of perfect combustion. This is a slight overestimate, but it has no impact on the computed overall efficiency because it compensates for the use of lower (instead of higher) heating values in computing the chemical energy loss.

-Chemical Energy loss was based on measured CO, hydrocarbons (FID), PM and creosote, each with its associated lower heating value (Table 5-5).

Table 5-5: Heating Values Used in Efficiency Computation

Component	Lower Heating Value (joules/gram)
CO	10,000
HC	50,000
PM	30,000
Creosote	30,000

The heating value for HC is that of methane. The heating values for PM and creosote are estimates. The sensitivity of the computed efficiencies to these estimates is low since only a small percentage of the wood energy input is lost in these components. The creosote loss was assumed to be a constant 15% of the PM loss. This estimate is based on the average of the measured creosote. The 15% relationship is taken as a constant for all phases of all tests for two reasons. 1) The measured creosote was determined only over a cold-to-cold test cycle (hence the measured data is not directly applicable to the main load cycles). 2) The sensitivity of the resulting efficiencies to this approximation is very small. (The creosote's contribution to the combustion efficiency ranges from 0 to 6 percentage points.)

This direct loss method is closely related to others whose agreement with room calorimetry is very good. We estimate the uncertainty in this direct loss method to be ± 3 percentage points for each of the three energy efficiencies.

Measurement of Flue Gas Flow

Flue gas velocity, which is needed for OM7 proportional sampling and efficiency calculations, was measured using the natural tracer technique. This technique requires a dilution tunnel over the flue. The mass flow in the tunnel is measured with conventional techniques (such as a Pitot tube).

CO and CO₂ are both convenient natural tracers. The ratio of the tracer concentration in the flue and the tunnel is in approximate inverse proportion to the flow ratio.

Assume CO is the tracer. By conservation of CO and total mass:

$$f_s M_s + f_a M_a = f_t M_t$$

$$M_s + M_a = M_t$$

Where

f = mole fraction of CO

M = molar flow rate

s,a,t = subscripts designating stack, ambient air and tunnel.

The solution for stack flow is:

$$M_s = \frac{f_t - f_a}{f_s - f_a} \cdot M_t$$

Thus measurement of tracer concentrations in the flue, air and tunnel plus the tunnel flow yields the stack flow. The equation is also valid if the M's are interpreted to be mass (instead of molar) flows, and the f's are interpreted as mass (instead of molar) fractions.

With CO as the tracer, ambient concentrations (f^a) are negligible. However, with clean burning appliances, concentrations of CO in the flue and tunnel may require gas analyzers of higher than usual (in wood stove research) sensitivity. With CO² as the tracer, ambient concentrations are not always negligible.

At SRI separate analyzers with different sensitivities are used for measuring flue and tunnel concentrations. Accuracy in stack flow is estimated to be about 3%.

Data Acquisition and Processing

Raw data were taken in by the Data Acquisition System (DAS) every 30 seconds and partially processed to engineering units and some computed quantities of interest (such as stack flow). Every minute the average of the two previous partially processed data sets was stored in the computer's memory, printed on paper and displayed on the computer screen. At the end of each test phase (kindling, main load, etc.) the partially processed data for the phase was stored on floppy disk as the "engineering" file.

After each complete cold-to-cold test, the engineering files for each phase were processed to obtain 1) an Oregon data file to be processed by the Oregon DEQ program, and 2) averages and integrals of interest. The integrals and averages were formatted in a file which could be read directly into a spreadsheet. Final processing and graphing were done in a spreadsheet environment.

Section 6

Results

Introduction

The total quantity of numerical results from this project is very large. There were a total of 44 tests averaging roughly six phases or phase combinations each, with over 20 parameters reported for each phase. Because of the large size of this data set, most of it is located in the Appendix. In this section of the report will be found data that does not fit into the format of the appendices and discussion of the data related to its quantity and quality. Discussion of correlations within the data and implications of the results are located in Section 7, Discussion.

Units for Emissions

Most emissions data in this report are reported as emission rates in units of grams per hour, or as emission factors in units of grams per dry kilogram. The choice is dictated by the nature of the data. For all quantities which were determined over a burn phase with a well defined duration, emissions rates are used. Such phases are kindling and main loads, and CO, PM, HC, and NO_x are all reported in g/hr over these phases.

Phases without well defined durations are the charcoal and the entire cold-to-cold phases. These durations are not well defined because of the lack of clear end point for the charcoal phase. For these phases, emissions are reported as factors (g/kg).

Emissions factors for cold-to-cold phases can be converted into approximate emissions rates by multiplying by the total fuel consumed and dividing by 24 hours. Such conversion assumes that average field use corresponds to the particular 24 hour firing cycle used in the testing in this project. This is not a justifiable assumption but does yield approximate emissions rates perhaps to within a factor of four. Cold-to-cold phase emissions are reported only in g/kg in this report.

Extra Tests

The originally planned test matrix specified 32 tests. In fact 44 tests were conducted.

One reason for some of the additional tests was to repeat a previous test where one or more parameters were not measured due to instrument failures or human errors.

However, a number of tests conducted late in the program were designed to provide additional data to help resolve particular issues. The fifth test of the Blaze King using Douglas fir as the fuel (test no. 44) was not conducted due to any loss of data in the previous test, but rather because the previous low burn rate test was unusually dirty -- emissions were unexpectedly high for this appliance. Normally this would not dictate a repetition. However, this particular test is critical for interlaboratory reproducibility and altitude effects. This is the only stove tested by both Oregon DEQ and EPA, and the Oregon weighted average weights the low

burn rate the most. Hence the test was repeated to see if the first result was a fluke or was reproducible. (The repetition yielded a substantially cleaner burn.)

Extra tests with the Pellefier pellet burner were conducted because of the unusual relation between the OM7 and dilution tunnel PM indicated by the initial tests. (The additional tests confirmed the earlier results.)

Extra Pellefier tests were also conducted with a design modification. The Pellefier stove was the very same unit used in certification testing in Oregon. However, it was delivered by the manufacturer with modifications to the combustion air supply intended to compensate for altitude. Since one of the program objectives was to explore the effect of altitude on emissions, additional tests were conducted in the original configuration. Since no significant change in emissions between the two configurations was noted, no distinction between the configurations has been made in this report.

PM

Particulate matter results were obtained using both the ASTM dilution tunnel method and Oregon Method 7. A single OM7 train was used. Dual ASTM trains were used on essentially all tests, and it is the average of the two trains' results which is given in the data.

There are some gaps in the OM7 data. The primary causes for lack of data are 1) failure of post-test leak check, 2) loss of sample due to disassembly or processing accidents, and 3) difficulties in having new sampling trains ready for every main load phase in multiple-phase short-burn-cycle tests.

The OM7 data for Tests 5 through 21 required different processing. A problem with the automatic proportional sampling system resulted in loss of accurate data on sampled volume. For these tests the sampled dry gas volume was calculated using the condition that the wood moisture content calculated in the Oregon flue loss algorithm equal the measured wood moisture content. The Oregon test method is "overdetermined" -- more quantities are measured than are necessary to solve the equations for the unknowns. The algorithm treats the wood moisture content as an unknown. Since the wood moisture content is in fact a measured quantity, the measured value can be used and any normally measured quantity can be solved for.

Although all the OM7 data are included in the Appendix, not all OM7 data have been used in the graphs and discussion in Section 7 (Discussion). Tests with OM7 catches of less than 100 mg have been excluded for lack of sufficient precision. At lower catches, three factors can contribute to imprecision. 1) A total of seven objects are weighed twice to determine the catch. Thus weighing errors can add up to a significant amount. 2) Four of the objects are glass beakers with clean weights of about 70 grams. Because of their large mass and their susceptibility to static electricity effects, the weighing errors can be larger than for filters. 3) Running OM7 blanks, there is usually a finite catch, on the order of tens of milligrams. (No correction for blanks has been made because of inadequate data on the effect.)

Creosote

An occasional test resulted in a decrease in chimney weight due to pyrolysis of the previously deposited creosote. This effect was minimized by 1) starting with a clean flue at the beginning of each appliance/fuel series, and/or 2) conducting tests within each appliance series in approximate order of decreasing burn rate. There is no Pellefier creosote data in the appendix because the accumulation was below the 2g limit of detectability.

PAH

The Appendix contains data for total PAHs -- the sum of all 16 of the particular compounds covered in EPA Method 610. All graphs of PAH in this report also represent the total of the sixteen compounds.

For tests 40 through 48, acenaphthene and fluorene were not resolved; the sum of both is reported as fluorene. For the same tests, benzo(a)anthracene was not available.

The relative amounts of each of the compounds is indicated in Table 6-1. The lower molecular weight compounds dominate.

For some tests, the results appear to be inconsistent; e.g., the high value for dibenzo(a,h)anthracene in tests 25 and 26. Since these tests are not unique in the appliance type or burn rate, we suspect this result does not reflect reality but rather an analysis problem.

For those tests in which all five elements of the sampling train were analyzed separately, the average percentage of the total PAH which was on the filters was 15%, the remainder being in the adsorbent. However, essentially all of the compounds from benzo(a)anthracene down to the end of the list were collected on the filters, whereas most of the four compounds naphthalene, acenaphthene, fluorene and phenanthrene were found in the adsorbent.

In a few tests there was detectable naphthalene in the last segment of XAD. This was the case for test nos. 4,5,6,7,8,12,20,21, and 25. The average fraction of the total naphthalene found in the last segment of XAD for these tests was 3.7%.

Two other PAHs were found in the last XAD segment: an insignificant amount of fluorene in test no.9 and larger amounts of acenaphthylene in tests no. 20 and 28, 1.5% and 13% of the total acenaphthalylene catches respectively. The apparent breakthrough of acenaphthylene to the last XAD segment in these tests is somewhat inconsistent with the rest of the data and may not represent reality.

NOx

The average NOx emissions factor was about .5g/kg, with a range of .2 to .1. These figures agree quite well with those of the 1983 TVA study⁴ and the 1980 Monsanto study⁵, both of which used the chemiluminescent method used here. They are considerably lower than the 1977 California Air Resources Board study¹² which used a wet chemical method.

Table 6-1. PAH results. (1)

TEST NO.	4	5	6	7	8	9	10	11
NAPHTHALENE	47.9	61.9	68.6	62.9	38.2	43.9	40.2	29.8
ACENAPHTHYLENE	20.3	24.9	3.8	3.9	32.0	18.7	18.8	28.7
ACENAPHTHENE	0.0	0.0	10.5	6.8	8.2	13.5	24.3	12.3
FLOURENE	21.0	5.6	6.2	11.5	8.0	0.1	1.3	4.7
PHENANTHRENE	5.1	2.1	2.0	2.5	4.3	4.6	3.4	1.6
ANTHRACENE	1.1	0.5	0.5	0.4	1.0	1.2	0.9	0.5
FLUORANTHENE	0.9	0.6	4.0	2.0	3.3	4.6	7.7	16.5
PYRENE	1.8	1.2	0.9	3.2	4.2	7.5	1.4	1.2
BENZO(A)ANTHRACENE	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CHRYSENE	0.8	0.4	0.7	0.5	0.4	1.3	0.4	0.7
BENZO(B)FLUROANTHACENE	0.6	0.4	0.5	0.3	0.2	1.2	0.4	0.0
BENZO(K)FLUROANTHACENE	0.4	0.2	0.3	0.2	0.1	0.4	0.1	3.2
BENZO(A)PYRENE	0.0	0.4	0.6	5.1	0.1	1.0	0.2	0.0
DIBENZO(A,H)ANTHRACENE	0.0	1.2	0.0	0.0	0.0	0.0	0.0	0.0
BENZO(GHI)PERYLENE	0.0	0.7	0.9	0.4	0.0	1.3	0.7	0.6
INDENO(1,2,3-CD)PYRENE	0.0	0.0	0.3	0.3	0.0	0.5	0.2	0.2
TOTAL	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
TOTAL IN G/KG	0.43	0.30	0.55	0.55	0.34	0.20	0.11	0.090

1. In percent of total unless otherwise indicated.

Table 6-1. PAH results. (1)

TEST NO.	12	13	14	15	16	17	18	19
NAPHTHALENE	44.1	27.5	50.7	48.6	41.2	56.2	ERR	56.2
ACENAPHTHYLENE	28.5	35.0	12.1	6.3	24.4	12.1	ERR	7.8
ACENAPHTHENE	15.1	14.6	9.0	6.1	12.4	12.6	ERR	14.3
FLOURENE	4.6	5.7	17.0	17.2	13.5	9.7	ERR	5.3
PHENANTHRENE	2.7	2.2	4.3	6.3	3.2	3.6	ERR	4.4
ANTHRACENE	0.8	1.0	0.8	2.2	0.8	0.8	ERR	1.1
FLUORANTHENE	0.9	7.5	0.0	3.3	2.0	1.7	ERR	3.3
PYRENE	1.1	2.5	1.9	2.3	1.6	1.0	ERR	2.2
BENZO(A)ANTHRACENE	0.0	0.0	0.0	0.0	0.0	0.0	ERR	0.0
CHRYSENE	0.9	0.0	0.6	0.9	0.4	0.6	ERR	0.6
BENZO(B)FLUROANTHACENE	0.0	1.0	0.5	1.0	0.2	0.4	ERR	0.3
BENZO(K)FLUROANTHACENE	0.0	0.6	0.3	0.5	0.1	0.3	ERR	0.2
BENZO(A)PYRENE	0.7	0.0	0.3	0.4	0.3	0.6	ERR	3.4
DIBENZO(A,H)ANTHRACENE	0.0	0.0	1.2	2.8	0.0	0.0	ERR	0.0
BENZO(GHI)PERYLENE	0.4	2.0	1.0	1.8	0.0	0.0	ERR	0.6
INDENO(1,2,3-CD)PYRENE	0.2	0.4	0.2	0.4	0.1	0.4	ERR	0.3
TOTAL	100.0	100.0	100.0	100.0	100.0	100.0	ERR	100.0
TOTAL IN G/KG	0.12	0.44	0.17	0.037	0.010	0.22		0.082

1. In percent of total unless otherwise indicated.

Table 6-1. PAH results. (1)

TEST NO.	20	21	22	23	24	25	26	27
NAPTHALENE	44.2	45.6	47.7	48.7	4.8	20.1	38.4	25.5
ACENAPHTHYLENE	23.6	6.5	10.0	11.6	57.4	39.3	16.9	49.9
ACENAPHTHENE	11.9	15.3	10.7	11.0	1.1	0.4	10.0	7.3
FLOURENE	9.0	19.6	16.6	13.6	13.8	11.5	14.7	1.7
PHENANTHRENE	3.7	4.5	3.8	3.9	7.6	6.6	2.2	5.2
ANTHRACENE	1.1	1.3	0.8	0.8	2.2	1.5	0.4	1.2
FLUORANTHENE	3.4	3.3	3.9	5.2	7.2	4.8	2.2	4.7
PYRENE	0.5	0.6	1.6	2.3	3.9	1.3	1.4	1.8
BENZO(A)ANTHRACENE	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CHRYSENE	0.5	0.5	0.6	0.7	0.4	0.4	0.5	0.8
BENZO(B)FLUROANTHACENE	0.4	0.5	0.5	0.5	0.5	0.7	0.4	0.9
BENZO(K)FLUROANTHACENE	0.3	0.3	0.3	0.3	1.0	0.2	0.3	0.2
BENZO(A)PYRENE	0.4	0.5	0.5	0.5	0.0	0.0	0.0	0.8
DIBENZO(A,H)ANTHRACENE	0.0	0.0	1.4	0.0	0.0	13.1	11.9	0.0
BENZO(GHI)PERYLENE	0.8	1.0	0.9	0.7	0.0	0.0	0.5	0.0
INDENO(1,2,3-CD)PYRENE	0.2	0.5	0.5	0.3	0.0	0.0	0.2	0.0
TOTAL	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
TOTAL IN G/KG	0.20	0.18	0.30	0.37	0.12	0.19	0.53	0.26

1. In percent of total unless otherwise indicated.

Table 6-1. PAH results. (1)

TEST NO.	28	29	30	31	33	40	41	42
NAPTHALENE	35.9	18.4	52.4	38.3	20.2	70.3	68.2	62.2
ACENAPHTHYLENE	39.2	61.7	14.0	20.7	0.0	2.6	8.9	11.9
ACENAPHTHENE	3.3	3.7	11.5	10.1	35.4	3.5	0.0	0.0
FLOURENE	13.1	7.5	10.9	12.1	25.0	6.5	7.5	9.8
PHENANTHRENE	2.3	3.9	2.0	6.5	11.4	2.0	2.8	3.3
ANTHRACENE	0.6	0.9	0.4	2.9	5.1	0.3	0.6	0.7
FLUORANTHENE	3.2	1.1	3.5	4.2	3.0	2.9	4.9	5.2
PYRENE	1.2	1.1	2.0	4.1	0.0	2.3	2.4	2.6
BENZO(A)ANTHRACENE	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CHRYSENE	0.3	0.4	0.6	0.4	0.0	0.5	0.7	0.7
BENZO(B)FLUROANTHACENE	0.4	0.8	0.5	0.2	0.0	0.4	0.3	0.3
BENZO(K)FLUROANTHACENE	0.2	0.2	0.4	0.1	0.0	0.2	0.3	0.3
BENZO(A)PYRENE	0.3	0.5	0.7	0.3	0.0	0.5	0.6	0.6
DIBENZO(A,H)ANTHRACENE	0.0	0.0	0.0	0.0	0.0	7.0	1.9	1.2
BENZO(GHI)PERYLENE	0.0	0.0	1.1	0.0	0.0	0.7	0.9	0.9
INDENO(1,2,3-CD)PYRENE	0.0	0.0	0.0	0.0	0.0	0.3	.0	0.4
TOTAL	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
TOTAL IN G/KG	0.41	0.22	0.47	0.32	0.037	0.55	0.28	0.34

1. In percent of total unless otherwise indicated.

Table 6-1. PAH results. (1)

TEST NO.	43	44	45	46	47	48
NAPHTHALENE	48.0	59.1	0.0	0.0	46.1	21.9
ACENAPHTHYLENE	15.4	6.3	0.0	0.0	24.9	40.2
ACENAPHTHENE	0.0	0.0	39.0	49.0	15.3	18.9
FLOURENE	10.9	10.8	0.0	0.0	0.0	0.0
PHENANTHRENE	8.6	6.5	39.0	27.5	2.7	3.0
ANTHRACENE	1.8	2.2	7.1	5.4	0.7	0.8
FLUORANTHENE	9.2	9.3	14.9	18.1	4.3	8.0
PYRENE	1.6	0.3	0.0	0.0	2.5	2.5
BENZO(A)ANTHRACENE	0.0	0.0	0.0	0.0	0.0	0.0
CHRYSENE	0.5	1.2	0.0	0.0	0.6	0.9
BENZO(B)FLUROANTHACENE	0.3	0.8	0.0	0.0	0.5	0.6
BENZO(K)FLUROANTHACENE	0.2	0.5	0.0	0.0	0.3	0.4
BENZO(A)PYRENE	0.3	0.6	0.0	0.0	0.6	0.7
DIBENZO(A,H)ANTHRACENE	2.4	0.0	0.0	0.0	0.0	0.6
BENZO(GHI)PERYLENE	0.5	2.1	0.0	0.0	1.0	1.1
INDENO(1,2,3-CD)PYRENE	0.1	0.3	0.0	0.0	0.3	0.4
TOTAL	100.0	100.0	100.0	100.0	100.0	100.0
TOTAL IN G/KG	0.15	0.038	0.0072	0.0037	0.084	0.30

1. In percent of total unless otherwise indicated.

Ammonia and Cyanide

Ammonia was detected in water of the first two impingers of the OM7 train. This water was tinted brown and required pH adjustment and distillation before colorimetric analysis. All traces of ammonia could not be eliminated in blank runs, introducing a comparatively large uncertainty into the analyses. Even so, the results (Table 6-2) indicate higher ammonia emissions factors for non-catalytic stoves than for the Blaze King.

Cyanide was never detected; only upper limits are given in Table 6-2.

Table 6-2: Ammonia and Cyanide Results

Test	Stove	Ammonia (g/kg)	Cyanide (mg/kg)
19	Blaze King		<.09
20	Blaze King	.001	<.02
21	Lopi		<.13
25	Lopi	.003	
29	Kent		<.52
44	Blaze King	.002	<.09
45	Pellefier		<.30
47	Fireplace Stove		<1.0
48	Fireplace Stove	.10	

Elemental Carbon

The average fraction of the PM catch attributable to elemental carbon was 8.6%, ranging from 1.2 to 21%. In general, the fraction of elemental carbon increased with increasing burn rate. The average emission factor was 0.67 g/kg, ranging from undetectable for the pellet burner to 2.2.

Section 7

Discussion

Introduction

Appliance and fuel effects are generally burn-rate dependent; e.g., the PM emissions of the Blaze King catalytic stove were much lower than those of the non-catalytic chunk-wood burners at low burn rates, but comparable at high burn rates.

It is generally felt that performance at low burn rates is most relevant. Both Oregon⁶ and Colorado¹³ include a climate weighting scheme as part of their wood stove regulations. The United States Environmental Protection Agency is leaning towards the same approach for the federal regulation. This approach involves the assumption most stoves are used most of the time at heat output rates less than roughly 18,000 Btu/hr. The weather weighting scheme gives a preponderance of weight to the test results at a low burn rate.

Because emphasis on low-burn rate data is becoming generally accepted, Oregon weighted averaging has been used in preparing data for Figures 7-1 through 7-11. Since the number of tests was not always the number (4) normally used in the Oregon weighting system, the weighting algorithm was modified to encompass any number of tests. Since the algorithm does not accommodate absent data, interpolation was used to generate the few missing data points for particular emittants in a few tests. For cold-to-cold cycle averaging, the heat output of the last main load was used.

The Oregon weighted average is very sensitive to the results for the lowest burn rates. Thus one or two tests may dominate the weighted averages. Relatively little work has been done on the reproducibility of tests on solid fuel heaters, and it is not possible to quantify the uncertainty in the Oregon weighted averages, particularly in the present case where the heat output distribution did not always satisfy the Oregon test method requirement. Our rough estimate of the uncertainty is $\pm 25\%$ of the values.

Because the initial low burn rate test on the Blaze King resulted in relatively high emissions, the test was repeated. Emissions were lower in the repeat test. The Oregon weighted averages presented in this section include the results of all five Blaze King tests, as there was no justification for being selective.

In many graphs in this report abbreviations are used to designate the appliance/fuel combinations. The last letter designates the fuel and other letter(s) designate the appliance, as indicated in Table 7-1.

Table 7-1: Stove/Fuel Identification Labels Used in Graphs

Symbol	Stove	Fuel
BF	Blaze King	Fir
BO	Blaze King	Oak
FPG	Fireplace Stove (open)	Green oak
FPO	Fireplace Stove (open)	Oak
KF	Kent	Fir
KO	Kent	Oak
LF	Lopi	Fir
P	Pellefier	Pellets
CG	Conventional Airtight	Green oak
CO	Conventional Airtight	Oak

Unless otherwise indicated, PM data is dilution tunnel data.

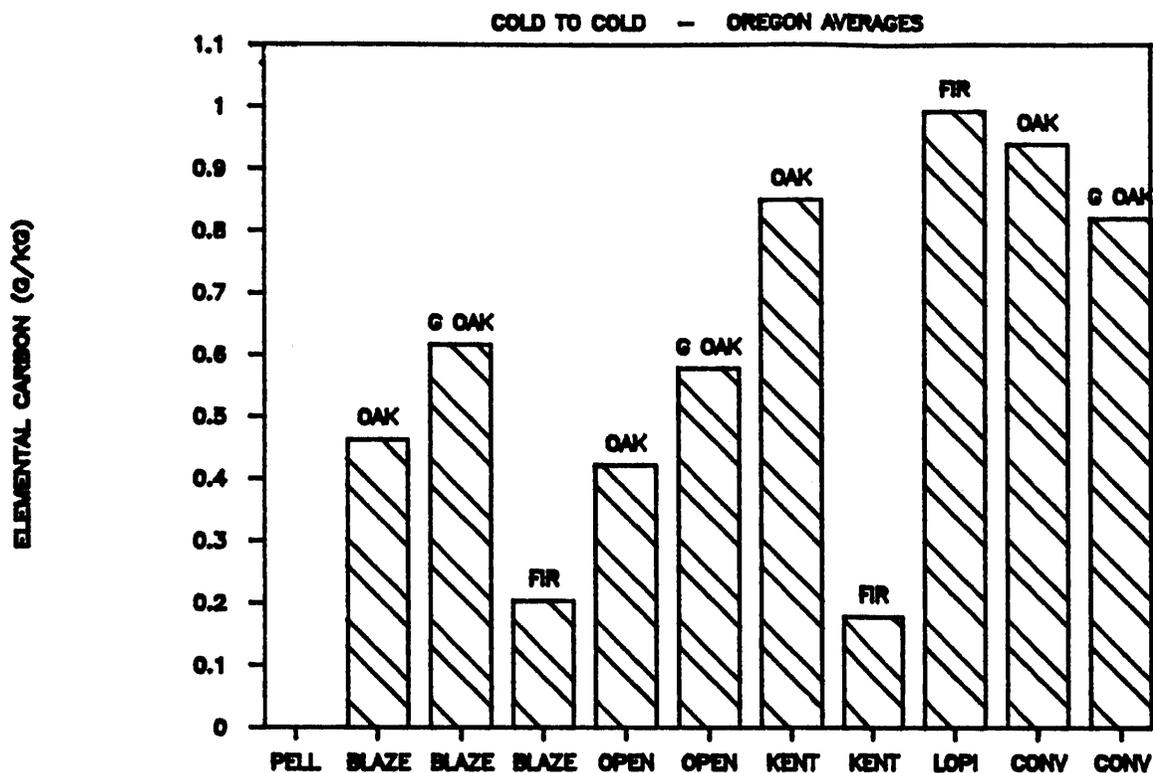
Fuel and Appliance Effects

Assuming a $\pm 25\%$ uncertainty in the Oregon weighted averages, what fuel effects were strong and consistent for all appliances in this project? 1) Elemental carbon factors (Figure 7-1) were the lowest with Douglas fir as the fuel and highest for green oak, with the difference appearing to be at least a factor of three. 2) The same trend holds for NO_x; NO_x emissions rates (Figure 7-2) appeared to be over two times larger for green oak than Douglas fir. (The term "appeared" is used because of the complication that all three fuels were used in only one appliance, necessitating the assumption that some of the trends seen for one appliance apply to others.)

The strong fuel dependence for NO_x across all appliance types suggest that perhaps some of the NO_x has its origins as nitrogen in the fuel. Elemental analysis of the fuels yielded dry-basis nitrogen contents of 0.15%, 0.11% and 0.31% for fir, seasoned oak and green oak respectively. Since the samples contained no bark, and since bark generally has a higher nitrogen content than wood, and since the Douglas fir as burned had no bark, whereas both oak fuels had bark, it is likely that the nitrogen content of the fuels as burned was in the same order as the NO_x emissions. It is also of interest that the amount of nitrogen in the fuel is over ten times the amount of nitrogen emitted in NO_x. Thus the data are consistent with the possibility most of the NO_x originates as nitrogen in the fuel. Evidence for other fuel effects is less strong. However, it appears the PAH emissions are highest for green oak and lowest for fir (Figure 7-3). CO emissions appear to be highest for Douglas fir, compared to both seasoned oak and green oak (Figure 7-4).

Appliance effects were much stronger than the fuel effects. Most products of incomplete combustion, including PM, CO, HC, PAH, elemental carbon and combustibles were lowest for the Pellefier pellet stove (Figures 7-1 through 7-7). In fact, elemental carbon was below its detectability limits. The Blaze King catalytic stove was next in order of completeness of combustion. The stove with the highest emissions of products of incomplete combustion was the conventional airtight stove. (The relatively high benzene factor for the Pellefier (Figure 7-8) is probably an artifact of sparse data and the Oregon averaging.)

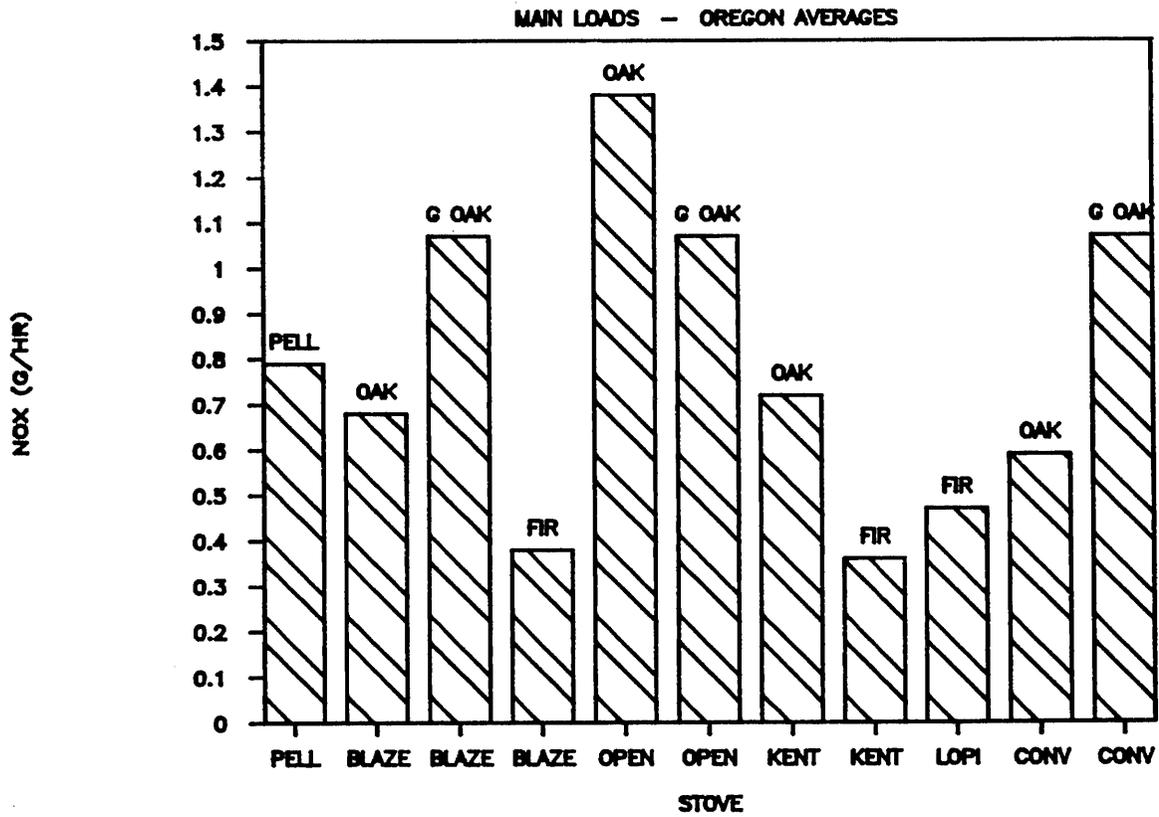
FIGURE 7-1. ELEMENTAL CARBON FACTORS.



KEY:

- G OAK = GREEN OAK
- PELL = PELLEFIER
- BLAZE = BLAZE KING
- OPEN = FIREPLACE STOVE IN OPEN MODE
- KENT = KENT TILE FIRE
- CONV = CONVENTIONAL AIRTIGHT

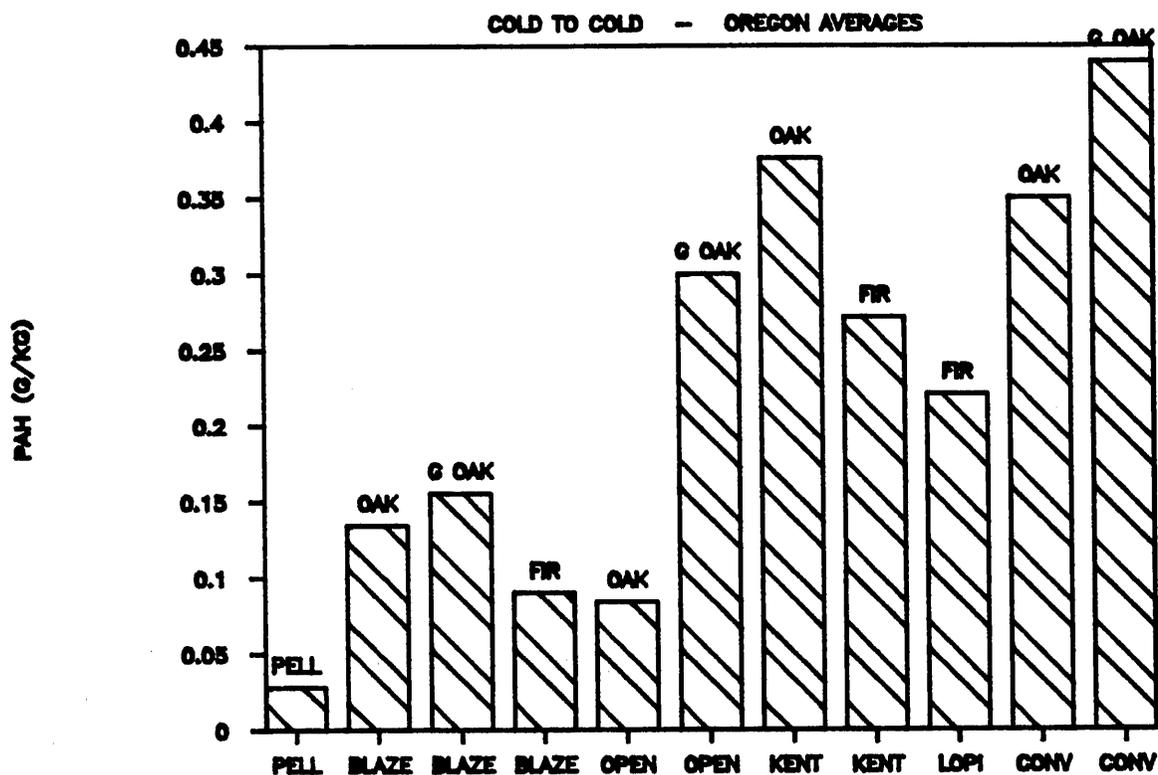
FIGURE 7-2. NOX EMISSION RATE.



KEY:

- G OAK = GREEN OAK
- PELL = PELLEFIER
- BLAZE = BLAZE KING
- OPEN = FIREPLACE STOVE IN OPEN MODE
- KENT = KENT TILE FIRE
- CONV = CONVENTIONAL AIRTIGHT

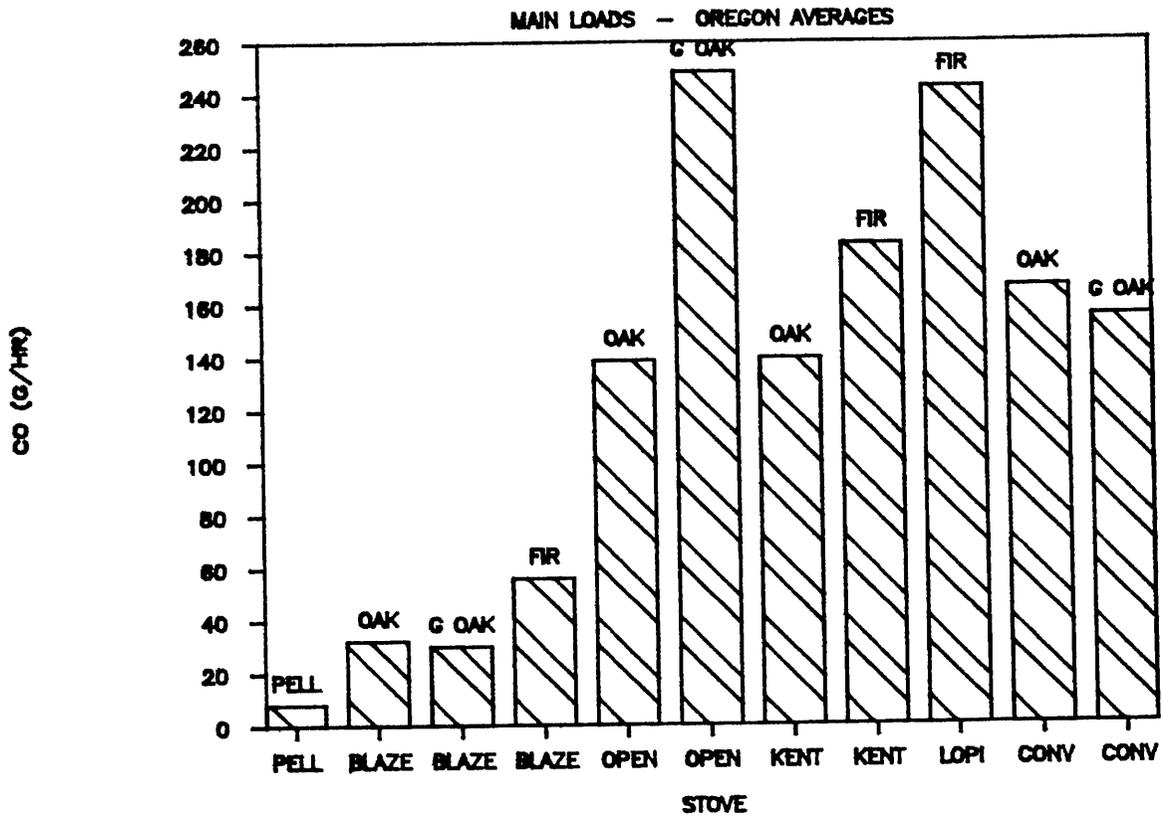
FIGURE 7-3. PAH FACTORS.



KEY:

- G OAK = GREEN OAK
- PELL = PELLEFIER
- BLAZE = BLAZE KING
- OPEN = FIREPLACE STOVE IN OPEN MODE
- KENT = KENT TILE FIRE
- CONV = CONVENTIONAL AIRTIGHT

FIGURE 7-4. CO EMISSION RATE.

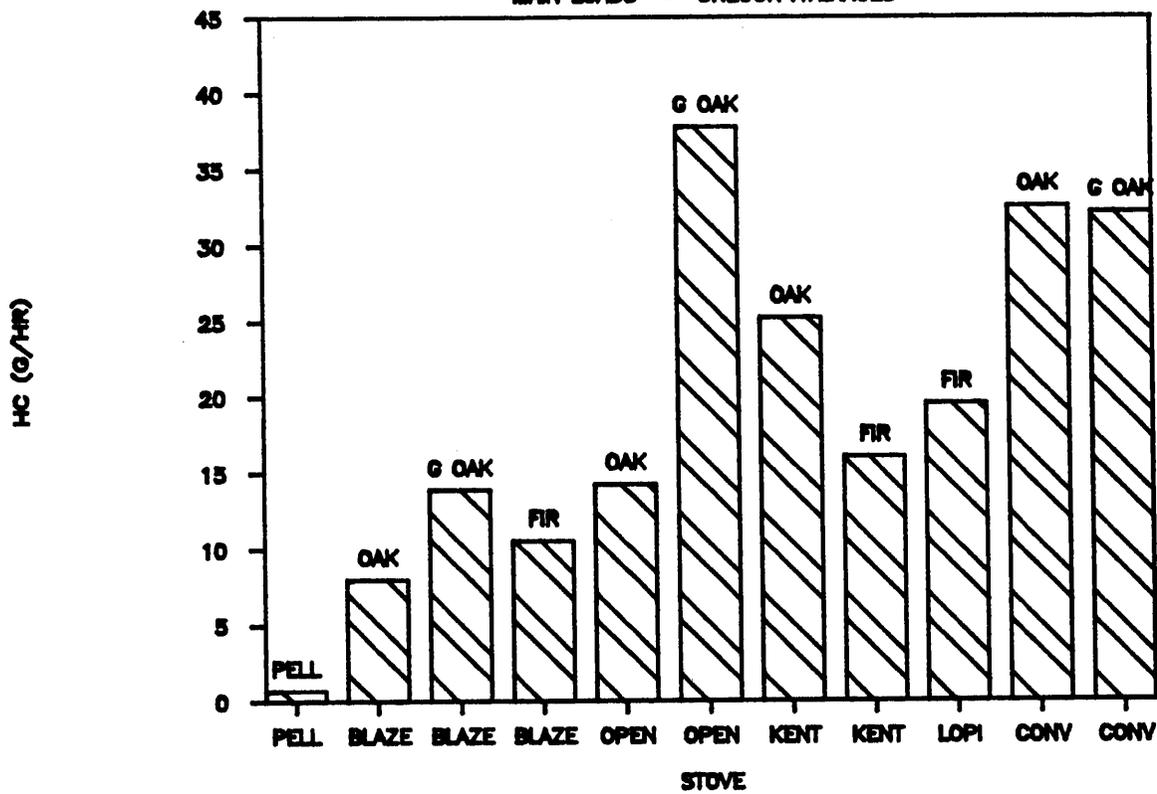


KEY:

- G OAK = GREEN OAK
- PELL = PELLEFIER
- BLAZE = BLAZE KING
- OPEN = FIREPLACE STOVE IN OPEN MODE
- KENT = KENT TILE FIRE
- CONV = CONVENTIONAL AIRTIGHT

FIGURE 7-5. HC EMISSION RATE.

MAIN LOADS - OREGON AVERAGES

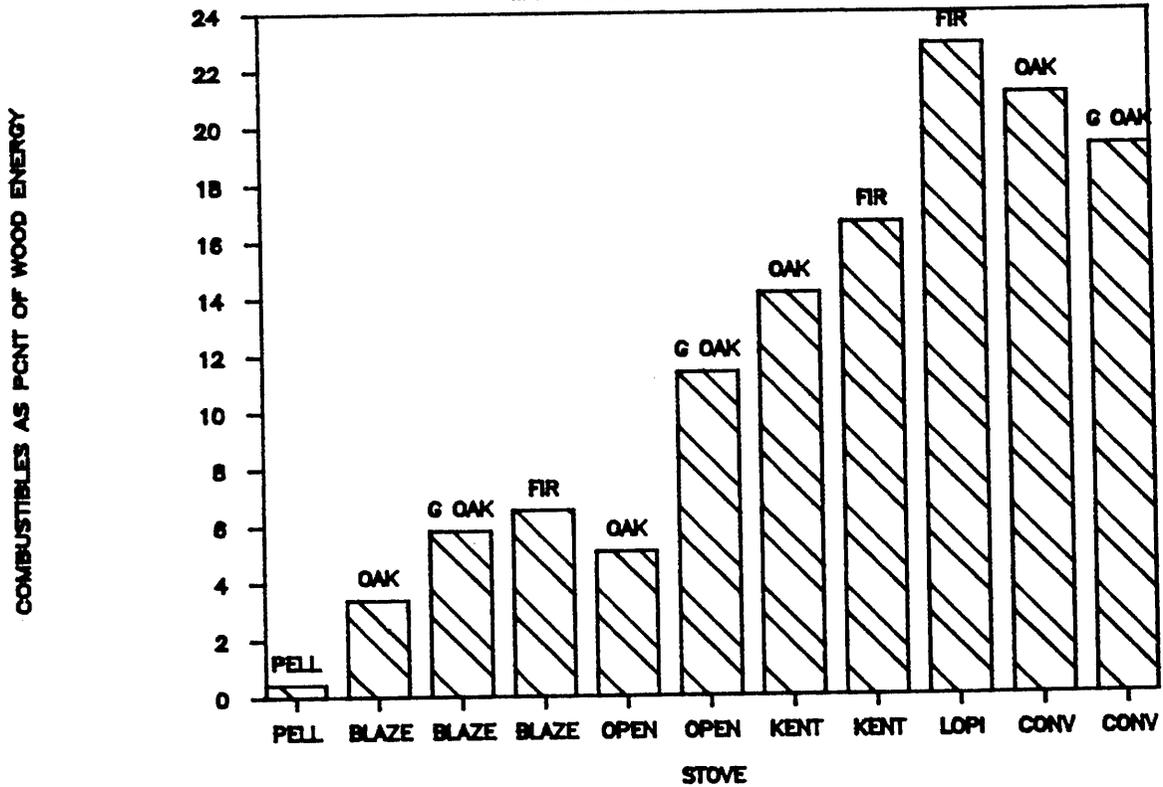


KEY:

- G OAK = GREEN OAK
- PELL = PELLEFIER
- BLAZE = BLAZE KING
- OPEN = FIREPLACE STOVE IN OPEN MODE
- KENT = KENT TILE FIRE
- CONV = CONVENTIONAL AIRTIGHT

FIGURE 7-6. COMBUSTIBLES.

MAIN LOADS - OREGON AVERAGES

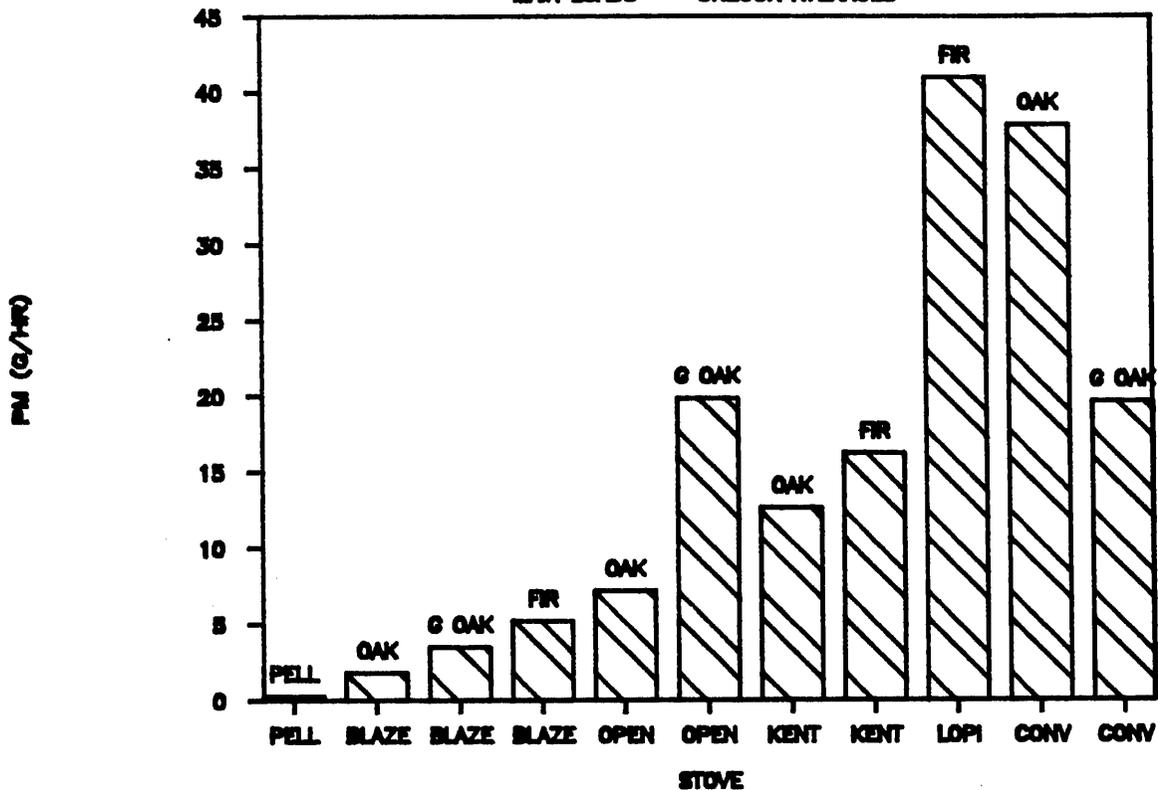


KEY:

- G OAK = GREEN OAK
- PELL = PELLEFIER
- BLAZE = BLAZE KING
- OPEN = FIREPLACE STOVE IN OPEN MODE
- KENT = KENT TILE FIRE
- CONV = CONVENTIONAL AIRTIGHT

FIGURE 7-7. PM EMISSION RATE.

MAIN LOADS - OREGON AVERAGES

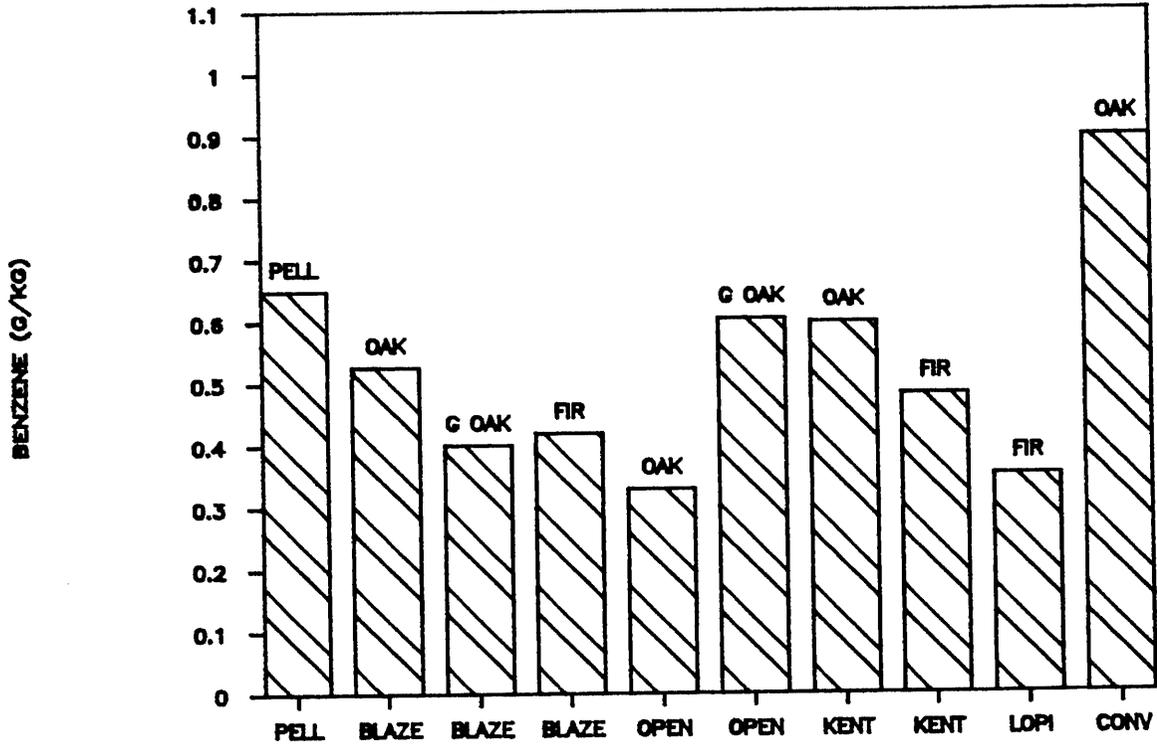


KEY:

- G OAK = GREEN OAK
- PELL = PELLEFIER
- BLAZE = BLAZE KING
- OPEN = FIREPLACE STOVE IN OPEN MODE
- KENT = KENT TILE FIRE
- CONV = CONVENTIONAL AIRTIGHT

FIGURE 7-8. BENZENE FACTORS.

COLD TO COLD - OREGON AVERAGES

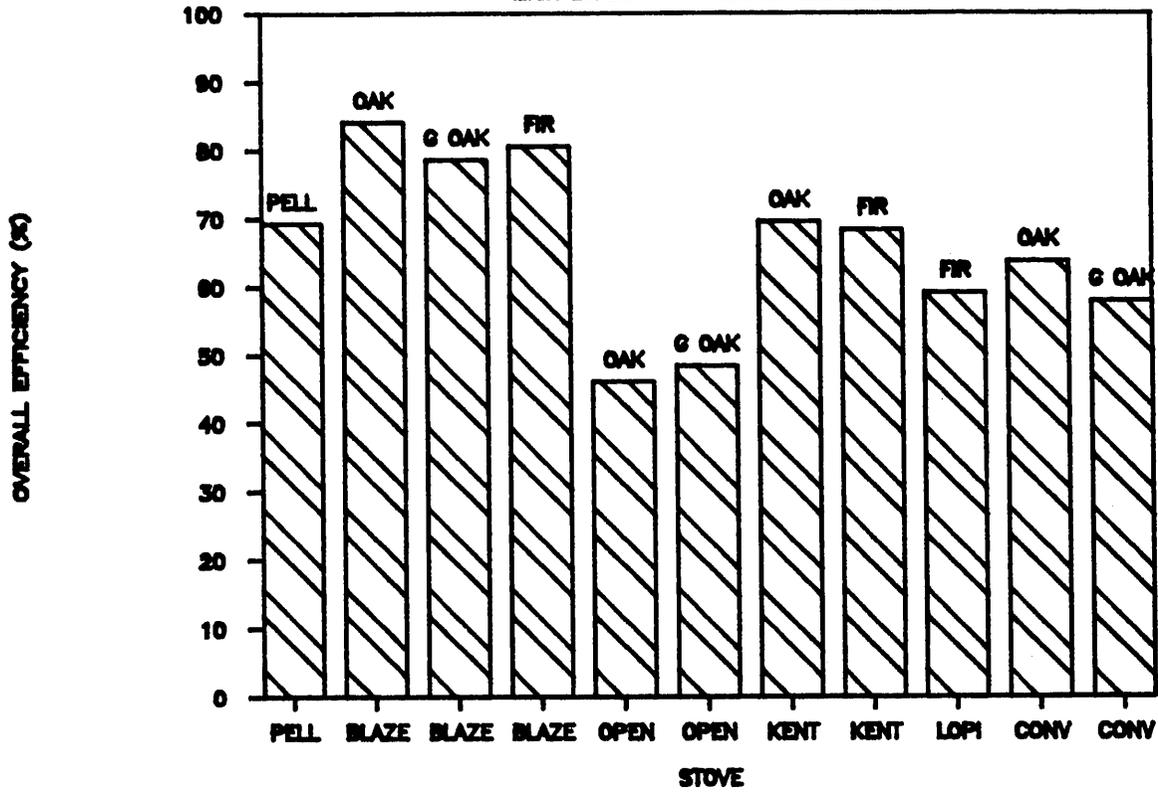


KEY:

- G OAK = GREEN OAK
- PELL = PELLEFIER
- BLAZE = BLAZE KING
- OPEN = FIREPLACE STOVE IN OPEN MODE
- KENT = KENT TILE FIRE
- CONV = CONVENTIONAL AIRTIGHT

FIGURE 7-9. OVERALL EFFICIENCY.

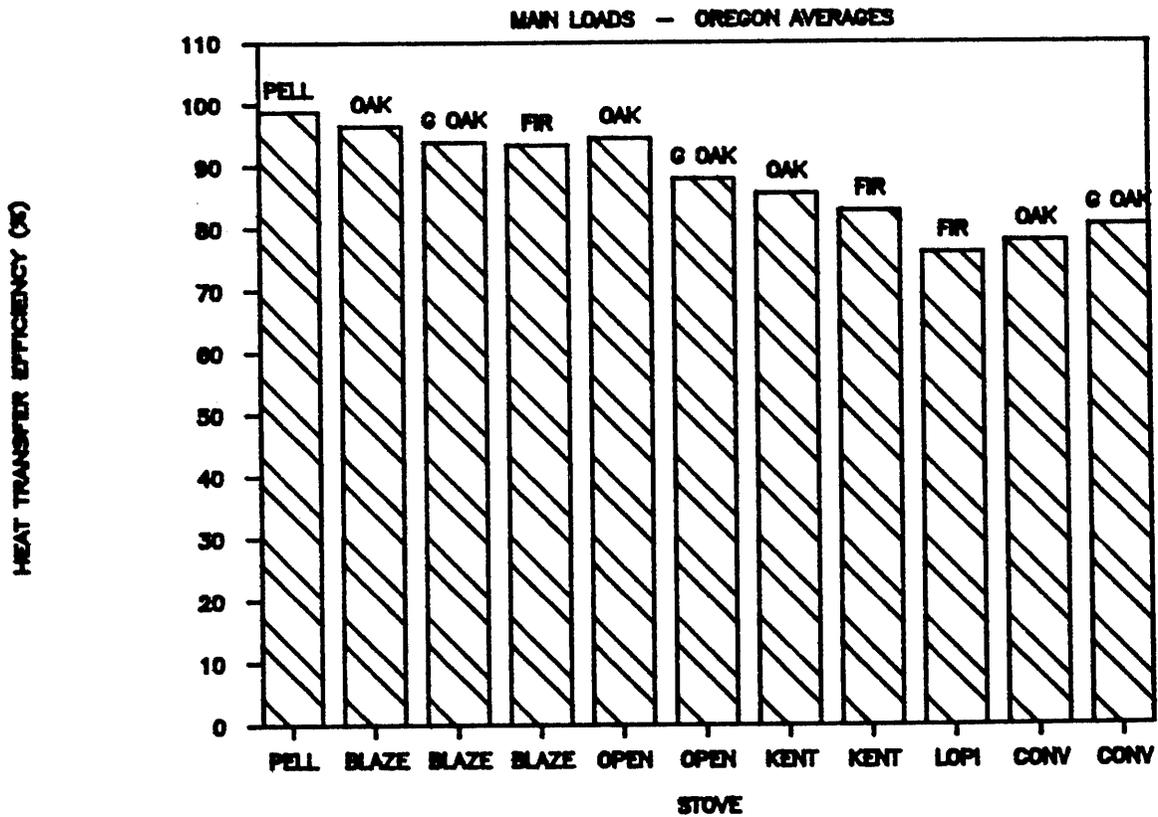
MAIN LOADS - OREGON AVERAGES



KEY:

- G OAK = GREEN OAK
- PELL = PELLEFIER
- BLAZE = BLAZE KING
- OPEN = FIREPLACE STOVE IN OPEN MODE
- KENT = KENT TILE FIRE
- CONV = CONVENTIONAL AIRTIGHT

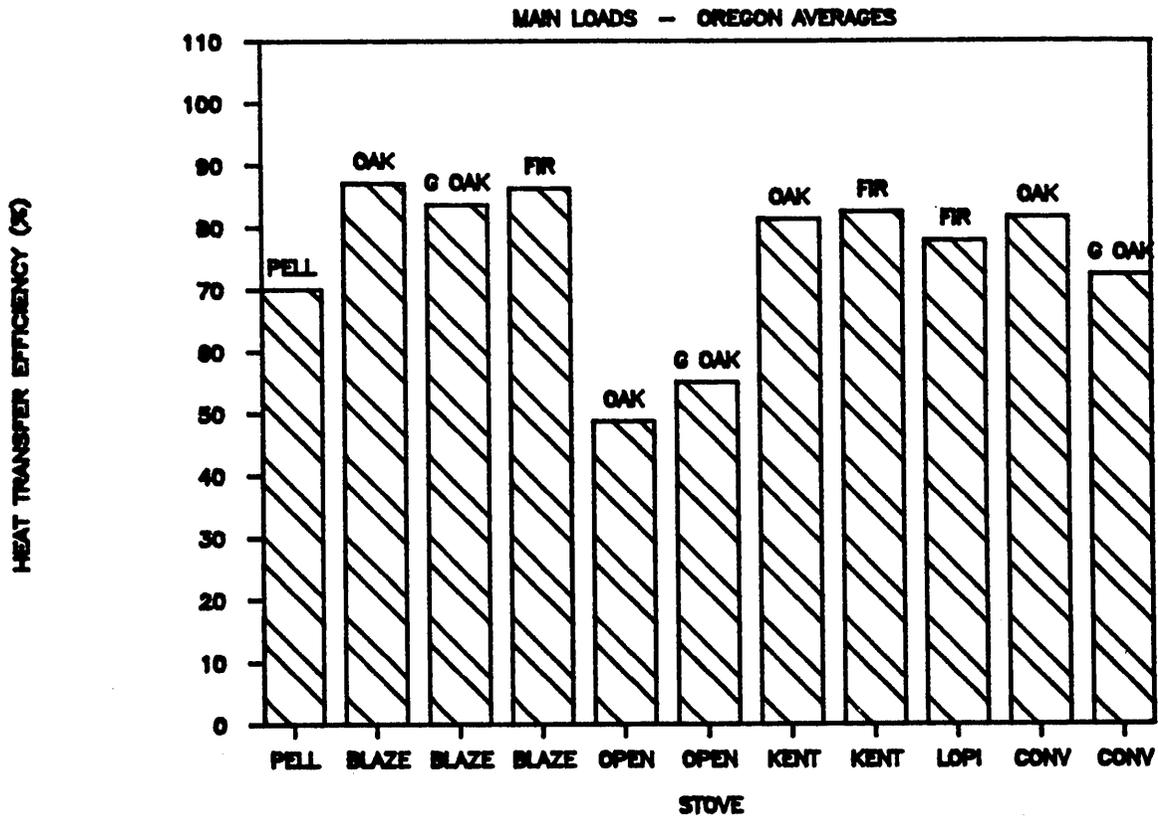
FIGURE 7-10. COMBUSTION EFFICIENCY.



KEY:

- G OAK = GREEN OAK
- PELL = PELLEFIER
- BLAZE = BLAZE KING
- OPEN = FIREPLACE STOVE IN OPEN MODE
- KENT = KENT TILE FIRE
- CONV = CONVENTIONAL AIRTIGHT

FIGURE 7-11. HEAT TRANSFER EFFICIENCY.



KEY:

- G OAK = GREEN OAK
- PELL = PELLEFIER
- BLAZE = BLAZE KING
- OPEN = FIREPLACE STOVE IN OPEN MODE
- KENT = KENT TILE FIRE
- CONV = CONVENTIONAL AIRTIGHT

Although the pellet burner had the lowest emissions of CO, PM, HC, PAH and combustibles, it had high emissions of NOx (Figure 7-2). The catalytic stove also had NOx emissions which were comparable to those from the other appliances burning the same fuel. There was no clear evidence that the catalytic stove produced significantly more NOx than the non-catalytic stoves.

At high burn rates, most of the advantage of the tested catalytic stove over the non-catalytic chunk-wood stoves lessens. CO emissions rates for both catalytic and non-catalytic stoves with oak as the fuel approach one another as do PM emissions rates with fir as the fuel. For some other emissions/fuel combinations, the catalytic system retains an advantage. These trends, however, should not necessarily be taken as representing the potential relative performance among various design types.

Energy Efficiencies

The highest Oregon weighted overall energy efficiency, a little over 80%, (Figure 7-9), was achieved by the Blaze King catalytic stove. This was achieved via a relatively high combustion efficiency of about 95% (Figure 7-10) and relatively high heat transfer efficiency of about 86% (Figure 7-11).

The Pellefier pellet burner had a higher combustion efficiency (about 99%) but its relatively low heat transfer efficiency in the 70's resulted in an overall energy efficiency in the 70's. The open fireplace stove had the lowest overall energy efficiency --a little under 50%. However, its combustion efficiency was significantly higher than that of any of the non-catalytic chunk wood stoves due to the unrestricted air supply and high minimum burn rate.

Both the Lopi insert and the Kent achieved a reasonably high combustion efficiency at the medium and high burn rates (Figure 7-12), but the Lopi's relatively high excess air levels (Figure 7-13) resulted in relatively low heat transfer efficiencies (Figure 7-14) and hence overall efficiencies (Figure 7-15) less than the Kent's. (See Table 7-1 for explanation of symbols plotted in these graphs.)

The difference between green and seasoned oak at medium burn rates in the conventional airtight stove was dramatic. For the green oak, the highest burn rate achievable was substantially lower than for seasoned oak. Even with the air inlet wide open, the moisture in the fuel slowed the maximum burn rate to about 1.9 kg/hr. Interestingly, the combustion efficiency (Figure 7-12) was the same for seasoned oak at the same burn rate. The substantially lower overall efficiency (Figure 7-15) was therefore not due to poor combustion (as is borne out by the emissions data) but rather to poor heat transfer. (Compare Figures 7-10 and 7-11.) All the extra air needed to keep green wood burning tends to carry more of the heat up the flue. In addition, there is a higher latent heat loss due to higher moisture content of the fuel.

A somewhat similar effect is seen for the three fuels burned in the Blaze catalytic stove. At medium and high burn rates, the overall energy efficiency decreases dramatically in going from fir to seasoned oak to green oak. In this case decreasing combustion efficiency is a significant

COMBUSTION EFFICIENCY (%)

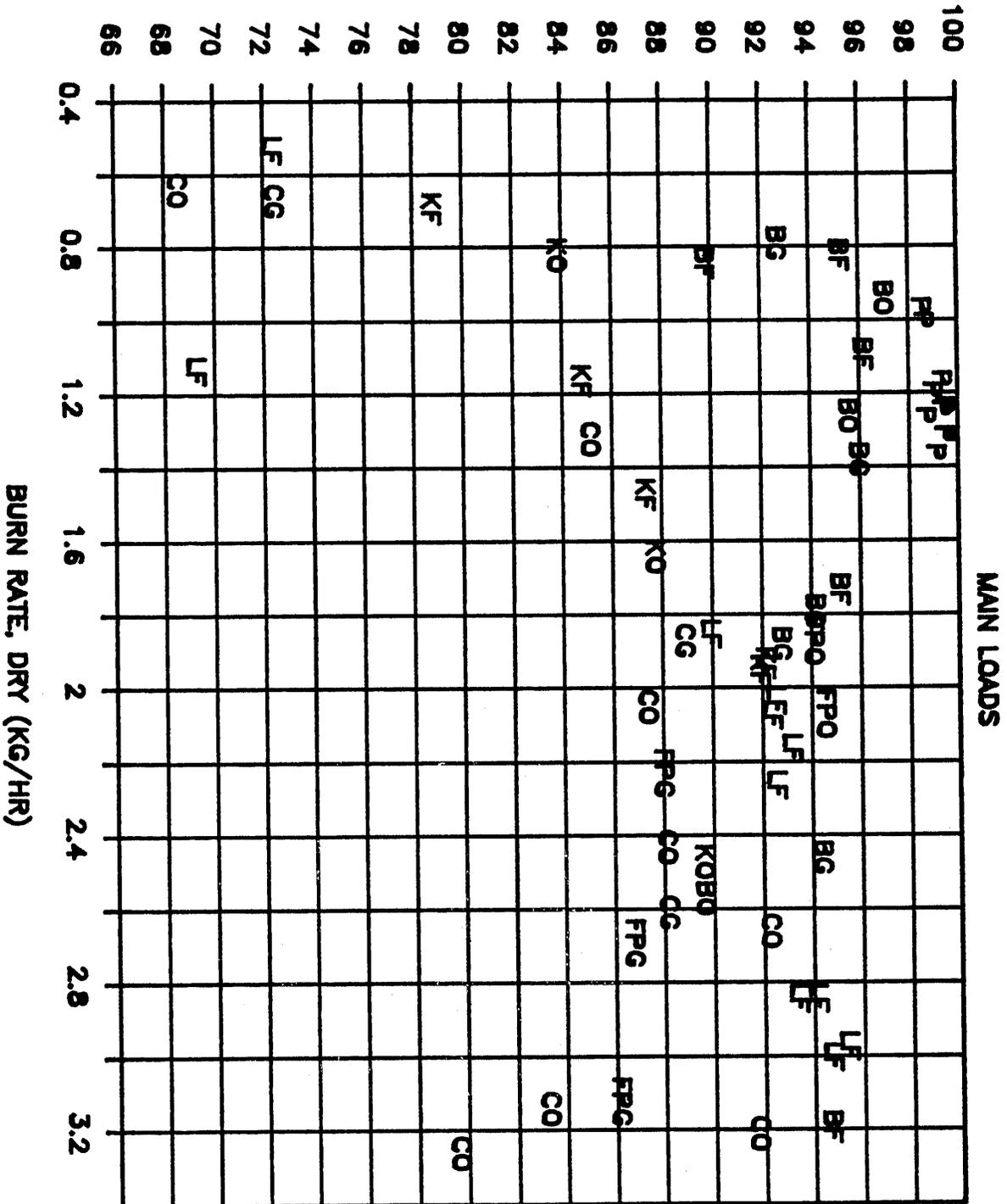


FIGURE 7-12. COMB. EFFIC. VS BURN RATE

HEAT TRANSFER EFF (%)

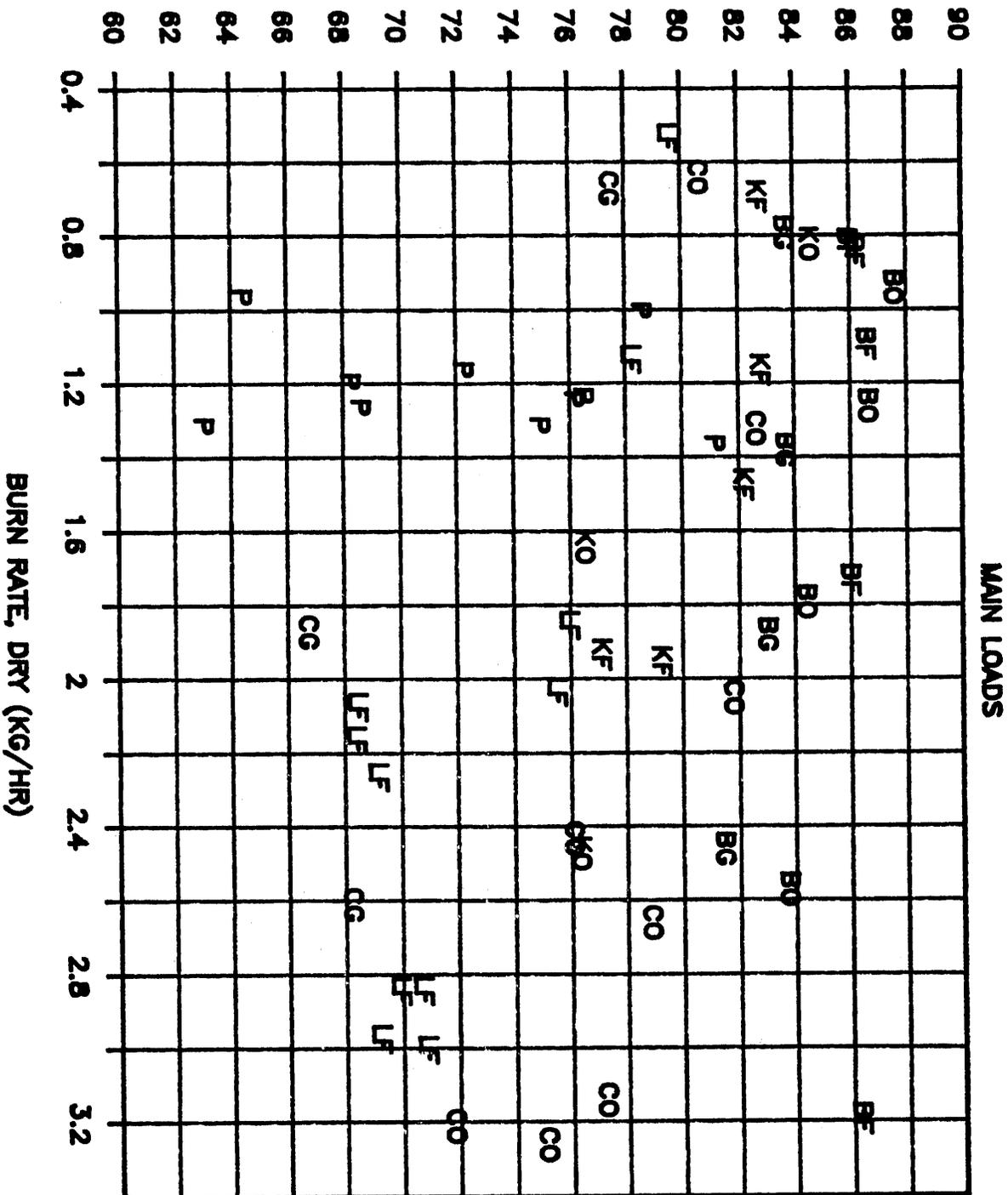
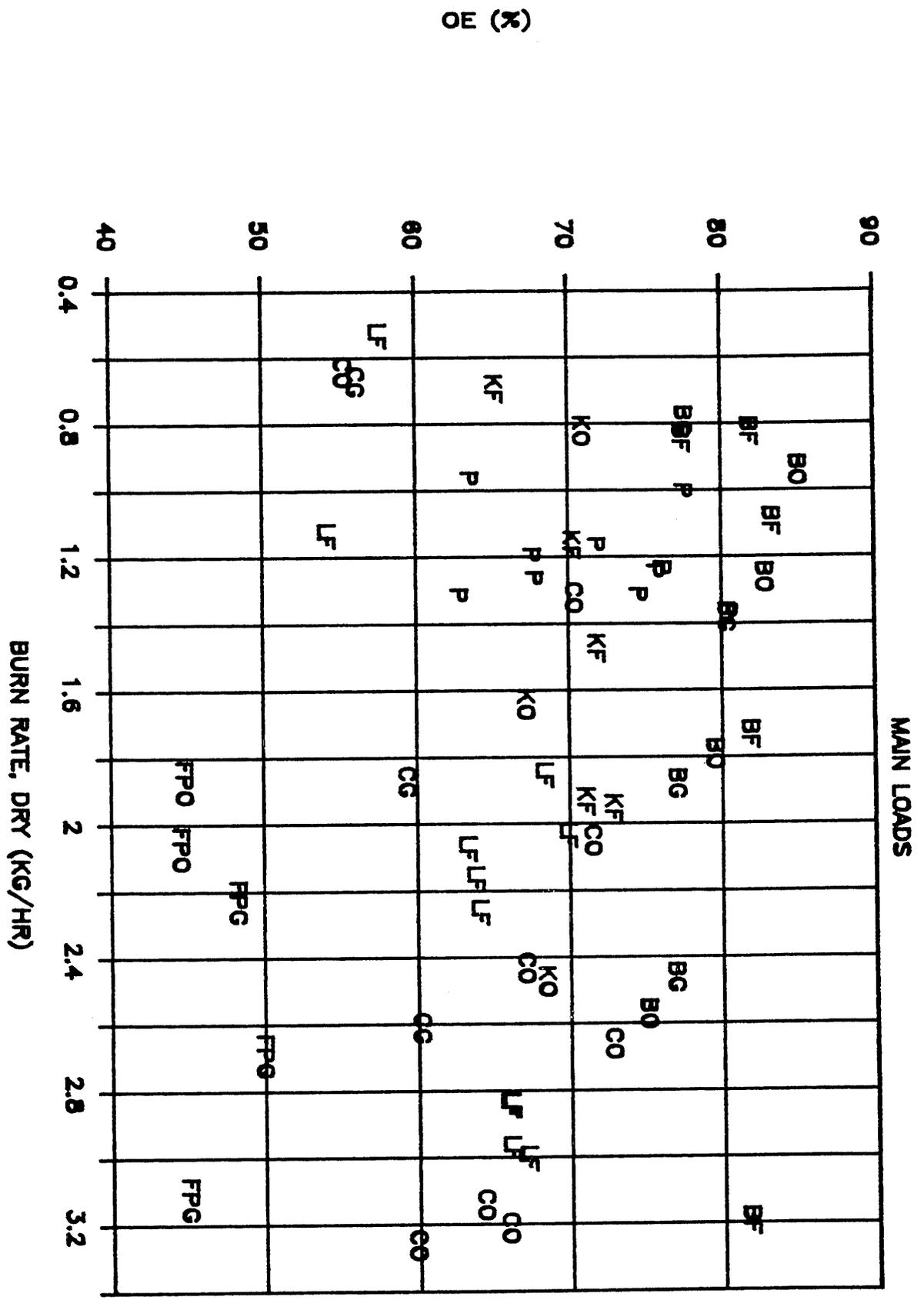


FIGURE 7-15. OVERALL EFF. VS BURN RATE



part of the effect, but so is decreased heat transfer, particularly for the green oak. The decreased heat transfer for the green oak is again due in part to the extra latent heat loss, and in part to the extra sensible heat loss related to higher excess air needed to get green fuels to burn.

Creosote

Measured creosote accumulation in the flue of individual tests ranged from less than 0.2 g/kg (the limit of detectability) to 10g/kg (Figure 7-16).

For all appliance/fuel combinations, the creosote factor decreased with increasing burn rate. This burn rate dependence was most dramatic for the conventional airtight stove; the creosote factor was approximately 20 times greater for low burn rates than high. The very sudden decrease in creosote factor for the Kent, Lopi and conventional airtight at about 1.6 to 2.0 kg/hr is probably related to the change from predominantly smoldering combustion to predominantly flaming combustion.

The fuel dependence of creosote accumulation is not as dramatic. Given the amount of data and their scatter, one can only conclude that the upper limit of the fuel effect is on the order of a factor of 2 for the non-catalytic appliances and on the order of 20% for the catalytic stove. There is a suggestion of a much more dramatic effect at a burn rate of about 1.8 kg/hr in the conventional airtight stove; green oak appears to have resulted in 1/4 as much creosote as seasoned oak. This is consistent with previous studies on the effects of moisture content on creosote accumulation. ^{14, 15, 16} However, at lower burn rates emphasized by the Oregon weighting system, there is no pronounced fuel effect (Figure 7-17). This is also consistent with previous studies.¹⁴

The appliance dependence of creosote is dramatic. Creosote accumulation with Pellefier was below the limits of detectability for the two to four hour burn times used in the tests. The open stove's creosote accumulation was also very low (Figure 7-17). The catalytic stove produced less than one-third as much creosote as the Kent and Lopi and roughly one-seventh as much as the conventional airtight stove, based on Oregon weighted averaging over all burn rates. At the higher burn rates, the advantage of the catalytic stove for reducing creosote falls significantly.

The open stove's low creosote accumulation is due both to relatively high combustion efficiency and to its high excess air. Excess air tends to carry the smoke through the chimney and into the atmosphere.¹⁷

Elemental Carbon

In general, the fraction of particulate matter in the form of elemental carbon showed an increase with increasing burn rate for any stove/fuel combination. However, since the PM factor tends to decrease with increasing burn rate, the emission factor for elemental carbon is not very burn rate dependent.

CREOSOTE FACTOR (G/KG)

FIGURE 7-16. CREOSOTE VS BURN RATE

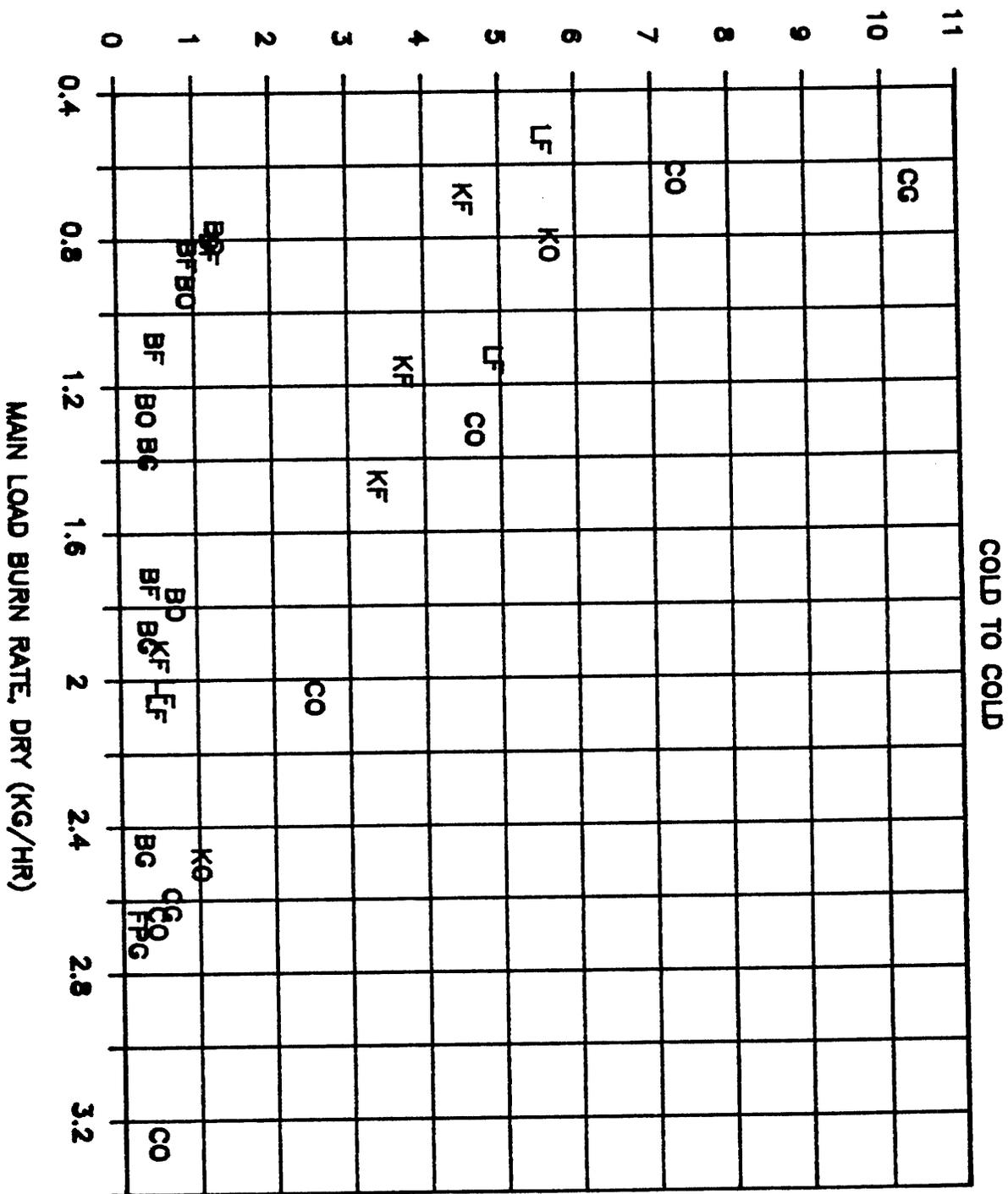
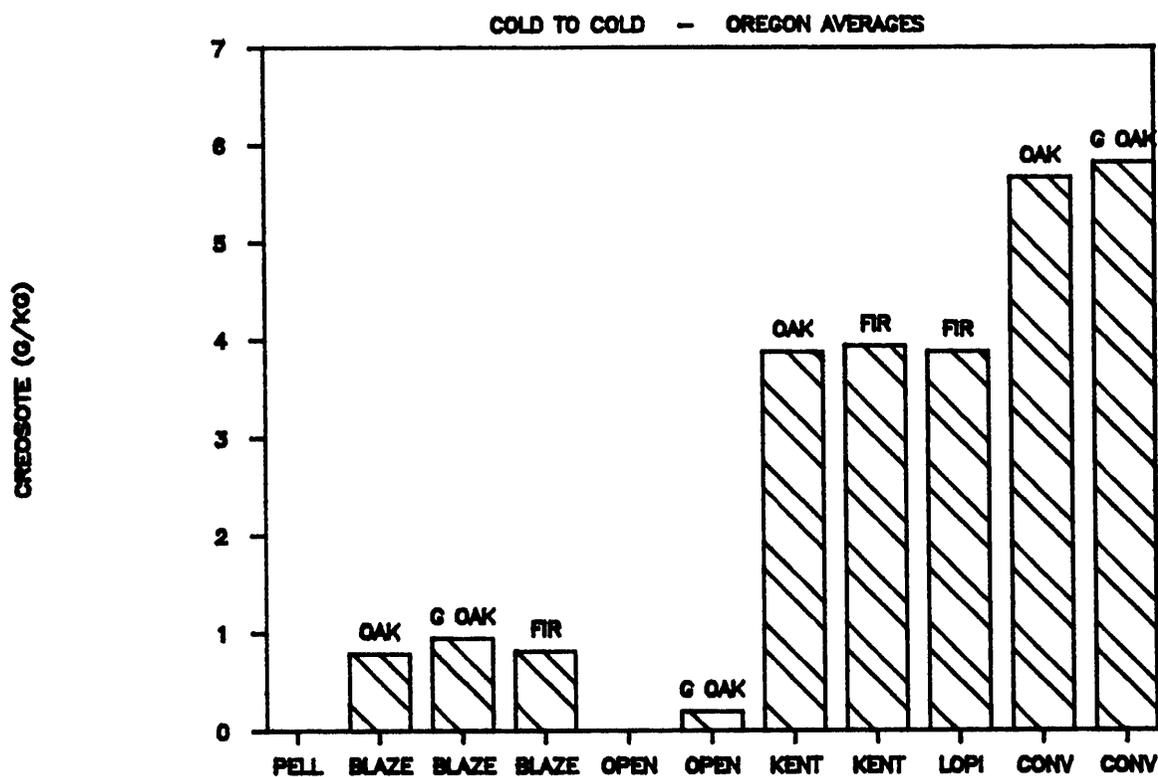


FIGURE 7-17. CREOSOTE FACTORS.



KEY:

- G OAK = GREEN OAK
- PELL = PELLEFIER
- BLAZE = BLAZE KING
- OPEN = FIREPLACE STOVE IN OPEN MODE
- KENT = KENT TILE FIRE
- CONV = CONVENTIONAL AIRTIGHT

Burn-Phase Dependence

The burn-phase dependence of emissions is strong and could have implications for emissions regulation. Total emissions in grams rather than emission factors (g/kg) or rates (g/hr) are appropriate in a discussion of burn phase dependence. The concept of emission rate is somewhat ambiguous when applied to a charcoal phase or cold-to-cold burn because the end point of these periods is arbitrary: the combustion rate gradually declines to zero over a period of up to 6 - 12 hours. Total emissions reflect the amount of fuel consumed, which tends to be less in kindling phases than in main loads. (The mass of fuel burned during the kindling phases was roughly one-half that of a main load). Kindling phase durations were usually between 0.25 and 1.5 hours.

The burn phase data for PM are plotted in Figure 7-18 in decreasing order of total PM from the main load phases. Hence the more conventional technologies tend to be on the left side of the graph, and the catalytic and pellet burner results are mostly on the right half of the plot. Directly above and/or below the main load PM symbol (a square) is plotted total PM for the corresponding kindling (K) and charcoal (C) phases. (Where a cold-to-cold test had more than one main load the kindling and charcoal phase results are plotted only for the first main load; hence some main loads have no plotted symbol corresponding to the kindling and charcoal phases. Also, there is no charcoal phase corresponding to the pellet burner tests.)

With the exception of the pellet burner, kindling phases tend to emit roughly the same amount of PM, independent of appliance design. This is to be expected since all the stoves start cold, and secondary combustion systems (catalytic or otherwise) do not start to work until the stove has warmed up. All catalytic and most non-catalytic stoves have a bypass damper. When the bypass is open, the gases do not pass through the combustor or secondary combustion chamber. The damper is open during the kindling phase and often at the beginning of each fuel addition. This is necessary to warm up the combustion system so it will work properly.

For all but the catalytic and pellet appliances, kindling phase total PM tends to be less than or equal to main load PM. For the catalytic stove, the kindling phase contribution was nearly always larger than that from a main load, ranging from approximately 2 to 5 times larger. This means that a regulation based on main load performance only (as is the case in Oregon and Colorado) will underestimate relative and absolute emissions from catalytic systems in the field unless most users of catalytic systems keep the fire going (with combustor engaged) most of the time. If there is more than one restarting of the fire for each day or two of operation, these restarts can dominate the total PM emissions.

The pellet burner was unique in that its total particulate emissions during its ignition and warm-up phase were nearly as low as during its steady-state operation.

For CO and HC emissions, the kindling phase contribution was usually less than a main load contribution (Figures 7-19 and 7-20). Hence the kindling phase does not usually contribute a disproportionate share to CO and HC emissions. The same is true for NO_x (Figure 7-21).

FIGURE 7-18

PHASE DEPENDENCE OF PARTICULATE MATTER

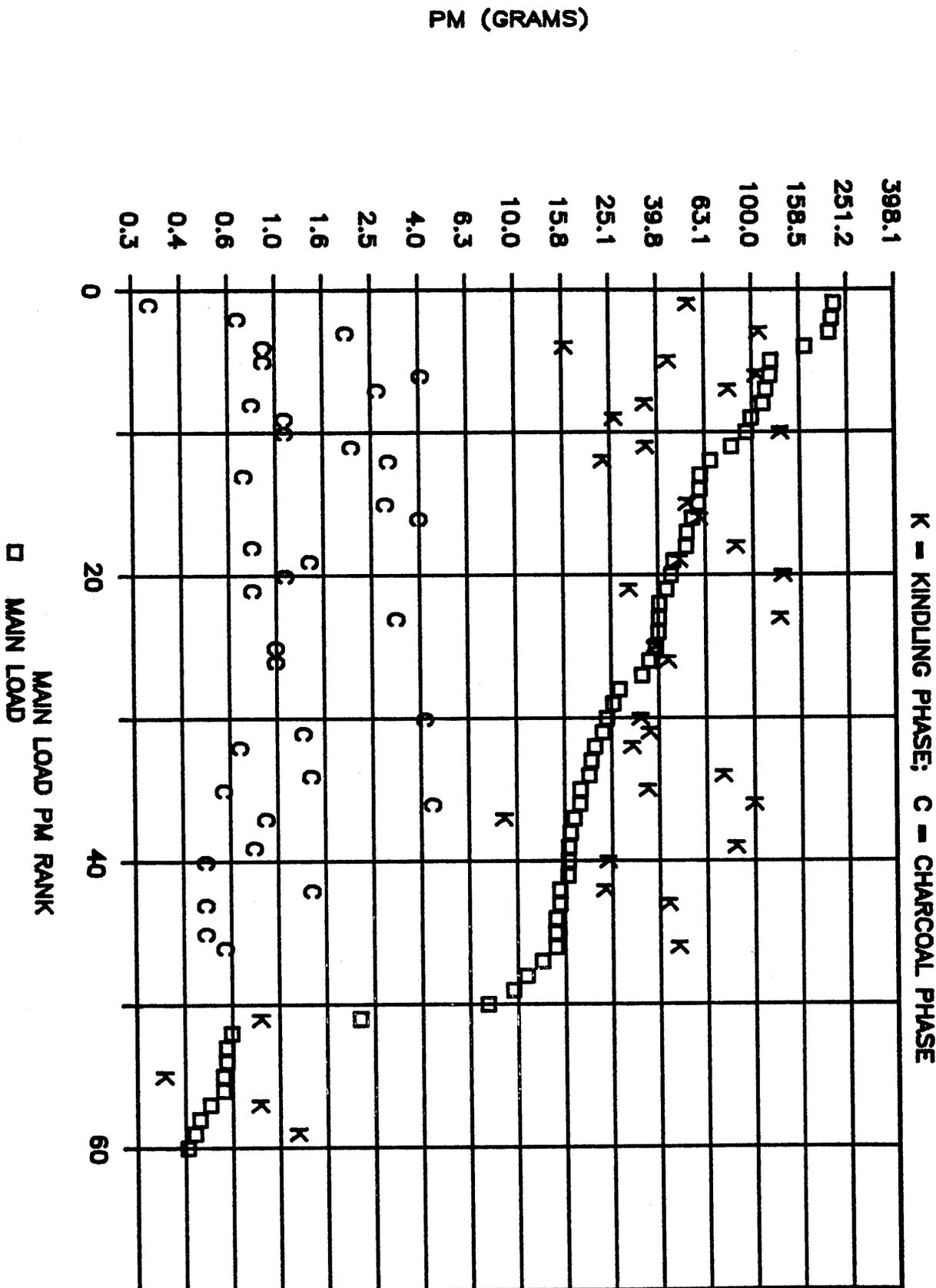


FIGURE 7-19

BURN PHASE DEPENDENCE OF CO

K = KINDLING PHASE; C = CHARCOAL PHASE

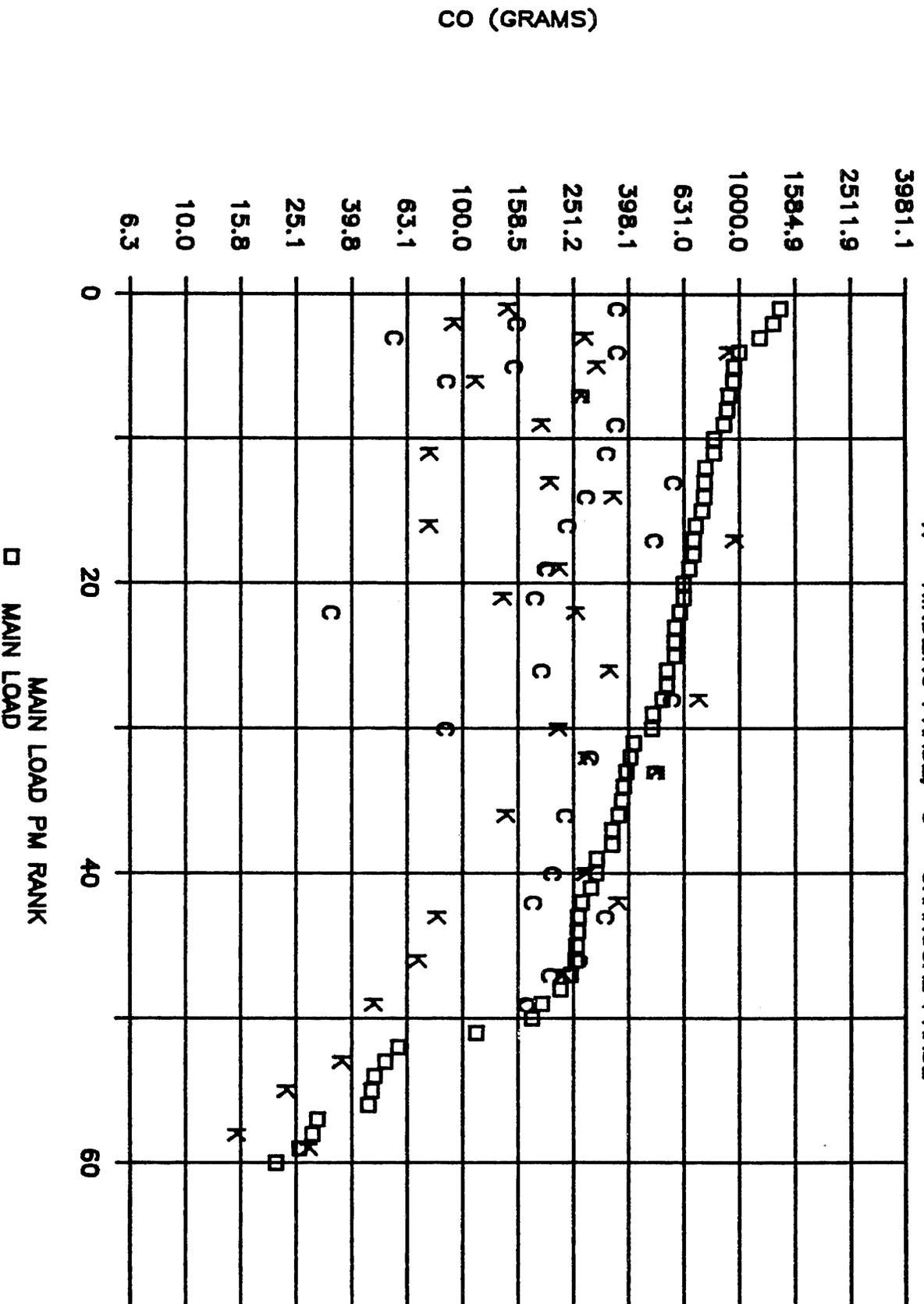


FIGURE 7-20

BURN PHASE DEPENDENCE OF HC

K - KINDLING PHASE; C - CHARCOAL PHASE

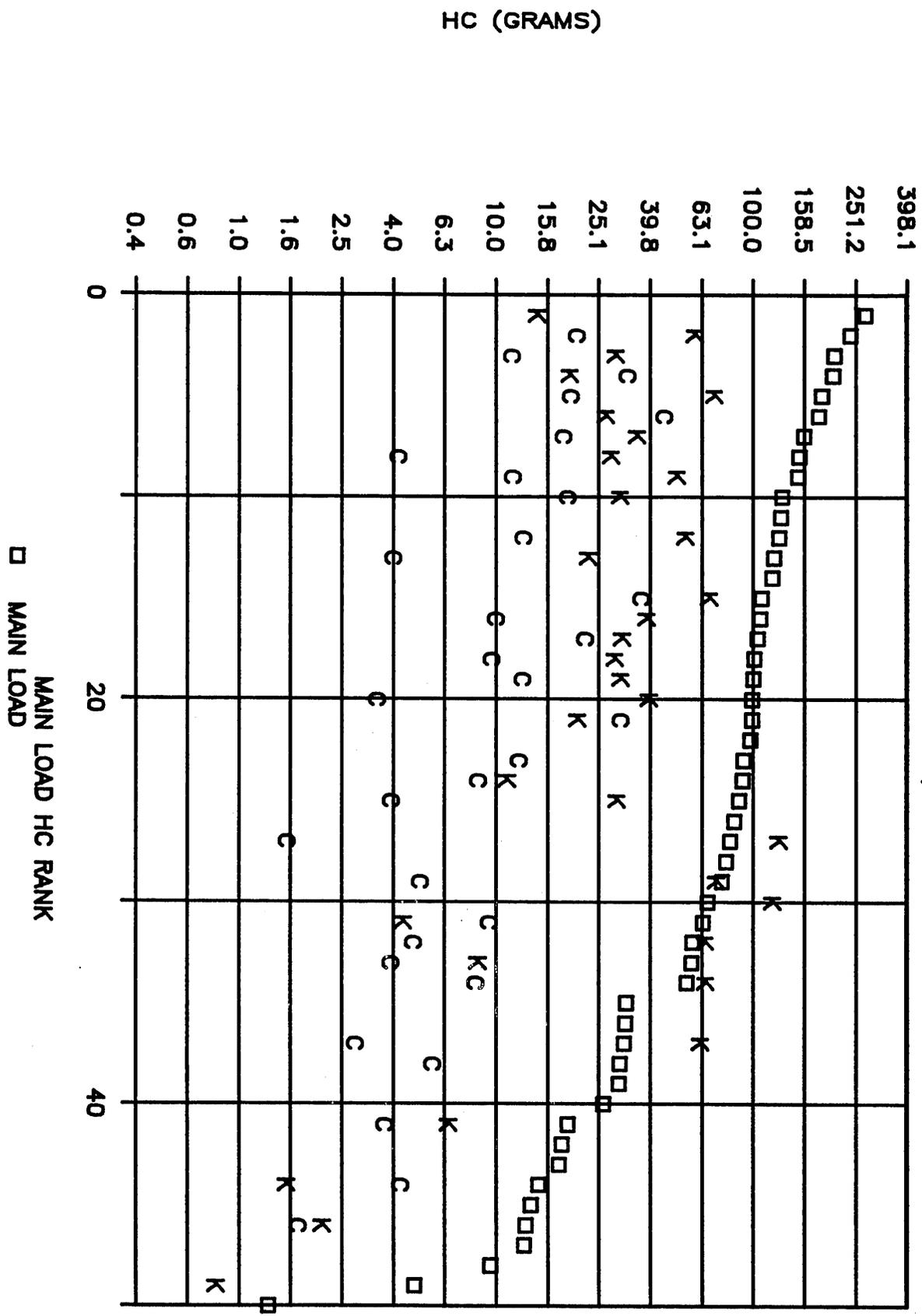
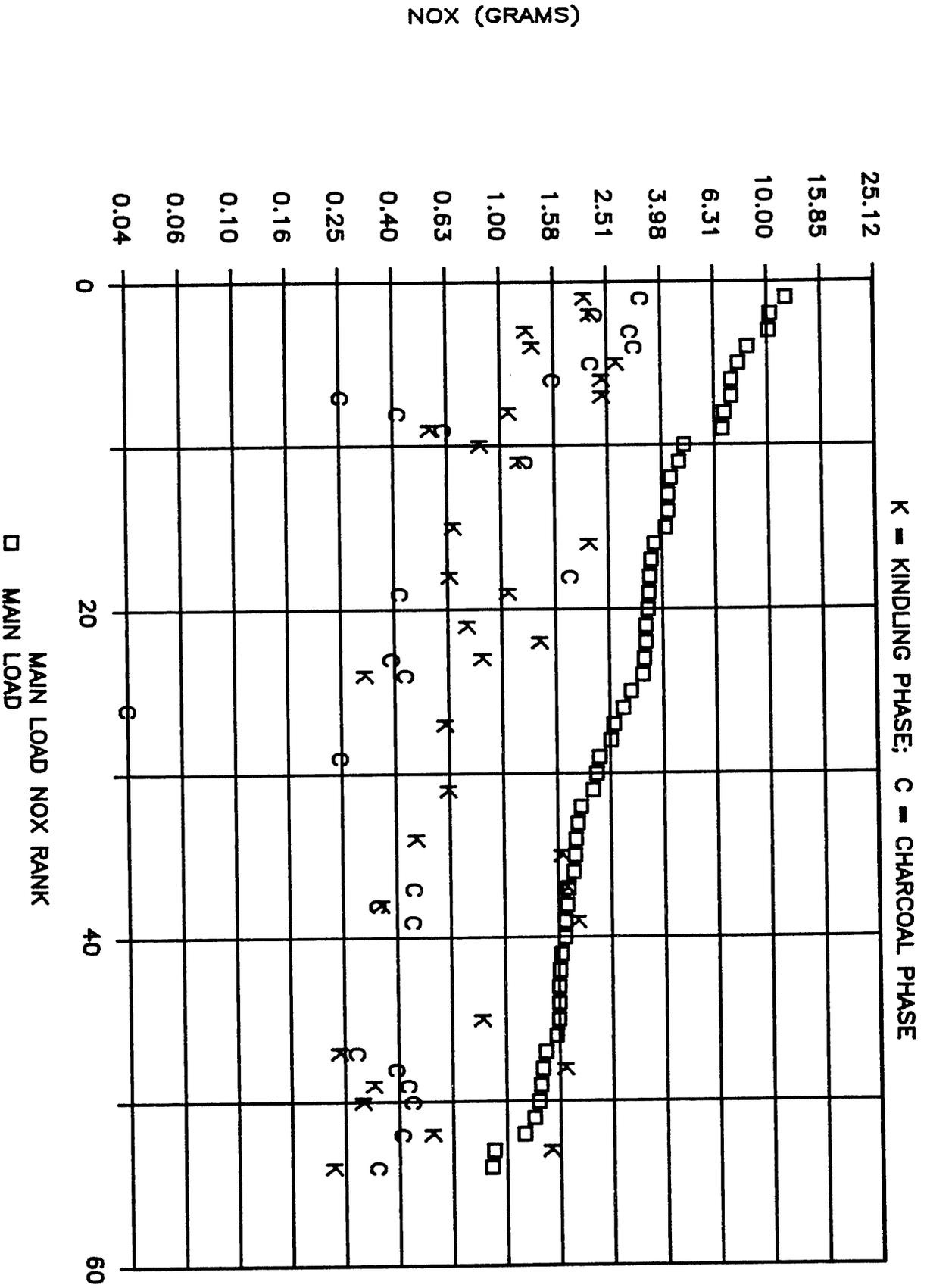


FIGURE 7-21

BURN PHASE DEPENDENCE OF NOX



Charcoal phases contribute very little to total emissions. Total PM emitted during the charcoal phase averages less than 5% of PM emitted during main load phases. The charcoal phase contribution of CO, HC and NOx was also much smaller than main load contribution.

The burn phase dependence of benzene, PAH's and creosote were not measured; for these emittants one integrated sample was obtained for each entire cold-to-cold test.

Correlations Among Emissions

The relation between PM and CO emissions is shown in Figure 7-22. The correlation is strong. The dynamic range for both parameters exceeds a factor of 200. The scatter in the relationship is on the order of a factor 3, only 1 to 2% of the dynamic range.

A comparison of HC to CO (Figure 7-23) also reveals appliance/fuel effects. Most of the Kent/fir and Lopi/fir tests fall in a small group somewhat apart from the other tests. These are the two non-catalytic advanced technology chunk-wood burners. Both CO emissions and HC emissions tend to be constant, independent of burn rate. The points representing the other appliance/fuel types are spread out over a much wider area in the graph. It is also apparent from the distribution of points in the graph that use of oak results in a higher ratio of HC to CO.

There is a reasonably good correlation between creosote and PM (Figure 7-24). This is not unexpected. As a consequence, a program regulating particulate emissions will also reduce creosote accumulation and hence reduce chimney fires.

At first glance the correlation between total PAH and PM does not appear to be very good (Figure 7-25). However, the lack of strong correlation is to be expected theoretically. In a three dimensional plot with an additional parameter, the correlation would be much higher.

It has been pointed out by Ray Merrill (private communication) that PAH production requires a threshold temperature. Below that temperature there is not much production of PAHs. Above the threshold temperature PAHs can be formed in larger quantities. At still higher temperatures, PAHs may be burned or modified.

Applying this notion to the data is difficult since there is no well defined combustion temperature in a wood stove. Temperature gradients are very large, particularly in non-catalytic systems. However, for a given appliance, combustion temperatures will increase with increasing burn rate.

The effect of burn rate on the relation between PAH and PM emissions is illustrated in Figure 7-26. The point labels inside the graph are a burn rate ranking for each appliance/fuel combination. For each appliance/fuel combination, the number 1 indicates the lowest burn rate and the number 9 the highest. Intermediate burn rates are uniformly distributed between 1 and 9. For each appliance/fuel combination, there is a tendency for the burn rate sequence to move from the lower right to the upper left. Low burn rates tend to be to the lower right of where a best linear fit through the origin to all the data would lie, and higher burn

FIGURE 7-22. CO RATE VS PM RATE.

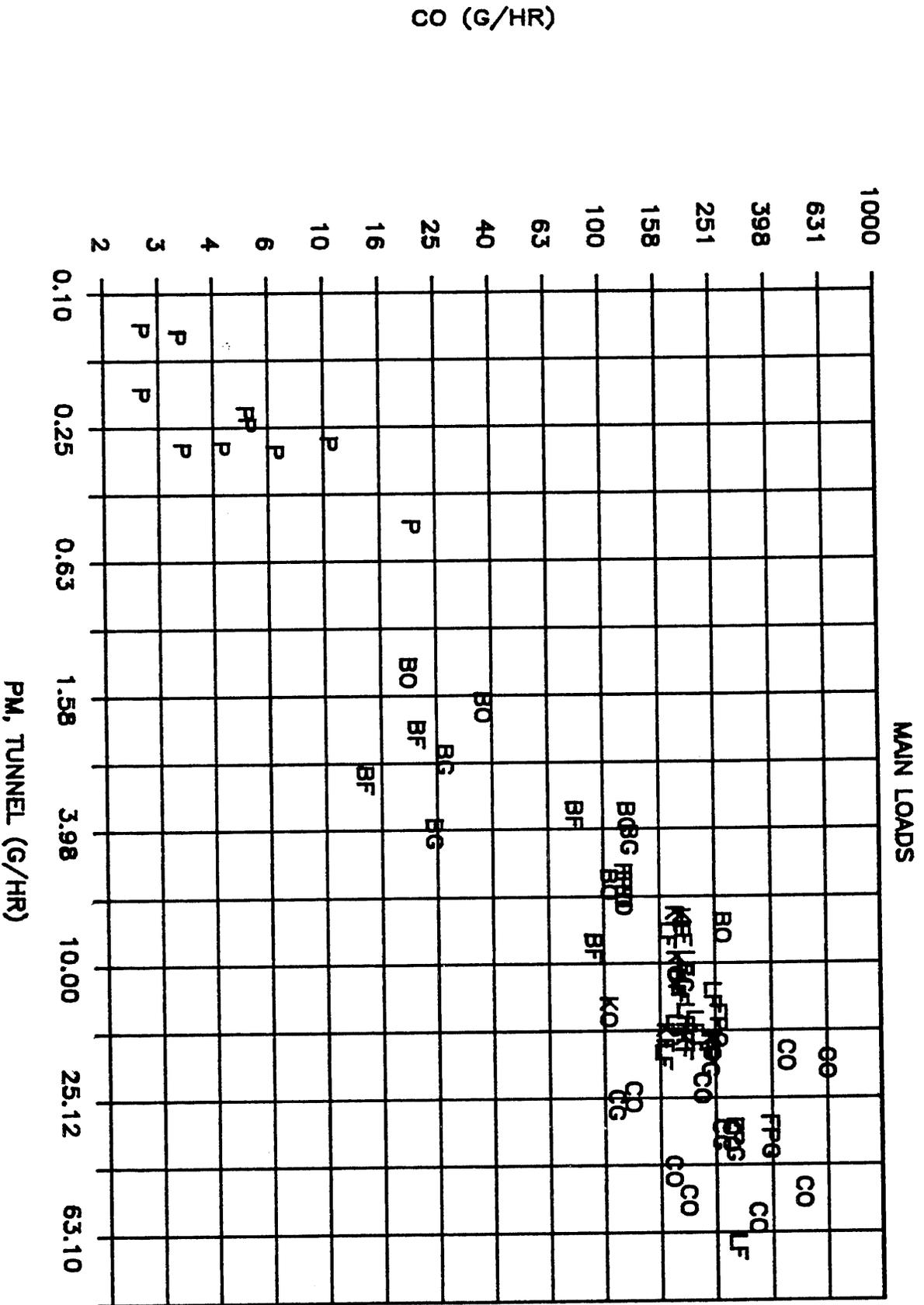


FIGURE 7-25. PAH VS PM.

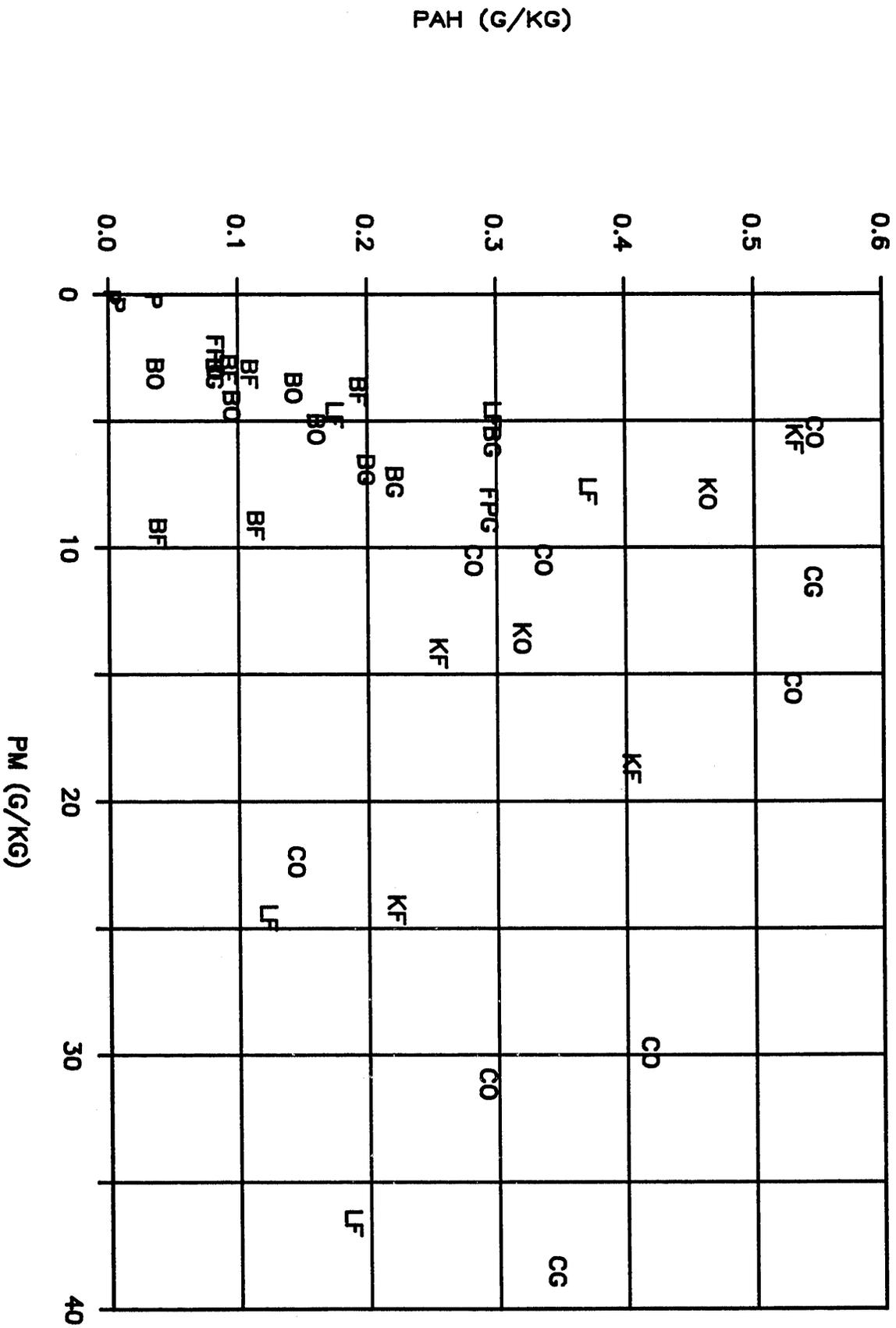


FIGURE 7-26. PAH VS PM, BURN RATE RANK

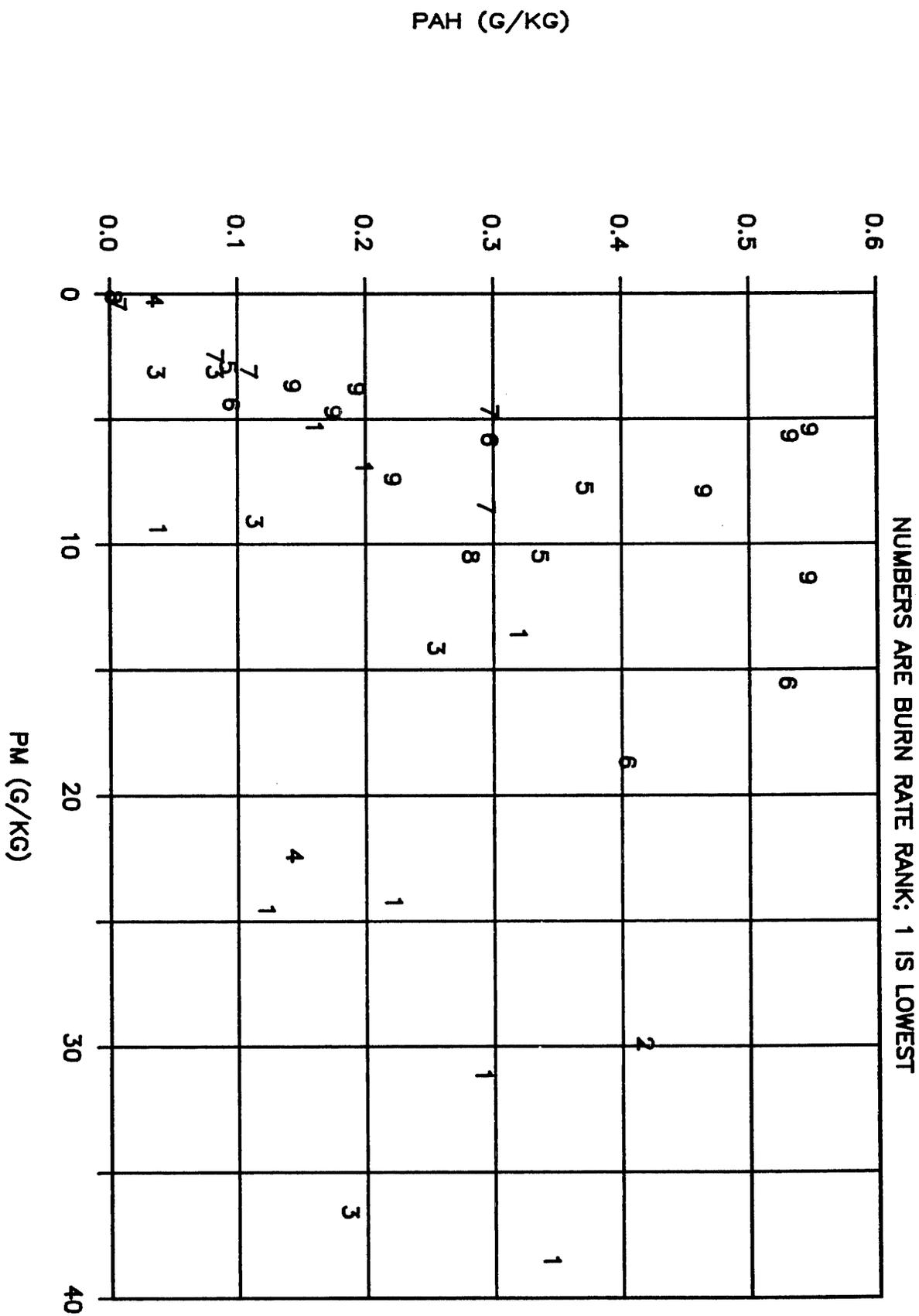


FIGURE 7-27. BENZENE VS PM.

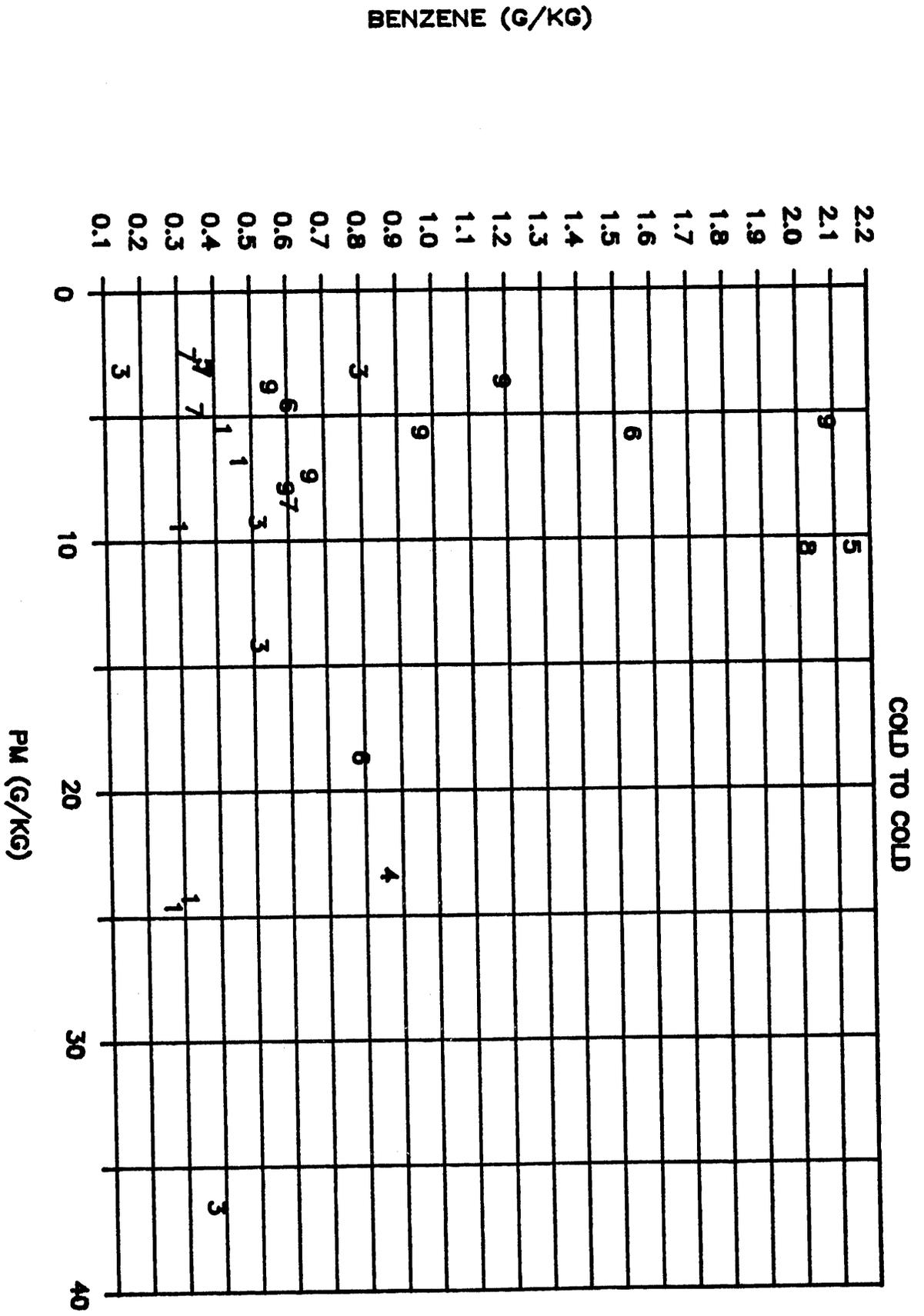
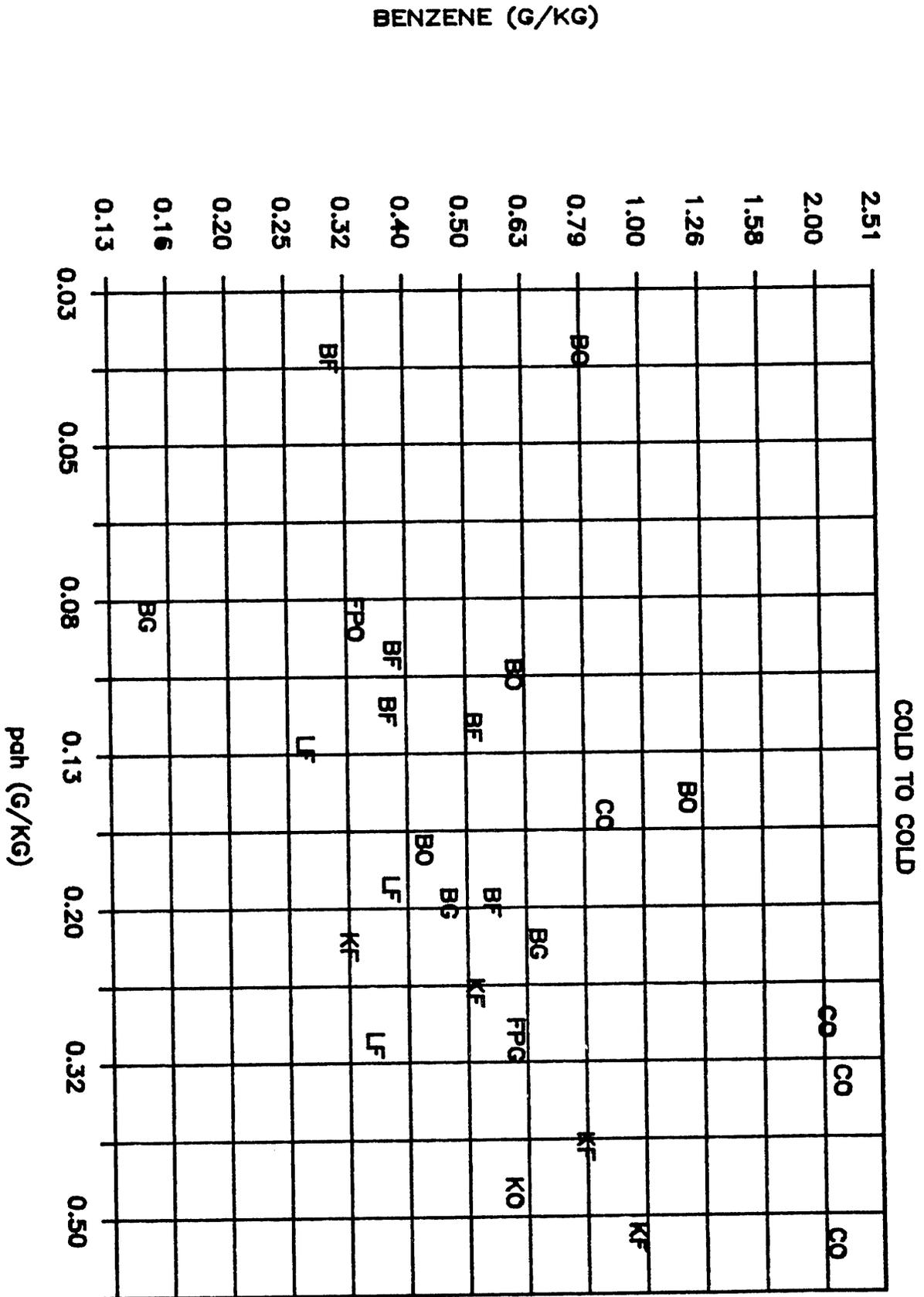


FIGURE 7-28. BENZENE VS PAH.



rates tend to be to the upper left. The flameless smoldering fires characteristic of low burn rates generate large amounts of PM, but the temperatures are too low to generate correspondingly large amounts of PAH. The flaming combustion characteristic of high burn rates tends to destroy PM but can provide the higher temperatures necessary for efficient formation of PAH.

The correlation of benzene with PM also appears to have considerable scatter (Figure 7-27). However, the distribution of points in the graph again has a correlation with burn rate rank and hence combustion temperature. There is a preponderance of high rank burn rates in the upper left corner of the graph.

The fact that both PAHs and benzene are correlated to PM in this way suggests a correlation between the two. In fact the correlation is quite good for any single fuel/appliance combination (Figure 7-28). Thus a standard limiting benzene also limits PAHs and vice versa.

Test Methods Comparisons

Efficiencies

A number of emissions and efficiency parameters were determined by different methods. Comparison of the results reveals some interesting differences.

Energy efficiencies and power outputs were determined by two methods, the standard Oregon indirect flue loss method⁶ and a version of the direct flue loss methods being developed by DOE¹⁸. Comparison of the results indicates basic agreement on overall trends but with some differences in the numerical values.

Measured power outputs (Figure 7-29) agree moderately well, but with direct loss powers tending to be slightly higher by an average of about 10%. This is consistent with the fact that the direct loss overall energy efficiency (Figure 7-30) tends to be higher than the Oregon efficiency by approximately the same amount. Since the heat transfer efficiencies are in relatively good agreement (Figure 7-31), it is the difference in combustion efficiencies (Figure 7-32) by the two methods which is the "source" of the differences in power output and overall energy efficiency. The direct loss method indicates a higher combustion efficiency by up to about 10 percentage points, with the biggest effect occurring for the cleanest burning stoves. (The two pellefier Oregon combustion efficiencies at about 84% appear to be anomalous, as are the corresponding Oregon overall efficiencies for these two tests -- numbers 38 and 39.)

Since both methods yield essentially the same CO emissions the difference in combustion efficiency is due to differences in the non-CO contributions to products of incomplete combustion. In the Oregon algorithm this component is assumed to be methane and is computed from an assumed combustion equation. In the direct stack loss method used in this project, the non-CO combustibles are based on measured PM (tunnel filter), measured low molecular weight hydrocarbons (FID), and approximate creosote accumulation (based on an average of measured creosote). Heating values for these contributions have been estimated, not measured, in this project

OREGON OVERALL EFFICIENCY (%)

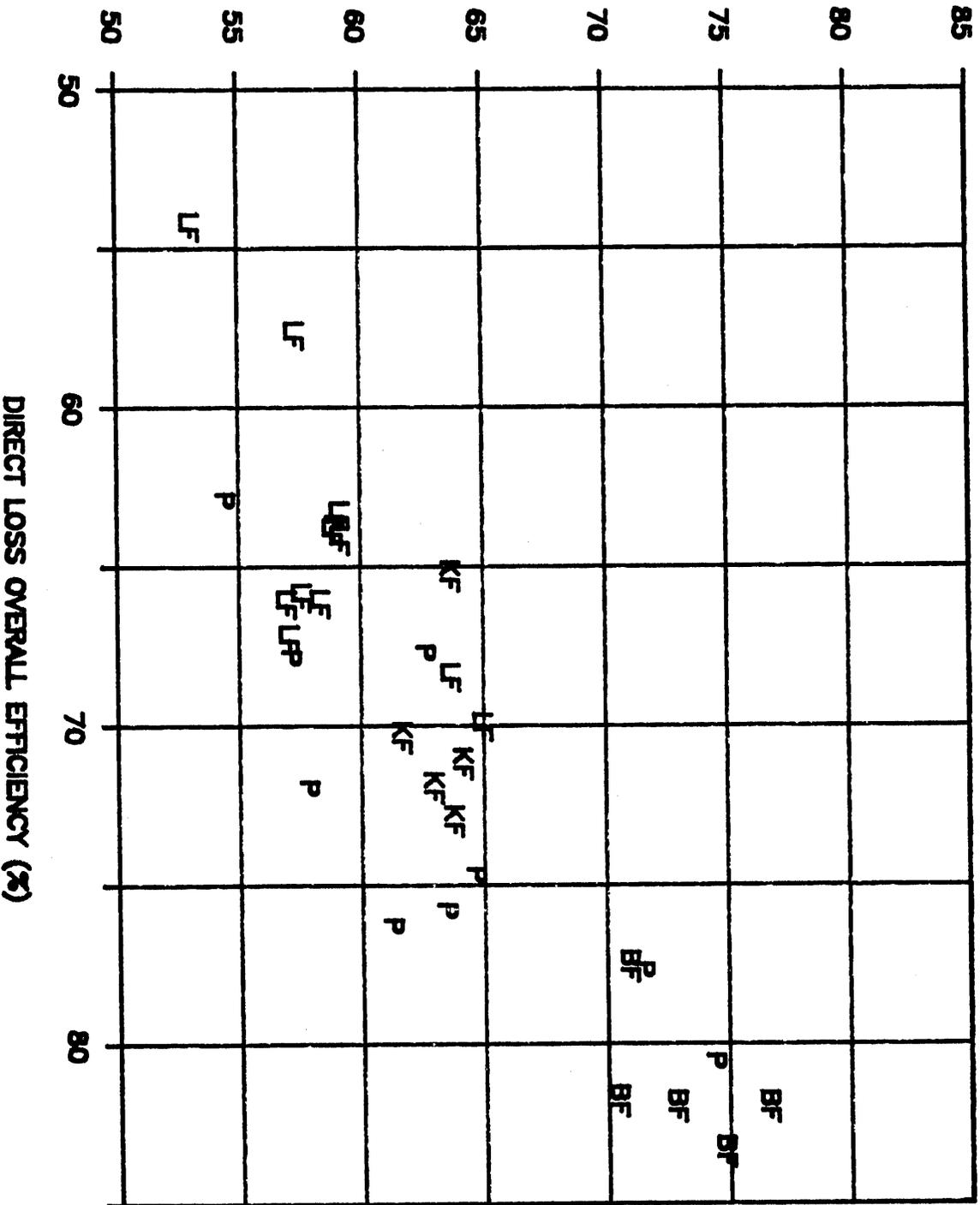


FIGURE 7-30. OVERALL EFFICIENCY
OREGON FUEL COMPOSITION

OREGON COMBUSTION EFFICIENCY (%)

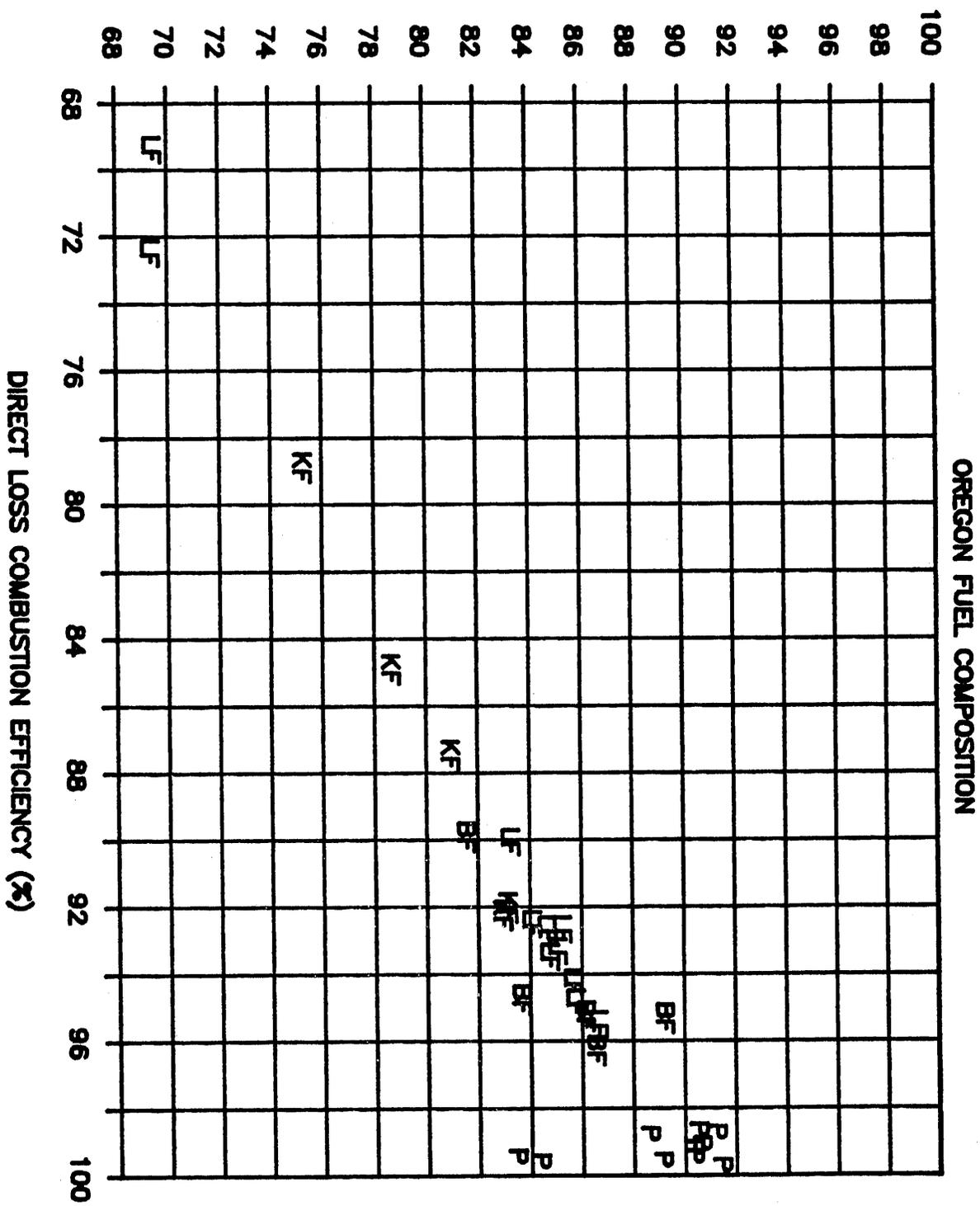


FIGURE 7-32. COMBUSTION EFFICIENCY

OREGON FUEL COMPOSITION

(Table 5-5). However, the uncertainty in these assumed values is far from adequate to explain the discrepancy in combustion efficiency; the discrepancy is largest for the tests in which the measured HC, PM, and creosote were the smallest. By the direct loss method, the Pellefier had a combustion efficiency from 98.9 to 99.9%. Thus an error of even a factor of two in the heating values could only lower the combustion efficiency to 97.8% which is still much higher than Oregon algorithm combustion efficiency. Recall that the combustion efficiency in the direct flue loss method is $(W-CL)/W$. If $(W-CL)/W = .99$, then $CL = .01W$, i.e., the chemical loss is 1% of the wood energy input. Increasing CL to $.02W$ lowers $(W-CL)/W$ to .98.

The direct-loss combustion efficiency is based on lower heating values of the products of incomplete combustion, whereas the Oregon results are based on higher heating values. This makes the direct loss combustion efficiencies higher, but by no more than one percentage point for the clean burning appliances, and by no more than about three percentage points at the low end of the combustion efficiency range. Thus, this also is inadequate to explain most of the discrepancy.

The most likely explanation for the discrepancy in combustion efficiencies appears to be the fact that the Oregon algorithm assumes a composition for wood fuel which may be incorrect. The majority of measurements for the elemental composition of Douglas fir have substantially lower values for hydrogen than are used in the Oregon algorithm (Table 7-2). Changing the values for C, H, and O in the Oregon algorithm to 50.8%, 5.8% and 42.9% increases combustion efficiency and brings it into much better agreement with the direct flue loss method (Figure 7-33). This then also improves the agreement for overall energy efficiency between the two test methods (Figure 7-34).

The small disagreement in combustion efficiency at low combustion efficiencies (Figure 7-33) is of the right magnitude and sense to be attributable to the use of lower heating values for computing combustibles losses in the direct flue loss method. Assuming a reasonable 15% difference between lower and higher heating values for the combustibles loss in the flue brings the two methods into even better agreement. The same correction to latent losses also brings the heat transfer efficiencies into even better agreement.

Particulate Matter

Particulate matter was measured using both Oregon Method 7 (OM7) and the dilution tunnel method. The correlation between the results is high (Figure 7-35) but they yield different numbers. The relation is best illustrated by plotting the ratio between the test methods as a function of either one of them (Figure 7-36). The tunnel result is always less than the OM7 result, and by an amount which increases for cleaner burning systems. For relatively high emitting appliances, the tunnel and OM7 results approach the same value (the ratio is close to unity). For results near 4 g/hr (the Oregon 1988 passing grade for catalytic systems), the tunnel method yields about half the emissions rate as the Oregon method.

Table 7-2 Douglas fir composition data (percent by weight).

LAB	SAMPLE NO	C %	H %	O %
COMMERCIAL TESTING	A2	51.03	5.9	42.62
COMMERCIAL TESTING	A4	51.1	5.91	42.52
GALBRAITH	A1	50.5	5.91	41.42
GALBRAITH	A3	50.29	6.16	42.55
ERL (CANADA)	A5	51.46	6.18	42.11
ERL (CANADA)	A6	51.56	6.13	41.97
AVERAGES		50.99	6.03	42.20
STANDARD DEVIATION		0.46	0.13	0.42
COMMERCIAL TESTING	1	51.64	6.16	
	2	50.4	5.74	
	3	51.1	5.98	
	4	52.24	5.32	
	5	50.95	6.01	
AVERAGES		51.27	5.84	
STANDARD DEVIATION		0.63	0.29	
NO. 1	AVERAGE OF 5 SAMPLES	50.46	5.61	43.79
	STANDARD DEVIATION	0.06	0.11	0.06
NO 2.	AVERAGE OF 10 SAMPLES	50.52	5.79	43.28
	SANDARD DEVIATION	0.24	0.23	0.48
AVERAGES OF ALL ABOVE AVERAGES		50.81	5.82	43.09

COMPOSITION ASSUMED IN OREGON DEQ ALGORITHM		51	7.3	41

- NOTES
1. SAMPLES A1-A6 SHOULD HAVE HAD IDENTICAL COMPOSITIONS. THEY WERE A HOMOGENIZED AVERAGE SAMPLE FROM ABOUT 90 CORES FROM ABOUT 35 PIECES OF WOOD.
 2. SAMPLES 1-5 WERE AN INTENTIONALLY BROAD DISTRIBUTION OF DENSITIES.
 3. DATA FROM LABORATORIES NOS. 1 AND 2 WERE SUPPLIED BY THE WOOD HEATING ALLIANCE. ALL OTHER DATA WAS REQUISITIONED BY SRI FOR A PROJECT FUNDED BY THE U.S. DEPARTMENT OF ENERGY.

OREGON COMBUSTION EFFICIENCY (%)

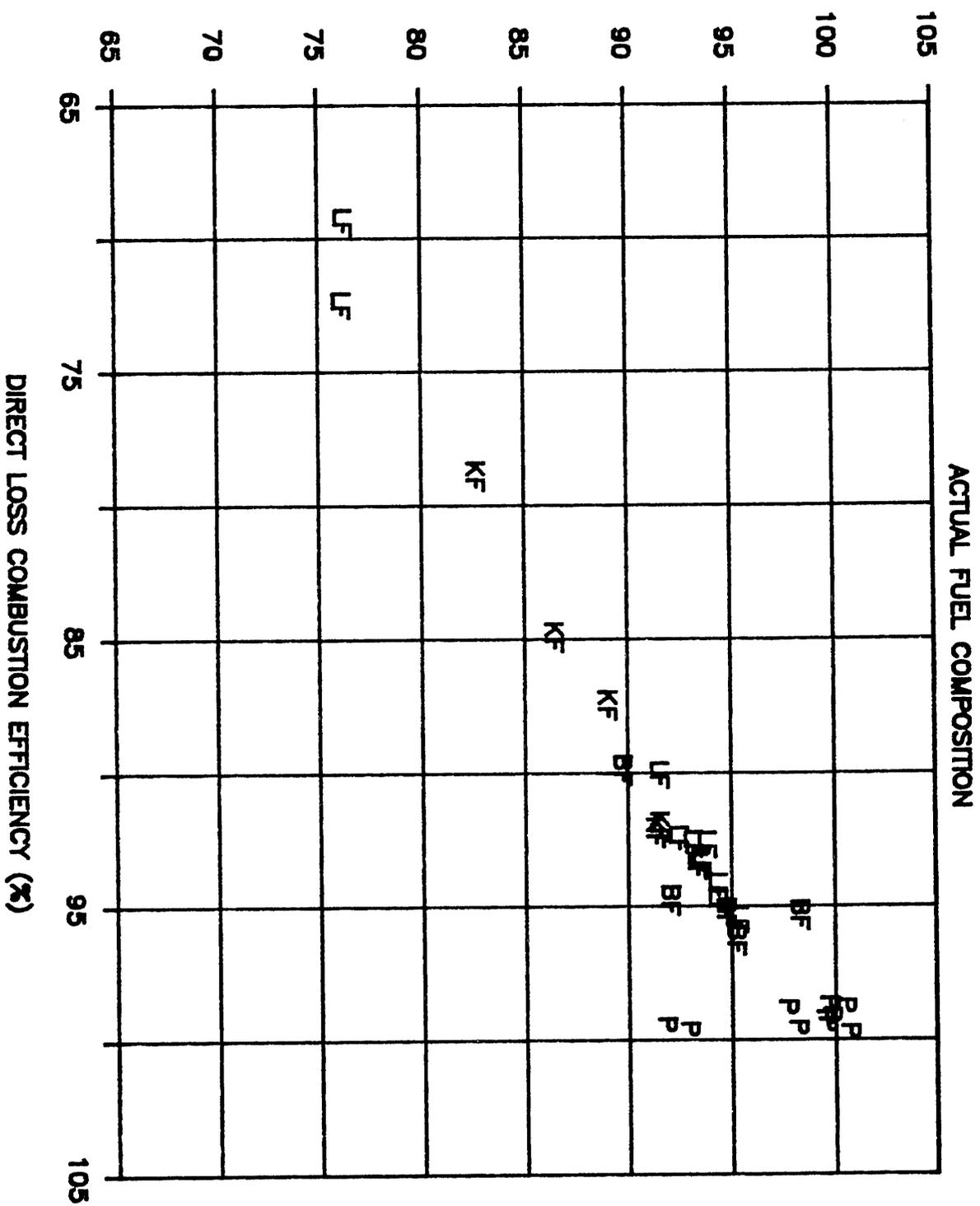


FIGURE 7-33. COMBUSTION EFFICIENCY

OREGON OVERALL EFFICIENCY (%)

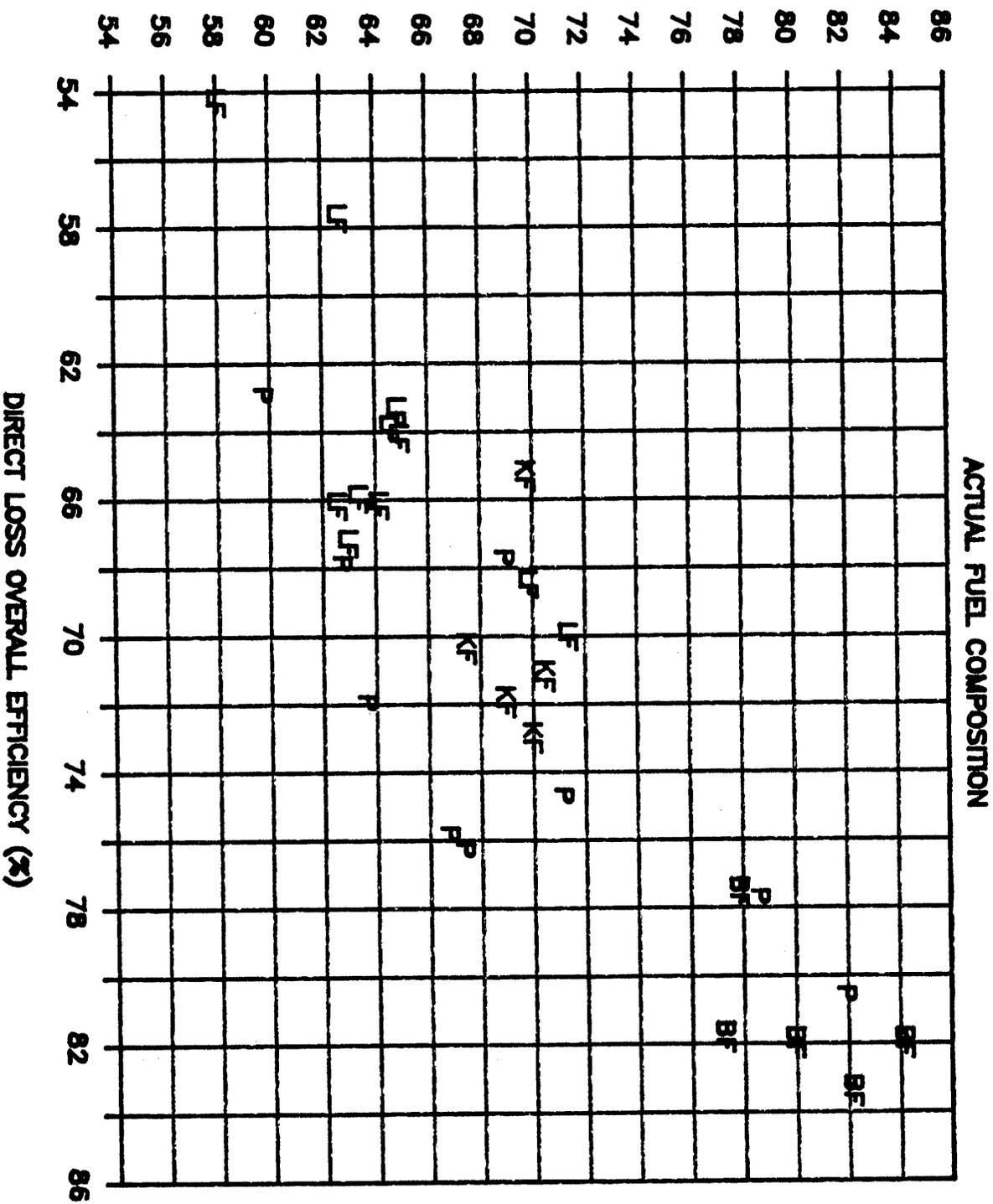


FIGURE 7-34. OVERALL EFFICIENCY.

OM7 PM (G/HR)

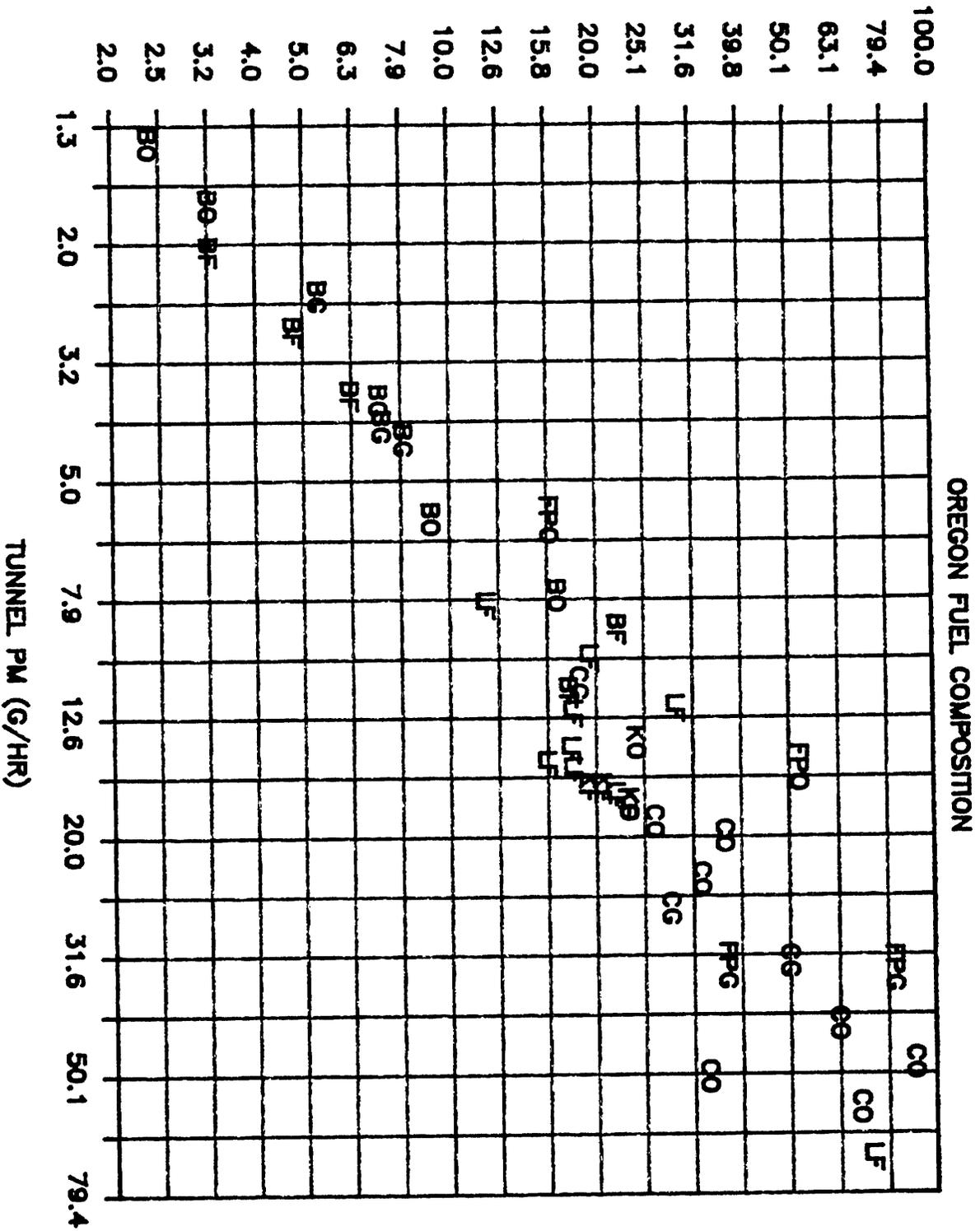


FIGURE 7-35. OM7 PM VS TUNNEL PM.

RATIO OM7/TUNNEL PM

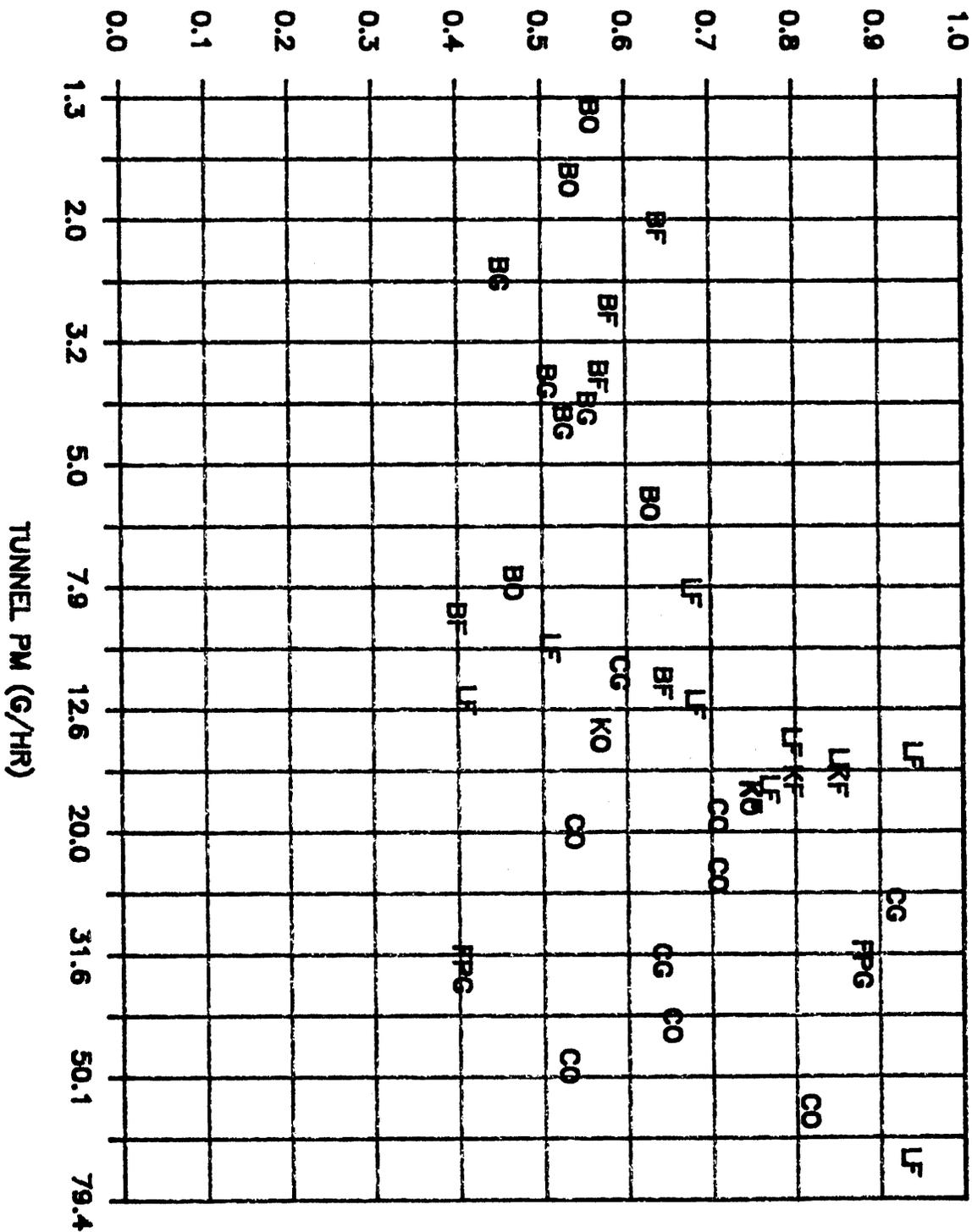


FIGURE 7-36. PM RATIO.

This relationship between the two PM measuring methods is consistent both with previous research conducted by SRI for the Colorado Department of Health¹⁹ and research conducted by Engineering-Science for the United States Environmental Protection Agency (EPA).²⁰ The Condor Method²¹ (which also involves dilution and filtration) yields a qualitatively similar relationship to OM7 results. Thus, this effect is well established.

There are a number of reasons why the two methods might be expected to yield different results, and they all suggest the tunnel results should be lower.

1. The tunnel method involves dilution before filtration, whereas OM7 processes concentrated smoke. The dilution shifts more matter into the vapor phase which the tunnel sampling system tends not to retain.

2. The tunnel method involves filtration of the diluted sample at room temperature, whereas OM7 involves condensation at 0°C. Thus, one would expect OM7 to collect more material.

3. OM7 counts as PM any material which sticks to the flue walls above the Oregon sample probe. Thus, creosote accumulation in the upper half (approximately) of the chimney is counted as PM emission in the Oregon method. The tunnel method only interprets what comes out the top of the chimney as PM.

4. In the tunnel method, there is a loss of PM to the tunnel walls.

5. Any PM withdrawn from the flue by sampling trains (OM7 and gas analyzers) does not reach the tunnel.

6. The collection efficiency of both sampling trains is dependent on the spectrum of emissions. Thus, a shift in this spectrum could result in a change in the ratio of the catches. It is plausible that the spectrum of emissions (e.g., relative amounts of high, medium and low molecular weights) correlates with combustion efficiency. A shift to lower molecular weights in cleaner burning systems could explain the difference in PM measures.

An upper limit on the creosote-deposition mechanism is provided by data generated in this project. Creosote accumulation in the entire flue ranged from 2 to 42% of the tunnel PM and averaged 14% (Appendix). Only the deposits above the OM7 sampling location would contribute to the observed difference in PM methods. The flue length above the OM7 sample probe is 48% of the total length, and previous research²² has shown that creosote deposits are usually lighter higher in the flue. Thus 48% of the average whole-flue deposit is an overestimate of the PM reduction expected by this mechanism. This amounts to an average effect of less than 7% -- significant, but much less than the observed effect.

Deposits of PM on the tunnel walls upstream of the tunnel PM probe were not quantified in this project. However, previous research²³ has indicated that this contribution may amount to a 2% reduction in the measured tunnel PM.

Sample withdrawal from the flue is typically less than 1% and hence cannot be a dominant mechanism to explain the difference in measured PM emissions.

The colder collection temperature in OM7 is likely to result in a larger catch compared to room temperature tunnel filtration. However, processing of the OM7 catch involves drying at room temperature to constant weight. This would seem to be an opportunity for the extra material that OM7 catches to escape during processing.

Thus the two most important mechanisms to explain the difference between OM7 and dilution tunnel PM emissions appear to be dilution and shifts in smoke chemistry. Dilution is likely to be the primary reason tunnel PM emissions are always lower. The changing spectrum of emittant chemistry as a function of cleanness of burn is a plausible explanation for the ratio of OM7 to tunnel PM changes as a function of cleanness of burn.

There is evidence both in this project and in previous research² for a shift in the spectrum of emissions. For the cleaner burning systems, the ratios of hydrocarbons to tunnel PM (Figure 7-37), and of hydrocarbons to C O (Figure 7-38) are both higher than for the dirtier tests. This does not lead to a quantitative prediction in the difference between OM7 and tunnel filter PM, but it suggests that relative changes in catch efficiency as the spectrum of emissions changes is a possible mechanism.

The higher scatter for the higher emitting tests may be related to one or more of the following. 1) Most of the open fireplace stove tests are in this group. The air-to-fuel ratio for these tests averaged 40, well over the limit of 30 specified in the Oregon test method. This limit is in part motivated by the fact that indirect stack loss measurement methods become overly sensitive to measurement errors at high air-to-fuel ratios; this can lead to inaccurate results.²⁴ 2) In the right half of Figure 7-36, there tends to be a separation between fuels, with oak having a lower ratio than Douglas fir. It is possible that oak and fir have sufficiently different elemental compositions that the use of the standard Oregon algorithm composition causes an artificial separation of the data.

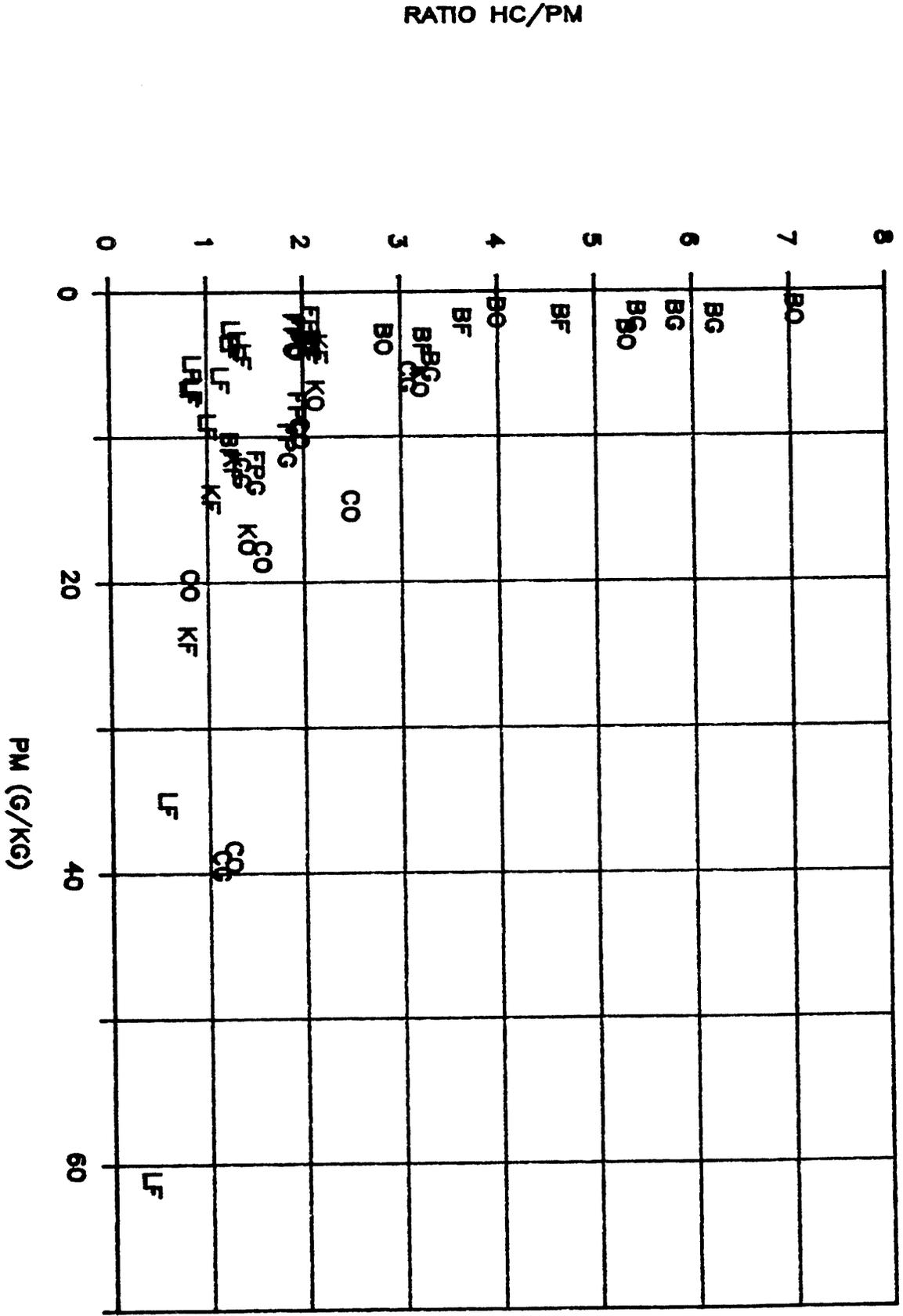
The relatively small scatter in the left hand side of Figure 7-36 is reassuring since this is the region in which stoves perform which are close to passing Oregon's and Colorado's 1988 standards.

Interlaboratory Reproducibility

A major issue in any emissions control program based on a performance standard is the reproducibility of the results, both within any given laboratory and among different laboratories. There is not much data available. No significant research had been published on this aspect of the Oregon test method.

Considerable data on intralaboratory reproducibility may exist, but it is mostly the property of individual manufacturers. In testing at independent laboratories for Oregon certification, extra tests are often conducted, and only the best set of four is submitted to Oregon DEQ. From what little evidence is available, it appears that there is an uncertainty on the order of at least 30% for PM emissions for each test. Much of this

FIGURE 7-37. RATIO HC/PM VS PM.



test-to-test variability is due to the variability in the stove's performance rather than weakness in measurement methods. Reducing this test-to-test variability is desirable. However, such a large uncertainty on each test is not too serious a problem for two reasons. 1) Oregon and Colorado regulate on the basis of a weighted average PM emission of four tests. The uncertainty in this average is less than the uncertainty in individual test results. 2) The dynamic range of PM emissions is on the order of a factor of 50 (from less than 1 g/hr to over 50 g/hr). Equivalently, the dirtiest stoves are more than 5000% dirtier than the cleanest. Thus the 30% resolution in each measurement represents less than 1% of the dynamic range.

Data on interlaboratory reproducibility is also scarce. Unpublished data from Oregon DEQ (from its laboratory accreditation program) reportedly indicates a variability on the order of 1g/hr in the weighted average PM emissions among laboratories at the same elevation. The appliance used in the laboratory accreditation program is the Blaze King catalytic stove. It is certified to have a weighted average emission of 1.6 g/hr. Note that a reproducibility of 1 g/hr is 63% of the stove's average emissions. It is likely that the interlaboratory reproducibility is worse than 1 g/hr for stoves with higher emissions.

By intent, four of the stoves tested in this project had also been tested at OMNI Environmental Services, Inc. and had been certified by Oregon DEQ. The results were obtained from Oregon DEQ. The primary objective was to investigate the possible effect of altitude on emissions. The altitude of OMNI is 300 feet; Shelton Research, Inc. is at 6900 feet.

For this purpose, Oregon weighted averages were calculated for both sets of data. The Oregon-supplied data contained the required 4 tests per stove. The data generated in this project consisted of more than four tests per appliance in most cases. Thus for the Lopi, Blaze King and Pellefier, data was selected in the same manner as was most likely used by the manufacturer -- namely selecting the best results among the available data, consistent with a full distribution of power outputs. (The highest burn rate test for the Kent did not have OM7 data. Thus the averaging was done with three tests. This had very little impact on the results since the weight given to the highest burn rate test in the Oregon averaging system is typically only a few percent.)

Another limitation of the data in this project is related to the fact that a precise distribution of power outputs was not a primary objective. The principal difference between this project's actual and Oregon-specified distributions is that the lowest power tests for the Blaze King, Lopi and Pellefier were 11,000 to 12,000 Btu/hr instead of less than 10,000 Btu/hr. The performance of some stoves can change dramatically in this vicinity, usually yielding high emissions at lower burn rates.

The results (Table 7-3) suggest that there is an altitude effect and that emissions increase with elevation (actually, with reduced air pressure). PM emission increases an average of 163% and combustion efficiency decreases by an average of 5%. CO emission increases an average of 20% (see below).

Table 7-3. Interlaboratory reproducibility data.

STOVE	DATA SOURCE	PM (G/HR)	CO (G/HR)	CE (%)	HT (%)	OE (%)
BLAZE	OREGON	1.6	14	93	85	79
	SRI	4.7	27	88	86	75
	CHANGE (%)	201	90	-5	1	-4
KENT	OREGON	14.2	197	79	81	64
	SRI	20.7	201	78	81	63
	CHANGE (%)	46	2	-2	0	-3
LOPI	OREGON	14.8	216	79	79	62
	SRI	52.4	292	75	74	55
	CHANGE (%)	255	35	-6	-6	-11
PELLEFIER	OREGON	0.7	13	95	80	76
	SRI	1.7	7	90	69	62
	CHANGE (%)	149	-47	-5	-14	-19

It is likely that there is an altitude effect. It is predicted theoretically, and it is a documented fact for automobile emissions.²⁵ However, there are many other causes for differences in measured emissions between laboratories.

1) Not all individual stoves of the same model will perform the same. Manufacturing tolerances can result in different degrees of airtightness of doors and bypass dampers. No study has been done to determine the variability in performance due to manufacturing tolerances.

2) Even if the same individual stove were tested at different elevations, there is a real chance that changes in seals can cause changes in performance. (A catalyst bypass damper which is only 95% tight can be the cause of a doubling of the stove's emissions.)

4) Although the pellet stove tested at SRI was the very same stove that had been tested at 300 feet (altitude), it had been slightly modified. An attempt was made to recreate its previous configuration, but there is no certainty this attempt was successful.

4) All standard test methods allow ranges for many parameters. Few of the ranges in the Oregon standard have been investigated to determine their importance. Examples are:

- Fuel moisture may be between 19 and 25% (dry basis).
- Charcoal bed may be between 20 and 25% of the weight of a test load.
- Fuel load weight may range over 20%.
- The density of the Douglas fir fuel may range from .45 to .60 g/cm³ (a 29% range relative to the midpoint).

There is likely to be a significant difference in the results between two tests wherein each parameter is taken to the clean-burning extreme and the dirty-burning extreme.

5. The Oregon tests may have been selected by the manufacturer from a larger set of tests. A similar procedure was followed with the data generated in this project (as discussed previously). However, the size of the effect on calculated average performance due to these selection processes is unlikely to be the same.

The data for each individual test (as opposed to the Oregon weighted averages) supports the conclusion that the altitude effect is real. Combustion efficiencies are nearly universally higher at 300 feet at all burn rates.

The average change in PM emissions excluding the Lopi is 125%, which is close to the 100% presently assumed by Oregon and Colorado. The rationale for excluding the Lopi is: 1) that its performance appears to be especially sensitive (as is the case for some other non-catalytic stoves; a very small change in operating conditions can make an enormous difference in combustion efficiency) and 2) that a similar rejection of data for the least clean appliance occurred when Oregon and Colorado adopted their altitude factor.

The apparent altitude effect would most likely be more dramatic had all stoves been tested at under 10,000 Btu/hr. This appears to be particularly true for the Pellefier CO emissions. Both sets of data (Oregon and SRI) indicate steeply rising CO emissions as the burn rate falls for this stove. This could well be the reason that the altitude effect on CO emissions for the Pellefier appears to be contrary to the general trends in emissions.

Thus the results of this project are in at least qualitative agreement with the altitude effect assumed in the Oregon and Colorado emissions programs, and are not inconsistent with the quantitative aspects -- that there is approximately a factor of two increase in emissions of PM and CO at 6900 feet relative to 300 feet.

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GLOSSARY

BF: Blaze catalytic stove burning Douglas fir.

BG: Blaze catalytic stove burning green oak logs.

BO: Blaze catalytic stove burning seasoned oak logs.

Cold-to-Cold test cycle: A test cycle beginning with an ambient temperature stove and ending after the final charcoal phase and after the stove has cooled back down to ambient temperature.

CG: Conventional airtight stove burning green oak logs.

CO: Conventional airtight stove burning seasoned oak logs.

CO: Carbon monoxide.

Combustibles: The total chemical energy loss up the flue; usually expressed as a percent of the fuel energy. If the combustibles loss is 20%, the combustion efficiency is 80%.

Combustion Efficiency: The percentage of the energy content of the fuel consumed, based on the higher heating value of the fuel, that is converted into heat in the combustion process, regardless of whether the heat is used or goes up the chimney.

Direct Stack Loss Method: A test method for determining the energy efficiency of a wood stove.

Emissions factor: Emissions per unit mass of dry fuel.

Emissions rate: Emissions per unit time.

Energy Efficiency: See combustion efficiency, heat transfer efficiency, and overall energy efficiency.

FID (Flame Ionization Detector): Many gases (especially hydrocarbons) are broken down into ions when burned in a hot flame. In a flame ionization detector positive and negative ions are drawn to oppositely charged electrodes and the resulting current measured by a sensitive electrometer.

FPG: Open fireplace stove burning green oak logs.

FPO: Open fireplace stove burning seasoned oak logs.

Heat Transfer Efficiency: The percentage of the total heat generated in the combustion process that is used in (or transferred to) the house for space heating.

HC: Hydrocarbons, as measured with a flame ionization detector in this project, and expressed as methane equivalent.

Glossary (Cont.)

Higher Heating Value: Energy release on complete combustion when products of combustion are returned to natural state at room temperature. The heat liberated when water condenses is counted as part of the heating value.

Hot-to-hot test cycle: A test cycle beginning with a hot stove and live charcoal bed, and ending when the charcoal bed returns to the original weight.

KF: Kent stove burning Douglas fir.

KO: Kent stove burning seasoned oak logs.

LF: Lopi insert burning Douglas fir.

Lower Heating Value: Energy release on complete combustion without recondensation of water vapor.

NO_x: Oxides of nitrogen.

P: Pellefier pellet stove.

PAH: Polycyclic aromatic hydrocarbons; hydrocarbons including two or more aromatic ring structures. PAH emissions in this report refer to the sum of the 16 PAHs in EPA methods 610.

PM: Particulate matter.

Primary Phases: Kindling, main load and charcoal phases.

APPENDIX:

DATA

MAIN LOAD DATA

STOVE/ TEST FUEL NO LABEL	STOVE	FUEL	FUEL MASS (DRY)	BURN RATE (DRY)	FUEL MOISTURE (DRY)	DURATION MIN	POWER OUTPUT	RATIO AIR/FUEL	FLUE O2	FLUE CO2	FLUE CO	FLUE FLOW (DRY)	FLUE TEMP	AMB TEMP	AMB HUMID	AMB PRESS
			KG	KG/HR	%		BTU/HR	%	%	%	G/SEC	DEG C	DEG C	%	MM	
4 CO	CONVENTIONAL	OAK	6.06	1.37	19.8	266	17187.	8.4	13.1	7.0	1.8	3.4	107	28	0.36	599
5 CO	CONVENTIONAL	OAK	5.86	0.66	19.8	531	6548.0	11.7	14.9	5.5	1.7	2.3	69	28	0.45	601
6 CO	CONVENTIONAL	OAK	6.54	3.24	19.8	121	37357.	6.1	9.1	11.1	1.7	6.2	233	26	0.50	597
6 CO	CONVENTIONAL	OAK	6.44	2.51	19.8	154	30150.	7.9	10.3	10.1	1.1	6.0	233	26	0.45	596
7 CG	CONVENTIONAL	GRN OAK	4.78	2.61	38.3	110	29068.	9.6	11.1	9.6	1.0	7.7	277	25	0.61	603
7 CG	CONVENTIONAL	GRN OAK	4.68	1.87	38.3	150	20533.	12.9	12.8	7.8	0.8	7.2	244	28	0.64	596
8 CG	CONVENTIONAL	GRN OAK	5.41	0.67	37.9	486	6960.6	16.0	16.1	4.4	1.3	3.2	71	24	0.56	598
9 BF	BLAZE	FIR	12.23	3.20	19.8	229	50175.	5.0	6.0	14.6	1.1	5.3	122	23	0.47	602
10 BF	BLAZE	FIR	11.73	1.74	19.8	405	27267.	8.5	8.9	11.8	0.5	4.5	97	23	0.41	602
11 BF	BLAZE	FIR	11.47	1.09	20.8	630	17481.	11.8	11.2	9.8	0.1	3.9	71	21	0.34	599
12 BF	BLAZE	FIR	11.62	0.85	19.8	817	12527.	14.0	12.9	7.7	0.7	3.5	58	23	0.54	601
13 BO	BLAZE	OAK	12.86	2.57	23.9	300	35699.	6.9	7.3	13.1	1.5	5.6	132	24	0.47	598
14 BO	BLAZE	OAK	12.01	0.97	19.8	740	14779.	9.8	11.3	9.6	0.2	2.8	64	23	0.43	603
15 BO	BLAZE	OAK	11.51	1.31	19.8	529	19297.	8.5	10.6	10.4	0.3	3.3	82	21	0.34	601
16 BO	BLAZE	OAK	11.70	1.85	19.8	379	26328.	11.4	9.6	11.2	0.7	6.1	99	24	0.38	599
17 BG	BLAZE	GRN OAK	10.64	2.46	41.2	260	34997.	7.1	8.0	12.7	0.7	5.5	144	24	0.47	601
18 BG	BLAZE	GRN OAK	10.41	1.88	40.8	333	26798.	6.5	8.1	12.7	0.9	3.9	106	24	0.75	599
19 BG	BLAZE	GRN OAK	10.54	1.38	41.0	457	20508.	9.1	10.3	10.4	0.2	3.9	93	24	0.50	594
20 BG	BLAZE	GRN OAK	10.62	0.77	43.7	828	11340.	12.4	13.7	7.1	0.2	2.9	70	21	0.37	592
21 LF	LOPI	FIR	2.95	3.00	21.1	59	38796.	11.3	11.7	8.8	0.5	10.3	279	19	0.36	592
21 LF	LOPI	FIR	2.75	2.84	21.1	58	36019.	11.8	11.7	8.8	0.6	10.1	283	20	0.33	592
21 LF	LOPI	FIR	2.73	2.97	21.1	55	37777.	12.3	11.8	8.7	0.5	11.0	284	20	0.38	592
21 LF	LOPI	FIR	2.91	2.16	21.1	81	26542.	14.2	13.0	7.5	0.7	9.1	252	21	0.37	592
22 LF	LOPI	FIR	2.55	2.07	21.1	74	25228.	15.0	13.3	7.2	0.6	9.2	243	20	0.46	597
22 LF	LOPI	FIR	2.94	2.84	21.1	62	36131.	11.3	11.7	8.8	0.8	9.7	273	22	0.49	597
22 LF	LOPI	FIR	3.12	2.26	21.1	83	27883.	13.7	12.6	7.8	0.7	9.3	249	23	0.53	597
23 LF	LOPI	FIR	2.77	2.03	21.1	82	27332.	10.5	10.2	10.1	0.9	6.5	223	21	0.62	598
23 LF	LOPI	FIR	2.81	1.85	21.1	91	24353.	10.6	11.0	9.3	1.1	6.0	204	22	0.65	598
24 LF	LOPI	FIR	2.85	0.53	21.1	320	5881.5	17.7	16.5	3.6	1.8	2.7	76	22	0.83	597
25 LF	LOPI	FIR	2.75	1.13	21.1	146	11799.	10.8	14.7	5.1	2.4	3.7	106	24	0.89	597
26 KF	KENT	FIR	3.79	1.93	21.1	118	26415.	8.9	9.8	10.6	1.1	5.3	220	23	0.61	602
26 KF	KENT	FIR	3.80	1.95	21.1	117	27368.	8.8	9.5	10.8	1.2	5.3	217	24	0.57	602
27 KF	KENT	FIR	3.73	1.16	21.1	192	15691.	7.5	9.9	9.7	2.4	2.7	119	25	0.43	598
28 KF	KENT	FIR	3.82	1.47	20.3	156	20331.	7.2	8.0	11.8	1.9	3.4	145	23	0.53	600
29 KF	KENT	FIR	3.98	0.69	20.3	347	8663.2	14.2	12.1	7.3	2.6	2.9	74	21	0.66	600
30 KO	KENT	OAK	6.54	2.47	23.9	159	31271.	9.1	9.9	10.7	1.2	6.9	220	21	0.43	600
30 KO	KENT	OAK	6.46	1.64	23.9	237	20378.	10.3	12.0	8.3	1.0	5.2	190	23	0.27	598
31 KO	KENT	OAK	6.58	0.82	23.9	484	10760.	8.0	11.3	9.0	1.6	2.1	82	20	0.62	594
32 P	PELLEFIER	PELLETS	2.19	0.97	7.3	135	11802.	43.6	17.8	3.0	.0	11.9	139	24	0.69	591
33 P	PELLEFIER	PELLETS	2.46	1.21	7.3	122	15569.	33.0	17.1	3.7	.0	11.2	154	24	0.70	591
34 P	PELLEFIER	PELLETS	4.07	1.18	7.3	207	16126.	27.9	17.0	3.8	.0	9.3	154	24	0.67	589
35 P	PELLEFIER	PELLETS	2.77	1.33	7.3	125	18909.	22.3	15.8	5.1	.0	8.5	163	24	0.59	592
36 P	PELLEFIER	PELLETS	2.11	1.02	7.3	124	15013.	23.8	15.7	5.1	.0	6.9	125	24	0.65	600
37 P	PELLEFIER	PELLETS	2.85	1.38	7.3	124	21176.	15.6	13.0	7.7	.0	6.3	146	24	0.66	599
38 P	PELLEFIER	PELLETS	2.50	1.24	7.3	121	18166.	22.7	16.3	4.8	.0	8.2	153	24	0.60	606
39 P	PELLEFIER	PELLETS	2.50	1.23	7.3	122	18132.	22.4	16.4	4.7	.0	8.0	153	23	0.57	605
40 CO	CONVENTIONAL	OAK	5.55	4.75	26.1	70	60724.	4.9	5.1	14.6	2.4	7.8	376	24	0.28	602
40 CO	CONVENTIONAL	OAK	5.82	3.21	26.1	109	39131.	7.3	7.4	12.4	1.8	7.4	337	24	0.20	601

MAIN LOAD DATA

TEST NO	STOVE/ FUEL LABEL	STOVE	FUEL	FUEL MASS	BURN RATE	FUEL MOISTURE	DURATION	POWER	RATIO AIR/FUEL	FLUE O2	FLUE CO2	FLUE CO	FLUE FLOW (DRY)	FLUE TEMP	AMB TEMP	AMB HUMID	AMB PRESS
				(DRY)	(DRY)	(DRY)		OUTPUT	FUEL	%	%	%	G/SEC	DEG C	DEG C	%	mm
41	CO	CONVENTIONAL	OAK	5.60	3.26	26.1	103	36078.	5.7	7.1	12.8	2.5	6.1	262	24	0.45	604
42	CO	CONVENTIONAL	OAK	5.45	2.66	26.1	123	35820.	6.8	9.7	10.6	1.5	5.8	228	24	0.46	603
43	CO	CONVENTIONAL	OAK	5.96	2.05	20.7	174	27118.	6.1	9.8	10.7	1.3	4.1	180	24	0.89	595
44	BF	BLAZE	FIR	11.88	0.82	20.7	864	12928.	15.1	13.7	7.0	0.1	3.7	69	23	0.92	599
45	P	PELLEFIER	PELLETS	5.58	1.26	6.8	266	16523.	34.0	17.8	3.0	0.1	12.3	153	23	0.85	595
46	P	PELLEFIER	PELLETS	5.66	1.31	7.0	259	15925.	44.6	18.4	2.5	0.0	16.6	149	24	0.93	590
47	FPD	FP STOVE	OAK	5.91	6.22	20.0	57	61917.	22.4	17.2	3.7	0.2	40.1	282	24	0.77	589
47	FPD	FP STOVE	OAK	5.31	1.88	20.0	169	15507.	59.6	19.3	1.6	0.1	31.5	139	25	0.76	588
47	FPD	FP STOVE	OAK	5.73	2.08	20.0	165	17067.	56.3	19.2	1.7	0.1	32.9	148	26	0.84	588
48	FPG	FP STOVE	GRN OAK	4.88	2.69	40.7	109	24879.	45.7	19.0	1.8	0.3	34.9	126	23	0.96	587
48	FPG	FP STOVE	GRN OAK	5.05	3.12	40.7	97	25985.	41.2	18.5	2.2	0.3	36.6	156	24	1.07	586
48	FPG	FP STOVE	GRN OAK	4.80	2.23	40.7	129	19928.	51.8	19.1	1.6	0.2	32.7	124	24	1.13	584

MAIN LOAD DATA

TEST FUEL NO LABEL	STOVE/ HC	HC as methane			CO	CO	CO	PM	PM	PM	NOX	NOX	NOX	COMBUS-	ELEM	CRES-	CRES-	BENZ
		6	G/KG	G/HR	(FLUE) G	(FLUE) G/KG	(FLUE) G/HR	(TUN) G	(TUN) G/KG	(TUN) G/HR	as NO G	as NO G/KG	as NO G/HR	TIBLES %	CARBON G/KG	SOTE G	SOTE G/KG	G
4 CD	152	25.1	34.3	892	147	201	223.6	36.9	50.4	4.127	0.68	0.93	14.6					
5 CO	275	46.9	31.1	1131	193	128	219.5	37.5	24.8	2.168	0.37	0.25	29.6					
6 CD	181	27.7	90.1	717	110	355	115.0	17.6	57.0	3.586	0.55	1.78	16.4					
6 CO	119	18.5	46.6	582	90	227	60.2	9.3	23.5	4.220	0.66	1.64	11.4					
7 CG	81	17.0	44.5	485	102	265	59.3	12.4	32.3	3.454	0.72	1.88	11.8					
7 CG	85	18.1	33.9	493	105	197	27.4	5.9	11.0	4.320	0.92	1.73	11.1					
8 CG	240	44.5	29.7	901	167	111	213.0	39.4	26.3	2.608	0.48	0.32	26.9					
9 BF	91	7.4	23.9	706	58	185	43.3	3.5	11.3	3.737	0.31	0.98	5.3					
10 BF	88	7.5	13.1	539	46	80	24.2	2.1	3.6	6.804	0.58	1.01	4.5					
11 BF	100	8.7	9.6	225	20	21	21.5	1.9	2.0	4.641	0.40	0.44	3.4					
12 BF	150	12.9	11.1	1267	109	93	120.9	10.4	8.9	3.554	0.31	0.26	10.5					
13 BO	208	16.2	41.7	1351	105	270	39.0	3.0	7.8	7.345	0.57	1.47	10.1					
14 BO	67	5.5	5.4	248	21	20	16.6	1.4	1.3	6.919	0.58	0.56	2.8					
15 BO	107	9.3	12.1	330	29	37	15.1	1.3	1.7	7.829	0.68	0.89	4.2					
16 BO	104	8.9	16.5	671	57	106	36.6	3.1	5.8	7.359	0.63	1.17	6.0					
17 BG	108	10.2	25.0	547	51	126	18.5	1.7	4.3	10.192	0.96	2.35	5.5					
18 BG	127	12.2	22.9	683	66	123	20.3	2.0	3.7	8.514	0.82	1.53	6.8					
19 BG	101	9.6	13.3	207	20	27	18.6	1.8	2.4	11.829	1.12	1.55	3.8					
20 BG	186	17.5	13.5	340	32	25	55.9	5.3	4.1	10.336	0.97	0.75	6.9					
21 LF	13	4.4	13.3	178	60	181	15.1	5.1	15.4	1.723	0.58	1.75	4.9					
21 LF	13	4.7	13.3	192	70	199	9.6	3.5	9.9	1.597	0.58	1.65	5.2					
21 LF	10	3.5	10.4	157	58	172	7.5	2.8	8.2	1.558	0.57	1.70	4.2					
21 LF	14	4.7	10.2	264	91	195	10.9	3.7	8.1	1.607	0.55	1.19	6.3					
22 LF	15	5.7	11.9	244	96	198	17.5	6.9	14.2	1.417	0.56	1.15	7.3					
22 LF	18	6.0	17.1	257	87	248	12.7	4.3	12.3	1.594	0.54	1.54	6.5					
22 LF	18	5.8	13.1	297	95	214	20.7	6.6	15.0	1.630	0.52	1.18	7.2					
23 LF	19	6.9	14.0	259	93	190	16.5	5.9	12.1	1.350	0.49	0.99	7.3					
23 LF	26	9.3	17.3	339	121	223	25.7	9.1	16.9	1.276	0.45	0.84	9.8					
24 LF	58	20.2	10.8	877	307	164	100.1	35.1	18.8	1.168	0.41	0.22	26.1					
25 LF	64	23.2	26.3	734	267	302	168.2	61.2	69.1	0.881	0.32	0.36	29.3					
26 KF	32	8.3	16.1	358	94	182	14.5	3.8	7.4	1.739	0.46	0.88	7.4					
26 KF	30	7.9	15.5	376	99	193	14.6	3.8	7.5	1.685	0.44	0.86	7.5					
27 KF	55	14.8	17.3	632	170	197	52.6	14.1	16.4	1.376	0.37	0.43	14.4					
28 KF	58	15.2	22.4	508	133	195	45.4	11.9	17.5	1.693	0.44	0.65	12.3					
29 KF	76	19.0	13.1	965	242	167	95.1	23.9	16.4	0.896	0.23	0.16	20.7					
30 KO	99	15.2	37.5	655	100	247	46.5	7.1	17.5	4.873	0.74	1.84	10.3					
30 KO	129	19.9	32.6	725	112	184	40.0	6.2	10.1	4.219	0.65	1.07	11.9					
31 KO	159	24.1	19.7	846	129	105	111.6	17.0	13.8	3.404	0.52	0.42	15.8					
32 P	NA	NA	NA	24	11	11	0.6	0.3	0.3	1.823	0.83	0.81	0.6					
33 P	NA	NA	NA	14	6	7	0.6	0.2	0.3	1.952	0.79	0.96	0.3					
34 P	NA	NA	NA	8	2	2	0.4	0.1	0.1	3.450	0.85	1.00	0.1					
35 P	NA	NA	NA	11	4	5	0.5	0.2	0.2	1.854	0.67	0.89	0.2				1.9	
36 P	NA	NA	NA	6	3	3	0.6	0.3	0.3	1.591	0.76	0.77	0.2					
37 P	NA	NA	NA	5	2	2	0.4	0.1	0.2	1.901	0.67	0.92	0.1					
38 P	NA	NA	NA	9	3	4	0.6	0.2	0.3	NA	NA	NA	0.2					
39 P	NA	NA	NA	11	4	5	0.5	0.2	0.2	NA	NA	NA	0.2				1.8	
40 CO	NA	NA	NA	745	134	639	23.2	4.2	19.9	NA	NA	NA	7.6					
40 CO	NA	NA	NA	824	141	454	34.1	5.9	18.8	NA	NA	NA	8.3					

MAIN LOAD DATA

TEST NO	STOVE/ FUEL LABEL	HC			CO	CO	CO	PM	PM	PM	NOX	NOX	NOX	COMBUS-	ELEM	CREO-	CREO-	BENZ
		g	g/KG	g/HR	(FLUE)	(FLUE)	(FLUE)	(TUN)	(TUN)	(TUN)	as	NO	g/HR	TIBLES	CARBON	SOTE	SOTE	
		as methane			g	g/KG	g/HR	g	g/KG	g/HR	g	g/KG	g/HR	%	g/KG	g	g/KG	g
41	CO : :	205	36.7	120.0	894	160	521	82.4	14.7	48.0	NA	NA	NA	20.2				
42	CO : :	121	22.2	59.0	589	108	287	66.8	12.3	32.6	NA	NA	NA	7.7				
43	CO : :	99	16.6	34.3	516	87	178	119.8	20.1	41.3	1.328	0.22	0.46	12.3				
44	BF : :	130	11.0	9.1	202	17	14	40.2	3.4	2.8	3.355	0.28	0.23	4.1				
45	P : :	5	0.9	1.5	93	17	21	2.2	0.4	0.5	1.862	0.33	0.42	1.1				0
46	P : :	1	0.2	0.4	13	2	3	0.6	0.1	0.1	3.626	0.64	0.84	0.2				
47	FPO : :	30	5.1	32.0	248	42	261	14.5	2.5	15.3	2.823	0.48	2.97	3.9				
47	FPO : :	32	6.0	11.3	336	63	119	16.4	3.1	5.8	3.031	0.57	1.08	5.4				
47	FPO : :	32	5.6	11.7	329	57	120	16.9	2.9	6.1	3.523	0.61	1.28	4.9				
48	FPG : :	92	18.8	50.5	538	110	296	60.6	12.4	33.4	2.298	0.47	1.27	12.7				
48	FPG : :	98	19.4	60.5	641	127	396	53.1	10.5	32.8	2.533	0.50	1.57	13.3				
48	FPG : :	79	16.3	36.5	522	109	243	40.3	8.4	18.7	2.247	0.47	1.05	11.2				

MAIN LOAD DATA

TEST FUEL NO LABEL	STOVE/BENZENE G/KG	PAH G	PAH G/KG	HEAT				LAT LOSS	HC LOSS	CO LOSS	PM LOSS
				OVERALL EFFIC	COMBUST EFFIC	TRANS EFFIC	SENS LOSS				
				%	%	%	%	%	%	%	%
4 CO				60	71	85	5	10		8	6
5 CO				55	69	81	4	10	12	10	6
6 CO				64	83	77	9	10	7	6	3
6 CO				67	88	76	11	10	5	5	1
7 C6				60	88	68	17	11	4	5	2
7 C6				59	89	67	18	11	5	5	1
8 C6				56	73	78	5	11	11	9	6
9 BF				82	95	86	4	9	2	3	1
10 BF				82	95	86	4	9	2	2	0
11 BF				83	96	87	4	9	2	1	0
12 BF				78	90	86	3	9	3	5	2
13 B0				75	90	84	5	9	4	5	0
14 B0				85	97	88	3	9	1	1	0
15 B0				83	96	87	3	9	2	2	0
16 B0				80	94	84	5	9	2	3	0
17 B6				77	94	82	6	11	3	3	0
18 B6				77	93	83	4	12	3	3	0
19 B6				80	96	84	4	11	2	1	0
20 B6				78	93	84	4	11	4	2	1
21 LF				67	95	71	18	9	1	3	1
21 LF				66	94	70	19	9	1	3	1
21 LF				66	95	69	20	9	1	3	0
21 LF				64	93	68	20	9	1	4	1
22 LF				63	92	69	20	9	1	5	1
22 LF				66	93	71	18	9	1	4	1
22 LF				64	93	69	19	9	1	5	1
23 LF				70	93	76	13	9	2	5	1
23 LF				68	90	76	12	9	2	6	1
24 LF				58	72	80	5	9	5	15	5
25 LF				54	69	78	6	9	6	13	9
26 KF				71	92	77	12	9	2	5	1
26 KF				73	92	79	10	9	2	5	1
27 KF				70	85	83	5	9	4	8	2
28 KF				72	87	82	6	9	4	7	2
29 KF				65	79	83	4	9	5	12	4
30 KO				68	90	76	12	9	4	5	1
30 KO				67	88	77	11	9	5	6	1
31 KO				71	84	85	4	9	6	7	3
32 P				64	99	64	27	8	0	1	0
33 P		0.089	0.036	68	99	68	24	8	0	0	0
34 P				72	99	72	20	8	0	0	0
35 P	0.7			75	100	75	17	8	0	0	0
36 P				78	99	79	13	8	0	0	0
37 P				81	99	81	11	8	0	0	0
38 P				76	99	76	16	7	0	0	0
39 P	0.7			76	100	77	16	7	0	0	0
40 CO				69	92	75	14	10	0	7	1
40 CO				66	92	72	16	10	0	7	1

MAIN LOAD DATA

TEST FUEL NO LABEL	STOVE/BENZENE G/KG	PAH G	PAH G/KG	HEAT				LAT LOSS	HC LOSS	CO LOSS	PM LOSS		
				OVERALL EFFIC	COMBUST EFFIC	TRANS EFFIC	SENS LOSS						
				%	%	%	%	%	%	%			
41	CO	:	:	60	80	75	10	10	9	8	2		
42	CO	:	:	73	92	79	10	10	0	6	2		
43	CO	:	:	72	87	82	7	9	4	4	3		
44	BF	:	:	82	95	86	4	9	3	1	1		
45	P	0.0	0.04	0.007	:	68	99	69	24	7	0	1	0
46	P	:	0.021	0.004	:	63	100	63	29	7	0	0	0
47	FPO	:	:	54	96	56	33	9	1	2	0		
47	FPO	:	:	45	94	48	40	9	2	3	0		
47	FPO	:	:	45	95	47	41	9	1	3	0		
48	FP6	:	:	50	87	58	25	11	5	6	2		
48	FP6	:	:	45	86	52	30	11	5	7	2		
48	FP6	:	:	48	88	55	28	11	4	6	1		

COLD TO COLD DATA

STOVE/ TEST FUEL		FUEL MASS (DRY)	BURN RATE (DRY)	FUEL MOISTURE (DRY)	DURATION	POWER OUTPUT	RATIO AIR/ FUEL	FLUE O2	FLUE CO2	FLUE CO	FLUE FLOW (DRY)	FLUE TEMP	AMB TEMP	AMB HUMID	AMB PRESS	
NO	LABEL	STOVE	FUEL	KG	KG/HR	%	MIN	BTU/HR	%	%	%	G/SEC	DEG C	DEG C	%	mm
4	CO	CONVENTIONAL	OAK	9.30		19.8	1326						28	0.33	600	
5	CO	CONVENTIONAL	OAK	9.59		19.8	1270						28	0.44	601	
6	CO	CONVENTIONAL	OAK	16.60		19.8	1293						26	0.43	597	
7	CG	CONVENTIONAL	GRN OAK	12.57		38.3	1259						25	0.65	599	
8	CG	CONVENTIONAL	GRN OAK	8.38		37.9	1369						24	0.50	598	
9	BF	BLAZE	FIR	19.56		19.8	1270						23	0.44	603	
10	BF	BLAZE	FIR	20.01		19.8	1331						23	0.43	603	
11	BF	BLAZE	FIR	18.19		20.8	1235						21	0.36	599	
12	BF	BLAZE	FIR	18.36		19.8	1383						23	0.52	601	
13	BO	BLAZE	OAK	21.51		23.9	1309						24	0.52	599	
14	BO	BLAZE	OAK	19.17		19.8	1462						23	0.43	604	
15	BO	BLAZE	OAK	19.10		19.8	1420						21	0.34	602	
16	BO	BLAZE	OAK	18.52		19.8	1339						20	0.37	599	
17	BG	BLAZE	GRN OAK	16.75		41.2	1248						20	0.46	601	
18	BG	BLAZE	GRN OAK	16.54		40.8	1278						24	0.70	599	
19	BG	BLAZE	GRN OAK	17.75		41.0	1324						24	0.49	594	
20	BG	BLAZE	GRN OAK	17.33		43.7	1633						21	0.37	592	
21	LF	LOPI	FIR	14.43		21.1	1287						20	0.36	592	
22	LF	LOPI	FIR	12.88		21.1	1300						22	0.49	597	
23	LF	LOPI	FIR	8.65		21.1	1428						22	0.65	498	
24	LF	LOPI	FIR	5.20		21.1	1268						24	0.79	597	
25	LF	LOPI	FIR	5.07		21.1	1296						23	0.86	597	
26	KF	KENT	FIR	13.63		21.1	1301						24	0.60	602	
27	KF	KENT	FIR	9.86		21.1	1335						24	0.51	598	
28	KF	KENT	FIR	9.72		20.3	1409						23	0.55	600	
29	KF	KENT	FIR	9.45		20.3	1356						21	0.63	600	
30	KO	KENT	OAK	17.42		23.9	1307						22	0.38	599	
31	KO	KENT	OAK	10.93		23.9	1261						20	0.61	593	
40	CO	CONVENTIONAL	OAK	17.48		26.1	945						24	0.27	601	
41	CO	CONVENTIONAL	OAK	11.49		26.1	1111						24	0.49	606	
42	CO	CONVENTIONAL	OAK	8.92		26.1	1173						24	0.52	603	
43	CO	CONVENTIONAL	OAK	10.27		20.7	1318						23	0.75	596	
44	BF	BLAZE	FIR	18.66		20.7	1354						22	0.86	599	
47	FPD	FP STOVE	OAK	23.20		20.0	1275						24	0.80	589	
48	FP6	FP STOVE	GRN OAK	20.68		40.7	11100						24	0.99	584	

COLD TO COLD DATA

TEST FUEL NO LABEL	STOVE/ HC	HC as methane			CO	CO	CO	PM	PM	PM	NOX	NOX	NOX	COMBUS-	ELEM	CREO-	CREO-	BENZ
		G	G/KG	G/HR	(FLUE) G	(FLUE) G/KG	(FLUE) G/HR	(TUN) G	(TUN) G/KG	(TUN) G/HR	as G	NO G/KG	G/HR	TIBLES %	CARBON G/KG	SOTE G	SOTE G/KG	G
4	CO	192	20.6		1388	149	278.0	29.9	12.6	4.914	0.53	0.22	13.8	NA	42	4.7	NA	
5	CO	292	30.5		1309	136	298.5	31.1	14.1	2.883	0.30	0.14	23.5	NA	68	7.3	NA	
6	CO	388	23.4		1787	108	258.0	15.5	12.0	10.633	0.64	0.49	15.0	NA	-24		NA	
7	CG	332	26.4		1399	111	142.9	11.4	6.8	9.122	0.73	0.43	14.7	NA	8	0.6	NA	
8	CG	324	38.6		1357	162	323.0	38.5	14.2	3.251	0.39	0.14	26.1	1.54	87	10.4	NA	
9	BF	115	5.9		955	49	74.2	3.8	3.5	6.278	0.32	0.30	4.6	0.23	-3		10.8	
10	BF	127	6.3		916	46	62.0	3.1	2.8	8.291	0.41	0.37	4.4	0.31	8	0.4	7.4	
11	BF	146	8.0		733	40	53.2	2.9	2.6	7.236	0.40	0.35	4.6	0.07	9	0.5	6.9	
12	BF	215	11.7		1827	99	166.6	9.1	7.2	5.222	0.28	0.23	10.1	0.18	17	0.9	9.4	
13	BO	263	12.2		1872	87	78.9	3.7	3.6	10.839	0.50	0.50	8.4	0.55	-4		25.7	
14	BO	196	10.2		836	44	101.8	5.3	4.2	8.949	0.47	0.37	6.1	0.47	17	0.9	7.9	
15	BO	162	8.5		666	35	59.3	3.1	2.5	13.233	0.69	0.56	4.7	0.40	7	0.4	14.8	
16	BO	166	9.0		1018	55	81.4	4.4	3.6	11.996	0.65	0.54	6.2	0.55	13	0.7	10.9	
17	BG	275	16.4		1336	80	123.8	7.4	6.0	15.272	0.91	0.73	9.7	1.26	5	0.3	11.1	
18	BG	232	14.0		1241	75	96.4	5.8	4.5	13.860	0.84	0.65	8.5	0.87	6	0.4	25.7	
19	BG	152	8.6		675	38	55.1	3.1	2.5	17.709	1.00	0.80	4.8	0.47	7	0.4	2.6	
20	BG	283	16.3		880	51	120.0	6.9	4.4	15.259	0.88	0.56	8.0	0.68	23	1.3	8.3	
21	LF	63	4.3		1251	87	68.2	4.7	3.2	7.731	0.54	0.36	6.2	0.61	-33		4.6	
22	LF	74	5.7		1287	100	60.6	4.7	2.8	6.429	0.50	0.30	7.3	0.47	6	0.5	4.5	
23	LF	63	7.3		1052	122	67.0	7.7	2.8	4.034	0.47	0.17	9.2	0.18	5	0.6	4.4	
24	LF	72	13.9		1053	203	127.5	24.5	6.0	2.208	0.42	0.10	21.7	0.59	29	5.6	1.4	
25	LF	86	16.9		1165	230	185.5	36.6	8.6	1.664	0.33	0.08	22.1	1.72	25	4.9	1.9	
26	KF	132	9.7		1621	119	77.8	5.7	3.6	5.914	0.43	0.27	9.5	0.14	7	0.5	13.2	
27	KF	134	13.6		1921	195	139.2	14.1	6.3	3.723	0.38	0.17	15.6	0.17	37	3.8	5.1	
28	KF	133	13.7		1711	176	181.4	18.7	7.7	4.305	0.44	0.18	15.7	0.24	33	3.4	7.7	
29	KF	156	16.5		2191	232	228.9	24.2	10.1	2.564	0.27	0.11	20.2	1.02	43	4.6	3	
30	KO	296	17.0		1897	109	137.3	7.9	6.3	10.552	0.61	0.48	11.6	0.61	18	1.0	10.4	
31	KO	221	20.2		1363	125	148.2	13.6	7.1	5.118	0.47	0.24	14.7	1.00	62	5.7	NA	
40	CO	NA	NA		2310	132	95.3	5.5	6.1	NA	NA	NA	7.8	0.82	3	0.2	36.5	
41	CO	327	28.4		1740	151	120.5	10.5	6.5	NA	NA	NA	17.1	1.15	5	0.4	23.3	
42	CO	177	19.8		1943	218	93.5	10.5	4.8	NA	NA	NA	13.4	2.20	4	0.4	19.2	
43	CO	181	17.6		1051	102	229.6	22.4	10.5	2.340	0.23	0.11	14.7	0.93	25	2.5	8.5	
44	BF	251	13.5		1063	57	175.0	9.4	7.8	4.362	0.23	0.19	9.0	0.38	23	1.2	5.6	
47	FPO	130	5.6		1190	51	57.3	2.5	2.7	11.630	0.50	0.55	4.7	0.42	-7		7.6	
48	FP6	333	16.1		2091	101	176.0	8.5	1.0	9.207	0.45	0.05	10.9	0.58	4	0.2	12.5	

COLD TO COLD DATA

STOVE/BENZENE		PAH	PAH	
TEST FUEL				
NO	LABEL	G/KG	G	G/KG
4	CO	NA	3.89	0.418
5	CO	NA	2.8	0.292
6	CO	NA	8.8	0.530
7	CG	NA	6.87	0.546
8	CG	NA	2.89	0.345
9	BF	0.6	3.8	0.194
10	BF	0.4	2.2	0.110
11	BF	0.4	1.7	0.093
12	BF	0.5	2.1	0.114
13	BD	1.2	3.1	0.144
14	BD	0.4	3.1	0.162
15	BD	0.8	0.7	0.037
16	BD	0.6	1.78	0.096
17	BG	0.7	3.72	0.222
18	BG	1.6	4.93	0.298
19	BG	0.1	1.47	0.083
20	BG	0.5	3.47	0.200
21	LF	0.3	2.54	0.176
22	LF	0.3	3.84	0.298
23	LF	0.5	3.22	0.372
24	LF	0.3	0.64	0.123
25	LF	0.4	0.95	0.187
26	KF	1.0	7.26	0.533
27	KF	0.5	2.52	0.256
28	KF	0.8	3.94	0.405
29	KF	0.3	2.1	0.222
30	KD	0.6	8.1	0.465
31	KD	NA	3.5	0.320
40	CO	2.1	9.58	0.548
41	CO	2.0	3.25	0.283
42	CO	2.2	3.01	0.337
43	CO	0.8	1.49	0.145
44	BF	0.3	0.718	0.038
47	FPO	0.3	1.94	0.084
48	FPG	0.6	6.11	0.295

KINDLING PHASE DATA

STOVE/ TEST FUEL NO LABEL	STOVE	FUEL	FUEL	BURN	FUEL	DURATION	POWER BTU/HR	RATIO			FLUE	FLUE	AMB	AMB	AMB		
			MASS (DRY)	RATE (DRY)	MOISTURE (DRY)			AIR/ FUEL	FLUE O2	FLUE CO2	FLUE CO	FLOW (DRY)	TEMP	TEMP	HUMID	PRESS	
			KG	KG/HR	%	MIN				%	%	%	G/SEC	DEG C	DEG C	%	MM
4 CO	CONVENTIONAL	OAK	1.61	1.79	19.8	54				13.8	6.3	1.4	6.5	163	28	0.40	601
5 CO	CONVENTIONAL	OAK	2.14	3.78	19.8	34				13.1	7.5	1.0	4.9	168	28	0.48	601
6 CO	CONVENTIONAL	OAK	1.47	3.69	19.8	24				10.3	9.9	1.7	10.7	247	26	0.52	598
7 CG	CONVENTIONAL	GRN OAK	1.44	3.20	38.3	27				10.0	10.3	1.6	8.3	250	25	0.50	598
8 CG	CONVENTIONAL	GRN OAK	1.53	1.61	37.9	57				13.4	6.8	1.7	5.0	152	24	0.53	600
9 BF	BLAZE	FIR	3.63	3.25	19.8	67				11.8	9.0	0.2	12.9	122	23	0.54	603
10 BF	BLAZE	FIR	4.01	2.70	19.8	89				11.2	9.4	0.7	10.7	99	23	0.41	603
11 BF	BLAZE	FIR	3.75	2.27	20.8	99				12.9	7.8	0.6	12.0	99	21	0.42	600
12 BF	BLAZE	FIR	3.70	1.68	19.8	132				13.5	7.2	0.5	8.1	75	23	0.61	600
13 BO	BLAZE	OAK	4.01	2.80	23.9	86				12.4	8.6	0.3	12.8	106	24	0.63	601
14 BO	BLAZE	OAK	3.63	3.57	19.8	61				10.2	10.6	1.8	9.9	76	23	0.45	605
15 BO	BLAZE	OAK	4.23	2.37	19.8	107				12.9	8.3	0.3	5.6	91	21	0.46	601
16 BO	BLAZE	OAK	3.52	2.05	19.8	103				14.0	7.0	0.3	9.1	96	24	0.39	601
17 BG	BLAZE	GRN OAK	2.77	6.93	41.2	24				9.3	11.4	3.5	18.9	141	20	0.46	602
18 BG	BLAZE	GRN OAK	2.99	6.19	40.8	29				9.0	11.0	3.1	9.0	161	24	0.74	600
19 BG	BLAZE	GRN OAK	3.64	2.76	41.0	79				12.0	8.6	0.8	10.1	109	24	0.62	596
20 BG	BLAZE	GRN OAK	3.38	2.33	43.7	87				11.8	9.1	0.8	4.4	88	21	0.41	593
21 LF	LOPI	FIR	1.01	2.43	21.1	25				17.1	3.7	0.2	15.4	141	19	0.36	593
22 LF	LOPI	FIR	1.04	5.20	21.1	12				14.5	5.7	0.8	25.7	174	20	0.41	597
23 LF	LOPI	FIR	0.99	3.50	21.1	17				12.3	7.9	1.1	13.9	154	21	0.59	598
24 LF	LOPI	FIR	1.54	1.92	21.1	48				13.4	7.2	0.8	5.7	145	22	0.76	598
25 LF	LOPI	FIR	0.88	3.52	21.1	15				11.4	8.6	1.3	8.3	163	24	0.90	598
26 KF	KENT	FIR	5.28	3.14	21.1	101				8.5	11.6	1.7	5.0	186	23	0.67	596
27 KF	KENT	FIR	4.64	1.02	21.1	274				12.0	7.6	2.4	2.9	101	24	0.54	599
28 KF	KENT	FIR	4.57	1.31	20.3	210				11.2	8.8	2.0	3.0	111	23	0.59	601
29 KF	KENT	FIR	4.04	0.51	20.3	472				14.1	5.7	2.1	1.6	56	21	0.69	602
30 KO	KENT	OAK	2.08	4.61	23.9	27				7.8	12.3	2.6	7.9	153	21	0.57	601
31 KO	KENT	OAK	2.00	2.31	23.9	52				10.0	10.5	1.8	4.0	118	20	0.56	595
32 P	PELLEFIER	PELLETS	1.13	1.04	7.3	65				18.1	2.7	.0	13.8	109	24	0.68	591
34 P	PELLEFIER	PELLETS	1.49	1.18	7.3	76				17.4	3.4	.0	16.1	123	24	0.69	589
35 P	PELLEFIER	PELLETS	2.43	1.39	7.3	105				16.1	4.8	.0	8.8	144	24	0.60	592
36 P	PELLEFIER	PELLETS	1.32	1.19	7.3	67				15.7	5.1	.0	7.6	119	24	0.61	600
38 P	PELLEFIER	PELLETS	1.31	1.28	7.3	61				17.1	4.0	.0	11.2	119	24	0.57	606
40 CO	CONVENTIONAL	OAK	1.66	7.13	26.1	14				10.4	9.8	2.6	18.2	218	24	0.37	602
41 CO	CONVENTIONAL	OAK	1.64	5.46	26.1	18				8.0	11.8	2.9	9.7	232	24	0.45	605
42 CO	CONVENTIONAL	OAK	1.74	6.96	26.1	15				8.1	11.8	2.9	10.4	259	24	0.51	604
43 CO	CONVENTIONAL	OAK	1.81	1.78	20.7	61				16.0	4.8	1.5	4.3	88	20	0.76	596
44 BF	BLAZE	FIR	2.60	5.56	20.7	28				11.7	8.3	2.6	10.3	86	19	0.87	601
45 P	PELLEFIER	PELLETS	2.04	1.33	6.8	92				18.1	2.7	.0	9.6	117	20	0.69	596
46 P	PELLEFIER	PELLETS	2.61	1.66	7.0	94				18.4	2.5	0.0	17.4	138	22	0.80	591
47 FP0	FP STOVE	OAK	1.74	8.70	20.0	12				15.3	5.3	0.5	27.4	285	21	0.80	589
48 FP6	FP STOVE	GRN OAK	1.61	4.39	40.7	22				18.8	2.0	0.3	25.5	130	20	0.92	588

KINDLING PHASE DATA

TEST FUEL NO LABEL	HC as methane			CO (FLUE)	CO (FLUE)	CO (FLUE)	PM (TUN)	PM (TUN)	PM (TUN)	NOX as NO		
	G	G/KG	G/HR	G	G/KG	G/HR	G	G/KG	G/HR	G	G/KG	G/HR
4 CO	28	17.5	31.3	296	184	328	54.3	33.8	60.3	0.669	0.42	0.74
5 CO	15	6.8	25.7	89	42	157	78.2	36.5	138.0	0.629	0.29	1.11
6 CO	27	18.2	67.4	207	140	517	80.2	54.4	200.5	0.646	0.44	1.62
7 CG	127	88.0	78.6	217	151	483	53.4	37.0	118.7	0.749	0.52	1.67
8 CG	60	38.9	62.9	305	199	321	108.0	70.5	113.7	0.616	0.40	0.65
9 BF	11	3.1	9.9	87	24	78	30.2	8.3	27.0	2.150	0.59	1.93
10 BF	30	7.4	20.0	265	66	179	33.6	8.4	22.7	0.547	0.14	0.37
11 BF	31	8.2	18.6	299	80	181	31.0	8.3	18.8	1.176	0.31	0.71
12 BF	51	13.7	23.1	520	141	236	44.7	12.1	20.3	1.063	0.29	0.48
13 BD	29	7.3	20.6	165	41	115	38.9	9.7	27.1	2.424	0.60	1.69
14 BD	119	32.9	117.7	387	107	381	84.4	23.2	83.0	1.080	0.30	1.06
15 BD	39	9.2	21.8	158	37	88	43.7	10.3	24.5	2.739	0.65	1.54
16 BD	31	8.8	18.1	149	42	87	43.9	12.5	25.6	2.421	0.69	1.41
17 BG	68	24.4	169.7	422	152	1054	100.8	36.4	252.0	1.260	0.45	3.15
18 BG	55	18.3	113.6	391	131	809	74.7	25.0	154.6	1.332	0.44	2.76
19 BG	29	8.0	22.1	261	72	198	35.9	9.9	27.3	2.092	0.57	1.59
20 BG	71	21.0	49.2	295	87	203	60.1	17.8	41.4	2.191	0.65	1.51
21 LF	2	2.1	5.1	39	38	93	23.6	23.3	56.6	0.350	0.35	0.84
22 LF	2	1.5	7.7	81	78	405	8.9	8.6	44.5	0.242	0.23	1.21
23 LF	7	6.6	23.2	84	84	295	24.4	24.6	86.1	0.325	0.33	1.15
24 LF	9	5.6	10.7	111	72	138	26.4	17.2	33.0	0.535	0.35	0.67
25 LF	4	5.0	17.5	70	79	279	16.4	18.6	65.6	0.229	0.26	0.92
26 KF	63	11.9	37.2	472	89	280	48.1	9.1	28.6	1.727	0.33	1.03
27 KF	65	14.1	14.4	879	190	193	85.8	18.5	18.8	1.676	0.36	0.37
28 KF	65	14.3	18.7	679	149	194	134.9	29.5	38.5	1.890	0.41	0.54
29 KF	72	17.8	9.2	858	212	109	132.7	32.8	16.9	1.479	0.37	0.19
30 KO	39	19.0	87.9	205	99	456	49.4	23.8	109.8	0.842	0.41	1.87
31 KO	36	17.8	41.2	185	93	214	35.8	17.9	41.3	0.851	0.42	0.98
32 P	NA	NA	NA	16	14	15	0.8	0.7	0.8	0.975	0.86	0.90
34 P	NA	NA	NA	8	5	6	1.2	0.8	0.9	1.393	0.93	1.10
35 P	NA	NA	NA	13	6	8	0.8	0.3	0.5	1.663	0.68	0.95
36 P	NA	NA	NA	11	8	10	0.7	0.5	0.6	0.826	0.62	0.74
38 P	NA	NA	NA	9	7	9	0.3	0.3	0.3	NA	NA	NA
40 CO	NA	NA	NA	203	122	870	36.7	22.0	157.3	NA	NA	NA
41 CO	20	11.9	65.3	172	105	575	36.0	22.0	120.0	NA	NA	NA
42 CO	23	13.2	90.8	222	128	888	23.7	13.6	94.8	NA	NA	NA
43 CO	21	11.5	20.5	197	109	194	105.7	58.3	104.0	0.295	0.16	0.29
44 BF	31	11.8	65.7	298	115	639	131.0	50.5	280.7	0.310	0.12	0.66
45 P	1	0.4	0.5	14	7	9	0.8	0.4	0.5	0.475	0.23	0.31
46 P	1	0.2	0.4	0	0	0	0.9	0.3	0.6	1.332	0.51	0.85
47 FPD	4	2.2	19.1	85	49	425	9.0	5.2	45.0	0.602	0.35	3.01
48 FPG	11	6.6	28.9	80	50	219	21.3	13.2	58.1	0.656	0.41	1.79

CHARCOAL PHASE DATA

STOVE/ TEST FUEL NO LABEL	STOVE	FUEL	FUEL	BURN	FUEL	DURATION	POWER BTU/HR	RATIO			FLUE	FLUE	AMB	AMB	AMB
			MASS (DRY)	RATE (DRY)	MOISTURE (DRY)			AIR/ FUEL	FLUE O2	FLUE CO2	FLUE CO	FLOW (DRY)	TEMP	TEMP	HUMID
			KG	KG/HR	%	MIN		%	%	%	6/SEC	DEG C	DEG C	%	mm
4 CO : CONVENTIONAL	OAK	1.21	0.09	19.8	799			18.8	1.7	0.2	1.0	40	28	0.31	601
5 CO : CONVENTIONAL	OAK	1.17	0.28	19.8	250			19.6	1.3	0.3	0.9	35	28	0.43	602
6 CO : CONVENTIONAL	OAK	1.31	0.09	19.8	833			19.2	1.6	0.1	1.9	53	26	0.40	597
7 CG : CONVENTIONAL	GRN OAK	0.96	0.16	38.3	369			19.7	1.3	0.1	2.8	65	28	0.67	597
8 CG : CONVENTIONAL	GRN OAK	1.08	0.17	37.9	384			18.1	2.4	0.4	1.2	48	24	0.46	597
9 BF : BLAZE	FIR	2.45	0.29	19.8	500			16.8	4.0	0.1	1.3	61	23	0.43	604
10 BF : BLAZE	FIR	2.35	1.38	19.8	102			10.9	9.8	0.1	4.8	87	23	0.43	603
11 BF : BLAZE	FIR	2.29	0.37	20.8	375			15.1	5.5	0.2	4.9	58	21	0.35	598
12 BF : BLAZE	FIR	2.32	0.45	19.8	308			15.1	5.8	.0	4.1	54	23	0.49	601
13 BO : BLAZE	OAK	2.57	0.25	23.9	614			17.1	3.5	0.1	4.8	61	24	0.47	598
14 BO : BLAZE	OAK	2.40	0.28	19.8	511			16.3	4.3	0.2	3.0	46	23	0.40	603
15 BO : BLAZE	OAK	2.30	0.20	19.8	691			17.6	3.2	0.1	3.0	49	21	0.24	603
16 BO : BLAZE	OAK	2.34	0.35	19.8	401			16.3	4.4	0.1	6.1	72	24	0.34	598
17 BG : BLAZE	GRN OAK	2.13	0.17	41.2	751			18.3	2.6	0.1	6.3	56	20	0.44	600
18 BG : BLAZE	GRN OAK	2.07	0.20	40.8	627			17.5	3.4	0.1	3.6	59	24	0.63	599
19 BG : BLAZE	GRN OAK	2.11	0.27	41.0	475			16.3	4.2	0.2	3.7	60	24	0.33	593
20 BG : BLAZE	GRN OAK	2.12	0.20	43.7	647			17.0	3.5	0.2	3.8	55	21	0.35	591
21 LF : LOPI	FIR	1.42	1.70	21.1	50			17.9	2.7	0.6	8.3	153	21	0.36	593
22 LF : LOPI	FIR	0.51	0.14	21.1	213			19.9	0.9	0.2	7.2	86	24	0.52	596
23 LF : LOPI	FIR	0.55	0.16	21.1	207			18.9	1.8	0.5	5.1	86	22	0.74	598
24 LF : LOPI	FIR	0.57	0.19	21.1	180			20.3	0.5	0.2	10.1	42	24	0.79	597
25 LF : LOPI	FIR	0.55	0.27	21.1	123			17.3	2.8	1.1	3.5	103	24	0.82	596
26 KF : KENT	FIR	0.76	0.13	21.1	364			19.1	1.6	0.4	2.7	79	24	0.62	602
27 KF : KENT	FIR	0.75	0.10	21.1	431			18.0	2.2	0.8	4.8	55	24	0.56	598
28 KF : KENT	FIR	0.76	0.13	20.3	356			17.9	2.2	1.0	4.3	65	23	0.57	599
29 KF : KENT	FIR	0.80	0.16	20.3	297			17.5	2.6	0.9	3.1	58	21	0.56	598
30 KO : KENT	OAK	1.31	0.21	23.9	366			18.7	1.8	0.2	3.4	79	24	0.35	598
31 KO : KENT	OAK	1.32	0.12	23.9	650			17.0	3.3	0.6	1.0	40	21	0.64	591
40 CO : CONVENTIONAL	OAK	1.11	0.15	26.1	444			18.8	1.9	0.2	3.7	85	24	0.32	600
41 CO : CONVENTIONAL	OAK	1.12	0.09	26.1	738			19.0	1.8	0.2	2.2	61	24	0.52	605
42 CO : CONVENTIONAL	OAK	1.09	0.09	26.1	735			18.8	1.9	0.2	1.5	61	24	0.58	603
43 CO : CONVENTIONAL	OAK	1.19	0.07	20.7	992			18.6	2.1	0.3	1.0	45	21	0.60	597
44 BF : BLAZE	FIR	2.38	0.59	20.7	240			17.3	3.0	0.7	3.6	55	22	0.81	597
47 FPD : FP STOVE	OAK	1.18	0.22	20.0	320			20.7	0.2	.0	13.4	37	23	0.80	589
48 FPG : FP STOVE	GRN OAK	0.98	0.28	40.7	206			20.3	0.5	.0	19.4	52	22	0.93	583

CHARCOAL PHASE DATA

TEST FUEL NO LABEL	STOVE/ HC G	HC as methane G/KG G/HR		CO (FLUE) G	CO (FLUE) G/KG	CO (FLUE) G/HR	PM (TUN) G	PM (TUN) G/KG	PM (TUN) G/HR	NOX G	NOX G/KG	NOX G/HR
		HC G/HR	HC G/KG	CO G/HR	CO G/KG	CO G/HR	PM G/HR	PM G/KG	PM G/HR	NOX G/HR	NOX G/KG	NOX G/HR
4 CD	11	4	3.5	173	143		0.3	0.2		NA	NA	
5 CD	11	NA	NA	57	49		0.7	0.6		NA	NA	
6 CD	11	45	34.7	186	142		2.7	2.1		1.819	1.39	
7 CG	11	2	1.6	79	83		2.9	3.0		NA	NA	
8 CG	11	21	19.2	120	111		2.0	1.8		NA	NA	
9 BF	11	9	3.5	129	53		0.8	0.3		NA	NA	
10 BF	11	4	1.7	18	8		4.2	1.8		0.615	0.26	
11 BF	11	13	5.6	204	89		0.7	0.3		1.238	0.54	
12 BF	11	12	5.0	30	13		0.9	0.4		0.421	0.18	
13 BO	11	12	4.5	221	86		1.0	0.4		0.256	0.10	
14 BO	11	NA	NA	169	71		0.8	0.3		0.417	0.17	
15 BO	11	10	4.4	163	71		0.5	0.2		2.200	0.96	
16 BO	11	22	9.6	160	68		1.0	0.4		1.577	0.67	
17 B6	11	37	17.4	233	110		4.5	2.1		3.100	1.46	
18 B6	11	13	6.2	150	72		1.4	0.7		3.200	1.55	
19 B6	11	10	4.6	163	77		0.6	0.3		3.400	1.61	
20 B6	11	20	9.2	225	106		4.0	1.9		2.286	1.08	
21 LF	11	2	1.2	154	109		1.4	1.0		0.340	0.24	
22 LF	11	4	8.3	218	426		0.9	1.8		0.280	0.55	
23 LF	11	4	6.7	270	487		0.5	0.9		0.435	0.78	
24 LF	11	4	6.9	39	69		1.1	1.9		0.411	0.72	
25 LF	11	9	17.2	302	549		0.9	1.6		0.334	0.61	
26 KF	11	3	3.7	346	457		0.6	0.8		0.464	0.61	
27 KF	11	8	11.2	348	466		0.8	1.1		0.393	0.53	
28 KF	11	5	6.3	469	614		1.1	1.4		0.459	0.60	
29 KF	11	5	6.4	325	408		1.1	1.4		NA	NA	
30 KO	11	3	2.7	160	122		1.4	1.1		NA	NA	
31 KO	11	18	14.0	258	196		0.8	0.6		0.390	0.30	
40 CO	11	NA	NA	202	182		1.3	1.2		NA	NA	
41 CO	11	33	29.2	246	220		2.1	1.9		NA	NA	
42 CO	11	4	3.7	190	174		3.0	2.8		NA	NA	
43 CO	11	31	25.8	217	182		4.1	3.4		0.450	0.38	
44 BF	11	19	8.1	361	152		3.2	1.3		0.440	0.19	
47 FPD	11	6	4.8	14	12		0.5	0.4		0.040	0.03	
48 FPG	11	12	12.7	52	53		0.7	0.8		0.250	0.26	

OREGON ALGORITHM DATA

TEST FUEL NO	STOVE/ LABEL	STOVE	FUEL	HEAT			OM7 PM	CO	HC	POWER OUTPUT	FLUE FLOW	FLUE FLOW	AIR/ FUEL RATIO	FLUE TEMP DEG C
				OVER EFFIC	COMB EFFIC	TRANS EFFIC								
				%	%	%	G/HR	G/HR	G/HR	BTU/HR	SCFM	G/S		
4	CO	CONVENTIONAL	OAK	62.6	76.1	82.3	34.1	267	150	16500	7.94	4.51	11.8	232
5	CO	CONVENTIONAL	OAK	60.9	71	85.7	NA	151	90	7745	4.92	2.80	15.1	159
6	CO	CONVENTIONAL	OAK	59.7	79.2	75.4	69.8	441	355	37429	13.31	7.57	8.3	451
6	CO	CONVENTIONAL	OAK	61.3	82.1	74.7	33.1	266	251	30098	11.75	6.68	9.4	460
7	CG	CONVENTIONAL	GRN OAK	56	81.7	68.5	50.4	267	279	29108	13.16	7.48	9.9	541
7	CG	CONVENTIONAL	GRN OAK	56.3	81.3	69.2	18.5	183	207	20821	11.37	6.46	12.1	477
8	CG	CONVENTIONAL	GRN OAK	57.2	71.9	79.5	28.6	148	88	7340	5.84	3.32	17.9	160
9	BF	BLAZE	FIR	70.5	83.7	84.2	17.6	220	323	43957	11.12	6.32	7.0	253
10	BF	BLAZE	FIR	72.9	86.2	84.6	6.3	76	158	24533	7.54	4.29	8.9	206
11	BF	BLAZE	FIR	74.9	86.6	86.5	3.2	18	107	15852	5.77	3.28	10.9	162
12	BF	BLAZE	FIR	71	81.6	87	22.2	79	90	11582	5.24	2.98	12.8	138
13	BO	BLAZE	OAK	66	81.1	81.4	16.7	277	285	34086	9.74	5.54	7.3	270
14	BO	BLAZE	OAK	74	85.7	86.3	2.4	21	100	13922	5.19	2.95	10.9	148
15	BO	BLAZE	OAK	71.8	84.8	84.7	3.2	42	138	18072	6.27	3.56	9.8	181
16	BO	BLAZE	OAK	70.6	83.2	84.8	9.2	106	200	25244	8.53	4.85	9.4	214
17	BG	BLAZE	GRN OAK	66.8	84.2	79.4	8.1	134	252	31939	9.68	5.50	7.9	291
18	BG	BLAZE	GRN OAK	67.7	83.3	81.2	7.2	132	192	24498	7.16	4.07	7.7	232
19	BG	BLAZE	GRN OAK	70.7	87.9	80.5	5.4	28	117	18592	6.86	3.90	10.4	201
20	BG	BLAZE	GRN OAK	71	85.7	82.8	7.3	19	78	10547	5.38	3.06	14.4	160
21	LF	LOPI	FIR	57.1	85.8	66.6	18	181	282	35203	17.67	10.04	11.4	542
21	LF	LOPI	FIR	57.6	85.7	67.2	19.5	193	253	33030	16.81	9.55	11.7	537
21	LF	LOPI	FIR	58.4	86.7	67.4	NA	154	272	36207	18.45	10.49	11.9	547
21	LF	LOPI	FIR	58.9	85.1	69.3	11.9	174	185	24805	13.76	7.82	13.1	496
22	LF	LOPI	FIR	59.2	84.1	70.4	17.8	181	195	24548	14.12	8.03	13.6	471
22	LF	LOPI	FIR	57	84.8	67.2	18	239	254	32413	16.16	9.19	11.3	528
22	LF	LOPI	FIR	59.2	84.7	69.9	15.9	191	205	26800	14.17	8.05	12.5	490
23	LF	LOPI	FIR	65	85.3	76.2	29.4	165	172	25952	9.98	5.67	10.0	442
23	LF	LOPI	FIR	63.7	83.3	76.5	22	201	165	23029	9.29	5.28	10.2	406
24	LF	LOPI	FIR	57.4	69.4	82.7	NA	171	62	5982	5.05	2.87	19.2	174
25	LF	LOPI	FIR	53.1	69.5	76.4	73.8	354	136	11816	7.71	4.38	13.6	233
26	KF	KENT	FIR	64.2	83	77.4	NA	182	188	24342	9.14	5.20	9.6	431
26	KF	KENT	FIR	63.8	83.2	76.6	NA	196	180	24209	9.38	5.33	9.8	424
27	KF	KENT	FIR	61.7	78.7	78.4	19.3	222	108	13947	5.15	2.93	9.0	265
28	KF	KENT	FIR	63	81	77.7	23.3	208	137	17955	6.33	3.60	8.7	308
29	KF	KENT	FIR	63.7	75.3	84.7	20.6	178	63	8419	3.71	2.11	11.1	169
30	KD	KENT	OAK	60.9	81.6	74.6	23.5	235	278	30414	11.61	6.60	9.1	436
30	KD	KENT	OAK	61.2	82.1	74.6	NA	192	161	19981	9.14	5.20	11.0	385
31	KD	KENT	OAK	61.9	78.1	79.3	24.3	123	96	10066	4.15	2.36	10.0	191
32	P	PELLEFIER	PELLETS	59	90.6	65.1	2.5	12	67	11100	17.56	9.98	37.5	283
33	P	PELLEFIER	PELLETS	62.7	90.7	69.2	NA	7	85	14625	17.59	10.00	30.3	309
34	P	PELLEFIER	PELLETS	57.9	90.4	64.1	0.8	2	87	13199	16.84	9.57	29.7	309
35	P	PELLEFIER	PELLETS	64.7	89.2	72.5	1.4	6	109	16609	14.04	7.98	21.9	325
36	P	PELLEFIER	PELLETS	71.6	91.3	78.4	1	4	67	14083	10.96	6.23	22.4	257
37	P	PELLEFIER	PELLETS	74.5	90.4	82.4	1.8	0	102	19845	9.71	5.52	14.6	294
38	P	PELLEFIER	PELLETS	63.5	83.5	76.1	1.1	5	161	15565	13.05	7.42	21.2	308
39	P	PELLEFIER	PELLETS	61.3	84.4	72.6	0.8	8	146	14633	13.21	7.51	22.0	307
40	CO	CONVENTIONAL	OAK	52.4	79.7	65.7	37	782	523	52944	15.79	8.98	6.0	717
40	CO	CONVENTIONAL	OAK	51.7	81.5	63.4	26.5	454	322	34495	12.59	7.16	7.4	655

OREGON ALGORITHM DATA

STOVE/ TEST FUEL			OVER EFFIC	COMB EFFIC	HEAT TRANS EFFIC	OM7 PM	CO	HC	POWER OUTPUT	FLUE FLOW	FLUE FLOW	AIR/ FUEL RATIO	FLUE TEMP	
NO	LABEL	STOVE	FUEL	%	%	%	G/HR	G/HR	G/HR	BTU/HR	SCFM	G/S	DEG C	
41	CD	CONVENTIONAL	OAK	47.6	77.1	61.8	90.7	568	402	32162	11.46	6.51	6.5	511
42	CD	CONVENTIONAL	OAK	60.3	79.6	75.7	NA	340	295	31432	11.79	6.70	8.8	447
43	CD	CONVENTIONAL	OAK	60.5	80.9	74.8	63.3	224	221	24274	8.97	5.10	8.7	362
44	BF	BLAZE	FIR	76.7	89.3	85.8	4.8	14	63	12259	6.44	3.66	16.2	156
45	P	PELLEFIER	PELLETS	57.2	88.7	64.4	2.6	22	101	13788	21.77	12.37	36.3	307
46	P	PELLEFIER	PELLETS	54.5	91.5	59.6	1.8	2	85	13734	28.82	16.38	46.1	300
47	FPO	FP STOVE	OAK	31.8	84.9	37.5	52.8	285	633	38968	83.93	47.71	27.4	540
47	FPO	FP STOVE	OAK	37.6	82.6	45.5	16.1	106	217	13870	50.54	28.73	54.9	311
47	FPO	FP STOVE	OAK	30.7	85.6	35.8	NA	117	193	12629	55.24	31.40	53.9	327
48	FP6	FP STOVE	GRN OAK	37.1	80.6	46.1	82.6	329	280	19408	68.24	38.79	52.4	267
48	FP6	FP STOVE	GRN OAK	42.6	82.5	51.6	37.3	393	272	25585	65.94	37.48	44.0	316
48	FP6	FP STOVE	GRN OAK	41.6	88.9	46.8	NA	302	76	18003	71.51	40.65	66.6	260



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