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EMISSIONS FROM DOMESTIC WOOD BURNING SYSTEMS
PROBLEMS AND POTENTIAL SOLUTIONS

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EMISSIONS FROM DOMESTIC WOOD-FIRED APPLIANCES:

PROBLEMS AND POTENTIAL SOLUTIONS

by

A.C.S. Hayden* and R.W. Braaten**

ABSTRACT

Air pollution from wood-fired appliances has become a major concern of regulatory authorities in many areas, and has caused some to seriously consider banning their use in certain critical regions.

The emissions are due to incomplete combustion, resulting from design shortfalls in present appliances. Emissions of concern are carbon monoxide and unburned hydrocarbons, including what are known as POM's (polycyclic organic matter), where known carcinogens have been identified as prime constituents. The levels and problems which can occur from these emissions are discussed, particularly when compared with alternative energy sources.

Performance of some new combustion designs which offer potential to reduce these emissions considerably is presented. Any technique which succeeds in reducing these emissions will have two additional benefits: efficiency will be increased and the propensity to produce creosote will be decreased.

Unless the industry can develop these or other advanced designs in the near future, severe limits are likely to be placed on its growth, due to the potential air pollution problem.

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INTRODUCTION

Until recently, the major thrust in North American energy usage was to eliminate the use of solid fuels in all but some of the largest installations, where coal was retained for the generation of electricity, with attendant high pollution potential. The premium, less polluting fuels, oil and gas, became predominant.

With the rapid increase in energy prices, as well as some supply shortfalls which have occurred since 1973, along with the realization that fossil fuels are a finite resource, have caused many to look to energy conservation and to forms of renewable energy to reduce demand.

In Canada, the National Energy Program, as announced in the fall of 1980, has set a goal to reduce the use of oil in each of the residential, commercial and industrial sectors to no more than 10% of the total energy used in those sectors by 1990. In order to achieve this, the Program is providing incentives for and promoting research into greater use of renewable energy options. Renewables, and particularly wood, are projected to provide 6% of Canada's total energy budget by the end of this period.

One of the major areas where wood can contribute significantly is in residential heating, either fired in a central furnace or boiler, or in a controlled combustion space heater, commonly known as a wood stove. In order that this new energy use does not seriously impinge on the environment, consideration must be given to the flue gas emissions from residential wood combustion. To ensure the wide-spread acceptability of wood-fired appliances, these emission levels must be such as not to dramatically influence ambient air quality levels. This is particularly true if wood is to be used as a heating fuel in populated areas.

This paper discusses the compounds formed during residential wood burning and attempts to quantify their relative levels.

Typical home heat demands are shown to be below the critical burn rate of a typical controlled-combustion stove for much of the heating season, resulting in field emissions which may be much higher than those indicated by laboratory tests above this rate. One way of reducing emission levels is to improve combustion design. This is also likely to reduce creosote formation, thus increasing safety; increased efficiency is another likely benefit.

The experimental program described in this paper was designed to determine the effect of firing rate on emissions, to define a more reliable

technique for measuring unburned hydrocarbons continuously and to determine if appliances with more sophisticated combustion designs offered performance with reduced emissions, relative to conventional wood-fired appliances.

Controlled combustion wood stoves have been shown to have a significant degree of incompleteness of combustion and corresponding high emissions. This paper shows that emission levels of carbon monoxide, unburnt hydrocarbons as measured by a flame ionization detector and polycyclic organic matter (POM's) are closely related, and are very sensitive to firing rate below a "critical rate", which is stove dependent. Above this, the firing rate has much less effect on emission levels.

Two technical strategies to reduce emission levels by improving combustion are primarily effective in shifting the critical burn rate to lower levels, with little effect on emissions at higher burn rates. This makes the determination of the critical rate one of the more important factors in the evaluation of wood-fired appliances.

FUEL ANALYSIS

While coal properties change dramatically from lignite to sub-bituminous to bituminous to anthracite, as well as from area to area, wood properties tend to be much more uniform.

Table I presents average proximate and ultimate analyses, on a dry basis, for averages of ten wood samples, as analyzed by the Solid Fuels Analysis Laboratory, CCRL. An ultimate analysis for a typical No.2 heating oil is also given.

In general, the volatile matter for wood waste tends to be slightly lower than for debarked woods, although all tend to be in the range of 76% to 83%. Ash is greater for wood waste than for debarked wood, but is still much lower than for most coals.

From the ultimate analysis of wood, carbon is about 50%, hydrogen 5-6%, with a very low sulphur content of 0.02%. The major difference from other common fuels is the high oxygen content, in the area of 40%. No.2 oil, on the other hand, has a carbon content of 88%, a hydrogen content of 12%, and 0.3% sulphur, with effectively no oxygen.

For residential wood combustion, the fuel is habitually air-dried for one year before use, and usually has a moisture level of 16% to 22%, on a wet basis.

EMISSIONS FROM RESIDENTIAL WOOD-FIRED EQUIPMENT

Emissions from combustion equipment in general and wood-fired equipment in particular have similar emissions, albeit at relatively different levels. For the gaseous emissions, there is carbon monoxide, sulphur dioxide, nitrogen oxides and hydrocarbons. Some of the hydrocarbons are known as polycyclic organic matter (POM). Solid emissions are also present in the form of particulates. A description of the various emissions and how they compare in relation to other sources follows. Ranges of emissions from residential wood-fired equipment are compared with those from domestic oil furnaces in Table 3 (5).

CARBON MONOXIDE (CO)

This gaseous emission, resulting from incomplete combustion of the fuel, is significant for wood combustion. For residential equipment volumetric flue gas measurements often exceed 0.5% during a burn cycle, due to poor combustion conditions. At this high level, it can constitute a major hazard to the home occupant in the event of flue reversal, leakage or blockage, as well as a downstream air pollution problem. Improved combustion design, whereby incomplete combustion products are brought back into the flame zone for ignition, can result in lower levels (1). From Table 3, CO levels are much higher than for oil furnaces.

HYDROCARBONS (HC)

This gaseous emission is also due to incomplete combustion. For residential equipment, its variation over the burning cycle, as measured with a flame ionization detector with heated cell, closely mirrors the levels for carbon monoxide (1). As for CO, hydrocarbon emissions are much higher than for oil furnaces.

SULPHUR DIOXIDE (SO₂)

For most fuels, SO₂ levels are a direct function of the amount of sulphur in the fuel, with about 98% of the sulphur going to sulphur dioxide and the rest to sulphur trioxide. Wood has a very low level of sulphur, usually from 0.02% to 0.08%, as seen from Table 1, about an order of magnitude less than for No.2 oil.

As well, wood ash is strongly alkaline, often with over 50% composed

of calcium, potassium and sodium. These compounds react readily with sulphur to neutralize it, so that the actual SO_2 emission is likely to be much lower than even predicted theoretically.

This property will be used to advantage in a CCRL-sponsored demonstration-scale fluidized bed boiler designed to burn high sulphur (greater than 5%) coal and wood chips, the latter supplying up to 30% of the design heat input of 22 MJ/h (40,000 Btu/h). Two of these boilers, now in the construction phase, are to supply steam for district heating for the Canadian Armed Forces Base at Summerside, Prince Edward Island (2). The alkaline properties of the wood ash will help to neutralize the sulphur in the coal, lowering the overall demand for limestone as a bed material.

NITROGEN OXIDES (NOX)

Wood-fired combustion systems tend to emit less nitrogen oxides (NOX) than do fossil fuel-fired units.

With the low nitrogen content of wood, nitrogen oxide formation is due primarily to fixation of atmospheric nitrogen. However, because combustion temperatures in wood-fired equipment is often much lower than in conventional systems, due both to the systems themselves and to the high moisture content of the fuel, this source of NOX is also minimized.

PARTICULATES

Particulate matter is any emission existing in the solid or liquid state under ambient conditions, excluding water. For wood burning, this includes ash from the fuel, inorganic material fed in with the fuel such as dirt, unburned carbon and condensed organic compounds. In general, actual solids emissions from residential wood burning is quite low, especially as the fuel is de-barked and fired at a low firing rate. Most of the ash, at a low content relative to coal to begin with, remains in the appliance, to be removed later. The major particulate emissions measured (3) are aerosols and condensed organic matter. Some of the condensed organic matter is of primary concern in terms of health effects - the POM's or PAH's, as described in the next section.

POLYCYCLIC ORGANIC MATTER (POM)

These are multi-ring organic compounds, sometimes referred to as polynuclear aromatic hydrocarbons (PAH), although POM's may be more

appropriate to wood combustion, because of the presence of oxygen in many of the compounds. They are of concern because many of the specific molecules have been shown to be carcinogenic, such as benzo(a)pyrene. They usually have high molecular weights and high boiling points.

POM's have been found to some degree in all forms of combustion systems, but seem to be most prominent in those instances where localized pyrolysis occurs, where the burning intensity is low or where the fuel has a significant amount of polycyclic (aromatic) compounds.

Table 2 (4) makes an estimate of the POM emissions from various sources. Open burning, such as wildfires and agricultural burning accounts for the largest amount, followed closely by residential wood combustion, especially from controlled combustion (airtight) space heaters or central furnaces. Table 3 emphasizes the much higher POM emissions from conventional wood stove designs, as compared to those from oil furnaces.

As described further on in this paper, preliminary data from an advanced design residential space heater, where the combustion intensity is increased by using forced combustion downdraft into refractory, show much lower POM levels than for state-of-the-art equipment.

CCRL EXPERIMENTAL PROCEDURE

TEST STOVES

Appliances used for these experiments were controlled combustion freestanding heaters having primarily radiant heat transfer. A previous paper (1) has outlined the four basic types of conventional wood stove combustion designs examined to date: updraft, horizontal baffle, downdraft and sidedraft.

Conventional stoves of the updraft, horizontal baffle and sidedraft type, determined to be typical of these genres, were selected for more extensive trials at various firing rates and to serve as a baseline against which two advanced combustion designs could be evaluated.

The first advanced-design stove examined was a horizontal baffle design with the addition of a combustion catalyst to initiate burning of combustible gases. Since this stove could be run with or without the catalyst in place, determination of the effect of the catalyst was possible. A schematic of this design is shown in Fig. 1.

The second advanced-design appliance was a prototype design employing internal baffling to achieve a downdraft combustion into a refractory chamber,

designed to enhance burnout of the combustible gases, as shown in Fig. 2.

FUEL

The choice of fuel species, moisture content and load size may have a measureable influence on test results. In order to achieve reproducible results, these values must be held as uniform as possible. Conversely, the desire to closely duplicate actual field usage and performance makes the choice of a standard fuel difficult.

Hence, tests were conducted on a common Eastern Canadian firewood, sugar maple, split to a fairly uniform size of 130 to 230 cm² face area by 40 cm length and uniformly air-dried to a moisture content of 15% on a wet basis.

The test stoves were loaded to approximately three-quarters normal capacity for all tests.

APPLIANCE TEST PROCEDURE AND EQUIPMENT

Wood stove performance is determined using an indirect, or stack loss method, where all the components of the flue gas are measured directly. This knowledge, along with temperatures allow calculation of the efficiency or any pollutant emission on a volume, mass or unit energy basis. Continuous analyzers are used, together with a digital weigh scale, with results collected by a data logging system onto magnetic tape, where they are stored for subsequent data reduction by digital computer. A full scan of output values can be obtained at intervals as short as 10 seconds. Flue gas components are measured with continuous analyzers, as follows: carbon dioxide and carbon monoxide with infrared; oxygen with paramagnetic; NOX with chemiluminescence and hydrocarbons with a heated flame ionization detector. A schematic of the experimental set-up is shown in Fig. 3.

Hydrocarbons

One essential component of wood flue gas composition is the level of unburned hydrocarbons. In some procedures to measure efficiency, the hydrocarbon level has been inferred by a calculated chemical mass balance from measured values of CO₂, O₂ and CO. However, this technique is sensitive to the accuracy of the other measurements, and is made more complex by the varying wood composition over the burn cycle. It would be preferable to measure the hydrocarbons directly. The only commonly available instrument is the flame ionization detector (FID). If unprotected, this instrument can

become clogged with condensed tars from the flue gas resulting from wood combustion.

CCRL has made simultaneous measurements of the hydrocarbons with two FID's: one uses a hot filter and sampling line heat-traced to 200°C; the other uses an additional cold filtering system. The systems are as shown in Fig. 4. The goal was to compare the readings from the two systems and attempt to determine a relationship between the two. Such a relationship would allow use of the cold filtering system with its clean gas and its corresponding high degree of instrument reliability to determine the hydrocarbon levels.

POM Measurement

For a number of runs, samples were collected using a modified EPA Method 5 train, as described in Reference 6. These samples were submitted to Environment Canada for detailed POM analysis, in accordance with standard techniques (7).

EXPERIMENTAL RESULTS

HOME ENERGY DEMAND

Other papers (8, 9) provide a complete description of the methodology used to obtain profiles of home fuel use as a function of outside temperature. A number of homes in the Ottawa area (4670 DD below 18°C) were instrumented to provide an accurate record of energy consumption on a twice-daily basis, together with hourly ambient temperatures. This allowed accurate profiling of the consumption rate.

Average stove firing rates should be below 4 kg/h over most of the heating season, for the majority of Canadian homes (1).

COLD VS HOT SAMPLING TRAINS FOR FID'S

Fig. 5 is a plot of hydrocarbon measurements for a cold sampling train vs a hot sampling train feeding into a heated flame ionization detector to measure unburned hydrocarbons as methane. A strong linear relationship exists between the two measurements. Multiplying the hydrocarbon value of the cold train FID by 1.67 will give accurate representation of the measurements which would be obtained by the hot train, while avoiding the inherent problems of instrument plugging and failure.

BASELINE CONVENTIONAL STOVES

Carbon Monoxide Emissions

Fig. 6 is a plot of carbon monoxide emissions as a function of firing rate. Resultant emissions were fairly uniform at about 50 g/kg of wood fired, for firing rates over 4 kg/h. However, below this rate, emissions increased rapidly with decreased burning rate. At a firing rate of 2 kg/h, emission levels average 200 g/kg. This rapid increase in emission levels occurs at the firing rate where the stove will typically spend the majority of its operating time, for most houses.

Hydrocarbon Emissions

Fig. 7 is a plot of hydrocarbon emissions as a function of firing rate. It indicates that levels are likely to be very low, less than 10 g/kg wood fired, at firing rates above 4 kg/h. Below that level, the emissions rise sharply, to 85 g/kg at 2 kg/h, although the data is somewhat scattered.

POM Emissions

Total POM emission levels are reported as normalized values in Fig. 8. Again, the sharp rise in levels below 3 kg/h is clearly visible.

ADVANCED DESIGN STOVES

Catalyst-Equipped Stove

The profiles of test results for the catalyst-equipped stove were similar to those for the baseline stoves discussed in the previous section. Because of sample contamination in the analysis laboratory, no POM data is presently available for this appliance.

Examining a typical plot, carbon monoxide vs firing rate, as given in Fig. 9, levels with no catalyst in place are similar to those for the baseline stoves. With the catalyst installed, the curve has a similar shape, but is displaced to the left, with the point of rapidly increasing emissions lowered from 3.5 kg/h to 2.2 kg/h. At 2 kg/h, emission levels are around 50 g/kg, compared to 140 g/kg without the catalyst. Given that efficiency is also likely to be increased, actual emissions per unit heat demand will be further reduced. Similar results were observed for the hydrocarbon emissions.

Advanced Downdraft Stove

Again, profiles for HC and CO emissions are similar, as shown in Fig. 10 and 11, respectively. These indicate a significant shift to the left for the point at which emissions begin to rise, now only at less than 2 kg/h. Above this rate, emission levels show no significant change from the baseline unit, so emissions reductions are achieved due to widening of the operating range. Limited POM results, presented in Fig. 12, give very low levels for all runs, well below those for other appliances measured to date. Further experiments will be carried out to validate these findings before firm conclusions can be drawn.

CONCLUSIONS

1. Carbon monoxide and hydrocarbon emissions from conventional wood-fired appliances are at least an order of magnitude above those from domestic oil furnaces.
2. Residential wood-fired appliances of conventional combustion design can be the major source of polycyclic organic emissions (POM's).
3. Typical home heat input requirements will be at or below the critical rate for typical well-designed conventional stoves, for the majority of the heating season.
4. Emission levels for carbon monoxide, hydrocarbons and POM's are strongly dependent on firing rate, below a critical rate which is design dependent. For well-designed conventional stoves, this rate is about 4 kg/h.
5. Above this critical firing rate, emission levels are much less sensitive to firing rate.
6. The critical burn rate is stove dependent. Combustion strategies, such as advanced downdraft into refractory or horizontal baffle with catalyst, can be used to reduce this rate, permitting operation at much reduced emission levels for most of the heating season.

7. Even though the critical burn rate is much reduced, emission levels above this rate may not be altered significantly. Thus, if a stove is to be evaluated for emission levels or propensity for creosote formation, it must be tested over a realistic operating range, with special emphasis on the lower end of this range.

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Table 1 - Average ultimate and proximate analysis of wood

<u>Parameter</u>	<u>Wood</u> <u>% by weight</u>	<u>No. 2 oil</u> <u>% by weight</u>
Proximate Analysis		
Volatile Matter	82.1	
Fixed Carbon	17.6	
Ultimate Analysis		
Carbon	49.7	87.5
Hydrogen	5.8	12.1
Sulphur	0.02	0.3
Nitrogen	0.09	-
Ash	0.3	-
Oxygen	44.1	-

Table 2 - Estimate of POM emissions by source type

<u>Source</u>	<u>% Total POM Emissions</u>
Open Burning	37
Residential Wood Combustion	35
Road Vehicles	10
Coal-Fired Boilers	0.6
Wood-Fired Boilers	0.1

Table 3 - Typical emissions from wood stoves and oil furnaces

Pollutant	Wood Stove		Oil Furnace
	<u>g/kg</u>	<u>g/J</u>	<u>g/J</u>
CO	150	10	.03
HC	25	2	.003
SO ₂	-	.02	.22
NO _X	2	.15	.1
Particulates	13	1	.03
POM	.3	.02	.000003

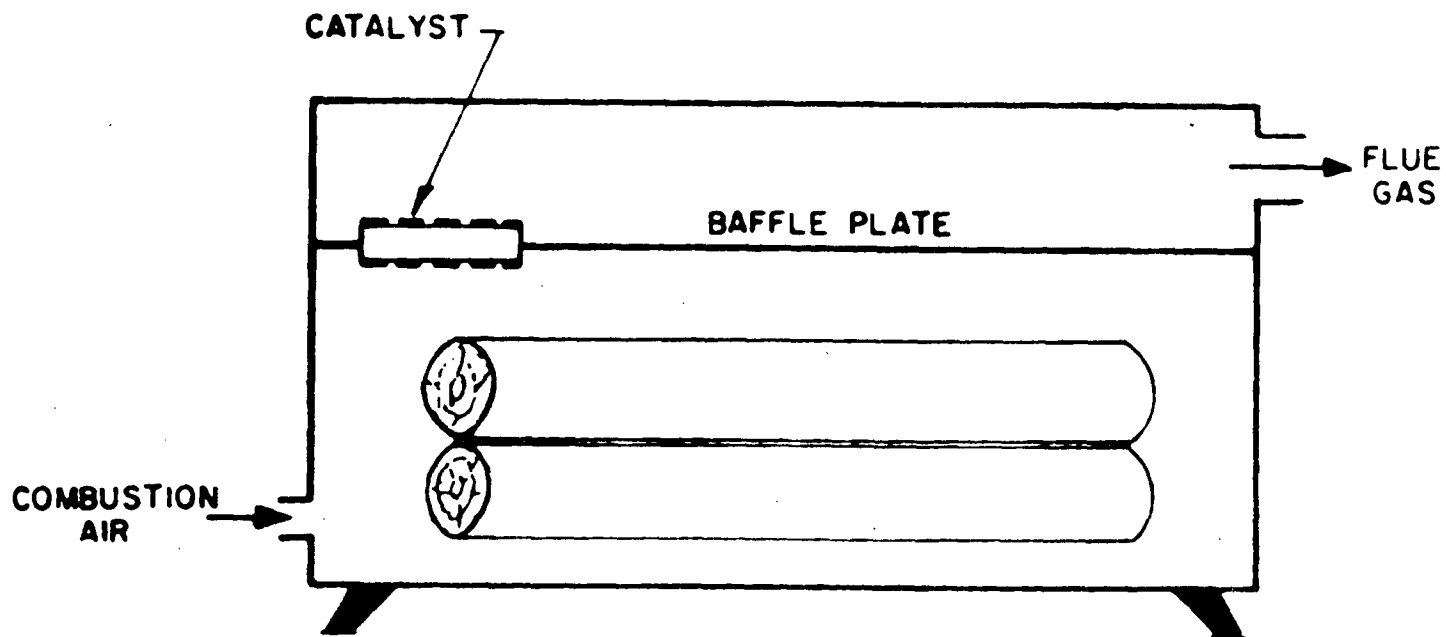


Figure 1. Advanced horizontal baffle stove with catalyst.

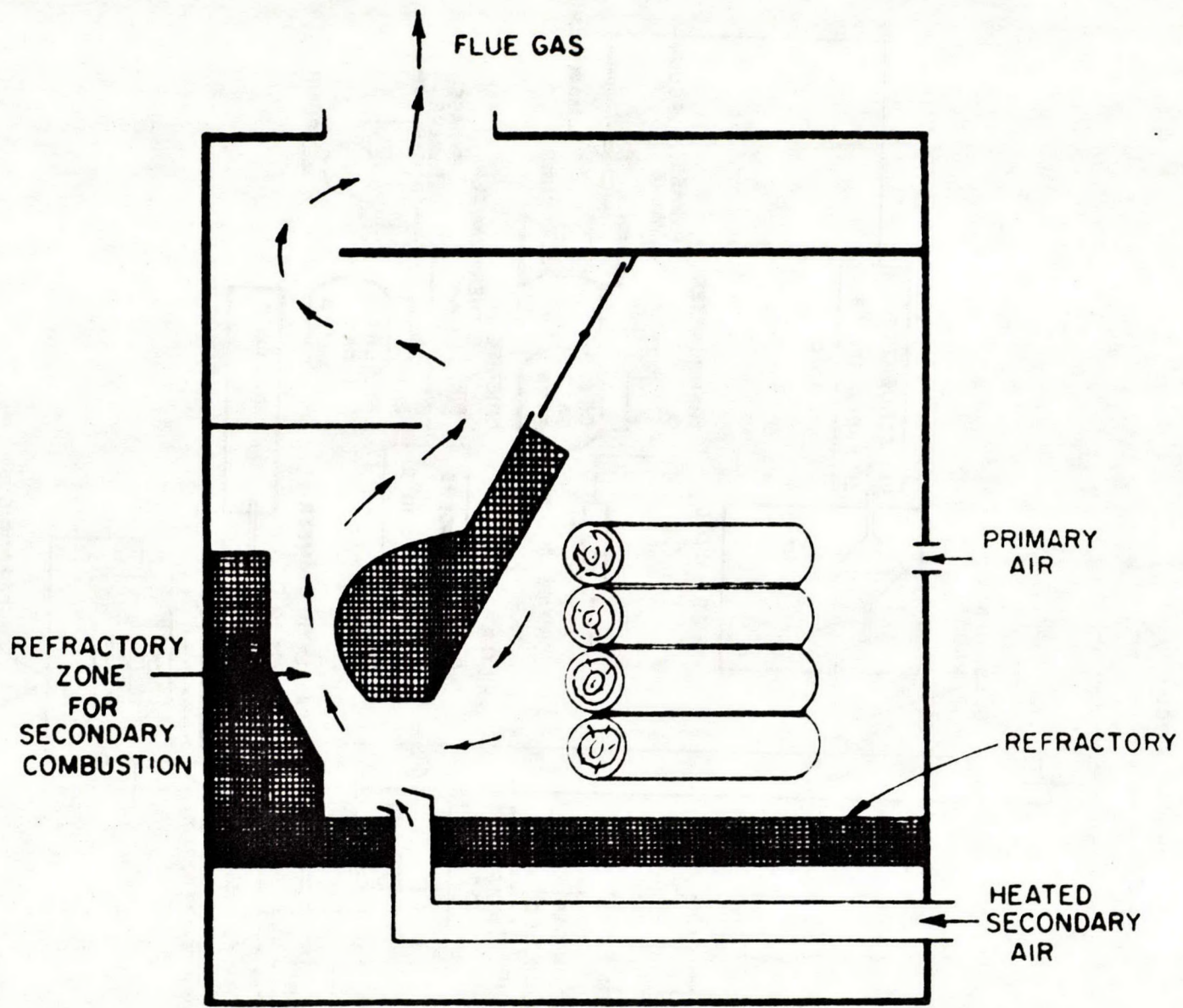


Figure 2. Prototype downdraft-into-refractory wood stove.

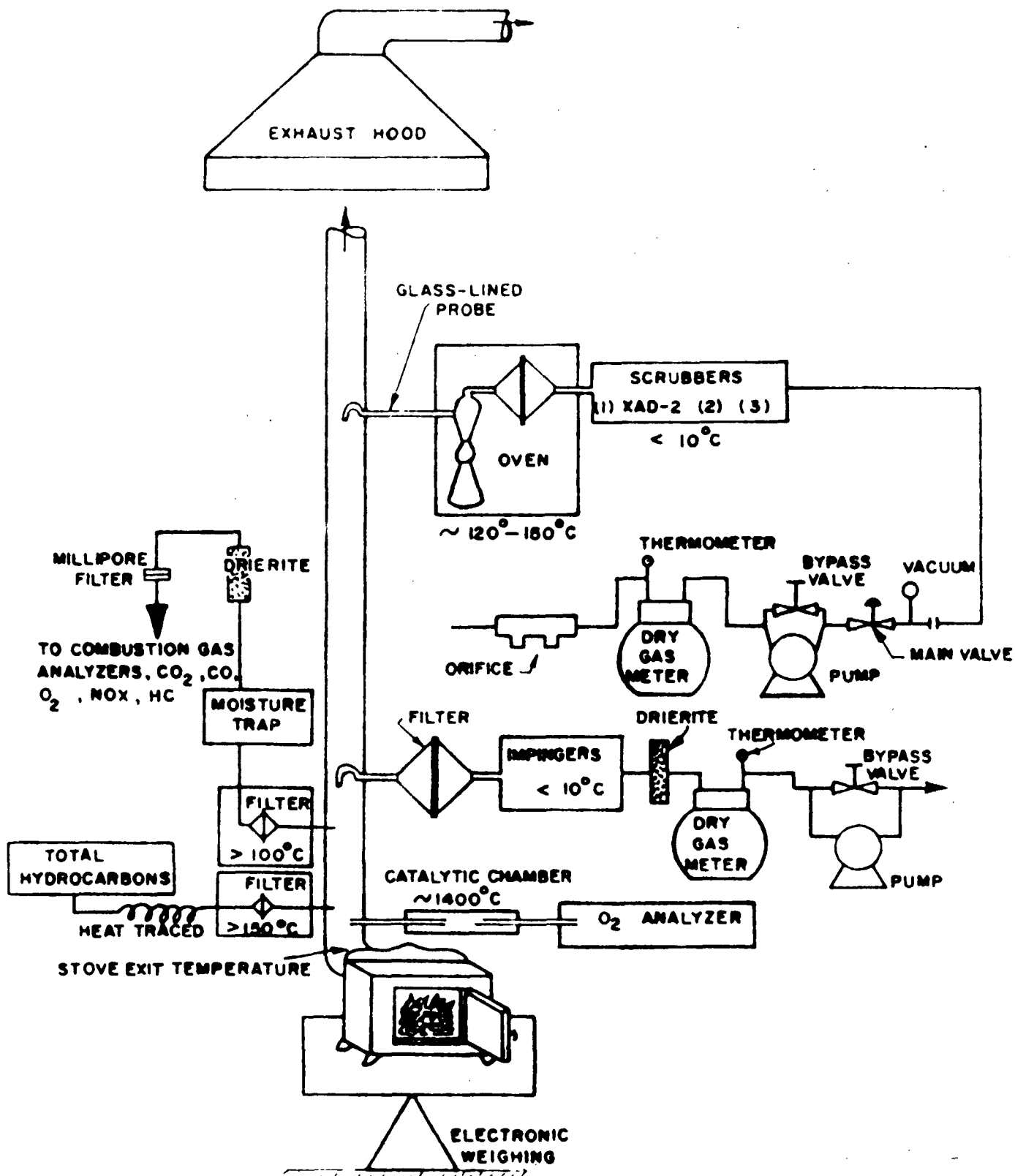
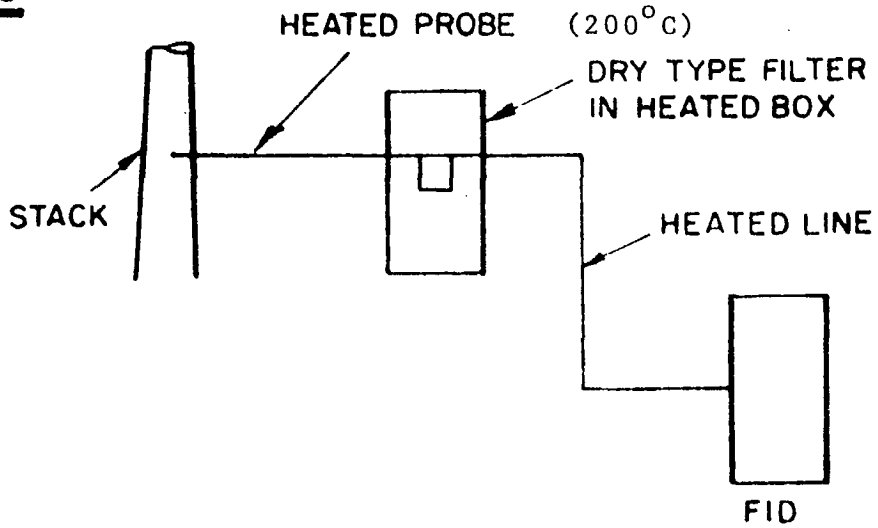


Figure 3. Schematic of CCRL sampling system to measure wood stove performance.

HOT FID



COLD FID

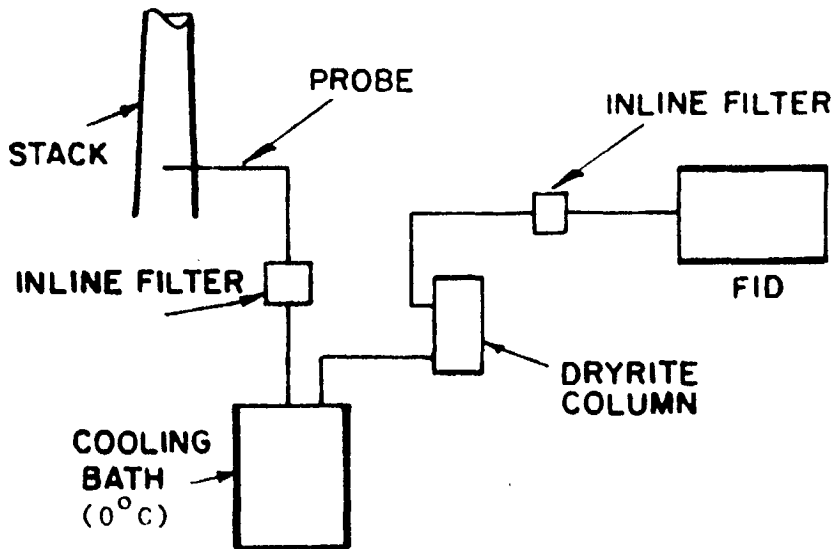


Figure 4. Schematics of hot and cold sampling systems for hydrocarbon measurement with flame ionization detector (FID).

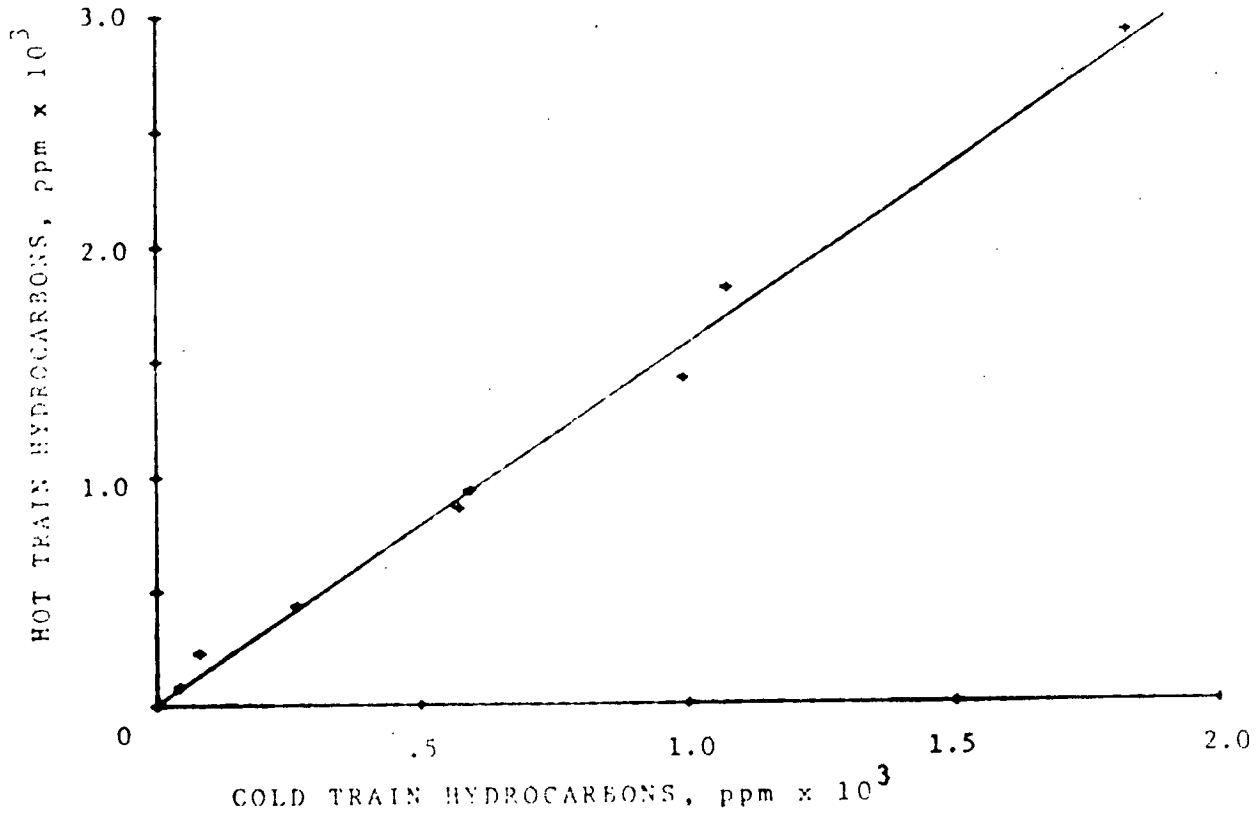


Figure 5. Hydrocarbon FID measurements with hot and cold sampling trains.

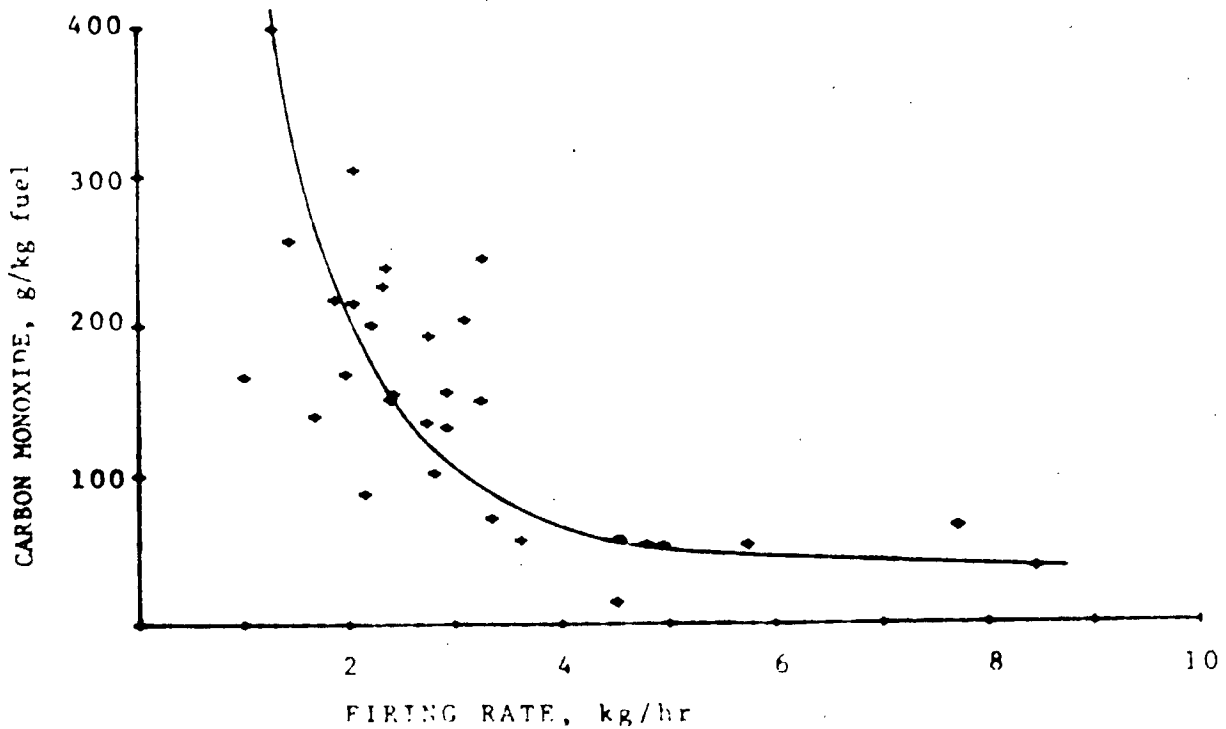


Figure 6. Variation of carbon monoxide with firing rate, conventional stoves.

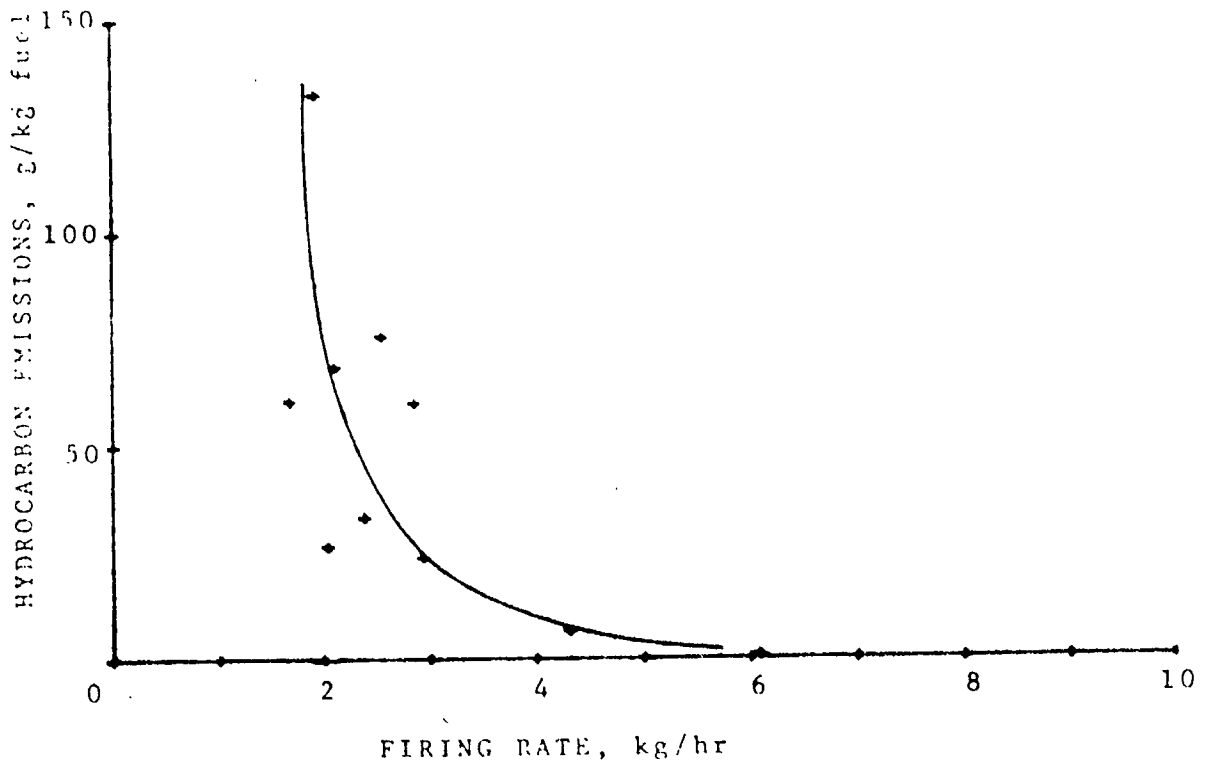


Figure 7. Variation of hydrocarbons with firing rate, conventional stoves.

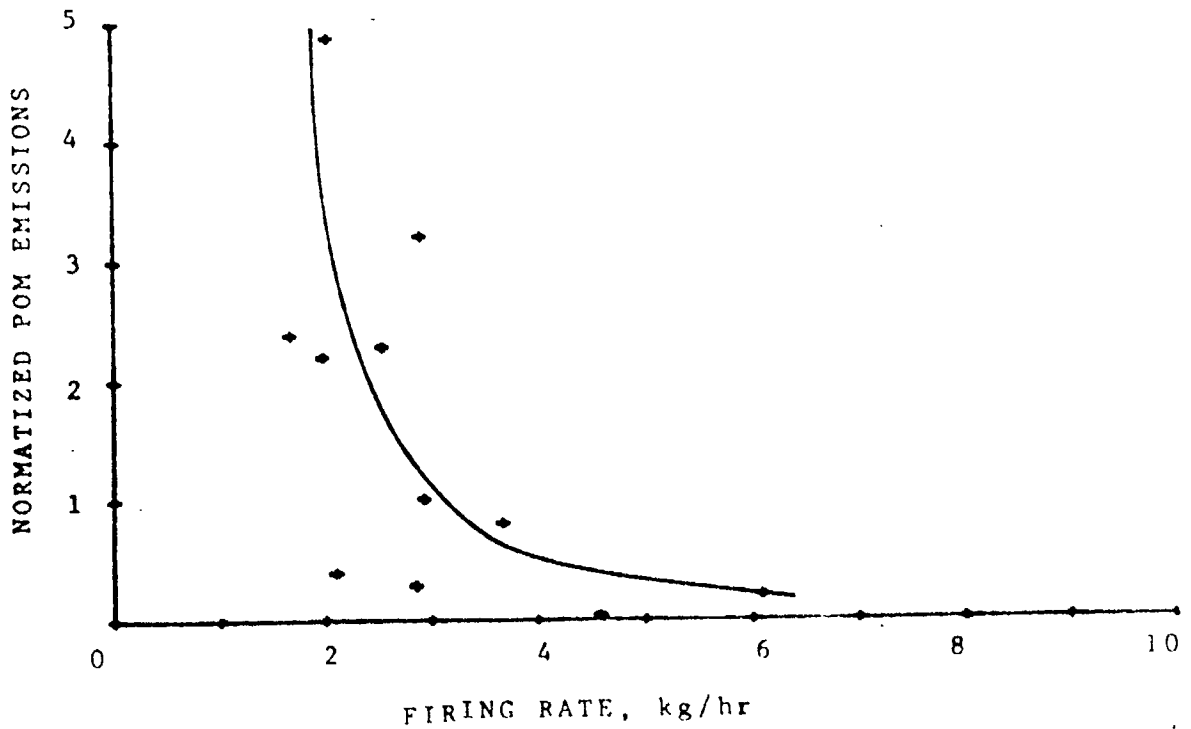


Figure 8. Variation of POM emissions with firing rate, conventional stoves.

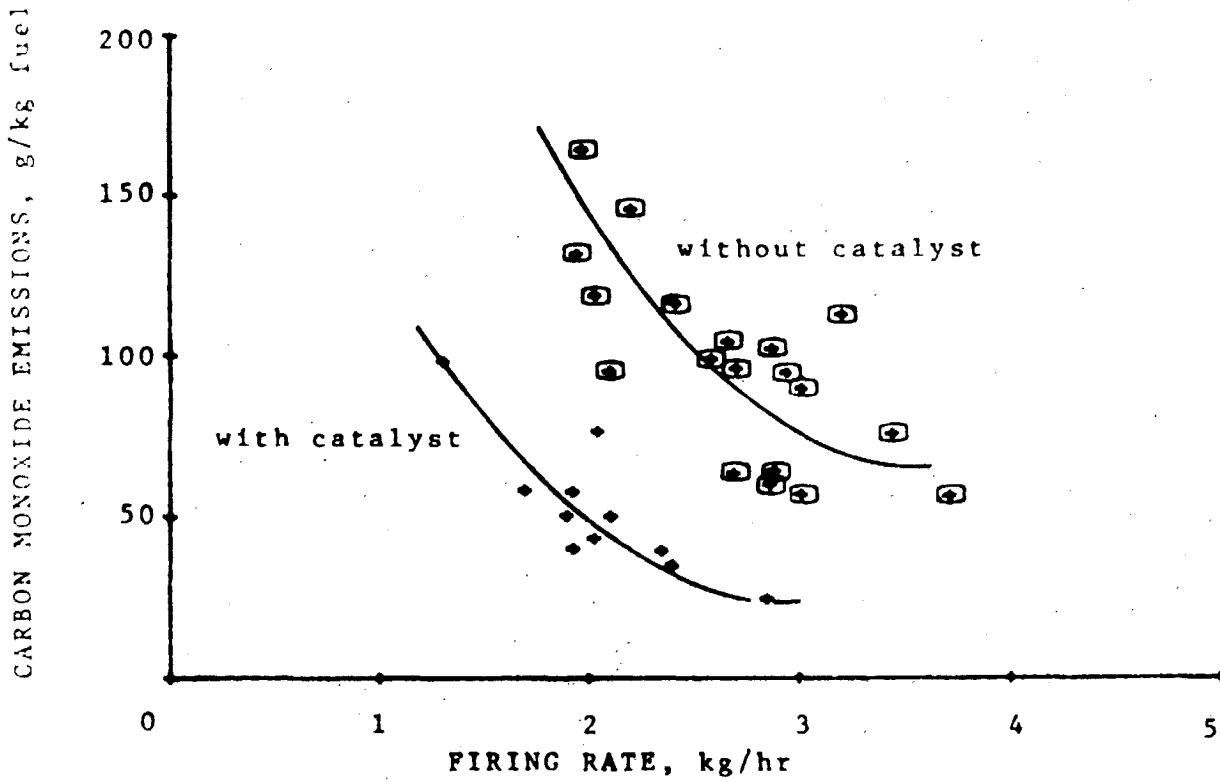


Figure 9. Variation of CO emissions with firing rate, catalyst-equipped horizontal baffle stove.

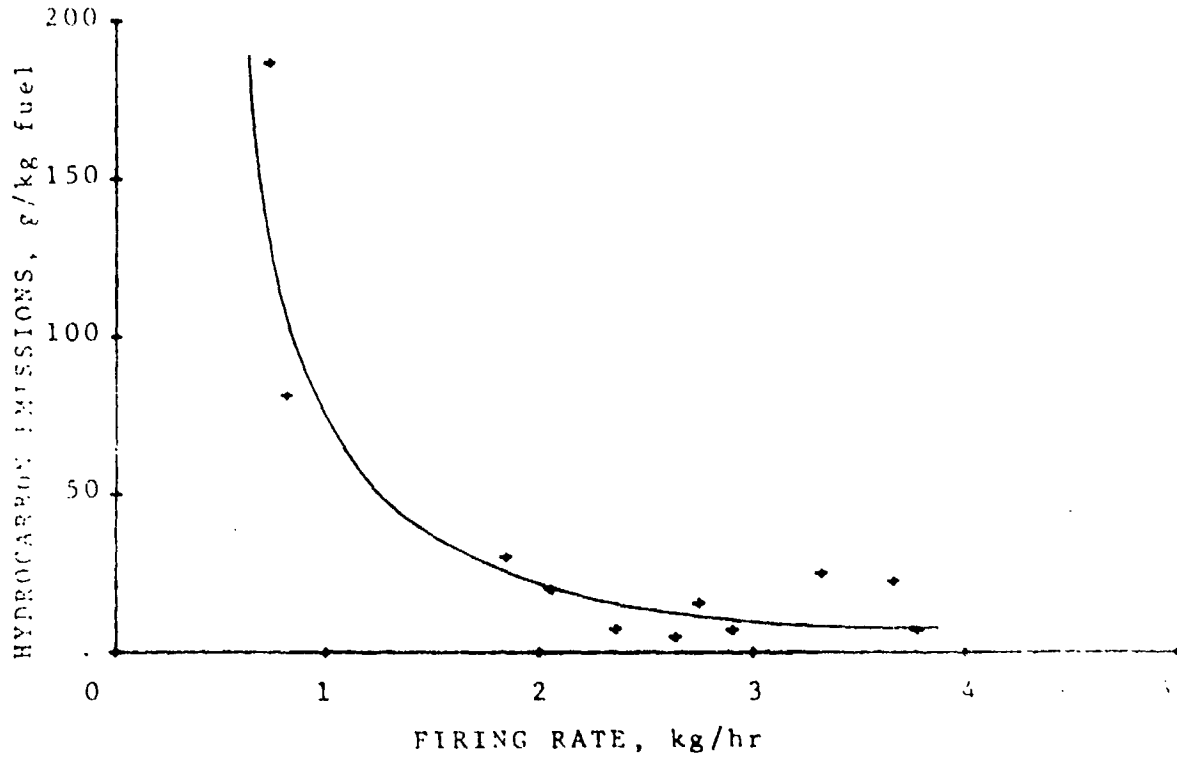


Figure 10. Effect of firing rate on hydrocarbon emissions, prototype downdraft-into-refractory stove.

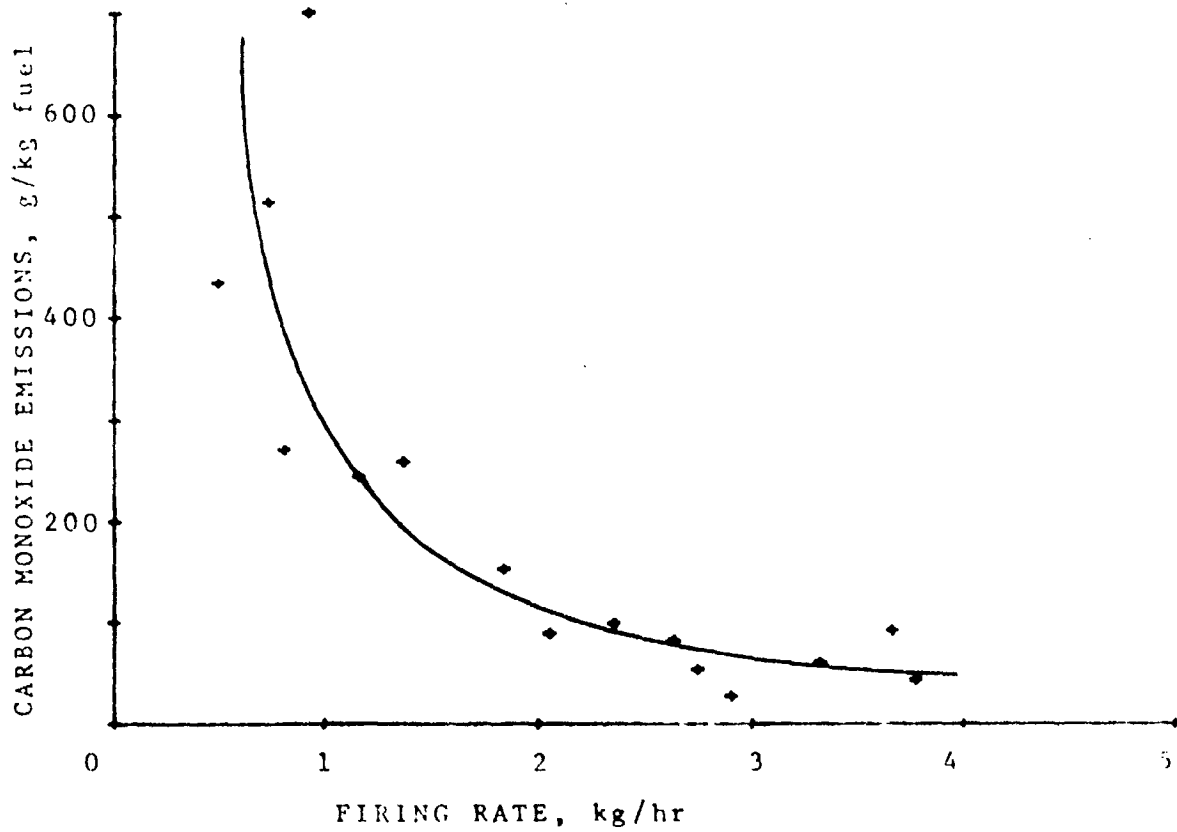


Figure 11. Effect of firing rate on carbon monoxide emissions, prototype downdraft-into-refractory stove.

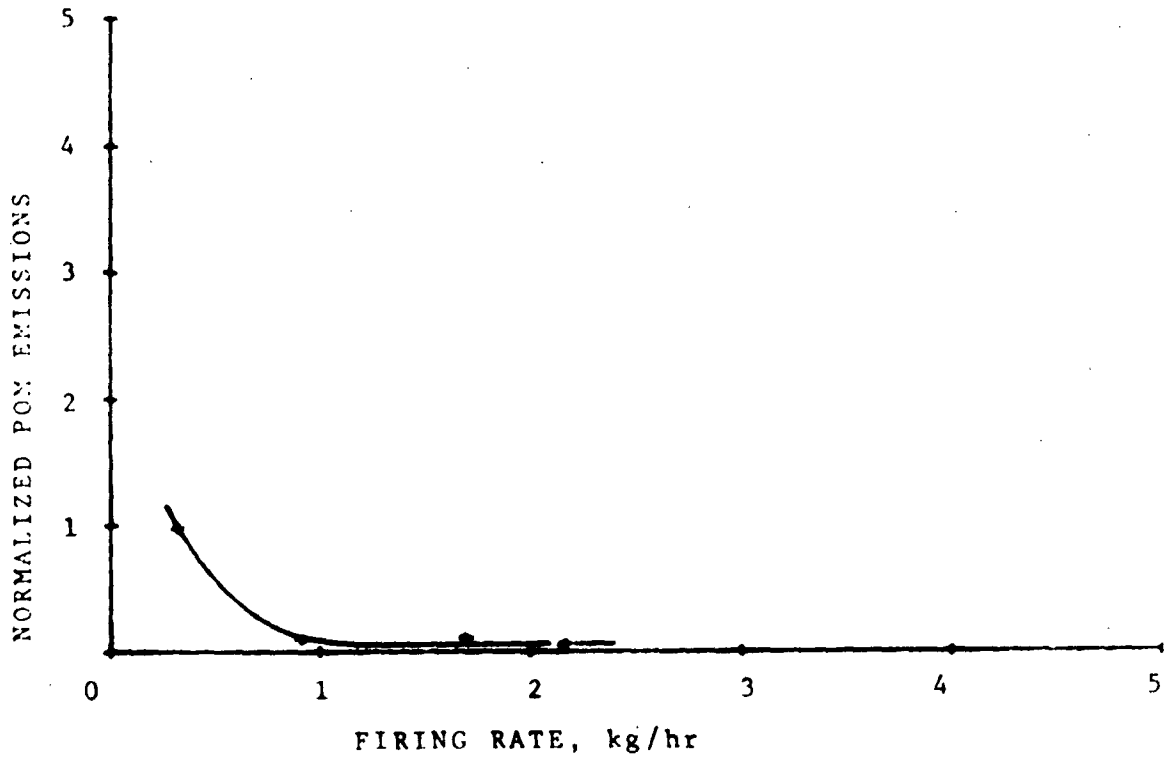


Figure 12. Effect of firing rate on polycyclic organic matter (POM) emissions, prototype downdraft-into-refractory stove.