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EFFECTS OF FIRING RATE AND DESIGN ON DOMESTIC WOOD STOVE PERFORMANCE

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by

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ABSTRACT

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.

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INTRODUCTION

To ensure the wide-spread acceptability of wood-fired appliances, their 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. 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.

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 a range of firing rates as well as 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 (4). These samples were submitted to Environment Canada for detailed POM analysis, in accordance with standard techniques (5).

EXPERIMENTAL RESULTS

HOME ENERGY DEMAND

Other papers (2, 3) 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.

From Reference 1, average stove firing rates should be below 4 kg/hr over most of the heating season, for the majority of Canadian homes.

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 are 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 are 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. 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.
2. 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.
3. Above this critical firing rate, emission levels are much less sensitive to firing rate.
4. 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.
5. 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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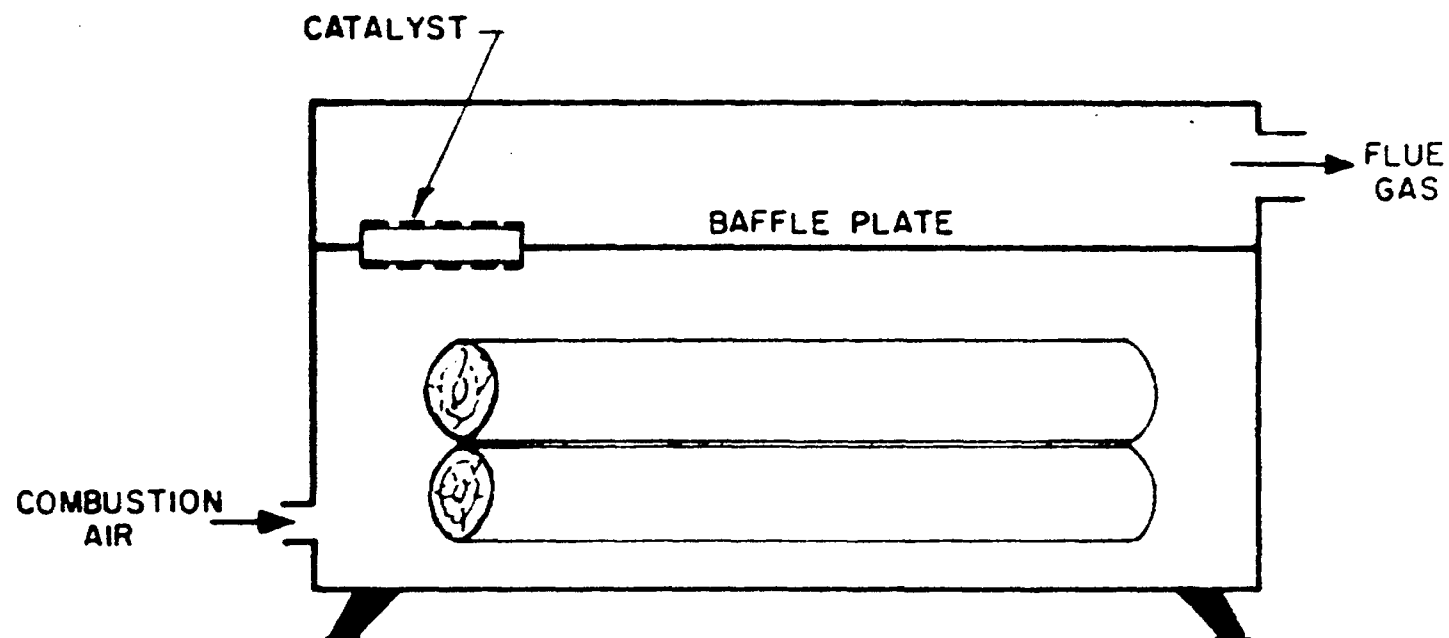


Figure 1. Advanced design horizontal baffle stove with catalyst

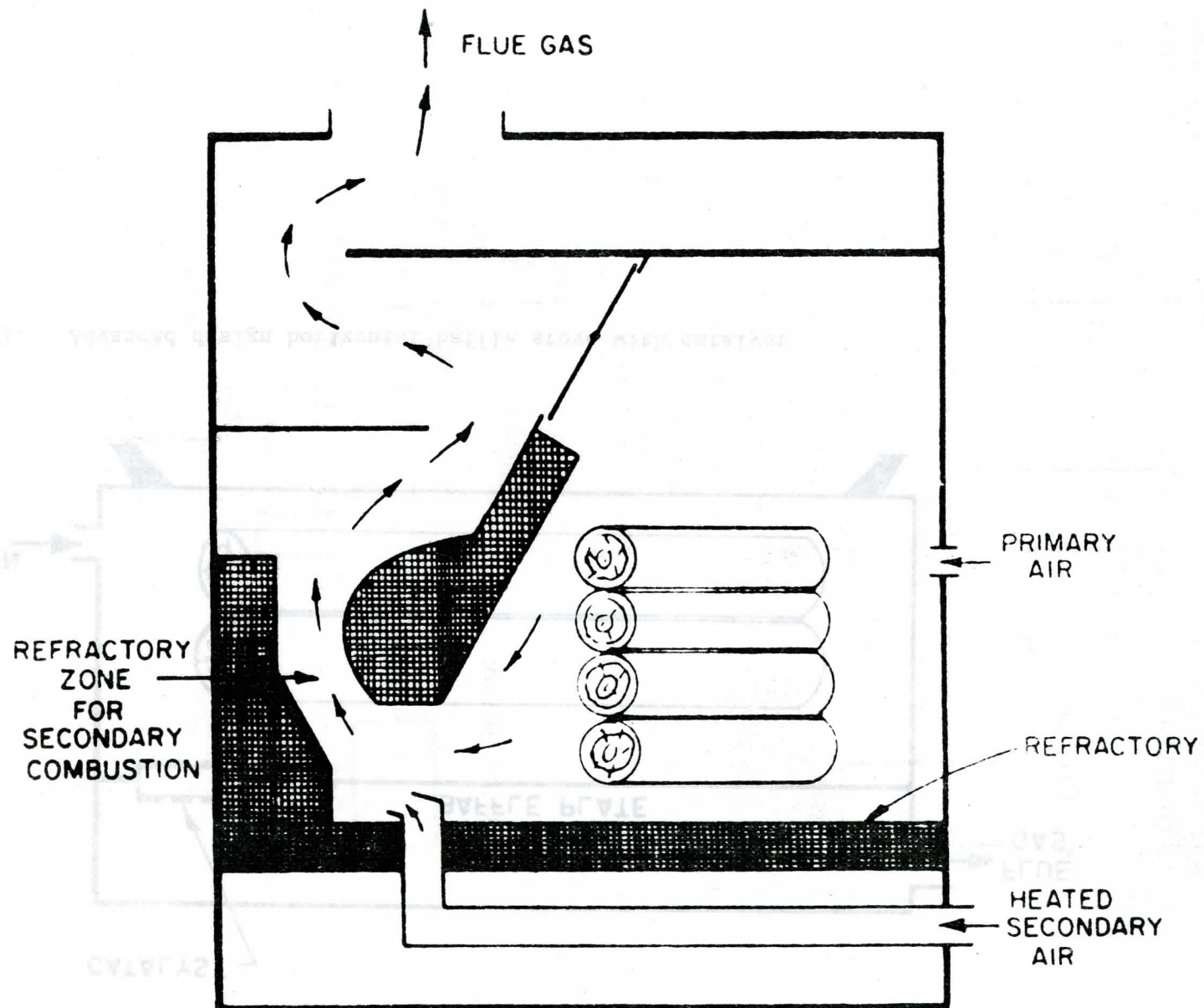


Figure 2. Prototype advanced design downdraft-into-refractory wood stove.

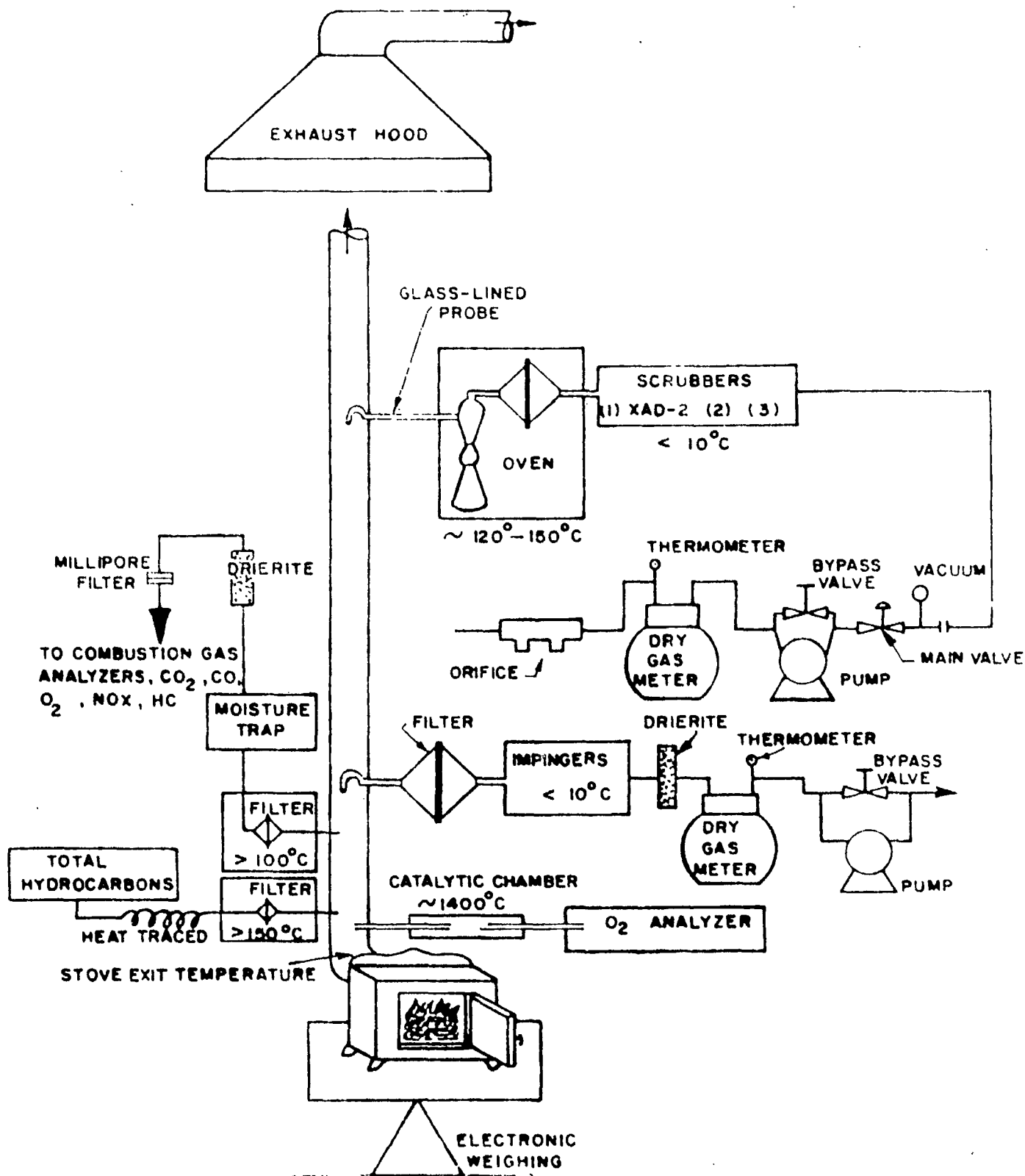
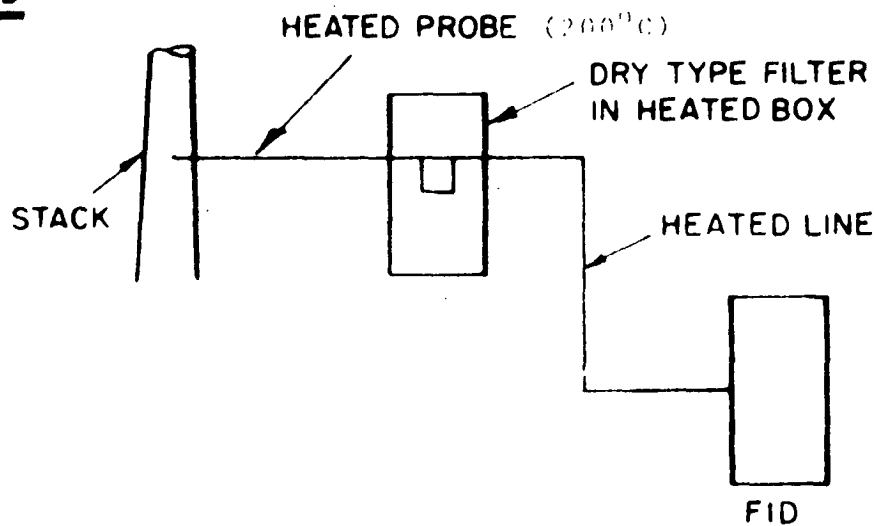


Figure 3. Schematic of CCRL sampling system to measure wood stove performance.

HOT FID



COLD FID

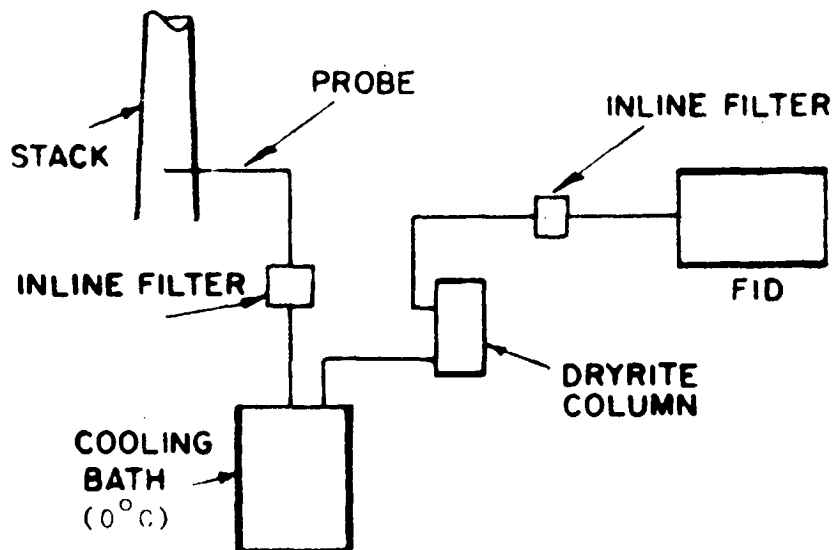


Figure 4. Schematics of hot and cold line sampling systems for hydrocarbon measurement with flame ionization detectors (FID).

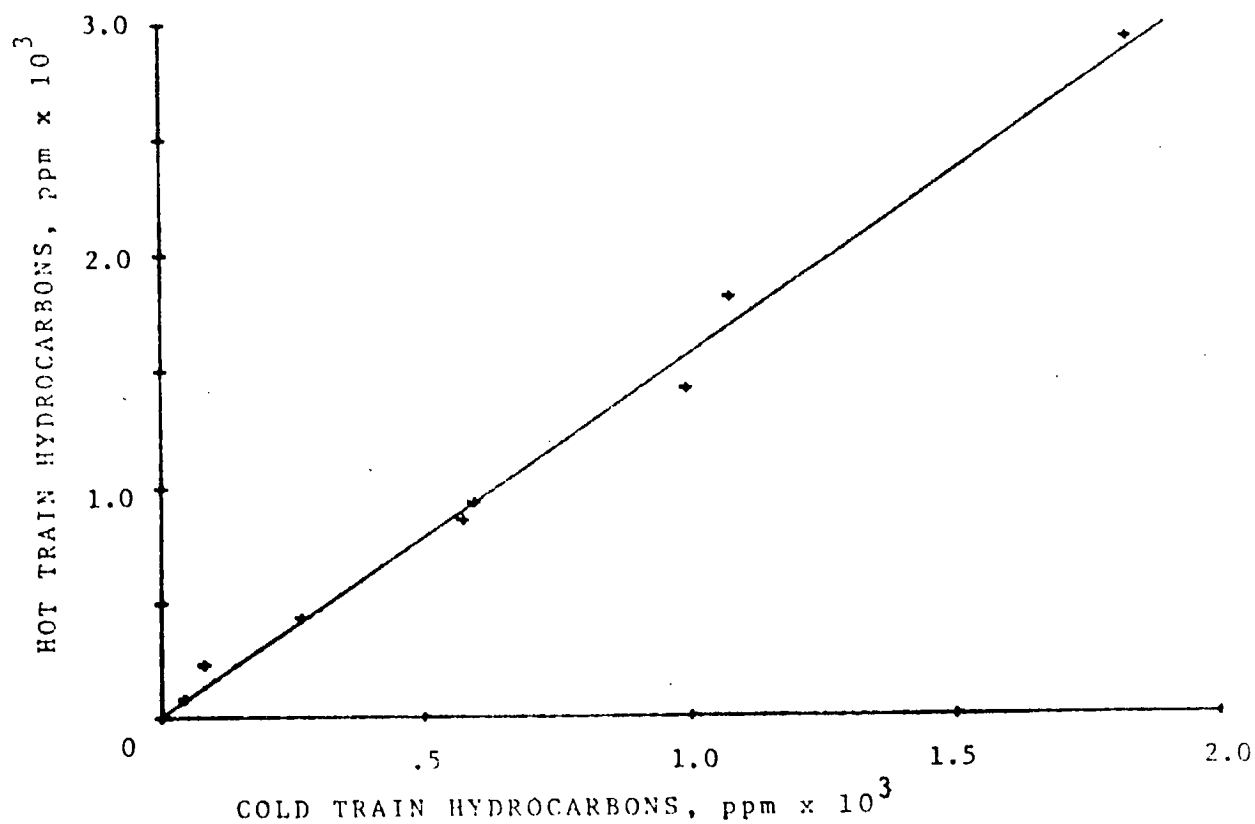


Figure 5. Hydrocarbon FID measurements with hot and cold sampling trains.

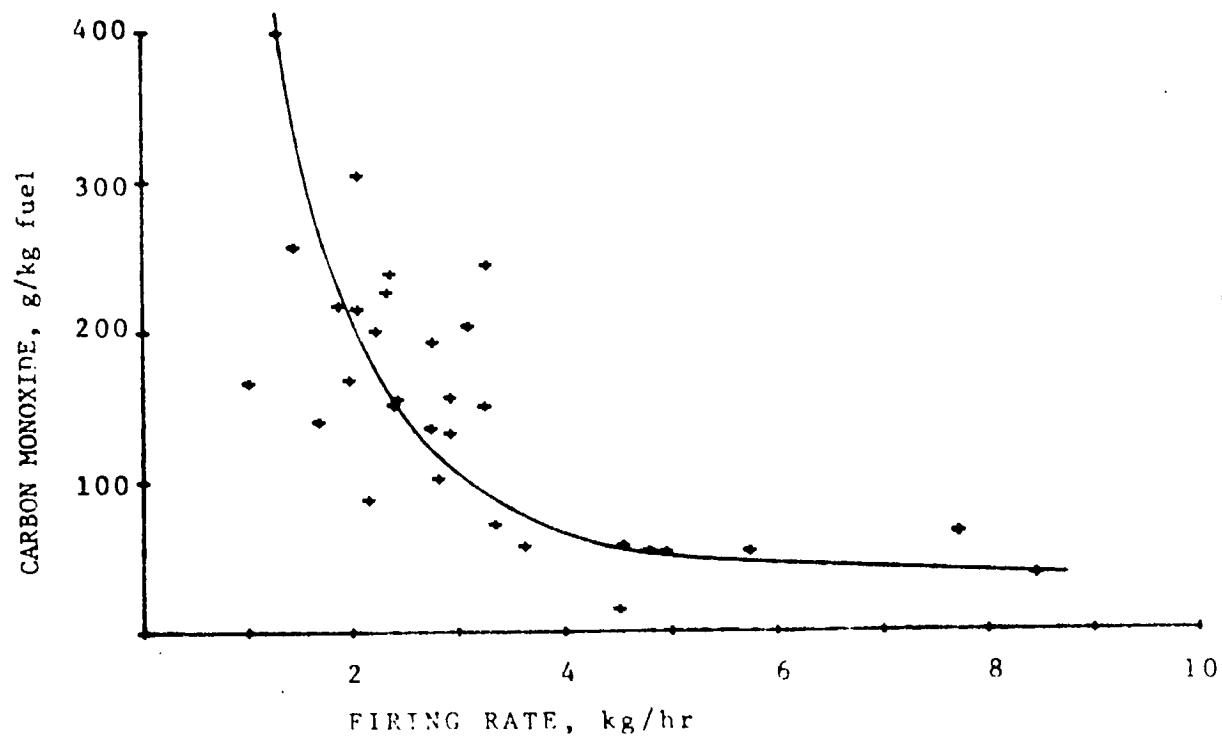


Figure 6. Variation in carbon monoxide with firing rate, conventional stoves.

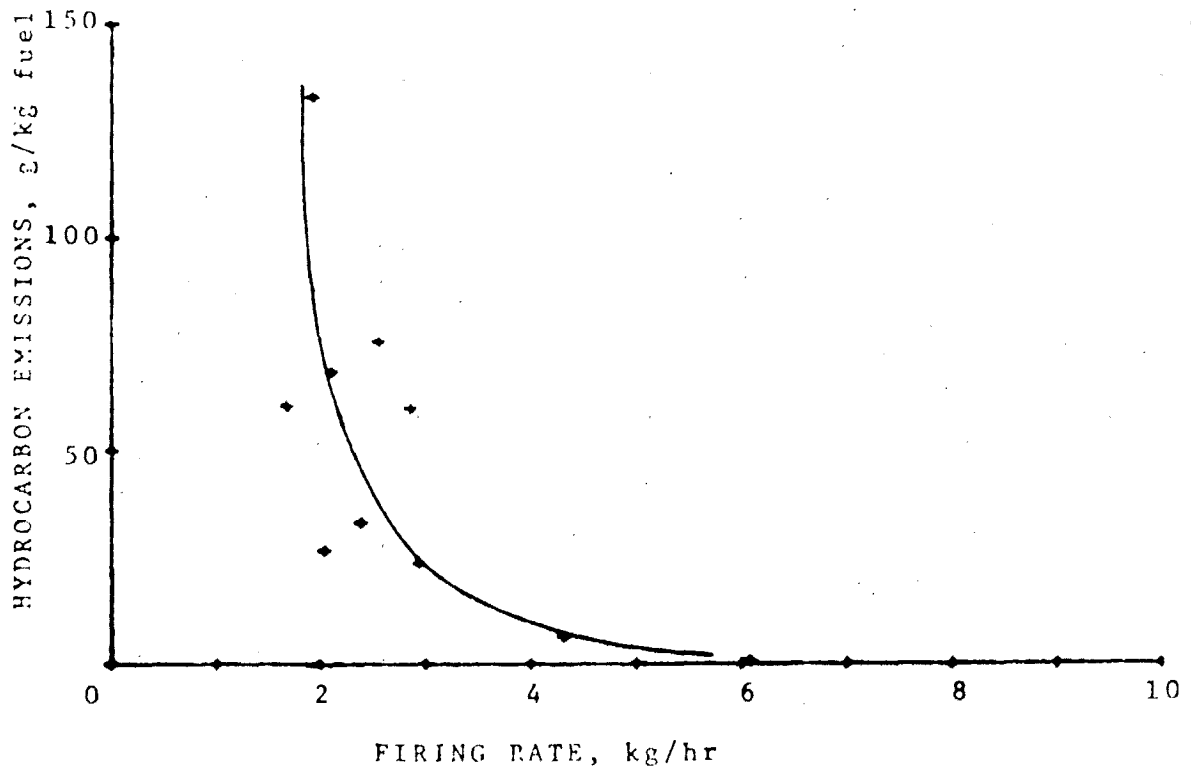


Figure 7. Variation in hydrocarbon emissions with firing rate, conventional stoves

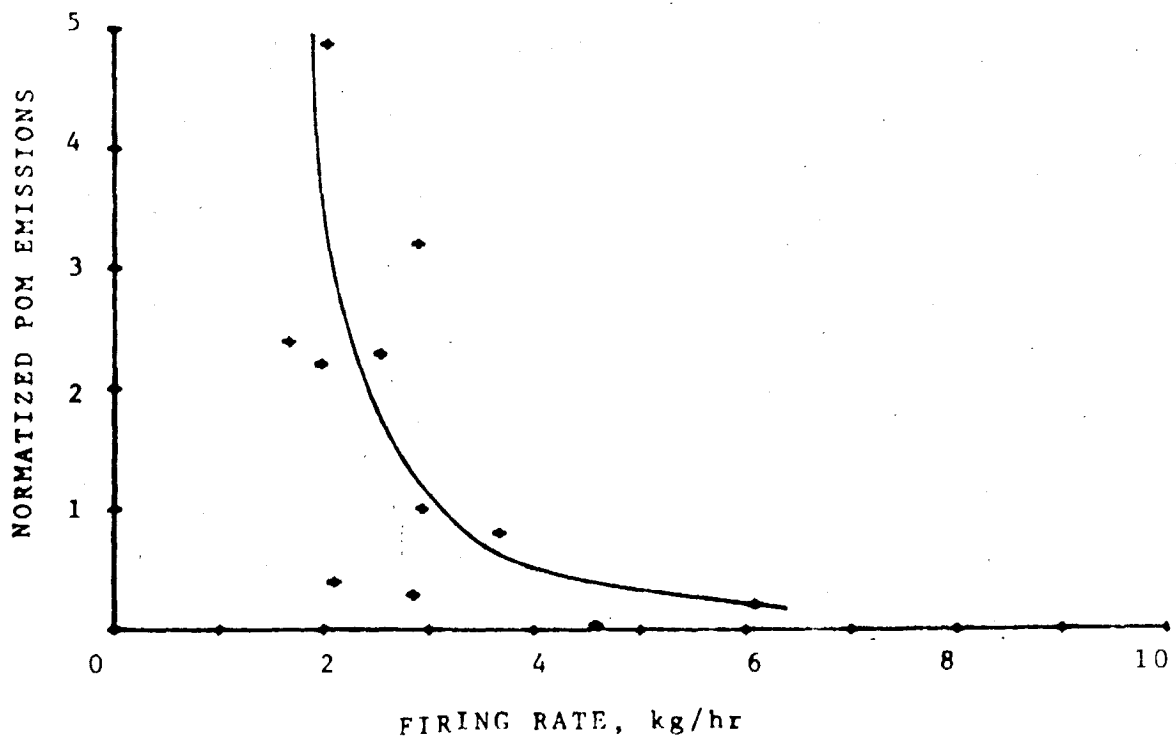


Figure 8. Variation in POM emissions with firing rate, conventional stoves.

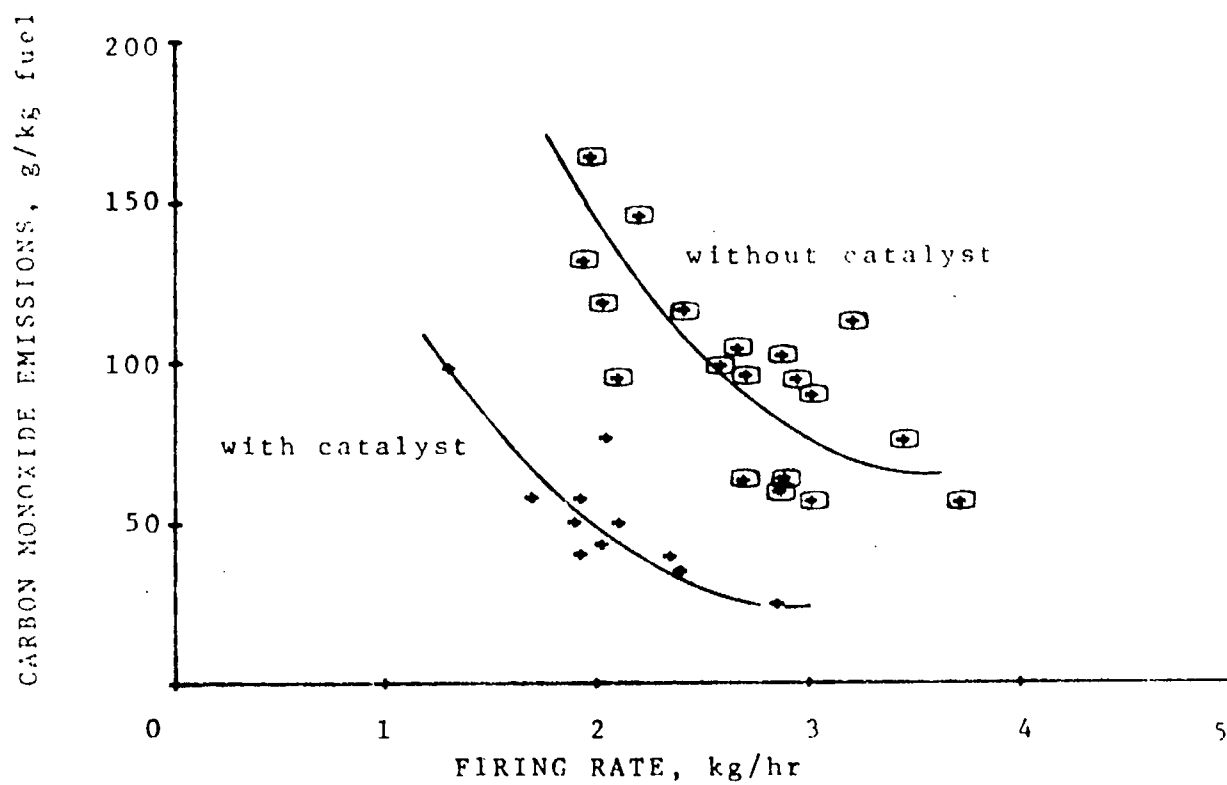


Figure 9. Variation of CO emissions with firing rate, catalyst-equipped horizontal baffle stove.

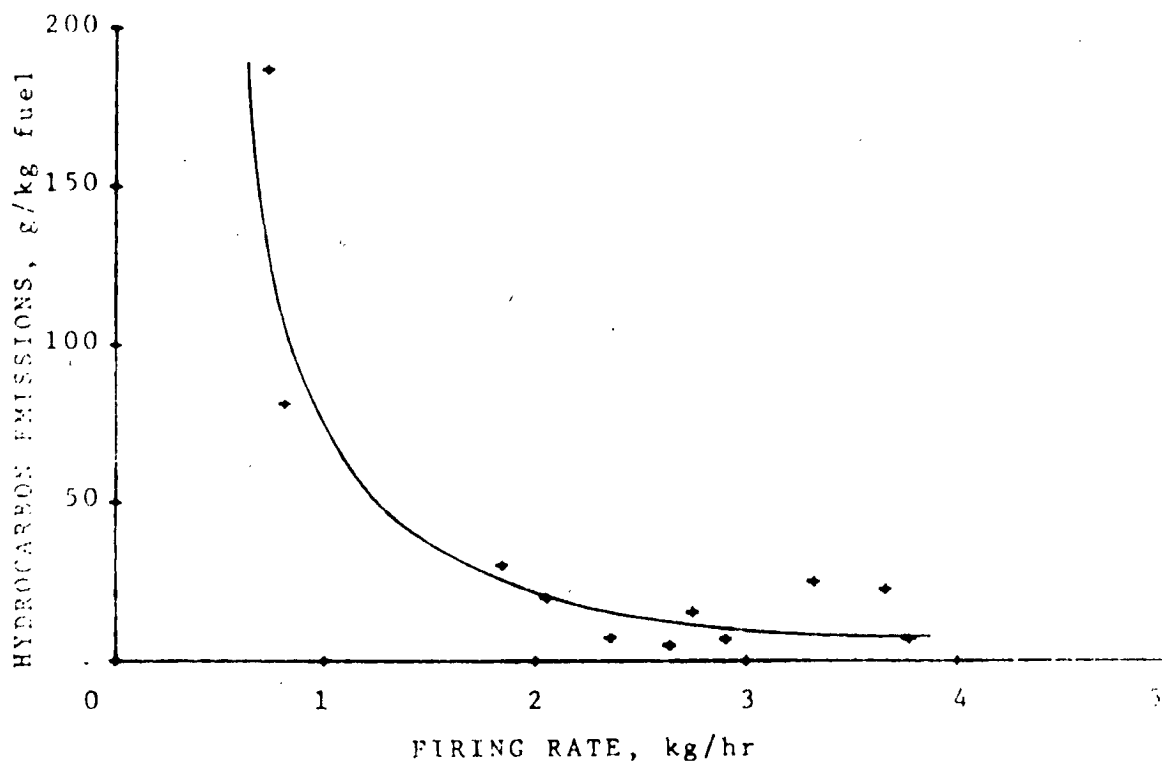


Figure 10. Effect of firing rate on hydrocarbon emissions, prototype downdraft-into-refractory stove.

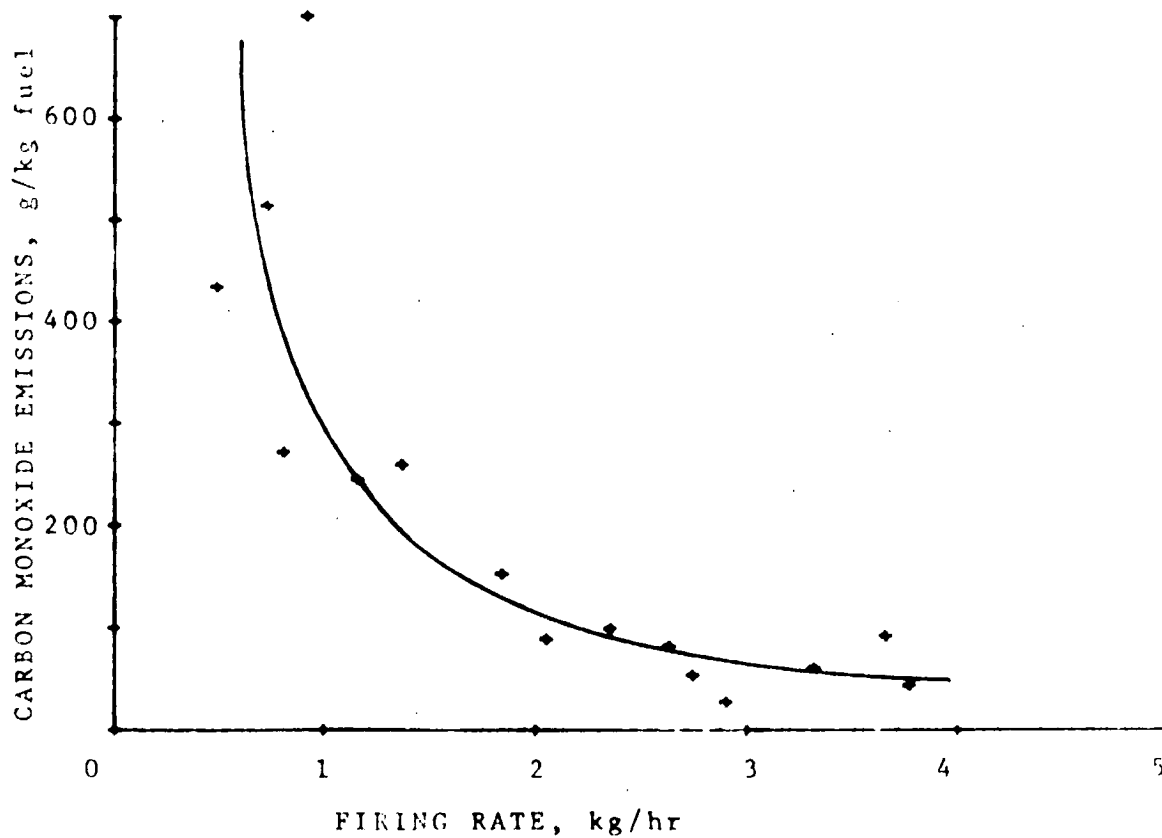


Figure 11. Effect of firing rate on CO emissions, prototype downdraft-into-refractory stove.

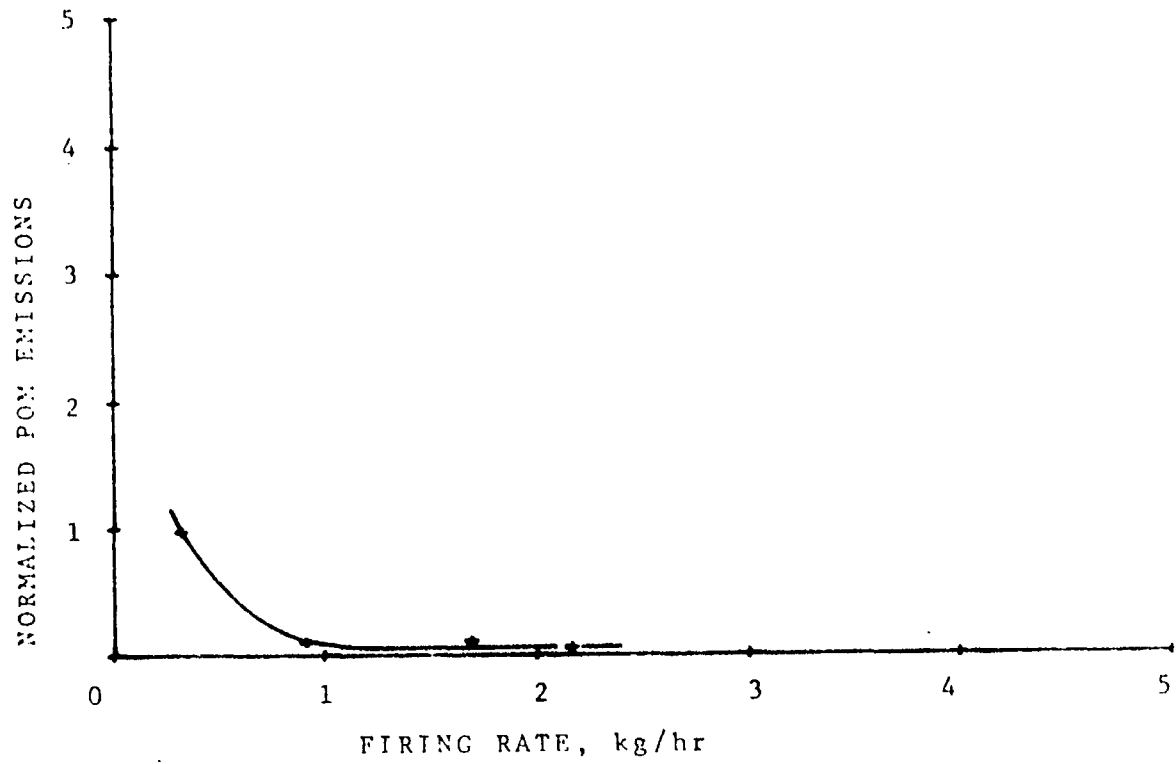


Figure 12. Effect of firing rate on POM emissions, prototype downdraft-into-refractory stove.