FIELD PERFORMANCE OF WOODBURNING STOVES IN CRESTED BUTTE, COLORADO

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Abstract. The carbon monoxide (CO) and particulate matter (PM) emissions of woodburning stoves have been measured under field conditions. Both conventional airtight stoves and newly installed airtight stoves certified by the U.S. Environmental Protection Agency to be low emitters of PM were monitored. The certified stoves were of two types, catalytic and noncatalytic. Compared to the conventional stoves, PM emission rates (g/hr) were reduced approximately 70% by both types of certified stoves. The CO emission rates were reduced 71% and 53% by catalytic and noncatalytic stoves respectively. These rate reductions occur because the certified stoves burn cleaner (less pollutant formation per kg of wood burned) and the average burn rate of certified stoves in field use is less than the average burn rate of conventional stoves.

1. Introduction

The town of Crested Butte nestles in a valley at an elevation of 8850 ft (2700 m) in the Rocky Mountains of Colorado. Wood is the primary fuel for home heating, and atmospheric inversions sometimes result in stagnant clouds of woodsmoke lingering over the town. In the summer of 1988, as part of an effort to improve air quality, the town embarked on a woodstove replacement program which was supported by a stove industry trade association, the Wood Heating Alliance (WHA), and monitored with the support of EPA Region 8 and EPA's Office of Research and Development (ORD). Homeowners were given discounts on new EPA-certified low emission woodstoves to replace their conventional woodstoves. People could keep their old stoves, but would be subject to a $30/month polluter's fee. To help assess the effectiveness of this stove replacement program the Town of Crested Butte contracted with Virginia Polytechnic Institute (VPI) for the field measurement of woodstove emissions during the winters of 1988–89 (i.e. prior to the woodstove replacement) and 1989–1990. Both particulate matter (PM) and carbon monoxide (CO) emissions were to be measured.

In the first winter of the study (1988–89) a total of 13 stoves were monitored: two were the same model certified catalytic stove and 11 were conventional. This study resulted in a database (46 site-weeks of stove monitoring) for conventional stove PM and CO emissions prior to the stove replacement program and also provided

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data on the performance of one certified stove model.

In the second winter of the study (1989-90) 24 appliances were monitored: seven were conventional stoves, 12 were catalytic, and five were noncatalytic. The catalytic and noncatalytic stoves were all certified for sale in Colorado; i.e. they passed both the EPA PM standard and the 200 g/hr Colorado CO standard which existed at that time but is no longer in effect. While the emphasis of the work during the second year of study was the measurement of emissions from certified woodstoves, seven conventional woodstoves in houses outside the town limits were also monitored to provide confirmatory data on old technology stoves. This second year of study produced 128 valid site-weeks of woodstove monitoring.

During the second year of the study a local chimney sweep was employed by WHA to watch for excessive smoke emissions and to provide remedial actions (e.g. operator training, catalyst replacement) where appropriate. Most certified stoves were new at the start of the 1989–90 heating season, and many of the older catalytic stoves had new catalysts installed just prior to the heating season.

The project was overseen by an advisory committee composed of representatives of the Town of Crested Butte, Colorado Department of Health, EPA Region 8, EPA's ORD, and the WHA. Major project decisions, such as the number and types of appliances to be sampled, were made by the advisory committee.

The study reported here is part of a continuing effort to quantify the field performance of woodburning stoves. Other field studies have been undertaken in North America since 1985 to establish the emission rates of typical, uncontrolled conventional technology stoves and the degree of emission control achieved by newer stoves designed to reduce emissions.

The first major field study of woodstoves in normal consumer use in North America was a two-year study in 66 houses in Waterbury, Vermont, and Glens Falls, New York, over the 1985–86 and 1986–87 heating, seasons [1]. This study is formally known as the Northeast Cooperative Woodstove Study (NCWS) Phase I but is often referred to as the CONEG (Coalition of Northeastern Governors) study after one of the sponsors. Stove performance was closely monitored in 44 of the houses: 17 had catalytic stoves, 11 had noncatalytic low emission stoves, 10 had add-on or retrofit stoves, and 6 had conventional stoves. Of the new technology stoves, there were in general four houses with each model. Another group of 20 houses switched stoves between seasons. PM emissions were measured using an automated woodstove emission sampler (AWES) controlled by an electronic datalogger. The AWES sampler was programmed to sample for 1 minute out of 30 whenever the stack temperature was above 38°C. Emissions of CO were not measured, but creosote deposition and wood use were.

During the winter of 1986–87, two additional one-year field studies were undertaken. One of these was the Whitehorse Efficient Woodheat Demonstration in Canada [2]. This study evaluated new technology stoves in 14 houses over one heating season. Each participant's conventional stove was tested for three 1-week periods during December 1986 and early January 1987. A new technology stove

was then installed in each house. After 2–3 weeks (to get used to the new appliance), the stoves were tested for five one-week periods. Sampling equipment and methodology closely paralleled that followed in the NCWS Phase I work. The other field study undertaken during the winter of 1986–87 was in Portland, Oregon, and consisted of six houses, one each with two different model catalytic, low emission noncatalytic, and conventional technology stoves [3]. The four new technology models were certified to the EPA 1988 standard. Sampling equipment and methodologies were essentially the same as those used in NCWS Phase I.

The second round of field tests in the NCWS took place during the winter of 1988–89 [4]. Three catalytic and two low emission noncatalytic model stoves were tested in 25 houses in Glens Falls, New York. Each model stove was tested in five houses. All five stove models were EPA certified to the 1988 standards and were judged capable of meeting the EPA 1990 standards. Samples were collected and analyzed following procedures similar to those used in Phase I. Sensors were added to the bypass handles on the catalytic stoves to record the time of bypass activation and the interval between actions. Stove selection for the study involved an evaluation of potential for degradation and a stress test to further test durability. House selection factors emphasized factors which would lead to good stove performance; in all cases, flues in the houses of participants were upgraded for the study.

In the Crested Butte work a field sampler developed at VPI (hereafter referred to as the VPI sampler) was used. The VPI sampler is designed to continuously draw a sample of the flue gas into an evacuated tank as long as the stove is in operation, as evidenced by stack temperature being above a predetermined setpoint. The CO and CO_2 concentrations of the collected stack gas sample are measured with an NDIR analyzer after sampler retrieval. This eliminates the need for long-term, accurate gas concentration measurements on-site. Also, short-term events such as reload periods are sampled due to the continuous nature of the sample flow. Both PM and CO emissions are determined by the VPI sampler.

The simplicity of the VPI sampler operation and its workup procedures makes it possible to obtain CO and PM emission results within 72 hours of the retrieval of the sampler. Thus emission results can be evaluated as a field study proceeds and, if corrective actions are required, they can be taken earlier than would otherwise be possible. However, the VPI sampler as used in this study does not have provisions for recording data such as stack temperatures, fueling times and loads, and central heater activity. The AWES/datalogger used in other field studies to date [1-4] records these data, which have proved useful in interpreting emissions results.

Laboratory comparability tests [5] have shown that the PM measurements of the VPI sampler have excellent correlation with EPA Method 5G emission measurements for a wide range of appliances operated at different burn rates. The precision of the method for PM measurements is slightly better than that for EPA Method 5H but not as good as that for 5G practiced with 47 mm filters. Precision for CO measurements is about 2% and average error in CO measurements is only 1.1%. All PM emissions reported in this paper are as measured by the VPI sampler.

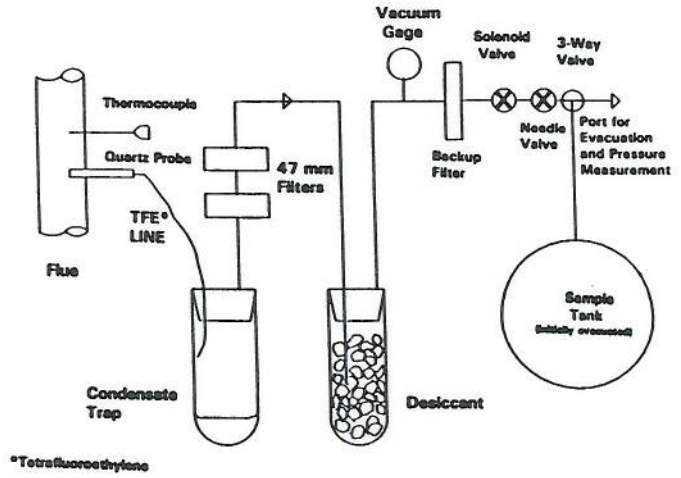

Fig. 1. Schematic of the VPI sampler.

2. Test Equipment and Procedures

The VPI sampler was used for all the emissions measurements and is shown schematically in Figure 1. The sampler consists of several components mounted atop a 0.074 m^3 steel tank. A 6 mm OD ×20 cm long quartz probe samples the flue gas. A 3 mm OD ×2 m long Teflon sample line directs the sample to a 30 mL glass trap, and the end of the sample line is positioned so that condensate coming out of the line will impinge on the inside wall of the trap. The trap is close-coupled to a pair of 47-mm polycarbonate filter holders containing glass fiber filters (Gelman 61631). Downstream of the second filter are a desiccant (calcium sulfate), vacuum gauge, solenoid valve, metering valve, and manually operated three-way valve with the common port connected to the tank. A temperature controller, which monitors flue gas temperature, determines when the solenoid valve is open; i.e., when gas is sampled from the flue. A typical case might be that the solenoid will remain open only when the flue temperature is above 60°C. An hourmeter wired in parallel with the solenoid valve records the time that the system is sampling. No sample pump is required at the field site because the tank, which is evacuated prior to placement in the field, provides the drawing force for the sample flow. Thus the sampler is virtually silent during its operation. The train may be thought of as an EPA Method 5G train with the addition of a room-temperature condensate trap between the probe and filters. Both the 5G and VPI trains end (as far as sample collection is concerned) with a room temperature filter.

Sampler operation was essentially the same as described previously [5]. The only significant difference between the laboratory and field procedures involved

TABLE I
Summary of 1988–1990 Crested Butte woodstove emission measurements.

Stove type	No. models	No. stoves	Fuel moisture	Burn rate	Particulate matter			Carbon monoxide		
			(dry %)	(dry kg/hr)	n[1]	g/kg	g/hr	n[1]	g/kg	g/hr
1988–89:										
Conv.	6	11	18.1	1.35	32	22.1	29.4	37	115	154
Cat.	1	2	26.8	0.86	6	5.5	5.2	9	40	35
1989–90:										
Conv.	6	7	16.1	1.64	27	22.2	35.2	27	111	178
Cat.	6	12	17.8	0.93	72	11.1	10.4	72	52	49
Noncat.	2	5	14.7	1.10	29	9.9	9.4	29	76	77
SUMMARY:										
Conv.	9	18	17.2	1.46	59	22.2	32.1	64	113	164
Cat.	6	13	18.8	0.92	78	10.6	10.0	81	51	48
Noncat.	2	5	14.7	1.10	29	9.9	9.4	29	76	77
All	17	36			166			174		

[1] Number of valid datapoints.

the measurement of fuel consumption. To avoid influencing operator behavior by requiring the operator to weigh wood just prior to putting it into the stove, the fuel consumption of the stove was monitored by the field staff. A part of the participant's woodpile, sufficient for over 7 days of burning, was weighed prior to the start of each sampling period. A brightly colored ribbon was laid on the unweighed wood and the weighed wood was restacked onto the pile. The wood on top of the ribbon was referred to as the 'designated woodpile'. The stove operator was instructed to use only the wood from the designated woodpile. Thus, the operator used the normal wood supply.

3. Results

Overall results of the project are shown in Table I. The following discussion deals with fuel moisture measurements, results of blank runs, and the field precision of the sampler before the emissions results are given.

3.1. Moisture Content Measurements

In the 1988–89 study and during the early part of the 1989–90 study wood moisture content was measured by desiccation of wood samples obtained by drilling holes in five pieces of wood at each site. About halfway through the 1989–90 study a drying oven became available and was used for the rest of the moisture determinations.

TABLE II
Moisture content of cordwood in Crested Butte.

	Site 1	Site 2	Site 3
Sample 1 (dry basis %)	24.3	15.5	8.6
Sample 2 (dry basis %)	25.2	17.0	8.6
Sample 3 (dry basis %)	30.2	14.5	8.5
Mean of 3 samples	26.6	15.7	8.6
Standard deviation (percentage points)	2.6	1.0	0.1

Experiments were performed to confirm earlier data indicating that desiccation can give accurate measurements, to show whether sampling five pieces of wood is adequate to characterize the moisture content of the fuel burned during an entire week, and to compare the desiccation method to use of an electrical resistance meter for moisture content measurements.

Unpublished laboratory data generated at VPI in early 1989 had shown that desiccation gave moisture contents about 1–2% lower than over drying. Since oven drying drives off organic material in addition to water, it is not surprising that oven-dry moisture contents are higher than desiccated values. Exactly how much of this difference is due to organic material is unknown, but it is commonly believed that the oven-dry value is more accurate; i.e., most of the 1–2% difference is generally believed to be due to moisture rather than organic material.

To quantify the relation between the desiccated and oven-dry values during this field study, 19 field samples were first desiccated to constant weight at room temperature and then dried in an oven at 102°C. For each run the moisture content was determined for both methods, and the average difference was 1.558% with a standard deviation of 0.436%. Based on these data all moisture contents determined by desiccation were increased by 1.558% for final data analysis.

Multiple moisture content samples were taken at three homes to see if the sampling of five logs gave a reasonably accurate measure of the average moisture content of the entire pile. The resulting dry basis percent moisture contents are shown in Table II. Each listed value represents the moisture content determined from a sample derived from five logs. Site 1 wood was exceptionally moist, site 2 wood was uncovered and wet on the surface, and site 3 wood was from a covered woodpile. These results indicate that random moisture content sampling errors

were on the order of a few percentage points at most. Such random errors are an inherent part of all field studies.

Although a resistance-type moisture meter was available during the study, resistance meter readings were not used because most of the wood is stored outdoors at temperatures reaching −40°C. Under these conditions it can be difficult to drive electrodes into the fuel, and the meter manufacturer has indicated that at high moisture contents (above the fiber saturation point) these resistance meters are not intended for use on frozen wood samples. Part way through the study, as part of a performance evaluation audit, two wood samples were measured by resistance meter and the same two samples were measured using the desiccation technique. Satisfactory agreement (within 1.1 and 1.5% respectively) was obtained.

3.2. BLANKS

Eleven blank runs were performed. The samplers were prepared as usual in the laboratory and were then transported to an apartment which did not have a woodstove. The samplers were allowed to sample room air for 46–115 hours and were then transported back to the laboratory for workup. The residue remaining on the O-rings was weighed for nine of the blank runs (the first two runs occurred before this procedure was instituted). Thus the first two blank runs used the average residue values computed from the rest of the project as estimates of the residues which would have been measured.

The average gravimetric catch for the blanks was 0.61 mg with a standard deviation of 0.50 mg. The highest blank had a catch of 1.2 mg, and the lowest had a catch of −0.44 mg. These values indicate that the equipment and personnel in the study were performing very well. A correction of 0.61 mg was applied to all the datapoints representing the sampling of an operating appliance. The magnitude of this correction is 5% for the average noncatalytic stove, 4% for the average catalytic stove, and 2% for the average conventional stove. The different effects are due to the average PM catch being different for each category of stove.

The CO_2 and CO concentrations of the blanks were very low (0.0 or 0.1% CO_2, 0.00 or 0.01% CO) except for the first blank. This sampler was located close to the kitchen of the apartment, and one possibility is that CO_2 formed from cooking contributed to the 0.3% CO_2 reading obtained. In any event, the blank CO_2 and CO levels are low enough that corrections were not required.

3.3. PRECISION

Eleven dual-train laboratory tests have previously shown [5] average precisions of 7.6% (PM) and 2.2% (CO) for the VPI sampler. During these earlier precision tests the samplers were turned on and off at the same time, and thus no precision for burn rate was measured. During the 1989–90 study, dual VPI samplers were deployed for 2 weeks of sampling on a model E catalytic stove. (Catalytic stove models are indicated by the letters A–F, noncatalytic certified models by the letters G and H, and conventional models by the letters I–Q.) The samplers operated completely

TABLE III
Results of dual-train VPI sampler precision tests in Crested Butte.

Deployment date	PM (g/kg)		CO (g/kg)		Burn rate (kg/hr)	
	A	B	A	B	A	B
3/19/90	21.08	21.97	78.46	79.32	0.592	0.590
3/26/90	13.92	14.00	49.07	49.07	0.593	0.596

independently of each other; i.e., each sampler used its own thermocouple and controller to determine when sampling would occur. The results are shown in Table III where A and B refer to the results of the two samplers. The worst-case precision for these data is 4% for the PM measurements of the samplers deployed 3/19/90, and the rest of the precisions are 1% or better. These results are extraordinarily good, and it is likely that for a large sample of dual-train runs the average field precision would be closer to the values observed during laboratory work. However, the agreement of the two dual-train runs helps to create confidence in the results of the study. Results of stove emissions tests by stove model are discussed in the following subsections of the paper.

3.4. Conventional Stoves

Conventional stoves were monitored during both years. In the 1988–89 study, 11 conventional stoves were monitored to give 37 datapoints for CO emissions and 32 datapoints for PM emissions. Equal numbers of datapoints for PM and CO were not obtained during the first year because the PM data for the earliest runs were questionable due to use of a faulty weighing procedure. In the 1989–90 study, 7 conventional stoves were monitored to give 27 useful datapoints. For the two studies each datapoint is one 'site-week' of data; i.e., it represents the average performance of a stove during a nominal 1 week period. The CO and PM emission factors and emission rates for the two seasons are shown in Figures 2 and 3, respectively.

Emission factors (g of pollutant per kg of dry wood burned) are fundamental measures of how clean combustion is. Emission rates (g of pollutant per hour of burn time) are of greatest interest to U.S. regulators and depend on both the emission factor and burn rate of a stove.

The average CO emission factors of Figure 2 are 19% lower than the 140 g/kg value used by EPA [6] at this time. Figure 3 shows that both conventional stove datasets have PM emission factors which are about 47% higher than the 15 g/kg value which EPA recommends for airshed modeling.

The emission factor agreement between the two years is very encouraging. The PM factors are within 1% of each other, and the CO factors differ by only about 4%. This indicates that the sample sizes give good estimates of average emission

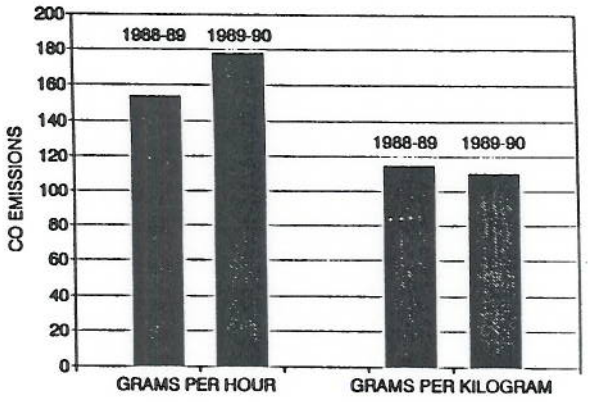

Fig. 2. Conventional stove CO emissions in Crested Butte.

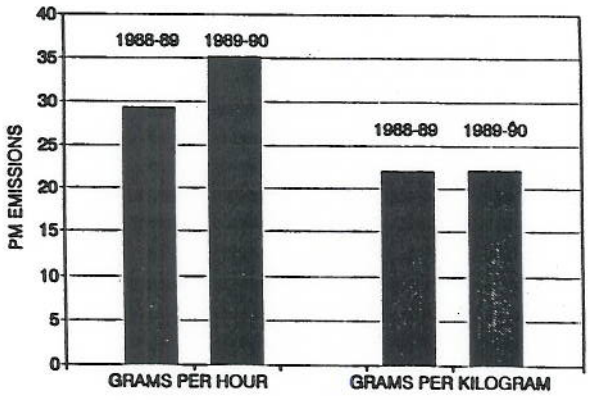

Fig. 3. Conventional stove PM emissions in Crested Butte.

factors for the Crested Butte conventional stove population. The higher PM and CO g/hr values (20% and 16% higher respectively) for the 1989–90 season are for the most part explainable by the fact that average burn rates were 1.35 and 1.64 kg/hr (21% increase) for the first and second years, respectively. Weather, choice of stoves monitored, or operator use patterns may have caused the increase.

3.5. Certified Stoves

For the two seasons, 13 catalytic stoves were monitored, resulting in 78 PM datapoints and 81 CO datapoints. Second year emission factors for PM and CO are 202% and 130% of first year values, respectively. Since only two catalytic stoves

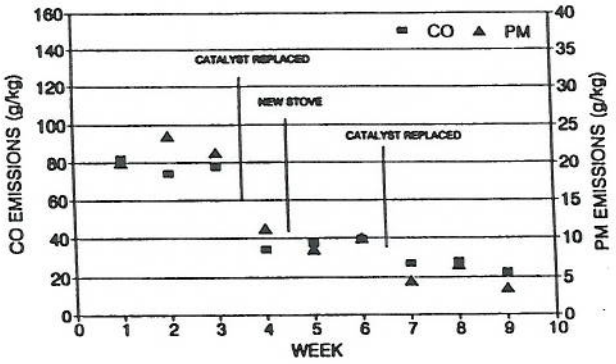

Fig. 4. Emissions history at site 16.

(both model A) were monitored during the 1988–89 season, comparison of the catalytic results between the two years is tenuous.

Most of the individual stoves performed consistently from week to week, but there were exceptions. One model E stove emitted like a conventional stove for 3 weeks, after which the catalyst was changed. Emissions were immediately reduced by about a factor of 2. After one week with the new catalyst, the stove was replaced by a new stove of the same model. After two weeks with the new stove, the catalyst of the new stove was replaced. Each catalyst change led to decreased emissions as shown in Figure 4. Catalyst replacement after three weeks of monitoring another model E stove was followed by a 45% drop in CO emissions and a 40% drop in PM emissions. Performance of this second model E stove before and after the catalyst change was very consistent.

Five noncatalytic certified stoves representing two stove models (G and H) were monitored to give 29 valid datapoints during the 1988–90 season, but none were monitored the first year. Thus no data are available for year-to-year noncatalytic stove comparison. The site 13 and site 20 stoves were both model G and both stoves performed fairly consistently at the 5–9 g/kg PM level.

Model H noncatalytic stoves were monitored at sites 15, 23, and 25. At site 23 model H performed consistently at the 6 g/kg PM level except for 1 week at 13 g/kg PM. This week had the lowest burn rate of the tests at that site. At sites 15 and 25 this model performed erratically at averages of 14 and 16 g/kg PM, respectively. Figure 5 shows all the PM factors for model H stoves as a function of burn rate, and the data suggest that the differences in performance correlate with burn rate. The data from all three sites combine to show a trend, and this increase in emissions with decreasing burn rate is what one would expect from a noncatalytic stove which was unable to sustain adequate combustion temperatures at low burn rates. Site 15 had substantially higher emissions during the final 3

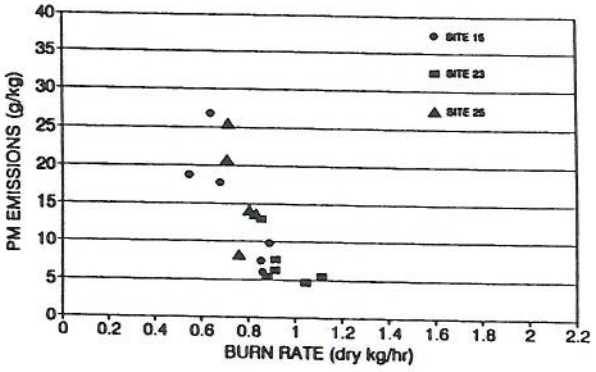

Fig. 5. PM emissions of noncatalytic model H stoves in Crested Butte.

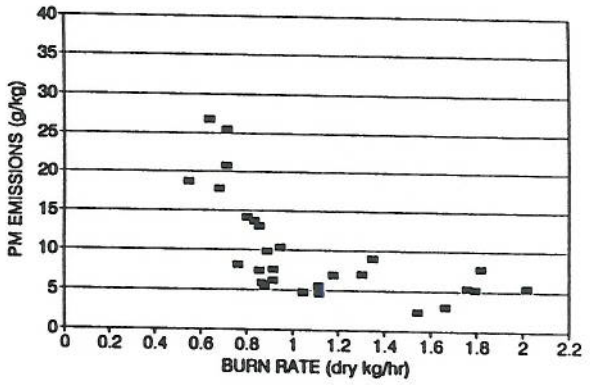

Fig. 6. PM emissions of noncatalytic certified stoves in Crested Butte.

weeks of monitoring, presumably because the average burn rates for those weeks were inadequate to maintain secondary combustion.

Considering both noncatalytic certified stove models, Figure 6 shows that the PM emission factor was about 10 g/kg or less whenever the average burn rate was greater than about 0.9 kh/hr. This type of performance variation with burn rate is to be expected, given the difficulty of sustaining noncatalytic secondary combustion at low burn rates. Comparison of Figures 5 and 6 shows why it is helpful for field studies to generate many datapoints. If only the data of Figure 5 were available, one might theorize that there was something unique about the stove at site 23, but this appears not to be the case based on Figure 6.

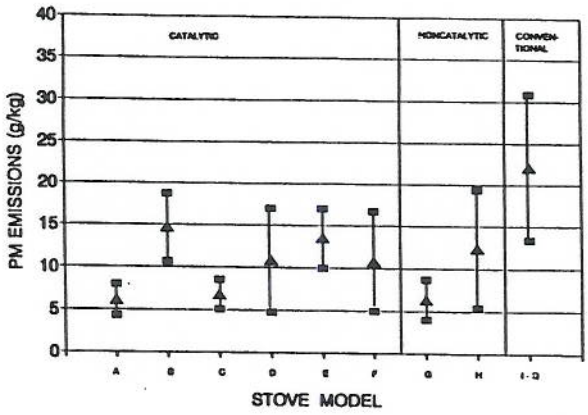

Fig. 7. PM emissions by stove model. (squares show +/− one std. dev.)

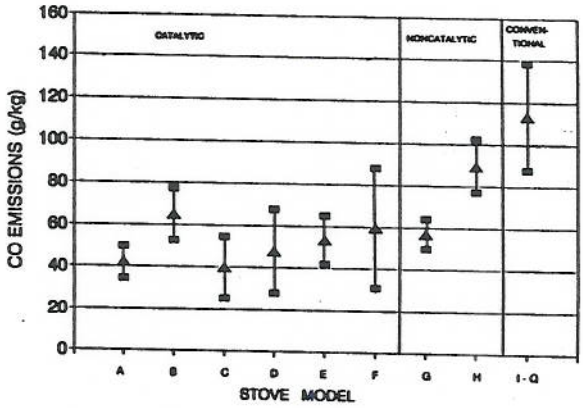

Fig. 8. CO emissions by stove model. (squares show +/− one std. dev.)

3.6. Differences Between Woodstove Models

Differences between stove models are apparent in Figures 7 and 8, which give averages and the standard deviations of the emission factors for each model tested.

The average PM reduction (relative to the average of 1988–89 and 1989–90 conventional stove PM emission factors) was about 70% for models A, C, and G; and in the 34 to 51% range for models B, D, E, F, and H. The average CO reduction ranged from 42 to 65% for all models except noncatalytic model H, which was operated at relatively low burn rates and reduced CO only 21% compared to conventional stoves. On average, each certified stove model performed better than

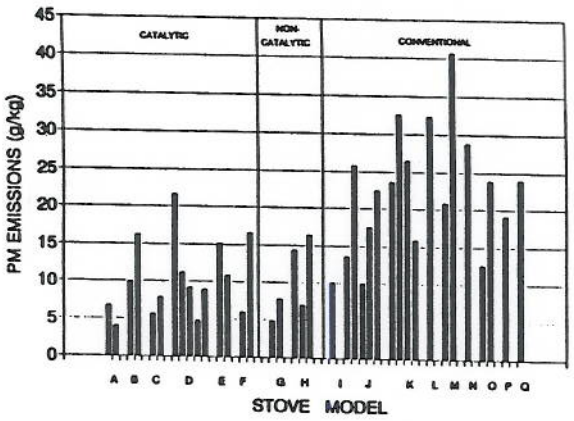

Fig. 9. Average PM emission factors of stoves in Crested Butte.

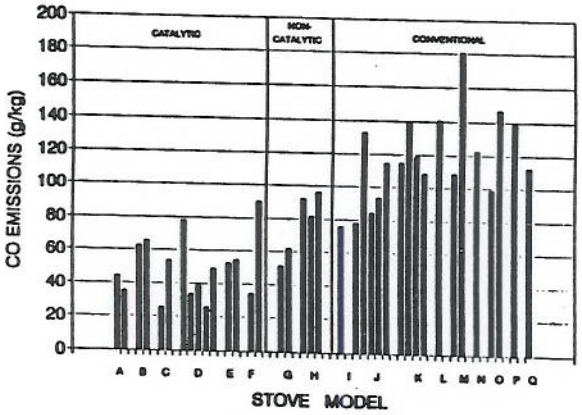

Fig. 10. Average CO emission factors of stoves in Crested Butte.

the average of conventional stove PM and CO emissions.

Differences between PM and CO emission factors of stoves which are the same model are apparent in Figures 9 and 10, where each group of bars represents stoves of the same model. For example, catalytic stove F1 (first bar shown in Figures 9 and 10) performed consistently at about 6 g/kg (except for one run, which had a relatively large sample line weight loss which suggested a possible weighing error), and catalytic stove F2 appeared to give increasing PM emissions, averaging about 17 g/kg. Emissions and operating conditions for these two stoves differed as shown in Table IV.

After testing was complete, stove F2 was inspected by WHA personnel who

TABLE IV
Data for model F stoves at two sites.

	Stove F1	Stove F2
PM Emissions (g/kg)	6	17
CO Emissions (g/kg)	34	90
Fuel moisture (dry basis %)	15	24
Burn rate (dry kg/hr)	0.75 – 0.93	0.97 – 1.28
Stack CO_2 (dry mol %)	6.0 – 8.3	4.3 – 5.3

TABLE V
Averages of maximum probable errors in emission factor measurements (as percent of reported values).

	Conventional woodstoves	Catalytic woodstoves	Noncatalytic woodstoves
PM	10.3	11.0	13.5
CO	13.0	14.7	12.7

reported that the bypass plate was cracked. Enough data are not available to tell if the difference in emissions is due to the bypass plate, fuel moisture content, operating pattern, or other physical differences in the stoves. The differences in CO_2 levels could be due to the difference in fuel moisture contents, the difference in burn rates, or the difference in the airtightness of the appliances, but a difference of this magnitude would not be explained by the cracked bypass.

An extensive error analysis was conducted. The analysis calculated a 'maximum probable error', defined as the error which occurs if each measured or assumed parameter is in error by the maximum anticipated amount and the errors occur randomly; i.e. they do not all occur in a way to cause an increase (or decrease) in the measured emissions. Averages of maximum probable errors are shown in Table V listed by appliance type.

The largest probable errors for CO emission factors occur for conditions where the sample gas is dilute. The lowest woodstove stack CO concentration measured

during the study was 0.09%, a value which occurred for a catalytic stove with a concomitant CO_2 concentration of 3.42%. Since the CO analyzer used in the study had a digital display with a resolution of 0.01 mole percent, the probable CO errors could be significantly reduced in future studies by use of a more sensitive instrument. Maximum probable CO errors are as much as 20% in only three runs, wherein the CO concentrations were near 0.09%.

The probable errors in PM emissions are dominated by the ability to measure the particulate catch. Only two runs had maximum probable PM errors greater than 30%. For the maximum probable PM errors of 34.5 and 33.3%, the corresponding maximum probable errors in PM factors are 1.4 and 2.7 g/kg. The average maximum probable error for PM was 1.1 g/kg for catalytic stoves and 1.2 g/kg for noncatalytic stoves.

4. Conclusions

The emissions from 18 certified stoves representing 8 models (6 catalytic, 2 noncatalytic) have been measured. Compared to the emissions measured from conventional stoves, the certified stoves reduced PM emission factors by 53% and CO emission factors by 49%.

There were significant differences in the performance of different stove models. Additional measurements and/or stove inspection would help determine the causes of the differences.

The two noncatalytic stove models had reduced emissions compared to conventional stoves. For model G, average PM and CO reductions were 71 and 48%, respectively, and for model H the reductions were 44 and 19%, respectively. Comparison of the two models is not straightforward, since two of the three model H stoves were operated at low burn rates compared to the burn rates for model G stoves. The noncatalytic models performed best at higher burn rates, and the data suggest that operators be encouraged to operate at burn rates averaging 0.9 kg/hr or more. Proper sizing of such stoves to the space to be heated is essential.

All the catalytic stove models had reduced emissions compared to conventional stoves. The average PM emission factor reduction for the catalytic models ranged from 34 to 71%, while CO reduction ranged from 41 to 64%. There is currently not enough data to determine the reasons for differences in performance, but additional work would help determine this.

Emission rate reductions were greater than emission factor reductions. The PM rates of certified stoves were 31% (catalytic) and 29% (noncatalytic) of conventional stove PM rates. The CO rates of certified stoves were 29% (catalytic) and 47% (noncatalytic) of conventional stove CO rates. Rate reductions are greater than factor reductions because certified stoves have lower average burn rates. Improved energy efficiency and smaller firebox size (lower peak burn rate) are probably the reasons.

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