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THE NORTHEAST COOPERATIVE WOODSTOVE STUDY
VOLUME I

by

Paul G. Burnet

OMNI Environmental Services, Inc.
10950 SW Fifth Street, Suite 160
Beaverton, Oregon 97005

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EPA Project Officer:

Robert C. McCrillis

Air and Energy Engineering Research Laboratory
Research Triangle Park, North Carolina 27711

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New York State Energy Research and Development Authority
2 Rockefeller Plaza
Albany, New York 12223

AIR AND ENERGY ENGINEERING RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
RESEARCH TRIANGLE PARK, NC 27711

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ABSTRACT

This report presents the results of a two-year study in Vermont and New York monitoring woodstove performance. The objective of the study was to determine the effectiveness of catalytic and non-catalytic low-emission woodstove technology in reducing wood use, creosote and particulate emissions. Measurements of wood use and creosote accumulation in chimney systems were made in a total of 68 homes over a period of two heating seasons. Forty-two of these homes were equipped with instrumentation to measure particulate emissions and directly-measured wood use. Catalytic woodstoves, catalytic add-on/retrofit devices and non-catalytic low-emission stoves were provided by various woodstove manufacturers for use by volunteer homeowners during the study period. Conventional technology stoves were also included to provide baseline data.

Averaged results indicate that the low-emission non-catalytic stoves and catalytic stoves had lower creosote accumulation, wood use, and particulate emissions than the conventional technology stoves, although the range of values was quite large. The reductions in particulate emissions by the catalytic and low-emission stoves were not as great as could be expected based on laboratory testing. The large number of variables affecting stove performance in "real world" conditions make identifying causative factors difficult. Additional analysis of data and further testing are currently planned.

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SUMMARY

A study of woodstove performance was conducted during the 1985-86 and 1986-87 heating seasons in the Northeast. Sixty-eight homeowners in the Waterbury, Vermont, and Glens Falls, New York, areas were provided with selected "advanced technology" stoves or asked to use their existing (conventional) stoves for the study period. The stoves were monitored for wood use, creosote accumulation in the chimney system, and particulate emissions. Three advanced technology stove categories (catalytic stoves, add-on/retrofit devices, and low-emission, non-catalytic stoves) were compared with conventional technology stoves. Objectives of the study were to evaluate the performance of the advanced technology stoves for safety factors (creosote), efficiency (wood use), and environmental impacts (particulate emissions). Special emphasis was placed on the effectiveness of catalytic combustors.

Creosote and volumetric woodpile measurements were conducted on all 68 homes. Creosote accumulation was measured by periodically sweeping the chimney system and weighing the collected material. Wood use was monitored by measuring wood piles during the heating season and normalizing for moisture content and fuel species.

Additionally, 34 homes were routinely sampled for particulate emissions over one-week periods. These homes had data logging systems to record stove temperatures, flue gas oxygen concentrations, and wood weights. Particulate samples consisted of integrated samples collected every half hour during each week-long sampling period. Flue gas flow rates were calculated based on combustion stoichiometry: burn rates, fuel species, flue gas oxygen measurements, and estimated CO/CO_2 levels.

It is important to note that a large number of variables were found in field stove installations: chimney systems, fuel characteristics, user practices, stove maintenance, etc. The range of values recorded in all categories was quite large. Reported data, while representing the values recorded during this study, may not be representative of other climates, fuel woods, stove or catalytic combustor models, chimney systems, or stove use patterns. Great care should be used in extrapolating these findings to other circumstances.

Due to the high variability and large range of data, averages from advanced technology stove groups were, in most cases, not statistically different from the conventional stove group. "Student's t" tests showed that only the low-emission non-catalytic stove group had a mean particulate emission rate with a greater than 90% probability of being different and hence lower than those from the conventional stove group. Emissions from individual stove models, however, were statistically different from the mean of the conventional stoves in many cases. All advanced technology devices (catalytic, add-on/retrofit, and low-emission non-catalytic) showed lower average particulate emission rates, wood use, and creosote than the conventional technology. Figure S-1 summarizes averaged results from the stove technology groups.

The stove technology group data represent averages, and reflect a wide range of values. In general, all stove categories, including conventional stoves, had models and specific installations with low (and high) particulate emissions. It is therefore most appropriate to evaluate stove performance on a model-by-model basis, recognizing that due to the relatively small number of installations and stove models, values may not be representative of "typical" stove performance.

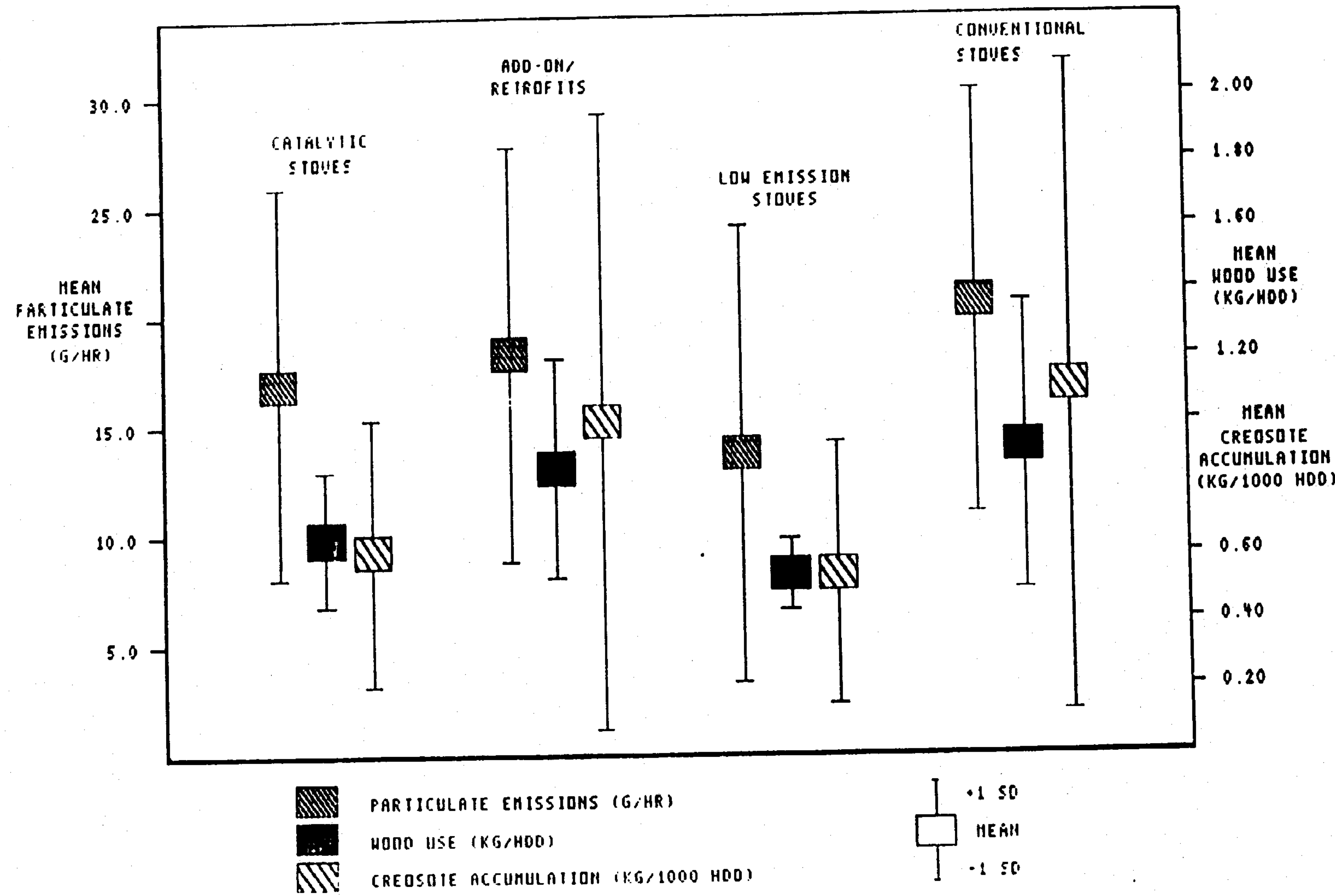
Even though the number of individual samples is high, the wide range of values and the large number of variables makes identifying causative factors difficult. Results presented in this report are from a number of different stove types and models in different installations, in which homeowners used different fuels and operating procedures. A thorough review of stove burn rates, fuel loading practices, catalyst operation time, and frequency of alternate heating systems did not identify a single factor responsible for emission patterns. This indicates that while many factors can affect particulate emission rates, no single factor appears to be dominant in all stove types or models. In general, however, it appears that stoves with smaller fireboxes, regardless of technology type, tend to have lower emission rates.

General conclusions are presented below in the following categories: Advanced Technology, Catalyst Performance, Operator Practices, Technology Factors, and Other Findings.

1.0 Advanced Technology Performance

1.1 Most stoves in the advanced technology categories (catalytic, add-on/retrofit, low-emission non-catalytic) episodically demonstrated

Figure S-1
Performance Comparison by Stove Technology



lower emissions than the baseline conventional stoves under "field use" conditions. Good performance in at least one installation for most of the stove models indicates that factors, such as stove maintenance and fueling practices, may be as important as stove technology features in achieving low emission rates. Stove firebox size, regardless of technology group, was a prime factor in determining emission rates; smaller stoves had lower emissions.

1.2 In general, performance of the stove technology groups appeared to be consistently ranked in terms of particulate emission rates, wood use, and creosote accumulation; low-emission non-catalytic stoves had the lowest particulate emission rate, wood use, and creosote accumulation, while conventional stoves had the highest. It should be noted that only low-emission non-catalytic stoves showed a mean emission rate which was statistically different from the conventional stoves. It should also be noted that creosote accumulation is strongly influenced by flue system type and wood use appears to be influenced by burning patterns and firebox size.

1.3 All advanced technology stove groups averaged lower wood use and creosote accumulation rates when households switched from conventional stoves between heating seasons. Average reductions by stove group ranged from about 10% to 35% for creosote and from about 15% to 30% for wood use.

1.4 The low-emission stoves, as a group, had the lowest average emissions. Each model had different burning characteristics; most showed relatively good performance. Average results from this technology group are strongly influenced by the good performance of two stoves (M and N) which may be EPA 1990-certifiable . Furthermore, excluding one high-emission home (V18, using non-EPA-certifiable Stove K) would reduce average emissions in this category from 13.4 to 10.0 g/hr, and reduce the standard deviation ( ) from 10.2 to 5.7.

1.5 User satisfaction was generally high with the advanced technology stoves provided to study homes. In particular, homeowners with catalytic and low-emission stove models were frequently pleased with the units. (In some cases, user satisfaction remained high even though the catalytic combustor had deteriorated.) Some add-on devices also received positive comments. The add-on with the lowest average particulate emission rate also received homeowner complaints about smoke spillage.

2.0 Catalyst Performance

2.1 Catalytic stoves showed variable performance. Most individual models performed well in some homes. Other installations had relatively high emissions. Overall, performance of these stoves did not match the expectations created under ideal laboratory conditions, although only one of the catalytic models may be EPA 1990 certifiable. The mean emission rates of existing catalytic stoves and new catalytic stoves were virtually identical. User education and further technology refinements remain possible factors which could help improve the performance of catalytic stoves.

2.2 Add-on retrofit devices did not perform well overall, but 2 devices reduced emissions considerably. The stoves on which these devices were mounted are a major factor in measured emission rates.

were mounted are a major factor in measured emission rates. Retrofit F, which consistently had high emissions, is no longer being produced.

2.3 Catalyst durability was quite variable. Rapid deterioration was noted in some combustors, all of which were cordierite-based, with corresponding increases in emissions. In one stove model (which apparently accelerated combustor deterioration), replacement with "second generation," non-cordierite combustors appeared to virtually eliminate the deterioration trend. Emissions from this stove model were reduced by about one-third by using "second generation" combustors during the second year, although it is not clear whether this was from improved catalytic performance or reduced degradation.

2.4 Overall, there did not appear to be a consistent increase in particulate emissions from catalytic devices over the two-year testing period. No clear trend of long-term loss of effectiveness was noted. However, a number of combustors (cordierite-based) were discovered to be deteriorating. These combustors were replaced; emission values reported in this study reflect relatively frequent catalyst inspections and replacement when necessary. It should be noted, however, that not all cordierite-based combustors in the study indicated signs of deterioration of the substrate. A cordierite-based combustor from an "existing" stove with an estimated 6000 hours of use showed relatively low emissions in lab retesting. All combustors retested in the laboratory had reduced performance relative to new combustors.

2.5 Condensation of moisture and organic material in flue systems and subsequent drainage or leaching of condensate was a problem in some homes during periods of very cold (< 20°C) weather. Only catalytic stoves experienced this problem. This appears to be related to inappropriate installation and is not necessarily a technology limitation.

2.6 Catalyst ΔT (temperature change across the combustor) and % operation time are not good indicators of stove particulate emissions. Factors such as fueling cycles (long burn-down "tails") and measurement difficulties may preclude the use of these parameters for predicting emission rates.

3.0 Operator Practices

3.1 Operator practices, in combination with other parameters, appear to be a significant factor in stove performance. Specific practices which may result in lower emissions from all stoves have not been identified from available data. However, routine maintenance inspections of the combustor, gasketing, and overall stove system can help identify deteriorated components in need of repair or replacement.

3.2 Burn rates did not demonstrate a strong correlation with emission rates for any of the stove technology groups, although "general trends" were observed. Often, as in the case with conventional stoves, the trend was opposite that which was expected; emissions increased with burn rate. This may be related to field conditions, in which lower burn rates may include longer "charcoal phase" burning periods.

3.3 Mean fuel loading frequencies were identical for the low-emission and conventional stove groups, although the average low-emission stove fuel load was 56% that of the average conventional stove fuel load. This indicates that smaller firebox capacity (typically associated with low-emission stoves) does not necessarily require more frequent fueling of the stove. User satisfaction was generally high with the low-emission stoves.

3.4 Average emission factors (g/kg) for all the stove catagories were quite similar. Differences in average emission rates (g/h●) were therefore driven by burn rates. The low average burn rate of the low-emission stoves, and resulting low average emission rate, may be due to more frequent "charcoal phase" burning periods.

3.5 Fuel loading frequencies did not correlate well with particulate emissions. However, loading frequencies did increase with smaller fuel loads for all technology groups, as was expected.

3.6 Fuel loading frequencies were significantly different between homes, even those using the same stove model.

3.7 The lack of strong correlations between particulate emissions and other variables indicated that many parameters have significant, if unquantified, effects on stove performance. Fueling and burning cycles are thought to be areas for further investigation.

4.0 Technology Factors

4.1 Firebox size is a major factor in determining particulate emissions from woodstoves; emission rates increased with firebox volume, regardless of stove technology.

4.2 Preliminary results from stove inspections conducted after the second heating season (September 1987) indicate that significant "leakage" of smoke around combustors may be a cause of high emissions in some stoves. (A report on this work will be issued under separate cover.) Stove inspections showed that gasketing, especially around the bypass damper and combustor, was the most frequent component in need of maintenance and the apparent cause of leakage. Leakage rates and particulate emissions do not appear to correlate well overall, but show some correlation for individual stove models.

4.3 Using a qualitative measurement methodology, insulated metal chimney systems accumulated the least amount of creosote. Masonry chimneys located on outside walls accumulated the most.

5.0 Other Findings

5.1 This study did not show that one stove model is necessarily "better" than another. As stated previously, a wide range of results were recorded. For a given stove model, the largest number of emission samples was 19; the smallest was 1. The largest number of installations for a given stove model was 4, while the smallest was 1.

The high degree of variability in performance and the relatively small sample populations make comparisons inappropriate.

5.2 Conventional stoves in this study may be cleaner-burning heaters than are "typical." Four of the six conventional stoves had relatively small fireboxes (< 2.4 ft^3), and two of these had small <u>effective</u> fireboxes (< 1.5 ft^3). Emissions from these stoves therefore may not be typical of existing stove technology. Additionally, the cold Northeast climate and commensurately higher burn rates preclude direct comparison to stove performance in milder climates.

5.3 Alternate heating system use did not correlate well with particulate emission rates or burn rates, although heating system use was monitored only in the room with the stove. In general, most homes in the study used their alternate heating system less than 3.5% of the time (while the stove was operating). This amounts to less than one hour per day. A large portion of the homes used no back-up heat at all.

5.4 Polycyclic organic material (POM) emissions were variable and non-conclusive. Testing method and analytical method limitations, and a very limited database, preclude any ranking of POM emissions by stove type.

Section 1

BACKGROUND AND STUDY DESIGN

BACKGROUND

The use of catalytic combustors in reducing particulate emissions from woodstoves has been shown to have considerable potential, based on laboratory test results. In recognition that the combustors would likely experience some loss of effectiveness over time and that "real world" conditions would have an unknown effect on combustor performance, documentation of catalytic woodstove performance was sought. A consortium of funding partners, comprised of the Coalition of Northeastern Governors (CONEG), New York State Energy Research and Development Authority (NYSERDA), and U.S. Environmental Protection Agency (EPA), sponsored a two-heating-season study to investigate the effectiveness of "advanced technology" woodstoves.

Direct project funding was provided by CONEG, NYSERDA, and EPA. In-kind contributions of services were provided by New York State Department of Environmental Conservation (NYSDEC), Vermont Agency of Environmental Conservation (VAEC), and Vermont Department of Health (VDOH). Woodstoves were provided by various stove manufacturers. Stoves were placed in the homes of volunteer participants.

The study objectives were to evaluate the performance of several types of stove technology <u>under typical use conditions</u> for:

- safety (creosote reduction)
- efficiency (wood use reduction)
- environmental impacts (particulate emission reduction)

It should be noted that the objectives were not to demonstrate the potential for advanced technology woodstoves, but to document typical performance of available (fall 1985) technology in the Northeast region.

STUDY DESIGN

Six stove technologies (Table 1-1) were selected for investigation, representing residential natural draft wood-burning devices.

Table 1-1

STUDY STOVE CATEGORIES

Stove Technology Type	Stove Model Types/ (Codes)	Comments
Catalytic	4 (A,B,C,D)	Four manufacturers provided new stoves for the study. Catalyst stoves are defined as having the combustor as an integral part of the new stove. Existing catalytic stoves (Group III homes) represented five additional models.
Add-on	4 (G,H,I,J)	Add-on devices are defined as units which can be added to virtually any stove at the flue collar. Three devices were used for the first year of the study, and one was added for the second year.
Retrofit	2 (E,F)	Retrofit devices are designed to fit one stove model or design type, and typically are close-coupled to the stove.
Low-Emission Non-Catalytic	4 (K,L,M,N)	"Low-emission" stoves are defined for this study as non-catalytic models which have been certified under the Oregon DEQ program. Two stove models were included for the first year of the study, and two more "EPA-1990-certifiable" models were added for the second year.
Conventional	6 (O)	These are defined as existing stoves in study homes, representing a range of designs. They are generally categorized as typical of conventional woodstove technology.
Existing Catalytic	6 (P)	These are defined as existing catalytic stoves in study homes with one to two heating seasons of prior use. One stove was the same model as one used in the catalytic group.

New woodstoves were provided to the study by woodstove manufacturers. Contributions of stoves and shipping/installation costs were solicited from producers making stoves which had passed or were capable of passing the Oregon Department of Environmental Quality (DEQ) Woodstove Certification Program. Stoves were provided in the fall of 1985 by manufacturers interested in participating in the study. Of the catalytic stoves, one met DEQ 1988 standards ("weather-weighted" average emission rate of 4.0 grams per hour), one was subsequently certified to 1986 standards ("weather-weighted" average emission rate of 6.0 grams per hour), and one, while never certified, appeared capable of meeting the 1988 standard, based on limited certification-type testing. The fourth catalytic model, while never tested in a laboratory, was a prototype of a model certified to DEQ 1986 standards. (The secondary air system was modified for the production model.)

Three catalytic add-on devices were originally used in the study. Add-on devices are not covered by current Oregon DEQ or U.S. EPA woodstove regulations, but research testing had been conducted on two of the three units. At the beginning of the second heating season, a fourth add-on device was added to the study, based on lab tests showing this unit to have the best emission reduction potential of tested add-on devices.

The two catalytic retrofit devices had both been certified to Oregon 1986 catalytic standards. One of the retrofit models was discontinued subsequent to its inclusion in the study. For purposes of analysis, add-ons and retrofits were considered as similar technologies; they would both be available for installation on existing woodstove installations and thus have the potential to reduce emissions from existing stoves.

All of the catalytic stoves and add-on/retrofit devices were equipped with combustors supplied by the stove manufacturer. Combustors were manufactured by Applied Ceramics, Corning, or Panasonic (Technical Glass Products). The three combustor makes were approximately equally represented in the catalytic devices.

Two low-emission stove models were included in the first heating season. One of these stoves met DEQ 1986 non-catalytic stove standards ("weather-weighted" average emission rate of 15.0 grams per hour), and one met DEQ 1988 standards ("weather-weighted" average emission rate of 9.0 grams per hour). Based on preliminary indications that this technology group may perform relatively well in the field, two more models were added at the beginning of the 1986-87 heating season. Both of these new models were certified to DEQ 1988 standards and should be capable of meeting U.S. EPA 1990 non-catalytic standards ("national weather-weighted" average emission rate of 7.5 grams per hour).

No special training was provided to homeowners regarding proper operation of the advanced technology stoves. Stoves were installed by professional installers, who answered questions but did not attempt to train homeowners. An instruction manual for each stove was left with the homeowners.

All of the stove models are coded in this report to provide anonymity to manufacturers who provided or donated equipment to the study. This is in recognition of their accepting the risk that, for whatever reasons, their product may not have performed as expected.

Stoves were installed in volunteer households selected from a list of applicants provided by VAEC and NYSDEC. Potential participants were interviewed, and the homes and existing woodstove systems inspected. Homes were evaluated for occupant enthusiasm for the project, chimney size and venting characteristics (to match with available stoves), geographic location, and other factors. A total of 66 homes were initially selected for the study; 33 in Glens Falls, New York, and 33 in the Waterbury, Vermont, area. All homes used wood as a primary heat source. Manufacturers offered homeowners a discount on buying the stove at the end of the study, or gave the appliance to the homeowners. All participants received chimney sweeping services free of charge during the study. Two homes were added to the study group for the 1986-87 heating season due to original participants dropping out of the study.

The study homes were divided into three groups, each receiving varying levels of investigation. Group I homes, totaling 32 with 16 in each state, were monitored for creosote accumulation, woodpile use, and particulate emissions. With the exception of isolated participant dropouts, most Group I homes continued to use the same stove through both heating seasons. Some Group I homes changed to low-emission stove models for the second heating season as part of an emphasis shift in the study. Each Group I home was scheduled for seven emission sampling periods. An additional four homes in this group were monitored for creosote accumulation and wood use while serving as backup homes in case a Group I home dropped out of the study.

Group II homes, totaling 24 with 12 in each state, received creosote accumulation and woodpile use measurements. No particulate data were collected. Group II homes switched stoves between heating seasons to allow comparisons of creosote accumulation and wood use, with the house, chimney, and occupants remaining constant.

Group III homes, totaling six with three in each state, were monitored for creosote accumulation, woodpile measurements, and particulate emissions. Group III homes already had catalytic stoves which had been in use for at least one heating season prior to this study. Emissions were measured once during the first heating season on all six homes and once during the second heating season on four homes.

Log books were left in all homes for occupants to record unusual events or occurrences.

Table 1-2 lists the stove technologies in each study group for the two heating seasons.

Table 1-2

STUDY STOVE POPULATIONS

	Catalytic		Add-on/Retrofit		Low-Emission		Conventional	
	'85-86	'86-87	'85-86	'86-87	'85-86	'86-87	'85-86	'86-87
Group I	14	14	12	6	3	10	7	5
Group II	3	6	0	7	0	3	21	5
Group III	6	6	0	0	0	0	0	0
Total	23	26	12	13	3	13	28	10

The shift in the types of Group I stove technology between heating seasons was due to reducing the number of add-ons and increasing the number of low-emission stoves. Based on relatively high emissions from most add-on devices and the discontinuation of one of the retrofit devices (F) by the manufacturer, many of these devices were pulled from the study. They were replaced by an add-on device which had performed well in laboratory tests (J) and two models of low-emission stoves (M,N) which were considered to be among the best available non-catalytic stove designs.

Group II homes were scheduled to run one heating season with one stove and the next with another stove, as described previously. This was conducted as planned. Group III homes were also tested as planned.

PARTICULATE EMISSIONS

Equipment

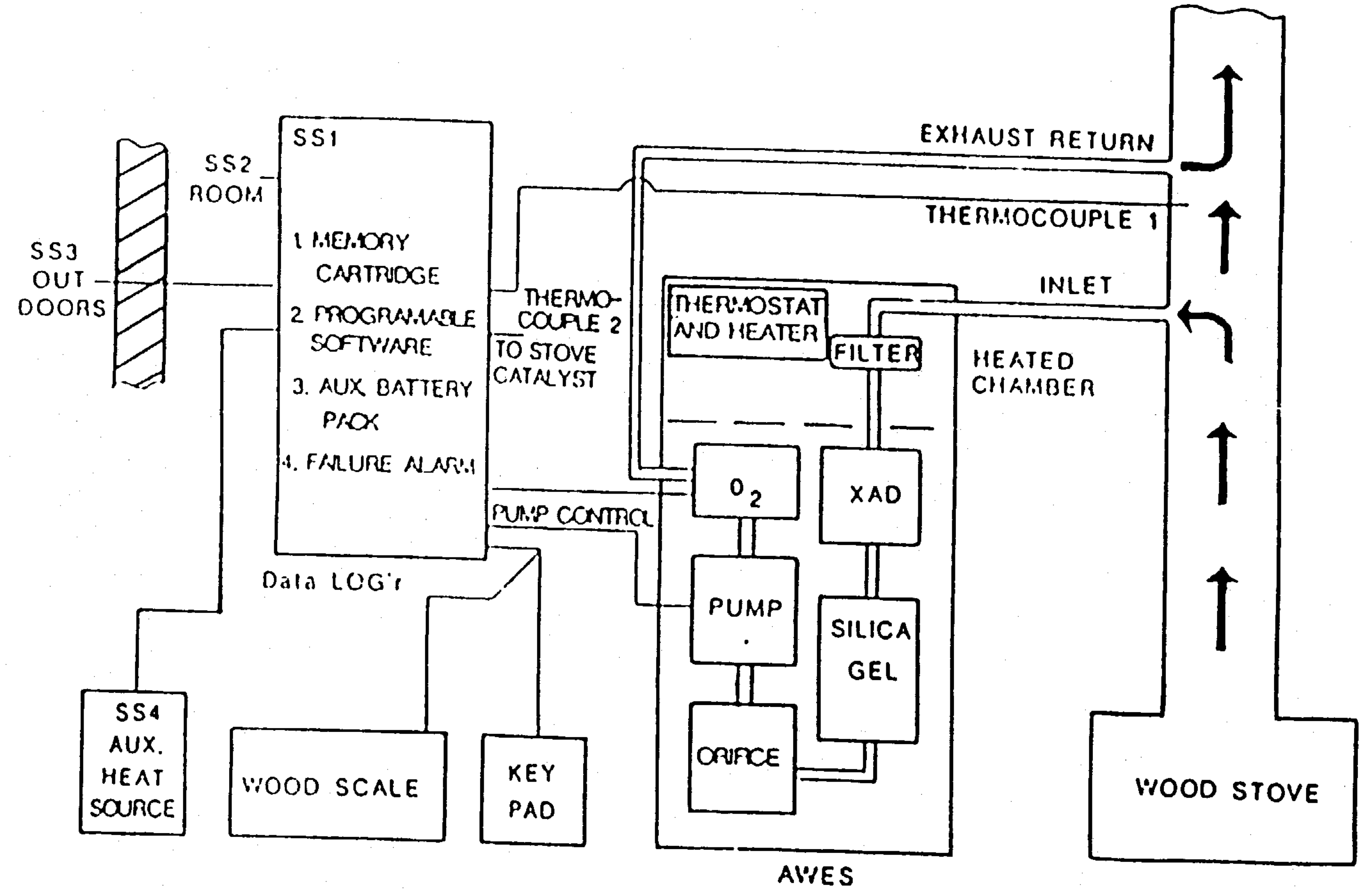
While extensive data are available on stove performance measured in a laboratory, virtually no data have been available on woodstove emissions under actual "field" conditions. Laboratory tests are conducted under a set of rigorously controlled conditions which minimize the variables that can affect emission values (2). Field conditions necessarily include such variable factors as fuel species, moisture, piece size, loading density, fueling frequency and burn rates, chimney system configurations, and stove operation factors. With catalytic stoves, additional factors such as bypass operation and catalyst "preheating" practices can be significant.

Particulate emissions were measured with a pair of instruments developed by OMNI for field measurements of woodstoves. Particulate samples were collected in an Automated Woodstove Emission Sampler (AWES). Wood use, flue gas oxygen, and various temperature values were recorded by a programmable microprocessor/controller dubbed the Data LOG'r. A schematic of the system is shown in Figure 2-1.

AWES Description. The AWES sampler was specifically designed for sampling residential woodstove particulate emissions. As programmed in this study, it was capable of sampling woodstove emissions for periods up to one week in length. Sample flow was maintained by a critical flow orifice, so no adjustment was required during operation. Sample start and stop times, dates, and frequency (minutes on and minutes off) were programmable and controlled by the Data LOG'r. Each sampler was installed prior to scheduled start time, left unattended, and removed for sample processing at the end of the sampling period.

Each AWES unit drew flue gases through a stainless steel probe, Teflon tubing, and a U.S. EPA Method-5-type filter (heated to about 75–115°C) for collection of particulate matter, followed by an adsorbent resin (XAD-2) trap for semi-volatile hydrocarbons. Water vapor was removed by a silica gel trap. Flue gas oxygen concentrations, which are used in conjunction with wood use data to determine flue gas volumes, were measured by an electrochemical cell. The AWES units use a critical orifice to maintain a nominal sampling rate of 1.0 liters per minute (0.035 cfm). Each AWES critical orifice was calibrated to determine the exact sampling rate. Appendix C shows data on AWES equivalency to other reference methods.

Figure 2-1
AWES/Data LOG'r System



Data LOG'r Description. The Data LOG'r is a multi-channel programmable microprocessor/controller with the capability of processing both digital and analog signals. The unit has data storage capacity of 32 kilobytes on a field-replaceable, non-volatile memory data cartridge. As programmed for this study, cartridge capacity allowed up to 30 days of continuous operation between servicing in most field project applications. The Data LOG'r was programmed to record and store the following information:

- Starting date, time, and unit serial number for data recording periods;
- Daily date and time, recorded at midnight, and a continuous time record in five-minute intervals;
- Flue gas, in-catalyst, and before-catalyst temperatures (where applicable) averaged over 15-minute intervals;
- Record of alternate heating system status (on or off) by use of a temperature sensor;
- Wood weights and coalbed condition, recorded when the woodstoves were fueled;
- Oxygen measurements when the AWES units were sampling, recorded every 30 minutes; and
- Home VAC power status (on or off), measured at five-minute intervals.

The attached electronic scale/woodbasket units supplied an analog voltage output proportional to the weight placed in the wood holder. Scale readings were recorded by having the homeowners use an attached keypad in a prescribed sequence. The keypad also allowed the homeowners to record the coalbed conditions at each time of stove fueling.

The Data LOG'r was programmed to activate the AWES unit(s) at a specific date and time. Sampling intervals were one minute every 30 minutes for seven-day sampling periods, commencing on Saturdays at midnight.

Probe Placement

AWES sampling probes were located at several points in the stove/flue system during the first heating season. All stoves were sampled at the flue collar for conventional, catalytic, and low-emission stoves, and at the exit of the add-on devices. AWES probes were placed 0.3 meters downstream from the flue collar or add-on unit. This permitted direct comparison of stove performance without chimney deposition effects. Modifications were also made to the probe placement plan for the second heating season, as noted in Table 2-1, based on field experience and results from the first heating season.

Table 2-1

PARTICULATE SAMPLING LOCATIONS

Heating Season	Homes Sampled	Firebox	Flue Collar	After Add-on	Chimney Exit	Additional Flue Collar
1985-86	38	8	38	8	12	0
1987-87	36	4	36	4	0	12

Firebox samplers were reduced in number due to secondary air introduced into the stoves between the pair of AWES samplers, while only the flue collar AWES was recording O_2. The resulting dilution of the sample affected all reported particulate values. Some firebox samplers were left in the study for the second heating season to allow reporting of organic compounds as a fraction of the total particulate catch. The total number of add-on devices in the study was reduced for the second heating season.

Chimney samplers were eliminated after the first heating season due to problems encountered with dilution of samples from leaking flue systems (only the flue collar AWES had an oxygen sensor), freezing sample lines, and dangerous working conditions on the rooftops.

Due to questions of the accuracy and representativeness of firebox and chimney exit samples, results from these sampling locations are not presented in this report.

Additional samplers were added at the flue collar for the second heating season in 11 homes to document AWES sampler precision in the field.

Sampling Regime

Emission sampling equipment was installed by OMNI personnel in study homes during the week preceding a sampling period. Wood moisture content measurements and species determination were recorded from wood placed by the stove. All wood moisture measurements were performed using a Delmhorst moisture meter (Model RC-1C) with insulated pins. The participants were given instructions on the operation of the Data LOG'r keypad/scale unit and provided with a log book for recording unusual events.

Field staff visited each study home to service the sampling equipment at the start and end of each sampling period. At the start of a sampling period, the AWES unit was installed; leak checks were performed; thermocouples, the woodbasket/scale unit, and the oxygen cell were calibrated; the Data LOG'r was programmed with the proper sampling interval and start/stop times; and wood moisture measurements were performed on the fuel in the home's storage area. At the end of each sampling period, end-of-sampling-period calibrations and leak checks were performed; the AWES unit, sampling line, and sampling probe were removed; and wood moisture content and species were recorded as before.

The Data LOG'rs were programmed to activate the AWES units for one minute per half hour for seven days. Study homes were sampled every four weeks. Two groups were located in Vermont and two in New York. Homes in the two states were sampled sequentially. For example, during the week while Group A (Vermont) woodstove emissions were being sampled, field personnel installed the AWES units and sampling probes in the Group B (New York) homes. All sampling periods commenced on Sunday at 0000 hours.

Laboratory Procedures

Each AWES unit was cleaned and prepared with a new filter and a purified XAD-2 adsorbent resin cartridge prior to field installation. After each sampling period, the stainless steel sampling probe, Teflon sampling line, and AWES unit were removed from the study home and transported to a laboratory for processing. Laboratory facilities at the Vermont Agency of Environmental Conservation (1985–86) and the Vermont Department of Health (1986–87) were used for AWES preparation and sample recovery. Prior to transporting the AWES unit, the sample intake port, sampling line, and sampling probe were sealed. The components of the AWES samplers were processed as follows:

1. Filters: Glass fiber filters were removed from the AWES filter housings and placed in petri dishes. The petri dishes were sealed and shipped to OMNI's Oregon laboratory for desiccation and gravimetric analysis for particulate catch.

2. XAD-2 Adsorbent Resin: Resin cartridges were capped and shipped to OMNI's Oregon laboratory. In the laboratory the cartridges were extracted in a Soxhlet extractor with dichloromethane (SEMI grade) for 21 hours. The extraction solvent was transferred to a tared glass beaker. The solvent was evaporated at ambient conditions, the beaker and residue desiccated, and the extractable residue weight determined. The purified XAD-2 resin remained in the cartridge and was reused.

3. AWES Hardware: All hardware exposed to the sample stream (stainless steel probe, Teflon sampling line, glass filter housing, and all Teflon, glass and stainless steel fittings) was rinsed with dichloromethane (SEMI grade) and methanol (reagent grade). The solvents were placed in 500 ml amber glass jars with Teflon-lined lids which were capped, sealed, and shipped to OMNI's Oregon laboratory. In the laboratory, the solvents were placed in tared glass beakers. The solvents were evaporated at ambient conditions, desiccated, and weighed to determine the residue weight.

After cleaning, the AWES units were reassembled for field use. The intake port, sampling probe, and sampling line were sealed for transportation to the study home, and unsealed immediately prior to installation.

POM/TCO Analysis. A subset of AWES samples was selected for analysis to determine concentrations of specific polycyclic organic materials (POM) and total chromatographable organics (TCO). Ten samples from the first heating season were analyzed for POM concentrations. The samples submitted for testing consisted of material extracted from the XAD-2 resin only. Although the specific POM compounds were selected as indicators of the total POM concentrations, concerns were raised regarding the possibility of significant POM concentrations in other portions of the total AWES sample (solvent rinses or filter). POM samples submitted for analysis during the second heating season were combined dichloromethane (CH_2Cl_2) rinses, filter extracts (CH_2Cl_2), and XAD-2 extracts (CH_2Cl_2). POM compounds selected for analysis were based on previous EPA research: naphthalene, acenaphthene, phenanthrene, pyrene, benzo(a)pyrene, indeno(1,2,3-c,d)pyrene, benzo(g,h,i)perylene and 3-methyl cholanthrene. POM analysis was conducted using a gas chromatograph/mass spectrometer (3).

TCO analysis was conducted using a gas chromatograph with a flame ionization detector (GC/FID) (4). Hydrocarbon compounds with boiling points between 100°C and 300°C were reported.

It should be noted that the AWES sampler was designed for gravimetric measurements. Several factors may influence the representativeness of reported POM/TCO values:

- Samples were at ambient temperatures (except the heated filter) in the sampler. Material collected at the beginning of a sampling period was therefore not recovered for 8-10 days.
- Samples were shipped from the field lab to OMNI's Oregon lab by air freight at ambient temperatures.
- Analytical procedures used for identifying POM compounds are, under the best conditions, relatively imprecise.

POM and TCO results were intended to provide a qualitative assessment of emissions characteristics from the various stove technologies.

Data Processing and Quality Assurance Procedures

Using a portable computer, data files stored in the Data LOG'r memory cartridges were downloaded in the field onto floppy disks at the conclusion of each sampling period. The files were copied in the field office and one copy shipped to OMNI's Oregon office. Each data file was reviewed to check for proper equipment operation. Data LOG'r files were used in conjunction with the AWES particulate sample and wood moisture data to calculate particulate emission rates, catalyst lightoff times (when applicable), stove operation time, overall thermal efficiency, and burn rates.

The Data LOG'r data files, log books, and records maintained by the field staff were frequently reviewed to ensure sample integrity. Any parameter or calibration objective that did not meet OMNI's in-house quality control criteria was rejected or flagged and noted. The emission rate values that incorporated a flagged quality assurance parameter were carefully reviewed and are footnoted in the data tables. No flagged data were used in data summaries or comparisons of stoves or technology groups.

Particulate emission rates were calculated with precision and accuracy values. Each individual measurement that was used in the emission calculations has some degree of uncertainty associated with it, and these uncertainties are propagated to determine the precision and accuracy attached to each calculated particulate emission rate. Appendix B lists the calculation procedures used for particulate emission rate determinations. Appendix C summarizes the criteria used in the precision and accuracy calculations.

Field blanks were collected with the AWES units to evaluate potential particulate contamination of the AWES components, fittings, and sampling lines. The field blank AWES units were prepared according to normal sampling protocols, leak checked, left unattended for one week without being programmed to sample, leak checked, and returned to the laboratory for sample processing. The mean particulate catch from field blanks was subtracted from the total particulate catch for each emission sample. Details of field blank factors are presented in Appendix C.

Audits of Data Quality (ADQ), a Technical Systems Audit (TSA), and a Performance Evaluation Audit (PEA) were conducted by an EPA-assigned auditor during the course of the project. Audit results are presented in Appendix C.

Reported Values and Calculations

All the data reported, unless otherwise noted, represent samples obtained at the flue collar (for catalytic, retrofitted, low-emission, and conventional stoves) or above the add-on device. This allows direct comparison of the stove technology groups without introducing direct chimney system effects. When duplicate samplers were used, this is noted, and an average of the two AWES samplers is reported, based on the flue O_2 readings from one of the samplers. (Data LOG'rs used in this study had only one O_2 recording channel.)

Emission data are presented in the following formats:

- grams particulate/hour
- grams particulate/kilogram dry wood burned
- grams particulate/10^6 joule energy released into home
- grams particulate/m^3

Data presented in this report were calculated as a function of stove operation time (stack temperature above 100°F at 0.3 meters above the flue collar or add-on device). Values therefore represent emissions when the stove was in operation.

Emission data in the gram/kilogram format were calculated using the following inputs:

1. Mass of particulate material collected by the sampler.
2. Measured flow rate of the sampler (calibrated orifice, flowmeter).
3. Sampling duration (minutes of actual sampler pump operation).
4. Stoichiometric volume of gas produced by burning a known mass of wood. This is a calculated value based on the elemental composition of the wood fuel and flue gases. Specific values for carbon, hydrogen, oxygen, and nitrogen were obtained from available literature for 20 species of wood, and stoichiometric gas volumes were calculated based on the mix of fuel species burned, moisture content, and burn rates. Average flue concentrations of CO and CO_2 were assumed based on technology type, and are shown in Appendix B.
5. Concentrations of oxygen in the flue (at the sampling location), measured by an oxygen sensor cell in the sampler. Excess air was calculated relative to ambient oxygen concentration.

When emissions were calculated in the gram/10^6 J format, additional input data were required:

6. Heat content of dry wood (J/kg). This was also obtained from literature values for 20 species and calculated based on the mixture of fuel used during the sampling period.
7. Stove efficiency. This was calculated for each sample based on stack gas temperature, fuel moisture, excess air, and particulate mass using the "Condar method." Details are presented in Appendix B. It should be noted that the Condar method is based on flue gas temperatures at approximately 1.5 meters above the stove, while in this study, flue gas temperatures were measured at about 0.5 meters. Gas temperatures measured in this study are therefore higher (estimated to be 40–100°C higher) than would be using the Condar lab procedure. Higher flue gas temperatures result in lower calculated thermal efficiencies.

   Particulate material is also used as a measure of combustion efficiency in the Condar system. Normally measured at 1.5 meters in the lab, field measurements of particulate material were made about 0.5 meters above the stove. With potentially higher particle loadings due to less flue pipe deposition, calculated efficiencies may be lower from field values than would be observed in the lab conditions used to calibrate the Condar method. For these reasons, efficiency values for this project are thought to be artificially low. Condar-calculated efficiencies are, however, used in calculating grams per million joule emission rates, which may result in these values being artificially high relative to laboratory-generated values, and should be used with great caution.

Calculation of emissions as a function of time (g/hr) required, in addition to "1" through "5":

8. Mass of dry wood burned (measured by scale basket, corrected with moisture measurements).

9. Total hours of stove operation. Data were computed on the basis of hours of stove operation (stack temperature >100°F).

Particulate emission data were calculated for samples for which all necessary parameters were currently available. These parameters include: lab particulate weights from dichloromethane and methanol rinses, filter catch and resin (XAD-2) extracts, valid field leak checks and flow calibrations, Data LOG'r data for sampling duration and stove operation, valid oxygen calibrations, and valid scale weighings.

COMBUSTOR LONGEVITY INSPECTIONS

Several efforts were made to evaluate the longevity of catalytic combustors in the study and to assess combustor effectiveness over time. The original study design included six catalytic stoves which had at least one heating season of use; these "Group III" stoves were to be qualitatively compared with the catalytic stoves used in Group I homes.

Based on reports of catalyst deterioration and preliminary emission performance results from the first heating season, two tasks were added to the study for the second heating season. These included:

Inspection of Catalytic Combustors

Between the first and second heating season, all catalytic combustors in the study were removed and inspected. Combustors were evaluated visually for evidence of plugging, cracking, erosion or structural damage, and peeling. Following the second heating season, all available stoves and catalytic combustors used in the study were inspected. Combustors were removed and replaced with new units. The used combustors were archived for future testing. Results of the final stove inspection will be reported under separate cover.

Conventional. The conventional stoves were not separated by stove model. Twenty-three individual conventional stove models are represented in the data set, which account for the relatively wide range of measured wood use values observed (0.45 to 1.58 kg dry wood/HDD for scale weighings, 0.28 to 2.05 kg dry wood/HDD for woodpile measurements).

Stove Switching. Table 3-9 presents the results of switching stove technology in Group II homes on wood use. Wood use, as measured by woodpile measurements, was compared for homes which changed stove model between heating seasons. Figure 3-5 shows the mean percentage wood use decrease (woodpile measurements) for catalytic stoves, add-on/retrofits, and low-emission stoves versus conventional stoves, and the mean percentage wood use decrease for low-emission stoves versus add-on retrofits.

All seven Group II homes which changed from conventional to catalytic technology showed a decrease in wood use, from an average of 0.93 kg dry wood/HDD to an average of 0.64 kg dry wood/HDD. Four of five homes switching from conventional to add-on retrofit technology showed decreases in wood use. The average wood use for the conventional vs. add-on/retrofit technology category decreased from 0.86 kg dry wood/HDD to 0.70 kg dry wood/HDD. Both (two) homes which switched from conventional stoves to low-emission stoves showed an average wood use decrease from 0.56 kg dry wood/HDD to 0.38 kg dry wood/HDD. Two of the three homes which switched from add-on/retrofit devices to low-emission stoves showed decreases in wood use. The average wood use for the add-on/retrofit vs. low-emission technology decreased from 0.79 kg dry wood/HDD to 0.53 kg dry wood/HDD.

As noted in the evaluation of creosote accumulation, stove switching results are intended to give qualitative results only. Nonetheless, the consistent reduction of wood use by the advanced technology stoves indicates that wood use is reduced with these stoves.

PARTICULATE EMISSIONS, BURN RATE, AND FUELING DATA

Introduction

One of the objectives of the original study design was to evaluate the emission reduction performance of catalytic woodstoves, add-on/retrofit devices, and low-emission stoves over a two-heating-season period. Tables 3-10A, 3-10B, and 3-10C present data obtained for each sampling period in Group I and Group III homes during the study. Data presented in Table 3-10A include stove codes, sampling

Table 3-9

EFFECTS OF STOVE TECHNOLOGY CHANGES ON WOOD USE[a/b/]

CATALYTIC VS. CONVENTIONAL:			
STUDY HOME	CONVENTIONAL STOVE (Dry Kg Wood Use/HDD)	CATALYTIC STOVE (Dry Kg Wood Use/HDD)	NET CHANGE IN WOOD USE
V19	1.22	0.55	-55
V20	1.16	0.95	-18
V22	0.80	0.57	-29
V28	0.54	0.38	-30
N18	0.63	0.59	-6
N20	0.91	0.53	-42
N22	1.25	0.89	-29
	----	----	----
Average	0.93	0.64	-30 [15]
ADD-ON/RETROFIT VS. CONVENTIONAL:			
STUDY HOME	CONVENTIONAL STOVE (Dry Kg Wood Use/HDD)	ADD-ON/RETROFIT (Dry Kg Wood Use/HDD)	NET CHANGE IN WOOD USE
V15	0.79	0.60	-24
V21	0.53	0.37	-30
V29	1.09	0.55	-50
N05	0.43	0.66	+53
N27	1.47	1.30	-12
	----	----	----
Average	0.86	0.70	-13 [35]
LOW-EMISSION VS. CONVENTIONAL:			
STUDY HOME	CONVENTIONAL STOVE (Dry Kg Wood Use/HDD)	LOW-EMISSION STOVE (Dry Kg Wood Use/HDD)	NET CHANGE IN WOOD USE
V23	0.51	0.36	-29
N16	0.60	0.39	-35
	----	----	----
Average	0.56	0.38	-32 [3]

(Continued)

Table 3-9 (Continued)

EFFECTS OF STOVE TECHNOLOGY CHANGES ON WOOD USE[a/b/]

LOW-EMISSION VS. ADD-ON/RETROFIT:			
STUDY HOME	ADD-ON/RETROFIT (Dry Kg Wood Use/HDD)	LOW-EMISSION STOVE (Dry Kg Wood Use/HDD)	NET CHANGE IN WOOD USE
V03	0.62	0.59	-5
V12	0.53	0.60	+13
N13	1.23	0.39	-68
	----	----	----
Average	0.79	0.53	-20 [35]

a/ Wood use data is from woodpile measurements only.

b/ Values inside brackets are standard deviations (σ).

Figure 3-5
Comparative Wood Use: Group II Homes (Woodpile Measurements)

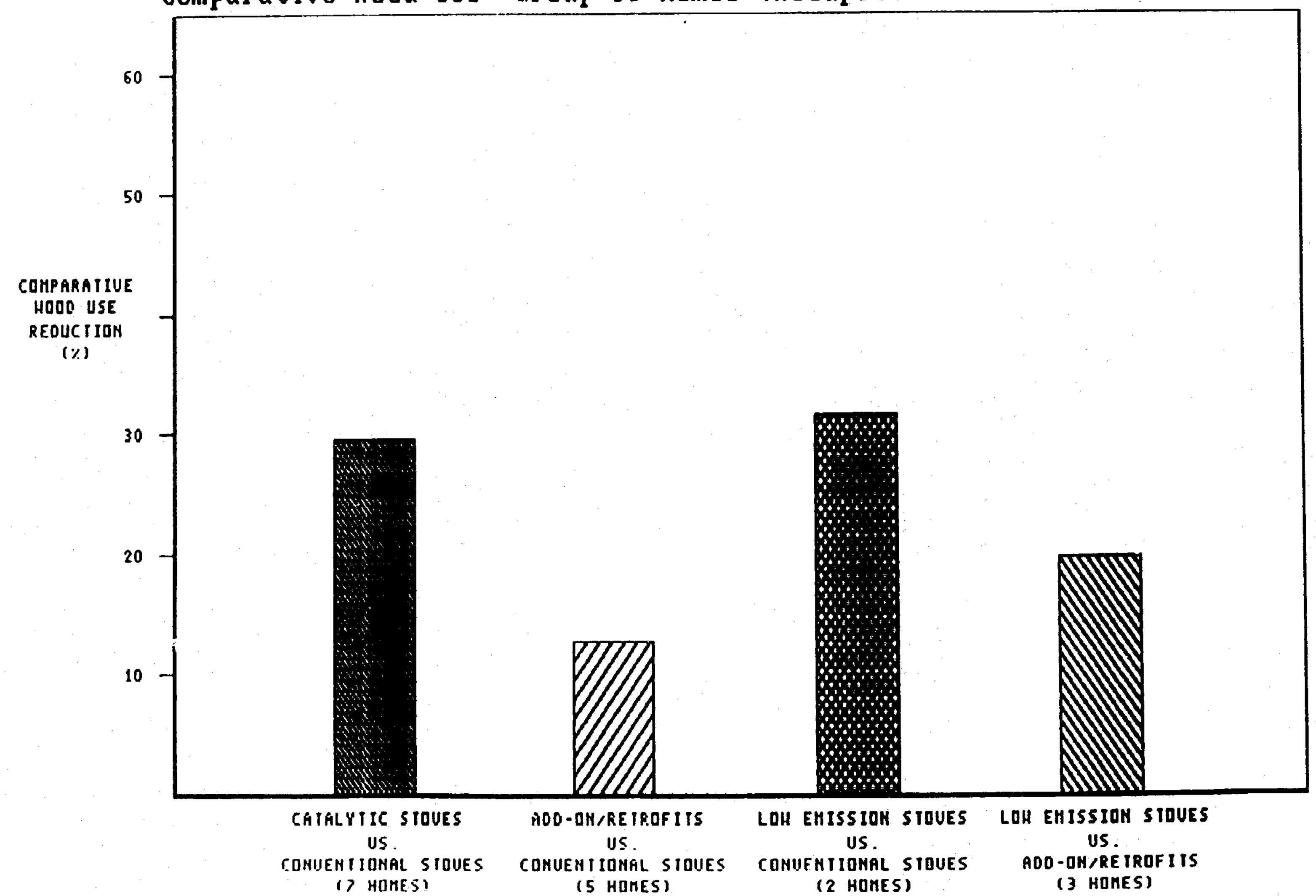


Table 3-10A
STOVE USE CHARACTERISTICS -- CATALYTIC STOVES

Sampling Code[a]	Stove Code[b]	Sampling Period[c]	HDD[d]	Catalyst Operation[e] (%)	Stove Operation[f] (%)	Heating System[g] Use (%)	Efficiency (%)[h]
V05(-1)[t]	B	01/07-01/13/86	345	(96.7)	100.0	3.1	(46.9)
(-2)[t]	B	02/09-02/15/86	355	(96.3)	100.0	1.7	(50.0)
-4[u]	B	11/16-11/22/86	266	88.1	100.0	0.0	66.1
-5[u]	B	12/14-12/20/86	272	87.8	85.7	2.8	0.0
V07-1	C	01/07-01/13/86	345	78.8	100.0	25.0	55.3
(-2)[v]	C	02/09-02/15/86	355	85.4	100.0	39.1	(51.0)
-3	C	03/09-03/15/86	252	55.7	70.9	38.3	50.5
(-5)[w]	C	12/14-12/20/86	272	65.5	99.3	15.9	(54.9)
-6	C	01/25-01/31/87	396	74.9	97.0	37.6	49.2
-7	C	02/22-02/28/87	300	70.9	97.2	11.2	61.5
V08-1	D	01/07-01/13/86	345	57.4	100.0	0.0	52.0
-2	D	02/09-02/15/86	355	57.7	99.8	0.0	53.9
(-3)[v]	D	03/09-03/15/86	252	40.9	93.8	0.0	(41.3)
-4[x]	D	11/18-11/23/86	266	58.4	85.7	0.1	55.2
-5[x]	D	12/14-12/20/86	272	68.7	100.0	0.0	57.0
-6[x]	D	01/25-01/31/87	396	70.9	95.5	0.0	53.8
-7[x]	D	02/22-02/28/87	300	62.0	93.7	0.0	54.0
V11-2[y]	B	02/26-03/02/86	244	74.5	67.2	0.0	61.1
-6[y]	B	02/08-02/11/87	173	45.0	98.8	0.0	65.1
-7[y]	B	03/08-03/14/87	306	42.9	54.7	0.0	64.2
V13-2	D	02/23-03/01/86	342	57.4	97.2	0.0	51.5
-3	D	03/23-03/29/86	173	31.8	79.8	0.0	40.1
-4[u/x]	D	12/02-12/07/86	229	39.9	99.8	0.0	55.5
-5[u/x]	D	01/11-01/17/87	307	45.0	100.0	0.4	55.8
-6[u/x]	D	02/08-02/14/87	392	49.2	100.0	0.0	52.5
-7[u/x]	D	03/08-03/14/87	306	49.6	96.3	0.9	58.1

(Continued)

Table 3-10A (Continued)
STOVE USE CHARACTERISTICS -- CATALYTIC STOVES

Sampling Code[a]	Stove Code[b]	Sampling Period[c]	HDD[d]	Catalyst Operation[e] (%)	Stove Operation[f] (%)	Heating System[g] Use (%)	Efficiency (%)[h]
V16-1	C	01/26-02/01/86	373	80.2	100.0	0.0	58.7
-4[u/z]	C	11/30-12/06/86	277	62.7	93.6	6.0	48.2
-5[u/z]	C	01/11-01/17/87	307	60.7	70.7	2.7	48.7
-6[u/z]	C	02/08-02/14/87	392	70.5	87.0	23.4	52.0
-7[u/z]	C	03/08-03/14/87	306	43.2	71.6	9.0	50.6
V31-4[y]	P	12/06-12/12/86	300	87.8	100.0	0.0	48.2
V32-1[y]	P	03/14-03/20/87	208	33.8	100.0	0.0	51.4
-5[aa/y]	P	01/21-01/27/87	409	48.0	100.0	0.0	62.5
(N01-2)[bb]	A	02/18-02/22/86	164	57.0	100.0	0.0	(71.8)
-3	A	03/16-03/22/86	224	29.5	99.7	0.0	55.1
-5	A	01/04-01/10/87	294	22.0	100.0	0.0	48.4
-6	A	02/03-02/08/87	226	10.9	100.0	0.0	46.3
-7	A	03/01-03/07/87	218	10.8	98.8	0.0	50.8
N02-1	D	01/18-01/25/86	243	83.1	100.0	0.0	59.0
(-2)[cc]	D	02/16-02/22/86	258	(50.5)	100.0	0.0	(44.8)
-3	D	03/16-03/22/86	224	74.1	98.2	0.0	59.9
-4[x]	D	11/23-11/29/86	196	60.7	98.2	0.0	59.6
-6[x]	D	02/01-02/07/87	264	59.9	100.0	0.0	57.9
-7[x]	D	03/01-03/07/87	218	53.9	100.0	0.0	57.3
N03-4[dd]	C	11/25-11/30/86	162	41.4	40.6	2.2	55.2
-5[dd]	C	01/04-01/10/87	294	58.4	76.5	1.0	52.3
-6[u/dd]	C	02/01-02/07/87	264	42.7	66.4	1.3	44.9
N09-1	B	02/04-02/08/86	238	88.2	99.7	0.0	58.3
-4[u]	B	12/07-12/13/86	275	83.1	100.0	0.4	48.7
-6[u]	B	02/17-02/22/87	273	70.1	99.0	0.0	52.2
-7[u]	B	03/15-03/21/87	242	67.3	84.8	0.5	56.7

(Continued)

Table 3-10A (Continued)
STOVE USE CHARACTERISTICS -- CATALYTIC STOVES

Sampling Code[a]/	Stove Code[b]/	Sampling Period[c]/	HDD[d]/	Catalyst Operation[e]/ (%)	Stove Operation[f]/ (%)	Heating System[g]/ Use (%)	Efficiency (%)[h]/
N10-1[y]/	A	02/02-02/08/86	249	91.1	100.0	2.8	67.7
(-2)[v]/[y]/	A	03/02-03/08/86	263	80.3	98.5	0.1	(58.7)
(-4)[v]/[y]/	A	12/09-12/14/86	241	82.3	100.0	0.0	(63.0)
-5[y]/	A	01/18-01/24/87	331	90.3	100.0	0.0	58.0
-6[y]/	A	02/15-02/21/87	376	86.6	100.0	0.0	60.6
-7[y]/	A	03/15-03/21/87	242	87.2	100.0	0.0	50.5
N11-2[y]/	D	03/02-03/08/86	263	31.7	88.9	21.9	56.6
-4[x]/[y]/	D	12/07-12/13/86	275	53.7	93.3	10.0	62.1
(-6)[v]/[x]/[y]/	D	02/17-02/22/86	273	65.0	100.0	8.5	(73.5)
(-7)[v]/[x]/[y]/	D	03/15-03/21/86	242	36.2	52.1	15.3	(54.0)
N18-4[u]/[y]/	B	11/23-11/29/86	196	85.1	100.0	0.0	60.4
-5[u]/[y]/	B	01/04-01/10/87	294	85.0	100.0	0.4	49.4
-6[u]/[y]/	B	02/03-02/08/87	226	89.6	78.6	0.0	50.8
-7[y]/	B	03/01-03/07/87	218	90.9	98.1	0.0	52.9
(N32-3)[v]/[y]/	P	03/02-03/08/87	263	76.8	100.0	0.0	(61.9)
-5[y]/	P	01/06-01/11/87	264	51.3	100.0	0.0	56.1
N33-3	P	02/27-03/05/86	255	58.8	100.0	0.0	50.0
-5[ee]/	P	01/18-01/24/87	331	(0.0)	100.0	0.0	49.8

(Continued)

Table 3-10A (Continued)
STOVE USE CHARACTERISTICS -- ADD-ON/RETROFIT STOVES

Sampling Code[a/]	Stove Code[b/]	Sampling Period[c/]	HDD[d/]	Catalyst Operation[e/] (%)	Stove Operation[f/] (%)	Heating System[g/] Use (%)	Efficiency (%)[h/]
V01-4[u/]	E (R)	11/16-11/22/86	266	69.2	99.9	0.3	62.2
-5[u/]	E (R)	12/14-12/20/86	272	74.7	100.0	1.9	58.0
(-6)[u/ff/]	E (R)	01/25-01/31/87	396	(75.3)	100.0	0.0	(54.6)
-7[u/]	E (R)	02/22-02/28/87	300	63.9	95.4	2.3	60.2
V02-1	G (A)	01/07-01/13/86	345	37.5	100.0	0.0	56.4
-2	G (A)	02/13-02/17/87	249	49.5	99.2	0.0	58.8
V03-1	F (R)	01/07-01/13/86	345	25.5	99.9	0.0	53.3
-3	F (R)	03/09-03/15/86	252	17.7	98.5	2.6	38.3
V10-2	H (A)	02/23-03/01/86	342	19.0	89.1	5.5	50.7
-5[gg/hh/]	J (A)	01/11-01/17/87	307	17.6	74.6	4.7	54.5
-6[gg/hh/]	J (A)	02/08-02/14/87	392	56.2	73.8	5.3	73.8
(V12-1)[v/ee/]	F (R)	01/26-02/01/86	373	(0.0)	99.6	0.0	(58.5)
-2[ee/]	F (R)	02/20-02/26/86	316	(0.0)	98.2	0.0	51.5
-3	F (R)	03/23-03/29/86	173	9.8	47.9	0.0	32.8
(V15-1)[w/y/]	H (A)	01/28-02/01/86	292	22.4	98.5	0.0	(58.1)
N04-1[ii/]	G (A)	01/19-01/25/86	243	46.4	92.4	2.7	54.5
-5[ii/]	J (A)	01/04-01/10/87	294	57.8	96.1	0.1	61.4
(-6)[v/ii/]	G (A)	02/01-02/07/87	264	9.4	99.3	0.1	(59.6)
N06-1	I (A)	01/19-01/25/86	243	53.2	99.3	0.0	52.3
-2	I (A)	02/16-02/22/86	258	66.6	100.0	0.0	55.5
-3	I (A)	03/16-03/22/86	224	56.3	84.7	0.0	45.6
N12-4	J (A)	12/07-12/13/86	275	53.6	93.9	0.2	59.3
N14-2	I (A)	03/02-03/08/86	263	53.7	99.9	0.0	49.5
(-4)[u/v/jj/]	J (A)	12/07-12/13/86	275	68.2	100.0	0.0	(63.2)
(-5)[u/v/jj/]	O (A)	01/18-01/24/87	331	N/A	100.0	0.0	(57.0)

(Continued)

Table 3-10A (Continued)
STOVE USE CHARACTERISTICS -- LOW-EMISSION STOVES

Sampling Code[a]	Stove Code[b]	Sampling Period[c]	HDD[d]	Stove Operation[f] (%)	Heating System[g] Use (%)	Efficiency (%)[h]
V03-5	N	12/14-12/20/86	272	100.0	1.8	48.0
-6	N	01/25-01/31/87	396	99.5	2.5	47.8
(V04-1)[v]	L	01/07-01/13/86	345	95.1	0.0	(52.3)
-3	L	03/09-03/15/86	252	80.3	2.3	48.2
-4	L	11/16-11/22/86	376	66.9	2.0	38.5
-6	L	01/25-01/31/87	396	91.3	0.0	42.4
V12-6[u]	M	02/08-02/14/87	392	100.0	0.0	55.5
V14-6	M	02/08-02/14/87	392	99.3	0.0	46.0
-7	M	03/08-03/14/87	306	100.0	0.0	51.0
V18-4[y]	K	11/30-12/06/86	277	82.8	1.2	44.5
-5[y]	K	01/11-01/17/87	307	96.0	0.1	49.2
-6[y]	K	02/08-02/14/87	392	87.5	7.7	50.8
-7[y]	K	03/08-03/14/87	306	97.5	0.8	39.8
V34-5[u]	M	12/14-12/20/87	272	100.0	1.0	54.3
-7[u]	M	02/22-02/28/87	300	100.0	1.9	56.9
V35-7[y]	N	03/08-03/14/87	306	84.1	0.0	52.6
N07-5	K	01/04-01/10/87	294	100.0	0.0	57.3
(-6)[v]	K	02/01-02/07/87	264	97.3	0.0	(40.5)
-7	K	03/01-03/07/87	218	100.0	0.0	59.0
(N13-5)[v/y]	M	01/18-01/24/87	331	100.0	0.0	45.4
N15-4[u/kk]	L	12/07-12/13/87	275	88.1	0.5	33.0
-5[u/kk]	L	01/18-01/24/87	331	98.5	11.1	48.4
-7[u/kk]	L	03/15-03/21/87	242	84.7	4.0	45.9
N16-4[y]	N	12/07-12/13/86	275	97.4	0.0	48.9
-6[y]	N	02/15-02/21/87	376	100.0	0.0	66.6
-7[y]	N	03/15-03/21/87	242	100.0	0.1	48.2

(Continued)

Table 3-10A (Continued)
STOVE USE CHARACTERISTICS -- TRADITIONAL/CONVENTIONAL STOVES

Sampling Code[a]	Stove Code[b]	Sampling Period[c]	HDD[d]	Stove Operation[f] (%)	Heating System[g] Use (%)	Efficiency (%)[h]
V06-1[y]	0	01/07-01/13/86	345	95.6	0.0	53.5
-2[y]	0	02/09-02/15/86	355	100.0	0.0	(50.2)
(-3)[v][y]	0	03/09-03/15/86	252	93.9	0.0	41.5
-5[y]	0	12/14-12/20/86	272	99.8	0.0	43.7
-6[y]	0	01/25-01/31/87	396	100.0	0.0	30.6
V09-1	0	01/26-02/01/86	373	95.9	0.0	52.6
V14-1	0	01/26-02/01/86	373	100.0	3.3	54.6
-2	0	02/26-03/02/86	244	100.0	3.1	48.7
-3	0	03/23-03/29/86	173	77.6	0.0	48.6
(N08-3)[v]	0	03/16-03/22/86	189	100.0	0.1	(53.5)
-4[u]	0	11/25-11/30/86	162	100.0	0.0	49.8
-6[u]	0	02/01-02/07/87	264	100.0	0.0	53.8
-7[u]	0	03/01-03/07/87	218	100.0	0.0	51.8
N14-6	0	02/15-02/21/87	376	100.0	0.0	53.9
-7	0	03/15-03/21/87	242	100.0	0.0	52.6
N16-1[y]	0	02/02-02/08/87	321	100.0	3.8	49.5

Table 3-10B
FUEL CHARACTERISTICS -- CATALYTIC STOVES

Sampling Code[a]	Stove Code[b]	Sampling Period[c]	HDD[d]	Fuel Moisture[i] (% DB)	Average Load[j] (kg dry)	Loading Frequency[k] (#/hr)	Burn Rate[l] (kg/hr)
V05(-1)[t]	B	01/07-01/13/86	345	28.0	(7.4)	(0.18)	(1.33)
(-2)[t]	B	02/09-02/15/86	355	29.5	(8.1)	(0.17)	(1.19)
-4[u]	B	11/16-11/22/86	266	18.2	4.4	0.19	0.84
-5[u]	B	12/14-12/20/86	272	19.0	6.0	0.15	0.92
V07-1	C	01/07-01/13/86	345	17.0	8.4	0.22	1.85
(-2)[v]	C	02/09-02/15/86	355	20.5	10.2	0.15	1.89
-3	C	03/09-03/15/86	252	25.0	9.5	0.11	1.47
(-5)[w]	C	12/14-12/20/86	272	20.1	(7.4)	(0.10)	(0.76)
-6	C	01/25-01/31/87	396	12.5	8.5	0.16	1.35
-7	C	02/22-02/28/87	300	13.8	9.1	0.16	1.45
V08-1	D	01/07-01/13/86	345	33.0	5.7	0.21	1.22
-2	D	02/09-02/15/86	355	25.0	6.1	0.21	1.27
(-3)[v]	D	03/09-03/15/86	252	28.5	4.9	0.20	0.96
-4[x]	D	11/18-11/23/86	266	33.0	3.8	0.16	0.61
-5[x]	D	12/14-12/20/86	272	26.0	4.3	0.18	0.79
-6[x]	D	01/25-01/31/87	396	28.4	5.2	0.21	1.08
-7[x]	D	02/22-02/28/87	300	29.0	5.2	0.21	1.09
V11-2[y]	B	02/26-03/02/86	244	27.0	14.0	0.07	1.02
-6[y]	B	02/08-02/11/87	173	28.0	9.0	0.13	1.19
-7[y]	B	03/08-03/14/87	306	24.0	15.1	0.08	1.15
V13-2	D	02/23-03/01/86	342	25.0	4.4	0.25	1.10
-3	D	03/23-03/29/86	173	24.5	3.2	0.22	0.73
-4[u/x]	D	12/02-12/07/86	229	23.0	4.1	0.29	1.21
-5[u/x]	D	01/11-01/17/87	307	20.5	4.3	0.27	1.18
-6[u/x]	D	02/08-02/14/87	392	19.8	4.1	0.30	1.24
-7[u/x]	D	03/08-03/14/87	306	27.0	3.9	0.30	1.18

(Continued)

Table 3-10B (Continued)
FUEL CHARACTERISTICS -- CATALYTIC STOVES

Sampling Code[a/]	Stove Code[b/]	Sampling Period[c/]	HDD[d/]	Fuel Moisture[i/] (% DB)	Average Load[j/] (kg dry)	Loading Frequency[k/] (#/hr)	Burn Rate[l/] (kg/hr)
V16-1	C	01/26-02/01/86	373	18.5	7.5	0.17	1.29
-4[u/z/]	C	11/30-12/06/86	277	29.2	6.5	0.17	1.11
-5[u/z/]	C	01/11-01/17/87	307	26.6	5.5	0.23	1.25
-6[u/z/]	C	02/08-02/14/87	392	27.2	6.2	0.20	1.28
-7[u/z/]	C	03/08-03/14/87	306	30.3	6.2	0.18	1.13
V31-4[y/]	P	12/06-12/12/86	300	32.4	2.9	0.35	1.01
V32-1[y/]	P	03/14-03/20/87	208	24.0	4.1	0.27	1.12
-5[aa/y/]	P	01/21-01/27/87	409	26.2	6.4	0.18	1.14
(N01-2)[bb/]	A	02/18-02/22/86	164	31.6	4.3	0.16	0.68
-3	A	03/16-03/22/86	224	29.0	4.5	0.13	0.57
-5	A	01/04-01/10/87	294	38.8	4.5	0.17	0.78
-6	A	02/03-02/08/87	226	43.0	4.9	0.15	0.74
-7	A	03/01-03/07/87	218	39.3	4.4	0.16	0.72
N02-1	D	01/18-01/25/86	243	15.6	5.3	0.22	1.17
(-2)[cc/]	D	02/16-02/22/86	258	16.7	(7.1)	(0.21)	(1.49)
-3	D	03/16-03/22/86	224	16.7	5.6	0.19	1.05
-4[x/]	D	11/23-11/29/86	196	14.6	5.7	0.15	0.82
-6[x/]	D	02/01-02/07/87	264	11.8	5.8	0.20	1.17
-7[x/]	D	03/01-03/07/87	218	15.0	4.8	0.20	0.97
N03-4[dd/]	C	11/25-11/30/86	162	16.7	5.3	0.19	1.00
-5[dd/]	C	01/04-01/10/87	294	16.7	5.7	0.17	0.97
-6[u/dd/]	C	02/01-02/07/87	264	20.2	5.5	0.19	1.03
N09-1	B	02/04-02/08/86	238	41.0	10.5	0.12	1.23
-4[u/]	B	12/07-12/13/86	275	15.8	11.6	0.11	1.31
-6[u/]	B	02/17-02/22/87	273	17.1	8.8	0.14	1.23
-7[u/]	B	03/15-03/21/87	242	16.7	11.5	0.12	1.37

(Continued)

Table 3-10B (Continued)
FUEL CHARACTERISTICS -- CATALYTIC STOVES

Sampling Code[a]	Stove Code[b]	Sampling Period[c]	HDD[d]	Fuel Moisture[i] (% DB)	Average Load[j] (kg dry)	Loading Frequency[k] (#/hr)	Burn Rate[l] (kg/hr)
N10-1[y]	A	02/02-02/08/86	249	36.0	5.3	0.28	1.46
(-2)[v/y]	A	03/02-03/08/86	263	41.4	4.7	0.25	1.16
(-4)[v/y]	A	12/09-12/14/86	241	26.0	6.9	0.17	1.16
-5[y]	A	01/18-01/24/87	331	39.4	7.2	0.21	1.51
-6[y]	A	02/15-02/21/87	376	37.2	8.1	0.21	1.69
-7[y]	A	03/15-03/21/87	242	37.0	11.1	0.14	1.58
N11-2[y]	D	03/02-03/08/86	263	17.8	2.9	0.31	0.90
-4[x/y]	D	12/07-12/13/86	275	16.6	2.4	0.38	0.90
(-6)[v/x/y]	D	02/17-02/22/86	273	15.7	2.9	0.40	1.16
(-7)[v/x/y]	D	03/15-03/21/86	242	16.5	2.7	0.22	0.58
N18-4[u/y]	B	11/23-11/29/86	196	11.0	7.6	0.18	1.37
-5[u/y]	B	01/04-01/10/87	294	16.6	9.1	0.17	1.57
-6[u/y]	B	02/03-02/08/87	226	16.6	5.9	0.20	1.19
-7[y]	B	03/01-03/07/87	218	17.8	7.4	0.19	1.40
(N32-3)[v/y]	P	03/02-03/08/87	263	23.5	6.5	0.17	1.09
-5[y]	P	01/06-01/11/87	264	22.0	7.4	0.16	1.18
N33-3	P	02/27-03/05/86	255	32.3	6.8	0.27	1.83
-5[ee]	P	01/18-01/24/87	331	30.0	6.9	0.33	2.26

(Continued)

Table 3-10B (Continued)
FUEL CHARACTERISTICS -- ADD-ON/RETROFIT STOVES

Sampling Code[a/]	Stove Code[b/]	Sampling Period[c/]	HDD[d/]	Fuel Moisture[i/] (% DB)	Average Load[j/] (kg dry)	Loading Frequency[k/] (#/hr)	Burn Rate[l/] (kg/hr)
V01-4[u/]	E (R)	11/16-11/22/86	266	17.5	5.3	0.22	1.17
-5[u/]	E (R)	12/14-12/20/86	272	27.1	6.4	0.21	1.36
(-6)[u/ff/]	E (R)	01/25-01/31/87	396	34.0	6.2	0.26	1.58
-7[u/]	E (R)	02/22-02/28/87	300	34.0	6.4	0.21	1.37
V02-1	G (A)	01/07-01/13/86	345	32.0	10.5	0.15	1.62
-2	G (A)	02/13-02/17/87	249	28.0	12.0	0.13	1.61
V03-1	F (R)	01/07-01/13/86	345	24.5	7.6	0.21	1.59
-3	F (R)	03/09-03/15/86	252	24.7	5.3	0.16	0.87
V10-2	H (A)	02/23-03/01/86	342	21.7	4.0	0.23	1.01
-5[gg/hh/]	J (A)	01/11-01/17/87	307	24.0	3.8	0.28	1.07
-6[gg/hh/]	J (A)	02/08-02/14/87	392	22.0	4.0	0.37	1.47
(V12-1)[v/]	F (R)	01/26-02/01/86	373	21.0	4.9	0.28	1.37
-2	F (R)	02/20-02/26/86	316	31.0	3.8	0.25	0.97
-3	F (R)	03/23-03/29/86	173	21.0	3.9	0.12	0.97
(V15-1)[w/y/]	H (A)	01/28-02/01/86	292	34.0	(5.2)	(0.06)	(0.29)
N04-1[ii/]	G (A)	01/19-01/25/86	243	14.2	8.2	0.21	1.70
-5[ii/]	J (A)	01/04-01/10/87	294	19.1	7.9	0.21	1.66
(-6)[v/ii/]	G (A)	02/01-02/07/87	264	16.3	7.9	0.23	1.86
N06-1	I (A)	01/19-01/25/86	243	21.7	7.3	0.32	2.32
-2	I (A)	02/16-02/22/86	258	22.3	9.2	0.25	2.29
-3	i (A)	03/16-03/22/86	224	22.5	8.0	0.26	2.08
N12-4	J (A)	12/07-12/13/86	275	27.6	6.9	0.19	1.31
N14-2	I (A)	03/02-03/08/86	263	42.0	6.9	0.34	2.35
(-4)[u/v/jj/]	J (A)	12/07-12/13/86	275	25.4	6.0	0.30	1.78
(-5)[u/v/jj/]	O (A)	01/18-01/24/87	331	30.0	5.4	0.40	2.16

(Continued)

Table 3-10B (Continued)
FUEL CHARACTERISTICS -- LOW-EMISSION STOVES

Sampling Code a/	Stove Code b/	Sampling Period c/	HDD d/	Fuel Moisture i/ (% DB)	Average Load j/ (kg dry)	Loading Frequency k/ (#/hr)	Burn Rate l/ (kg/hr)
V03-5	N	12/14-12/20/86	272	34.0	5.2	0.24	1.28
-6	N	01/25-01/31/87	396	33.0	4.6	0.30	1.38
(V04-1) v/	L	01/07-01/13/86	345	21.0	2.8	0.38	1.07
-3	L	03/09-03/15/86	252	15.2	2.8	0.33	0.90
-4	L	11/16-11/22/86	376	15.0	2.5	0.31	0.76
-6	L	01/25-01/31/87	396	13.0	2.5	0.32	0.81
V12-6 u/	M	02/08-02/14/87	392	27.0	2.2	0.30	0.67
V14-6	M	02/08-02/14/87	392	28.3	3.7	0.29	1.07
-7	M	03/08-03/14/87	306	27.0	3.5	0.24	0.85
V18-4 y/	K	11/30-12/06/86	277	31.0	3.1	0.35	1.09
-5 y/	K	01/11-01/17/87	307	34.3	3.8	0.29	1.10
-6 y/	K	02/08-02/14/87	392	34.0	3.5	0.31	1.08
-7 y/	K	03/08-03/14/87	306	26.0	4.0	0.32	1.26
V34-5 u/	M	12/14-12/20/87	272	21.1	2.8	0.27	0.76
-7 u/	M	02/22-02/28/87	300	21.0	3.8	0.24	0.92
V35-7 y/	N	03/08-03/14/87	306	35.5	3.1	0.29	0.90
N07-5	K	01/04-01/10/87	294	20.2	5.7	0.15	0.84
(-6) v/	K	02/01-02/07/87	264	21.1	4.6	0.18	0.85
-7	K	03/01-03/07/87	218	20.9	4.6	0.20	0.90
(N13-5) v/y/	M	01/18-01/24/87	331	32.5	3.9	0.31	1.18
N15-4 u/kk/	L	12/07-12/13/87	275	15.5	2.2	0.53	1.19
-5 u/kk/	L	01/18-01/24/87	331	15.5	2.7	0.50	1.34
-7 u/kk/	L	03/15-03/21/87	242	15.5	2.9	0.32	0.93
N16-4 y/	N	12/07-12/13/86	275	25.0	2.9	0.34	0.97
-6 y/	N	02/15-02/21/87	376	23.2	3.3	0.33	1.10
-7 y/	N	03/15-03/21/87	242	24.0	3.2	0.27	0.87

(Continued)

Table 3-10B (Continued)
FUEL CHARACTERISTICS -- LOW-EMISSION STOVES

Sampling Code[a/]	Stove Code[b/]	Sampling Period[c/]	HDD[d/]	Fuel Moisture[i/] (% DB)	Average Load[j/] (kg dry)	Loading Frequency[k/] (#/hr)	Burn Rate[l/] (kg/hr)
V03-5	N	12/14-12/20/86	272	34.0	5.2	0.24	1.28
-6	N	01/25-01/31/87	396	33.0	4.6	0.30	1.38
(V04-1)[v/]	L	01/07-01/13/86	345	21.0	2.8	0.38	1.07
-3	L	03/09-03/15/86	252	15.2	2.8	0.33	0.90
-4	L	11/16-11/22/86	376	15.0	2.5	0.31	0.76
-6	L	01/25-01/31/87	396	13.0	2.5	0.32	0.81
V12-6[u/]	M	02/08-02/14/87	392	27.0	2.2	0.30	0.67
V14-6	M	02/08-02/14/87	392	28.3	3.7	0.29	1.07
-7	M	03/08-03/14/87	306	27.0	3.5	0.24	0.85
V18-4[y/]	K	11/30-12/06/86	277	31.0	3.1	0.35	1.09
-5[y/]	K	01/11-01/17/87	307	34.3	3.8	0.29	1.10
-6[y/]	K	02/08-02/14/87	392	34.0	3.5	0.31	1.08
-7[y/]	K	03/08-03/14/87	306	26.0	4.0	0.32	1.26
V34-5[u/]	M	12/14-12/20/87	272	21.1	2.8	0.27	0.76
-7[u/]	M	02/22-02/28/87	300	21.0	3.8	0.24	0.92
V35-7[y/]	N	03/08-03/14/87	306	35.5	3.1	0.29	0.90
N07-5	K	01/04-01/10/87	294	20.2	5.7	0.15	0.84
(-6)[v/]	K	02/01-02/07/87	264	21.1	4.6	0.18	0.85
-7	K	03/01-03/07/87	218	20.9	4.6	0.20	0.90
(N13-5)[v/y/]	M	01/18-01/24/87	331	32.5	3.9	0.31	1.18
N15-4[u/kk/]	L	12/07-12/13/87	275	15.5	2.2	0.53	1.19
-5[u/kk/]	L	01/18-01/24/87	331	15.5	2.7	0.50	1.34
-7[u/kk/]	L	03/15-03/21/87	242	15.5	2.9	0.32	0.93
N16-4[y/]	N	12/07-12/13/86	275	25.0	2.9	0.34	0.97
-6[y/]	N	02/15-02/21/87	376	23.2	3.3	0.33	1.10
-7[y/]	N	03/15-03/21/87	242	24.0	3.2	0.27	0.87

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Table 3-10B (Continued)
FUEL CHARACTERISTICS -- TRADITIONAL/CONVENTIONAL STOVES

Sampling Code[a]	Stove Code[b]	Sampling Period[c]	HDD[d]	Fuel Moisture[i] (% DB)	Average Load[j] (kg dry)	Loading Frequency[k] (#/hr)	Burn Rate[l] (kg/hr)
V06-1[y]	0	01/07-01/13/86	345	26.5	8.0	0.31	2.45
-2[y]	0	02/09-02/15/86	355	26.6	6.7	0.24	1.60
(-3)[v/y]	0	03/09-03/15/86	252	27.5	7.4	0.22	1.59
-5[y]	0	12/14-12/20/86	272	25.0	6.7	0.23	1.52
-6[y]	0	01/25-01/31/87	396	28.0	7.3	0.26	1.86
V09-1	0	01/26-02/01/86	373	41.2	3.8	0.30	1.12
V14-1	0	01/26-02/01/86	373	23.0	4.7	0.35	1.67
-2	0	02/26-03/02/86	244	28.2	4.7	0.31	1.45
-3	0	03/23-03/29/86	173	26.3	3.5	0.26	0.92
(N08-3)[v]	0	03/16-03/22/86	189	29.7	9.8	0.20	1.92
-4[u]	0	11/25-11/30/86	162	24.7	7.2	0.26	1.91
-6[u]	0	02/01-02/07/87	264	26.5	7.8	0.28	2.19
-7[u]	0	03/01-03/07/87	218	29.5	8.4	0.24	2.00
N14-6	0	02/15-02/21/87	376	35.2	5.6	0.43	2.45
-7	0	03/15-03/21/87	242	41.0	5.4	0.29	1.57
N16-1[y]	0	02/02-02/08/87	321	26.0	3.5	0.45	1.55

Table 3-10C
EMISSION CHARACTERISTICS -- CATALYTIC STOVES

Sampling Code[a]	Stove Code[b]	HDD[d]	Burn Rate[l] (kg/hr)	Particulate Emissions[m] (g/hr)[n]	(g/kg)[o]	(g/10^6J)[p]	(g/m^3)[q]	Average Flue O_2[r] (%)	Average Flue Temp[s] (°C)
V05(-1)[t]	B	345	(1.33)	(33.7)	(25.4)	(2.7)	(0.73)	(17.9)	(103.3)
(-2)[t]	B	355	(1.19)	(18.5)	(15.6)	(1.6)	(0.58)	(17.1)	(148.5)
-4[u]	B	266	0.84	9.0	10.8	0.9	0.45	16.5	70.7
-5[u]	B	272	0.92	31.4	34.1	0.0	1.02	17.8	61.6
V07-1	C	345	1.85	10.1	5.5	0.5	0.29	15.4	231.5
(-2)[v]	C	355	1.89	(10.3)	(5.4)	(0.5)	0.24	(16.2)	232.3
-3	C	252	1.47	11.4	7.7	0.8	0.29	16.9	189.8
(-5)[w]	C	272	(0.76)	(4.8)	(6.3)	(0.6)	0.26	16.6	179.9
-6	C	396	1.35	14.3	10.5	1.1	0.43	16.6	204.2
-7	C	300	1.45	1.7	1.2	0.1	0.06	15.7	214.6
V08-1	D	345	1.22	18.2	15.0	1.4	1.04	13.7	225.7
-2	D	355	1.27	20.4	16.1	1.5	1.22	13.1	211.6
(-3)[v]	D	252	0.96	(25.4)	(26.3)	(3.2)	1.13	(16.5)	190.6
-4[x]	D	266	0.61	7.6	12.4	1.1	0.68	15.2	171.9
-5[x]	D	272	0.79	14.1	17.8	1.6	1.31	13.3	170.0
-6[x]	D	396	1.08	13.4	12.4	1.2	0.96	12.9	249.2
-7[x]	D	300	1.09	12.7	11.7	1.1	0.78	14.0	225.1
V11-2[y]	B	244	1.02	6.1	6.0	0.5	0.24	16.8	131.6
-6[y]	B	173	1.19	6.3	5.3	0.4	0.30	15.0	144.8
-7[y]	B	306	1.15	7.0	6.1	0.5	0.29	16.0	126.2
V13-2	D	342	1.10	17.8	16.1	1.6	0.85	15.5	180.9
-3	D	173	0.73	19.4	26.7	3.3	0.88	17.5	160.8
-4[u/x]	D	229	1.21	12.4	10.3	1.0	0.61	14.7	205.3
-5[u/x]	D	307	1.18	9.7	8.1	0.7	0.44	15.3	206.1
-6[u/x]	D	392	1.24	12.4	10.0	1.0	0.52	15.6	213.5
-7[u/x]	D	306	1.18	10.5	8.9	0.8	0.53	14.7	187.6

(Continued)

Table 3-10C (Continued)
EMISSION CHARACTERISTICS -- CATALYTIC STOVES

Sampling Code[a]/	Stove Code[b]/	HDD[d]/	Burn Rate[l]/ (kg/hr)	Particulate Emissions[m]/ (g/hr)[n]/	(g/kg)[o]/	$(g/10^6 J)$[p]/	(g/m^3)[q]/	Average Flue O_2[r]/ (%)	Average Flue Temp[s]/ (°C)
V16-1									
-4[u/z]/	C	373	1.29	8.2	6.3	0.5	0.36	15.0	203.6
-5[u/z]/	C	277	1.11	19.0	17.1	1.8	0.83	15.9	192.9
-6[u/z]/	C	307	1.25	21.8	17.4	1.8	0.82	16.0	184.8
-7[u/z]/	C	392	1.28	16.8	13.1	1.3	0.70	15.4	197.7
	C	306	1.13	15.1	13.3	1.3	0.63	16.0	192.2
V31-4[y]/	P	300	1.01	17.7	17.5	1.8	0.76	16.4	171.1
V32-1[y]/	P	208	1.12	13.9	12.4	1.2	0.54	16.4	177.5
-5[aa/y]/	P	409	1.14	11.8	10.3	0.8	0.71	13.8	141.4
(N01-2)[bb]/	A	164	0.68	(4.6)	(6.8)	(0.5)	0.79	(8.8)	96.4
-3	A	224	0.57	13.0	22.9	2.1	1.10	16.0	84.5
-5	A	294	0.78	21.9	28.1	2.9	1.41	15.7	120.6
-6	A	226	0.74	21.2	28.6	3.1	1.07	17.1	110.6
-7	A	218	0.72	15.9	22.2	2.2	0.98	16.3	119.6
N02-1	D	243	1.17	9.9	8.5	0.7	0.71	12.2	257.4
(-2)[cc]/	D	258	(1.49)	(44.5)	(29.9)	(3.3)	(2.44)	(12.3)	(252.1)
-3	D	224	1.05	7.0	6.7	0.6	0.44	14.1	215.6
-4[x]/	D	196	0.82	6.9	8.4	0.7	0.61	13.3	221.3
-6[x]/	D	264	1.17	10.0	8.6	0.7	0.66	12.9	256.5
-7[x]/	D	218	0.97	8.4	8.7	0.7	0.63	13.3	245.9
N03-4[dd]/	C	162	1.00	8.1	8.1	0.7	0.28	17.3	146.2
-5[dd]/	C	294	0.97	19.0	19.7	1.9	0.91	16.1	139.8
-6[u/dd]/	C	264	1.03	24.3	23.6	2.6	0.74	17.7	133.8
N09-1	B	238	1.23	15.7	12.8	1.1	0.86	14.0	152.6
-4[u]/	B	275	1.31	21.2	16.2	1.6	1.08	14.0	268.3
-6[u]/	B	273	1.23	17.1	13.9	1.4	0.89	14.3	232.1
-7[u]/	B	242	1.37	29.6	21.5	1.9	1.41	14.1	110.0

(Continued)

Table 3-10C (Continued)
EMISSION CHARACTERISTICS -- CATALYTIC STOVES

Sampling Code[a]	Stove Code[b]	HDD[d]	Burn Rate[l] (kg/hr)	Particulate Emissions[m] (g/hr)[n]	(g/kg)[o]	$(g/10^6 J)$[p]	(g/m^3)[q]	Average Flue O_2[r] (%)	Average Flue Temp[s] (°C)
N10-1[y]	A	249	1.46	9.7	6.7	0.5	0.62	11.2	143.6
(-2)[v/y]	A	263	1.16	(17.9)	(15.4)	(1.3)	1.17	(13.1)	134.5
(-4)[v/y]	A	241	1.16	(13.9)	(12.0)	(0.9)	1.26	(10.1)	161.3
-5[y]	A	331	1.51	23.4	15.5	1.3	1.55	10.6	181.7
-6[y]	A	376	1.69	18.2	10.8	0.9	0.90	12.3	175.4
-7[y]	A	242	1.58	39.7	25.1	2.5	1.86	13.2	161.7
N11-2[y]	D	263	0.90	14.9	16.7	1.4	1.40	12.1	189.2
-4[x/y]	D	275	0.90	5.5	6.0	0.5	0.43	13.4	212.3
(-6)[v/x/y]	D	273	1.16	(6.6)	(5.7)	(0.4)	0.48	(12.1)	89.5
(-7)[v/x/y]	D	242	0.58	(4.6)	(7.9)	(0.7)	0.37	(16.1)	200.4
N18-4[u/y]	B	196	1.37	20.6	15.1	1.2	1.24	12.0	159.9
-5[u/y]	B	294	1.57	41.3	26.4	2.6	1.64	14.3	165.3
-6[u/y]	B	226	1.19	31.6	26.5	2.5	1.92	13.1	164.5
-7[y]	B	218	1.40	29.2	20.8	1.9	1.64	12.5	195.4
(N32-3)[v/y]	P	263	1.09	(5.4)	(5.0)	(0.4)	0.29	(14.8)	186.1
-5[y]	P	264	1.18	19.6	16.6	1.5	0.97	14.9	143.9
N33-3	P	255	1.83	22.3	12.2	1.2	0.57	16.1	197.5
-5[ee]	P	331	2.26	34.6	15.3	1.5	0.85	15.2	208.1

(Continued)

Table 3-10C (Continued)
EMISSION CHARACTERISTICS -- ADD-ON/RETROFIT STOVES

Sampling Code[a]	Stove Code[b]	HDD[d]	Burn Rate[l] (kg/hr)	Particulate Emissions[m] (g/hr)[n]	(g/kg)[o]	$(g/10^6 J)$[p]	(g/m^3)[q]	Average Flue O_2[r] (%)	Average Flue Temp[s] (°C)
V01-4[u]	E (R)	266	1.17	6.3	5.3	0.4	0.35	14.3	200.0
-5[u]	E (R)	272	1.36	10.1	7.5	0.7	0.52	13.9	226.2
(-6)[u/ff]	E (R)	396	1.58	(16.7)	(10.6)	(1.0)	(0.74)	14.0	227.1
-7[u]	E (R)	300	1.37	7.1	5.3	0.4	0.36	14.1	212.4
V02-1	G (A)	345	1.62	17.1	10.5	0.9	0.69	14.3	196.8
-2	G (A)	249	1.61	15.5	9.6	0.8	0.72	13.5	199.3
V03-1	F (R)	345	1.59	18.6	11.7	1.1	0.53	16.4	166.4
-3	F (R)	252	0.87	31.8	36.5	4.7	1.06	18.0	123.8
V10-2	H (A)	342	1.01	16.2	16.1	1.6	0.62	17.0	145.4
-5[gg/hh]	J (A)	307	1.07	21.3	19.9	1.8	1.26	14.5	138.7
-6[gg/hh]	J (A)	392	1.47	8.4	5.7	0.4	0.41	13.7	67.3
(V12-1)[v]	F (R)	373	1.37	(16.1)	(11.8)	(1.0)	0.92	(13.1)	196.1
-2	F (R)	316	0.97	16.5	17.1	1.7	0.87	15.8	162.1
-3	F (R)	173	0.97	36.7	37.9	5.8	1.31	17.4	183.2
(V15-1)[w/y]	H (A)	292	(0.29)	(2.1)	(7.1)	(0.6)	0.35	16.0	164.6
N04-1[ii]	G (A)	243	1.70	18.7	11.0	1.0	0.76	13.9	242.6
-5[ii]	J (A)	294	1.66	14.2	8.6	0.7	0.79	11.6	226.1
(-6)[v/ii]	G (A)	264	1.86	(13.9)	(7.5)	(0.6)	0.42	(15.1)	181.8
N06-1	I (A)	243	2.32	16.9	7.3	0.7	0.47	14.4	280.0
-2	I (A)	258	2.29	13.6	5.9	0.5	0.41	13.9	273.1
-3	I (A)	224	2.08	37.3	17.9	1.9	0.88	15.9	216.8
N12-4	J (A)	275	1.31	7.3	5.5	0.5	0.33	14.8	202.1
N14-2	I (A)	263	2.35	25.7	10.9	1.1	0.56	15.6	217.6
(-4)[u/v/jj]	J (A)	275	1.78	(11.9)	(6.7)	(0.5)	0.64	(11.1)	227.9
(-5)[u/v/jj]	O (A)	331	2.16	(27.3)	(12.7)	(1.1)	1.14	(11.8)	222.5

(Continued)

Table 3-10C (Continued)
EMISSION CHARACTERISTICS -- LOW-EMISSION STOVES

Sampling Code[a]	Stove Code[b]	HDD[d]	Burn Rate[l] (kg/hr)	Particulate Emissions[m] (g/hr)[n]	(g/kg)[o]	(g/10^6J)[p]	(g/m^3)[q]	Average Flue O_2[r] (%)	Average Flue Temp[s] (°C)
V03-5	N	272	1.28	18.3	14.3	1.5	0.63	16.6	181.1
-6	N	396	1.38	2.0	1.4	0.2	0.05	17.2	222.8
(V04-1)[v]	L	345	1.07	(7.2)	(6.7)	(0.6)	0.39	(15.2)	252.8
-3	L	252	0.90	6.9	7.7	0.8	0.34	16.5	230.9
-4	L	376	0.76	14.1	18.4	2.4	0.64	17.5	203.1
-6	L	396	0.81	6.5	8.0	0.9	0.28	17.5	215.4
V12-6[u]	M	392	0.67	5.2	7.7	0.7	0.38	16.1	182.4
V14-6	M	392	1.07	26.3	24.6	2.7	1.04	16.8	146.1
-7	M	306	0.85	17.2	20.4	2.0	0.94	16.4	132.9
V18-4[y]	K	277	1.09	28.3	26.1	2.9	1.36	15.8	179.8
-5[y]	K	307	1.10	24.6	22.4	2.3	1.59	13.9	193.3
-6[y]	K	392	1.08	17.3	16.0	1.6	0.94	15.2	191.4
-7[y]	K	306	1.26	47.6	37.9	4.8	2.18	15.3	179.8
V34-5[u]	M	272	0.76	7.9	10.4	0.9	0.55	15.7	188.1
-7[u]	M	300	0.92	5.9	6.4	0.6	0.30	16.2	182.5
V35-7[y]	N	306	0.90	3.6	4.0	0.4	0.15	17.1	183.2
N07-5	K	294	0.84	12.9	15.3	1.3	1.18	13.3	170.8
(-6)[v]	K	264	0.85	(25.2)	(29.7)	(3.6)	1.17	(17.0)	168.9
-7	K	218	0.90	9.4	10.4	0.9	0.71	14.2	180.7
(N13-5)[v/y]	M	331	1.18	(13.3)	(11.3)	(1.2)	0.50	16.6	219.3
N15-4[u/kk]	L	275	1.19	9.4	7.9	1.2	0.25	17.8	251.8
-5[u/kk]	L	331	1.34	7.9	5.9	0.6	0.32	15.5	286.9
-7[u/kk]	L	242	0.93	11.4	12.2	1.3	0.51	16.7	214.2
N16-4[y]	N	275	0.97	10.0	10.3	1.0	0.47	16.4	209.1
-6[y]	N	376	1.10	4.3	3.9	0.3	0.40	10.7	234.6
-7[y]	N	242	0.87	10.3	11.9	1.2	0.45	17.2	175.8

(Continued)

Table 3-10C (Continued)
EMISSION CHARACTERISTICS -- TRADITIONAL/CONVENTIONAL STOVES

Sampling Code[a]	Stove Code[b]	HDD[d]	Burn Rate[l] (kg/hr)	Particulate Emissions[m] (g/hr)[n]	(g/kg)[o]	(g/10^6J)[p]	(g/m^3)[q]	Average Flue O_2[r] (%)	Average Flue Temps[s] (°C)
V06-1[y]	0	345	2.45	2.9	1.2	0.1	0.06	16.3	241.7
-2[y]	0	355	1.60	4.7	2.9	0.3	0.12	16.9	219.3
(-3)[v/y]	0	252	1.59	(30.4)	(19.1)	(2.3)	0.80	(16.9)	204.4
-5[y]	0	272	1.52	12.7	8.4	1.0	0.31	17.4	208.1
-6[y]	0	396	1.86	17.3	9.3	1.5	0.29	17.9	247.6
V09-1	0	373	1.12	15.4	13.7	1.3	0.67	16.3	153.3
V14-1	0	373	1.67	16.9	10.2	0.9	0.69	14.2	232.4
-2	0	244	1.45	23.5	16.3	1.7	0.93	15.4	206.2
-3	0	173	0.92	20.3	22.0	2.3	1.11	16.1	154.8
(N08-3)[v]	0	189	1.92	(26.5)	(13.8)	(1.3)	1.20	(12.6)	246.3
-4[u]	0	162	1.91	32.6	17.1	1.7	1.48	12.7	274.2
-6[u]	0	264	2.19	26.6	12.2	1.2	1.26	11.0	305.4
-7[u]	0	218	2.00	30.9	15.4	1.5	1.43	12.0	274.1
N14-6	0	376	2.45	34.0	13.9	1.3	1.29	12.1	249.8
-7	0	242	1.57	29.0	18.4	1.7	1.39	13.8	180.4
N16-1[y]	0	321	1.55	13.9	9.0	0.9	0.59	14.5	285.9

(Continued)

Table 3-10 (Continued)

a/ Sampling Code--Refers to home and sampling rotation. For example, V05-4 is the fourth scheduled sampling rotation in Vermont home 5. Sampling rotations 1 through 3 were conducted in approximately January, February, and March in the 1985-86 heating season, while rotations 4 through 7 were conducted in approximately December, January, February, and March in the 1986-87 heating season. Missing rotations indicate that data were unavailable, unusable, or unacceptable (see Appendix B for Quality Assurance issues).

b/ Stove Code--Stoves were donated to the study by participating manufacturers. Study sponsors agreed to mask the identity of the stoves in exchange for the generosity of the donors. Commercial use of study results by stove manufacturers requires prior approval by the project sponsors.

c/ Sampling Period--The period during which the AWES system was collecting sample. For virtually all samples, this was from 0000 hours Sunday through 2355 hours Saturday. All wood weights, heating degree data, etc. correspond with this period.

d/ HDD--Heating degree days during the sampling period. Weather data was recorded in Vermont at Waterbury, and in New York at Glens Falls by the Northeast Regional Climate Center.

e/ Catalyst Operation (%)--Defined as the percent of time the catalyst was in operation (>260°C) while the stove was in operation (flue gas temperature >38°C). Absolute combustor temperature was used instead of catalyst ΔT due to temperature measurement anomalies caused by some stove designs.

f/ Stove Operation (5)--Defined as the percent of time during the sampling period that the flue gas temperature was >38°C. Flue gas temperature was measured approximately 45 cm above the flue collar of the stove or add-on device.

g/ Heating System Use (%)--Defined as the percent of time during the sampling period that an alternate heat source was used in the room with the stove while the stove was operational (flue gas temperature >38°C). A thermal sensor with a trip point of 35°C was placed in the vent of forced-air central heaters and base-board electric heaters.

h/ Efficiency (%)--Overall thermal efficiency of the stove, calculated using a modified version developed by the Condar Company. However, flue gas temperatures were measured lower in the flue system, resulting in higher flue temperatures and lower efficiencies. These values should be considered consistently low and for general comparison use only. High particulate values on some samples required extrapolation.

i/ Fuel Moisture (% DB)--Fuel moisture on a dry basis (DB), as measured by a resistance pin meter. Measurements were made at the beginning and end of each sampling period in fuel stacked near the stove for immediate use. Fuel moistures above about 30% have a higher degree of uncertainty, due to limitations of measurement technology.

Table 3-10 (Continued)

j/ -Average Fuel Load (kg dry)--The average amount of fuel, normalized to 0% moisture, placed in the stove each time the stove was fueled. Weights and fueling events were recorded automatically when the homeowner used the scale and keypad provided.

k/ Loading Frequency (#/hr)--The average number of stove fuelings per hour of stove operation (flue gas temperature >38°C).

m/ Particulate Emissions--Measured by AWES sampler. The AWES sampler, in comparison with EPA Method 5H, showed comparable accuracy, especially in the particulate emission ranges measured in field testing. See Appendix for details.

n/ g/hr--Particulate emission rate in grams material per hour of stove operation (flue gas temperature >38°C).

o/ g/kg--Particulate emission rate in grams material per kilogram fuel (normalized to 0% moisture) burned.

p/ $g/10^6J$--Particulate emission rate in grams material per million joule. Stove efficiency calculated using modified Condar method (see note h). Heat content of fuel based on reference values for individual wood species burned.

q/ g/m^3--Concentration of particulate material collected by sampler. Normalized by periods of stove operation (flue gas temperature >38°C). Sampling was conducted at the collar of stoves or exit of add-on devices.

r/ Average Flue O_2 (%)--Average concentration of oxygen in flue gas, measured by an electrochemical cell in the AWES sampler, during periods of stove operation (flue gas temperature >38°C).

s/ Average Flue Temperature (°C)--Average flue gas temperature 30 cm above stove flue collar or add-on exit during periods of stove operation (flue gas temperature >38°C).

t/ Catalyst was improperly seated during sampling, allowing flue gas to pass around, as well as through, catalyst. Data not used in averaging or summaries.

u/ Averaged results from 2 AWES units sampling simultaneously.

v/ O_2 > ±2% absolute at final calibration or during no-burn period. Calculated emissions (g/hr, g/kg, $g/10^6J$) therefore have a higher degree of associated uncertainty. Concentration (g/m^3) and burn rate (kg/hr) are unaffected. Affected values not used in averaging or summaries.

w/ Only one homeowner was weighing wood for this sampling period. All parameters except concentration (g/m^3) affected. Affected values not used in averaging or summaries.

Table 3-10 (Continued)

x/ Combustor was replaced with "Long Life" catalyst for second heating season.

y/ Zoned electric baseboard heat used in this home. Heating system use (%) reflects use of the heater in the room with the stove. Undocumented use of uninstrumented baseboard heaters outside the stove room may have occurred.

z/ Catalyst temperatures and field observations indicate that the combustor was less active/not active during the second heating season.

aa/ Homeowner replaced combustor between first and second year.

bb/ Low average O_2 (8.8%) results in low calculated emission rates. Other samples from this home had average O_2 of about 16% at similar burn rates. Particulate concentration is not remarkably low. Data not used in averaging or summaries.

cc/ Catalyst found to be damaged after this sampling period; center of combustor had dropped out. Combustor was replaced. Note lower emission rates before catalyst failure and after replacement. Data not used in averaging or summaries.

dd/ Solar alternate heat source used in this home. Had difficulty setting trip point of thermal sensor; recorded alternate heat use percentages are probably lower than actual heat use percentages.

ee/ Catalyst thermocouple failed; catalyst operation (%) not calculated.

ff/ Failed combustor (substrate deterioration) discovered after this sampling period. Data not used in averaging or summaries.

gg/ Different add-on device was used for runs V10-5 and V10-6 than for V10-2.

hh/ Add-on by-pass lever was being left in partial by-pass mode during operation period for V10-5. Homeowner was instructed to fully close by-pass lever during V10-6 sampling period.

ii/ Different add-on device used for N04-5 than for N04-1 and N04-6.

jj/ Different add-on device used for N14-4 and N14-5 than for N14-2.

kk/ Homeowner installed flue damper. Used periodically to "hold coals" at end of burn and not typically used during burning periods.

period dates, heating degree-days (Fahrenheit basis), catalyst operation (%), stove operation (%), alternate heating system use (%), and overall woodstove efficiency (%). Data presented in Table 3-10B include fuel moisture (% dry basis), average fuel load (dry kg), fuel loading frequency (#/hr), and burn rate (kg/hr). Data presented in Table 3-10C include burn rate (kg/hr), particulate emission rates (g/hr, g/kg, g/10^6 joule, and g/m^3), average flue oxygen (%), and average flue gas temperature (°C).

The data presented in Tables 3-10A, 3-10B, and 3-10C include only results with a high degree of confidence. "Atypical" results are shown (in parentheses, with explanations), but are not included in data summaries or figures. The data from these tables form the basis for the majority of the analyses undertaken in this report. Figures 3-6A through 3-6D show the gram-per-hour emission rates measured in the Group I and Group III homes during individual sampling periods. Figure 3-7A through 3-7D show the burn rates (kg/hr) measured in the Group I and Group III homes during individual sampling periods.

Tables 3-11A and 3-11B summarize several data columns from Tables 3-10A, 3-10B, and 3-10C by stove code. Each stove code subsection contains data for homes which used that particular stove. Table 3-11A contains data on catalyst operation time (%) where applicable, average fuel load (dry kg), and fuel loading frequency (#/hr). Table 3-11B contains data on particulate emissions (g/hr and g/kg) and burn rate (kg/hr). Overall means, standard deviations, ranges of values, and sample populations are presented for the parameters in the tables.

Figure 3-8 is a bar graph showing the mean particulate emissions (g/hr) by individual stove model for all stoves evaluated in the study. Figures 3-9 and 3-10 graph the overall mean particulate emission rates (g/hr for Figure 3-9, g/kg for Figure 3-10) by stove technology type.

Although the stoves in this study are compared by technology group, it should be remembered that these units were provided to the study and do not necessarily represent the typical performance of any stove technology.

Catalyst Operational Time

Catalyst operational time was examined to evaluate the frequency of catalytic activity in catalyst-equipped stoves, retrofits, and add-ons. Defined as the percentage of time the catalyst was operational (in-catalyst temperature greater than 380°C [500°F]) while the stove was operational (flue gas temperature greater

Section 5

DISCUSSION AND CONCLUSIONS

The objective of this study was to document the performance of different types of woodstoves as operated in typical Northeast homes. Data were collected on wood use, creosote accumulation, and particulate emissions in 42 homes over a two-heating-season period. Catalytic stoves, catalytic add-on/retrofit devices, non-catalytic low-emission stoves, and "conventional" stoves were evaluated, with data from conventional stoves serving as the baseline. One to four units of 14 different stove models or add-on/retrofit devices were installed in study homes.

The breadth of this study limited the capacity for in-depth analysis. The study is intended to serve as a broad assessment of field performance of stoves and stove operators.

GENERAL

The four stove technology groups (catalytic, add-on/retrofit, low-emission, and conventional) showed consistent ranking by particulate emissions, wood use, and creosote accumulation. While the relationships between these parameters are by no means simple, nor the statistical significance certain in all cases, it appears that the advanced technology devices do show improvement over conventional stoves in all catagories. The magnitude of the improvement is affected by numerous factors, many of which are addressed in Section 4.

WOOD USE AND CREOSOTE ACCUMULATION

Measurements of wood use were intended to provide an indication of relative woodstove efficiency. Significant differences were observed between the stove technology groups. While not directly correlated with measured particulate emissions, the stove technology groups are ranked by wood use (kg/1000 HDD) in the same order they are ranked by particulate emissions (g/hr); conventional stoves were highest, while low-emission stoves were lowest. The lower wood use by the advanced technology stoves and devices probably reflects both higher efficiencies and fueling patterns characteristic of the technology.

Chimney type appears to play a significant role in creosote accumulation, with exterior masonry flues collecting the most and metal chimneys collecting the least. This is probably due to heat losses through the chimney walls and subsequent cooling of flue gasses. However, due to the large number of stove/chimney combinations and limitations of the sampling method, a larger data set is needed before conclusive statements can be made.

PARTICULATE EMISSIONS

Stove Technology Groups

Firebox size showed the strongest correlation with emission rates, and was clearly a factor in the catalytic and conventional stove groups. Burn rate, fueling frequency, fuel load and moisture content, catalyst operational time, and other factors were investigated without identifying a clear relationship to particulate emissions. The most significant observation is that stove performance data can be highly variable, from single installations, stove models, and technology groups. Although all measured parameters (wood use, creosote accumulation, and particulate emissions) showed variability, particulate emissions are of special concern because of recent EPA regulations aimed at reducing stove emissions.

Averages from stove technology groups may not be an appropriate way to evaluate stove performance, due to several factors:

- Stoves used in the study were provided by stove manufacturers interested in the study, and therefore do not necessarily represent best or "typical" performance.

- Stoves were installed in homes without any detailed verbal instructions given to homeowners on the use of their new stove. Although they were provided with the stove instruction manual, it is possible that if homeowners were to purchase the stove, more time would be spent on user education.

- The study was conducted in areas of New York and Vermont which average about 8,000 to 9,000 heating degree-days (Fahrenheit basis) per year. Stoves are burned at higher rates than other regions, which may increase emissions from catalytic stoves and add-ons/ retrofits and reduce emissions from non-catalytic and conventional stoves.

- Although "Student's t" test results show that the data sets are probably different, it is unclear how different the values would be if the same stoves were used under different conditions. It should be stressed that these results reflect specific stoves in specific installations, operated and fueled in a specific manner.

- Stove and catalyst technologies were not equally represented. Stoves in the catalytic, add-on/retrofit, and low-emission categories included models certified to Oregon DEQ 1986 and 1988 standards and EPA 1990 standards, as well as non-certified stoves. A variety of combustor types and thicknesses were used. Some combustors were replaced in mid-study.

Stove Models

For the reasons mentioned above, stove performance is best evaluated by examining individual installations. Several stoves appear to work well in one installation, but poorly in another, indicating that while the stove may be capable of low-emission performance, other factors can be significant. In some cases there are major differences in stove performance in a given home during sampling periods. Overall, there did not appear to be a progressive increase in emissions over the two-heating-season period.

Stove D, which had new combustors installed at the start of the 1986-87 (second) heating season, showed marked reduction in emission rates. However, due to the problem with deteriorating combustors noted during the first heating season, it is not clear whether the reduced emissions were due to better actual catalytic performance or less operating time with deteriorating combustors. In other words, the apparent improvement in performance may be due to the stove operating more as a catalytic and less as a non-catalytic. Stove D had the lowest average emissions in the catalytic stove group. It should be noted, however, that the low emission rate reflects relatively frequent stove inspections and the replacement of combustors. Without stove inspections, emissions would likely have been higher.

It may be significant that among the catalytic stoves, average stove emissions are ranked by firebox size (Retrofit E is an apparent exception). Large firebox stoves, when not operating catalytically, may produce higher emissions, increasing average overall emissions. The integrated one-week samples appear to represent significant periods of non-catalytic operation, as documented in Table 3-10A. If emissions are higher during non-catalytic periods from large firebox stoves, overall average emissions would be expected to be higher. Stove D, with the lowest emissions among catalytic stoves, had the smallest firebox. However, each stove had at least one catalyst replacement during the two-year study.

The variability of emissions from a given stove model between homes suggests that caution should be used when evaluating stoves in the field. With two or three installations per stove model, it is difficult to tell whether measured emissions are representative. Consistent emissions from a single home may simply reflect consistent operation practices by the homeowner. Considering the range of values measured, data sets should be larger before conclusions can be made with a high degree of confidence.

Most stove models, existing or provided for the study, had relatively low emissions for some periods in some homes. This includes conventional stoves. The indication is that operational and fueling practices can significantly reduce particulate emissions. Virtually all stove models with small fireboxes (with the exception of one Stove K home) had relatively low emissions. The small firebox sizes found in three stoves may act as a "governor," limiting maximum emissions when the stoves' low-emissions features are not active. The limitation may be in the form of enhanced combustion, smaller fuel loads, or more frequent "burn down" phases. While certainly not the only factors in explaining stove performance, these may be significant ones.

The apparent low-emission/small firebox size relationship may reflect the parameters used to define "stove operational time." For this study, a stove was considered operational if flue gas temperatures at the exit of the appliance were greater than 38°C (100°F). This value may be low enough to include long periods of "charcoal phase" burning when particulate emissions would be low. Review of temperature data (see Appendix D in Volume II, a companion document to this report) from the sampling periods indicates that smaller firebox stoves tend to burn down more frequently before refueling, which may result in more sampling during charcoal phase periods.

It is important to note that emission samples represent one-week averages, during which time an average of 30 to 50 fuel loads are added. Stoves with high average emissions may have short but acute periods of high emissions which raise the overall average.

Many of the parameters investigated (burn rate, fueling practices, alternative heating system use) did not appear to correlate well with particulate emissions, although general trends appeared in some cases. The small data sets, the large degree of variability, and the number of potential variables made more detailed analysis difficult.

Significant findings from emission testing in study homes include:

1.0 Advanced Technology Performance

1.1 Most stoves in the advanced technology categories (catalytic, add-on/retrofit, low-emission non-catalytic) episodically demonstrated lower emissions than the baseline conventional stoves under "field use" conditions. Good performance in at least one installation for most of the stove models indicates that factors, such as stove maintenance and fueling practices, may be as important as stove technology features in achieving low emission rates. Stove firebox size, regardless of technology group, was a prime factor in determining emission rates; smaller stoves had lower emissions.

1.2 In general, performance of the stove technology groups appeared to be consistently ranked in terms of particulate emission rates, wood use, and creosote accumulation; low-emission non-catalytic stoves had the lowest particulate emission rate, wood use, and creosote accumulation, while conventional stoves had the highest. It should be noted that only low-emission non-catalytic stoves showed a mean emission rate which was statistically different from the conventional stoves. It should also be noted that creosote accumulation is strongly influenced by flue system type and wood use appears to be influenced by burning patterns and firebox size.

1.3 All advanced technology stove groups averaged lower wood use and creosote accumulation rates when households switched from conventional stoves between heating seasons. Average reductions by stove group ranged from about 10% to 35% for creosote and from about 15% to 30% for wood use.

1.4 The low-emission stoves, as a group, had the lowest average emissions. Each model had different burning characteristics; most showed relatively good performance. Average results from this technology group are strongly influenced by the good performance of two stoves (M and N) which may be EPA 1990-certifiable . Furthermore, excluding one high-emission home (V18, using non-EPA-certifiable Stove K) would reduce average emissions in this category from 13.4 to 10.0 g/hr, and reduce the standard deviation ( ) from 10.2 to 5.7.

1.5 User satisfaction was generally high with the advanced technology stoves provided to study homes. In particular, homeowners with catalytic and low-emission stove models were frequently pleased with the units. (In some cases, user satisfaction remained high even though the catalytic combustor had deteriorated.) Some add-on devices also received positive comments. The add-on with the lowest average particulate emission rate also received homeowner complaints about smoke spillage.

2.0 Catalyst Performance

2.1 Catalytic stoves showed variable performance. Most individual models performed well in some homes. Other installations had relatively high emissions. Overall, performance of these stoves did not match the expectations created under ideal laboratory conditions, although only one of the catalytic models may be EPA 1990 certifiable. The mean emission rates of existing catalytic stoves and new catalytic stoves were virtually identical. User education and further technology refinements remain possible factors which could help improve the performance of catalytic stoves.

2.2 Add-on retrofit devices did not perform well overall, but 2 devices reduced emissions considerably. The stoves on which these devices were mounted are a major factor in measured emission rates.

Retrofit F, which consistently had high emissions, is no longer being produced.

2.3 Catalyst durability was quite variable. Rapid deterioration was noted in some combustors, all of which were cordierite-based, with corresponding increases in emissions. In one stove model (which apparently accelerated combustor deterioration), replacement with "second generation," non-cordierite combustors appeared to virtually eliminate the deterioration trend. Emissions from this stove model were reduced by about one-third by using "second generation" combustors during the second year, although it is not clear whether this was from improved catalytic performance or reduced degradation.

2.4 Overall, there did not appear to be a consistent increase in particulate emissions from catalytic devices over the two-year testing period. No clear trend of long-term loss of effectiveness was noted. However, a number of combustors (cordierite-based) were discovered to be deteriorating. These combustors were replaced; emission values reported in this study reflect relatively frequent catalyst inspections and replacement when necessary. It should be noted, however, that not all cordierite-based combustors in the study indicated signs of deterioration of the substrate. A cordierite-based combustor from an "existing" stove with an estimated 6000 hours of use showed relatively low emissions in lab retesting. All combustors retested in the laboratory had reduced performance relative to new combustors.

2.5 Condensation of moisture and organic material in flue systems and subsequent drainage or leaching of condensate was a problem in some homes during periods of very cold (< 20°C) weather. Only catalytic stoves experienced this problem. This appears to be related to inappropriate installation and is not necessarily a technology limitation.

2.6 Catalyst ΔT (temperature change across the combustor) and % operation time are not good indicators of stove particulate emissions. Factors such as fueling cycles (long burn-down "tails") and measurement difficulties may preclude the use of these parameters for predicting emission rates.

3.0 Operator Practices

3.1 Operator practices, in combination with other parameters, appear to be a significant factor in stove performance. Specific practices which may result in lower emissions from all stoves have not been identified from available data. However, routine maintenance inspections of the combustor, gasketing, and overall stove system can help identify deteriorated components in need of repair or replacement.

3.2 Burn rates did not demonstrate a strong correlation with emission rates for any of the stove technology groups, although "general trends" were observed. Often, as in the case with conventional stoves, the trend was opposite that which was expected; emissions increased with burn rate. This may be related to field conditions, in which lower burn rates may include longer "charcoal phase" burning periods.

3.3 Mean fuel loading frequencies were identical for the low-emission and conventional stove groups, although the average low-emission stove fuel load was 56% that of the average conventional stove fuel load. This indicates that smaller firebox capacity (typically associated with low-emission stoves) does not necessarily require more frequent fueling of the stove. User satisfaction was generally high with the low-emission stoves.

3.4 Average emission factors (g/kg) for all the stove catagories were quite similar. Differences in average emission rates (g/hr) were therefore driven by burn rates. The low average burn rate of the low-emission stoves, and resulting low average emission rate, may be due to more frequent "charcoal phase" burning periods.

3.5 Fuel loading frequencies did not correlate well with particulate emissions. However, loading frequencies did increase with smaller fuel loads for all technology groups, as was expected.

3.6 Fuel loading frequencies were significantly different between homes, even those using the same stove model.

3.7 The lack of strong correlations between particulate emissions and other variables indicated that many parameters have significant, if unquantified, effects on stove performance. Fueling and burning cycles are thought to be areas for further investigation.

4.0 Technology Factors

4.1 Firebox size is a major factor in determining particulate emissions from woodstoves; emission rates increased with firebox volume, regardless of stove technology.

4.2 Preliminary results from stove inspections conducted after the second heating season (September 1987) indicate that significant "leakage" of smoke around combustors may be a cause of high emissions in some stoves. (A report on this work will be issued under separate cover.) Stove inspections showed that gasketing, especially around the bypass damper and combustor, was the most frequent component in need of maintenance and the apparent cause of leakage. Leakage rates and particulate emissions do not appear to correlate well overall, but show some correlation for individual stove models.

4.3 Using a qualitative measurement methodology, insulated metal chimney systems accumulated the least amount of creosote. Masonry chimneys located on outside walls accumulated the most.

5.0 Other Findings

5.1 This study did not show that one stove model is necessarily "better" than another. As stated previously, a wide range of results were recorded. For a given stove model, the largest number of emission samples was 19; the smallest was 1. The largest number of installations for a given stove model was 4, while the smallest was 1. The high degree of variability in performance and the relatively small sample populations make comparisons inappropriate.

5.2 Conventional stoves in this study may be cleaner-burning heaters than are "typical." Four of the six conventional stoves had relatively small fireboxes (< 2.4 ft^3), and two of these had small effective fireboxes (< 1.5 ft^3). Emissions from these stoves therefore may not be typical of existing stove technology. Additionally, the cold Northeast climate and commensurately higher burn rates preclude direct comparison to stove performance in milder climates.

5.3 Alternate heating system use did not correlate well with particulate emission rates or burn rates, although heating system use was monitored only in the room with the stove. In general, most homes in the study used their alternate heating system less than 3.5% of the time (while the stove was operating). This amounts to less than one hour per day. A large portion of the homes used no back-up heat at all.

5.4 Polycyclic organic material (POM) emissions were variable and non-conclusive. Testing method and analytical method limitations, and a very limited database, preclude any ranking of POM emissions by stove type.

Section 7

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