TVA

Tennessee Valley Authority

Residential Wood Heater Test Report

Phase II Testing, Volume I
Energy Use Test Facility

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TENNESSEE VALLEY AUTHORITY

Division of Energy Conservation and Rates

RESIDENTIAL WOOD HEATER TEST REPORT

PHASE II (1981-1983)

Volume I

KNOXVILLE

Energy Use Test Facility
Chattanooga, Tennessee

August 1983

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EXECUTIVE SUMMARY

The residential wood heater test program was designed to provide information concerning the efficiency and emissions of residential wood heaters typically used in the TVA region. The information gained from these tests will be used to support the overall TVA Wood Heater Program which provides financial and technical assistance for the safe installation of wood heaters. Phase I test results were presented in the Residential Wood Heater Test Report for phase I testing which was published in November of 1982. This report concerns the second phase of the wood heater test program which involved tests on new technology wood heaters. Even though the primary purpose of the wood heater program is to benefit TVA and its customers, the results of these tests will have a positive impact far beyond the confines of the Tennessee Valley because of the nationwide interest in new technology wood heaters.

This study involved the evaluation of efficiencies, emissions, and other environmental effects for five residential wood heaters. The first wood heater tested was a typical airtight circulator which is popular with consumers in the TVA area. The remaining four heaters were either catalytic or secondary combustion models. These five wood heaters were selected to provide a direct comparison between a conventional airtight model and the new technology models which are purported to offer reduced emissions and increased efficiency.

Testing was conducted at TVA's Energy Use Test Facility in Chattanooga, Tennessee. Emission monitoring equipment consisted of a system of continuous analyzers, thermocouples, data storage equipment, and a modified EPA Method 5 sampling system for particulate and organic sample recovery.

Emission factors (grams of emittant/kg of wood burned), efficiencies, and other environmental effects were evaluated using the TVA efficiency and emissions model. The model was based on a mass/energy balance of the process and predicted efficiencies and emission factors based on flue gas temperature, flue gas composition, and fuel consumption. Emission factors were determined for carbon monoxide (CO), total hydrocarbons (THC), sulfur dioxide (SO_2), nitrous oxides (NO_x), polynuclear aromatic hydrocarbons (PAH), total particulates, and volatile organics. Net thermal efficiency, heat transfer efficiency, and combustion efficiency were calculated by the model and used as diagnostic tools in analyzing the performance features of each wood heater.

Red Oak was chosen as the test fuel since it is a hardwood widely available in the Tennessee Valley. During the first part of the testing the wood heater was fueled with "brands" which were lattices of 2-inch by 4-inch oak boards. Shortly thereafter, the fuel was changed to red oak cordwood which provided a fuel that was more similar in composition and configuration to that normally used by the consumer. Phase I testing and the "brands" testing in this phase of the test program had shown that the wood heater's performance was very dependent upon the nature of the fuel; i.e., cordwood versus brands. By testing with the cordwood fuel, the results could be used to analyze the wood heater's performance characteristics common to the TVA region while realistically predicting the environmental effects of residential wood combustion.

Earlier testing by TVA had revealed the effect of burn rate on the efficiency and emissions of wood heaters. The results of this test program indicate that the overriding influence on performance is the amount of fuel used to load the wood heater and the damper setting; both of which

consequentially affect the burn rate. As a general rule, emissions were decreased and efficiency was increased by using smaller loads of fuel (reloading more often) while maintaining a medium damper setting. Test on the conventional airtight model with closed damper settings usually produced fairly high thermal efficiency and low burn rates for larger wood loads but the emissions were higher. Open damper settings usually produced low efficiencies and low emissions with larger wood loads.

The catalytic wood heater emissions and thermal performance showed less dependence on wood load size and damper setting than did the conventional airtight wood heater tested. Comparison of the results of the tests indicates that catalytic wood heaters, if properly designed, perform better than conventional airtight models. The best catalytic model tested had an average overall efficiency of 71.5 percent as opposed to 54 percent for the conventional model. This catalytic wood heater could be operated at burn rates of 2 kg/hour (compared to an average of 6 kg/hour for the conventional model) at about 70 percent efficiency. At this burn rate the catalytic wood heater produced about one-sixth the amount of pollutants per Kg of fuel consumed as did the conventional model. The limiting factor for conventional airtight wood heaters has been their high emissions at low burn rates. Since the catalytic can operate at these low burn rates and by way of catalysis can reduce emissions the potential advantages are substantial.

A wood heater was also tested which employed the principle of secondary combustion. This model produced lower emissions (during periods of active secondary combustion) than any other wood heater tested. But the particular design of this wood heater resulted in low thermal efficiencies

because of inadequate provisions for heat recovery. Operation of the unit also required constant operator attention due to the sensitivity of the secondary combustion feature.

The results indicate that catalytically assisted combustion is an effective means of reducing emissions in a residential wood heater while offering increased potential for useful heat output. Improved emissions performance at low burn rates makes this type of combustion feature even more attractive since thermal efficiency is usually at is highest during a slow burn. Recognizing the fact that most users fire a wood heater at the lowest possible burn rate, properly designed catalytic and secondary combustion wood heaters should offer those who are interested in reducing emissions a method by which to achieve this goal.

INTRODUCTION

Several important research efforts have been completed since 1979 in an effort to relate thermal output and emissions performance to operating conditions for generic types of airtight wood heaters. Several other studies (1), (2), and (3) have looked specifically at either emissions or thermal performance without consideration being given to the interdependency of emissions and thermal output. Much effort has been expended by the Wood Heating Alliance in developing a wood heater thermal efficiency test standard; but currently, no method has surfaced whereby the emissions performance of wood heaters can be evaluated by some standard sampling and analysis procedure. Many research efforts have used a calorimeter room to evaluate the wood heater's thermal performance. But these test programs did not provide the detailed flue gas data required for correlating thermal and emissions performance.

In 1979, the Monsanto Corporation (4) conducted twelve tests on two airtight wood heaters and a fireplace. Thermal output and emissions performance results were reported by Monsanto using the indirect or "stack loss" method of testing for thermal efficiency evaluation and Modified EPA Method 5 and other grab sampling techniques for quantifying the emissions for each test. However, the tests in the Monsanto study were performed at burn rates of 12 lb/hr or higher due to heavy condensible organic loading of the sampling system at lower burn rates which are more common to residential airtight wood burning. Battelle Laboratory completed an emissions study (5) in 1980 whereby the effects of operating variables and wood heater design were related to emissions. The Argonne Laboratory (6) and Canadian Combustion Laboratory have reported test results for limited tests on airtight wood burning heaters. Neither of

these studies provided thermal efficiency and emissions performance over the full range of operations typically associated with the wood burning appliance. Each study chose a limited operational mode or modes to minimize the total testing effort for a single appliance. These studies pointed out problems and areas of mutual agreement and disagreement related to testing procedures. They also compared test results based on very limited testing and often the tests were conducted using different methods. The results of these tests have been used recently in formulating regulatory policies for wood heaters. Hence, it was imperative that additional testing be completed to determine thermal efficiencies and emissions over the full range of operation associated with airtight wood heaters while using a wood fuel most typical to the TVA region.

New technology wood heaters were included in this test program since they were thought to offer increased thermal efficiency while reducing the potential emissions. A recent Shelton study (7) concluded that catalytically assisted combustion in residential wood heaters did offer great potential for reducing creosote and emissions while increasing the overall thermal energy efficiency. Yet, an Oregon study (3) found that a catalytic model offered little improvement in performance as compared to common airtight wood heaters. The TVA test program was developed to clarify these issues.

TEST PROGRAM AND PROCEDURES

Test Site and Facilities

The residential wood heater testing program was conducted by the personnel of the TVA Energy Use Test Facility at the Power Service Center in Chattanooga, Tennessee. Earlier testing by TVA and Battelle Memorial

Laboratory in Columbus, Ohio, under contract with TVA, has been previously reported (8). All phases of this test program were completed at TVA facilities.

Testing took place in an area of the building that included electronic scales and a test room which contained a continuous gas analysis system and a modified Method 5 sampling system as shown in Figure 1. The continuous gas analysis method was chosen over the ORSAT method because of the detailed flue gas data which was necessary for indirectly correlating thermal and emissions performance.

The composition of the flue gas was obtained using a flue gas continuous monitoring system built under contract for TVA by Tess-Com, Inc., as shown in Figure 2. In addition to conditioning equipment the system contained the following analyzers:

- Two Beckman Model 864 Infrared Analyzers for CO and CO_2.
- Thermoelectron Model 40 Pulsed Fluorescent Analyzer for SO_2.
- Thermoelectron 20A Chemiluminescent Analyzer for NO/NO_x.
- Anarad Model 600 Infrared Analyzer for H_2O.
- Beckman Model 755 Paramagnetic Analyzer for O_2.
- Beckman Model 402 Flame Ionization Analyzer for total hydrocarbons (THC).

The flue gas sample was transported from the flue to the monitoring system by a 25-foot heated sample line. The monitoring system could effectively handle high concentrations of particulates and creosote typical of wood stove combustion because of a series of heated primary filters and heat tracing on the sample line. In addition, each of the analyzers had an in-line, "see-through" filter to give further protection without interfering with component analysis. After passing through the primary

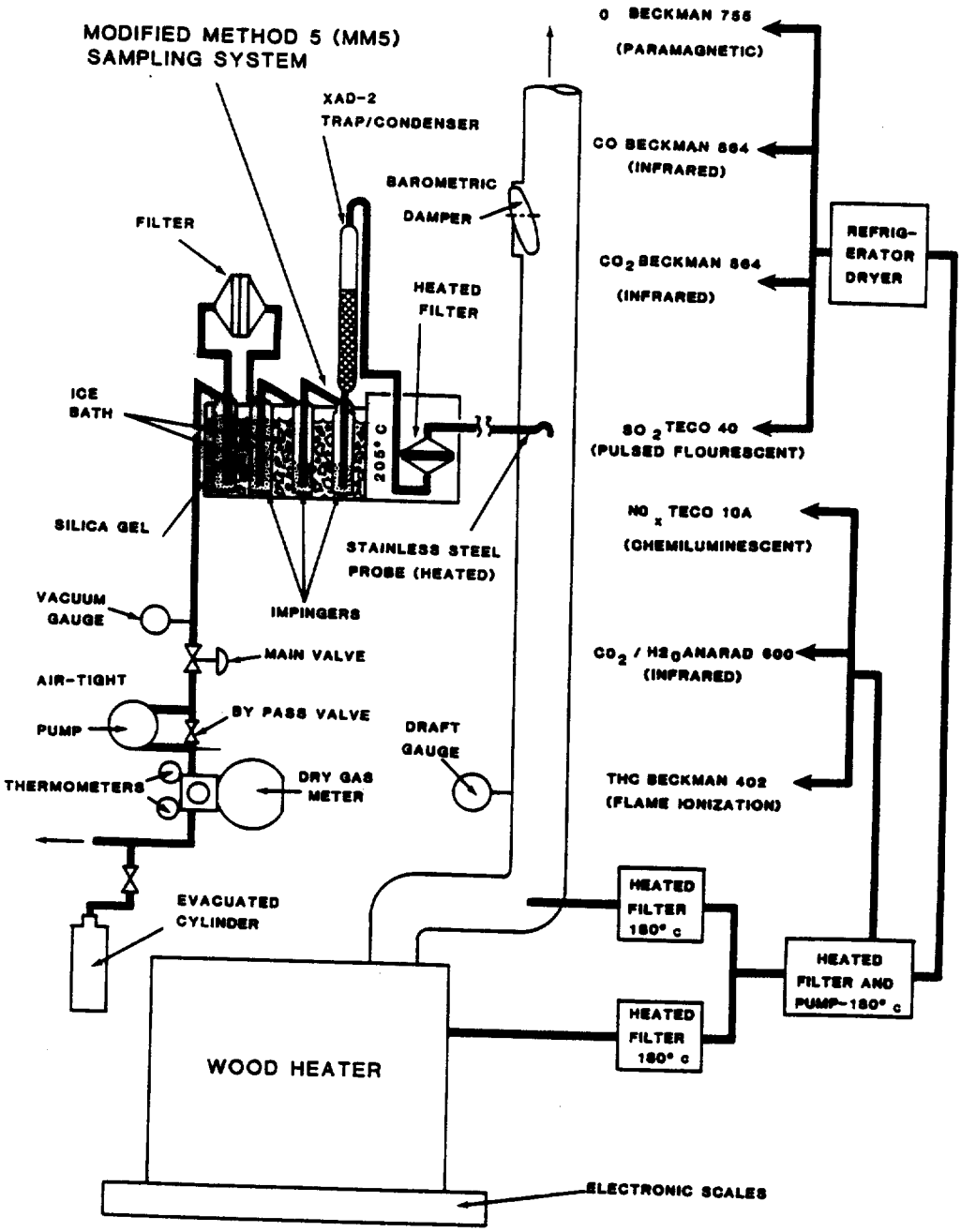

FIGURE 1. EMISSIONS SAMPLING SYSTEM

GAS ANALYSIS SYSTEM

Item	Name and Function
1	CHESSELL STRIP CHART RECORDED (O_2, NO_x, CO)
2	CHESSELL STRIP CHART RECORDER (H_2O, SO_2, CO_2)
3	CHESSELL STRIP CHART RECORDER (HC)
4	EUROTHERM TEMPERATURE INDICATOR (°F)
5	BECKMAN 864 ANALYZER (CO)
6	ANARD AR-600 ANALYZER (CO_2, H_2O)
7	MAGNEHELIC PRESSURE GAUGE (CO_2)
8	MAGNEHELIC PRESSURE GAUGE (SO_2)
9	MAGNEHELIC PRESSURE GAUGE (CO)
10	MAGNEHELIC PRESSURE GAUGE (O_2)
11	SHO-RATE FLOW METER (SO_2)
12	SHO-RATE FLOW METERS (CO, CO_2)
13	SHO-RATE FLOW METERS (O_2, BYPASS)
14	BECKMAN 755 ANALYZER (O_2)
15	BECKMAN 402 HYDROCARBON ANALYZER
16	WEIGH-TRONIX WI-102 DIGITAL SCALE
17	THERMO-ELECTRON S-40 ANALYZER (SO_2)
18	ATHENA TEMPERATURE CONTROL
19	BECKMAN 864 ANALYZER (CO_2)
20	SAMPLE TO CALIBRATION SWITCHES
21	SAMPLE TO PURGE SWITCH
22	FILTER 1 TO FILTER 2 SWITCH
23	SAMPLE TO SPAN SWITCHES
24	GAS PUMP SWITCHES
25	THERMO-ELECTRON 10 ANALYZER (NO_x) WITH HEATED MODULE 700
26	DRAIN FROM NORGEN D10-120-0010 AIR DRYER

Figure 2

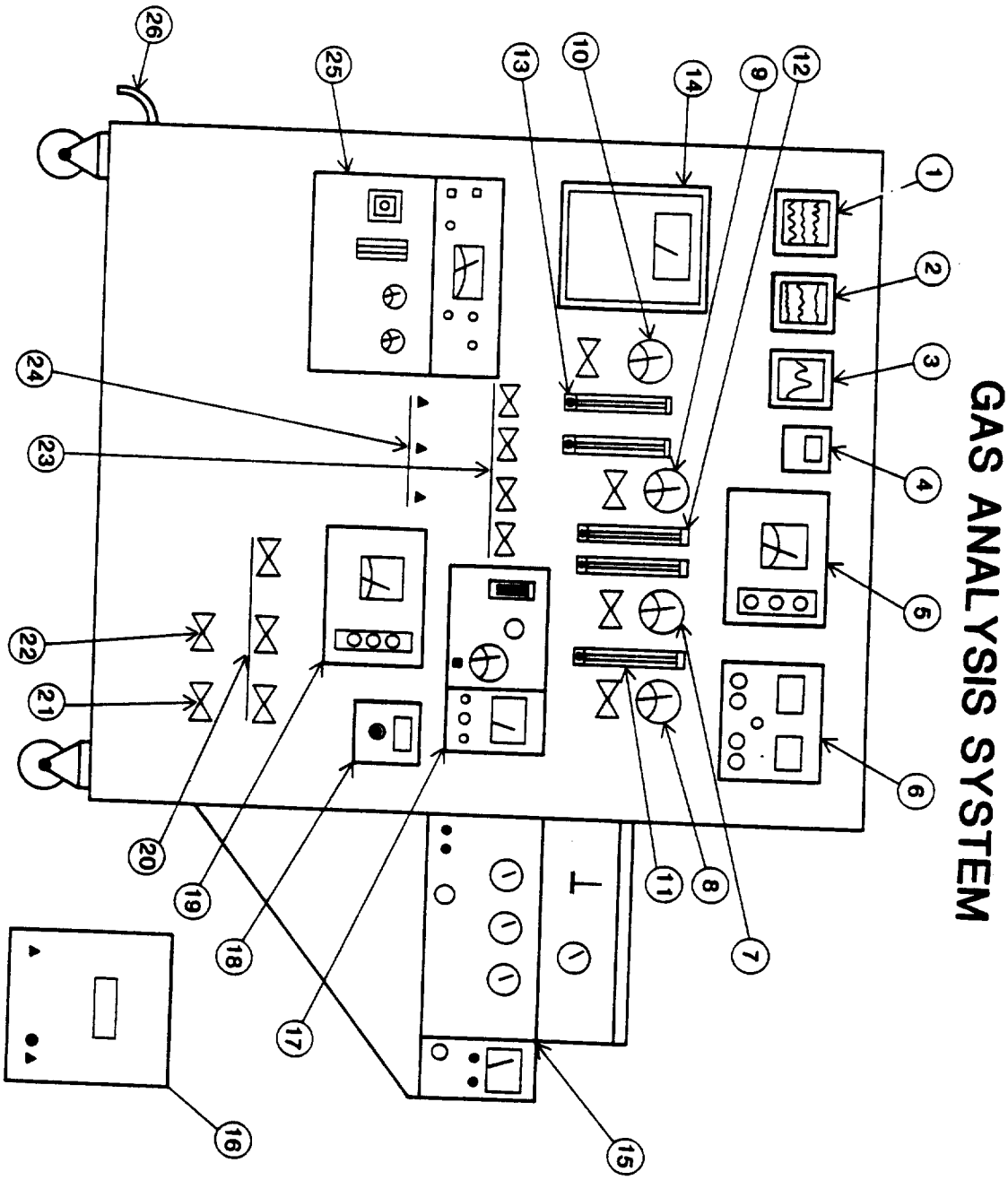
GAS ANALYSIS SYSTEM
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Figure 2.

filters, the flue gas sample was split with smaller samples going to the NO_x, H_2O, and THC analyzers and the refrigerated dryer. The sample leaving the dryer was then distributed to the CO, O_2, CO_2, and SO_2 analyzers.

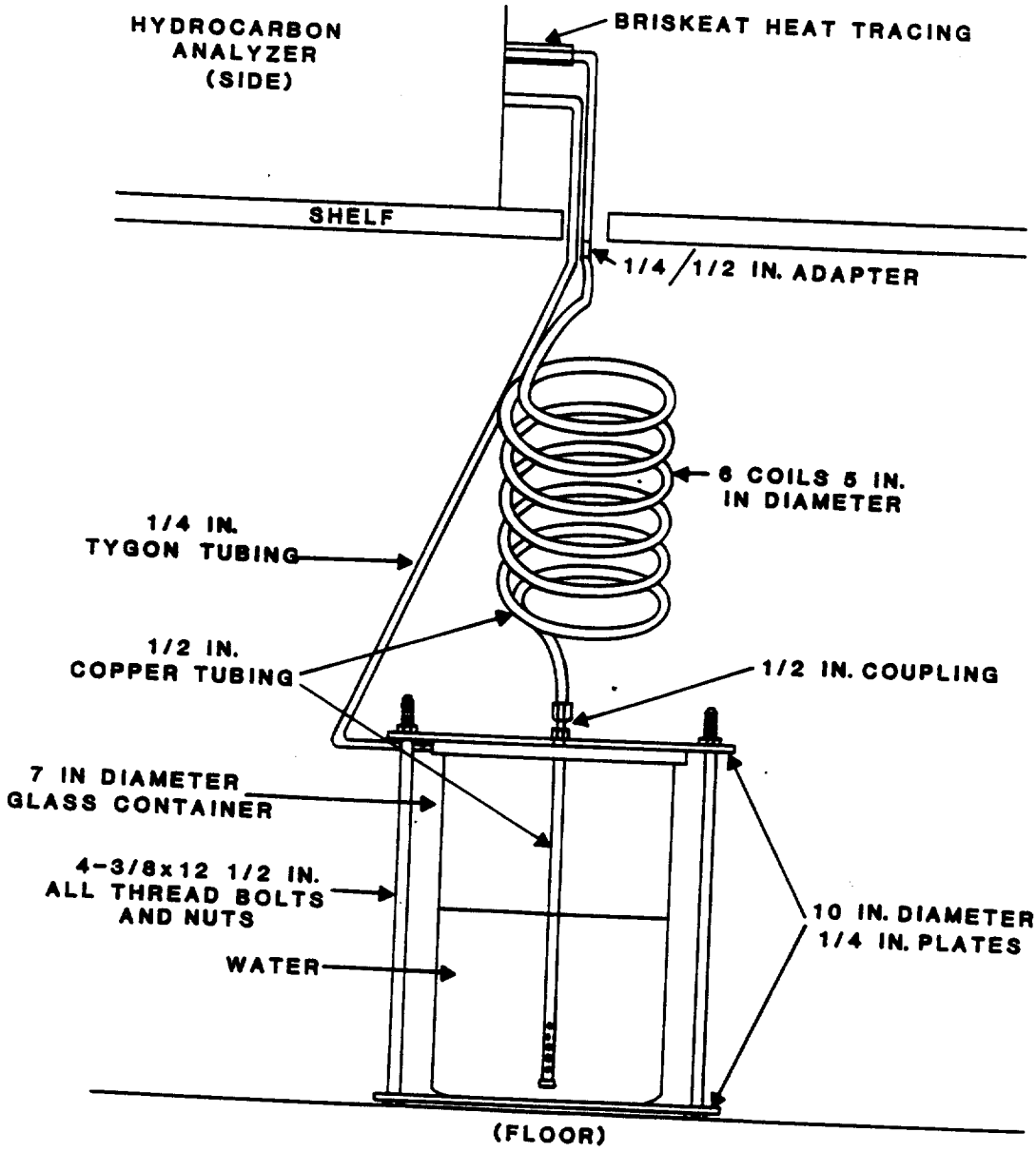
The THC analyzer used only a very small fraction of the available sample flowing to the analyzer. Other than the small amount which entered the capillary tube to the burner, most of the sample bypassed the burner into (originally) an unheated section containing the pressure regulating valve and flow meter. (See discussion of feature development below.) The bypass gases were then vented out of the test bay area.

After passing through the primary filters the portion of the sample going to the CO, CO_2, SO_2, and O_2 analyzers was dried as it flowed through a self-contained refrigerated dryer. The condensed water, containing organics, was then removed from the system. Condensible organics were also removed from the sample going to the H_2O analyzer by means of a temperature-controlled, limited condenser.

To prevent the accumulation of organic deposits (creosote) in the system, several features were incorporated into the original design of the monitoring system.

1. Air-cooled condenser. Instead of being passed through the pressure regulator valve in the unheated section of the THC analyzer and then discharged through a length of line, the bypass flow was diverted from the analyzer into a small heat exchanger/condenser where the organics were trapped in water as shown in Figure 3. The bypass was then returned to the pressure regulator valve and vented from the test bay area. This prevented heavy buildup of creosote in the flow control regulator and flow meter in the unheated section of the THC analyzer.

FIGURE NO. 3 HYDROCARBON CONDENSER



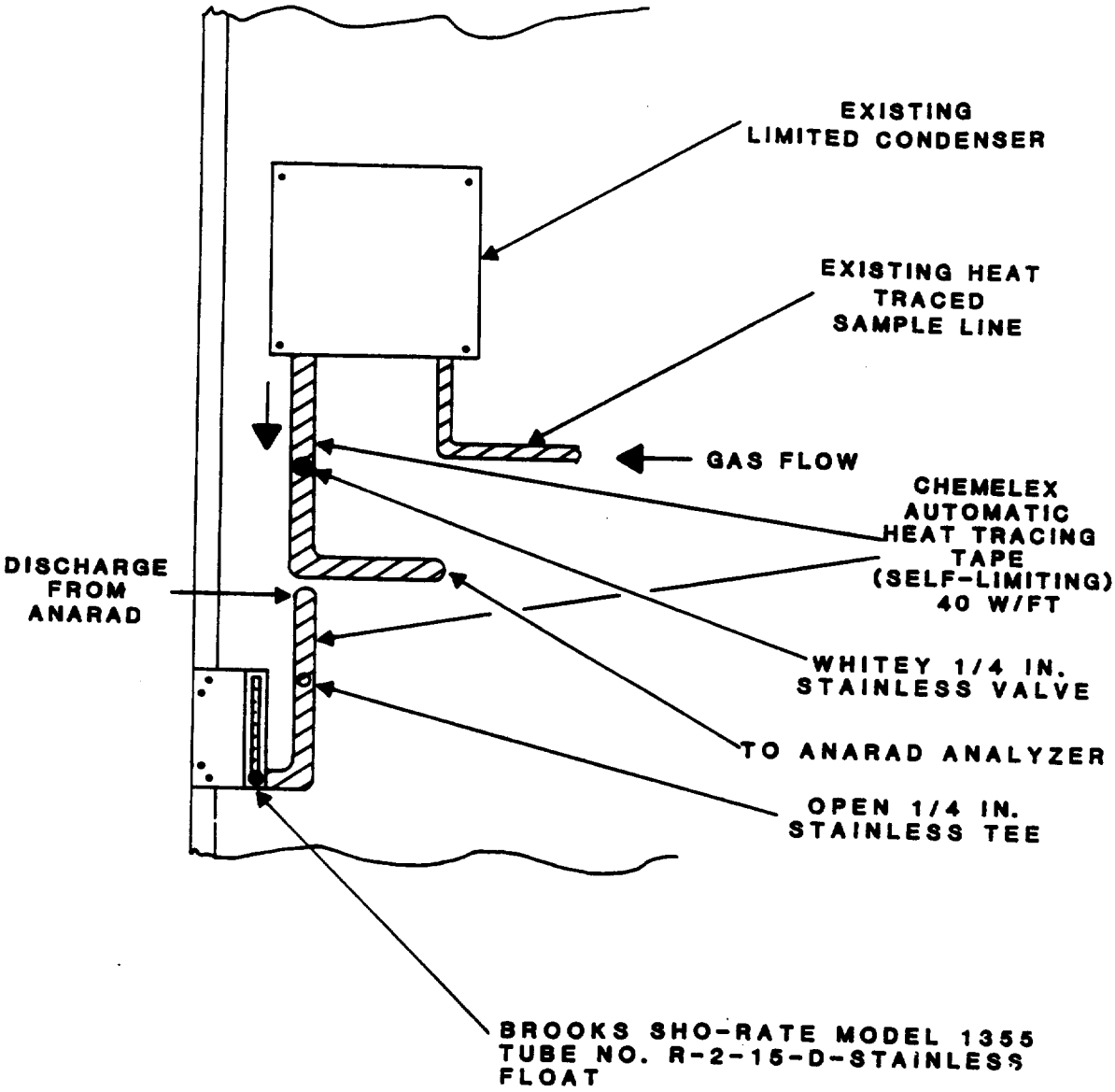
2. Heat tracing. The heat tracing of all flue gas sample handling lines was accomplished using a self-limiting heat tape at 40 watts per foot. The bypass flow from the THC analyzer was heat traced to prevent condensation from developing in the line. Also, the line from the limited condenser to the Anarad H_2O analyzer and the discharge line from the Anarad analyzer were heat traced as shown in Figure 4.

An electronic scale was used during testing to provide continuous weight monitoring of the fuel load. The scale had a 1000-lb capacity and was a Weigh-Tronix deck scale model DS48481. Its digital indicator provided a visual display and an electronic signal to the data logger.

The insulated stack assembly is shown in Figure 1. The stack was composed of 8-inch inside diameter stainless steel residential chimney pieces manufactured by Metalbestos Systems and was 14 feet high. Depending upon the design of the unit, the stack assembly rested either on top or upon a support at the rear of the wood heater. The joints between the individual stack pieces were sealed with gummed asbestos furnace tape and then wrapped with fiberglass tape. A Dwyer draft pressure gauge was installed on the stack along with a barometric damper to control the draft.

The stack was fitted with thermocouple connections and sampling ports for recovering two flue gas samples and two flue gas temperatures. The sample probe for the continuous monitoring system was placed into the stack approximately two feet from the exit of the wood heater. Thermocouples were placed in the stack gases at approximately the same point as the sample probe. The modified Method 5 sampling probe was located in the stack approximately three feet above the continuous sampling probe and a second set of thermocouples was placed at this position.

FIGURE NO.4 MODIFICATIONS TO EXISTING ANARAD FLOW CONDITIONING SYSTEM



NOTE: THE GAS FLOW LINES ARE 1/4 IN.STAINLESS TUBING THAT ARE HEAT TRACED AT APPROXIMATELY 40 W/FT

The sample flowed from the probe through the sampling line to the analyzers. To prevent the filter probes from clogging with organic deposits, a heated oven containing a fiberglass filter was inserted between the sampling probe and the heated sampling line as shown in Figure 5. The insulated oven was maintained at 380°F with a 400-watt heating element controlled by a voltage regulator.

During the testing of the catalytic heaters, two completely separate flue gas samples were monitored using a 3-way solenoid operated switching valve as shown in Figure 6. The valve body of the solenoid was heat-traced with heat tape over-wrapped with fiberglass tape. Thermocouples were placed at each sampling point in the catalytic heaters and one thermocouple was inserted directly into the catalytic combustor itself. Flue gas composition before the catalyst and at the exit of the wood heater was obtained over alternating periods of time using this sampling technique.

All data from the analyzers within the continuous monitoring system were recorded on Chessell strip chart recorders. In addition, the output from all analyzers was scanned by a Fluke 2240-B data logger at selected time intervals. This data, together with data from the scales and thermocouples, was printed on data logger tape and on magnetic tapes (Kennedy 9800 recorder) for direct input into the TVA wood heater computer model. These various data records provided some measure of backup and an efficient means of obtaining test results with a minimum turnaround time.

During selected tests, the modified Method 5 (MM5) sampling system shown in Figure 1 was used to obtain integrated grab samples of flue gases. The basic MM5 sampling system used was manufactured by Andersen Samplers, Inc., primarily to test for particulates and organics present

FIGURE NO. 5 IN-LINE HEATED FILTER UNIT

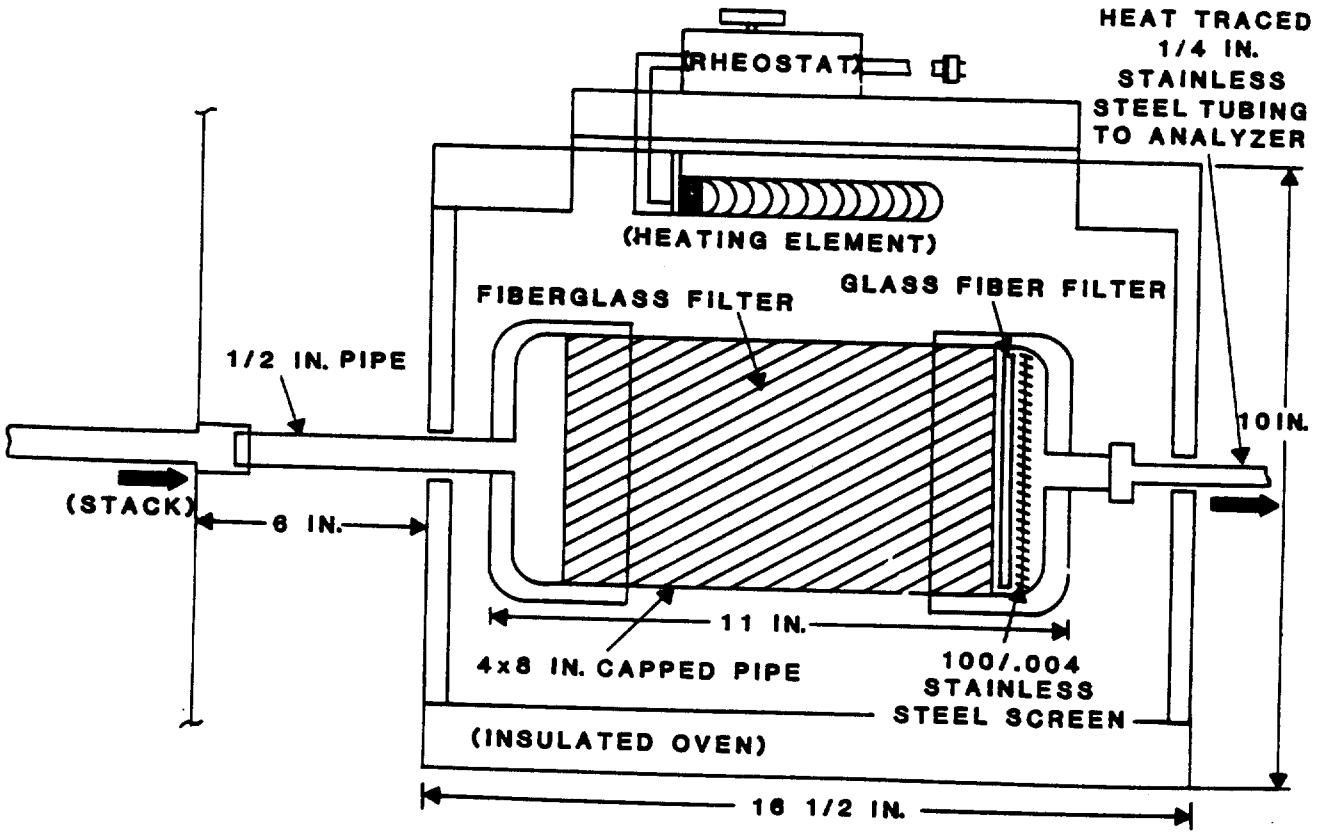
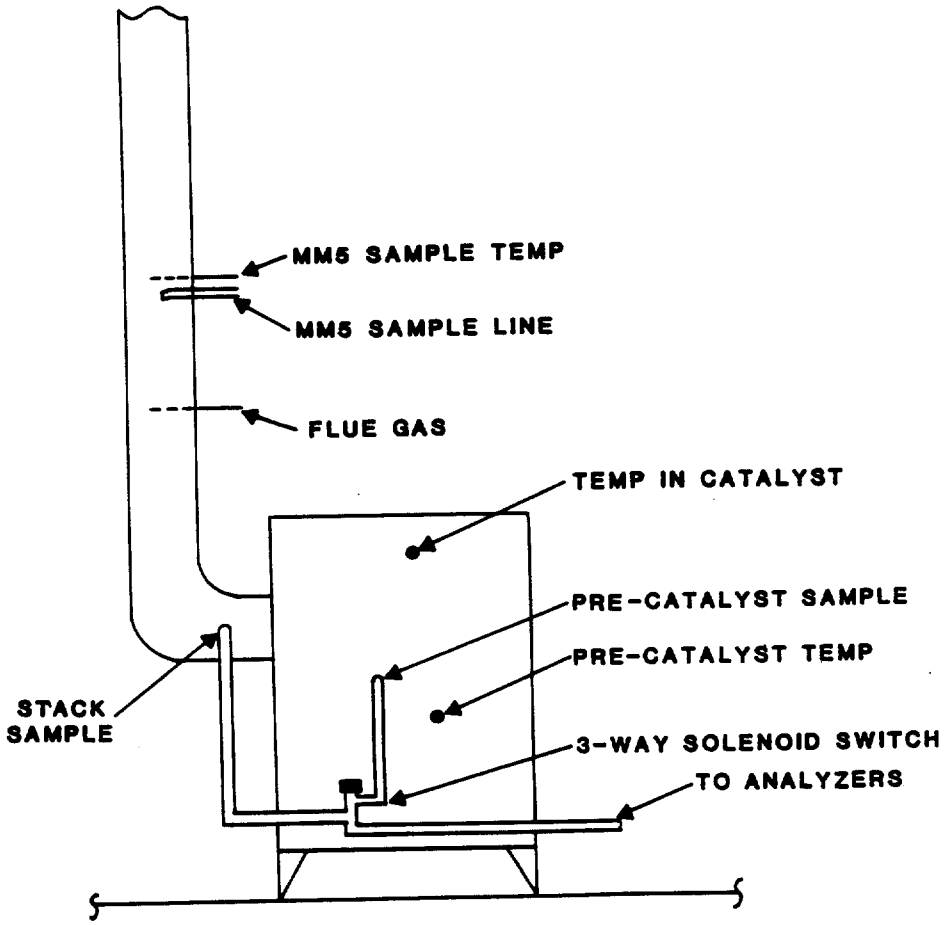


FIGURE NO. 6 THREE WAY SWITCH FOR CATALYTIC TESTING

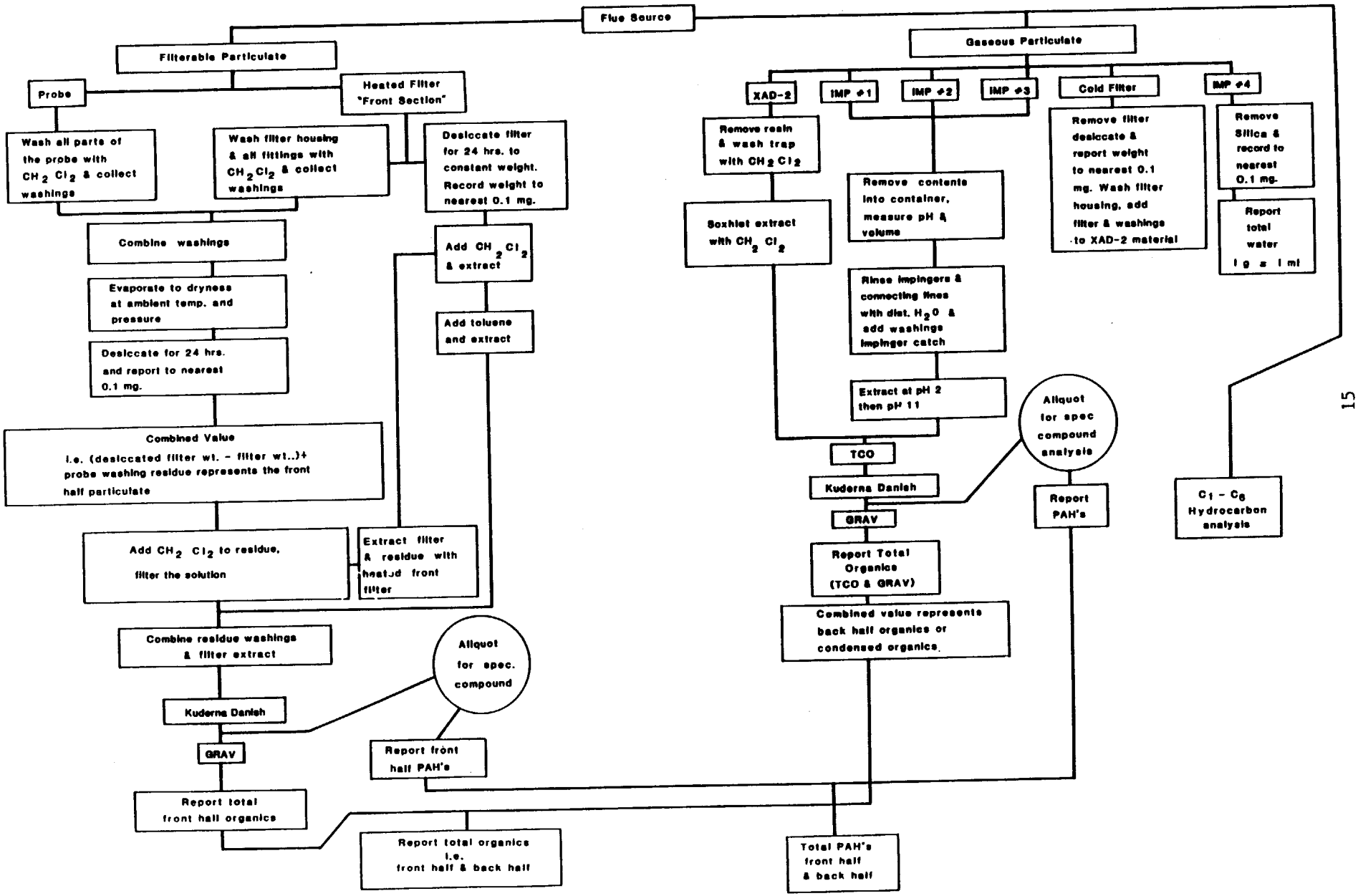


in coal or oil combustion gases. The flue gas sample was drawn through a heated probe into a heated filter which removed ash and organic particulates. This was followed by a series of chilled water traps that collected the condensible organics before they were passed on to the pump and gas meter. The gas was finally vented to the atmosphere.

The basic MM5 sampling system was modified by TVA according to the EPA/Battelle Laboratory sampling protocol (9) to collect a more representative sample of condensible organics. The modifications included the elevation of the heated filter temperature from 100° to 205°C, the addition of an XAD-2 resin trap/condenser behind the heated filter section, and the insertion of a final "cold" filter before the silica gel trap. To recover the volatile hydrocarbons in the flue gases which were not condensed in the sampling train, an evacuated cylinder was placed at the exit of the MM5 control unit and partially filled with equal volumes drawn at prescribed percentages of fuel consumption over the duration of the test.

The method of sample recovery, handling, and analysis is shown in Figure 7. The method used is in general agreement with the Battelle protocol, except for inclusion of several refinements that were implemented after consultation with Battelle Laboratory. All efforts associated with the analyses were completed by the TVA Laboratory Branch. These analytical data were necessary to determine the emission factors for filterable particulates, condensible organics, volatile hydrocarbons, and polynuclear aromatic hydrocarbons (PAH's). The total chromatographable organics (TCO) and the volatile hydrocarbons in the C_1 - C_6 range were analyzed using a gas chromatograph/flame ionization detector (GC/FID) manufactured by Hewlett-Packard (HP) (Models 5710 and 5840). After the sample was prepared using a Kuderna-Danish (K-D) apparatus, gravimetric analysis was performed

FIGURE 7. ORGANICS HANDLING AND ANALYSIS SCHEME



with a Mettler mass balance, type B6, accurate to five places. Analysis for specific compounds was done with an HP Model 5980 gas chromatograph/ mass spectrometer (GC/MS).

Wood fuel analysis data were provided by the personnel of TVA Central Laboratories, Power Service Center, Chattanooga. These analytical data were required for completing the combustion modeling included in the TVA wood heater computer model. The percent total moisture was determined by means of a cold moisture oven, while the percent ash was determined using a furnace with supplied air. A Model 1241 automatic adiabatic calorimeter from Parr Instrument Company was used to calculate the Btu content. The ultimate analysis (dry) of the wood fuel was performed using a Model 123-3 carbon and hydrogen train from the Heavy-Duty Electric Company.

Residential Wood Heaters

The wood heaters tested in this study included: (1) a conventional nonbaffled airtight circulator typically used in the TVA region, (2) a new nonbaffled airtight catalytic radiant unit, (3) a new retrofit, add-on catalytic combustor connected to the exit of wood heater No. 1, (4) a new baffled airtight catalytic circulator using metal instead of ceramic as a catalyst base, and (5) a new airtight unit specially designed to provide secondary combustion features.

Test Fuel

Initially, 2-inch by 4-inch oak brands with 3/4-inch spacings were used as one of the test fuels. The oak was purchased in board stock (2-inch by 4-inch), fabricated into the brand configuration, and oven dried at approximately 200°F for varying periods depending upon the

moisture level desired. These brands were then stored in polyethylene bags under a shelter until used. Proximate, ultimate, and moisture analyses were performed on the fuel. The higher heating value of the brands on a dry basis was determined using a bomb calorimeter.

The more extensive testing used red oak cordwood as the test fuel. The cordwood was ordered precut into lengths of approximately 18 inches and split into triangular 4-inch by 4-inch pieces. The oak was then oven-dried at 200°F for varying periods of time and stored under a shelter until used. Proximate, ultimate, moisture, and dry higher heating value analyses were completed for the oak cordwood fuel.

Twenty-nine tests were conducted using the oak brand fuel. The remaining 103 tests utilized the oven-dried, red oak cordwood--a fuel more typical to that used in the TVA region.

The average of the results of the wood analysis for the oak brand and oak cordwood fuels are shown in Table 1.

Table 1

AVERAGE WOOD ANALYSIS FOR OAK BRAND AND CORDWOOD FUEL

Wood Composition	Oak Brands	Red Oak Cordwood
Moisture, %	11.7	10.4
Ash, %	0.9	0.5
Sulfur, %	0.05	0.05
Carbon, %	49.8	50.1
Hydrogen, %	5.9	6.0
Nitrogen, %	0.2	0.2
Oxygen, %	43.2	43.1
Higher Heating Value Btu/lb (dry)	8245	8455

Sampling Train

The EPA modified Method 5 (MM5) sampling system used to recover the samples is shown in Figure 1. The heated stainless steel-lined probe was inserted into the stack at the MM5 port. The probe was maintained at 230°C and the front heated filter assembly was maintained at approximately 205°C. The condenser/trap was located immediately behind and above the heated filter. The sample was transported up to the condenser through a heated glass tube. Most of the condensible portion (B.P. >20°C) of the sample was then condensed and drained down into and through the trap section. The trap contained Amberlite (R) XAD-2 resin which was prepared according to the procedure given in (10). The condenser was cooled by circulating ice water through the jacket, thereby reducing the temperature of the medium entering the trap to approximately 75°F (well below the decomposition temperature of the resin). The remaining gas was scrubbed in three impingers; the first two containing 100 ml each of reagent grade water and the third was dry. A secondary filter was placed after the third impinger and the fourth impinger contained silica gel. The secondary filter was maintained at ambient temperature. After exiting the last impinger, the dry gas then passed through a control unit where the flow rate was measured. An evacuated, 1-liter stainless steel cylinder was placed at the exit of the control unit and filled periodically during a test providing a sample of the volatile organic compounds not recovered in the sampling train.

Test Procedures

The testing was generally conducted over the entire range of operation for each wood heater. Each test was preceded by a conditioning burn which was conducted using a fuel load and damper setting identical to

the actual test requirements. Every effort was made to place the wood into the appliance in a consistent manner using the same mixture of sizes and the same stacking arrangement. Tests were conducted at fuel loadings of 32, 56, 80, and 104 kilograms per cubic meter of internal combustion chamber volume and at representative damper settings of 60, 30, 20, and 10 percent of full open position and at closed and open settings. This technique provided a matrix of results for a wide combination of operating parameters. Samples were taken using the MM5 system on tests with high and low wood loadings and open, 30 percent, and closed damper settings for each appliance. A distributed char bed equal to 5 percent of the fuel load being added was used for kindling of the test fuel. Draft measurements ranged from 0.08 in. H_2O for high burn tests (open damper) to 0.02 in. H_2O for low burn rate tests (closed damper).

The fuel consisted of 2-inch by 4-inch oak brands for the early tests and red oak cordwood for the remainder of the tests. A consistent wood loading configuration was maintained through all the tests so that a direct comparison of emissions could be made based solely on the performance features of each unit for each particular mode of operation.

Prior to each test the glassware components of the MM5 system were cleaned and the reagent grade water, preweighed glass fiber filters, and preweighed silica gel were placed in their respective components at the laboratory. Glass male plugs and female ball caps were used to seal all glassware components until the sampling system was assembled as shown in Figure 1. After assembly the MM5 system was leak checked at a vacuum of 20 psig to ensure that the leak rate was less than 0.0006 m^3/min.

The probe, probe tip, and heated filter section were preheated prior to the initiation of the test. The probe was then inserted into the stack

concurrent with the introduction of the official test charge of wood into the wood heater and the pump was activated to begin sampling. A flow rate of approximately 0.02 m^3/min was maintained over the duration of the test (until 90 percent of the wood charge was consumed). No attempt was made to sample isokinetically since it had been determined in an earlier study (11) that over 95 percent of the particulates were below 0.4 microns in size and therefore acted essentially as a moving gas molecule.

After conclusion of the sampling, the MM5 system components were removed, capped, and packed for shipment to the laboratory for analysis. In addition, the probe and probe tip were washed using methylene chloride and the washings collected and sent to the laboratory along with the glassware components.

The MM5 sample catch and the stainless steel cylinders were analyzed in the laboratory for filterable particulates, condensible organics, volatile organics, and PAH's. The analysis scheme is shown in Figure 7 and is based on the proposed EPA protocol (9). The total chromatographable organics (TCO) were determined by gas chromatography using a flame ionization detector (GC/FID) (Reference 10, pp. 140-142).

After TCO analysis, the extracts were concentrated to 10 ml and then dried to a constant weight, desiccated, and weighed to the nearest 0.1 mg to determine the gravimetric (GRAV) portion (Reference 10, p. 142).

Volatile hydrocarbons were analyzed by withdrawing a sample from the cylinder using a gas-tight syringe and analyzed by GC/FID. A 6-foot by 2-mm column of Poropak Q was used with the oven temperature programmed from 30°C to 200°C at 20°C/min. Calibration was accomplished using known concentrations of C_1 to C_6 n-hydrocarbons in He. Integration began at C_1 and terminated at the retention time of C_6.

The PAH's were analyzed using GC/MS. A 6-foot by 2-mm column of 3 percent SP2100 on 100/120 Supelcoport was programmed at 8°C/min from 50° to 300°C and held until complete sample elution. The spectra were identified using the Eight Peak Index of Mass Spectra (12) and the EPA/NIH Mass Spectral Data Base (13). Quantification was accomplished by injection of known concentrations of available PAH's using instrument conditions identical to the sample analysis.

The filterable particulates were defined to be the total (dry) catch at the probe tip, probe, and front filter. The condensible organics were defined as the sum of the TCO and GRAV obtained from analysis of the material in the glassware after the heated filter section. The volatile organics were the total ppm measured in the gas cylinder. The total PAH's were defined as the sum of the individual PAH's quantified from the filterable particulate extract and the individual PAH's quantified from the combined trap and impinger extracts.

The emission factors (g/kg wood) were calculated using the total mass of the component determined to be in the MM5 catch or gas cylinder per cubic meter of sample drawn. The wood burn rate, the stack gas flow rate, the water condensed in the MM5 impingers, and the ratio of the stack gas temperature to the temperature at the outlet of the MM5 sampling train were used in calculating the emission factors. The wood burn rate was determined by dividing the total wood weight loss during the test by the time interval associated with the test. The weight changes used in the computation of the burn rate included the total weight of fuel (dry wood and moisture). The stack gas flow rate was computed from a mass/energy balance for the process as no reliable method existed for determining stack gas velocities in wood combustion effluent. The water condensed in the MM5 system was included to correct for the change in volumetric

flow associated with the water condensation. The temperature ratio was used as an ideal gas correction for the decrease in volumetric flow rate due to the lower outlet temperature of the MM5 system.

EFFICIENCY AND EMISSIONS MODEL

This section of the report deals with the basic equations and the software used in the wood heater computer program. This version of the wood heater program was developed from an earlier Auburn University program which was capable of producing efficiency data only. The program has been lengthened considerably to deal with a wider range of parameters concerning wood heater performance. The model consists of a main or controlling program and 10 subroutines which instruct the computer to perform the calculations and output necessary to meet the required objectives. The objectives of this study fall into two main categories: thermal efficiencies and emission factors.

The basic calculations are presented in detail in the following sections which describe each of the subroutines used for calculations and conversions (Calc 1-3). The output subroutines (Out 1-3) are not covered in detail since the software used was simple and requires no detailed explanation.

A brief flowchart shown in Figure 8 depicts the basic movement of data within the program. Volume II contains a listing of the FORTRAN program used to analyze the data.

Description of Model

As mentioned earlier, the program uses the FORTRAN language. The program was structured such that the bulk of the calculations were performed in the subroutines. The main program performed the necessary

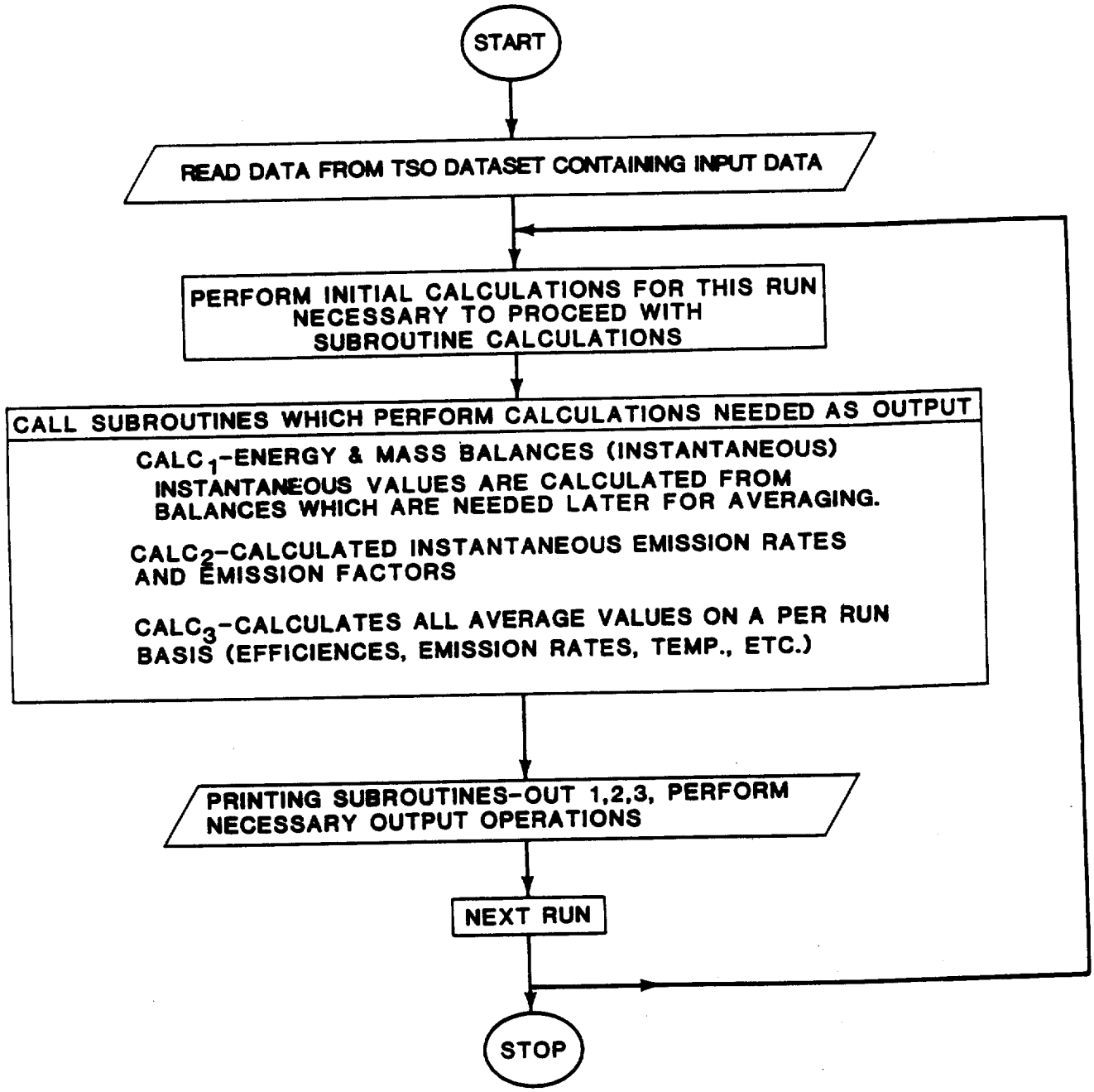


Figure 8. Simplified Flowchart Of Efficiency And Emissions Model

controls, conversions, and other commands which directed the flow of operation (see program flowchart on page 23). The data was distributed through the program by "common" statements.

The subroutines and their major calculations are outlined following this introduction. The detailed subroutine information can be found in Volume II. Three subroutines were used for calculations (Calc 1-3) and three subroutines were used for output. A brief description of each is given in the program flowchart on page 23.

Calc1

The calculations performed in the program were based on mass and energy balances associated with combustion chemical reactions. The chemical equation used to describe the combustion of wood was:

$$\alpha C_A H_B O_C + \alpha p H_2O + aO_2 + 3.76aN_2 \rightarrow dCO_2 + eCO + gO_2 + hN_2 + jH_2O + kCH_4$$

where

α = moles of dry fuel
p = moles of H_2O/moles of dry fuel
a = moles of O_2 used to combust wood
d = moles of CO_2 in stack gas
e = moles of CO in stack gas
g = moles of O_2 in stack gas
h = moles of N_2 in stack gas
j = moles of H_2O in stack gas
k = moles of equivalent CH_4 representing all total hydrocarbons in the stack gas

In the combustion equation, the effects of moisture in the air and trace elements in the wood fuel are neglected. The burning wood molecules is assumed to be the same as the raw wood molecules ($C_A H_B O_C$) which typically contain A atoms of carbon, B atoms of hydrogen, and C atoms of oxygen with

$$A = \frac{W_m F_{CD}}{1200}, \quad B = \frac{W_m F_{HD}}{100}, \quad \text{and } C = \frac{W_m F_{OD}}{1600}.$$

The dry fuel properties: F_{CD}, F_{HD}, and F_{OD} are the elemental percentages of carbon, hydrogen, and oxygen, respectively, in the wood on a dry basis. The molecular weight of the wood molecules (W_m) must be arbitrarily assigned with 100 being commonly used. The moles of water per mole of dry wood (p) is $[(W_m/18)(R/(100-R))]$ where R is the wood percentage moisture on a wet basis.

The following balances were made.

Carbon balance:	$A\alpha = d + e + k$
Hydrogen balance:	$(2p + B)\alpha = 2j + 4k$
Oxygen balance:	$(p + C)\alpha + 2a = 2d + e + 2g + j$
Nitrogen balance:	$3.76a = h$

The flue gas composition was measured on a dry basis using continuous flow electronic analyzers.

The moles of dry wood involved in combustion are as follows:

$$\alpha = \frac{\%CO_2 + \%CO + \%CH_4}{A}$$

The moles of H_2O in the stack gas followed from a hydrogen balance:

$$j = [(\alpha B) + (2\alpha p) - (4k)]/2$$

The number of moles of O_2 induced in combustion air was found from

$$a = \%O_2 + \%CO_2 + [(\%CO + j - ((p + C)\alpha))/2]$$

The percentage of N_2 (dry) in the products of combustion is found from

$$\%N_2 = 100 - \%CO_2 - \%CO - \%O_2 - \%CH_4$$

The energy losses associated with hot stack gases or the products of combustion were found from

$$H_p = \sum_p n\bar{h}$$

where $\bar{h} = \bar{h}_f + \Delta\bar{h}_{537 \rightarrow T}$

$\bar{h}_f$ = enthalpy of formation at 537°R

$\overline{\Delta h}_{537 \rightarrow T}$ = increase in enthalpy from 537°R to the temperature T

n = number of moles of each product gas specie

The following enthalpies of formation at 537°F were used for each major product of combustion:

Product	$\overline{h}_f$ (Btu/lb mole)
CO_2	-169,297
CO	- 49,551
O_2	0
N_2	0
H_2O (gas)	-104,036
H_2O (liquid)	-122,971
CH_4	- 32,211

The increase in enthalpy from 537°R to the flue gas temperature may be found from

$$\overline{\Delta h}_{537 \rightarrow T} = \int_{537}^{T} \overline{C}_p dt$$

Where $\overline{C}_p$ is the molar constant pressure specific heat for each flue gas product as shown below:

Products	$\overline{C}_p$ (Btu/lb-mole-°R)	a	b	c
CO_2	$(a - \frac{b}{T} + \frac{c}{T^2})$	16.2	6530	1.41×10^6
CO		9.46	3290	1.07×10^6
N_2		9.47	3470	1.16×10^6
O_2	$(a - \frac{b}{T} + \frac{c}{T})$	11.515	172	1530
H_2O_g		19.86	597	7500
CH_4	$a + bT$	4.52	7.37×10^{-3}	

The energy associated with the combustion reactants were similarly found by

$$H_r = \sum_r n\overline{h}$$

where $\overline{h} = \overline{h}_f + \overline{\Delta h}_{537 \rightarrow T}$

and $\overline{\Delta h}_{537 \rightarrow T}$ was neglected for all reactants as they entered at about 537°R (77°F). The dry wood enthalpy at formation ($\overline{h}_{f_{wood}}$ = HFWOOD) was computed using the dry wood higher heating value (HHVW) as follows:

$$HFWOOD = (A)HFCO2 + 0.5(B)HFH2OL - HHVW(W_m)$$

where HFCO2 and HFH2OL are heats of formation for CO_2 and H_2O (liquid), respectively. The net thermal efficiency can be written as

$$\text{Efficiency} = \frac{(H_p - H_r)100}{n(HHVW)W_m}$$

with the difference in enthalpies of the products and reactants representing the output heat transfer. The "n" in the efficiency equation represents the number of moles of dry fuel involved in the basic combustion equation.

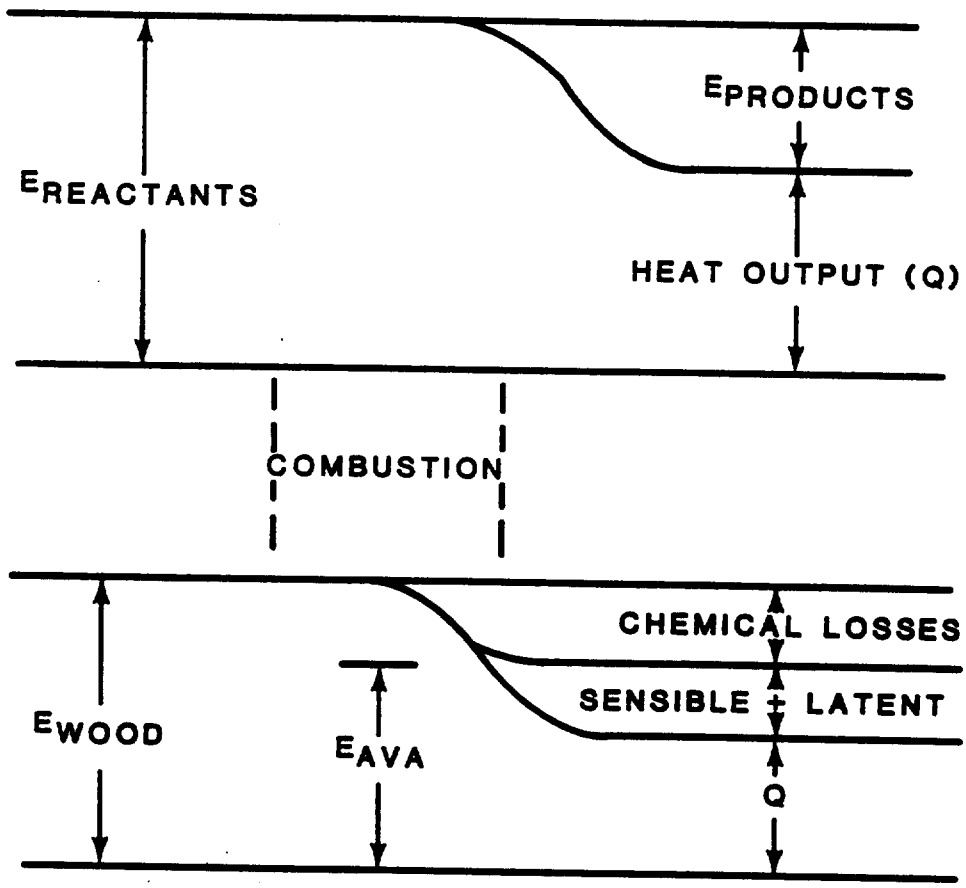
The combustion efficiency can be written as the sum of the thermal efficiency and the ratio of the heat content of the stack gases to the heat content of the wood as follows:

$$\text{Combustion Efficiency} = \left[\frac{H_p + H_{v,H_2O}}{n(-HHVW)W_m}\right] 100 + \left[\frac{H_p - H_r}{n(HHVW)W_m}\right] 100$$

or,

$$\text{Combustion Efficiency} = \left[\frac{H_r + H_{v,H_2O}}{n(-HHVW)W_m}\right] 100$$

The total energy involved in the combustion process can be illustrated graphically where the energy contained in the wood fuel is converted or lost through heat transfer to the surroundings, heat lost in the flue gases and the chemical losses involved in the reactions. Figure 9 depicts the combustion energy distribution for the process.



$$EFFC = \frac{E_{AVA}}{E_{WOOD}} \quad \text{and} \quad EFFHT = \frac{Q}{E_{AVA}}$$

$$EFF = EFFC \times EFFHT$$

$$EFF = \frac{Q}{E_{WOOD}}$$

Figure 9. Distribution Of Energies In The Products

The air fuel ratio was written as

$$AFR = (4.76)(28.96)AIR1/(\alpha W_m)$$

where

$$AIR1 = g + d + [(e + j - ((p + c)\alpha))/2]$$

The percent excess air was found from

$$PEA = [\frac{AFR\ (actual) - AFR\ (theoretical)}{AFR\ (theoretical)}](100)$$

where

$$AFR\ (theoretical) = [(A + (B/4) - (c/2))(4.76)(28.96)]/W_m$$

and A, B, and C are elemental values associated with the wood molecules.

The instantaneous heat release was found from

$$OHTRLS = 3600[\Delta \text{ wet wood weight}(100 - R)/100]HHVW/\Delta \text{ time difference}$$

The instantaneous air flow in cfm was found using ideal gas relationships from

$$AFLOW = AFLOWW/[\alpha(W_m + (18p))(HHVW)(BAPSI)]$$

where

$$AFLOWW = 0.85[\alpha(OHTRLS)(ATEMP)100/(100-\%moisture))]$$

ATEMP = Ambient air temperature (°R)

BAPSI = Ambient pressure in psi

The flue gas flow rate in cfh was found after the molecular weight (MGAS) of the flue gas was determined by using fundamental perfect gas relationships:

$$MGAS = (44d + 32a + 28e + 28h + 18j)/100$$

where

d, a, e, h, and j are the moles of each unique gas making up the flue gas.

The flue gas flow (GFLOW) is then computed as follows:

$$GFLOW = GFLOWW + [BURNR(REAR)STEMP/(BARPSF(MGAS))]$$

where

GFLOWW = 28.9[60(AFLOW)STEMP/(ATEMP(MGAS))]

BURNR = Wood burn rate (lbm/hour)

REAR = Universal gas constant (1545 ft-lb ft/lbm °R)

ATEMP & STEMP = Ambient and Stack gas temperatures (°R)

The monitored dry flue gas percentages were converted to a wet flue gas composition by addition of the water contained in the products as follows:

$$\%\ \text{gas}_{(\text{wet})} = \%\ \text{gas}_{(\text{dry})}(100/(100 + j))$$

All printouts of instantaneous flue gas species and instantaneous emission considerations used the wet flue gas composition.

The program also contains an option whereby THC concentrations in the flue gas may be computed from the carbon balance when measured THC values are not available. In this option, all hydrocarbons are considered to be methane (CH_4).

Calc2

This was a small subroutine which was used to calculate the instantaneous emission rates and the instantaneous emission factors. Each gas specie was converted to parts per million (ppm) by

$$\text{ppm} = (\%)(10{,}000) = \text{liters}/10^6 \text{ liters mixture}$$

Instantaneous emissions in lbm/ft^3 of flue gas mixture were found by the following relationship:

$$\frac{\text{lbm}}{\text{ft}^3} = \frac{(\text{liters emittant})(\text{liters flue gas})}{(10^6 \text{ liters flue gas})(\text{ft}^3 \text{ flue gas})} \frac{(\text{gm moles emittant})(\text{gm emittant})(\text{lbm emittant})}{(\text{gm mole emittant})(\text{gm emittant})}$$

$$\text{or } \frac{\text{lbm}}{\text{ft}^3} = \frac{(\text{ppm})(\text{m.w.})}{(7.30 \times 10^5)(\text{stove gas temp.}^\circ\text{R})}$$

for any gas specie in the flue gas.

The emission of a particular flue gas specie in units of (lbm/million Btu) was found as follows:

$$\frac{\text{lbm}}{10^6 \text{ Btu}} = \frac{(\text{lbm})(\text{ft}^3 \text{ gas})(\text{hour})(\text{lbm wood})(100)}{(\text{ft}^3 \text{ gas})(\text{hour})(\text{lbm wood})(\text{Btu})(100\% \text{ moisture})} (1 \times 10^6)$$

or in units of (lbm/ton wood)

$$\frac{\text{lbm}}{\text{ton wood}} = \frac{(\text{lbm})(\text{ft}^3 \text{ gas})(\text{hour})(2000 \text{ lbm wood})}{(\text{ft}^3 \text{ gas})(\text{hour})(\text{lbm wood})(\text{ton wood})}$$

Calc3

This subroutine used the instantaneous values calculated in the previous subroutines to calculate average values for the various parameters. The averages were weighted using either of two function subprograms: "Aver," which used a mass weighted average, and "Averr," which used a time weighted average. Shown below is a list of the averages and the method used to obtain each. Where the function subprograms are not employed, the equation is given.

1. Average thermal efficiency - mass weighted
2. Average heat output = $\frac{(\text{Average heat release})(\text{average efficiency})}{100}$
3. Average heat release = $\frac{(\text{wood used})(\text{high heating value})(1 - \text{moisture content of the wood}/100)}{(\text{Total Test Time})}$
4. Average air flow rate - time weighted
5. Average gas flow rate - time weighted
6. Average wood burn rate = $\frac{\text{wood used}}{\text{total test time}}$
7. Average combustion efficiency - mass weighted

8. Average heat transfer efficiency = $\frac{\text{Average thermal efficiency}}{\text{Average combustion efficiency}}$

9. Average sensible and latent heat loss = Average combustion efficiency - Average thermal efficiency

10. Average chemical losses = 100 - Average sensible & latent heat percent losses - average thermal efficiency

11. Average flue gas temperature - mass weighted and time weighted

12. Average wood heater gas temperature - mass weighted

The average emission values (lbm/MBTU) and (lbm/ton wood) were calculated using the mass weighted function subprogram.

NOTE: The following description of the Calc4 and Calc5 subroutines should be disregarded for the purpose of this test report since source severity and affected population were not considered for the purpose of this study.

Calc4

This subroutine calculated the source severity values for each of the emittant species. The source severity was given as a fraction of the maximum allowable concentration. The data needed for these calculations and for calculations in the next subroutine were carried into each subroutine by means of common statements, continuing the method employed in the previous subroutines.

The particular form of the source severity equation used depended on the emittant species. Table 2 gives the equations used in this subroutine for calculating the source severity.

Table 2

POLLUTANT SEVERITY EQUATIONS FOR ELEVATED POINT SOURCES

Pollutants	Severity Equation
Particulate	$S = \frac{70\ Q}{H_2}$
SO_x	$S = \frac{50\ Q}{H_2}$
NO_x	$S = \frac{315\ Q}{H_2 H_1}$
Hydrocarbon	$S = \frac{162\ Q}{H_2}$
CO	$S = \frac{0.78\ Q}{H_2}$
Other[a]	$S = \frac{5.5\ Q}{*TLV \cdot H_2}$

[a]"Other" includes (non-criteria pollutants) of which PAH material is included.
*The threshold limit value (TLV) used for the evaluation of the PAH source severity was $.001 \times 10^{-3}$ g/m^3.

where

Q = mass flow rate (grams/second)

TLV = threshold limit value

H = height of emission release (meters)

The derivations of these equations can be found in reference (14). The controlling relationship for the source severity was given as

$$S = \frac{\bar{x}_{max}}{F}$$

where

S = Source severity

$\bar{x}_{max}$ = time averaged maximum ground level concentration

F = hazard factor

Each equation given in Table 2 was derived from this relationship.

For purposes of this study, it became necessary to adjust the value of H. Since we were dealing with wood heater emissions, it was determined that the effective height of emission release or the effective stack height (HE) consisted of two parts.

$$HE = H + DELTH \tag{1}$$

where

H = height of the stack (meters)

DELTH = allowance for plume rise (meters)

The majority of the programming in this subroutine involved the calculation of DELTH since the values for H, Q, and TLV are either input or can be easily calculated from other previously determined values. The mass flow rates (Q) to be used in the equations given in Table 2 were obtained using the individual average emission factors $A_n(2)$* and the average wood burn rate AEF(6)* along with an appropriate constant (unit conversion factor). The average emission factors $A_n(2)$ were given in lbm/ton wood burned where n (used as a variable here) was found in the FORTRAN program to be either CO, SO_2, NO, THC, POM, or PART. The average wood

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*The (2) and the (6) are matrix designations.

burn rate for a particular test was a constant in the calculation of Q. In the case of CO, for example, Q was calculated using the following relationship.

$$Q \text{ (grams/second)} = \frac{A_{CO}(2)AEF(6)}{15847} \qquad (2)$$

As previously mentioned, the evaluation of DELTH involved the largest amount of programming in this subroutine. Once the DELTH was calculated for a particular run, it did not change and was a constant for each emittant species. The DELTH was calculated as follows:

$$DELTH = [((ASTGV)(DIAM)(WISP))((1.5 + 2.69 \times 10^{-3})(BAP)(TVS)(DIAM))] \qquad (3)$$

where

ASTGV = average stack gas velocity (m/sec)

DIAM = inside stack diameter (meters)

WISP = windspeed (m/sec)

BAP = barometric pressure (millibars)

TVS = stack temperature differential correction

The values for DIAM, WISP, and BAP were input into the program. The values for ASTGV and TVS were calculated as follows:

$$ASTGV = \frac{(AEF(5)(7.9 \times 10^{-6}))}{.25\pi\ (DIAM)^2} \frac{(AEF(11) + 460)}{(AEF(12) + 460)}$$

where

AEF(5) = average gas flow rate (ft^3/hour)

AEF(11) = average flue gas temperature (°F)

AEF(12) = average stove gas temperature (°F)

and $$TVS = 1 - \frac{(ATEMP + 460)}{(AEF(11) + 460)}$$

where

ATEMP = ambient air temperature (°F)

ASTGV, TVS, and other constants were then used in equation 3 to evaluate DELTH. The plume rise (DELTH) was then substituted into equation 1 to obtain the effective stack height (HE). The value obtained for HE was then used in the equations given in Table 2 (in place of H) along with the appropriate mass flow rates (Q), to obtain the emittant source severity. The source severity varied linearly (for a given test run) with the value of Q as HE is a constant. The calculated values for the source severity were then stored in an array for listing in the output subroutines to follow.

Modified Method 5 Data Analysis Program

This program was an interactive FORTRAN computer program which operated independently of the Efficiency and Emissions Model. It was used to analyze data accumulated from operation of the Modified Method 5 sampling train. The objectives of the program were to calculate emission factors for volatile hydrocarbons, filterable particulates, condensible organics, polynuclear aromatic hydrocarbons (also called polycyclic organic materials) total particulates, and the ratio of condensible organics to filterable particulates.

A program flowchart can be found on page 40; and Volume II gives a program listing.

The input data to the program included: The volume of gas drawn through the MM5 sampling system (determined during operation of the sampling train); the milliliters of water condensed, grams filterable particulates, grams condensible organics, and grams polycyclic organic materials (determined from chemical analysis of the sampling train glassware); the parts per million light hydrocarbons (determined from chemical analysis of volatile sample cylinder); and the average flue gas temperature, average flue gas flow rate, and average wood burn rate (taken from the output of the efficiency and emissions model).

The emission factors calculated in the program were determined on a wet basis with respect to the volume of flue gas drawn through the sampling train. A constant was derived to achieve this as follows:

$$C_1 = \frac{V\ dry\ gas}{V\ wet\ gas} = \frac{V\ dry\ gas}{V\ dry\ gas + V_{water}} = \frac{V\ dry\ gas}{V\ dry\ gas + \frac{nRT}{P}} \quad \frac{T}{Gtemp + 460}$$

where:

V	=	Volume
V_{water}	=	milliliters water gain
n_{water}	=	lbmoles water gain = $V_{water}/8172$
R	=	Universal gas constant (10.73 psi/(lbmole°R))
T	=	Ambient temperature (530°R)
P	=	Atmospheric pressure (14.7 psi)
Gtemp	=	Average flue gas temp (°F)

$$C_1 = \frac{1}{1 + \left(\frac{V_{water}}{V_{dry\ gas}}\right)\left(\frac{(.0473)}{1}\right)} \frac{530}{Gtemp + 460}$$

Since the emission factors were to be calculated in units of lbm/ton wood, calculations were simplified by deriving another constant relating the average flue gas flow rate (GFLOW) to the average wood burn rate (BURNR):

$$C_2 = \frac{GFLOW}{BURNR} \frac{2000\ lb\ wood}{ton\ wood} \frac{1\ lb\ emission}{454\ grams\ emission}$$

$$C_2 = \frac{GFLOW}{BURNR}\ 4.405\ \frac{cu.\ ft.\ gas\ drawn}{(ton\ wood)\ (gram\ emission)}$$

The emission factor for volatile hydrocarbons was obtained by converting parts per million light hydrocarbons (LHC) to grams light hydrocarbons using an average molecular weight of 26 lb/lb mole (based on an observed LHC composition of 48 percent methane, 40 percent ethylene, and 12 percent higher molecular weight compounds) and multiplying by constants C_1 and C_2.

$$\text{Volatile Hydrocarbons} = (\text{ppm LHC}\ \ 1.16 \times 10^{-6})\ C_1\ C_2\ \frac{lbm}{ton\ wood}$$

The emission factors for filterable particulates, condensible organics, and polynuclear aromatic hydrocarbons (PAH's), in units of lbm/ton wood, were calculated as follows:

$$\text{Emission Factor} = C_1\ C_2\ \frac{grams\ emission}{volume\ of\ gas\ drawn\ through\ system}\ \frac{lbm}{ton\ wood}$$

The total particulate emission factor was calculated as the sum of the condensible organics and filterable particulates emission factors. The ratio of the condensible organics emission factor to the filterable particulates emission factor was also calculated by the program.

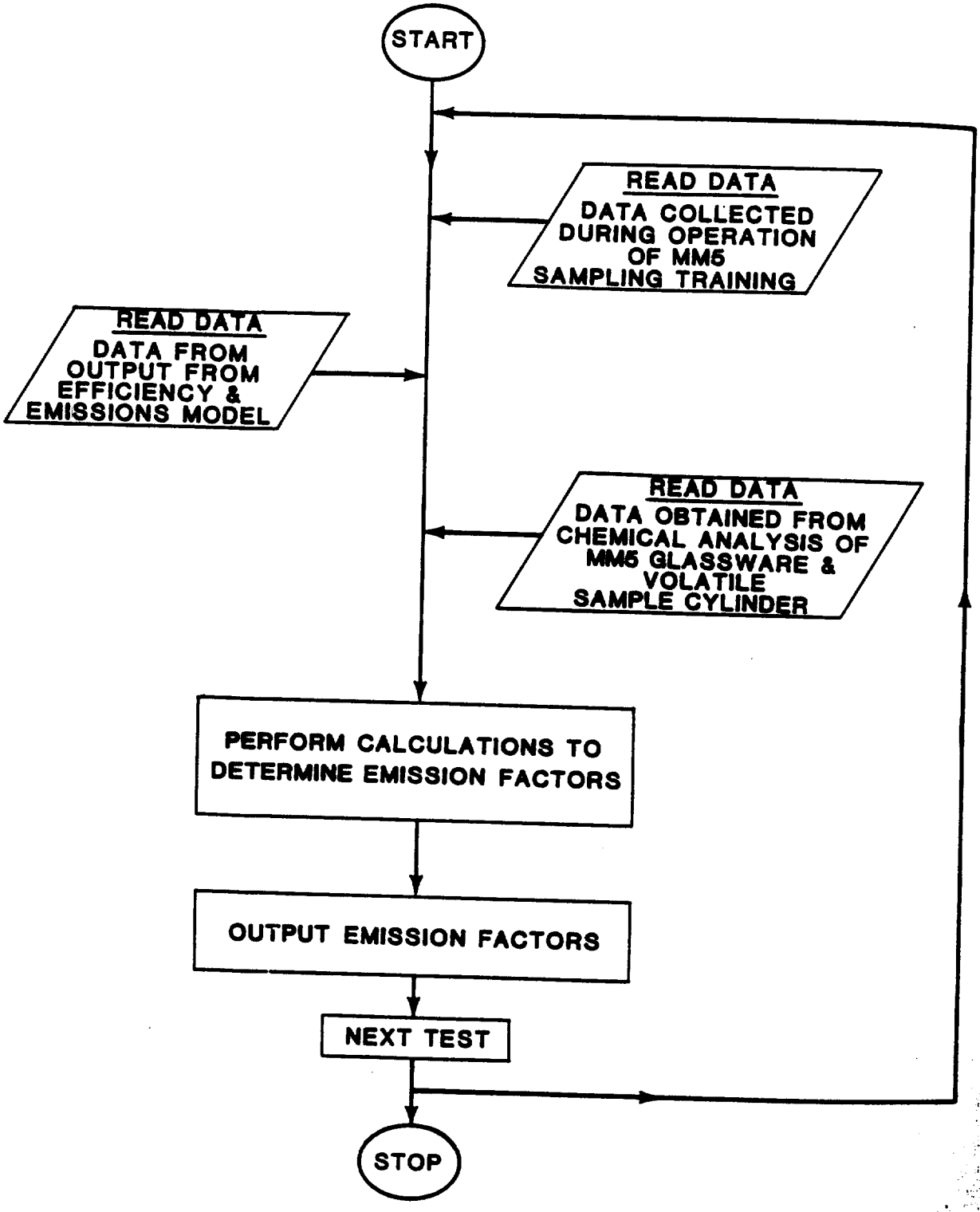


Figure 10. Simplified Flowchart Of Modified Method 5 Data Analysis Program

RESULTS AND DISCUSSION

Wood Heater #1

The experimental data was recorded on magnetic tape and then analyzed by the efficiency and emissions model. Many parameters are computed by the model which makes it possible to analyze the test results as they relate to thermal and emissions considerations. Table 3 presents a series of key diagnostic conditions for wood heater #1. The data shown in the table are presented in figure form and discussed later in the Wood Heater #1 Results section.

A complete summary of emission factors for wood heater #1 is presented in Table 4. All tests have continuous analyzer emission factors for CO, NO_x, and flame ionization detector (FID) total hydrocarbons. Integrated samples were recovered on designated tests for use in generating the other emission factors.

Of the 60 tests performed using wood heater #1, 29 used oak brands as fuel and the remaining 31 tests were conducted with red oak cordwood. The results of the brand fuel tests should be used only in analyzing the performance characteristics of this heater. They should not be included with the cordwood fuel tests when considering atmospheric pollution effects since the brand fuel is not typical of the fuel used by the average homeowner.

Wood Heater #1: Efficiencies

The thermal efficiency of wood heater #1 was very dependent on the air control position (damper) and the size of the wood load used for fueling. (See Figure 11.) Closed damper position "1" provided the lowest thermal efficiencies due to very inadequate combustion conditions. But even at the closed damper position, high thermal efficiencies were obtained when

Table 3. WOOD HEATER #1
AVERAGE AIRTIGHT TEST RESULTS - THERMAL - OAK 2"x4" BRANDS

Test	Wood Charge (lb)	Damper Setting	Supply Air (CFM)	Wood Burn Rate (lb/hr)	T Flue Gas (°F)	Excess Air (%)	Thermal Efficiency	Diagnostic Efficiencies (%)		Flue Gas Losses (%)		Heat Output (Btuh)
								Combustion	Heat Transfer	Sen+Latent	Chemical	
17	25.4	1	21.0	17.8	713	18	54.1	75.7	71.5	21.6	24.3	70,987
19	19.6	1	36.3	12.6	854	180	46.1	92.0	50.0	46.0	7.9	42,691
20	13.7	1	26.6	11.0	772	140	57.5	94.8	60.6	37.3	5.2	46,467
21	7.9	1	22.7	8.4	751	165	53.2	91.8	57.9	38.6	8.2	32,770
1	25.4	2	19.6	19.2	1,024	-8	53.7	80.6	66.6	26.9	19.4	75,873
2	19.6	2	18.2	17.3	938	-3	54.1	79.6	67.9	25.5	20.4	69,043
3	13.7	2	18.9	14.2	969	29	60.2	91.2	65.9	31.0	8.8	62,875
4	7.8	2	17.4	12.6	924	32	62.3	92.5	67.4	30.2	7.6	57,643
14	25.4	3	19.9	17.8	968	7	54.6	81.9	66.6	27.4	18.0	71,328
15	19.5	3	18.7	16.3	936	11	56.8	83.8	67.8	27.0	16.2	67,898
16	13.7	3	18.5	14.4	1,086	23	57.9	90.8	63.8	32.8	9.2	61,490
18	7.8	3	21.0	8.4	767	144	60.0	96.9	61.9	36.9	3.1	37,195
5	25.4	4	23.1	21.8	1,162	-2	52.2	83.4	62.6	31.2	16.6	83,830
6	19.5	4	26.3	22.5	1,373	7	50.6	89.3	56.7	38.7	10.7	83,580
7	13.7	4	23.0	16.3	1,105	38	53.8	89.8	60.0	35.9	10.2	64,693
8	7.8	4	24.0	15.9	1,091	48	54.1	91.1	59.4	36.9	8.9	63,188
10	25.1	5	42.0	26.8	1,542	55	39.1	92.5	42.2	53.4	7.5	77,053
11	19.3	5	57.5	28.4	1,413	103	25.6	83.9	30.5	58.4	16.0	53,370
12	13.4	5	64.3	26.5	1,503	140	16.4	87.6	18.7	71.2	12.4	31,947
13	8.0	5	29.6	14.1	885	110	60.1	98.5	61.1	38.3	1.6	62,418
26	25.4	5	37.5	26.2	1,431	41	42.7	88.8	48.1	46.1	11.2	82,285
27	19.6	5	30.1	22.5	1,266	30	53.0	92.4	57.4	39.4	7.6	87,785
28	13.7	5	30.4	22.3	1,168	32	59.5	96.8	61.5	37.3	3.2	97,524
29	7.8	5										

Table 3. WOOD HEATER #1 (CONT'D)
AVERAGE AIRTIGHT TEST RESULTS - THERMAL - OAK 2"x4" BRANDS

Test	Wood Charge (lb)	Damper Setting	Supply Air (CFM)	Wood Burn Rate (lb/hr)	T Flue Gas (°F)	Excess Air (%)	Thermal Efficiency	Diagnostic Efficiencies (%) Combustion	Heat Transfer	Flue Gas Losses (%) Sen+Latent	Chemical	Heat Output (Btuh)
31	25.4	6	41.9	28.0	1,361	26	38.6	82.9	46.5	44.3	17.1	79,988
32	19.6	6	23.6	17.2	1,410	25	46.9	88.3	53.2	41.3	11.8	59,790
33	13.7	6	27.4	14.3	1,224	80	54.1	98.2	55.1	44.1	1.8	57,406
34	7.8	6										
35	7.5	6	28.7	15.5	1,068	81	55.3	96.1	57.5	40.8	3.9	63,420
36	13.6	6	26.6	17.5	1,221	46	54.4	94.6	57.5	40.2	5.4	70,437
37	19.4	6	28.7	18.5	1,318	43	51.9	94.7	54.8	42.8	5.3	71,275
38	25.4	6	31.2	20.7	1,362	41	51.4	95.4	53.9	44.0	4.6	78,930
39	7.7	5	33.2	15.9	905	108	57.8	98.7	58.6	40.8	1.4	67,980
40	13.8	5	37.1	16.5	1,130	78	45.8	92.8	49.3	47.1	7.2	55,850
41	19.4	5	29.3	15.3	1,297	60	46.4	93.1	49.8	46.7	6.9	52,680
42	25.4	5	36.7	19.0	1,334	62	43.2	92.5	46.7	49.3	7.5	60,875
44	7.8	4	20.7	15.5	912	33	60.9	90.0	67.6	29.1	10.0	70,050
45	13.8	4	21.0	17.7	997	16	58.6	88.0	66.5	29.5	11.9	76,865
46	19.3	4	21.3	19.0	1,011	11	55.3	84.2	65.7	28.9	15.8	77,855
47	25.5	4	20.4	19.0	979	6	55.5	82.6	67.1	27.1	17.4	78,184
48	7.8	3	15.0	10.3	809	47	63.3	91.2	69.5	27.8	8.8	48,185
49	13.8	3	15.0	10.8	729	40	61.9	86.4	71.6	24.5	13.6	49,47
50	19.4	3	16.1	13.7	773	19	58.5	81.9	71.8	23.4	18.1	59,41
51	25.5	3	16.9	16.0	756	8	57.7	79.3	72.8	21.6	20.7	68,52
52	7.8	2	13.3	7.7	521	77	60.2	80.6	74.7	20.4	19.4	34,22
53	13.8	2	11.5	8.3	482	43	60.9	78.2	77.9	17.3	21.8	37,66
54	19.4	2	15.5	9.0	467	78	55.8	74.6	74.9	18.9	25.4	37,24
55	25.5	2	19.7	9.4	531	110	52.9	76.3	69.4	23.3	23.8	36,9
56	7.8	1	25.4	4.0	259	461	37.8	60.4	62.4	22.7	39.5	11,2
57	13.8	1	23.9	4.1	260	421	41.1	62.4	65.9	21.3	37.6	12,3
58	19.3	1	21.2	5.1	294	285	44.1	63.5	69.4	19.4	36.5	16,5
59	26.0	1	10.7	5.2	302	111	57.9	71.9	80.6	13.9	28.2	22,2
60	19.3	1	10.5	4.3	270	140	55.2	68.9	80.3	13.5	31.3	17,3
25	6.8	6	50.3	14.3	948	232	40.9	98.3	41.6	57.4	1.7	43,4

Table 4. WOOD HEATER #1
AVERAGE AIRTIGHT TEST RESULTS - EMISSIONS (g/kg) - OAK 2"x4" BRANDS

Test	CO[1]	Total Hydrocarbons[2]	NO_x[3]	SO_2[4]	Filterable Particulates[5]	Condensible Organics[6]	Total Particulates	Volatile Hydrocarbons[7]	Polycyclic Organic Material[8]
17	197	41	0.15	1.21					
19	49	14	0.30	0.16	0.30	5.07	5.37	0.15	0.12
20	39	7	0.36	0.07					
21	83	16	0.30	0.26	0.61	2.17	2.78	0.004	0.01
1	157	34	0.23	1.48					
2	177	39	0.16	1.65					
3	66	15	0.42	0.68					
4	58	12	0.34	0.61					
14	140	32	0.23	1.25					
15	139	26	0.25	1.30	0.14	2.17	2.31	0.22	0.39
16	53	18	0.36	0.65					
18	18	5	0.35	0.05	0.55	10.27	10.82	0.05	0.01
5	120	32	0.32	1.53					
6	56	25	0.48	1.37					
7	72	18	0.38	0.70					
8	66	20	0.39	0.57					
10	35	17	0.29	0.26					
11	67	37	0.19	0.55	1.23	0.70	1.93	0.15	0.05
12	44	30	0.25	0.37					
13	7	2	0.51	0.03	0.57	0.75	1.32	0.03	0.02
26	77	20	0.29	0.75					
27	54	13	0.41	0.43					
28	22	5	0.49	0.10					
29									

[1]Beckman 864 Analyzer (Infrared)
[2]Beckman 402 FID Analyzer
[3]TECO model 10A (Chemiluminescent)
[4]TECO model 40 (Pulsed Fluorescent)
[5]EPA Modified Method 5 (205°C filter section), gravimetric
[6]EPA Modified Method 5, ice bath impingers and resin trap, gravimetric, TCO (GC/FID)
[7]GC/FID, sample taken from dry gas flow leaving Method 5 flow meter
[8]EPA Modified Method 5 with XAD-2 resin trap, GC/MS

Table 4. WOOD HEATER #1 (CONT'D)
AVERAGE AIRTIGHT TEST RESULTS - EMISSIONS (g/kg) - RED OAK CORDWOOD

Test	CO[1]	Total Hydrocarbons[2]	NO_x[3]	SO_2[4]	Filterable Particulates[5]	Condensible Organics[6]	Total Particulates	Volatile Hydrocarbons[7]	Polycyclic Organic Material[8]
31	113	35	0.71	1.37	0.73	7.86	8.60	0.85	1.57
32	68	26	0.53	0.69					
33	37	8	0.77	0.23	0.12	0.84	0.96	0.01	0.01
34									
35	25	6	0.51	0.17					
36	31	11	0.60	0.30					
37	28	12	0.63	0.33					
38	26	9	0.66	0.28					
39	8	1	0.57	0.05	0.23	0.73	0.96	0.06	0.01
40	57	17	0.67	0.57					
41	44	14	0.77	0.55	0.09	1.18	1.27	0.07	0.02
42	55	14	0.75	0.61					
44	62	20	0.53	1.24					
45	73	25	0.54	1.68					
46	107	31	0.45	1.64					
47	111	26	0.39	1.66					
48	43	19		0.80	0.41	3.38	3.79	0.16	0.05
49	79	29	0.11	1.57					
50	125	35	0.18	1.62	0.15	13.45	13.60	0.78	0.42
51	155	33	0.13	1.51					
52	91	44	0.20	0.30					
53	126	45	0.15	0.72					
54	119	57	0.11	0.61					
55	108	53	0.12	0.79					
56	98	105	0.10	0.25	5.19	92.10	97.29	1.55	0.58
57	100	99	0.11	0.34					
58	102	95	0.13	0.41	0.32	80.51	80.83	1.90	0.45
59	112	67	0.08	0.32					
60	135	78	0.08	0.21				0.02	0.02
25	20	3	0.97	0.10	1.60				

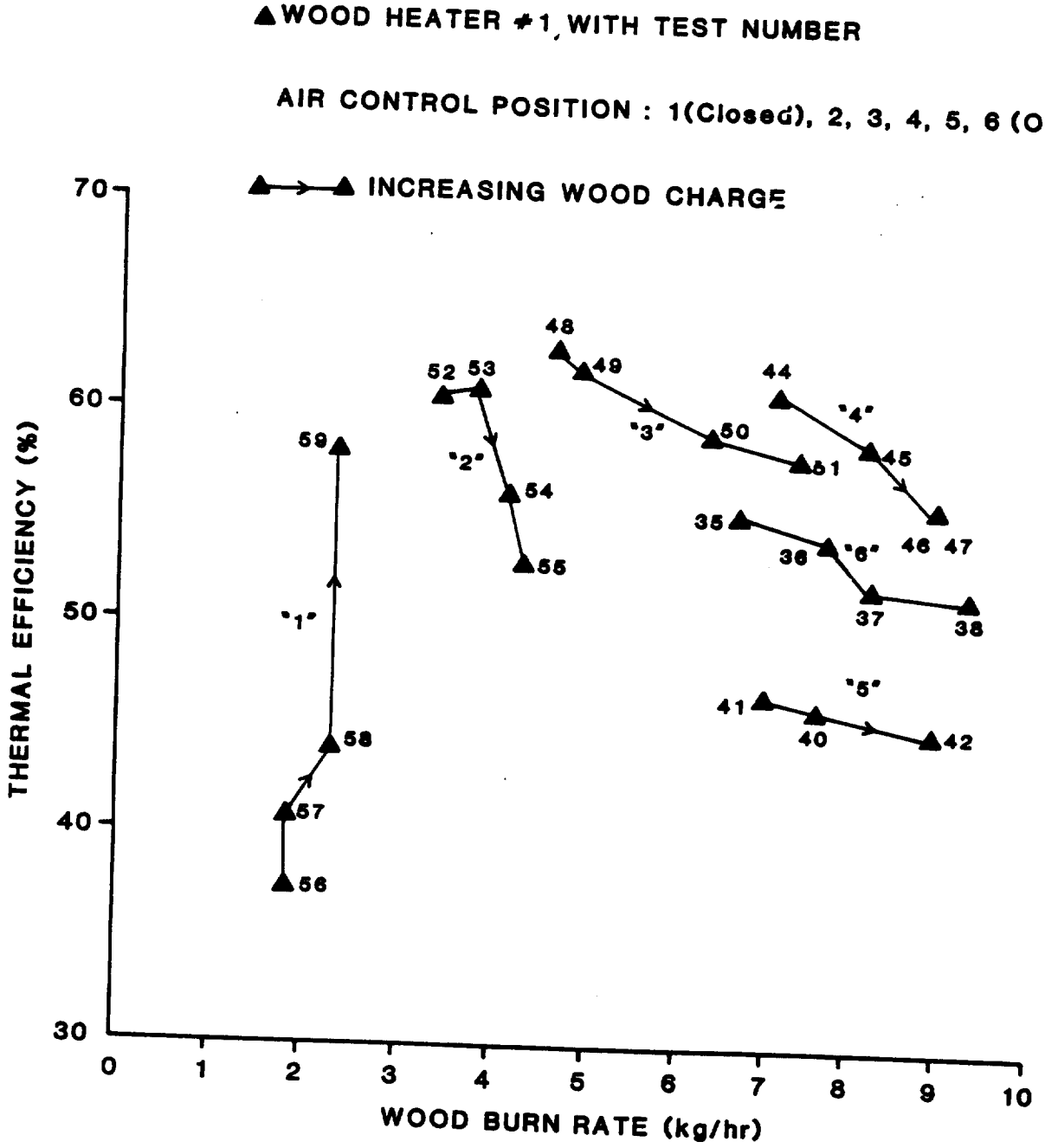


Figure 11. Thermal Efficiency Versus Burn Rate-Wood Heater# 1

the larger wood loads were fired. Generally, as the air control position was opened in increments, the thermal efficiency increased with a maximum thermal efficiency at damper position "3." This damper position gave the highest thermal efficiency for the full range of wood loads fired. The thermal efficiency proceeded to drop for more open damper positions. Tests associated with damper positions "5" and "6" seemed to be misplaced. This was not the case, however, since damper position "5" provided higher flue gas temperatures and more combustion supply air than did damper position "6." Therefore, the damper position should be critically viewed as 1 (closed), 2, 3, 4, 6, and 5 (open) with positions 5 and 6 reversed. Overall, the thermal efficiency may be represented by an inverted parabola with low thermal efficiencies at both low and high burn rates. Previous results reported by TVA (14,15) noted this unique relationship between thermal efficiency and burn rate but neither study revealed the effect shown in Figure 12. The low thermal efficiencies at the closed damper position resulted from low combustion efficiencies while the low thermal efficiencies at the open damper positions resulted from low heat transfer efficiencies. Since thermal efficiency equals the product of combustion and heat transfer efficiencies, the thermal efficiency was a maximum at the intermediate damper position where the product of combustion and heat transfer efficiencies was a maximum.

Increased size of wood fuel loadings for fixed damper positions produced lower thermal efficiencies, except for the closed damper position where highest thermal efficiencies were obtained with the largest loadings.

Figure 12 presents combustion efficiencies for wood heater #1. The combustion efficiencies increased generally with burn rate as the combustion activity was stimulated. Higher combustion efficiencies were obtained

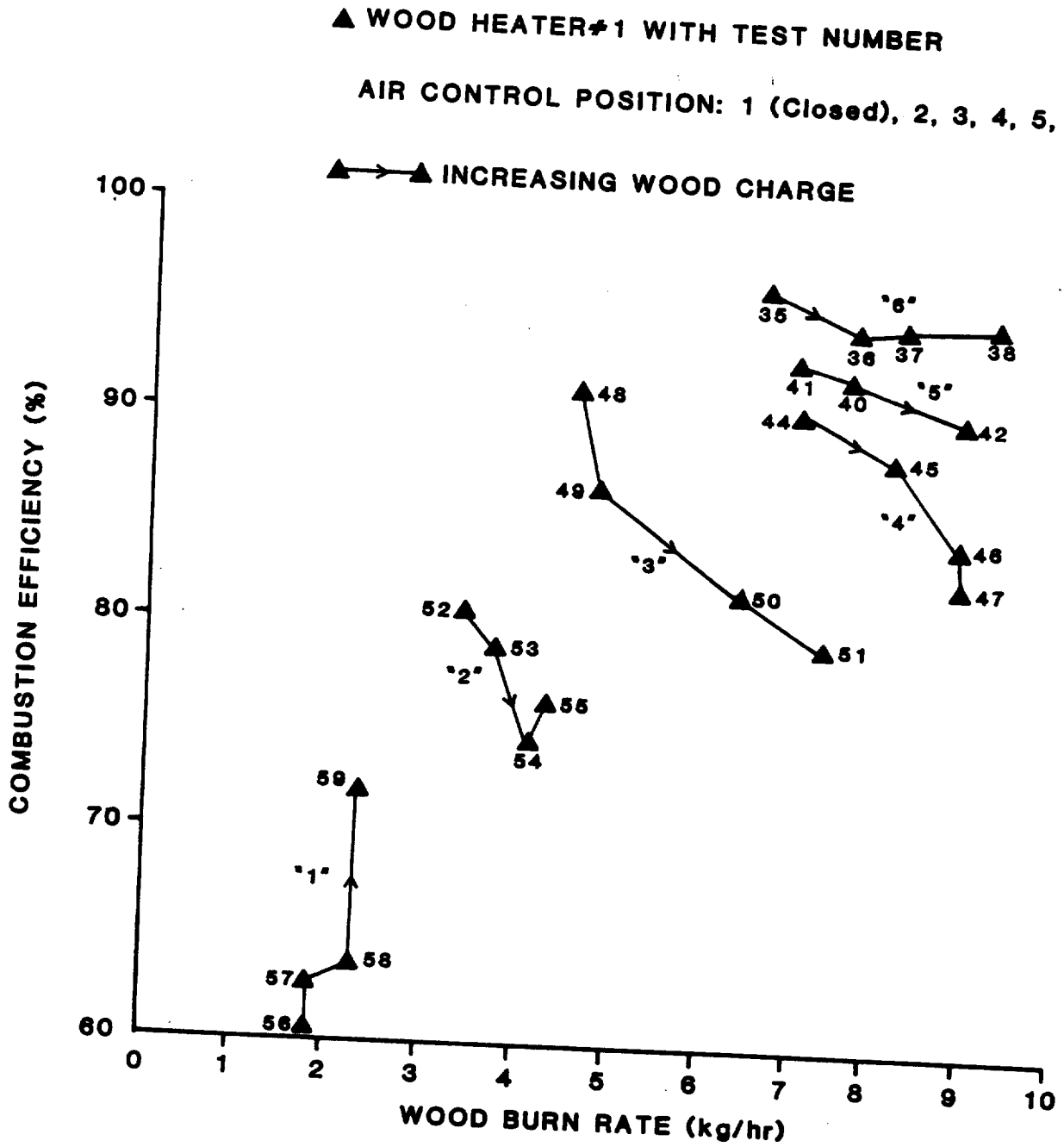


Figure 12. Combustion Efficiency Versus Burn Rate–Wood Heater#1

for small wood load fuelings at all damper positions except closed. The low combustion efficiencies were associated directly with high emissions of CO and organics resulting from incomplete combustion.

Heat transfer efficiencies for wood heater #1 are presented in Figure 13. Intermediate and low damper positions had the highest heat transfer efficiencies since the flue gas volumetric flow rates were low and the long retention times provide for more effective heat exchange between the flue gases and the ambient air. As the damper was opened, the heat exchange effectiveness was significantly reduced. The heat transfer efficiency was rather independent of wood load size except for closed damper position firings where the larger wood loads developed much higher heat transfer efficiencies. High combustion and heat transfer efficiencies existed for test 59 due to the restriction of the larger wood load on the air supply which caused the excess air to dip to 111 percent. The smaller wood loadings (tests 58, 57, and 56) had excess air values of 285, 421, and 461, respectively. These excess air values corresponded to average combustion air supplies of approximately 11, 21, 24, and 25 cubic feet per minute for tests 59, 58, 57, and 56, respectively. A close review of combustion data in Table 3 shows exit flue gas temperatures at 302, 294, 260, and 259°F for the same sequence of tests. The higher exit flue gas temperature for test 59 indicates that localized fuel bed temperatures necessary for supporting combustion were higher than for the tests using smaller fuel loads. Figure 12 shows that the actual combustion efficiency was very low for test 59 when it is compared with more open damper positions which maintained much higher fuel bed temperatures. The heat transfer efficiency for test 59 is the highest shown in Figure 13. Table 3 also shows that test 59 operated with a

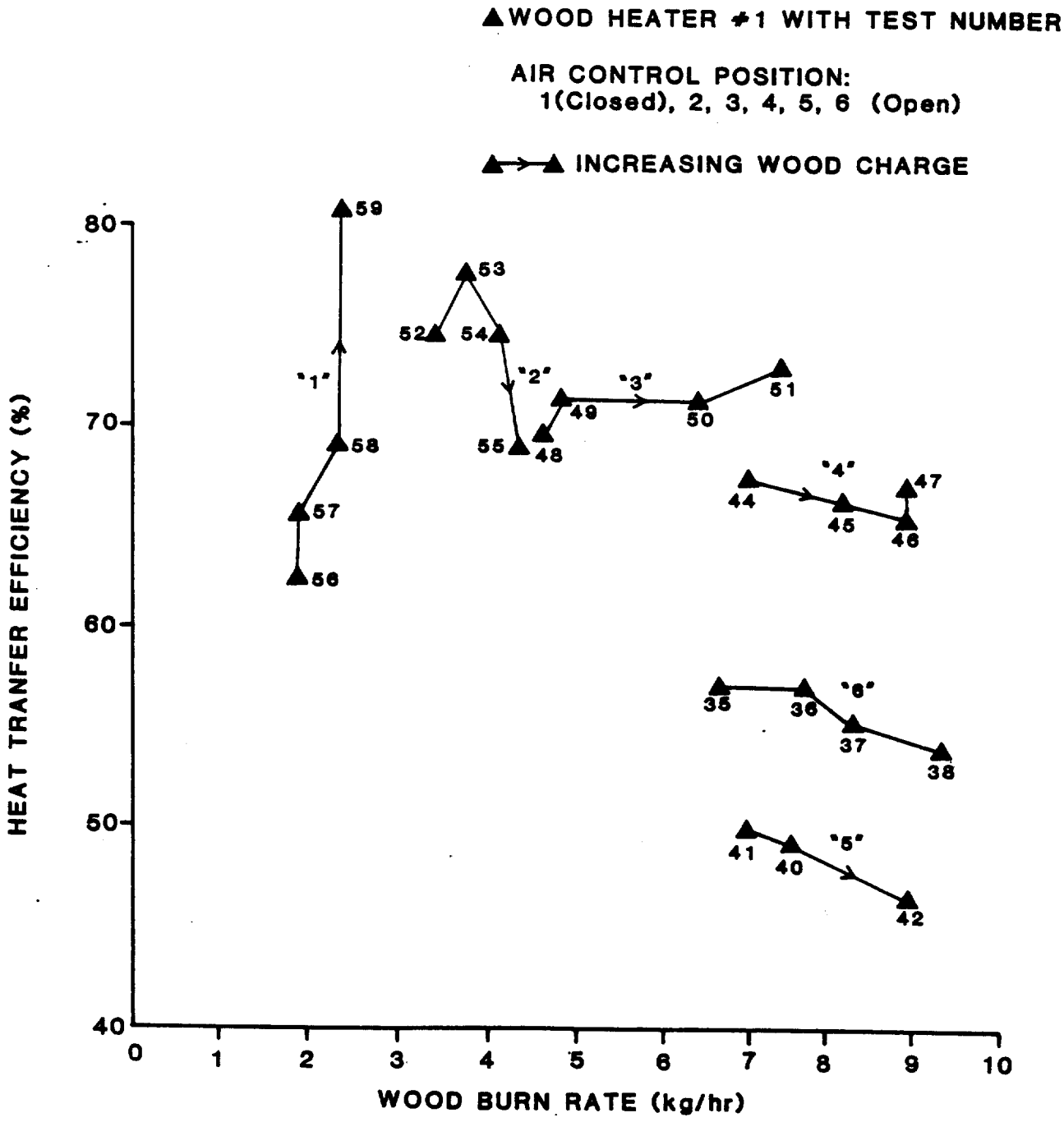


Figure 13. Heat Transfer Efficiency Versus Burn Rate-Wood Heater#1

combustion air supply of 10.7 cfm; the lowest value associated with any sequence of tests. The long retention times required for effective heat exchange between the flue gases and ambient air existed for test 59. A replicate test number 60 was conducted to confirm the findings of test 59. The results of test 60 as presented in Table 3 verify test 59 and support the findings that large wood fuel loadings were much preferred over small loadings with regard to thermal, combustion, and heat transfer efficiencies.

The thermal efficiency results for Wood Heater #1 as presented in Table 5 may be viewed by some as the only parameter of importance with regard to the operation of a wood burning heater. But the combustion and heat transfer efficiencies are directly related to the composition and temperature of the gas exiting the wood heater. The wood structure must first be converted to hot combustion gases in the primary fuel magazine. The more complete the combustion, the higher the combustion efficiency and the lower the chemical losses associated with incompletely oxidized CO and organics in the combustion gases. After leaving the primary combustion zone the gases are rapidly cooled by radiant and convective heat transfer in the heat exchanger area of the wood heater. The design of this heat exchanger surface area varies with each model and manufacturer. The function of this heat exchanger is to extract as much thermal energy from the hot gases as possible. The fraction of thermal energy transferred to the surroundings in comparison with the potential thermal energy generated through combustion (combustion efficiency x wood's heating value) is called the heat transfer efficiency. It is important to have a high heat transfer efficiency since this reduces the sensible and latent flue gas losses which can result from an inadequately designed heat exchanger.

Table 5. SUMMARY OF DISTRIBUTED ENERGIES[a] (%) FOR WOOD HEATER #1

Damper Setting	Burn Rate (kg/hr)	Thermal Efficiency	Combustion Efficiency	Heat Transfer Efficiency	Sensible Plus Latent Losses	Chemical Losses
Open(5)	8.5	48.3	94.3	51.1	46.0	5.8
60%(4)	8.1	57.6	86.2	66.7	28.7	13.8
30%(3)	5.8	60.4	84.7	71.4	24.3	12.3
10%(2)	3.9	57.4	77.4	74.2	20.0	22.6
Closed(1)	2.1	45.2	64.6	69.6	19.3	35.4
Average	5.7	53.7	81.4	66.6	22.7	18.6

[a]Average of four tests, each having a different cordwood fuel loading size.

Thermal Efficiency = Combustion Efficiency x Heat Transfer Efficiency

Thermal Efficiency + (Sensible and Latent Losses) + Chemical Losses = 100%

The combustion efficiency and the percent chemical losses represent the total energy available from the wood. If wood is burned in air and the only products are CO_2, H_2O, and N_2 then the combustion efficiency is 100 percent and the chemical losses are zero. However, products of incomplete combustion like CO, light hydrocarbons, and heavy organics invariably result from combustion of wood in airtight wood heaters. After the products of incomplete combustion are formed, they can be cooled along with the CO_2, H_2O, and other flue gases, but the full thermal output potential of the wood cannot be obtained because the products of incomplete combustion are discharged without having been fully oxidized. For example, for each mole of carbon that is released as CO instead of CO_2 about one-third of its potential heat release is lost.

A wood heater should operate with high combustion and heat transfer efficiencies in order to minimize the thermal and chemical losses and maximize the thermal efficiency. Table 5 shows that wood heater #1 operated with average thermal efficiencies between 45 and 60 percent with the highest thermal efficiency occurring at an intermediate damper setting of 30 percent open.

The combustion efficiency for wood heater #1 was a maximum for fully open damper firings while the heat transfer efficiency was a minimum. The results for a fully open primary damper as well as a partially open ash pan door were not included in Table 5 since such a firing condition is not commonly used except for initiating a cold start.

The sensible and latent losses were inversely related to heat transfer efficiency since high heat transfer efficiencies provided low sensible losses. The high burn rate firings for wood heater #1 produced low chemical losses of 5.7 percent while the closed damper firings produced high

chemical losses of 35 percent. This means that about 35 percent of the ultimate heating capacity for the cordwood was lost due to large concentrations of CO and incompletely oxidized organics being in the flue gases. The average values for each distributed energy are presented in Table 5 and will be discussed in the Comparative Discussion section of this report.

Wood Heater #1: Emissions

Carbon monoxide (CO) emission factors for wood heater #1 are presented in Figure 14. The CO emission factors generally increased as the combustion air supply became more limited due to damper or air control closure. For tests conducted with the air control fully open and fully closed the CO emissions were independent of wood charge size being burned. However, the CO emissions were dependent on wood charge size at all intermediate air control positions. The largest dependence existed at position "3" with the CO emissions increasing by a factor of four for incremental increases in wood load from 7.8 to 25.5 pounds. The CO emissions at the closed position were higher than those associated with the high burn rates at an open damper by a factor of 4.

Figure 15 presents total hydrocarbon emission factors associated with wood heater #1. The THC emission factors increased by an order of eight when the air supply control was moved from fully open to fully closed. Very similar findings have been reported by Canadian Combustion Laboratory (16). The fully closed air supply control (damper) did not provide complete absence of primary combustion air as small air leaks existed around doors, etc. However, the fully closed position did represent the most restricted mode of operation that the homeowner may use. During high burn rate firings, with fully open damper, the THC emission factors were rather independent of wood load size while at the low burn

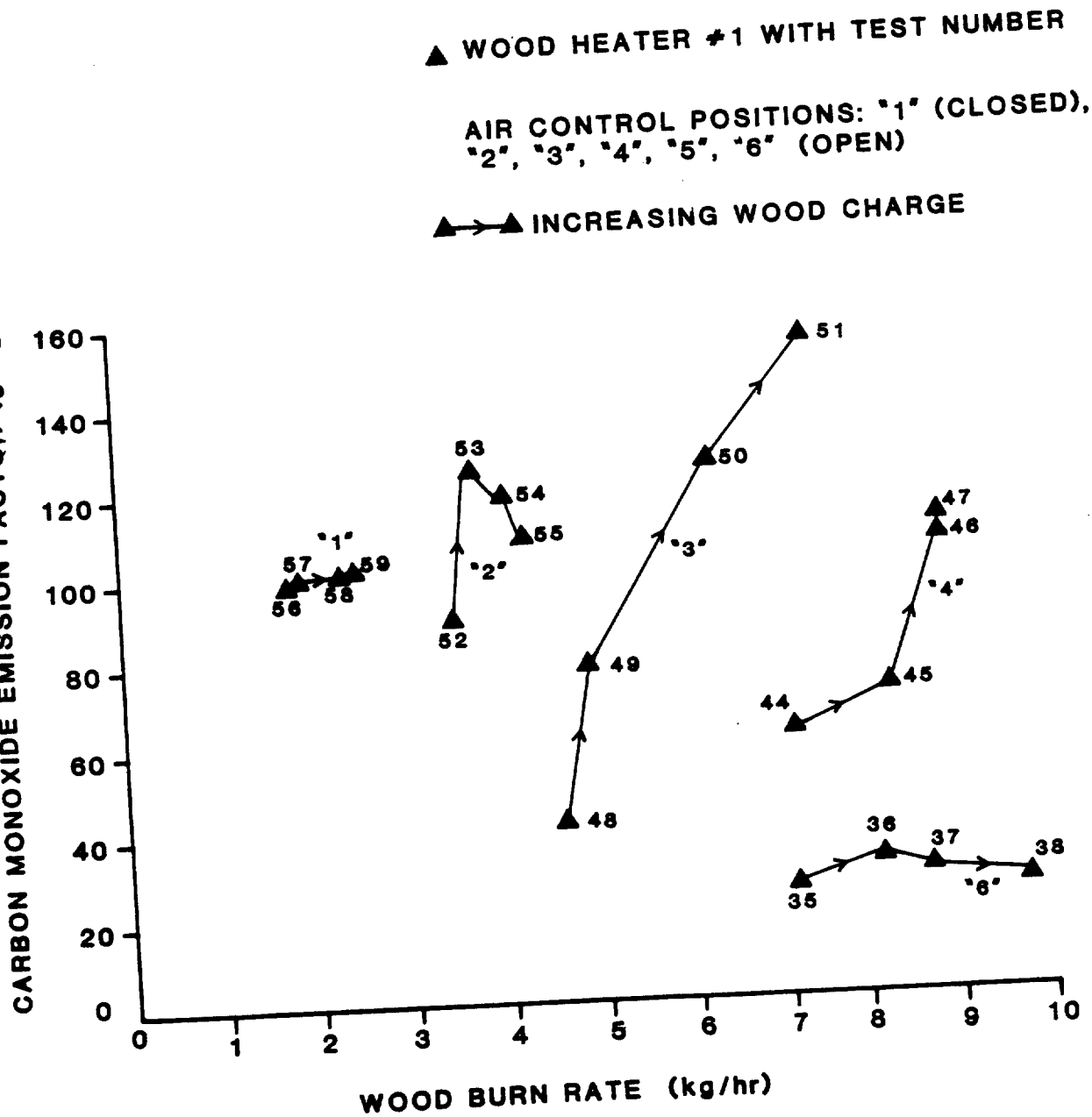


Figure14 Carbon Monoxide Emission Factor Versus Burn Rate-Wood Heater #1.

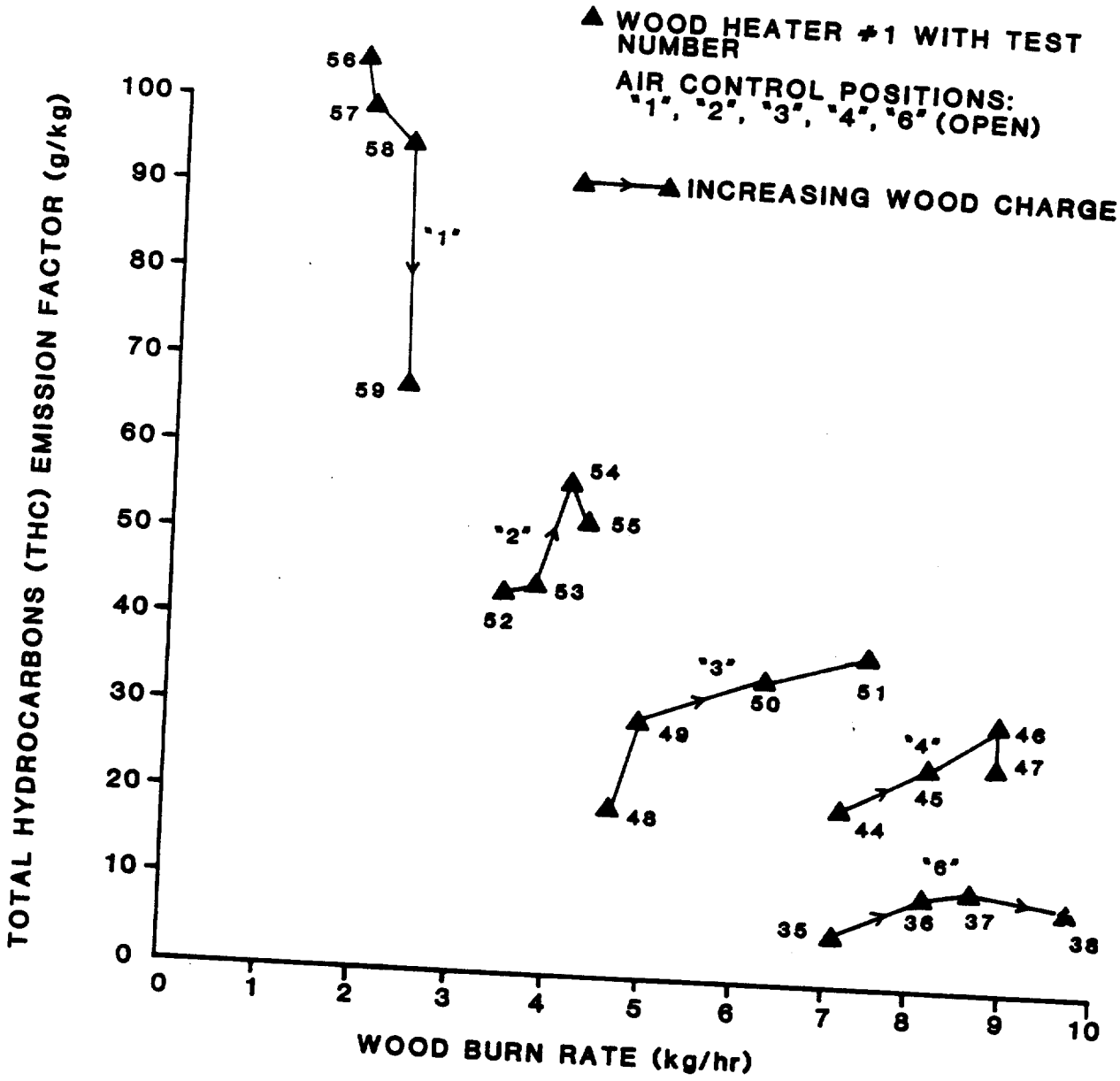


Figure 15. THC Emissions Versus Burn Rate-Wood Heater #1

rates with the closed damper the emissions were inversely dependent upon wood load size. This decrease in the emission factor for large wood loads at the closed damper firing is important in that most homeowners operate in this mode during the overnight period.

Table 4 presents NO_x emission factors for wood heater #1. The NO_x emission factor ranged between 0.08 g/kg for low burn rate firings with the oak cordwood to 0.97 g/kg for the higher burn rates. The NO_x emissions were typically 90 percent NO and 10 percent NO_2 by volume fraction, while a mass fraction basis the NO component was 84 percent while the NO_2 was 16 percent. Lower NO_x emissions were found for the high burn rate tests using fir brand fuel.

Sulfur dioxide (SO_2) emission factors are presented in Table 4 also. The SO_2 emission factor ranged between 0.10 and 1.62 g/kg. Similar SO_2 emissions were found for the fir brand fueled tests.

Figure 16 presents volatile hydrocarbons emission factors taken from Table 4. The volatiles were made up primarily of methane and ethylene, reaching a level of 1.9 g/kg of wood consumed for the lowest burn rates using the cordwood fuel. The volatile emission factors decreased with increased burn rate. Very low volatile emission factors resulted when small wood fuel charges were used in sustaining the high burn rates.

A summary of polynuclear aromatic hydrocarbons (PAH) for wood heater #1 are shown in Tables 6 and 7. The total PAH emission factor is shown for each test as well as the amounts of each specific class of PAH making up the total. The naphthalene/methynaphthalenes/phenylnaphthalenes represented approximately 50 percent of the total PAH emissions for all tests on wood heater #1. Phenanthrene/anthracene was the second largest specie in the total PAH emissions. The benzo(a)pyrene component of the total

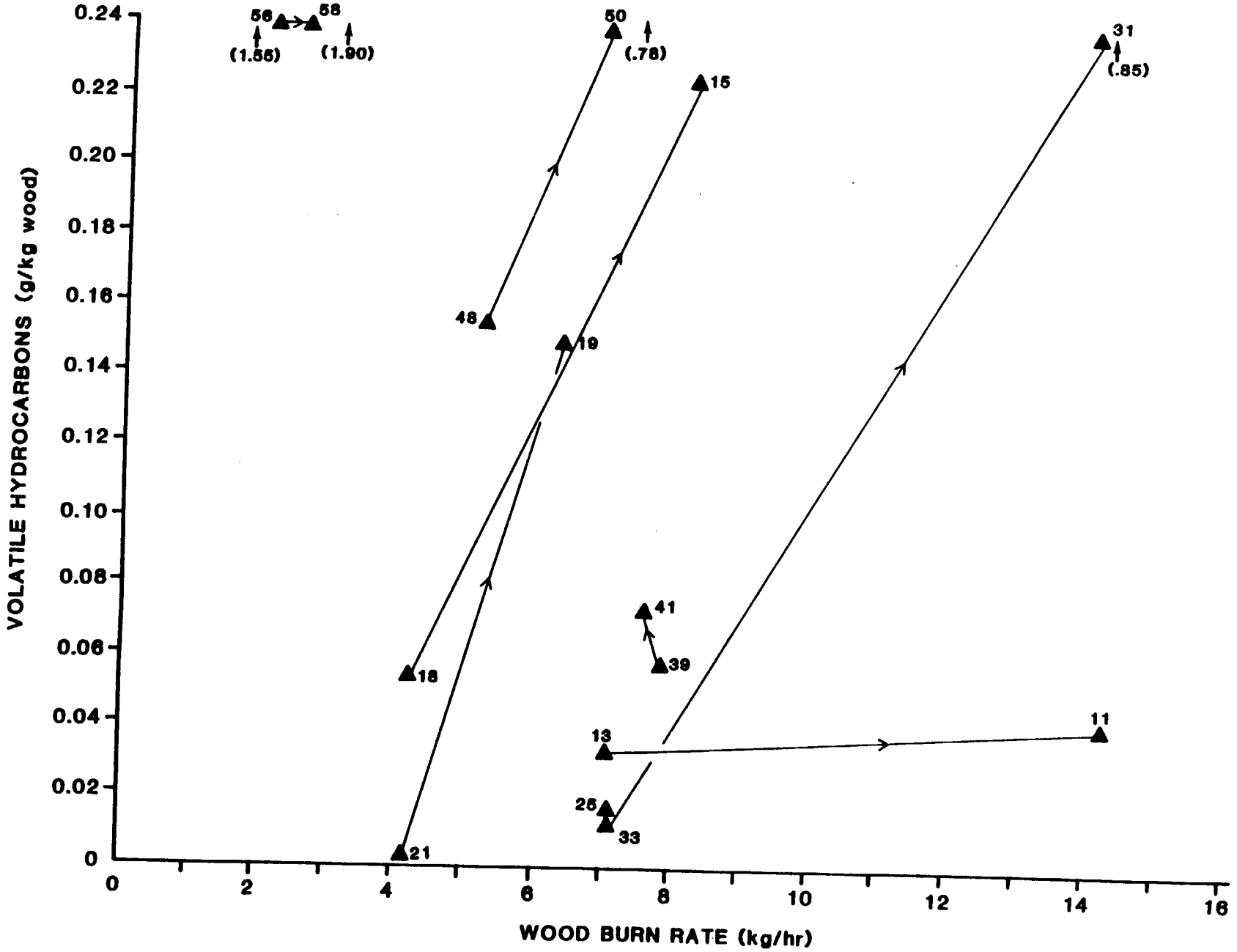


Figure 16. Effect of Wood Burn Rate on Volatile Hydrocarbon Emissions-Wood Heater # 1

Table 6. WOOD HEATER #1
PAH EMISSION FACTORS (g/kg) - 2x4 OAK BRANDS

	Test Number					
	19	21	15	18	11	13
Naphthalene/Methylnaphthalenes/ Phenylnaphthalenes	0.0630	0.0070	0.1590	0.0054	0.0230	0.0109
Acenaphthylene	0.0109	0.0012	0.0310	0.0005	0.0056	0.0024
Acenaphthene	———	———	0.0052	———	0.0005	———
Fluorene	0.0053	0.0005	0.0171	———	———	———
Phenanthrene/Anthracene	0.0265	0.0021	0.0743	0.0017	0.0100	0.0040
Fluoranthene	0.0036	0.0005	0.0138	0.0005	0.0014	0.0009
Pyrene	0.0032	0.0005	0.0148	0.0005	0.0013	0.0009
Benzo (g,h,i) fluoranthene	0.0028	0.0005	0.0200	———	0.0011	———
Chrysene/Benzo (a) anthracene	0.0034	0.0005	0.0214	———	0.0014	0.0009
Benzo (b) fluoranthene/ benzo (k) fluoranthene	0.0007	0.0005	0.0090	———	0.0046	———
Benzo (a) pyrene	0.0007	———	0.0105	———	0.0046	———
Indeno (1,2,3-c,d) pyrene/ Benzo (g,h,i) perylene	———	———	0.0100	———	———	———
Dibenzo (a,h) anthracene	———	———	0.0025	———	———	———
Total	0.1201	0.0625	0.3886	0.0086	0.0535	0.0200

Table 7. WOOD HEATER #1
PAH EMISSION FACTORS (g/kg) - OAK CORDWOOD

	Test Number								
	31	33	39	41	48	50	56	58	25
Naphthalene/Methylnaphthalenes/ Phenylnaphthalenes	0.7860	0.0067	0.0040	0.0097	0.0245	0.2040	0.2920	0.2370	0.0094
Acenaphthylene	0.1493	0.0005	0.0007	0.0029	0.0037	0.0302	0.0761	0.0525	0.0014
Acenaphthene	0.0173	———	———	0.0003	0.0004	0.0062	0.0227	0.0212	———
Fluorene	0.0314	0.0005	0.0007	0.0003	0.0012	0.0138	0.0243	0.0175	———
Phenanthrene/Anthracene	0.2279	0.0020	0.0007	0.0038	0.0123	0.0788	0.0961	0.0762	0.0014
Fluoranthene	0.0362	0.0005	0.0007	0.0008	0.0021	0.0144	0.0146	0.0097	0.0014
Pyrene	0.0330	0.0005	0.0007	0.0003	0.0017	0.0184	0.0156	0.0100	0.0014
Benzo (g,h,i) fluoranthene	0.0865	———	———	0.0008	0.0014	0.0144	0.0123	0.0077	———
Chrysene/Benzo (a) anthracene	0.0755	0.0005	———	0.0003	0.0020	0.0184	0.0170	0.0115	———
Benzo (b) fluoranthene/ benzo (k) fluoranthene	0.0346	———	———	0.0003	0.0004	0.0060	0.0044	0.0031	———
Benzo (a) pyrene	0.0346	———	———	0.0003	0.0004	0.0050	0.0037	0.0031	———
Indeno (1,2,3-c,d) pyrene/ Benzo (g,h,i) perylene	0.0464	———	———	———	———	0.0079	———	———	———
Dibenzo (a,h) anthracene	0.0110	———	———	———	———	0.0024	———	———	———
Total	1.5697	0.0112	0.0075	0.0198	0.0501	0.4199	0.5788	0.4495	0.0100

PAH was lower than 2.5 percent in all tests. Table 6 presents PAH emissions for 2-inch by 4-inch oak brands while Table 7 is associated with split red oak cordwood. The PAH results for the oak cordwood tests were generally higher. This is due to the fact that the oak cordwood tests were generally conducted at lower burn rates. The importance of burn rate on PAH emissions will be demonstrated later. The oak brand tests will not be discussed in detail since such a fuel is not typically used by the consumer. The oak brand tests were used to develop and validate the testing procedure. Results for both fuels will be shown in some figures to give more supportive evidence to PAH trends that have been noted.

Figure 17 presents PAH emission factors versus wood burn rate for wood heater #1. In Figure 17 the tests using small wood load charges are connected to tests using large charges with each test having a fixed damper setting. Therefore, tests 56 and 58 were run at the same damper setting but with wood load size changing from 7.8 to 19.3 pounds. At the lower burn rates associated with the closed damper, the PAH emissions dropped with use of the larger wood load charges. With the intermediate burn rates, the PAH trend changed with PAH emissions increasing with increased wood load size. Yet, the PAH emission factors for tests 48 and 50 were lower than those found for low burn rate tests 56 and 58. Tests 39 and 41 were conducted with the same fuel loading as 48 and 50 but with a fully open damper. The PAH emission factor dropped dramatically for the open damper tests; yet, the PAH emissions were again higher for the larger wood loading tests.

Through the six tests mentioned earlier, the conventional procedure for conducting each test was followed. This consisted of performing tests

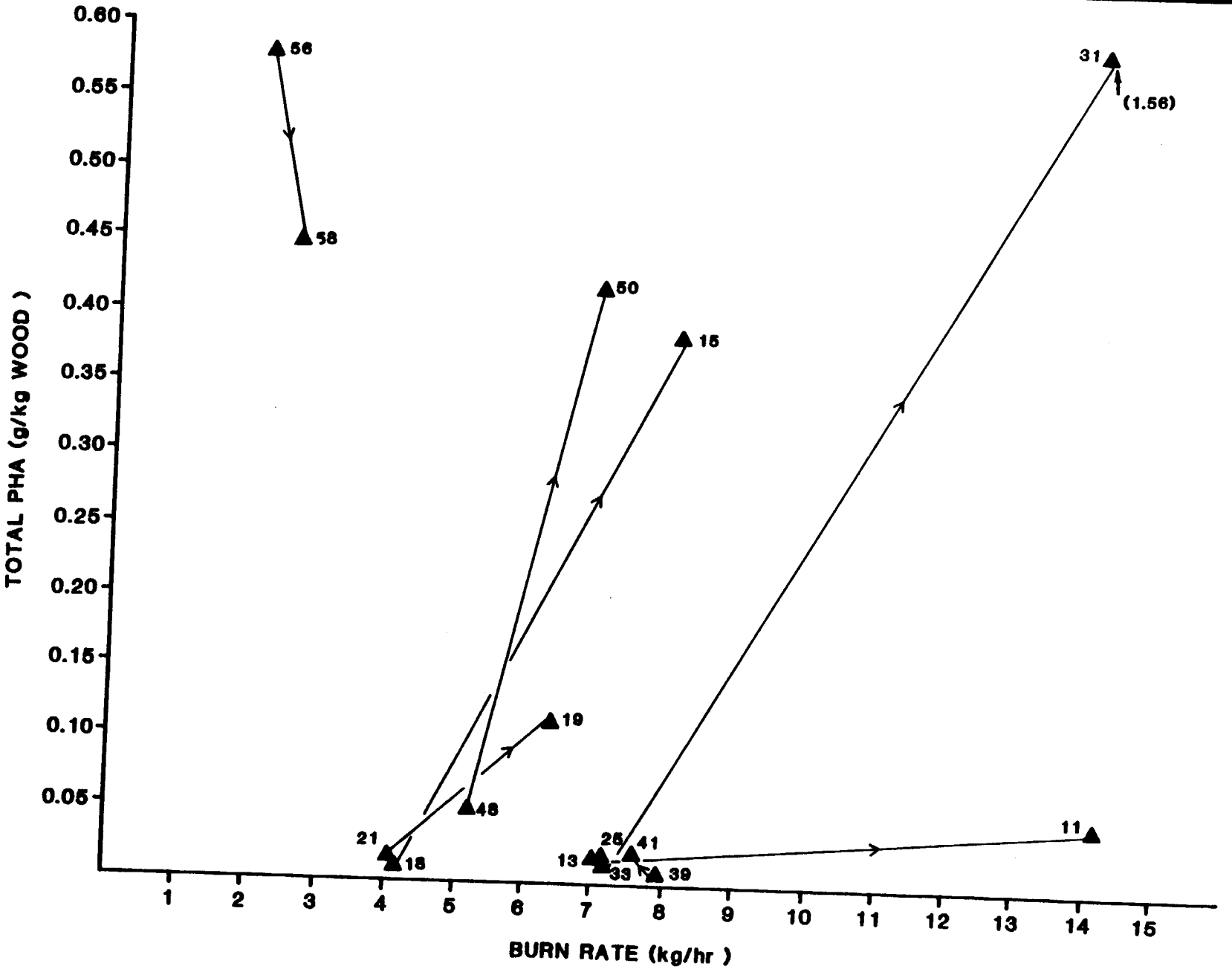


Figure 17. Effect of Burn Rate on PAH Emissions–Wood Heater # 1

with progressively larger wood loadings being burned while the damper position was fixed. Tests 33 and 31 were run in the reverse order as the larger wood loads were run first with smaller loads following. This reverse firing procedure provided greatly different PAH emissions when tests 39 and 41 were compared with 33 and 31. The larger wood loading in test 31 produced very high PAH emissions and a burn rate of over 14 kg/hr while the PAH emissions for the small wood loading of test 33 remained near those for tests 39 and 41. This showed that the preconditioning of the wood heater seriously affected the PAH emissions performance if large fuel loads were burned. The data also pointed out the adverse sensitivity of the wood heater's PAH emissions performance related to wood load size and preconditioning if high burn rates were sustained to obtain high heat outputs. The small wood fuel loadings reduced PAH emission factors at all but the lowest burn rates. For typical overnight firing at the closed damper position, wood heater #1 should be fueled by the larger wood fuel loadings. This is a rewarding result as currently most homeowners operate their heater in this mode for long periods of time.

Paired tests 18-15, 21-19, and 13-11 for the oak brand fuel showed the same dependency of emissions on size of wood fuel loading. The inverse dependency of low burn rate on the size of oak brand wood loading was not found as no low burn rate oak brand tests were conducted. The oak brand tests did not show the same degree of dependency on PAH emissions since the prefabricated, crossed lattice structure of a brand prevented close compaction of the fuel.

The same test results for PAH are plotted versus average excess air in Figure 18. The results show that the PAH emissions were minimized by

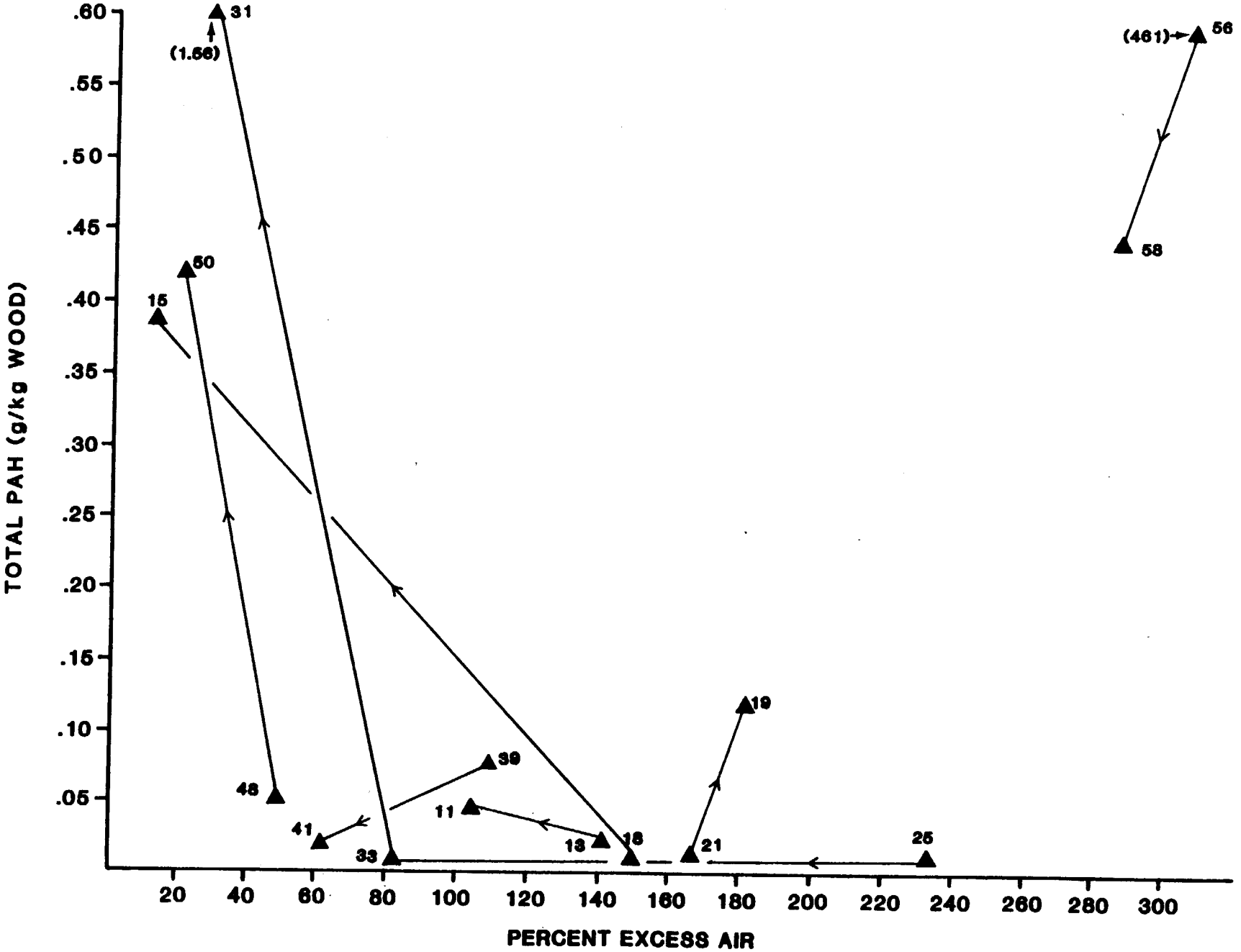


Figure 18. Effect of Percent Excess Air on PAH Emissions– Wood Heater # 1

operating the wood heater with excess air values between 100 to 200 percent. Tests 56 and 58 were low burn rate tests and operated with higher excess air values and increased PAH emission factors. The higher burn rate tests with low excess air showed also higher PAH emissions when the large fuel loading were fired.

Figure 19 presents the PAH emission factors for each test versus wood charge size. PAH emission factors increased dramatically with wood load size except for the one very low burn sequence of tests (56 and 58).

The PAH emission factor versus exit temperature are presented in Figure 20. The PAH emissions were generally inversely related to the exit temperature of the flue gases. Yet, within a sequence of tests like 48 and 50, very little PAH dependence was associated with the exit temperature since both tests had essentially the same exit temperature but greatly different PAH emission factors.

Table 8 presents the emission factors for compounds other than PAH that are associated with the integrated sample recovered by the modified Method 5 sampling system. The table also presents the volatile hydrocarbon emission factors for each test. Several volatile samples were analyzed to determine the major constituents. Methane was found to be the largest component with ethylene the second largest.

The total particulates for wood heater #1 are presented in Figure 21. The cordwood sequence of tests (56-58, 48-50, and 39-41) showed that the total particulates increased significantly with decreased burn rate. The oak brand tests showed that the use of much smaller fueling pieces did not change the total particulate emission factor for medium and high burn rates. The influence of the brand fuel on total particulates at low burn rates was not determined as no low burn rate tests were conducted

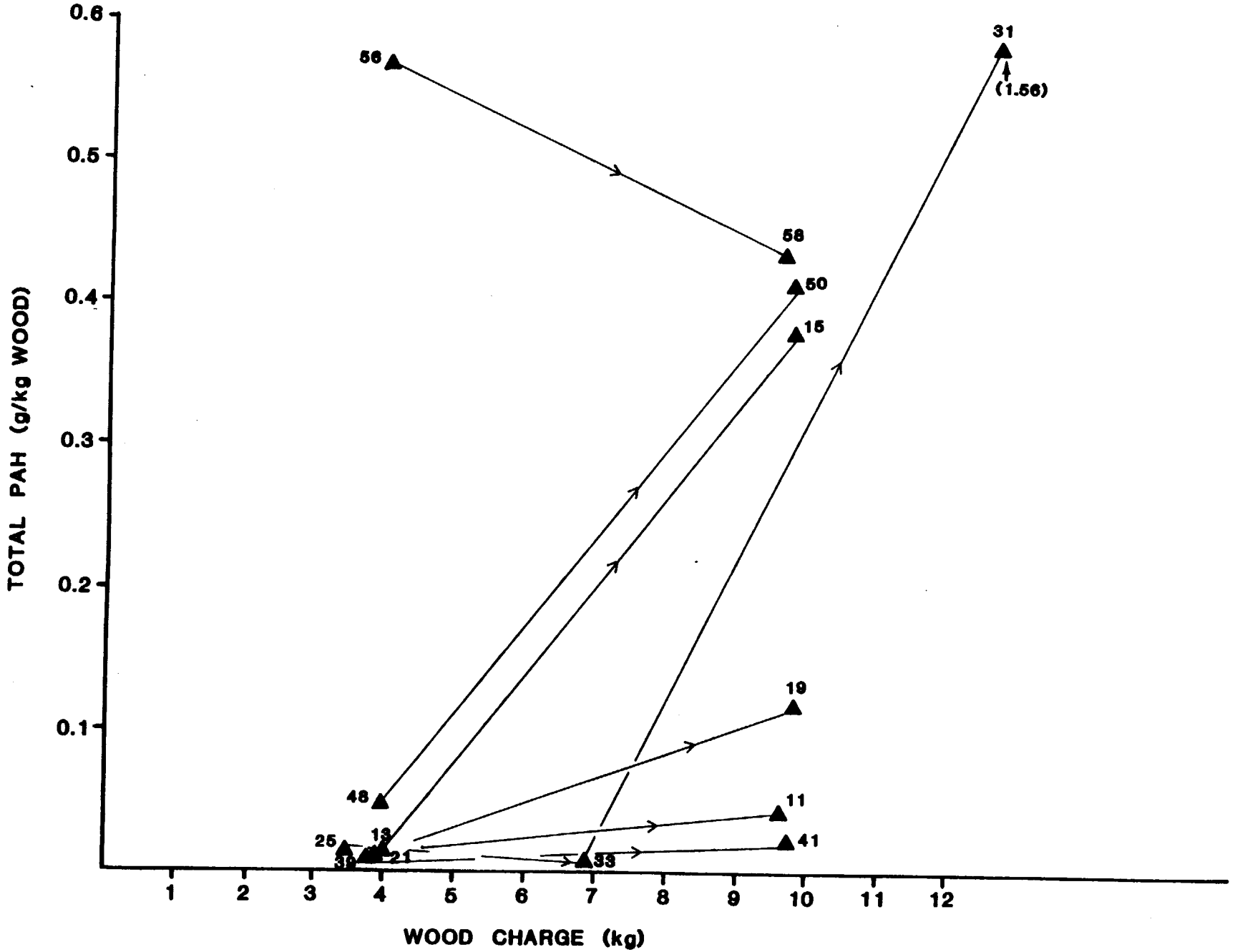


Figure 19. Effect of Wood Charge on PAH Emissions–Wood Heater # 1

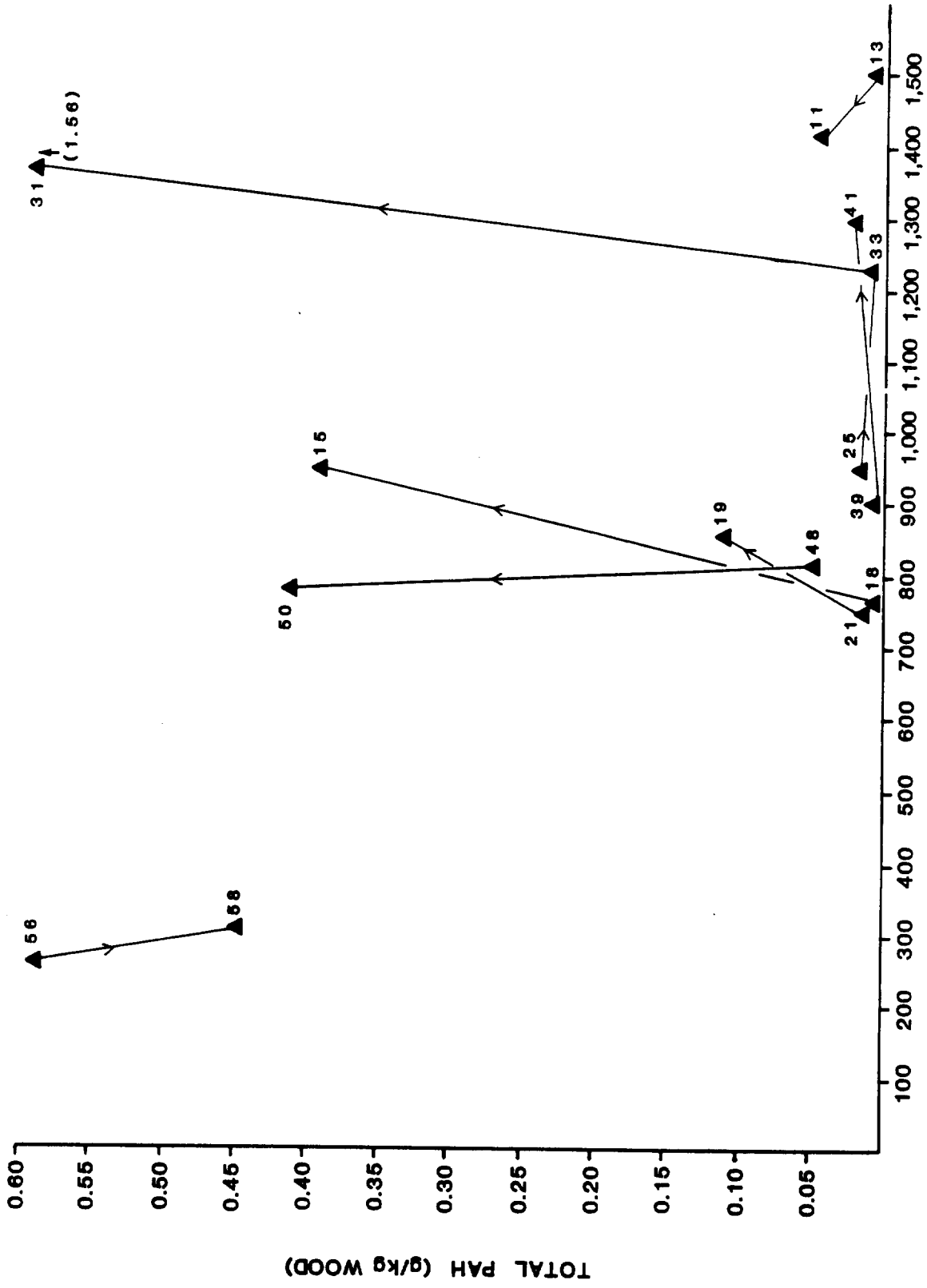


Figure 20. Effect of Stove Exit Temperature on PAH Emissions–Wood Heater #1

Table 8. WOOD HEATER #1
EMISSION FACTORS FOR COMPOUNDS OTHER THAN PAH (g/kg)

	Test Number							
	19	21	15	18	11	13	31	33
Filterable Particulate[a]	0.7756	1.1700	0.6439	0.7834	1.230	1.180	2.8739	0.4533
Front half Gravimetric[b]	0.1801	0.6234	0.1551	0.5508	0.0274	0.1509	0.4066	0.1203
Back half Gravimetric[c]	4.0719	0.3069	1.2267	1.040	0.1521	0.6791	4.9579	0.8510
Back half TCO[d]	0.831	1.439	0.9400	9.1800	0.553	0.1372	2.9716	0.0925
Total Condensible Organics[e]	4.9029	1.7454	2.1667	10.2200	0.7051	0.8163	7.9295	1.3968
Total Particulates[f]	5.6785	2.9154	2.8106	11.0034	1.935	1.9963	10.8034	0.013
Volatile Hydrocarbons (g/kg)	0.150	0.004	0.225	0.054	0.042	0.035	0.848	0.004
major constituents								
Methane (vol.%)	47	—	48	—	—	—	51	—
Ethylene (vol.%)	42	—	37	—	—	—	42	—

Note: f = a + e
e = c + d

Table 8. WOOD HEATER #1 (CONT'D)
EMISSION FACTORS FOR COMPOUNDS OTHER THAN PAH (g/kg)

	Test Number						
	39	41	48	50	56	58	25
Filterable Particulate[a]	0.7186	0.2291	0.6138	1.3398	8.9487	3.8775	3.0491
Front half Gravimetric[b]	0.2377	0.0866	0.5284	0.2772	2.9340	0.7837	0.9136
Back half Gravimetric[c]	0.6850	0.8991	2.5330	8.1972	66.0802	54.4001	3.4546
Back half TCO[d]	0.0489	0.2797	0.8547	5.2800	26.0800	26.1240	*
Total Condensible Organics[e]	0.7339	1.1788	3.3877	13.4772	92.1602	80.5241	*
Total Particulates[f]	1.4525	1.4079	4.0015	14.8170	101.1089	84.4016	*
Volatile Hydrocarbons (g/kg)	0.059	0.074	0.156	0.784	1.550	1.902	0.017
major constituents							
Methane (vol.%)	—	—	32	47	39	39	—
Ethylene (vol.%)	—	—	25	36	16	16	—

Note: f = a + e
e = c + d
* Data lost in laboratory

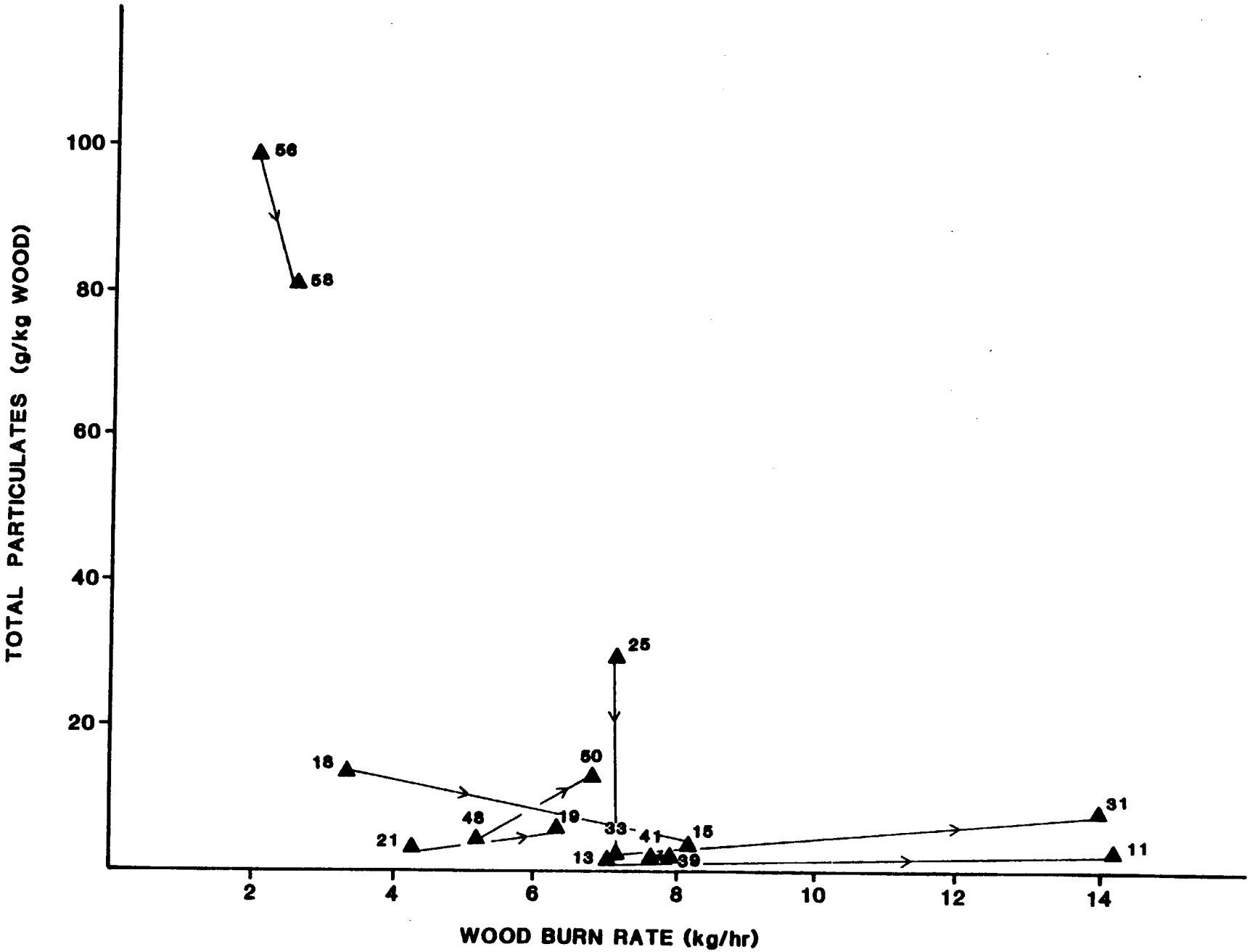


Figure 21. Effect of Burn Rate on Total Particulate Emissions–Wood Heater # 1

using the oak brands. The use of small fuel loadings at the medium and high burn rates generated lower total particulates while at the lowest burn rates the larger fuel loadings showed reduced total particulates.

Filterable particulate emission factors versus burn rate are presented in Figure 22. All filterable particulate emission factors were less than 2 g/kg except for the low burn rate test 56.

The ratio of condensible to filterable particulates is presented in Figure 23. Larger fuel loadings provided much greater recovery of the condensibles at the lower burn rates.

Wood Heater #2

Table 9 presents a series of key diagnostic conditions for wood heater #2. Averages for before the catalyst and at the exit of the wood heater are presented. The data shown in the table are presented in figure form and discussed later in the Wood Heater #2 Results section.

Table 10 presents results obtained through the thermodynamic modeling of wood heater #2. Continuous sampling of combustion gases before the catalyst and at the exit of the wood heater provided the detail gas compositions required to perform such modeling. Tests A, AA, B, and BB at the bottom of the table are special in that they show how the catalytic wood heater performed when the catalytic combustor's effect had been removed by using a noncoated ceramic base (A and AA) or by completely removing the catalyst and the base from the wood heater (B and BB).

A complete summary of emission factors for wood heater #2 is presented in Table 11. All tests have continuous analyzer emission factors for CO, NO_x, and FID total hydrocarbons while integrated samples were recovered on designated tests for use in generating the organic emission

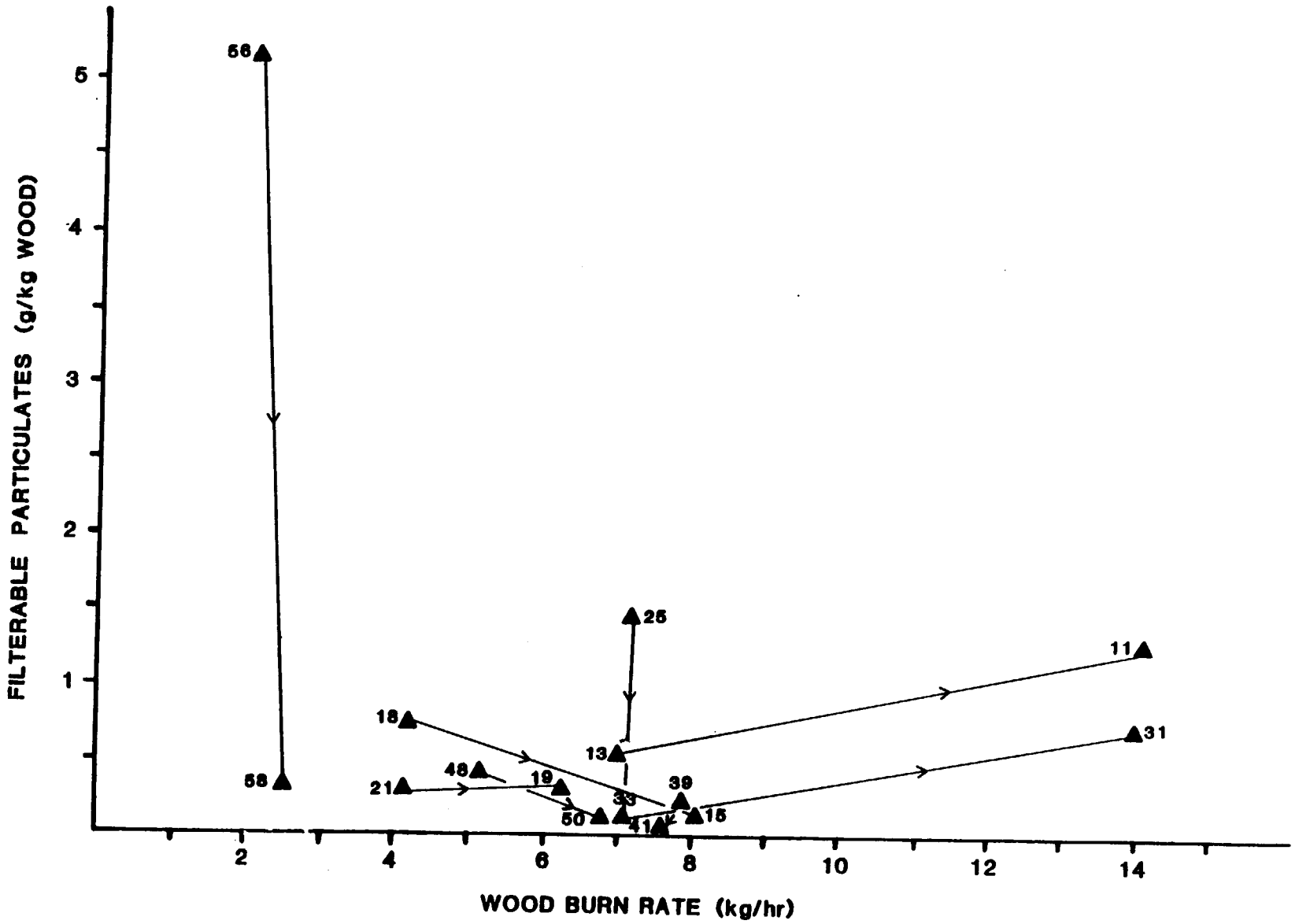


Figure 22. Effect of Burn Rate on Filterable Particulate Emissions– Wood Heater #1

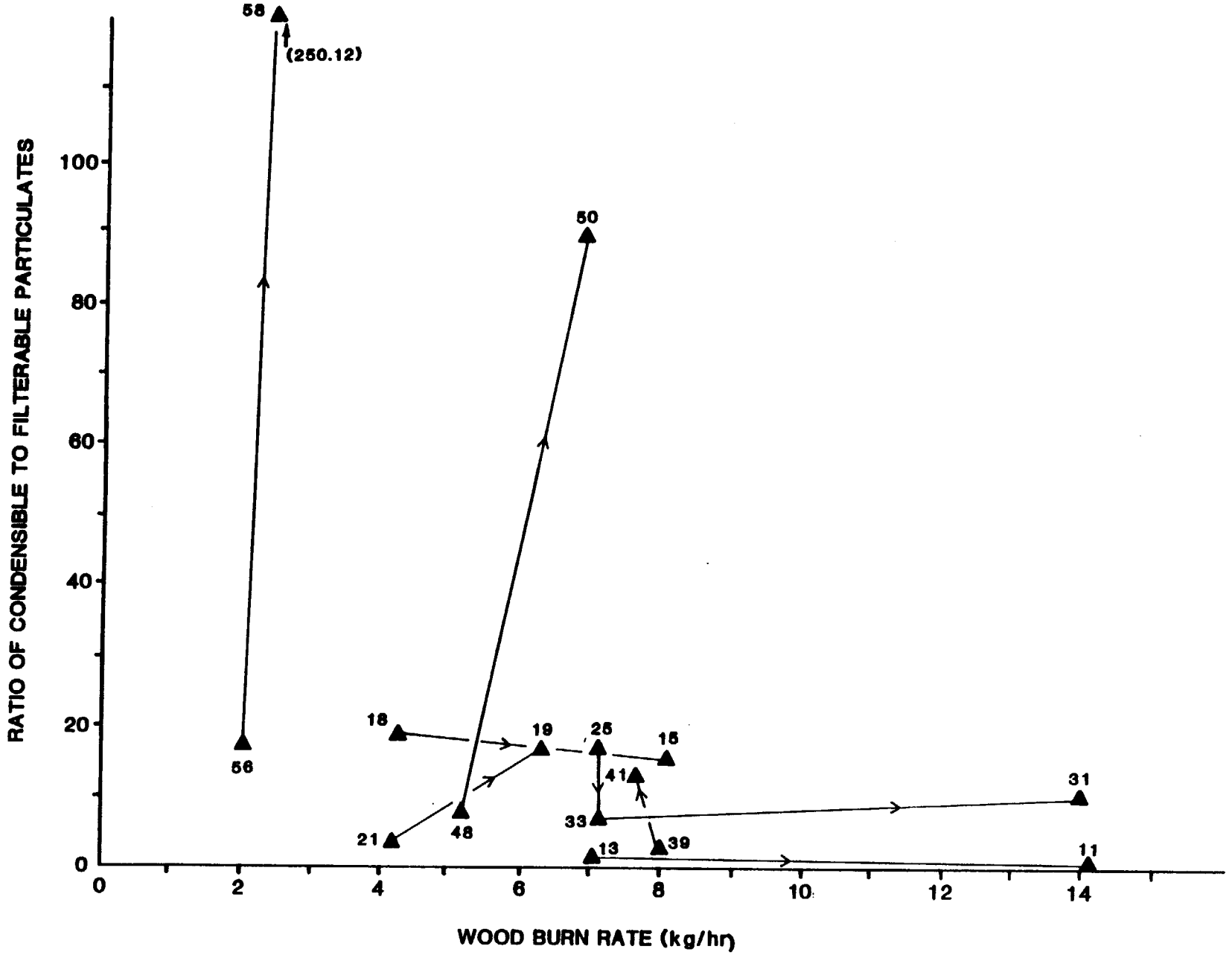


Figure 23. Effect of Burn Rate on the Ratio of Condensible to Filterable Particulates-Wood Heater #1

Table 9. WOOD HEATER #2
AVERAGE CATALYTIC TEST RESULTS - THERMAL - RED OAK CORDWOOD

Test	Wood Charge (lb)	Wood Burn Rate (lb/hr)	Damper Position	Air Supply (CFM)	Temp Flue Gas (°F)	Before Catalyst		Heat Output (Btuh)	Temp Flue Gas (°F)	Exit of Wood Heater		Heat Output (Btuh)
						Excess Air(%)	Thermal Efficiency			Excess Air(%)	Thermal Efficiency	
63	4.8	5.9	E (open)	10.6	979	97	53.5	24,610	488	84	75.3	33,694
64	8.2	5.9	E	11.7	1,014	115	49.7	21,060	511	103	72.4	31,864
65	11.6	6.7	E	10.0	1,112	87	45.2	22,187	560	64	69.4	34,474
71	15.3	8.9	E	12.5	1,241	38	44.9	32,732	648	32	66.7	45,842
61	4.7	6.4	D	10.6	954	74	55.1	26,587	462	71	76.7	36,443
62	8.2	6.3	D	9.4	1,047	64	49.3	21,649	532	46	71.9	33,781
66	11.6	7.0	D	11.3	1,138	49	45.3	25,284	543	31	66.7	34,595
67	15.2	7.2	D	9.5	1,168	39	45.4	25,542	579	30	66.5	35,630
68	4.7	3.8	C	8.3	790	108	59.6	17,491	386	109	77.9	24,920
69	8.2	4.4	C	9.6	835	102	53.5	18,152	410	85	75.0	24,745
70	11.6	4.8	C	9.4	904	82	47.6	17,525	422	63	70.3	25,987
72	15.3	7.3	C	10.0	1,096	31	47.6	26,666	516	23	65.8	37,833
77	4.7	3.0	B	6.9	599	123	52.7	12,051	282	129	71.9	15,939
78	8.2	2.1	B	5.4	585	137	47.0	7,731	274	137	66.6	10,802

Table 9. WOOD HEATER #2 (CONT'D)
AVERAGE CATALYTIC TEST RESULTS - THERMAL - RED OAK CORDWOOD

Test	Wood Charge (lb)	Wood Burn Rate (lb/hr)	Damper Position	Air Supply (CFM)	Temp Flue Gas (°F)	Before Catalyst		Heat Output (Btuh)	Temp Flue Gas (°F)	Exit of Wood Heater		Heat Output (Btuh)
						Excess Air(%)	Thermal Efficiency			Excess Air(%)	Thermal Efficiency	
73	4.7	2.7	A	5.6	193	98	53.5	11,204	249	93	76.8	14,940
74	8.2	2.5	A	4.4	686	65	56.4	10,981	276	92	76.8	14,787
75	11.6	2.9	A	4.6	759	50	46.9	10,382	278	87	72.9	16,247
76	15.3	3.0	A	5.2	730	71	49.7	11,568	275	79	71.9	16,586
A*	11.6	8.4	E	14.8	1,155	47	50.3	32,572	576	55	69.8	43,871
AA*	11.6	6.4	B	14.6	869	119	57.0	28,249	509	133	70.5	34,135
B**	11.4	3.7	B	17.8	563	224	32.6	9,382	317	155	52.8	14,484
BB**	10.4	4.1	B	22.9	651	208	31.2	9,895	371	265	54.3	17,523

*Ceramic cell foundation only, without catalyst plating
**Without ceramic cell (i.e., an empty hole)

Table 10.
AVERAGE DIAGNOSTIC CONDITIONS FOR CATALYTIC WOOD HEATER #2

Test	Before Catalyst (%)					Exit of Wood Heater (%)				
	Thermal Efficiency	Combustion Efficiency	Heat Tra. Efficiency	Sensible & Lat. Losses	Chemical Losses	Thermal Efficiency	Combustion Efficiency	Heat Tra. Efficiency	Sensible & Lat. Losses	Chemical Losses
63	53.5	93.0	57.5	39.6	6.9	75.3	96.6	77.9	21.3	3.4
64	49.7	93.6	53.1	43.9	6.4	72.4	95.6	75.8	23.2	4.4
65	45.2	87.5	51.6	42.4	12.5	69.3	91.3	76.0	21.9	8.8
71	44.9	83.2	54.0	38.3	16.8	66.7	88.0	75.8	21.3	12.0
61	55.1	90.9	60.6	35.8	9.1	76.7	96.2	79.8	19.5	3.8
62	49.3	85.9	57.4	36.7	14.0	71.9	91.9	78.2	20.0	8.1
66	45.3	82.2	55.1	35.9	17.8	66.7	85.6	78.0	18.8	14.4
67	45.4	82.0	55.3	36.7	18.0	66.4	86.3	77.1	19.8	13.7
68	59.6	93.2	64.0	33.6	6.8	77.9	96.2	80.9	18.3	3.8
69	53.5	86.7	61.7	33.2	13.3	75.0	92.8	80.9	17.7	7.3
70	47.6	79.5	60.0	31.8	20.6	70.3	86.7	81.1	16.4	13.3
72	47.6	80.2	59.4	32.6	19.8	65.8	82.5	79.7	16.8	17.5
77	52.7	78.4	67.3	25.7	21.6	71.9	86.3	83.3	14.4	13.7
78	47.0	72.9	64.5	25.9	27.1	66.6	80.3	83.0	13.7	19.7
73	53.5	79.4	67.4	25.9	20.6	76.8	89.2	86.2	12.3	10.9

Table 10. (CONT'D)
AVERAGE DIAGNOSTIC CONDITIONS FOR CATALYTIC WOOD HEATER #2

	Before Catalyst (%)					Exit of Wood Heater (%)				
Test	Thermal Efficiency	Combustion Efficiency	Heat Tra. Efficiency	Sensible & Lat. Losses	Chemical Losses	Thermal Efficiency	Combustion Efficiency	Heat Tra. Efficiency	Sensible & Lat. Losses	Chemical Losses
74	56.4	81.1	69.5	24.7	18.9	76.8	90.1	85.2	13.3	9.9
75	46.9	71.4	65.7	24.5	28.7	72.9	85.7	85.1	12.8	14.3
76	49.7	75.5	65.9	25.8	24.5	71.9	84.3	85.3	12.4	15.7
A*	50.3	90.1	55.9	39.8	10.0	69.8	92.2	75.7	22.5	7.8
AA*	57.0	95.0	60.0	38.0	5.0	70.5	94.8	74.3	24.3	5.2
B**	32.6	70.8	46.0	38.2	29.2	52.8	71.2	74.2	18.4	28.8
BB**	31.2	81.8	38.1	50.6	18.2	54.3	82.4	65.9	28.1	17.6

*Ceramic cell foundation only, without catalyst plating
**Without ceramic cell (i.e., an empty hole)

Table 11. WOOD HEATER #2
AVERAGE CATALYTIC TEST RESULTS - EMISSIONS (g/kg) - RED OAK CORDWOOD

				Exit of Wood Heater					Before Catalyst		
Test	CO	Total Hydrocarbons	NO_x	Filterable Particulates	Condensible Organics	Total Particulates	Volatile Hydrocarbons	Polynuclear Aromatic Hydrocarbons	CO	Total Hydrocarbons	NO_x
63	6	8	0.76	0.45	0.73	1.18	0.03	0.03	20	17	0.65
64	4	11	1.06						16	16	0.94
65	23	23	0.81	1.10	1.11	2.21	0.08	0.06	37	32	0.79
71	74	26	0.71						80	41	0.76
61	8	9	1.00						26	28	0.83
62	38	18	0.68						56	38	0.59
66	68	34	0.47						73	43	0.51
67	70	31	0.59						77	43	0.60
68	3	10	1.02	0.45	1.21	1.66	0.07	0.01	27	15	0.82
69	11	21	0.91						44	34	0.73
70	50	34	0.88	0.43	6.06	6.49	0.20	0.13	81	53	0.69
72	102	39	0.44						100	47	0.45
77	23	39	0.94						71	56	0.64
78	31	57	0.86						83	72	0.41

Table 11. WOOD HEATER #2 (CONT'D)
AVERAGE CATALYTIC TEST RESULTS - EMISSIONS (g/kg) - RED OAK CORDWOOD

Test	CO	Total Hydrocarbons	NO_x	Exit of Wood Heater			Volatile Hydrocarbons	Polynuclear Aromatic Hydrocarbons	Before Catalyst		
				Filterable Particulates	Condensible Organics	Total Particulates			CO	Total Hydrocarbons	NO_x
73	26	30	0.85	0.42	4.59	5.01	0.18	0.23	97	48	0.56
74	25	27	0.85						101	43	0.49
75	27	41	0.03	0.34	6.90	7.24	0.01	0.02	93	78	0.02
76	44	42	0.77						118	57	0.30
A*	41	17	0.73						44	25	0.80
AA*	23	11	0.93						21	11	0.97
B**	99	84	0.72						97	84	0.68
BB**	102	41	1.06						104	43	1.05

*Ceramic cell foundation only, without catalyst plating
**Without ceramic cell (i.e., an empty hole)

factors. The activity of the catalytic combustor is revealed when comparing emission factors determined from samples taken before and after the catalyst. No integrated samples were recovered before the catalyst.

Wood Heater #2: Efficiencies

Figure 24 presents results taken from Table 11. Catalytic wood heater #2 operated with thermal efficiencies near 77 percent--independent of the wood burn rate when fueled by small wood loads. Its thermal efficiency decreased with increasing burn rate as larger wood loads were consumed and the air control damper was progressively opened. As would be expected, the damper positions more nearly closed (A) provided lower burn rates than those associated with fully open (E). Four special tests were conducted to determine the thermal efficiency of wood heater #2 when the catalytic combustor was inoperative or totally removed. Tests "A" and "AA" represent tests conducted with an uncatalyzed (uncoated) Corning ceramic combustor used in place of the Corning catalytic combustor provided with the wood heater. The thermal efficiency for these two special tests showed no significant difference from conventional tests conducted with the same wood load and damper position. The special tests burned the same 5.3 kg wood load with the air controls being set fully open for test "A" and nearly closed for test "AA."

Table 10 shows that test "A" and its counterpart in wood load and damper setting, test 65, had approximately the same combustion and heat transfer efficiencies as well as sensible and chemical losses even though the burn rate changed from 3.1 to 3.7 kg/hr. During test 65 the unshielded thermocouple located in the central cell area of the catalyst typically showed temperatures 300°F higher than that measured immediately prior to the cell entry. No increase in temperature was found in the central cell

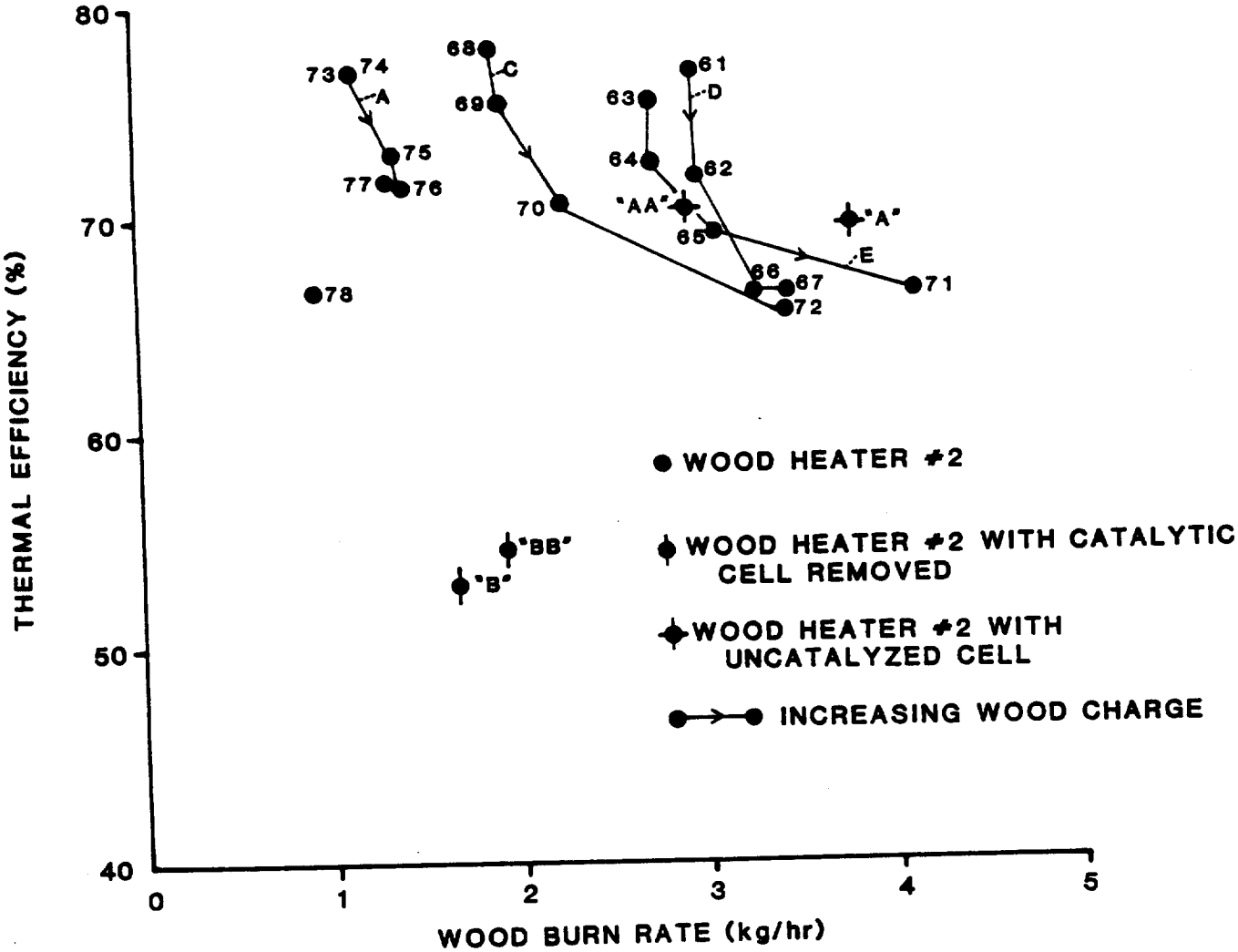


Figure 24. Thermal Efficiency Versus Burn Rate - Wood Heater#2

area for test "A" when an uncatalyzed cell was used. Therefore, test "A" provided lower flue gas temperatures exiting the wood heater and hence less position draft associated with stack height.

Friction head losses associated with flow through the catalytic cell passages were directly related to the kinematic viscosity of the flow. Therefore, the head losses associated with flow through the cell passages dropped as the combustor temperature dropped since viscosity and temperature are directly related. The loss of catalysis serves to increase the net draft in the combustion zone since the loss of stack draft was more than matched by lower flow losses in the catalytic combustor.

Tests "B" and "BB" were conducted with the catalytic combustor totally removed from the wood heater. Figure 24 shows that the thermal efficiency dropped for both tests. Table 10 shows that the combustion and heat transfer efficiencies dropped significantly from levels associated with tests using the ceramic combustor, either catalyzed or uncatalyzed. The sensible and chemical losses associated with reduced combustion and heat transfer efficiencies was shown to increase also. When the wood heater was operated without the cell "in place" the thermal efficiency was similar to a conventional airtight with restricted combustion air supply.

The combustion efficiencies for wood heater #2 are shown in Figure 25. The combustion efficiencies were reduced as the wood load size was increased for each damper setting.

Combustion efficiencies for tests "A" and "AA" using the uncatalyzed ceramic combustor were similar to those obtained using a catalyzed combustor. The friction losses in the combustor, combined with the draft associated with the stack height noted previously, provided for higher primary combustion temperatures in test "A" than in test 65. This increased thermal

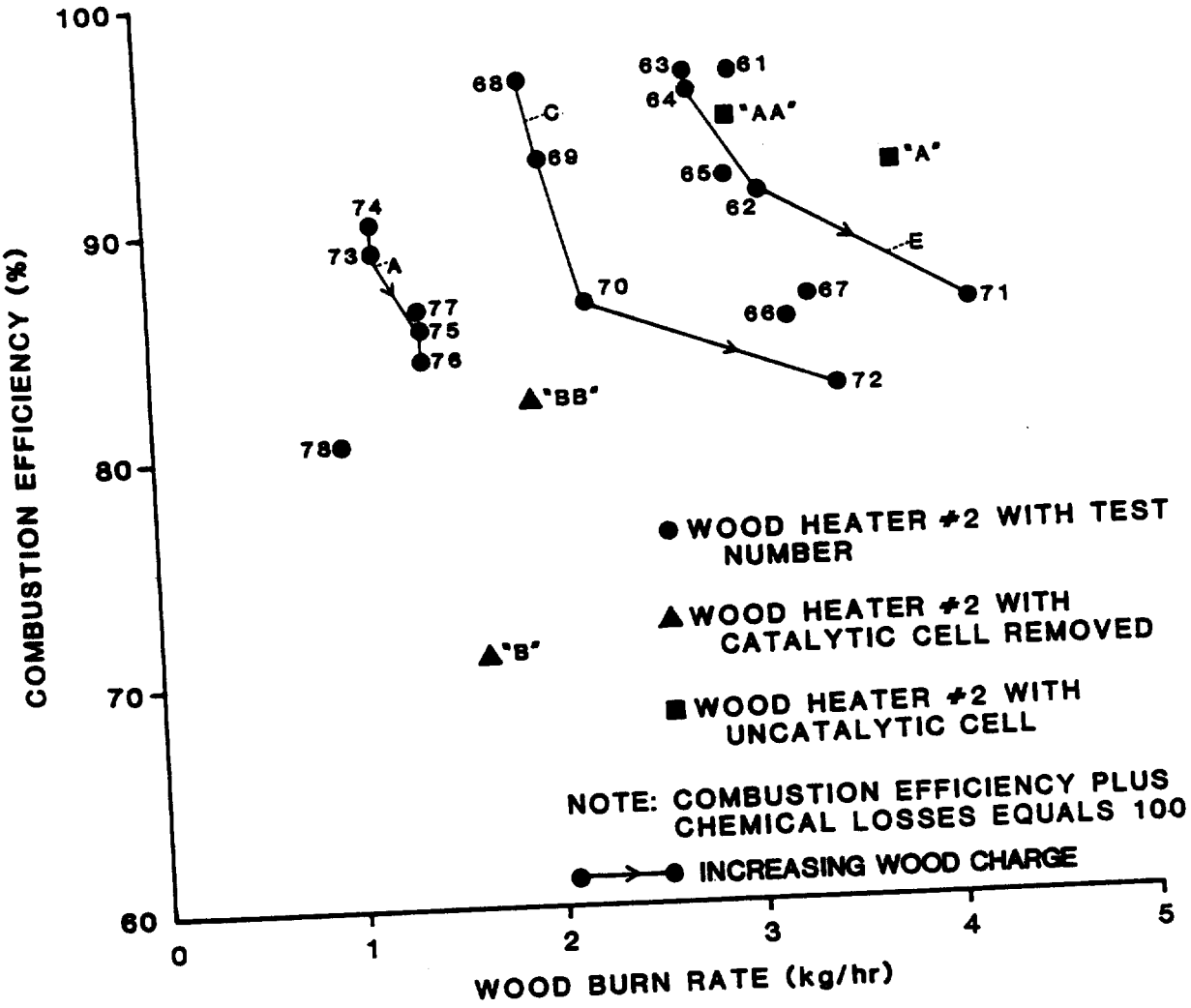


Figure 25. Summary–Combustion Efficiency Versus Burn Rate – Wood Heater #2

activity provided improved primary combustion conditions with fewer products of incomplete combustion leaving the wood heater.

In test 65 similar high combustion efficiencies were found. In this case, however, they resulted directly from activity associated with the catalytic combustor. The high combustion efficiencies were obtained by sustaining high burn rates and/or by using a catalyzed combustor. Either high burn rates or catalysis will increase the thermal energy and produce a corresponding decrease in chemical losses.

Tests "B" and "BB" with the catalytic combustor totally removed from the wood heater show lower combustion efficiencies than obtained from any other test on wood heater #2. Combustion efficiencies less than 80 percent as found for test "B" are commonly associated with low burn rate tests for conventional airtight appliances (like wood heater #1, Table 3). The four tests (73, 74, 75, and 76) conducted at damper position A (not to be confused with test "A") which was one-half turn on both air screws had burn rates lower than those found for special tests "B" and "BB." Yet, their combustion efficiencies were much higher due to observed catalytic activity. The flue gases typically entered the catalytic combustor at about 450°F throughout these tests with a temperature of nearly 675°F being measured within a catalytic central cell passage. Overall, the catalytic combustor in wood heater #2 provided a means whereby the wood heater, unlike most conventional airtight wood heaters, could operate with high combustion efficiencies even at low burn rates.

Studies by Corning Glass Works (17) have found that the noble metal catalytic combustors reduce ignition temperature of typical flue gases so that they start burning around 440°F. The heat released by this burning process increases the temperature of the catalyst which in turn

increases its catalytic activity. Ideally, the catalyst temperature increases until an equilibrium exists between incoming flue gas temperature, flow rate and the amount of energy released through oxidation of CO and organics in the flue gases. Hence, the air supply screws on wood heater #2 could not be closed beyond about one-half open turn and still maintain flue gas temperatures adequate for supporting catalytic reaction.

The heat transfer efficiencies for wood heater #2 are shown in Figure 26. The heat transfer efficiencies were basically independent of wood load while being inversely related to the air supply setting. The highest heat transfer efficiencies existed for tests using the lowest air supply settings where secondary retention time for flue gas cooling was maximized. Special tests "B" and "BB" had heat transfer efficiencies lower than those obtained with the catalyzed combustor. This loss in efficiency is thought to result from the existence of flow channeling through the secondary heat transfer area. The use of a catalytic combustor, whether active or inactive (tests "A" and "AA"), tended to disperse the flow more evenly upon entry into the secondary heat transfer area thereby providing for more effective heat transfer.

The summary of the distributed energies for wood heater #2 is presented in Table 12. The thermal efficiency varied between 69 and 75 percent over a rather narrow burn rate range of 1.1 to 3.1 kg/hr. Combustion efficiencies varied between 83 and 93 percent. A heat transfer efficiency range of 76 to 85 percent was found for wood heater #2. The high heat transfer efficiencies resulted from a well designed secondary heat exchanger. Sensible and latent losses ranged from 12 to 22 percent due to the effectiveness of this heat exchanger. The chemical

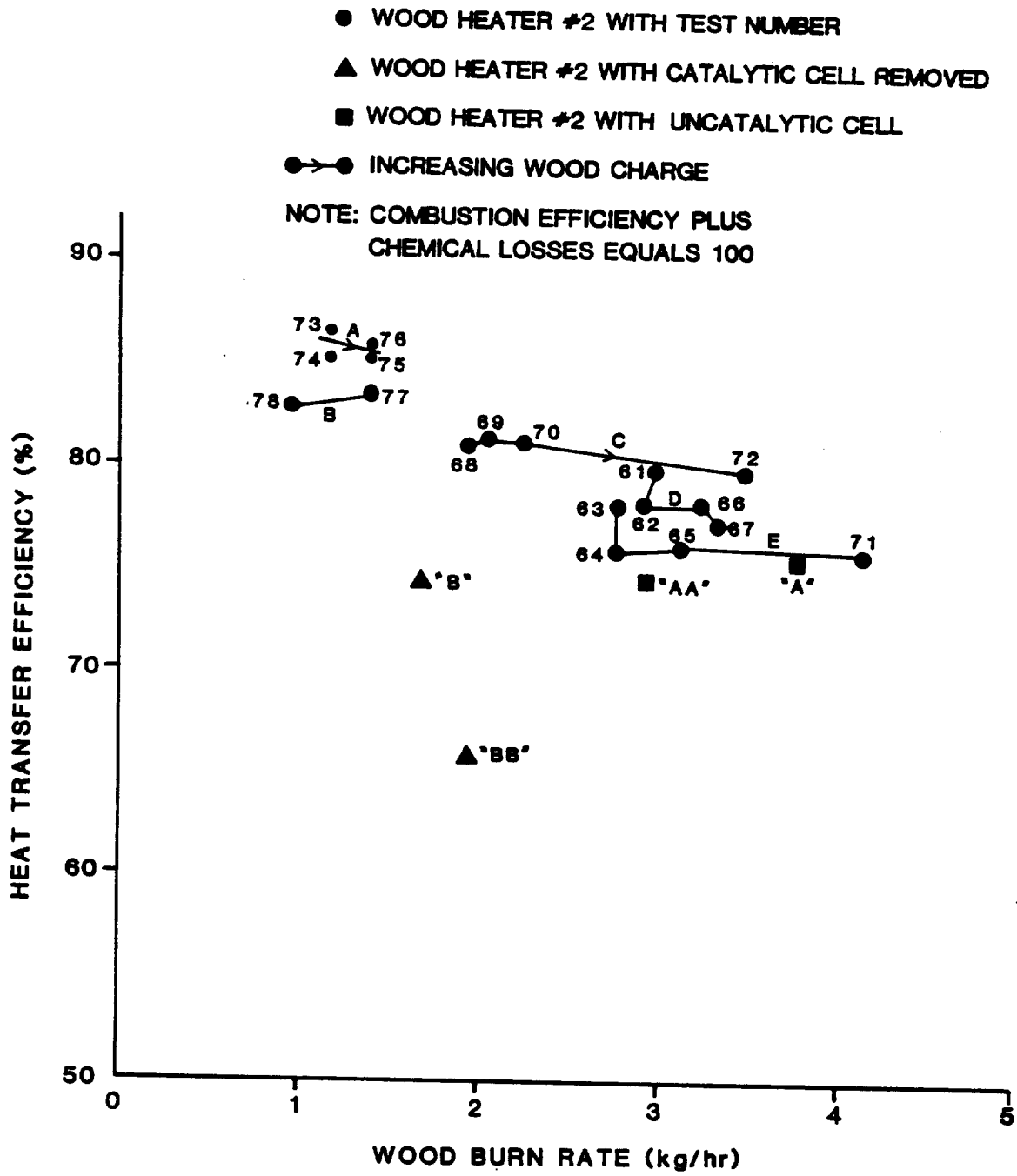


Figure 26. Summary-Heat Transfer Efficiency Versus Burn Rate-Wood Heater # 2

Table 12. SUMMARY OF DISTRIBUTED ENERGIES[a] (%)
FOR WOOD HEATER #2

Damper Setting	Burn Rate (kg/hr)	Thermal Efficiency	Combustion Efficiency	Heat Transfer Efficiency	Sensible Plus Latent Losses	Chemical Losses
E(Open)	3.1	70.9	92.9	76.4	21.9	7.2
D	3.0	70.4	90.0	78.3	19.5	10.0
C	2.4	72.3	89.6	81.0	17.3	10.5
B	1.1	69.3	83.3	83.1	14.0	16.7
A(Closed)	1.3	74.6	87.3	85.5	12.7	12.7
Average	2.2	71.5	88.6	80.9	17.0	11.4

[a]Average of four tests, each having a different cordwood fuel loading size.

losses ranged from 7 to 17 percent and were a result of the active catalytic combustion. The average values shown at the bottom of Table 12 will be discussed in the Comparative Discussion section of this report.

Wood Heater #2: Emissions

Carbon monoxide (CO) emission factors for wood heater #2 are shown in Figure 27. The grams of CO emitted per kg of wood consumed increased with increasing wood fuel charge for fixed air control damper settings. The larger changes in CO emissions resulting from increased fuel charge occurred for high burn rates where the air control settings were more open. Special tests "A" and "AA" had CO emissions similar to tests using the catalyzed combustor.

Tests "B" and "BB" with the cermanic combustor totally removed had CO emissions much higher than that associated with the conventional operation of wood heater #2. The CO emissions were reduced by passage through the catalytic combustor.

Total hydrocarbon emissions measured by the FID analyzer correlated with the CO emission factors and were about one-half that for CO. The emission factors shown in Figure 28 were less than 60 g/kg except for test "B" where the ceramic combustor had been removed.

Wood heater #2 NO_x emission factors are presented in Table 11 for the cordwood fuel. The NO_x emission factor ranged between 0.03 and 2 g/kg with an increase in NO_x across the catalytic combustor for most tests.

A summary of PAH emission factors for wood heater #2 is shown in Table 13. The naphthalene class of PAH represented about 50 percent of the total PAH emissions with phenanthrene being the second largest contributor. Table 13 contains only test results for the oak cordwood fuel

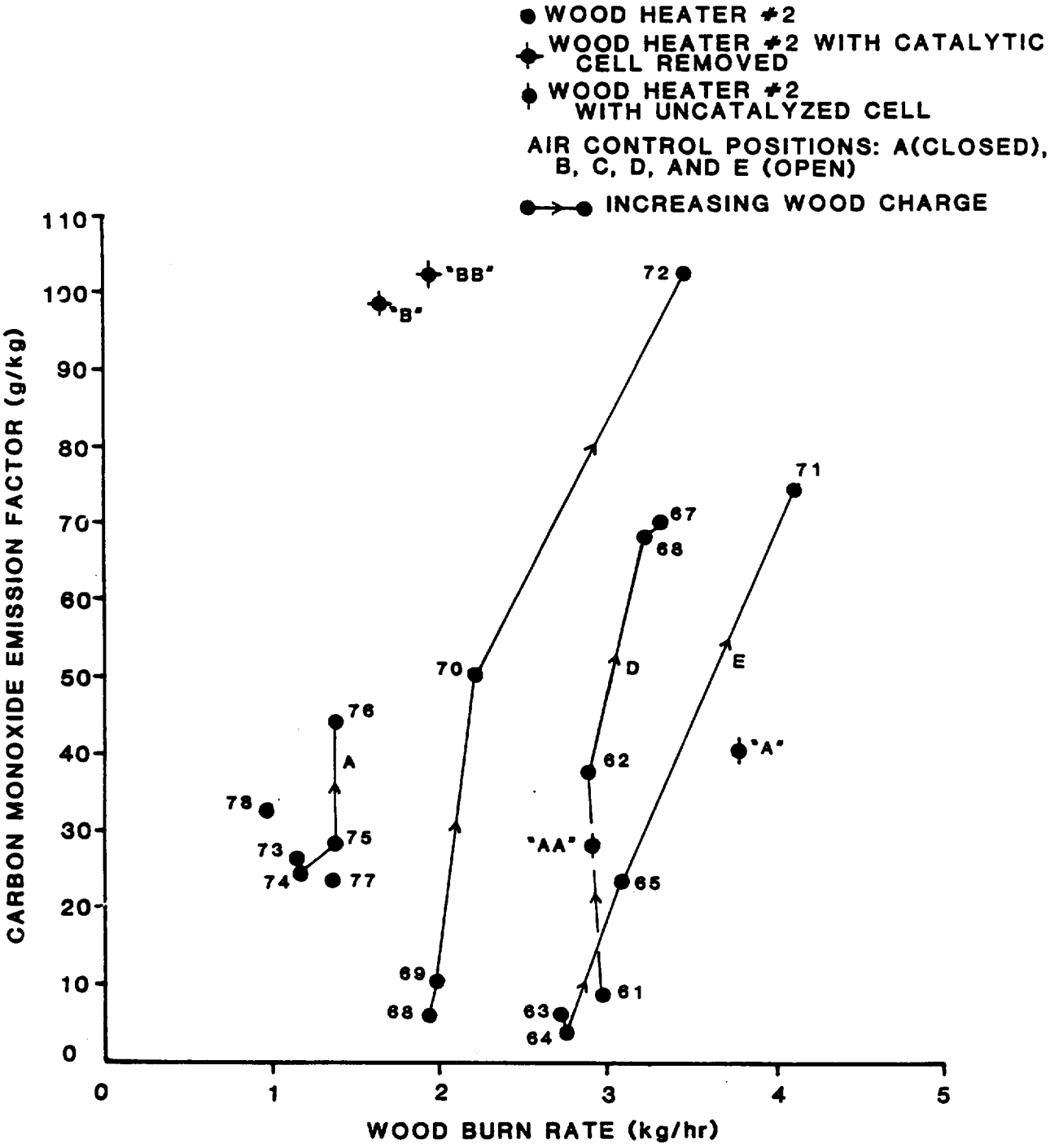


Figure 27. Carbon Monoxide Emission Factor Versus Burn Rate- Wood Heater #2.

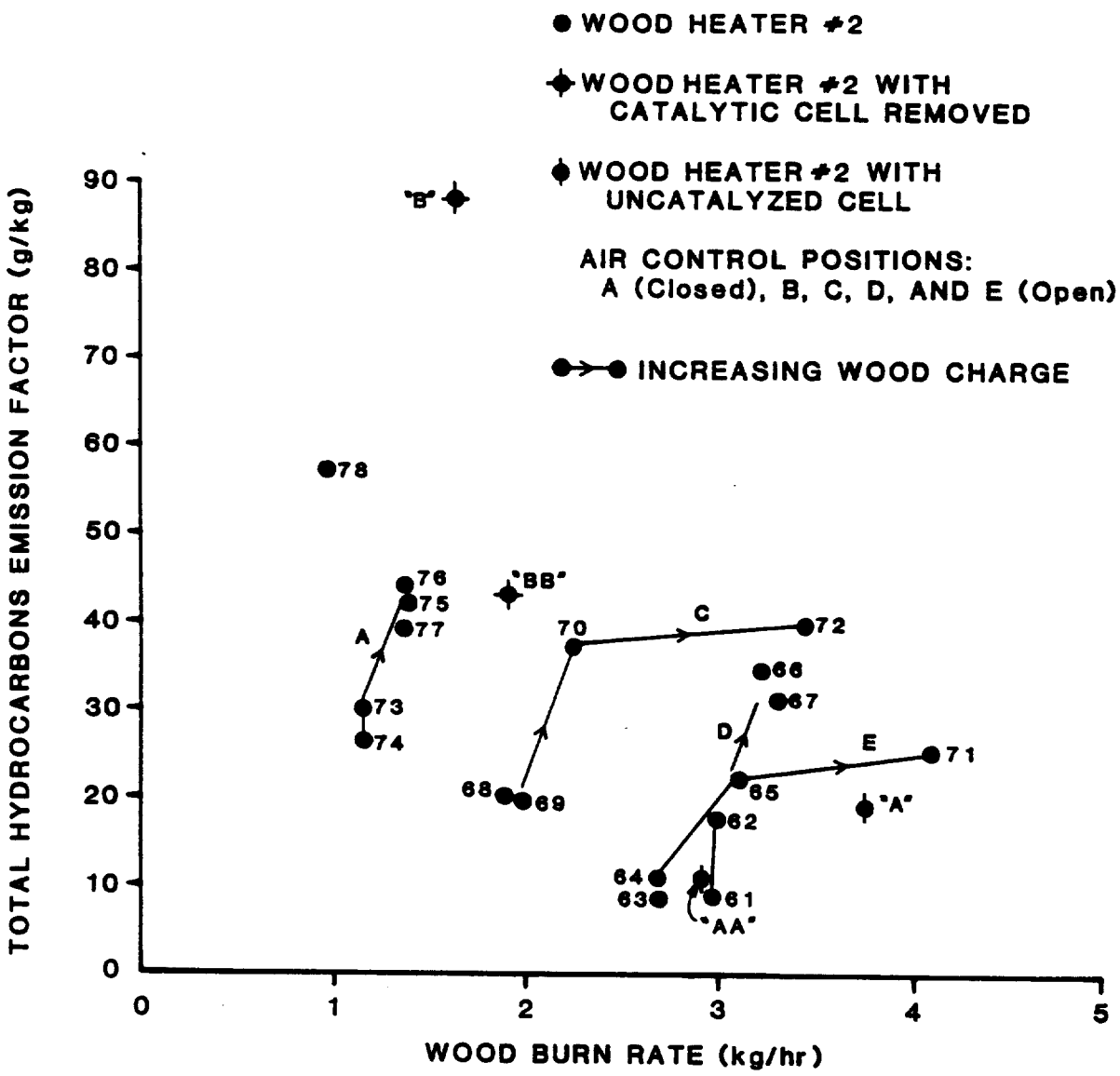


Figure 28. THC Emissions Factor Versus Burn Rate-Wood Heater#2

Table 13. WOOD HEATER #2
PAH EMISSION FACTORS (g/kg) - OAK CORDWOOD

	Test Number					
	63	65	68	70	73	75
Naphthalene/Methylnaphthalenes/ Phenylnaphthalenes	0.0141	0.0269	0.0028	0.0653	0.0127	0.0150
Acenaphthylene	0.0040	0.0035	0.0005	0.0150	0.0025	0.0010
Acenaphthene	———	———	———	———	———	———
Fluorene	0.0060	0.0009	0.0005	0.0037	0.0006	0.0009
Phenanthrene/Anthracene	0.0088	0.0141	0.0010	0.0284	0.0039	0.0055
Fluoranthene	0.0015	0.0029	0.0005	0.0042	0.0006	0.0003
Pyrene	0.0016	0.0026	0.0005	0.0046	0.0006	0.0003
Benzo (g,h,i) fluoranthene	0.0006	0.0017	———	0.0042	0.0006	———
Chrysene/Benzo (a) anthracene	0.0006	0.0021	———	0.0042	0.0006	0.0003
Benzo (b) fluoranthene/ benzo (k) fluoranthene	0.0006	0.0009	———	0.0018	0.0006	0.0003
Benzo (a) pyrene	0.0006	0.0008	———	0.0016	0.0006	0.0003
Indeno (1,2,3-c,d) pyrene/ Benzo (g,h,i) perylene	———	0.0006	———	0.0013	———	———
Dibenzo (a,h) anthracene	———	———	———	———	———	———
Total	0.0384	0.0570	0.0058	0.1343	0.0233	0.0239

as no brands were fired in wood heater #2. The benzo(a)pyrene component represented less than 2.6 percent of the PAH emissions from tests presented in Table 13.

Figure 29 presents PAH emission factors versus burn rate for wood heater #2. The highest PAH emissions were associated with the largest fuel loadings. Figure 30 shows that wood heater #2 had a rather narrow range in burn rate between fully open and closed damper air supply settings. The PAH emission factors were less than 0.15 g/kg for all six tests. Small wood loadings were preferred relative to reduced PAH emissions since the PAH emission factors for the small wood loadings were less than 0.03 g/kg for all three primary air control settings. Many homeowners operate their wood heater at the lowest burn rate obtainable by manipulating the primary air control. Figure 29 shows that the PAH emissions did not increase with sustained operation at the very low burn rates. Surprisingly, the lowest burn rates provided the lowest total PAH emission factors. The total PAH emission factors in Figure 30 show that the PAH emissions were reduced at the higher excess air values. The small wood load tests showed lower PAH emissions for each fixed connective sequence of tests. Wood heater #2 did not operate at high excess air values commonly associated with airtight wood heaters at low burn rates. Nor did wood heater #2 operate at very low excess air values. The two primary air screws were opened one quarter of a turn when operating in the closed primary air position. The manufacturer of wood heater #2 requested that the unit be operated in such a manner. Current production models of wood heater #2 are manufactured with a spacer in place behind the air screws to insure that the primary air screws cannot be totally closed. The secondary air port was left fully open throughout all testing of wood heater #2.

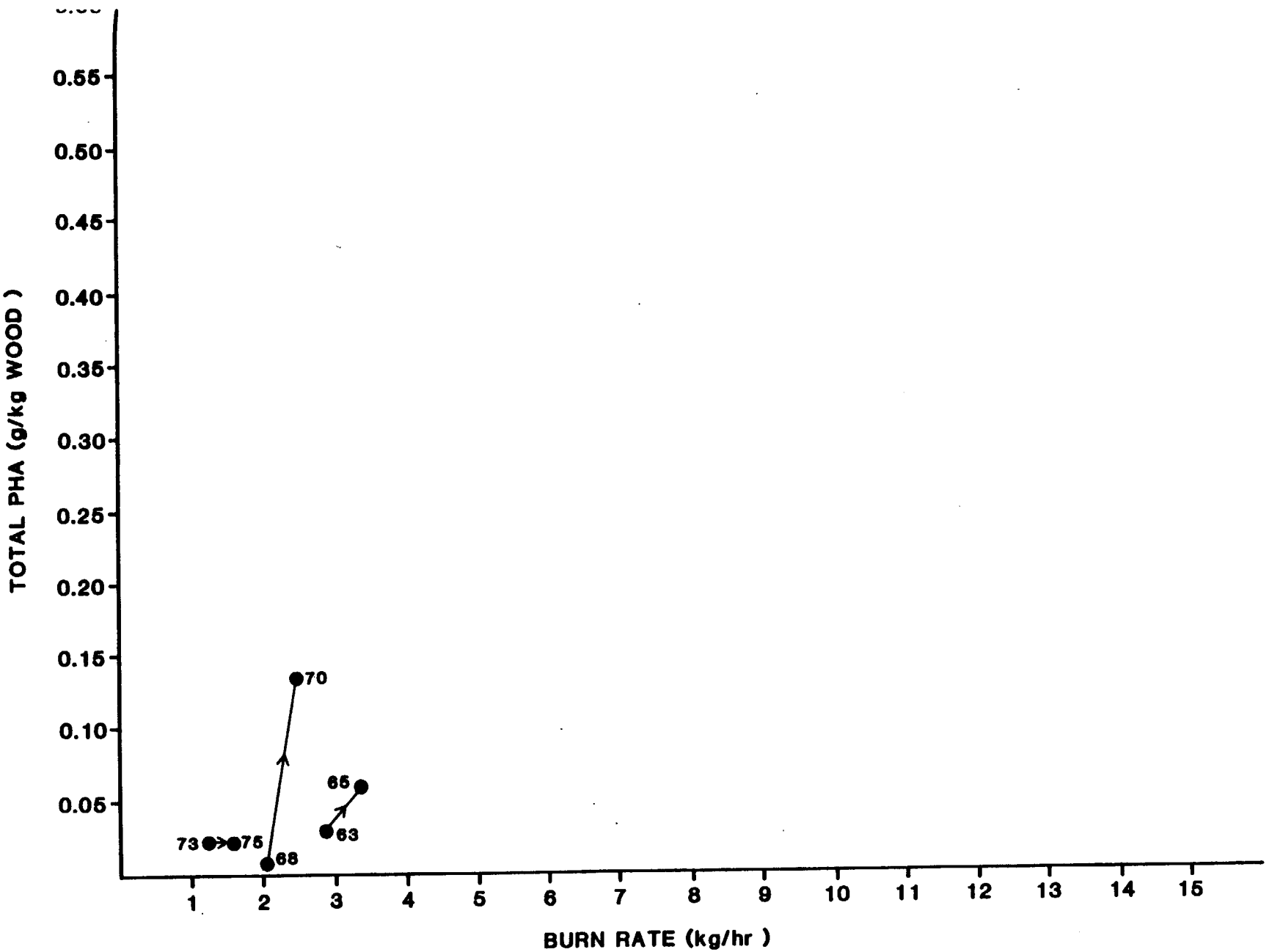


Figure 29. Effect of Burn Rate on PAH Emissions-Wood Heater # 2

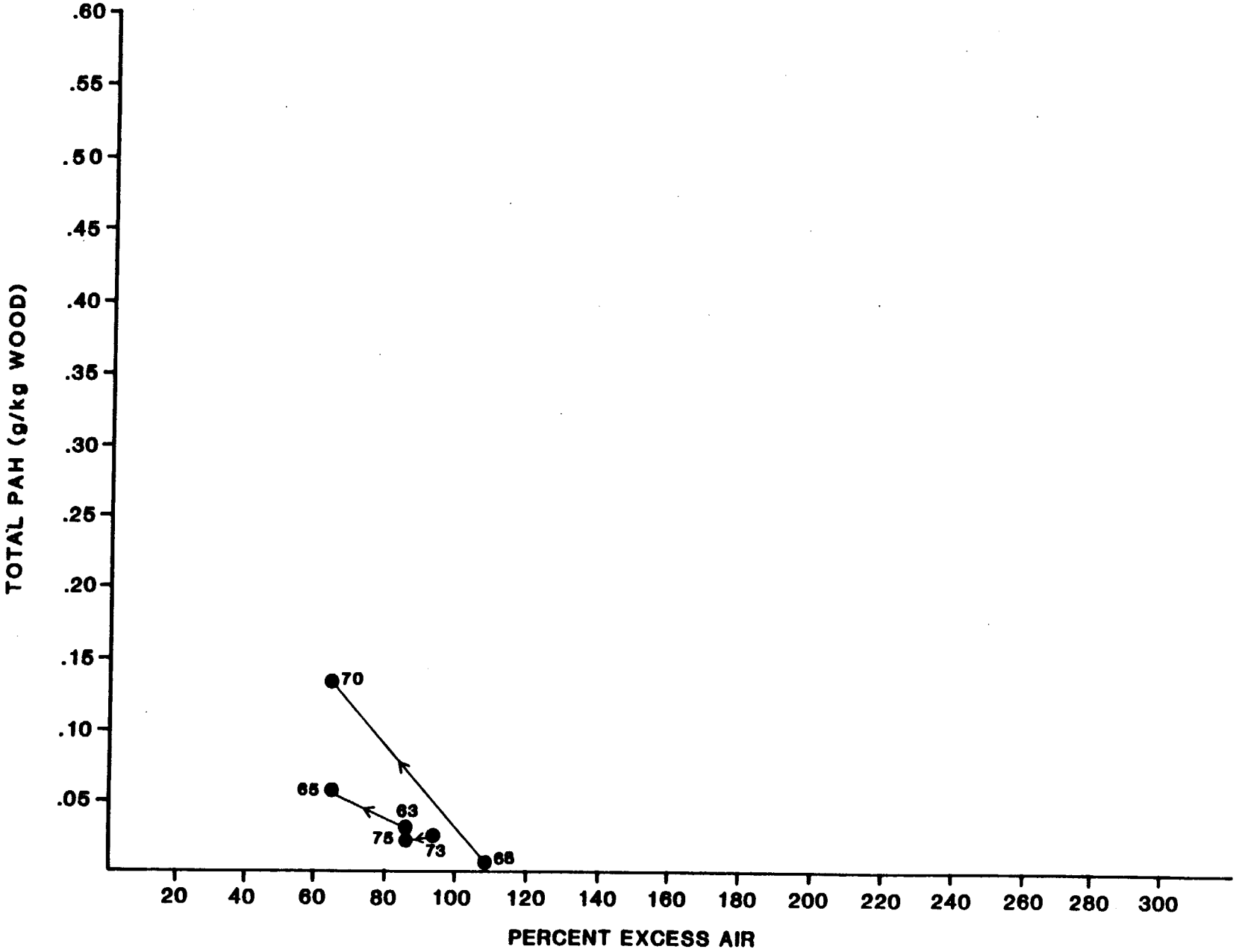


Figure 30. Effect of Percent Excess Air on PAH Emissions- Wood Heater # 2

The effect of wood loading size on the total PAH emissions is shown in Figure 31. There existed a consistent dependence between fuel loading size and total PAH emissions.

Figure 32 shows that total PAH emissions for wood heater #2 increased as the exit temperature of the flue gases increased. The larger fuel loadings sustained higher burn rates, exit temperatures, and PAH emissions.

Table 14 presents the emission factors for compounds other than PAH that were associated with the integrated sample recovered by the modified Method 5 sampling system. The table also presents volatile hydrocarbon emission factors along with the volume percent of methane and ethylene making up the volatiles.

Figure 33 shows that the total particulate emission factors for wood heater #2 were less than 10 g/kg and not really dependent upon wood fuel loading size.

The effect of burn rate on filterable particulate emissions is shown in Figure 34 and the ratio of condensible to filterable particulates is shown in Figure 35. Wood heater #2 operated with very low filterable particulate emissions and very low condensible organic emissions.

Volatile hydrocarbon emission factors for wood heater #2 are shown in Figure 36. The volatile emissions were dependent upon fuel loading size for medium and high burn rates for the wood heater.

The diagnostic efficiencies and key parameters presented earlier for each test are presented in Table 15 for wood heater #2. Averages before the catalyst and at the exit of the wood heater are shown in the table to point out the significant improvement in thermal performance and emissions associated with catalytic activity and good heat exhange.

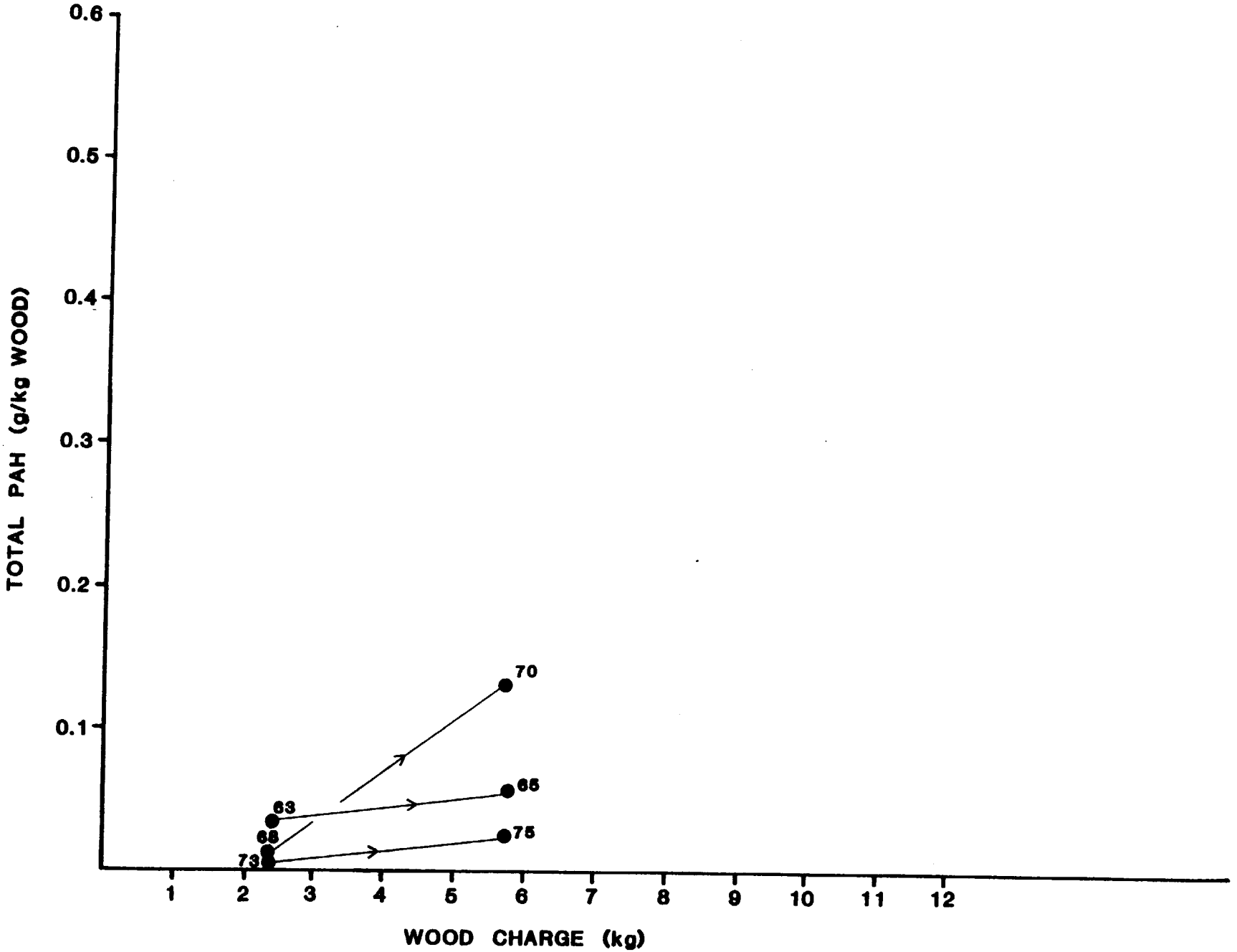


Figure 31. Effect of Wood Charge on PAH Emissions–Wood Heater # 2

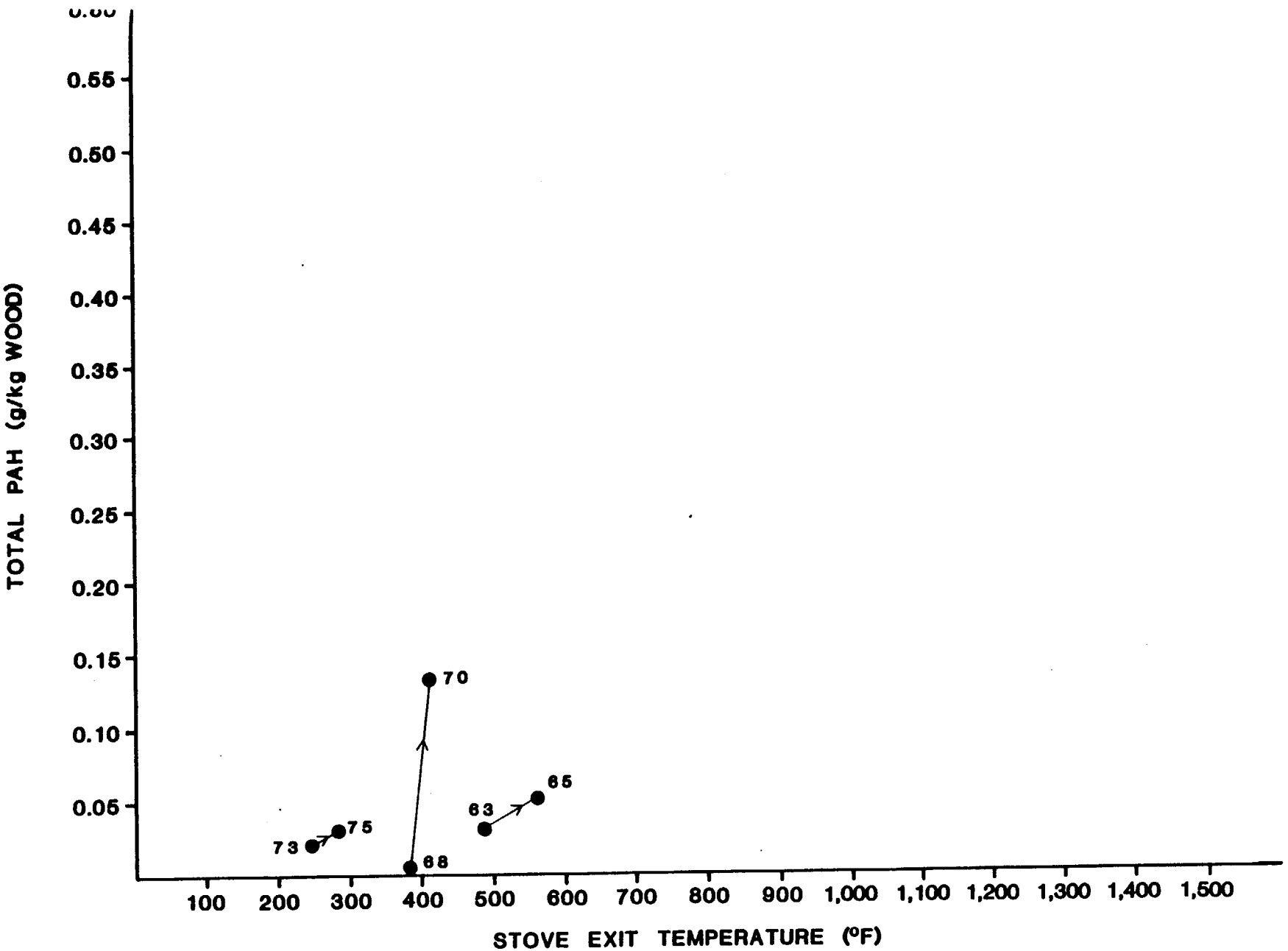


Figure 32. Effect of Stove Exit Temperature on PAH Emissions–Wood Heater #2

Table 14. WOOD HEATER #2
EMISSION FACTORS FOR COMPOUNDS OTHER THAN PAH (g/kg)

	Test Number					
	63	65	68	70	73	75
Filterable Particulate[a]	0.4535	1.0984	0.4455	0.4309	0.4185	0.3422
Front half Gravimetric[b]	0.1745	0.4277	0.5242	0.1111	0.0794	0.0621
Back half Gravimetric[c]	0.6513	0.9428	1.0670	4.3202	3.2678	4.9841
Back half TCO[d]	0.0756	0.1701	0.1404	1.5320	1.3230	1.9320
Total Condensible Organics[e]	0.7269	1.1129	1.2074	5.8522	4.5908	6.9161
Total Particulates[f]	1.1804	2.2113	1.6529	6.2831	5.0093	7.2583
Volatile Hydrocarbons (g/kg)	0.030	0.078	0.070	0.200	0.018	0.011
Major constituents:						
Methane (vol.%)		49		66		
Ethylene (vol.%)		13		18		

Note: f = a + e
e = c + d

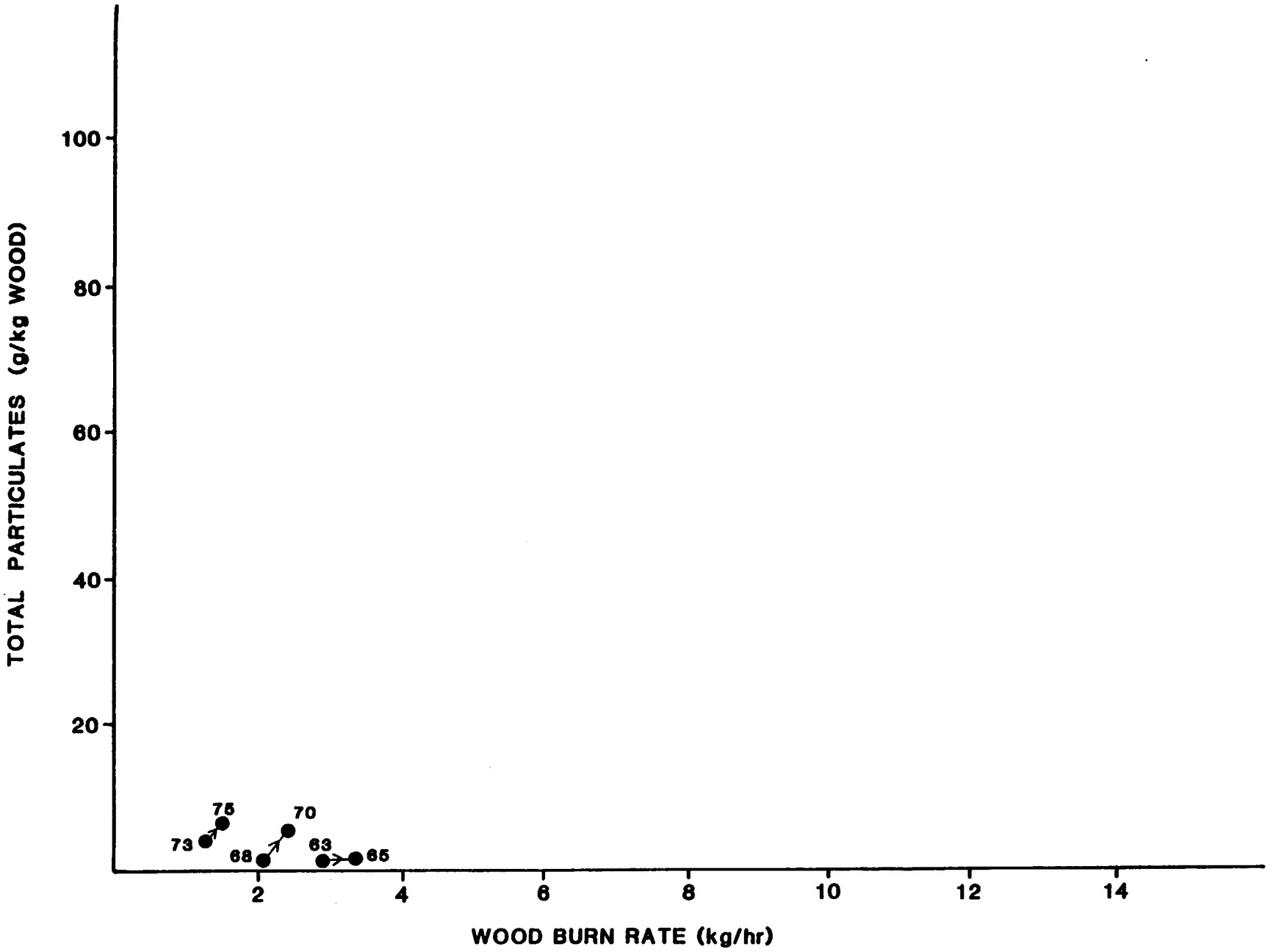


Figure 33. Effect of Burn Rate on Total Particulate Emissions-Wood Heater # 2

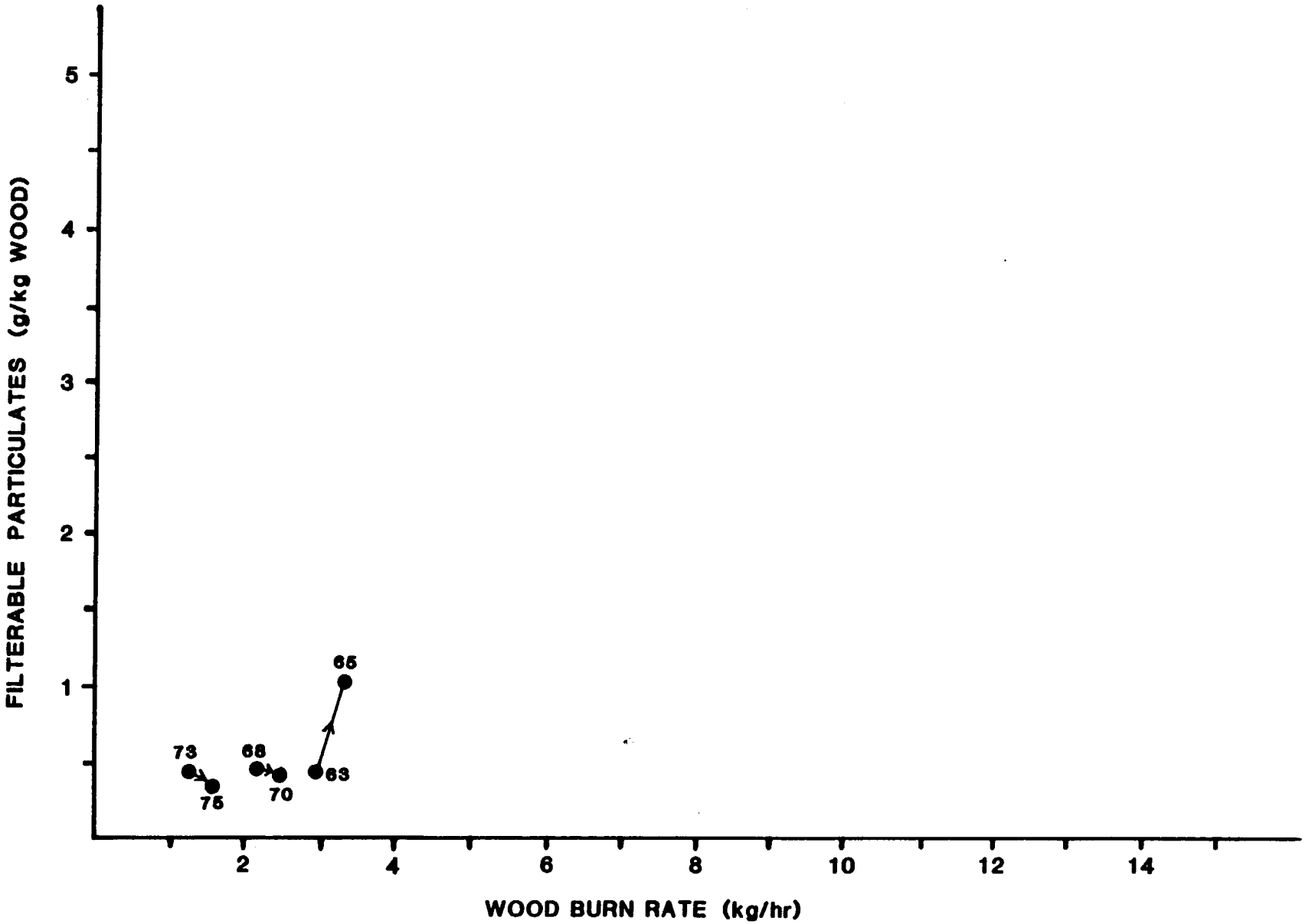


Figure 34. Effect of Burn Rate on Filterable Particulate Emissions–Wood Heater # 2

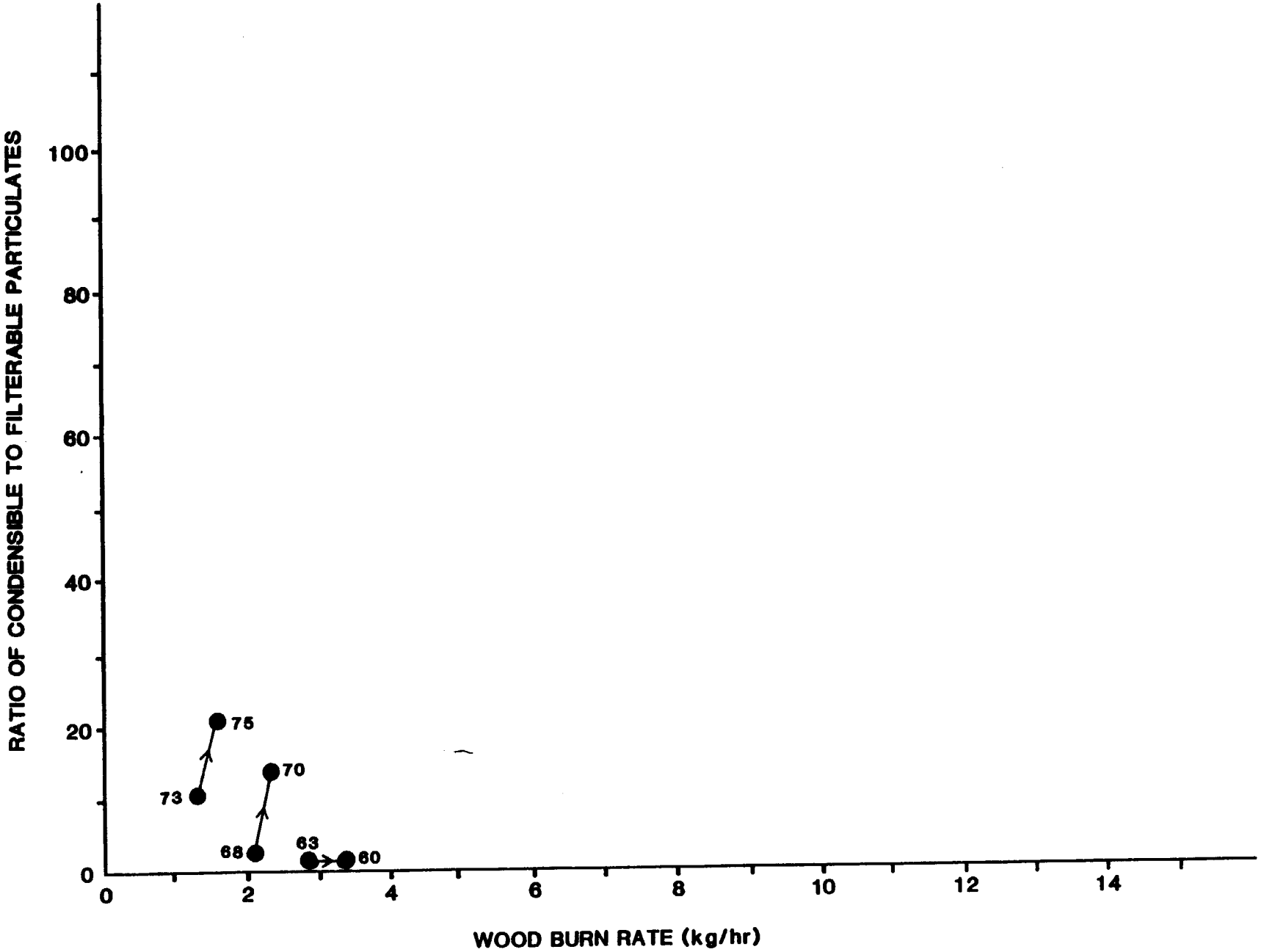


Figure 35. Effect of Burn Rate on the Ratio of Condensible to Filterable Particulates – Wood Heater # 2

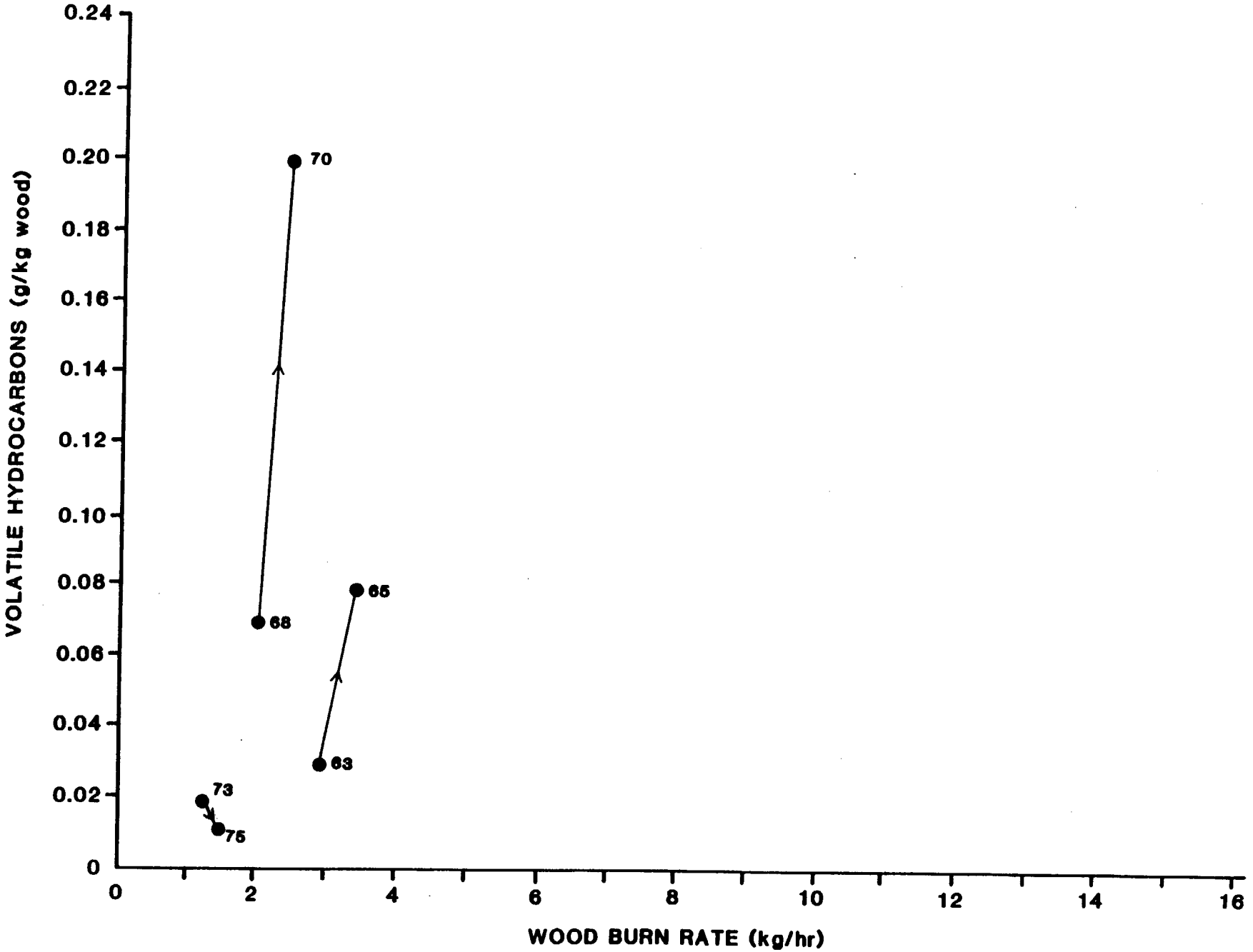


Figure 36. Effect of Wood Burn Rate on Volatile Hydrocarbon Emissions–*Wood Heater # 2*

Table 15. WOOD HEATER #2
TEST RESULTS AVERAGED

	Before the Catalyst		At Exit of Wood Heater	
	Average	Std. Deviation	Average	Std. Deviation
emperature of Gases (°F)	879.4	261.8	427.3	128.4
xcess Air (%)	79.4	31.2	75.4	33.7
hermal Efficiency (%)	50.2	4.4	71.8	4.1
eat Output (Btuh)	19,078	7,174	27,173	10,225
O Emission Factor (g/kg)	66.6	31.5	35.2	30.0
HC Emission Factor (g/kg)	42.3	17.5	27.8	13.5
O_x Emission Factor (g/kg)	0.599	0.219	0.757	0.251
ombustion Efficiency (%)	83.1	6.7	89.2	5.0
eat Transfer Efficiency (%)	60.6	5.5	80.5	3.5
ensible + Latent Losses (%)	32.9	6.3	17.4	3.6
hemical Losses (%)	16.9	6.8	10.8	4.9

	Average	Standard Deviation
ood Burn Rate (lb/hr)	5.0	2.1
raft Air Supply (CFM)	8.6	2.6

Overall Performance Changes[a]	
CO Reduction (%)	68
THC Reduction (%)	35
NO_x Increase (%)	26
Thermal Efficiency Increase (%)[b]	43

[a]These changes result from analysis of samples taken from the gases before entering the catalytic combustor area and at the exit of the wood heater.
[b]Change in efficiency divided by the precatalyst efficiency.

The change in thermal efficiency noted in Table 15 for wood heater #2 was revealed by analysis of combustion gas samples entering the catalytic combustor and exiting the wood heater. This change in thermal efficiency did not necessarily reflect the precise effects directly attributed to catalyst action. Some combustion gas composition changes took place due to continued oxidation following the primary zone combustion regardless of whether any catalytic activity existed in the catalytic combustor.

The thermal efficiency (TE) equals the product of the combustion and heat transfer efficiencies (CE x HTE). Therefore, any increase in either will correspondingly increase the thermal efficiency. Representing this relationship in terms of a differential gives

$$d(TE) = \frac{\Delta(TE)}{\Delta(CE)}\, d(CE) + \frac{\Delta(TE)}{\Delta(HTE)}\, d(HTE)$$

With TE = CE x HTE the differential becomes

$$d(TE) = (HTE)_{av}\, d(CE) + (CE)_{av}\, d(HTE)$$

or $$\Delta(TE) = (HTE)_{av}\, \Delta(CE) + (CE)_{av}\, \Delta(HTE)$$

From Table 15 the following values were found for wood heater #2: HTE_{av} = 0.70, $\Delta(CE)$ = 0.06, $\Delta(HTE)$ = 0.20, and $(CE)_{av}$ = 0.86. Applying these values to the differential gives

$$\Delta(TE) = 0.042 + 0.172 = 0.21$$

where the first term to the right of the equal sign is attributed to improved combustion efficiency; i.e., reduced concentrations of CO and organics in the flue gases. The last term results solely from improved heat exchange provided in the top flow passage region of the wood heater. In effect, about 20 percent of the total 21 percent increase in thermal efficiency is related to catalytic combustor activity while the remaining 80 percent is totally unrelated to the use of a catalytic combustor in

the wood heater. Table 15 shows that the large increase in thermal efficiency for the highest burn rate tests may be attributed to an improved heat transfer efficiency as the combustion efficiency was typically over 90 percent. The sensible and latent losses dropped by about 47 percent due to the improved heat transfer. The chemical losses associated with improved oxidation of flue gases, like CO and hydrocarbons, were reduced by 36 percent. The averaged CO emission factor at the exit of wood heater #2 was reduced by about 68 percent below that leaving the primary combustion zone and entering the catalytic combustor. This reduction in CO compares well with a range of 58 to 98 percent found by Jaasma (18). A close review of Table 10 shows that the highest reductions of CO occurred on the low burn tests.

The average total hydrocarbon emission factor was reduced by 35 percent during transit through the catalytic combustor and the secondary heat exchanger. The reduction in the emissions was unlike that for CO in that the largest reductions occurred on high burn tests. The 35 percent was much less than found by Corning Glass Works (17) who conducted tests with the flue gas organics by recovering them in water-cooled traps before and after the catalytic combustor. Their tests showed that the condensible organics decreased by 75 to 95 percent due to the catalyst. During TVA testing, the total hydrocarbon emissions were determined by using a flame ionization detector (FID) instrument that was sensitive to both the low and high molecular weight organics existing in the flue gases. The high molecular weight organics that readily condense were kept in gas phase by the 400°F heat tracing of the line going from the combustion zone to the FID instrument, where they were quantified. In comparison, the cold trap removed most organics readily condensible, but the traps

could not capture the volatile organics like methane, propane, and others that existed in the flue gases.

Nitrous oxide (NO_x) emission factors increased by 26 percent between the two sampling positions in wood heater #2. This was due to increased temperatures associated with catalytic activity. During some tests temperatures in excess of 1400°F were measured in the central cell structure of the catalyst.

Wood Heater #3

Table 16 presents a series of key diagnostic conditions for wood heater #3. Averages before the catalyst and at the exit of the wood heater are presented. The data shown in the table are presented in figure form and discussed later in the wood heater #3 results section.

Table 17 presents results obtained using the efficiency and emissions model and gives parameters considered important with regard to comparing combustion conditions before and after the catalytic combustor. Continuous sampling of combustion gases before the catalyst and at the exit of the wood heater provided the detail gas compositions required to perform such modeling.

A complete summary of emission factors for wood heater #3 is presented in Table 18. All tests have continuous analyzer emission factors for CO, NO_x, and FID total hydrocarbons while integrated samples were recovered on designated tests for use in generating the organic emission factors. The activity of the catalytic combustor is shown when before and after catalyst emission factors are compared. No integrated samples were recovered before the catalyst.

Table 16. WOOD HEATER #3
AVERAGE CATALYTIC TEST RESULTS - THERMAL - RED OAK CORDWOOD

Test	Wood Charge (lb)	Wood Burn Rate (lb/hr)	Damper Position	Air Supply (CFM)	Temp Flue Gas (°F)	Before Catalyst		Heat Output (Btuh)	Temp Flue Gas (°F)	Exit of Wood Heater		Heat Output (Btuh)
						Excess Air(%)	Thermal Efficiency			Excess Air(%)	Thermal Efficiency	
92	7.9	7.3	Open	17.0	803	73	59.6	31,764	527	168	63.4	33,472
93	13.7	9.8	Open	19.7	907	49	54.6	40,719	622	113	62.0	46,617
94	19.4	8.9	Open	16.6	814	37	59.3	40,481	555	108	65.7	45,374
95	25.6	10.2	Open	15.7	853	18	56.6	44,119	566	69	60.9	48,404
96	7.8	5.2	30%	11.6	664	70	58.7	23,182	422	163	61.4	27,100
97	13.7	9.2	30%	13.7	749	20	53.8	37,592	546	78	58.4	39,270
98	19.6	9.9	30%	15.6	722	25	49.5	37,419	611	69	57.1	43,364
99	25.4	8.5	30%	14.3	772	30	53.5	34,605	546	75	61.2	40,149
100	7.7	4.9	30%	15.2	592	135	54.1	19,503	374	229	64.3	24,165
101	13.7	8.4	30%	18.0	732	64	51.6	32,128	520	112	62.2	39,214
102	19.6	7.8	30%	16.4	707	59	48.4	27,829	541	97	59.5	34,520
90	7.9	2.5	Closed	8.1	379	145	56.6	10,651	214	443	58.5	11,088
91	19.5	2.6	Closed	6.2	276	67	49.4	10,051	156	255	44.5	9,104

Table 17.
AVERAGE DIAGNOSTIC CONDITIONS FOR CATALYTIC WOOD HEATER #3

	Before Catalyst (%)					Exit of Wood Heater (%)				
Test	Thermal Efficiency	Combustion Efficiency	Heat Tra. Efficiency	Sensible & Lat. Losses	Chemical Losses	Thermal Efficiency	Combustion Efficiency	Heat Tra. Efficiency	Sensible & Lat. Losses	Chemical Losses
92	56.9	91.1	62.5	34.2	8.9	63.4	95.3	66.5	32.0	4.7
93	54.6	88.7	61.6	34.1	11.3	62.0	93.1	66.5	31.2	6.9
94	59.3	89.9	66.0	30.6	10.1	65.7	94.5	69.5	28.8	5.5
95	56.6	85.2	66.4	28.6	14.9	60.9	86.2	70.6	25.3	13.8
96	58.7	87.4	67.2	28.7	12.6	61.4	87.0	70.5	25.7	13.0
97	53.8	79.1	68.0	25.3	20.9	58.4	83.2	70.2	24.8	16.8
98	49.5	74.5	66.5	25.0	25.5	57.1	83.4	68.5	26.3	16.6
99	53.5	81.0	66.0	25.6	19.0	61.2	86.1	71.1	24.9	13.9
100	54.1	87.7	61.8	33.5	12.3	64.3	92.8	69.3	28.5	7.2
101	51.6	83.6	61.7	32.1	16.4	62.2	90.4	68.7	28.3	9.6
102	48.4	78.4	61.7	30.0	21.6	59.5	87.1	68.4	27.6	13.0
90	56.6	77.3	73.1	20.8	22.7	58.5	78.6	74.4	20.1	21.4
91	49.4	62.4	79.1	13.0	37.6	44.5	55.4	80.4	10.9	44.6

Table 18. WOOD HEATER #3
AVERAGE CATALYTIC TEST RESULTS - EMISSIONS (g/kg) - RED OAK CORDWOOD

				Exit of Wood Heater					Before Catalyst		
Test	CO	Total Hydrocarbons	NO_x	Filterable Particulates	Condensible Organics	Total Particulates	Volatile Hydrocarbons	Polynuclear Aromatic Hydrocarbons	CO	Total Hydrocarbons	NO_x
92	32	8	1.33	0.789	1.444	2.234	0.0600	0.0193	93	11	0.91
93	54	12	1.15						104	18	0.85
94	32	11	1.01	0.507	3.462	3.969	0.1840	0.0842	92	16	0.70
95	89	30	0.78						127	28	0.63
96	55	33	1.42	0.823	3.377	4.200	0.1970	0.1293	109	21	0.96
97	103	36	0.73						154	41	0.50
98	98	36	0.75	1.413	26.874	28.287	1.1580	0.7370	165	55	0.45
99	89	30	0.72						141	55	0.47
100	42	14	1.53						105	19	1.08
101	39	22	1.43						120	30	0.75
102	54	31	1.41						136	45	0.69
90	137	44	0.73	0.744	12.810	13.554	0.2010	0.1405	163	45	0.65
91	193	116	0.45	1.278	47.504	48.782	0.541	0.0880	193	95	0.39

Wood Heater #3: Efficiencies

The thermal efficiencies for wood heater #3 associated with three different damper positions are shown in Figure 37. The damper positions referred to are those associated with primary air control for wood heater #1 since wood heater #3 was an "add-on" catalytic unit attached to the rear of wood heater #1 and did not contain any form of air control or damper. The retrofitted unit (wood heater #3) operated with reduced thermal efficiencies at the closed damper position, with the smaller wood load being much more efficient than the larger wood load due to a high combustion efficiency. The thermal efficiency generally increased with burn rate resulting in thermal efficiencies over 61 percent for all fully open damper tests. Catalytic activity was found for all tests except those conducted with a fully closed damper. This catalytic activity was responsible for the increase in combustion efficiency and the decrease in chemical losses shown in Table 17 and Figure 38. The instantaneous temperature at three positions (prior to the catalyst, within the catalyst, and at the exit of the appliance) are presented for each test in Appendix C. The temperature in the central passageway of the catalyst was never higher than the temperature of the combustion gases entering the catalyst for test 91. This means that the catalyst was not active during test 91. The catalyst would generally not become active until the gas temperature entering the catalyst reached about 450°F.

Wood heater #3 combustion efficiencies are shown in Figure 38. The combustion efficiency generally increased with progressive opening of the air control damper. The low combustion efficiencies at the closed damper position may have resulted from too much secondary combustion air being added by design in the retro-fitted unit. During low burn tests

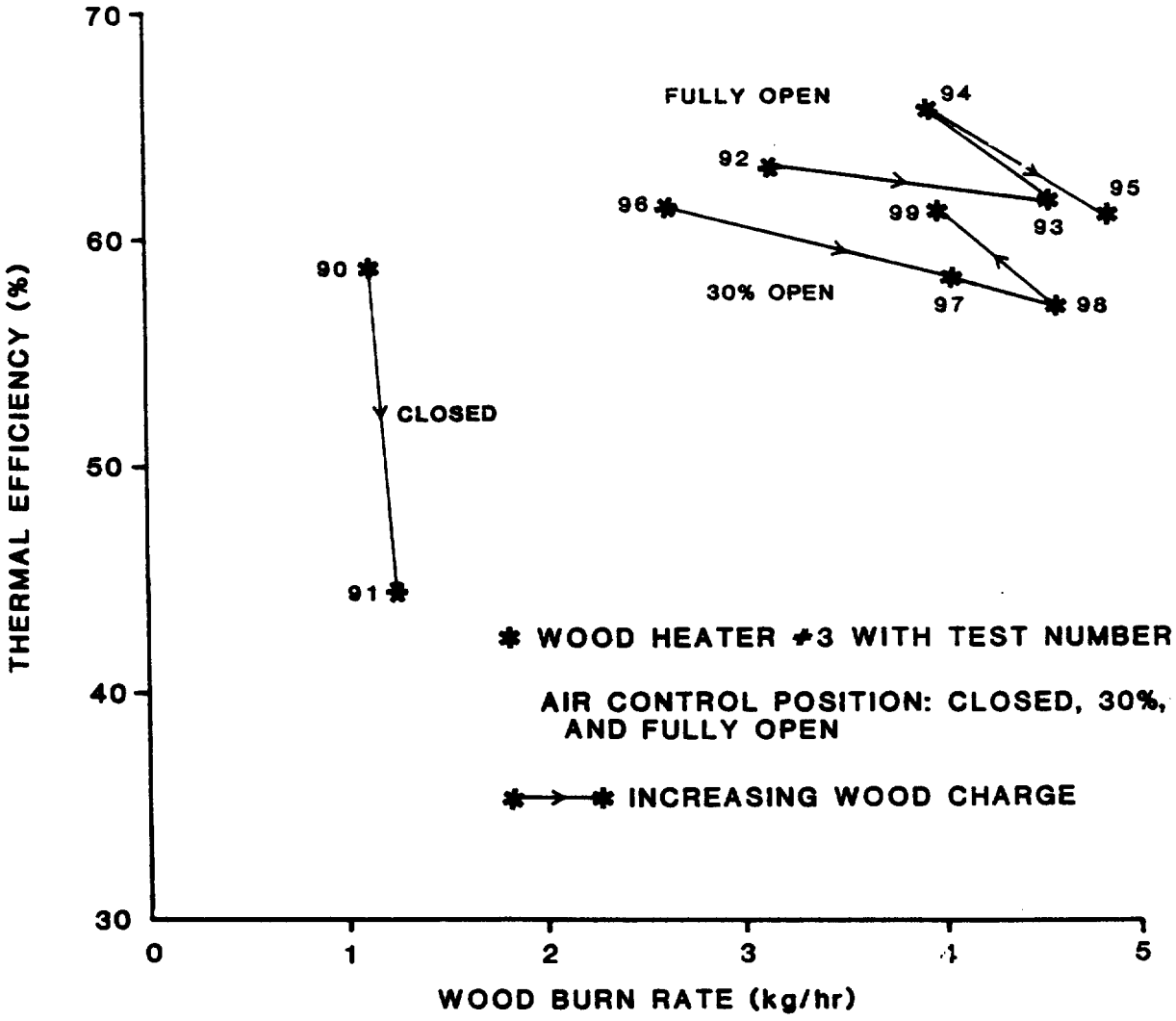


Figure 37. Thermal Efficiency Versus Burn Rate-Wood Heater#3

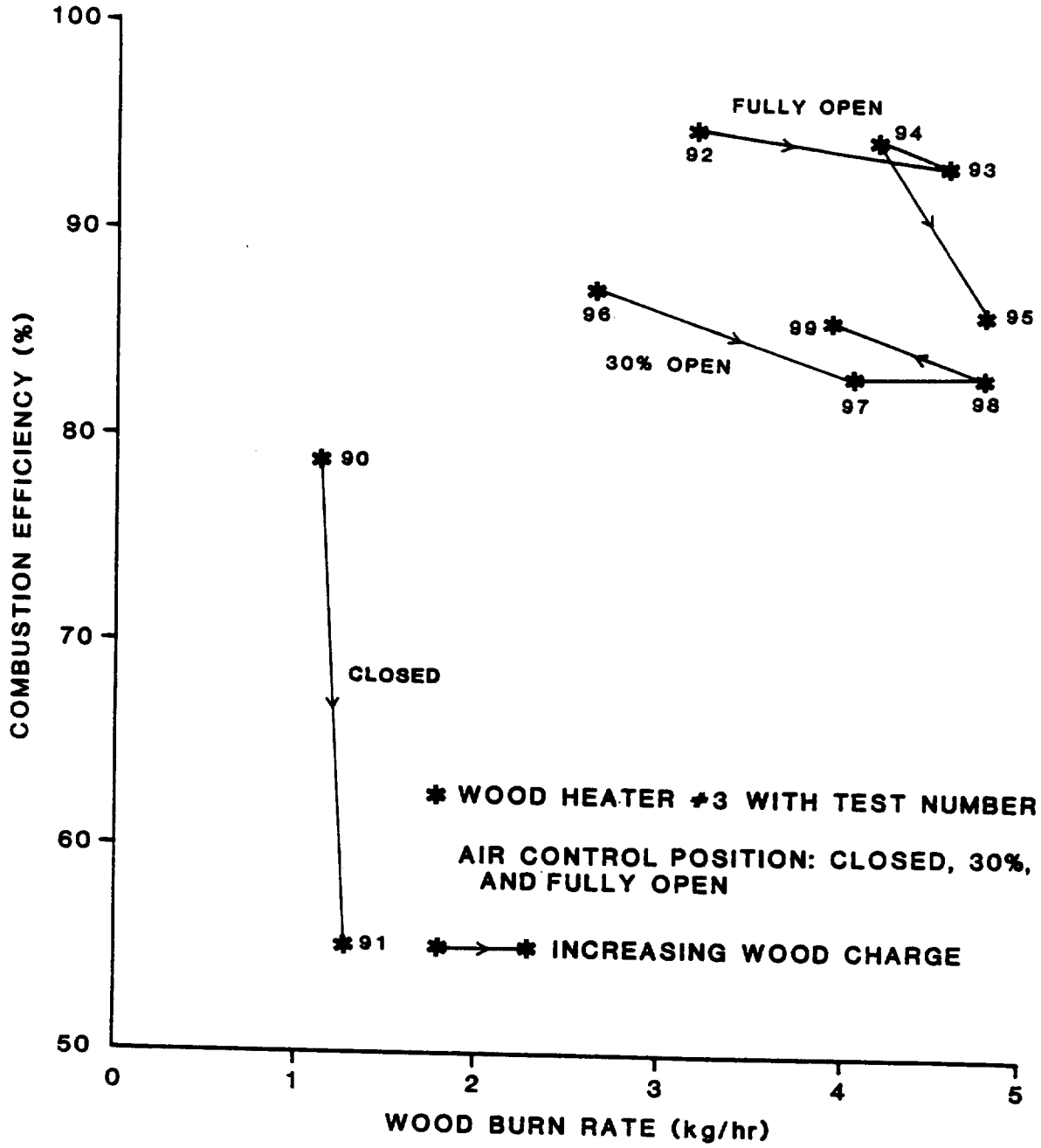


Figure 38. Combustion Efficiency Versus Burn Rate-Wood Heater#3

where the possibility of maintaining an inlet temperature over 450°F at the catalytic combustor was unlikely, the secondary air added just prior to the catalyst served to quench the combustion gases to a point where active catalysis could not be maintained. The "add-on" unit did not contain a secondary air supply damper that would enable an operator to maintain more catalytic activity at the low burn rates. During some tests this uncontrolled secondary air supply exceeded the primary air supply.

Heat transfer efficiencies for wood heater #3 are shown in Figure 39. The heat transfer efficiencies were not significantly dependent upon wood load size except for the closed damper position firings. Generally, the heat transfer efficiency increased as the air control or damper position was moved toward the closed position.

A summary of the distributed energies for wood heater #3 is presented in Table 19. The thermal efficiency varied between 51 and 63 percent over a burn rate range of 1.2 to 4.1 kg/hr. Combustion efficiencies ranged from 67 to 92 percent and the heat transfer efficiency ranged from 68 to 77 percent. The sum of the sensible and latent losses ranged from 15 to 29 percent and the chemical losses ranged from 7 to 33 percent. The 33 percent chemical loss existed when the add-on catalytic combustor was inactive due to low burn rate firing conditions. The average values shown at the bottom of Table 19 will be discussed in the Comparative Discussion section of this report.

Wood Heater #3: Emissions

Figure 40 shows that the CO emission factors for wood heater #3 decreased with increased burn rate; dropping by a factor of five between closed and opened damper firings. The CO emission factors were directly

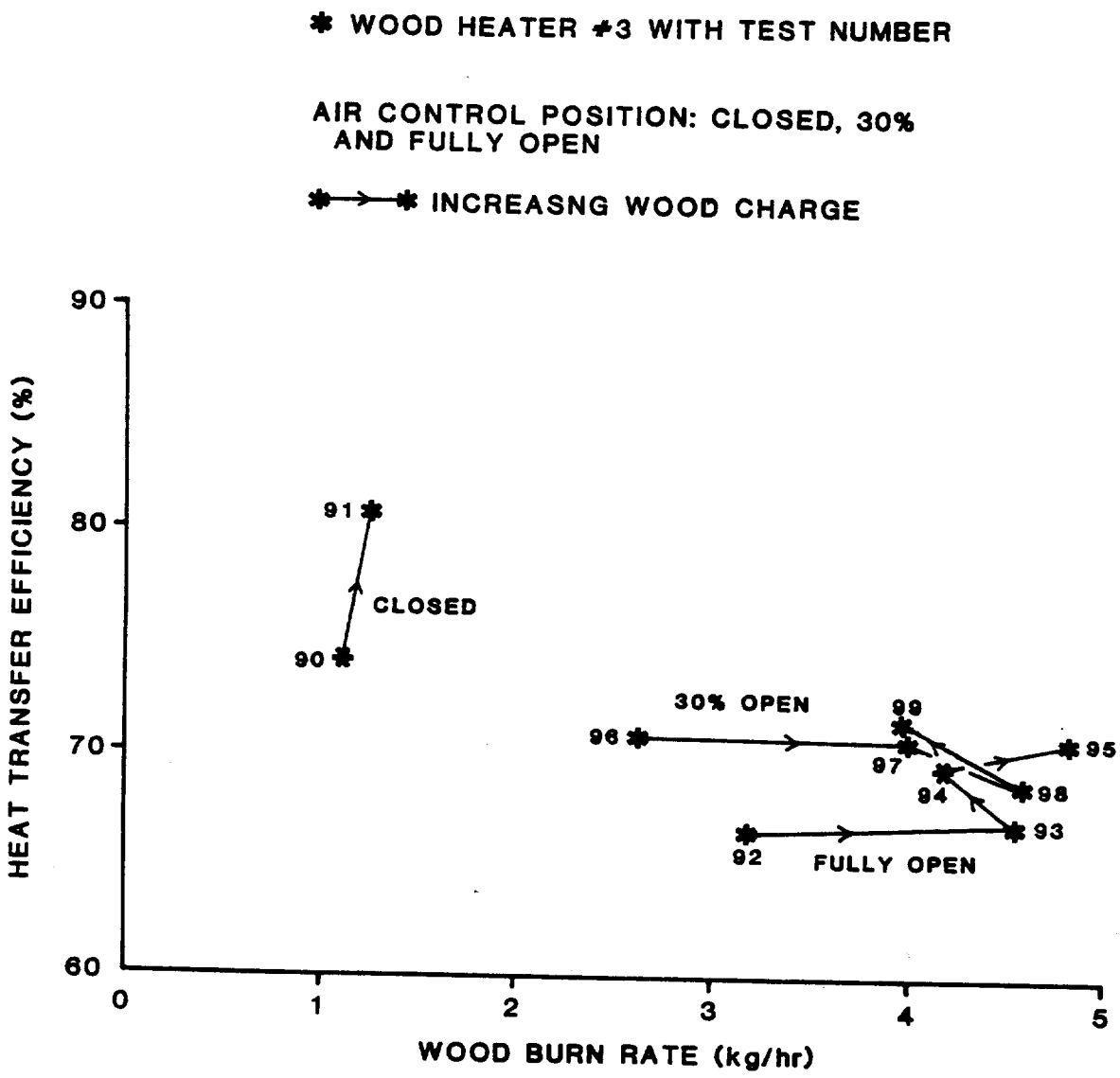


Figure 39. Heat Transfer Efficiency Versus Burn Rate-Wood Heater#3

Table 19. SUMMARY OF DISTRIBUTED ENERGIES[a] (%)
FOR WOOD HEATER #3

Damper Setting	Burn Rate (kg/hr)	Thermal Efficiency	Combustion Efficiency	Heat Transfer Efficiency	Sensible Plus Latent Losses	Chemical Losses
Open	4.1	63.0	92.3	68.3	29.3	7.7
30%	3.5	60.6	86.4	69.5	26.6	12.9
Closed	1.2	51.5	67.0	77.4	15.5	33.0
Average	2.9	58.4	81.9	71.7	23.8	17.9

[a]Average of four tests, each having a different cordwood fuel loading size.

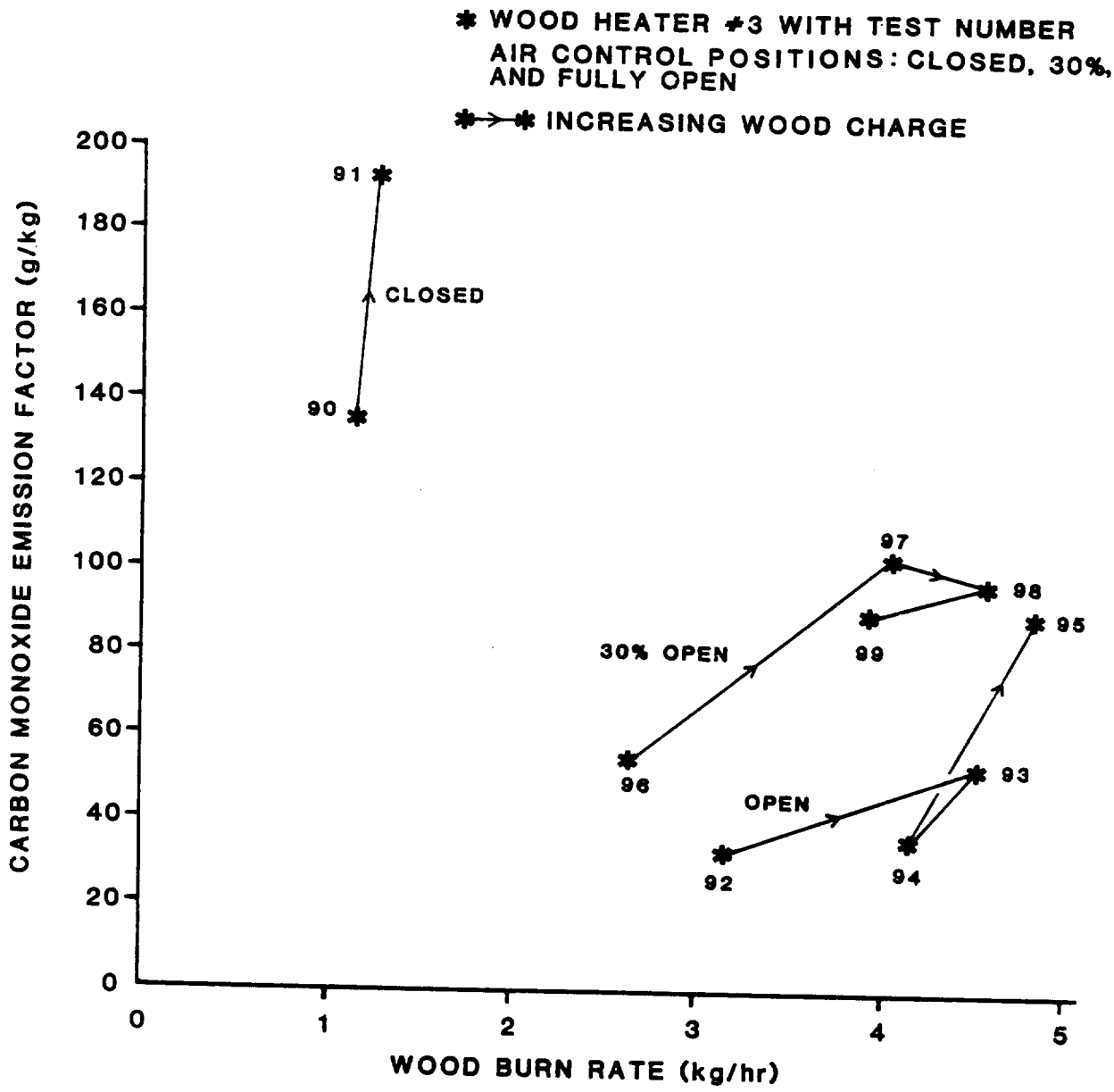


Figure 40. Carbon Monoxide Emission Factor Versus Burn Rate - Wood Heater #3

dependent upon wood load size for each different air control position used in the test program.

Total hydrocarbon emission factors for wood heater #3 are shown in Figure 41. The THC emission factors were not significantly related to wood load size except for the closed damper position. The THC emissions were found to increase from 45 to 115 g/kg when the wood load was increased from about 8 to 19 pounds. This represents a 6-fold increase in THC mass emitted since the product of the emission factor and the wood load consumed determines the total emission. The THC emission factor increased by a factor of 12 for the same wood loading when the damper was moved from fully open to fully closed. This finding reveals the significance of making the homeowner more aware of the variability in wood heater emissions resulting from operator decisions as to the size of wood load to be added. Generally, THC emission factors for wood heater #3 increased with decreasing burn rate and closure of the damper air supply.

The NO_x emission factors for wood heater #3 are presented in Table 18. The NO_x emission factor ranged from 0.5 to 1.42 g/kg for all tests. The NO_x emissions were higher downstream of the catalytic combustor than they were at the entrance.

A summary of PAH emission factors for wood heater #3 are presented in Table 20. The naphthalene component represented about 50 percent of the total PAH emissions while the benzo(a)pyrene component was less than 1.7 percent. Phenanthrene was the second largest component and constituted about 20 percent of the total PAH.

Figure 42 presents total PAH versus wood burn rate. Wood heater #3 represents a merged unit composed of wood heater #1 with an add-on retro catalytic combustor and a blower/heat exchanger added directly to the

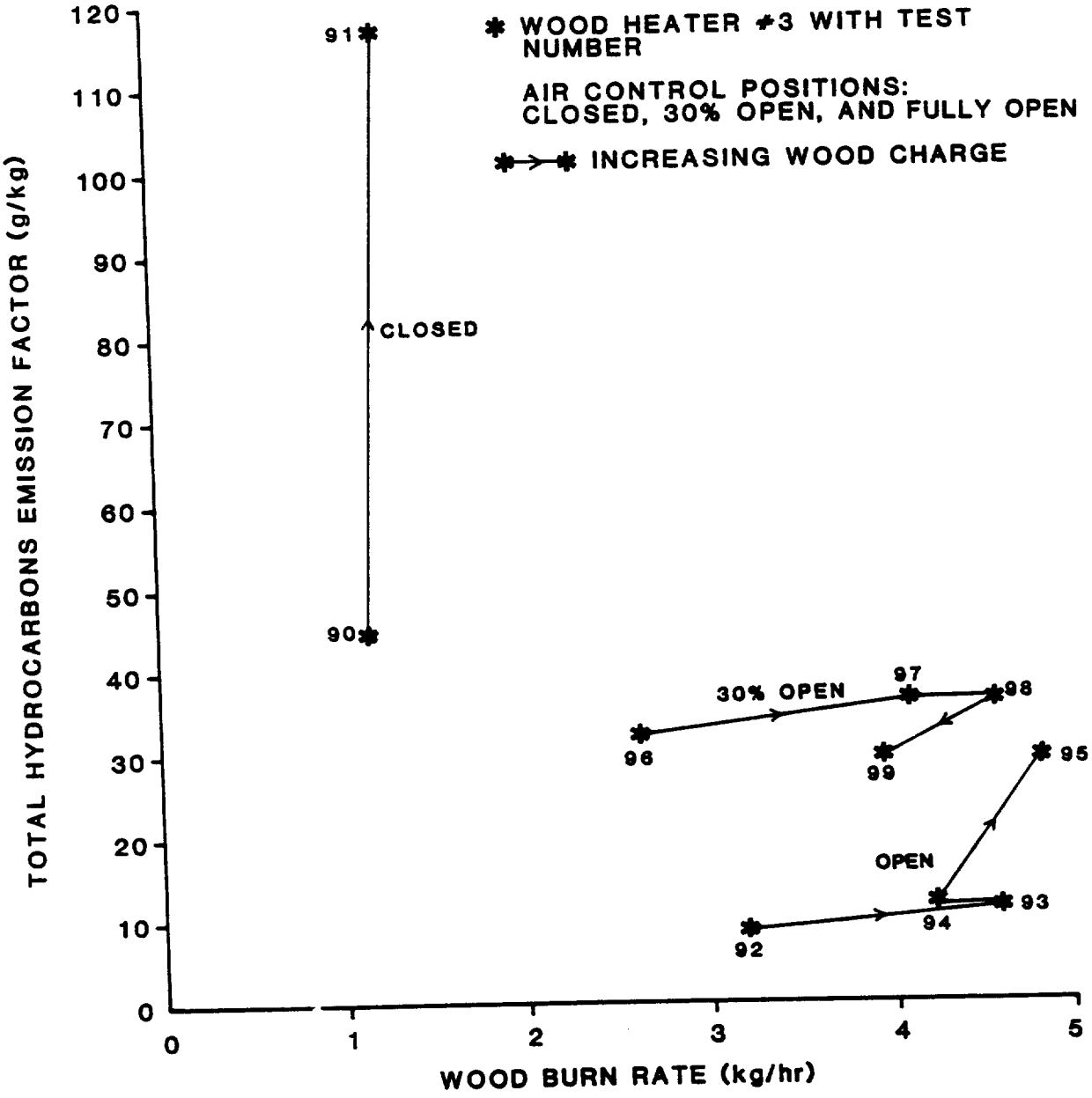


Figure 41. THC Emissions Versus Burn Rate-Wood Heater#3

Table 20. WOOD HEATER #3
PAH EMISSION FACTORS (g/kg) - 2x4 OAK BRANDS

	Test Number					
	92	94	96	98	90	91
Naphthalene/Methylnaphthalenes/ Phenylnaphthalenes	0.0120	0.0435	0.0634	0.3600	0.0740	0.0686
Acenaphthylene	0.0007	0.0073	0.0120	0.0562	0.0143	_____
Acenaphthene	0.0007	0.0028	0.0046	0.0332	0.0061	_____
Fluorene	0.0007	0.0018	0.0031	0.0186	0.0046	_____
Phenanthrene/Anthracene	0.0036	0.0165	0.0250	0.1350	0.0235	0.0193
Fluoranthene	0.0007	0.0027	0.0045	0.0247	0.0038	_____
Pyrene	0.0007	0.0021	0.0045	0.0260	0.0040	_____
Benzo (g,h,i) fluoranthene	_____	0.0017	0.0034	0.0260	0.0026	_____
Chrysene/Benzo (a) anthracene	_____	0.0022	0.0040	0.0350	0.0038	_____
Benzo (b) fluoranthene/ benzo (k) fluoranthene	_____	0.0011	0.0017	0.0135	0.0015	_____
Benzo (a) pyrene	_____	0.0007	0.0015	0.0120	0.0015	_____
Indeno (1,2,3-c,d) pyrene/ Benzo (g,h,i) perylene	_____	_____	0.0013	0.0101	0.0006	_____
Dibenzo (a,h) anthracene	_____	_____	_____	0.0013	_____	_____
Total	0.0191	0.0824	0.1290	0.7516	0.1403	0.0879

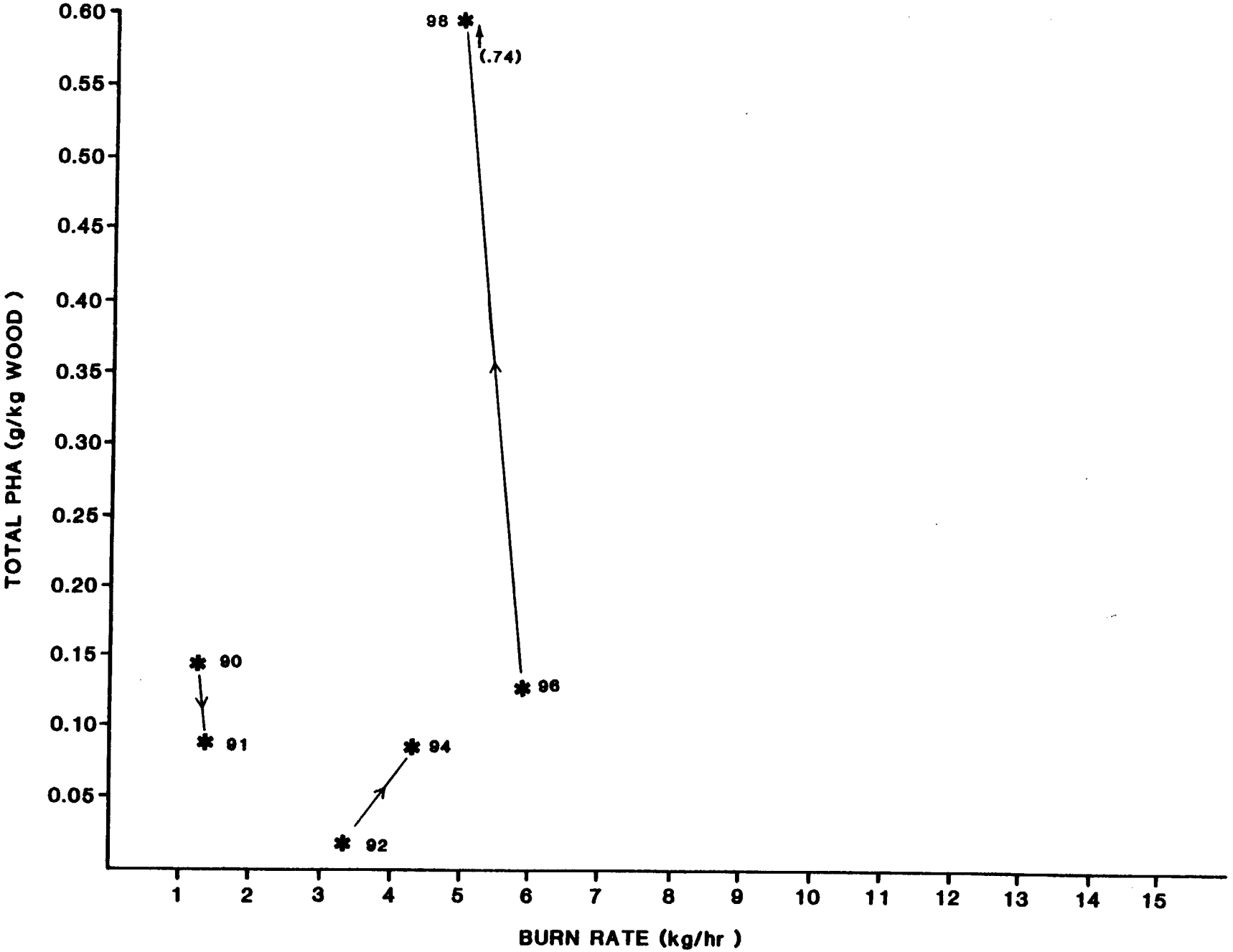


Figure 42. Effect of Burn Rate on PAH Emissions–Wood Heater # 3

Theoretically, the retro catalytic unit should not be operational at very low burn rates due to very low wood heater exit temperatures. The merged heater was capable of sustaining burn rates much lower than for wood heater #1 alone.

Tests 90 and 91, for closed damper operation of wood heater #3, showed the same pronounced drop in total PAH with increased wood loading size as was exhibited in tests 56 and 58 for wood heater #1 alone. The total PAH for tests 90 and 91 were lower than those of tests 56 and 58 by an order of 4. More importantly, the use of the add-on catalytic unit improved the total PAH emissions performance of wood heater #1 while allowing it to operate at a very low burn rate of 1.5 kg/hr. This shows that the retro-equipped wood heater #1 was capable of operating at a very low burn rate while providing very low total PAH emissions--a desirable mode of operation for the homeowner. It is thought that these low PAH levels at very low burn rates may be due to a lack of sufficient energy. Since a burn rate of 1.5 kg/hr is actually a smoldering fire, the large amount of energy necessary for PAH formation is not readily available. Therefore, the levels of PAH are, as expected, very low for these extremely low burn rates. Wood heater #1 alone was not capable of sustained operation at such low PAH emissions except at much higher burn rates with small fuel loadings. The total PAH emissions are shown to be low in Figure 43 except for the large wood loading at the fully open damper settings.

The general trend for the PAH emission factors to increase with decreased burn rate (as noted earlier in Figure 42 for wood heater #1) was not as prevalent, although test 98 showed a dramatic increase over test 96 in this regard. This again points out the great importance of using small wood loadings in fueling a wood heater independent of whether it is a catalytic or traditional airtight wood burning wood heater.

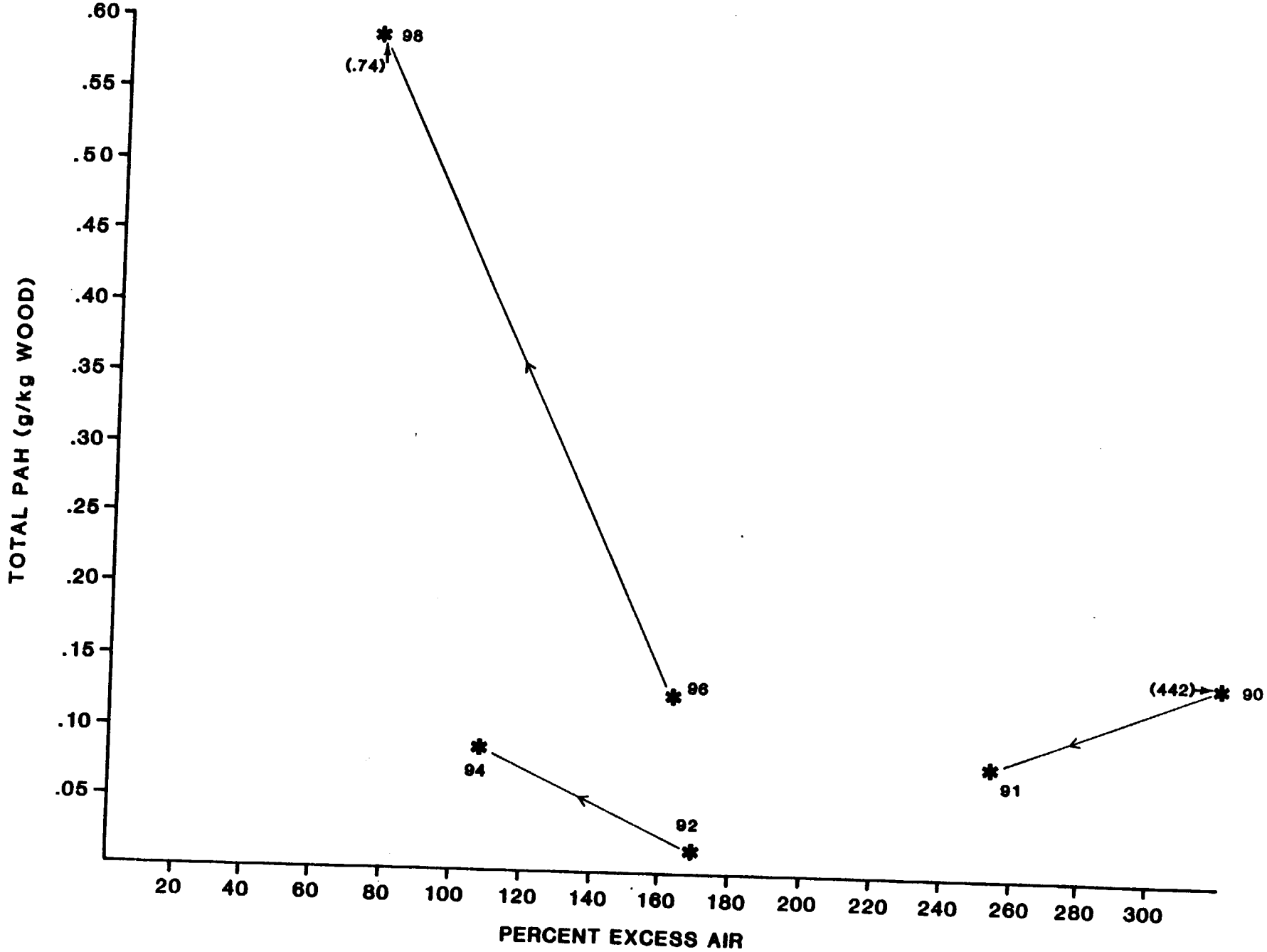


Figure 43. Effect of Percent Excess Air on PAH Emissions- Wood Heater #3

Figure 44 shows that the total PAH emission factor for wood heater #3 was only weakly dependent upon wood load size except for test 98 where a large fuel load was fired with an open damper.

The effect of wood heater exit temperatures on total PAH are shown in Figure 45. It is evident from this figure that small fuel loadings were required to ensure low total PAH emission factors for any burn rate and exit temperature.

Table 21 presents the emission factors for components other than PAH that were associated with the integrated sample recovered by the MM5 sampling system. The table also presents volatile hydrocarbon emission factors and the volume percent of methane and ethylene making up the volatiles.

The effect of burn rate on total particulates for wood heater #3 is shown in Figure 46. The total particulates were generally reduced with increased burn rate. Small size fuel loadings are also shown to reduce the total particulates.

Filterable particulate emission factors for wood heater #3 are presented in Figure 47. All such filterable particulate emissions were found to be less than 2 g/kg. The ratio of condensible organic emissions to filterable particulates is shown in Figure 48. Small wood load sizes were shown to generate less flue gas condensibles in comparison with the filterable particulates.

The volatile hydrocarbons emission factors as presented in Figure 49 again showed that the emissions could be reduced by using small size fuel loadings.

The most important parameters that controlled the combustion process for wood heater #3 after averaging are presented in Table 22. The "add-on"

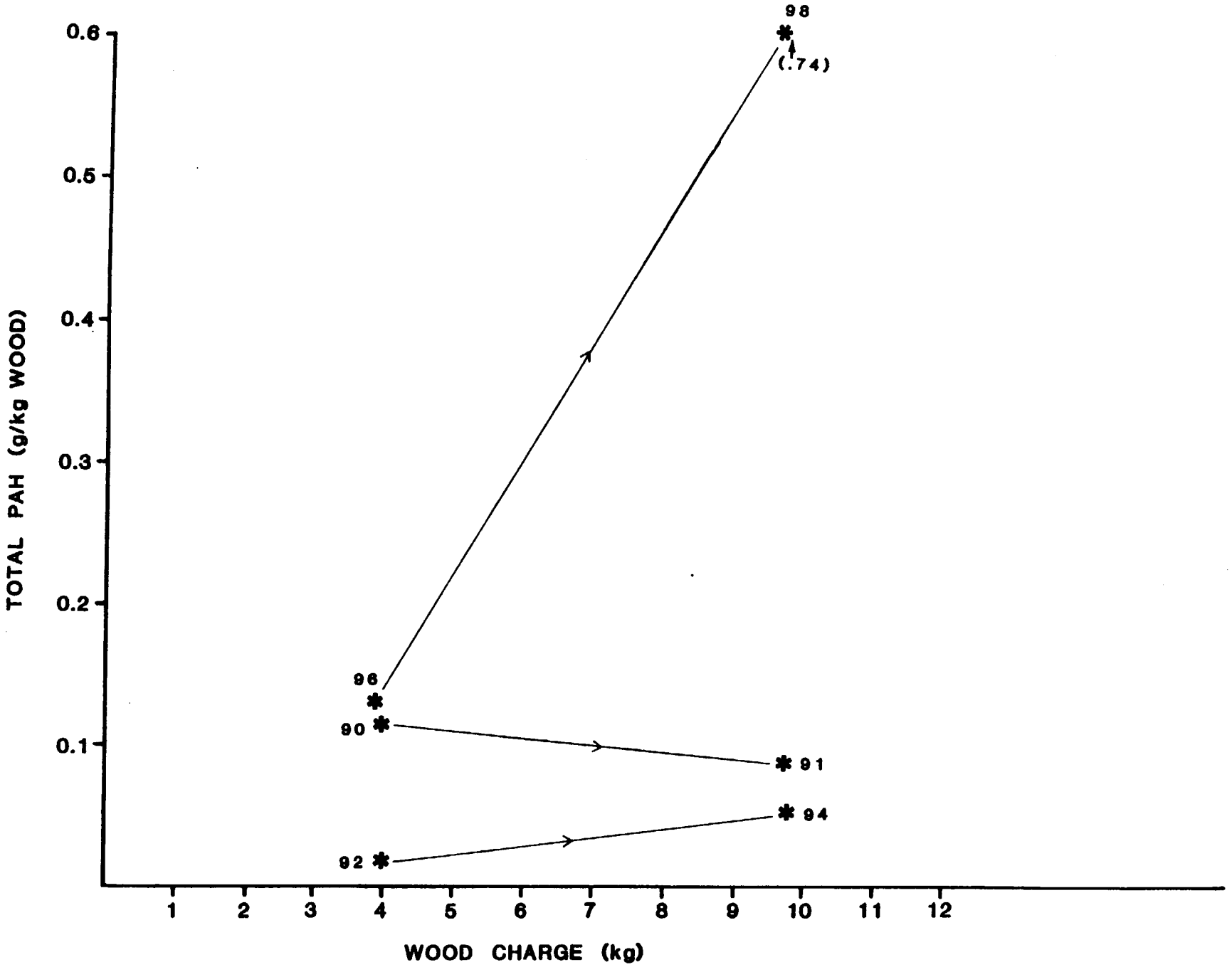


Figure 44. Effect of Wood Charge on PAH Emissions–Wood Heater # 3

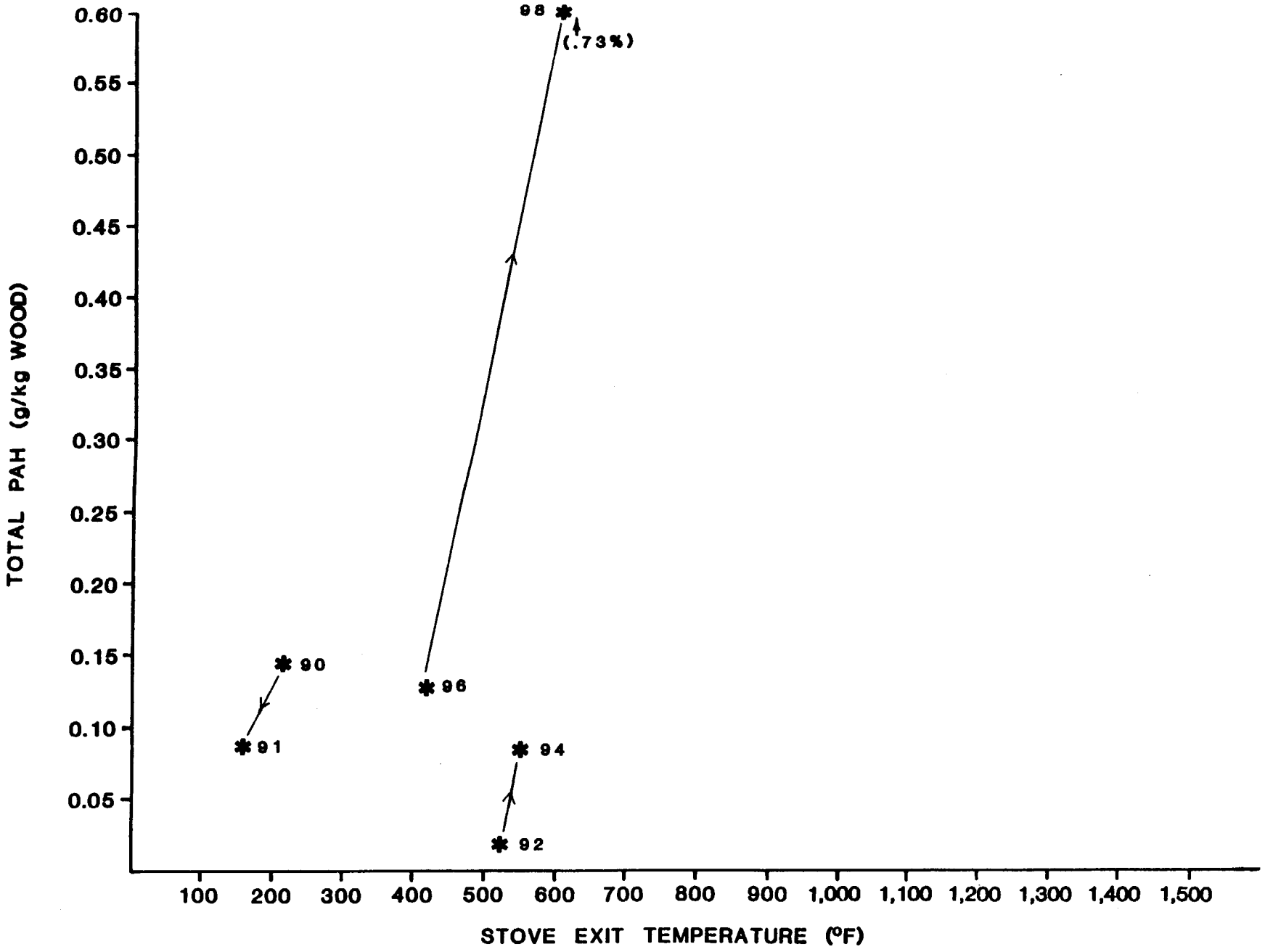


Figure 45. Effect of Stove Exit Temperature on PAH Emissions–Wood Heater #3

Table 21. WOOD HEATER #3
EMISSION FACTORS FOR COMPOUNDS OTHER THAN PAH (g/kg)

	Test Number					
	92	94	96	98	90	91
Filterable Particulate[a]	0.7893	0.5075	0.8190	1.413	0.7422	1.2761
Front half Gravimetric[b]	0.3438	0.0876	0.2192	0.1490	0.2124	0.1878
Back half Gravimetric[c]	1.3750	2.8645	2.7014	17.4929	8.9090	28.3766
Back half TCO[d]	0.1375	0.5999	0.6734	0.9384	3.8940	19.0930
Total Condensible Organics[e]	1.5125	3.4644	3.3748	18.4313	12.8030	47.4696
Total Particulates[f]	2.3018	3.9719	4.1938	19.843	13.5452	48.7457
Volatile Hydrocarbons (g/kg)	0.060	0.184	0.197	1.158	0.201	0.541
Major constituents:						
Methane (vol.%)		46	60	50		59
Ethylene (vol.%)		20	16	32		91

Note: f = a + e
e = c + d

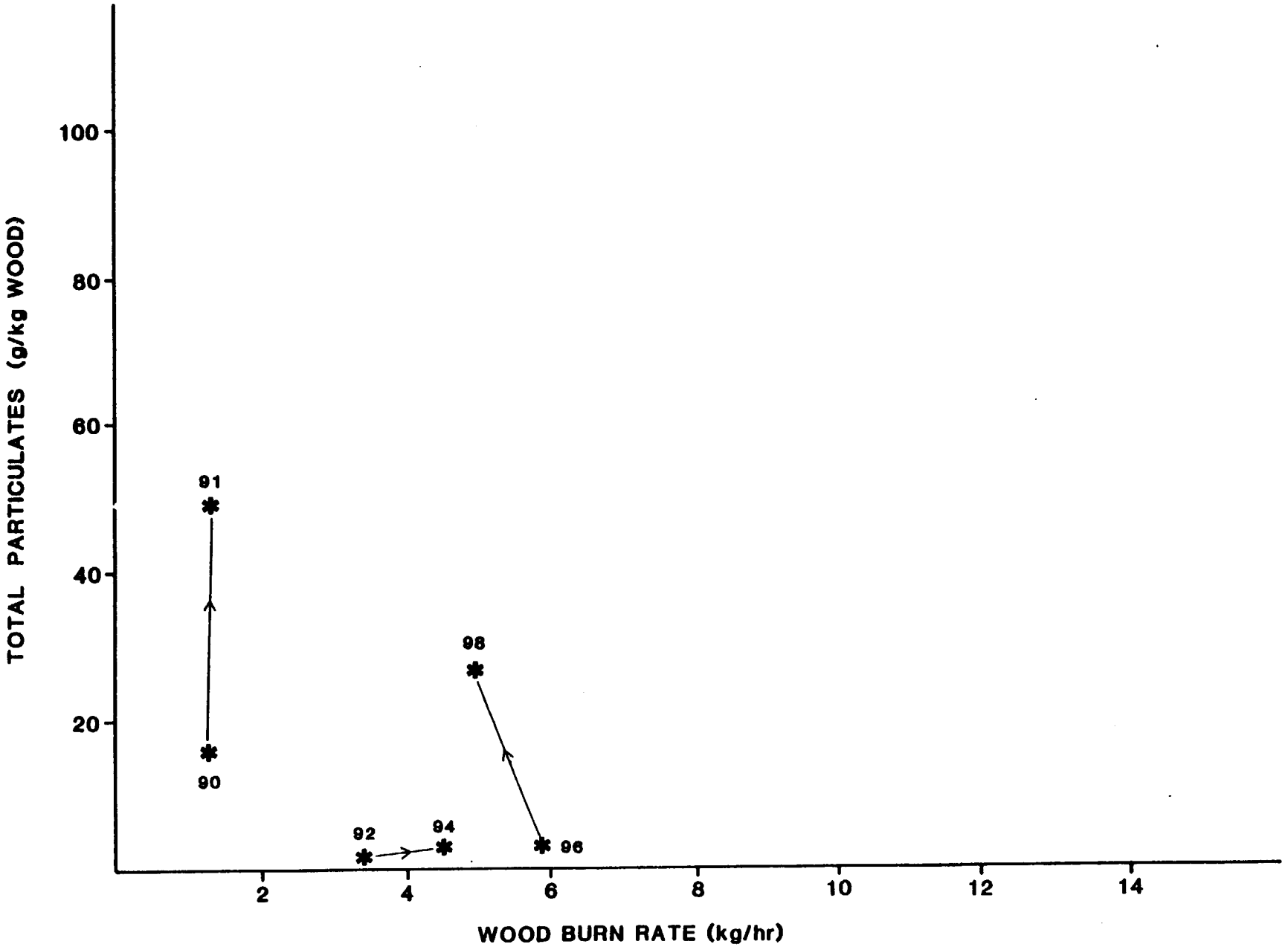


Figure 46. Effect of Burn Rate on Total Particulate Emissions–Wood Heater # 3

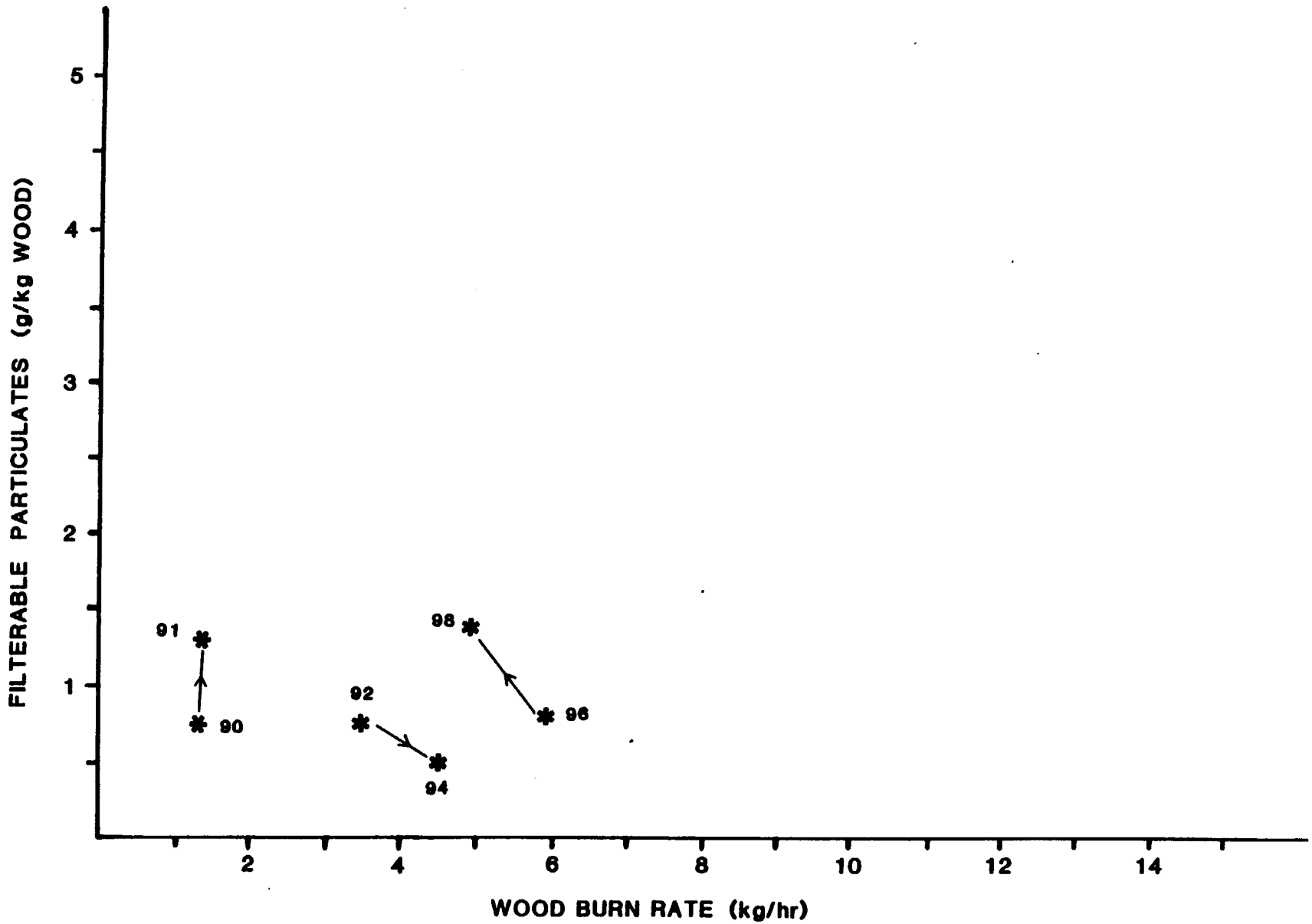


Figure 47. Effect of Burn Rate on Filterable Particulate Emissions - Wood Heater # 3

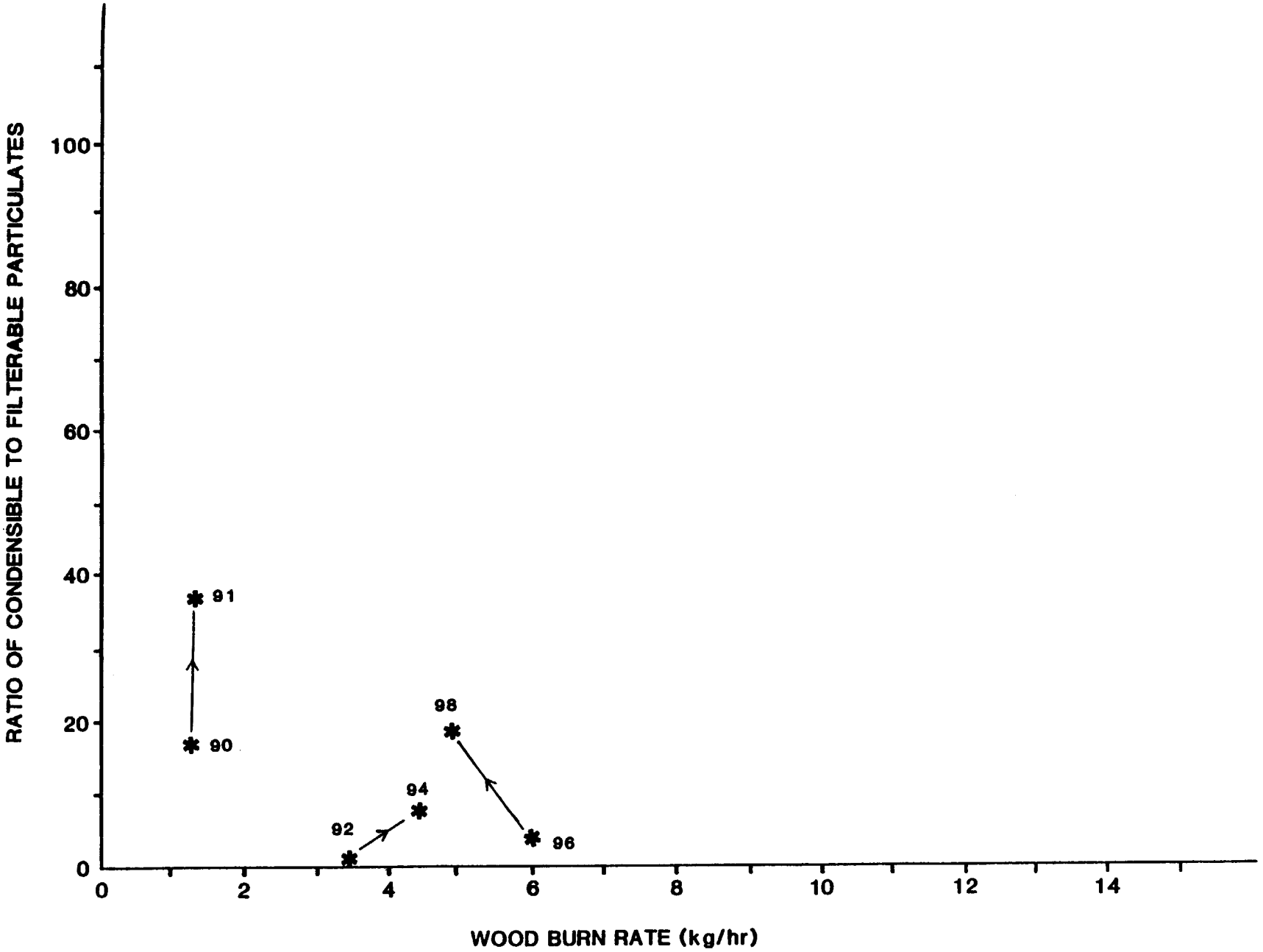


Figure 48. Effect of Burn Rate on the Ratio of Condensible to Filterable Particulates– Wood Heater # 3

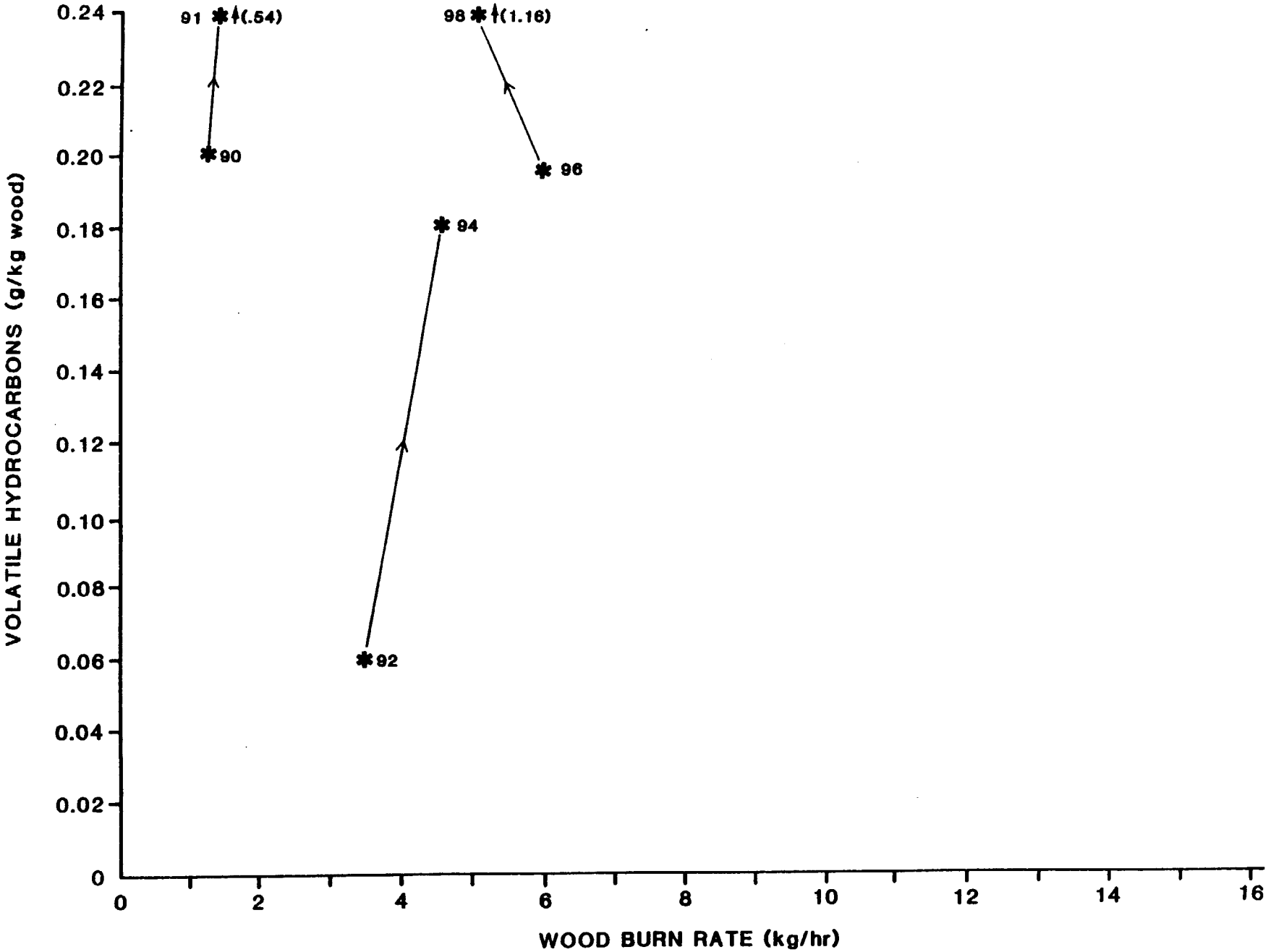


Figure 49. Effect of Wood Burn Rate on Volatile Hydrocarbon Emissions–Wood Heater #3

Table 22. WOOD HEATER #3
TEST RESULTS AVERAGED

	Before the Catalyst		At Exit of Wood Heater	
	Average	Std. Deviation	Average	Std. Deviation
erature of Gases (°F)	690.0	181.1	476.9	146.3
ss Air (%)	60.9	40.12	152.23	106.0
mal Efficiency (%)	54.2	3.8	59.9	5.2
Output (Btuh)	30,003	11,178	33,988	12,800
Emission Factor (g/kg)	130.9	31.2	78.2	47.2
Emission Factor (g/kg)	36.8	22.9	32.5	27.5
Emission Factor (g/kg)	0.695	0.212	1.034	0.361
bustion Efficiency (%)	82.0	7.9	85.6	10.3
t Transfer Efficiency (%)	66.3	5.1	70.4	3.6
sible + Latent Losses (%)	27.8	6.0	25.7	5.4
mical Losses (%)	21.9	7.7	14.4	10.3

	Average	Standard Deviation
od Burn Rate (lb/hr)	7.3	2.7
aft Air Supply (CFM)	14.5	3.8

Overall Performance Changes[a]	
CO Reduction (%)	40
THC Reduction (%)	12
NO_x Increase (%)	49
Thermal Efficiency Increase (%)[b]	11

[a] These changes result from analysis of samples taken from the gases before entering the catalytic combustor area and at the exit of the wood heater.
[b] Change in efficiency divided by the precatalyst efficiency.

catalytic unit in conjunction with wood heater #1 showed improved overall performance when the before catalyst and exit results are compared.

Wood heater #1, when retro equipped with the "add-on" unit, operated within a lower range of burn rates than found in earlier test results for wood heater #1. Over this lower range of burn rates, the average CO emission factor for wood heater #3 at the exit was reduced by 40 percent from that before the catalyst. The total hydrocarbons were reduced by 12 percent while the NO_x emissions were increased by 49 percent. The thermal efficiency was increased by 11 percent [i.e., (59.9-54.2)/54.4] from the entry to the catalyst to the exit of the wood heater. Only a small portion of the 11 percent increase in thermal efficiency was directly attributable to increased combustion efficiency which resulted from catalytic activity. Most of the thermal efficiency increase resulted from improved heat transfer efficiency.

Wood Heater #4

Table 23 presents a series of key diagnostic conditions for wood heater #4. Averages for before the catalyst and at the exit of the wood heater are presented. The data shown in the table are presented in figure form and discussed later in the Wood Heater #4 Results section.

Table 24 presents results from tests on wood heater #4 obtained using the efficiency and emissions model and gives the parameters considered important with regard to comparing combustion conditions before and after the catalytic combustor. Greater details of all wood heater #4 tests are presented in Volume II where many figures produced by computer graphics are shown. Continuous sampling of combustion gases before the catalyst and at the exit of the wood heater provided the detailed gas compositions required to perform such modeling. Tests 122 and 123 at

Table 23. WOOD HEATER #4
AVERAGE CATALYTIC TEST RESULTS - THERMAL - RED OAK CORDWOOD

Test	Wood Charge (lb)	Wood Burn Rate (lb/hr)	Damper Position	Air Supply (CFM)	Temp Flue Gas (°F)	Before Catalyst		Heat Output (Btuh)	Temp Flue Gas (°F)	Exit of Wood Heater		Heat Output (Btuh)
						Excess Air(%)	Thermal Efficiency			Excess Air(%)	Thermal Efficiency	
119	6.6	5.00	Open	18.5	749	180	41.8	15,459	511	202	54.5	10,817
120	11.6	7.97	Open	16.6	969	62	45.3	26,669	583	87	57.6	36,737
121	16.6	8.94	Open	16.2	957	43	46.4	30,643	605	63	56.1	37,867
118	21.5		Open	13.6	915	9	43.1	31,073	560	26	51.7	37,879
114	6.6	5.44	60%	30.4	677	312	31.9	12,830	483	367	41.4	15,847
117	21.5	9.65	60%	16.5	558	31	44.3	31,607	632	51	55.4	39,640
110	6.8	4.91	30%	18.1	698	168	44.1	15,999	419	247	53.4	20,742
111	11.5	6.62	30%	13.4	881	55	50.2	24,549	548	96	58.8	28,027
113	16.5	8.76	30%	14.3	1007	25	49.3	31,886	605	61	57.3	38,944
112	21.5	8.39	30%	12.4	879	19	49.0	30,378	568	53	54.4	33,925
104	11.6	3.02	10%	11.0	420	170	38.6	8,621	258	264	41.6	9,076
106	21.5	3.84	10%	8.8	649	74	40.6	11,517	348	139	47.2	13,528
122*	21.0	10.6	Open	16.1	947	-1	41.5	32,319	601	10	49.4	38,860
123*	21.0	9.29	Open	16.3	911	13	41.5	28,512	567	20	52.2	34,162

*Test run with catalyst-coated plates reversed.

Table 24.
AVERAGE DIAGNOSTIC CONDITIONS FOR CATALYTIC WOOD HEATER #4

	Before Catalyst (%)					Exit of Wood Heater (%)				
Test	Thermal Efficiency	Combustion Efficiency	Heat Tra. Efficiency	Sensible & Lat. Losses	Chemical Losses	Thermal Efficiency	Combustion Efficiency	Heat Tra. Efficiency	Sensible & Lat. Losses	Chemical Losses
119	41.8	88.8	47.1	47.0	11.2	54.5	90.0	60.5	35.6	10.0
120	45.3	85.5	53.0	40.2	14.5	57.6	86.4	66.6	28.9	13.6
121	46.4	82.9	56.0	36.5	17.2	56.1	82.9	67.6	26.8	17.1
118	43.1	72.4	59.5	29.3	27.6	51.7	73.2	70.7	21.5	26.8
114	31.9	86.7	36.8	54.8	13.3	41.4	86.5	47.8	45.1	13.5
117	44.3	80.1	55.4	35.7	19.9	55.4	82.3	67.4	26.9	17.7
110	44.1	86.9	50.8	42.7	18.1	53.4	86.2	61.9	32.8	13.8
111	50.2	86.1	58.4	35.8	14.0	58.8	86.7	67.8	28.0	13.3
113	49.3	85.7	57.5	36.4	14.3	57.4	84.9	67.5	27.5	15.1
112	49.0	78.7	62.2	29.7	21.3	54.4	78.5	69.3	24.2	21.5
104	38.6	62.0	62.3	23.4	38.0	41.6	60.5	68.7	18.9	39.5
106	40.6	68.3	59.4	27.7	31.7	47.2	66.9	70.5	19.8	33.1
122*	41.5	72.6	57.1	31.1	27.4	49.4	71.8	68.7	22.5	28.2
123*	41.5	74.0	56.2	32.4	26.1	52.2	74.9	69.7	22.7	25.1

*Test run with catalyst-coated plated reversed.

the bottom of the table are special in that they show how the catalytic wood heater performed when the catalytic combustor's activity had been removed.

A complete summary of emission factors for wood heater #4 is presented in Table 25. All tests have continuous analyzer emission factors for CO, NO_x, and FID total hydrocarbons. Integrated MM5 samples were recovered on designated tests for use in generating the organic emission factors. The activity of the catalytic combustor is shown when before and after catalyst emission factors are compared. No integrated samples were recovered before the catalyst.

Wood Heater #4: Efficiencies

The thermal efficiencies for wood heater #4 varied by less than 20 percent over the full range of tests conducted. Figure 50 shows that the heater's best performance was obtained when the air control (damper) was set at 30 percent open. The same general thermal efficiency was obtained for any damper setting of 30 percent or more when a large fuel load was fired. The burn rate for these large fuel loads varied between about 4 and 5 kg/hr even though the damper position was moved from 30 percent to fully open. For small wood loads, the thermal efficiency was more dependent on wood load. Since large wood loads were typically added at each firing, the heat output of wood heater #4 could not be reduced unless the damper was set lower than 30 percent. The results shown in Figure 50 show that the wood heater thermal output could be controlled by damper setting alone at damper settings less than 30 percent. At larger damper settings the size of the wood load being fired determined the burn rate. This means that in a situation requiring a burn rate of over 2.5 kg/hr the size of wood load must be used in controlling the burn

Table 25. WOOD HEATER #4
AVERAGE CATALYTIC TEST RESULTS - EMISSIONS (g/kg) - RED OAK CORDWOOD

Test	Exit of Wood Heater						Polynuclear Aromatic Hydrocarbons	Before Catalyst		
	CO	Total Hydrocarbons	NO_x	Filterable Particulates	Condensible Organics	Total Particulates	Volatile Hydrocarbons		CO	Total Hydrocarbons	NO_x
119	96	11	1.12						108	13	1.05
120	108	22	0.81						118	23	0.71
121	129	29	0.74						133	29	0.66
118	201	50	0.57						213	51	0.52
114	113	20	1.2						107	20	1.21
117	136	31	0.74						145	37	0.66
110	90	26	1.23	1.096	4.007	5.103	0.1380	0.0931	92	29	1.14
111	115	22	0.74						109	21	0.83
113	119	26	0.74	0.685	7.382	8.067	0.2240	0.2323	125	22	0.71
112	140	43	0.64						152	40	0.49
104	200	88	0.54						212	82	0.48
106	171	75	0.74						174	71	0.69
122*	213	55	0.57						218	52	0.52
123*	190	49	0.67						192	52	0.65

*Test run with catalyst-coated reversed.

■ WOOD HEATER #4 WITH TEST NUMBER

AIR CONTROL POSITION: 10, 30, 60%, AND FULLY OPEN

■→■ INCREASING WOOD CHARGE

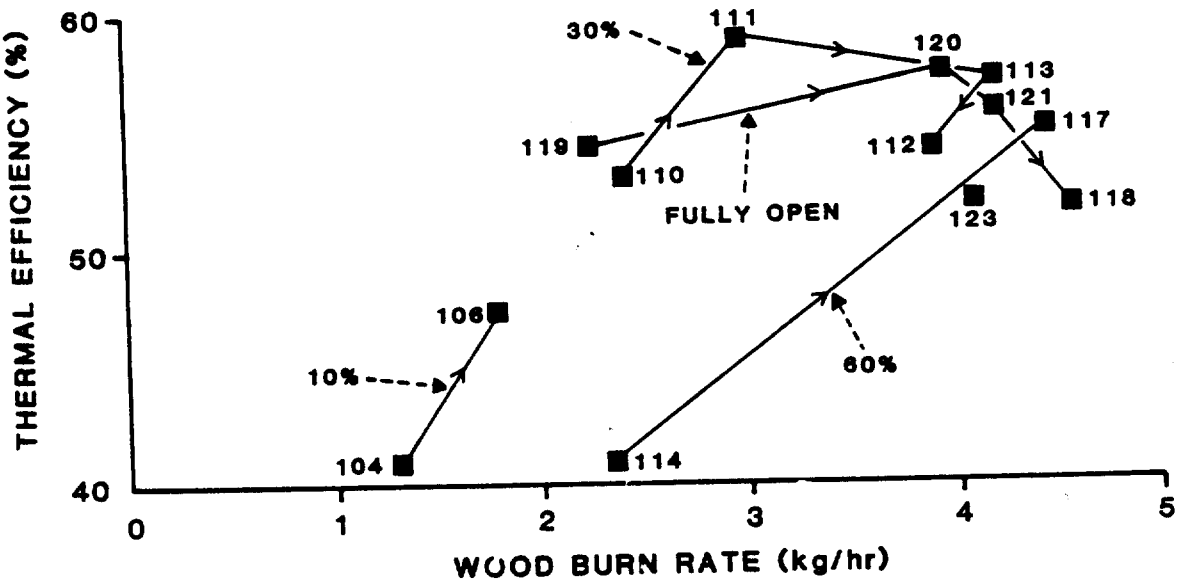


Figure 50. Thermal Efficiency Versus Burn Rate-Wood Heater #4

rate, not the damper. The actual heat output was determined by the damper setting as the 30 percent and fully open air control positions had much higher thermal efficiencies. Tests 123 and 118 were similar with respect to damper setting and wood load size. In test 123, however, the stainless steel catalytic plates were turned over thereby removing any potential catalytic action. Table 24 and Figure 50 show that there was no significant change in performance between these two tests.

Wood heater #4 combustion efficiencies varied inversely with burn rate for the mid- to higher burn rates. Figure 51 shows that the combustion efficiencies were over 80 percent except for the 10 percent air control setting and two more open damper tests using large fuel loadings. For damper positions over 10 percent open, wood heater #4 combustion efficiency was generally not significantly dependent upon air control setting or wood load size. The combustion efficiency for test 123 was shown to be higher than that for test 118.

Heat transfer efficiencies for wood heater #4 are shown in Figure 52. All air control positions other than 60 percent open showed heat transfer efficiencies over 60 percent. Additional tests are needed to determine whether the low heat transfer efficiency obtained for test 114 is reproducible and unique.

The summary of the distributed energies for wood heater #4 is presented in Table 26. The thermal efficiency ranged from 44 to 58 percent. Combustion efficiencies ranged from 63 to 84 percent while the heat transfer efficiency ranged from 58 to 70 percent. The sum of the sensible and latent losses varied from 19 to 36 percent, and the chemical losses varied from 16 to 36 percent. No closed damper results were available. The average values shown at the bottom of Table 26 will be discussed in the Comparative Discussion section of this report.

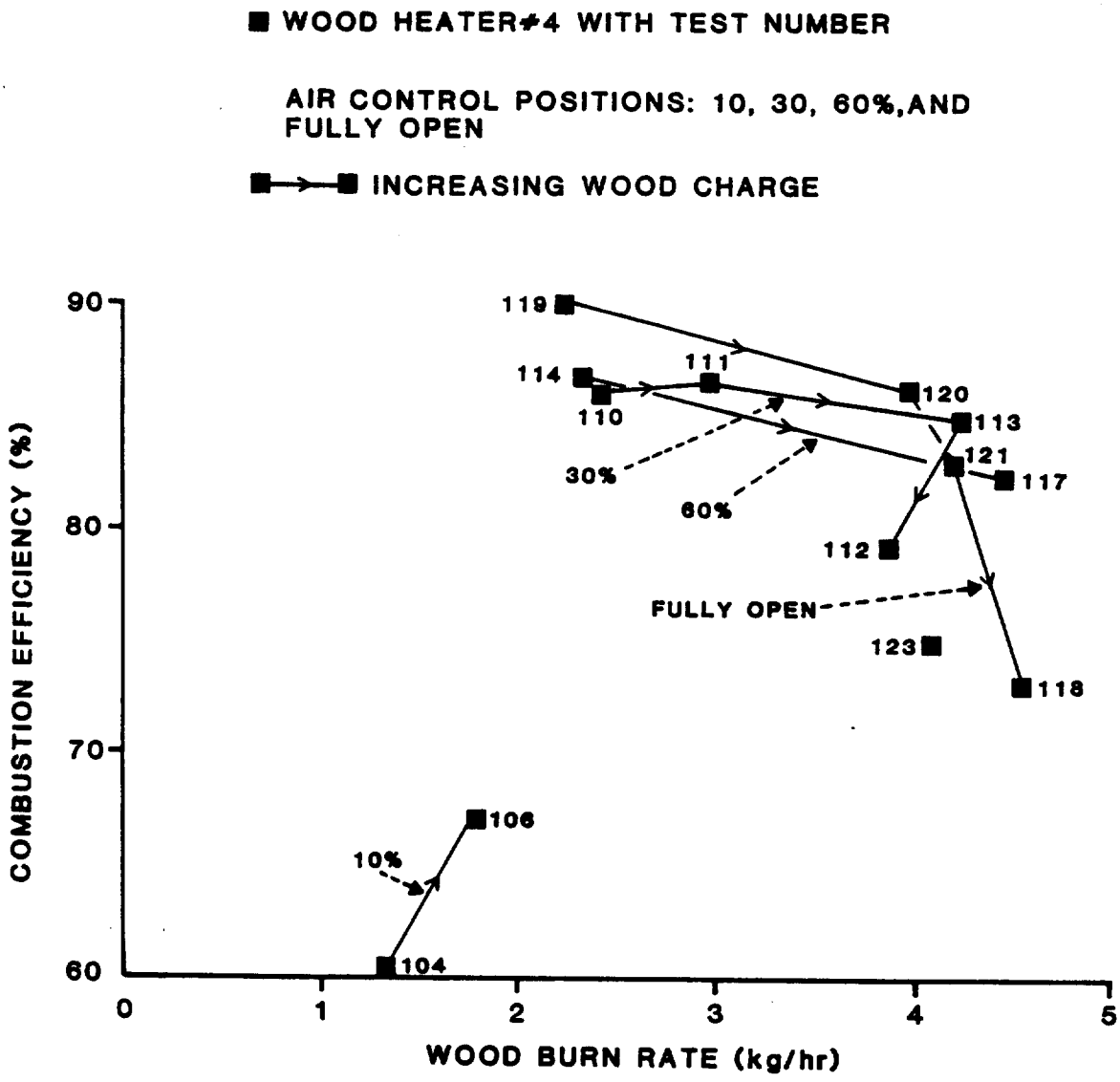


Figure 51. Combustion Efficiency Versus Burn Rate-Wood Heater#4

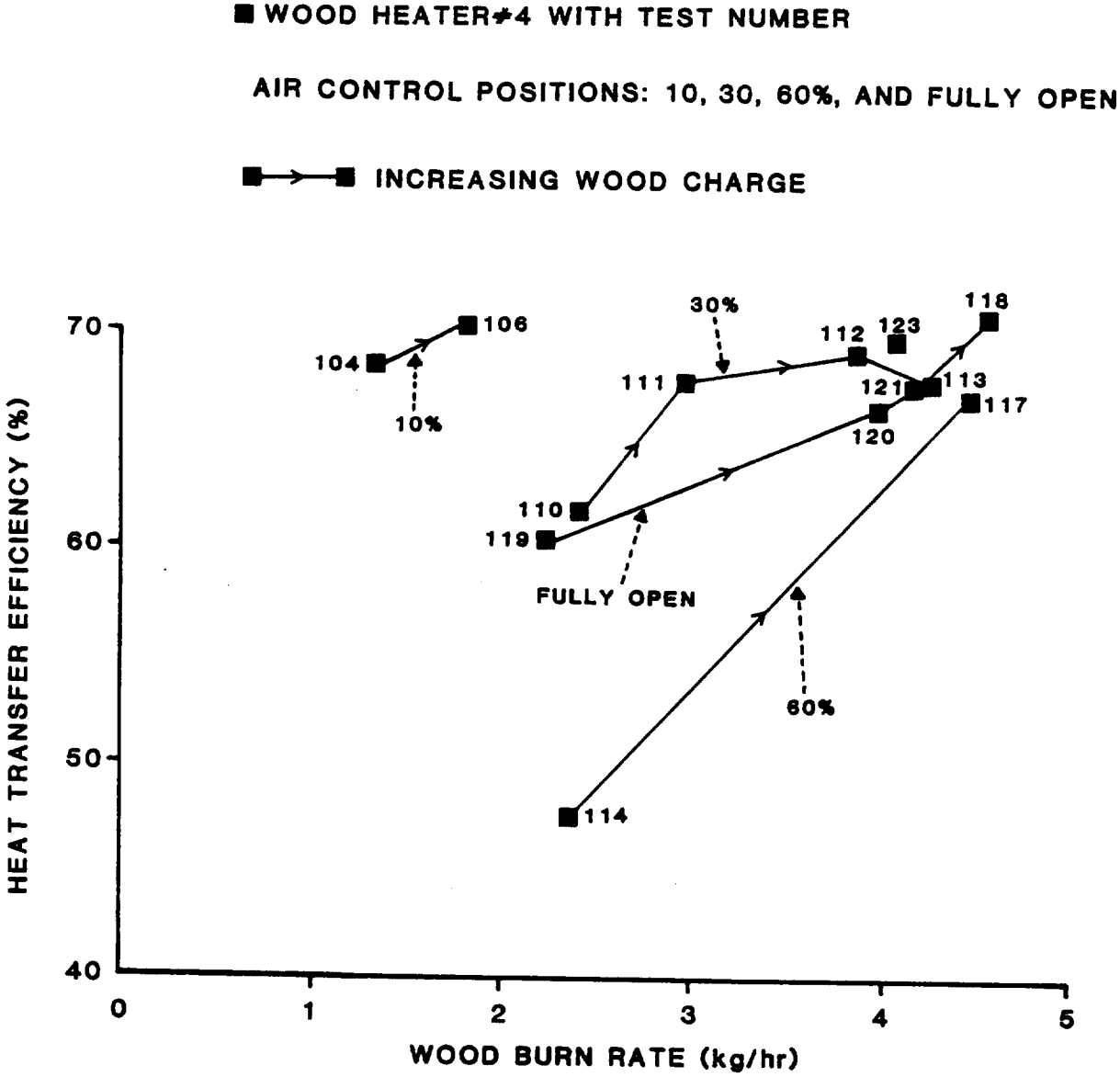


Figure 52. Heat Transfer Efficiency Versus Burn Rate-Wood Heater#4

Table 26. SUMMARY OF DISTRIBUTED ENERGIES[a] (%)
FOR WOOD HEATER #4

Damper Setting	Burn Rate (kg/hr)	Thermal Efficiency	Combustion Efficiency	Heat Transfer Efficiency	Sensible Plus Latent Losses	Chemical Losses
Open	3.7	55.0	83.1	66.4	28.2	16.8
60%	3.4	48.4	84.4	57.6	36.0	15.6
30%	3.3	56.1	84.1	66.6	28.1	15.9
10%	1.6	44.4	63.7	69.6	19.3	36.3
Average	3.0	51.0	78.8	65.1	27.9	21.2

[a]Average of four tests, each having a different cordwood fuel loading size.

Wood Heater #4: Emissions

Carbon monoxide (CO) emission factors shown in Figure 53 increased with increase in wood load size for 30 percent and fully open damper settings. Similar CO emission factors were found for both 30 percent and fully open damper settings. At the fully open damper setting, the CO emission factor increased from 90 to 200 g/kg as the wood load size increased from 3 kg to 9.8 kg. At a damper setting less than 30 percent, the CO emission factors increased with decreased burn rate. The 10 percent damper setting shown in Figure 53 represents this poor mode of operation as the CO emissions increased to 200 g/kg for the smaller wood load size. Figure 53 shows that CO emission factors were primarily dependent upon wood load size and independent of damper setting for damper settings equal to 30 percent open or larger.

Total hydrocarbon emission factors for wood heater #4 are shown in Figure 54. The total hydrocarbon (THC) emission factors were also primarily dependent upon wood load size and independent of damper setting for damper settings equal to 30 percent open or larger. The THC emission factors also increased rapidly with decreased damper setting below 30 percent open. The 10 percent damper setting included in Figure 54 clearly shows this trend.

Table 25 presents NO_x emission factors for wood heater #4. The NO_x emission factor ranged from 0.5 to 1.23 g/kg for all tests with little change existing across the catalytic sections.

Two intermediate burn rate tests (110 and 113) were conducted on wood heater #4 and the MM5 catch was used to quantify the total PAH emission factors. Table 27 presents data for the two tests. The naphthalene component represented about 50 percent of the total PAH while benzo(a)pyrene

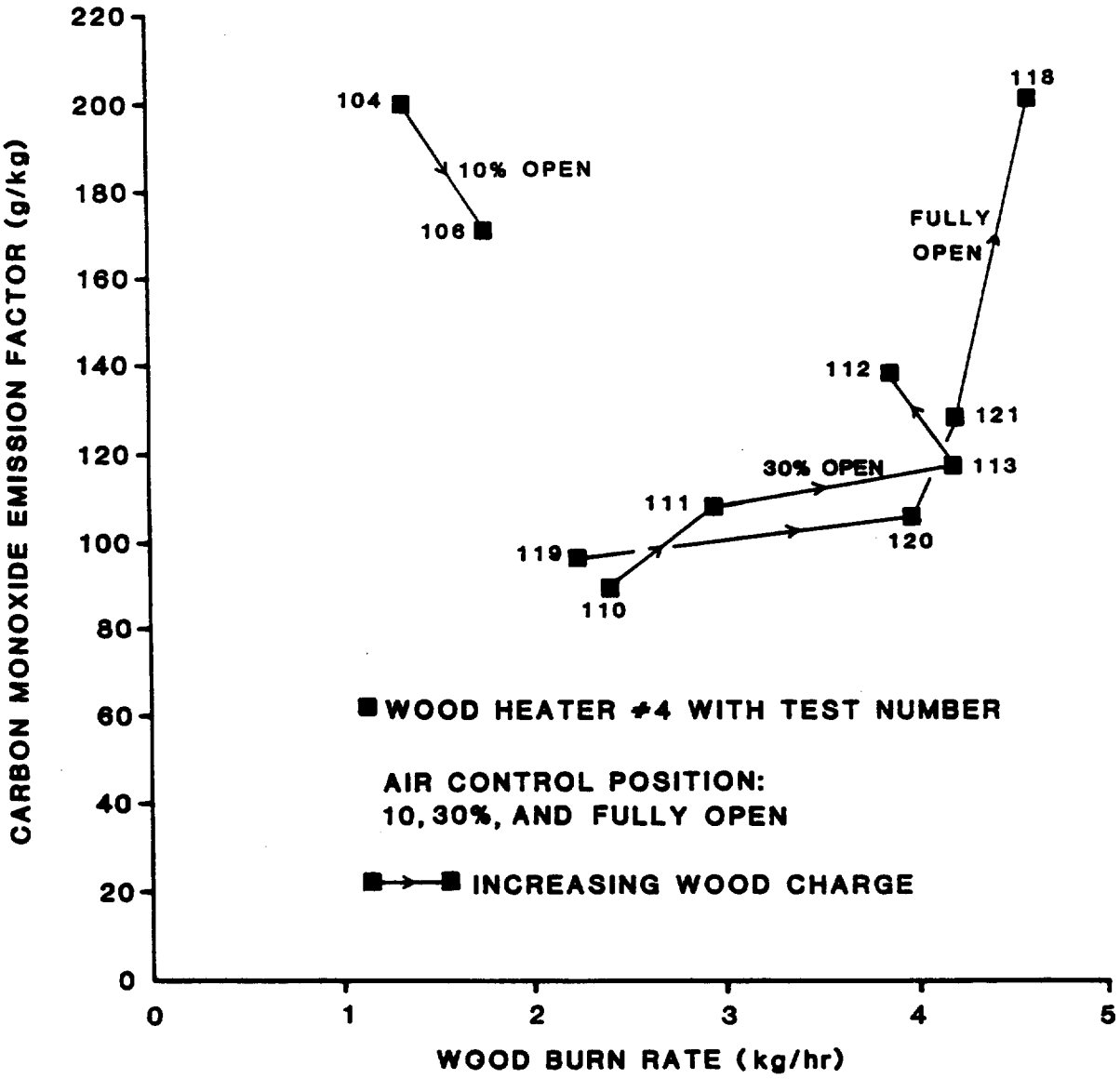


Figure 53. Carbon Monoxide Emission Factor Versus Burn Rate-Wood Heater #4.

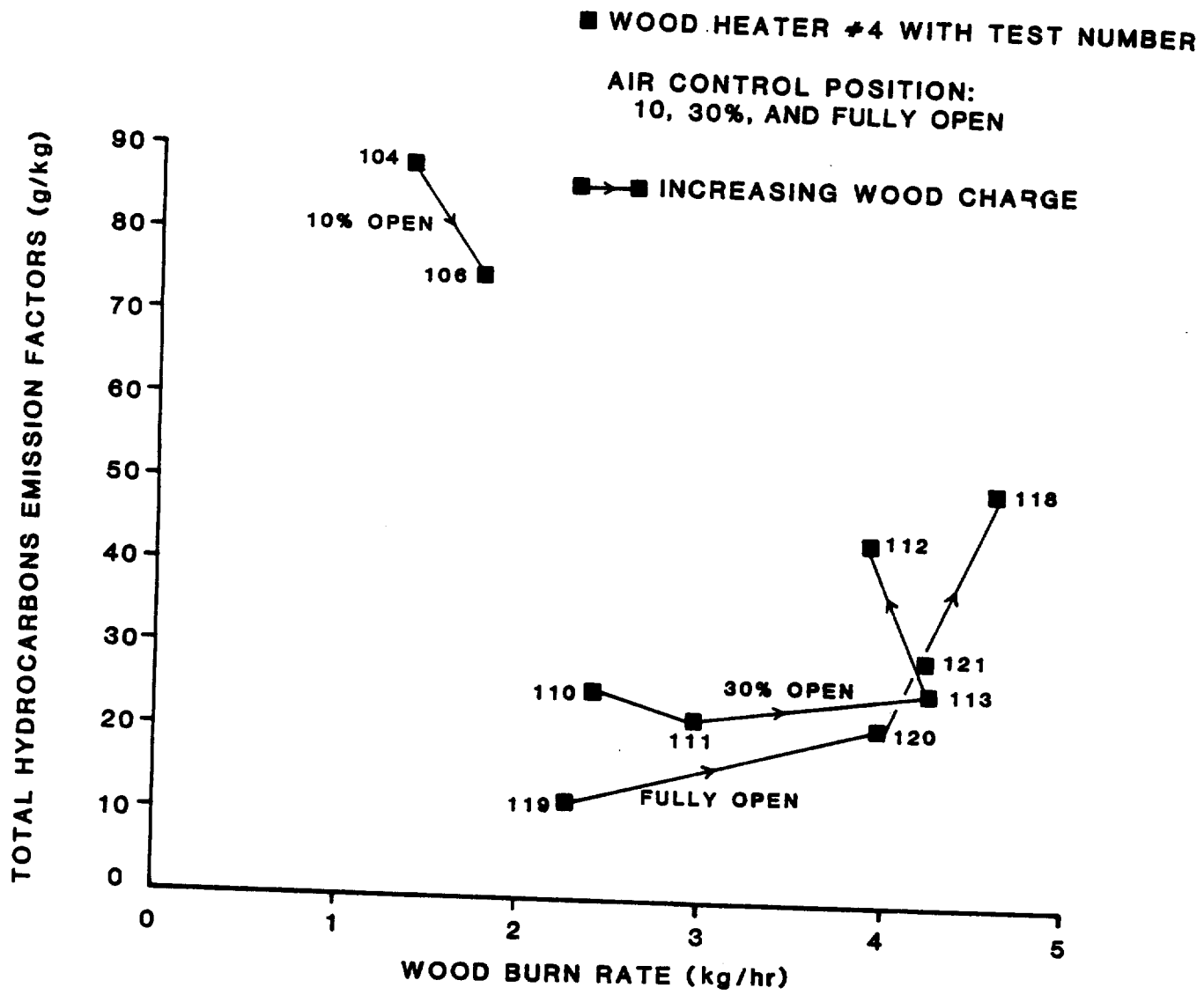


Figure 54. THC Emissions Versus Burn Rate – Wood Heater #4

Table 27. WOOD HEATER #4
PAH EMISSION FACTORS (g/kg) - OAK CORDWOOD

	Test Number	
	110	113
Naphthalene/Methylnaphthalenes/ Phenylnaphthalenes	0.0565	0.1166
Acenaphthylene	0.0066	0.0224
Acenaphthene	0.0028	0.0083
Fluorene	0.0020	0.0054
Phenanthrene/Anthracene	0.0141	0.0452
Fluoranthene	0.0021	0.0078
Pyrene	0.0022	0.0063
Benzo (g,h,i) fluoranthene	0.0015	0.0054
Chrysene/Benzo (a) anthracene	0.0025	0.0073
Benzo (b) fluoranthene/ benzo (k) fluoranthene	0.0014	0.0035
Benzo (a) pyrene	0.0015	0.0017
Indeno (1,2,3-c,d) pyrene/ Benzo (g,h,i) perylene	———	0.0026
Dibenzo (a,h) anthracene	———	———
Total	0.0932	0.2325

made up less than 1.7 percent. Phenanthrene was the second largest component in the total PAH.

The total PAH emission factor for wood heater #4 increased with the size of the wood fuel load as is shown in Figures 55 and 56. The excess air shown in Figure 57 for test 113 was reduced from the 250 associated with the small wood fuel loading in test 110. The total PAH emission factors shown in Figure 58 will take on more significance when they are used for comparative evaluation of each wood heater.

Table 28 presents the emission factors for compounds other than PAH that are associated with the integrated sample recovered by the MM5 sampling system. The table also contains volatile hydrocarbon emission factors along with the volume percent of methane and ethylene making up the volatiles.

Table 28. WOOD HEATER #4
EMISSION FACTORS FOR COMPOUNDS OTHER THAN PAH (g/kg)

	Test Number	
	110	113
Filterable Particulate[a]	1.0932	0.6833
Front Half Gravimetric[b]	0.4712	0.1312
Back Half Gravimetric[c]	3.4515	5.6327
Back Half TCO[d]	0.5537	1.7496
Total Condensible Organics[e]	4.0052	7.3823
Total Particulates[f]	5.0984	8.0656
Volatile Hydrocarbons (g/kg)	0.138	0.224
Major Constituents:		
Methane (vol. %)		54
Ethylene (vol. %)		28

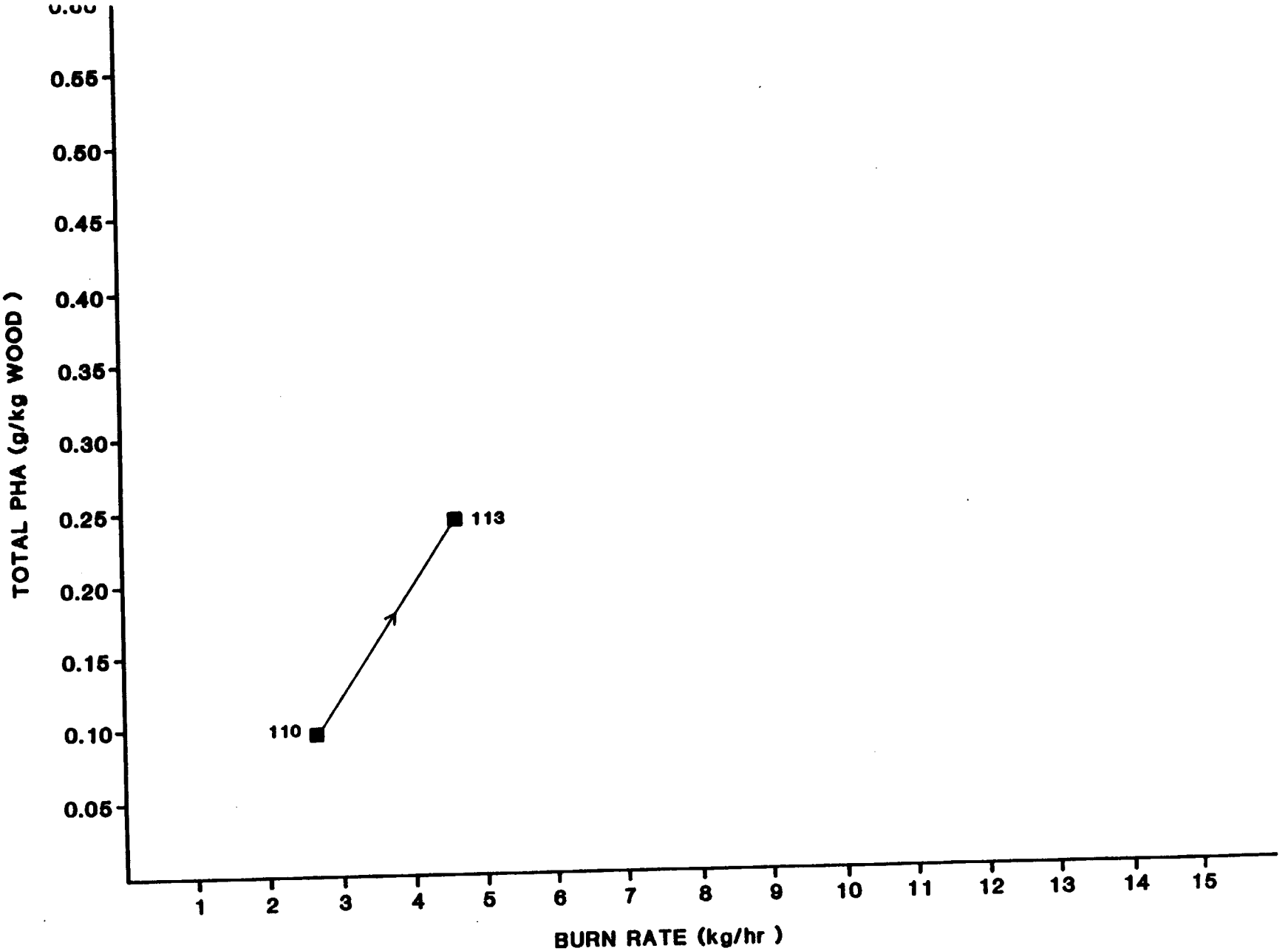


Figure 55. Effect of Burn Rate on PAH Emissions–Wood Heater # 4

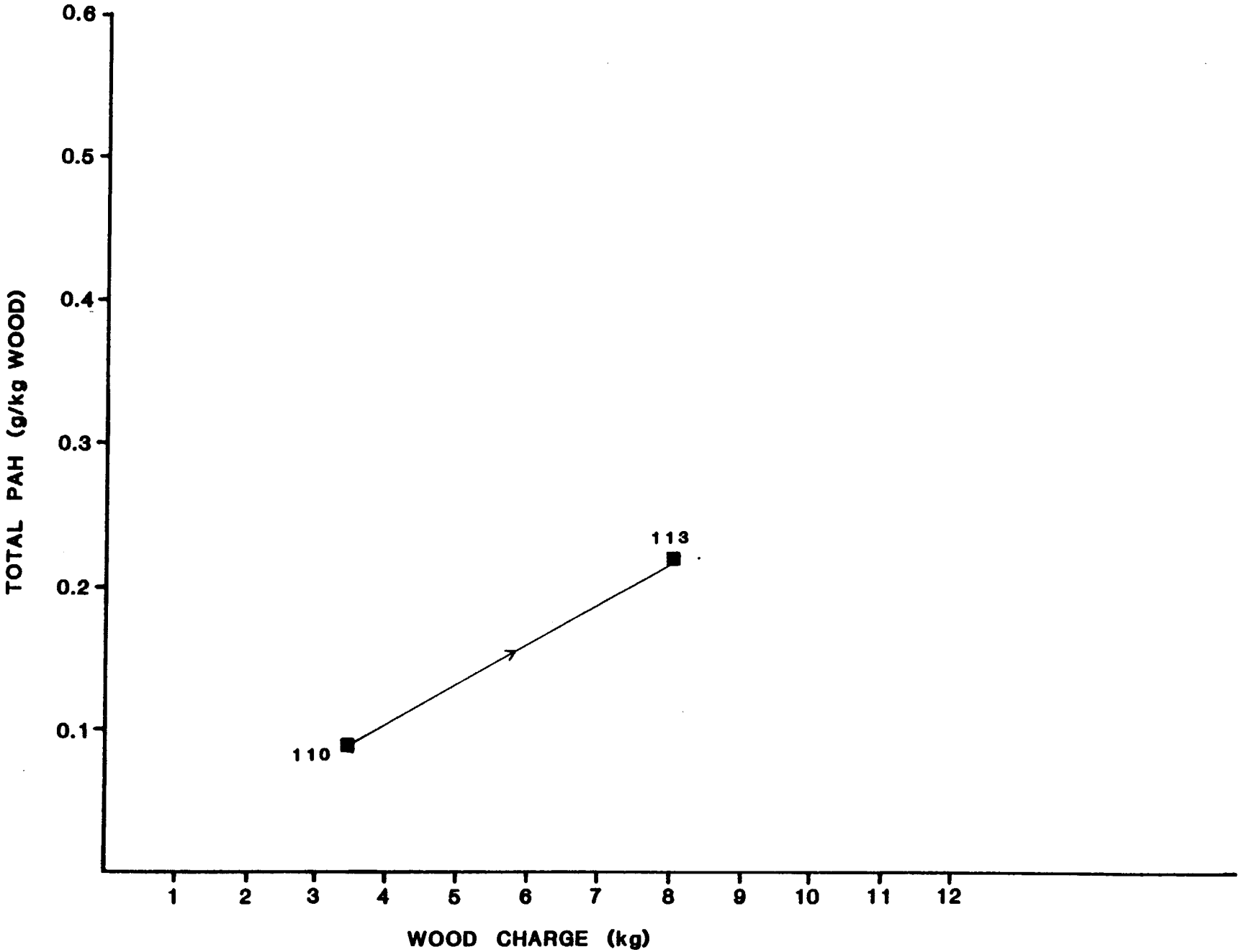


Figure 56. Effect of Wood Charge on PAH Emissions–Wood Heater # 4

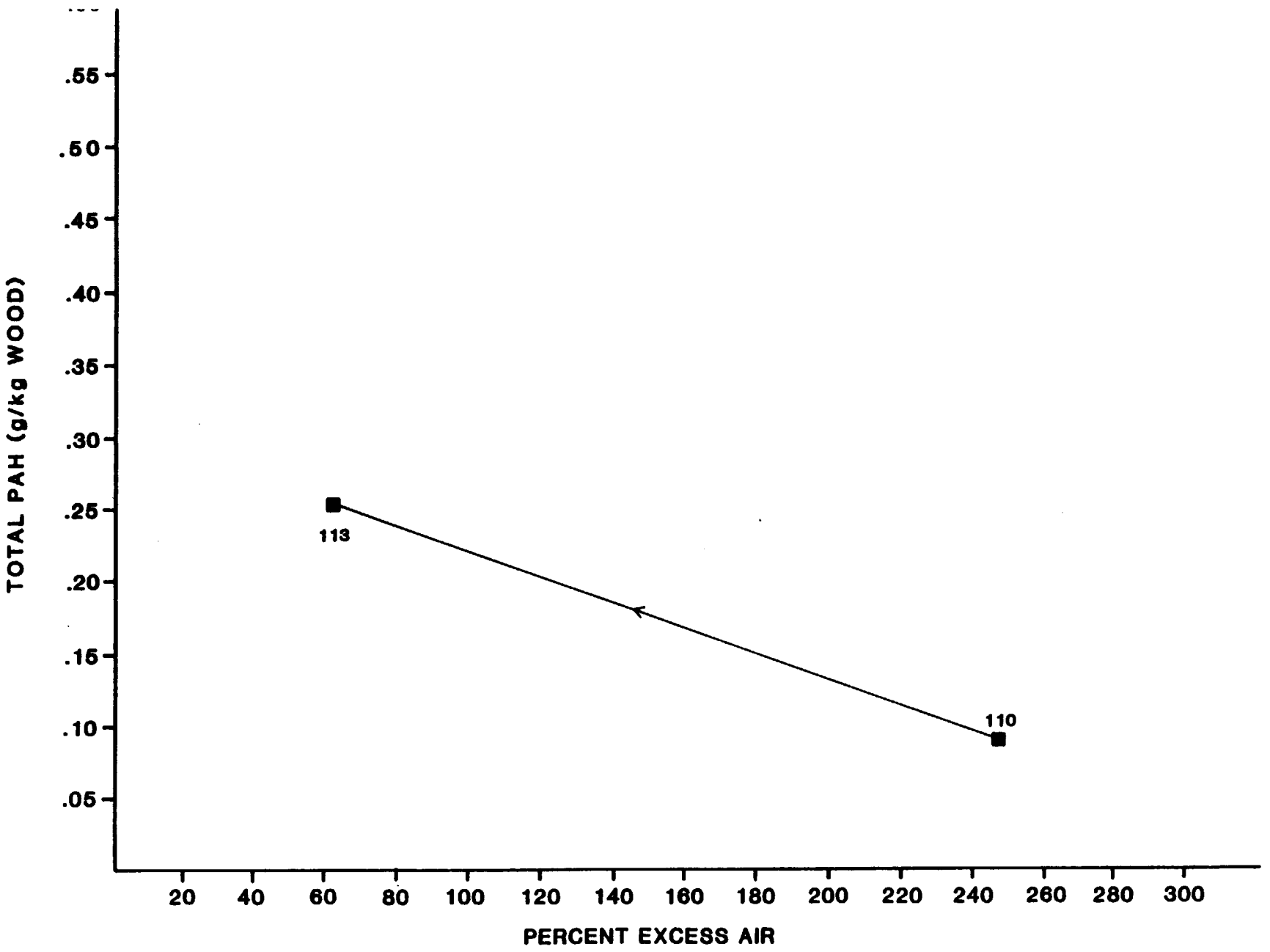


Figure 57. Effect of Percent Excess Air on PAH Emissions– Wood Heater # 4

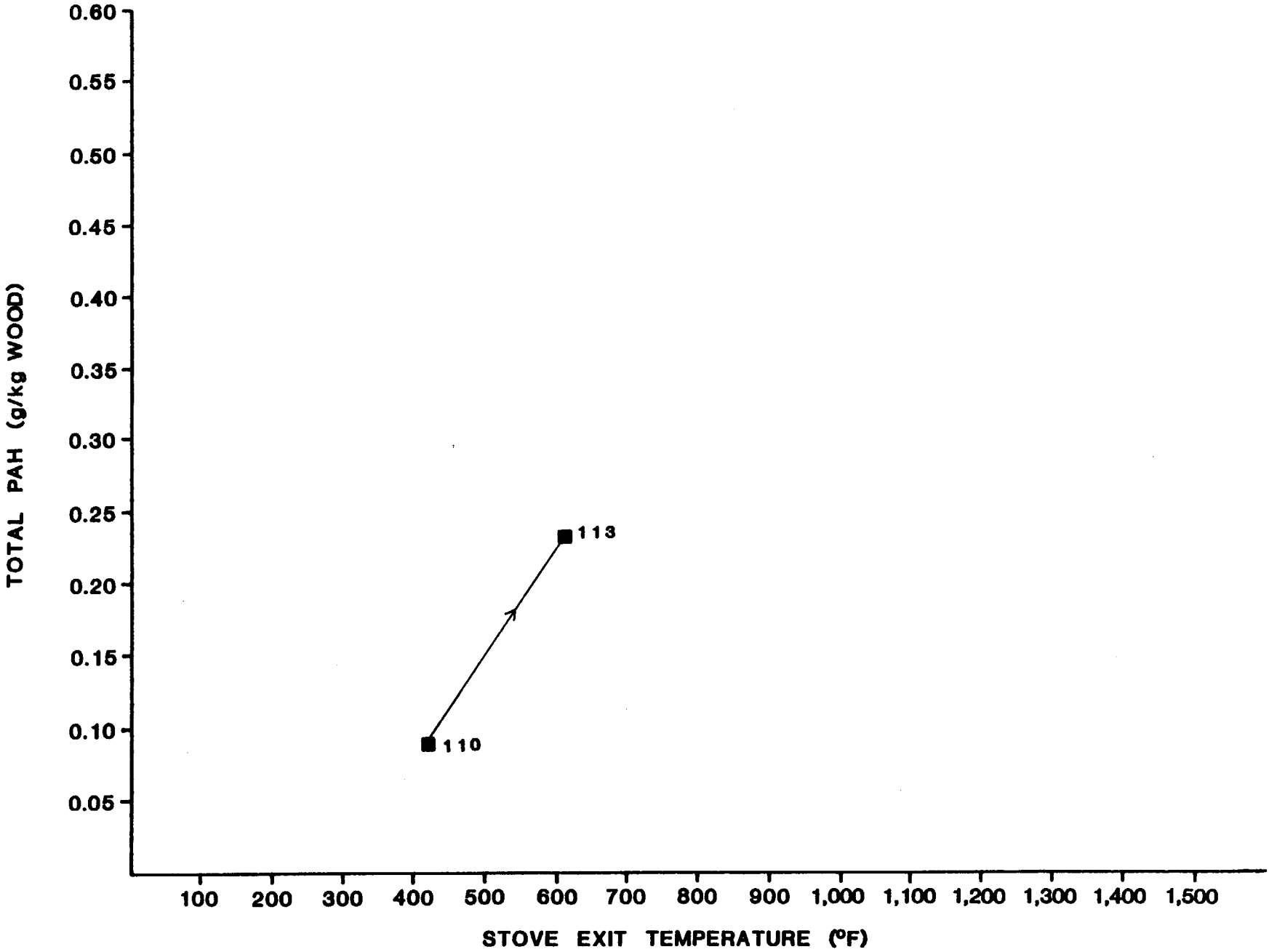


Figure 58. Effect of Stove Exit Temperature on PAH Emissions- Wood Heater # 4

The two total particulate emission factors presented in Figure 59 show that wood heater #4 had low total particulates at medium burn rates. Total particulates were not developed for low and high burn rates.

Filterable particulate emission factors are presented in Figure 60 and the ratio of condensible organics to filterable particulates is shown in Figure 61.

Figure 62 presents two volative emission factors. The volatiles were shown to be again dependent upon wood fuel loading size.

Table 29 presents comparative averages for diagnostic parameters and emission factors. The overall reduction of CO between the two sampling positions was 4 percent while that for total hydrocarbons was -1 percent. A 7 percent increase in NO_x was found. The thermal efficiency was improved by 20 percent due to additional heat exchange following the catalytic assembly. This result was due only to heat recovery since the combustion efficiency was unchanged across the catalyst while the sensible and latent heat losses were reduced from 36.6 to 28.0 percent. The chemical losses associated with incomplete combustion were not changed across the catalytic elements.

Wood Heater #5

Table 30 presents a series of key diagnostic conditions for wood heater #5. The data shown in the table are presented in figure form and discussed later in the wood heater #5 results section.

A complete summary of emission factors for wood heater #5 is presented Table 31. All tests have continuous analyzer emission factors for CO, NO_x, and FID total hydrocarbons. Integrated samples were recovered on designated tests for use in generating the organic emission factors.

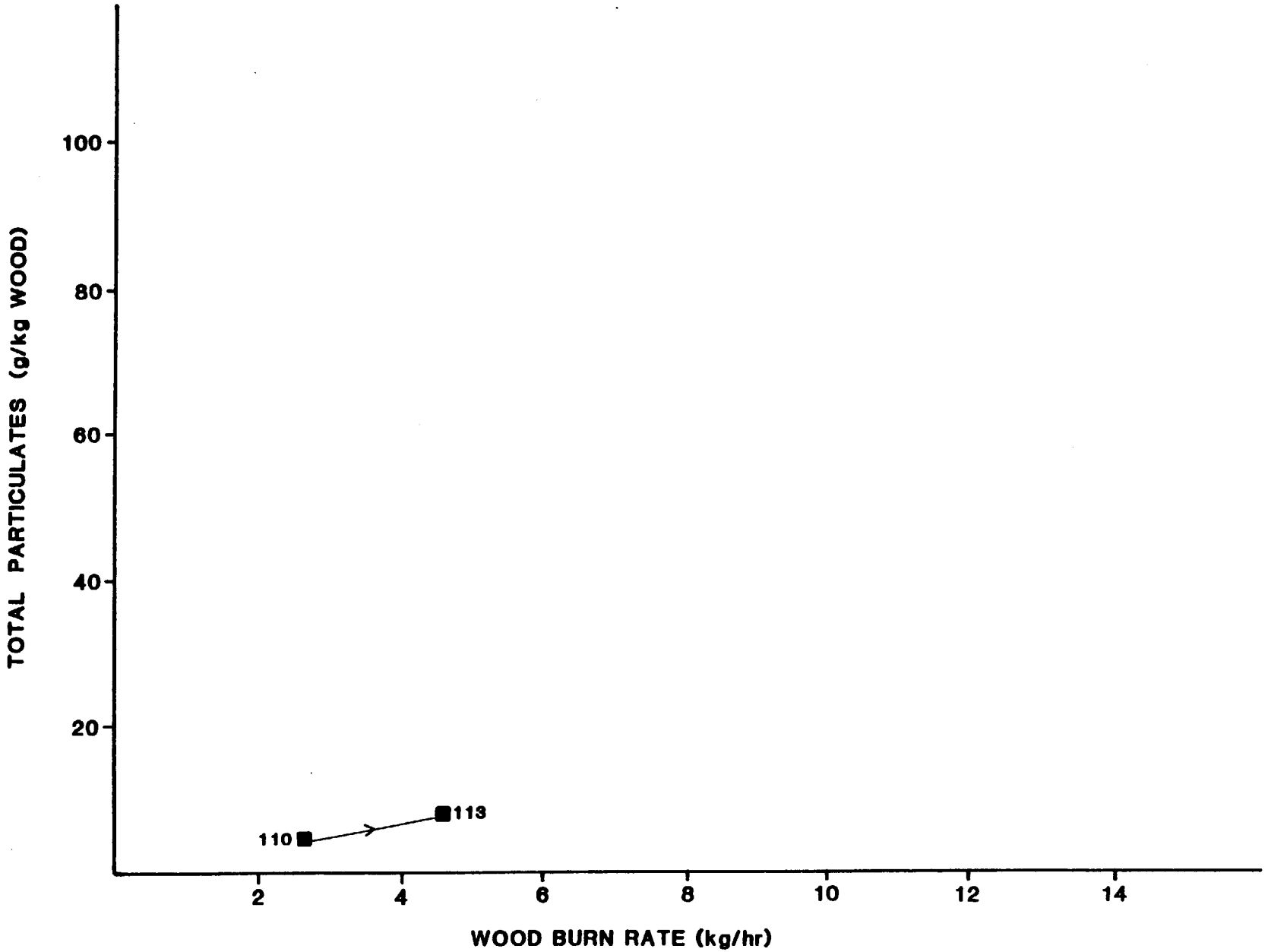


Figure 59. Effect of Burn Rate on Total Particulate Emissions–Wood Heater #4

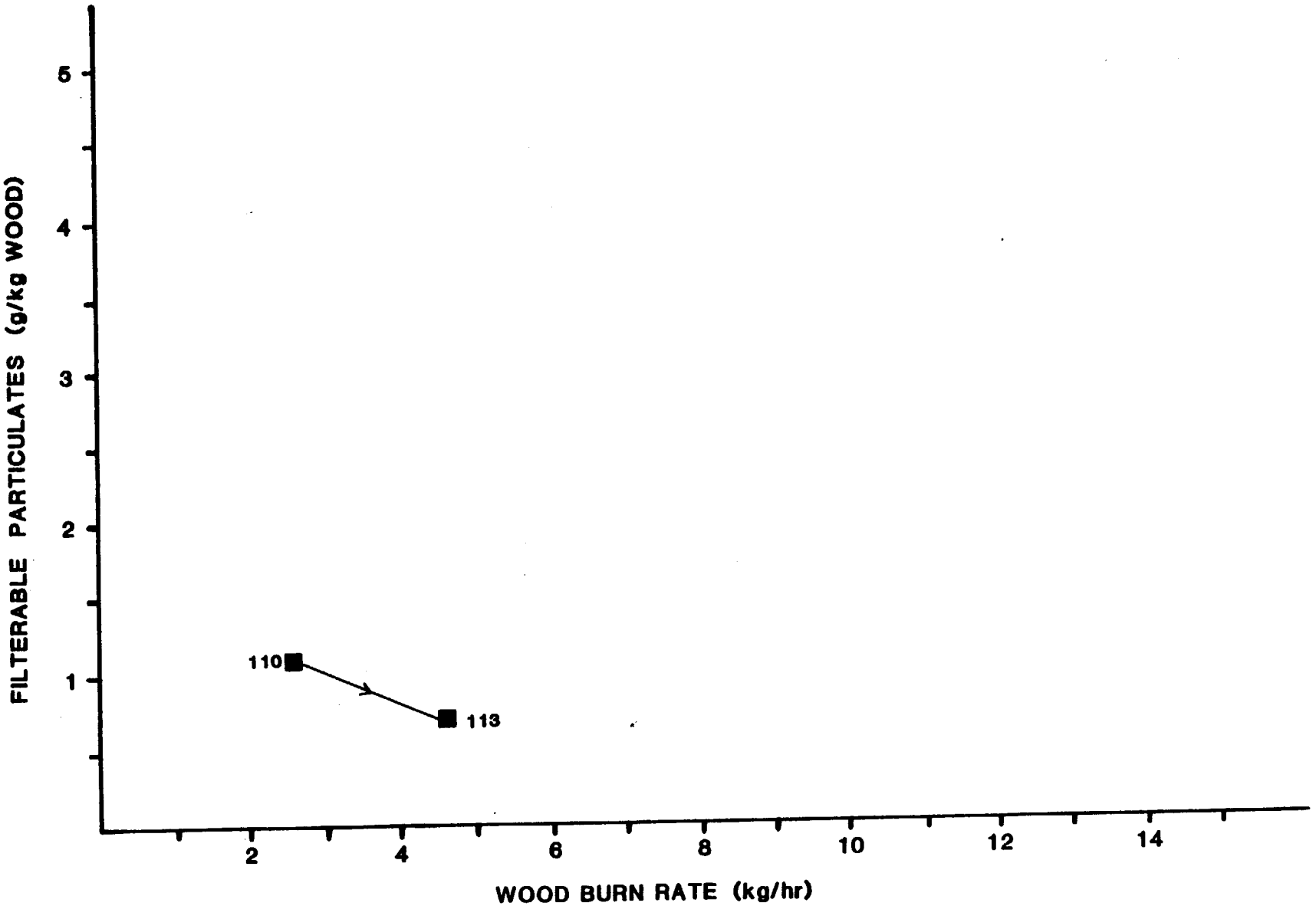


Figure 60. Effect of Burn Rate on Filterable Particulate Emissions–Wood Heater # 4

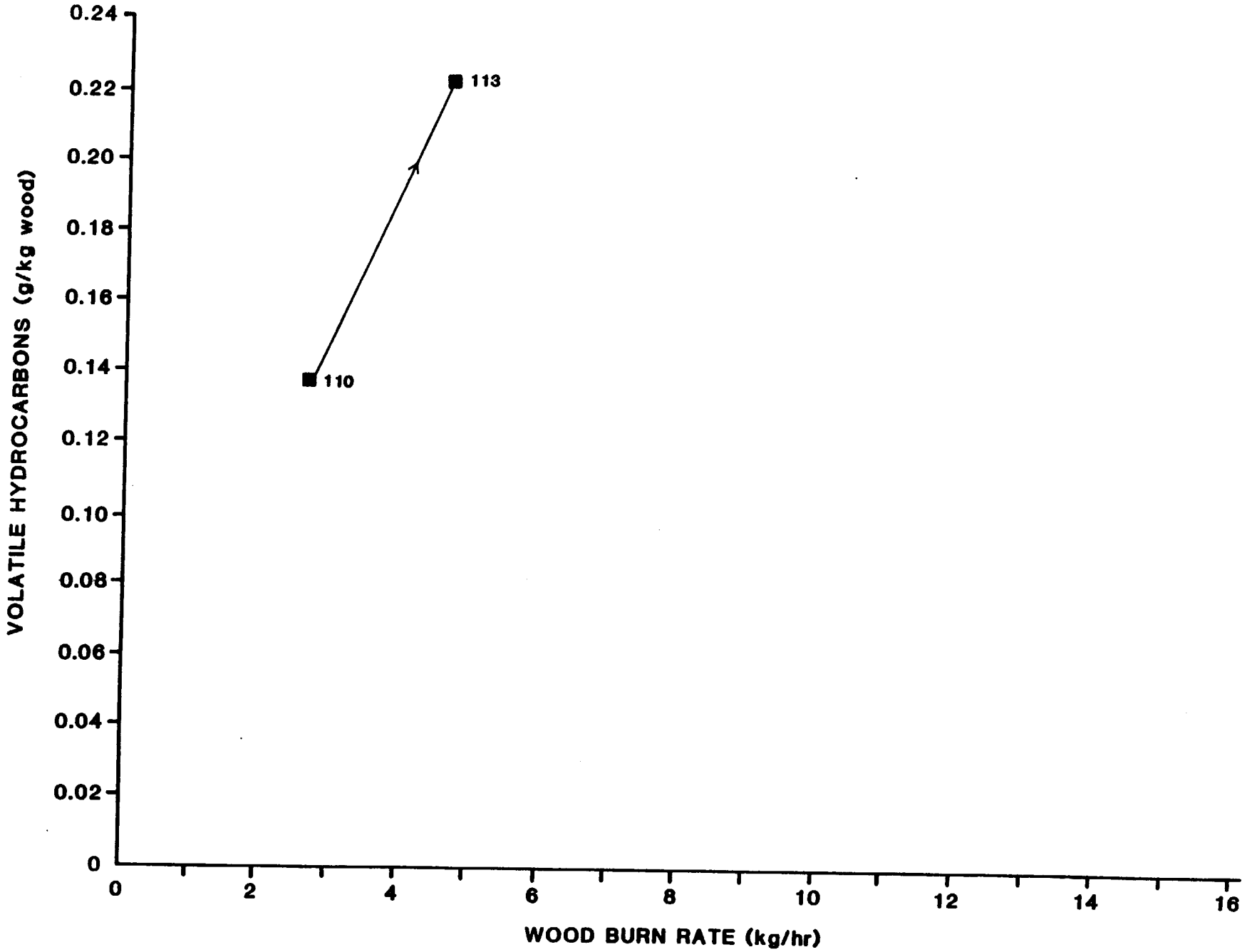


Figure 62. Effect of Wood Burn Rate on Volatile Hydrocarbon Emissions–Wood Heater # 4

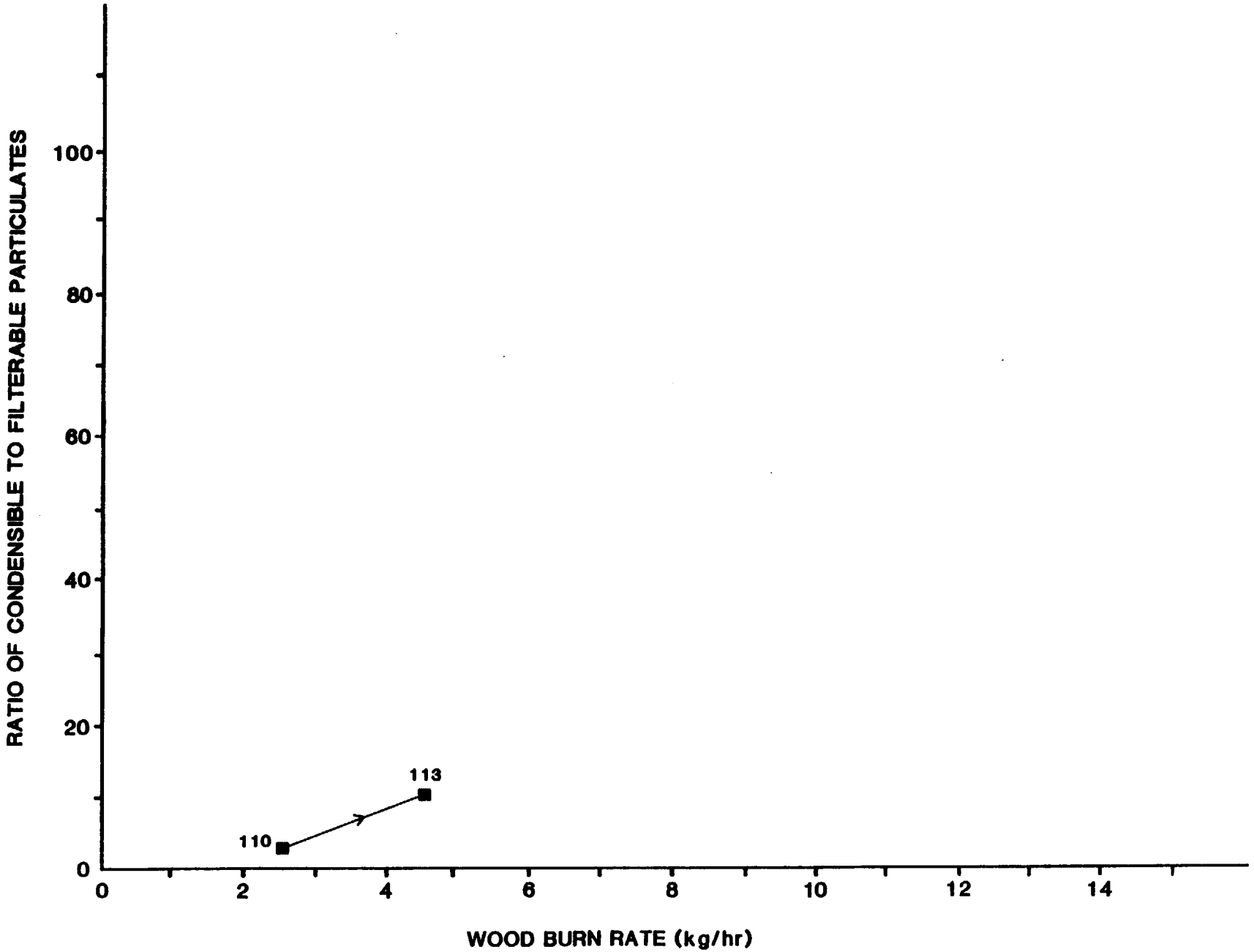


Figure 61. Effect of Burn Rate on the Ratio of Condensible to Filterable Particulates--Wood Heater # 4

Table 29. WOOD HEATER #4
TEST RESULTS AVERAGED

	Before the Catalyst		At Exit of Wood Heater	
	Average	Std. Deviation	Average	Std. Deviation
Temperature of Gases (°F)	779.9	183.7	510.0	114.5
Excess Air (%)	95.6	92.1	138.0	107.7
Thermal Efficiency (%)	43.7	5.1	52.5	5.9
Heat Output (Btuh)	22,603	9,010	27,669	11,262
CO Emission Factor (g/kg)	140.7	40.4	134.8	37.4
THC Emission Factor (g/kg)	36.5	21.4	36.9	23.4
NO_x Emission Factor (g/kg)	0.763	0.248	0.818	0.235
Combustion Efficiency (%)	80.3	8.5	80.4	9.1
Heat Transfer Efficiency (%)	54.9	7.3	65.5	6.4
Sensible + Latent Losses (%)	36.6	8.8	28.0	7.3
Chemical Losses (%)	19.7	8.5	19.6	9.1

	Average	Standard Deviation
Wood Burn Rate (lb/hr)	6.6	2.3
Draft Air Supply (CFM)	15.8	5.4

Overall Performance Changes[a]	
CO Reduction (%)	4
THC Reduction (%)	-1
NO_x Increase (%)	7
Thermal Efficiency Increase (%)[b]	20

[a]These changes result from analysis of samples taken from the gases before entering the catalytic combustor area and at the exit of the wood heater.
[b]Change in efficiency divided by the precatalyst efficiency.

Table 30. WOOD HEATER #5
AVERAGE AIRTIGHT TEST RESULTS - THERMAL - OAK 2"x4" BRANDS

Test	Wood Charge (lb)	Damper Setting	Supply Air (CFM)	Wood Burn Rate (lb/hr)	T Flue Gas (°F)	Excess Air (%)	Thermal Efficiency	Diagnostic Efficiencies (%) Combustion	Flue Gas Losses (%) Heat Transfer	Sen+Latent	Chemical	Heat Output (Btuh)
130	4.0	Open	12	4.13	582	122	64.2	96.5	66.5	32.3	4.1	19,594
124	6.0	Open	13	6.53	719	53	59.3	89.3	66.4	30.0	10.7	28,619
129	8.0	Open	14	7.13	712	42	60.4	89.6	67.4	29.2	10.4	31,826
133*	8.0	Open	11	6.67	790	37	68.2	98.3	69.4	30.1	1.7	33,606
131	4.0	60%	10	4.50	554	64	68.9	94.3	73.1	25.4	5.7	22,928
128	6.0	60%	16	6.62	722	72	61.3	94.2	65.0	32.9	5.8	29,949
127	8.0	60%	15	5.58	669	101	61.5	95.0	65.0	33.6	5.0	25,329
132	4.0	30%	16	4.77	522	152	47.4	77.5	61.1	30.1	22.5	16,675
125	6.0	30%	14	8.38	664	29	57.8	82.7	69.9	24.9	12.3	35,798
126	8.0	30%	18	6.18	505	113	41.8	67.6	61.9	25.8	32.4	19,085

*Segment of test run during optimum secondary combustion.

Table 31. WOOD HEATER #5
AVERAGE AIRTIGHT TEST RESULTS - EMISSIONS (g/kg) - RED OAK CORDWOOD

Test	CO[1]	Total Hydrocarbons[2]	NO_x[3]	SO_2[4]	Filterable Particulates[5]	Condensible Organics[6]	Total Particulates	Volatile Hydrocarbons[7]	Polycyclic Organic Material[8]
130	41	2	1.47	0.77					
124	79	19	1.17	1.00	1.90	0.69	0.88	0.06	0.43
129	89	17	0.99	1.07					
133	11	1	1.50	0.58					
131	55	6	1.15	0.67					
128	45	8	1.12	0.90					
127	47	6	1.27	0.85	0.29	2.23	2.52	0.11	0.11
132	118	49	0.86	0.92					
125	114	35	1.00	0.98					
126	137	79	0.90	1.12					

[1]Beckman 864 Analyzer (Infrared)
[2]Beckman 402 FID Analyzer
[3]TECO model 10A (Chemiluminescent)
[4]TECO model 40 (Pulsed Fluorescent)
[5]EPA Modified Method 5 (205°C filter section), gravimetric
[6]EPA Modified Method 5, ice bath impingers and resin trap, gravimetric, TCO (GC/FID)
[7]GC/FID, sample taken from dry gas flow leaving Method 5 flow meter
[8]EPA Modified Method 5 with XAD-2 resin trap, GC/MS

Wood Heater #5: Efficiencies

Thermal efficiencies for wood heater #5 are shown in Figure 63. The 60 percent open primary air control setting provided the highest thermal efficiencies. Values for fully open air control position were not much lower. Secondary combustion was maintained for about one-half of the burn cycle for both 60 percent and fully open air control positions. Secondary combustion could not be maintained for 30 percent open tests. Test 133 represented the optimum performance of wood heater #5. Secondary combustion was maintained throughout the period of pyrolysis on test 133. The high combustion efficiencies and low emission factors for test 133 are presented in Table 30.

The highest burn rates were established when secondary combustion was not present because the addition of the secondary air supply just above the primary combustion zone reduced the effective draft in the fire zone, thereby reducing the wood burn rate. Since the secondary air supply was added for 60 percent and fully open primary air control settings, the highest burn rates were developed with 30 percent primary air control settings. Overall, the burn rate was rather independent of the primary damper setting. The loss in thermal efficiency as the primary air control setting was reduced resulted primarily from a sharp drop in combustion efficiency and an increase in emissions resulting from incomplete combustion.

Wood heater #5 combustion efficiencies are shown in Figure 64. Very high combustion efficiencies typically associated with high burn rate firings of conventional airtight wood heaters were obtained for burn rates as low as 1.6 kg/hr. Wood heater #5 maintained combustion efficiencies of 90 percent or better even when the primary air control setting was reduced

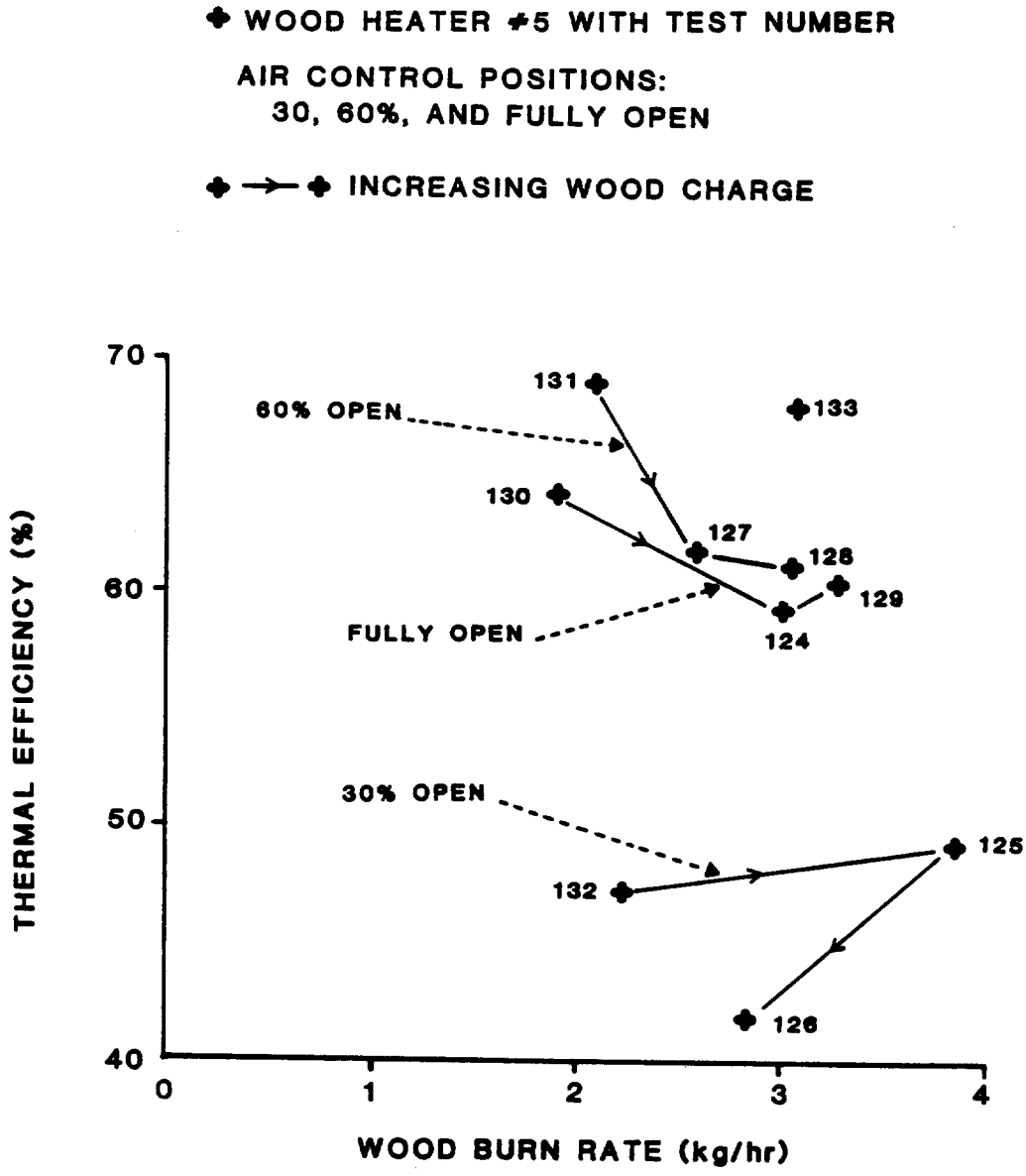


Figure 63. Thermal Efficiency Versus Burn Rate-Wood Heater #5

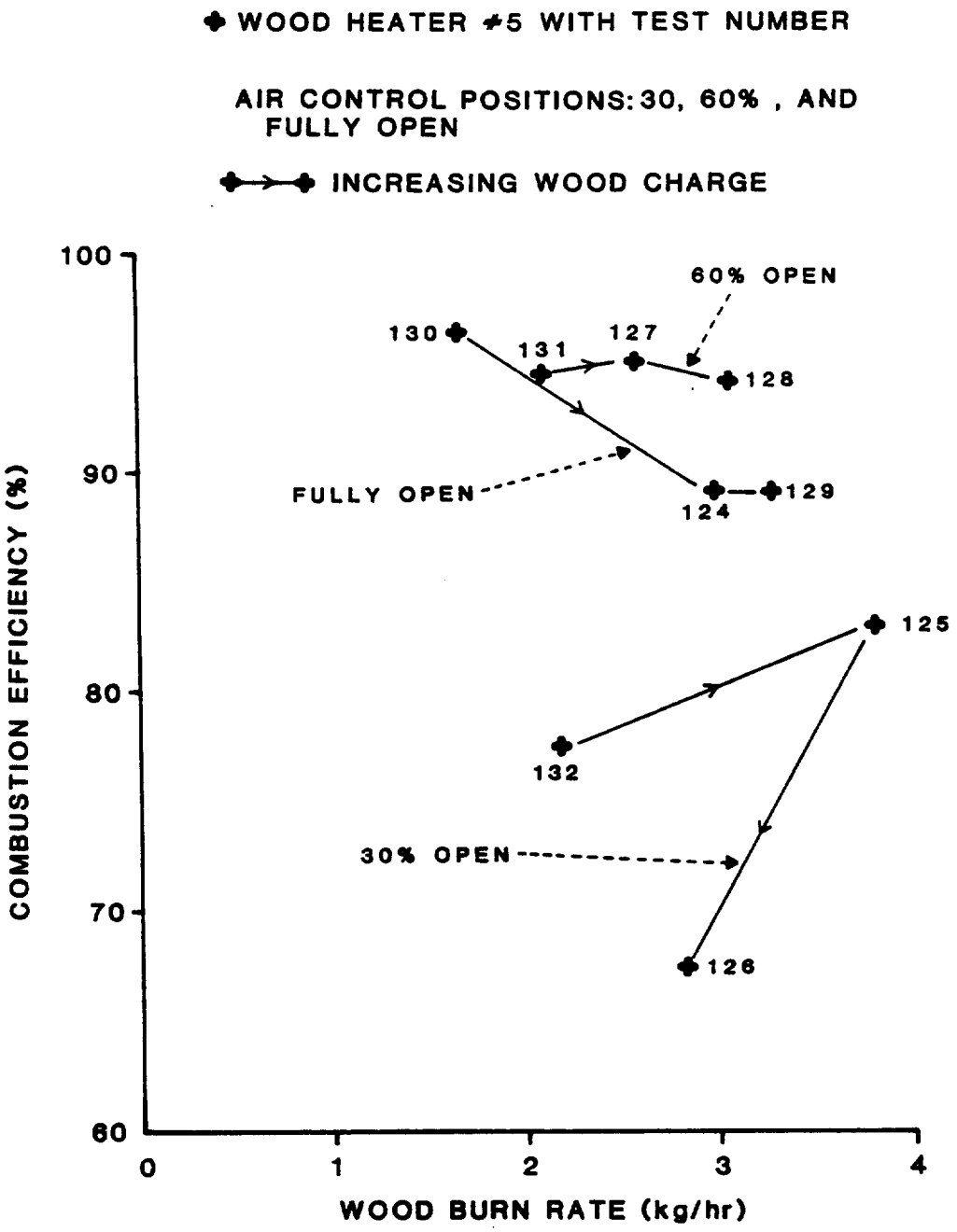


Figure 64. Combustion Efficiency Versus Burn Rate- Wood Heater #5

from fully open to 60 percent open. As Figure 64 shows, the 60 percent primary air control setting developed even higher combustion efficiencies than the fully open setting. The combustion efficiency dropped significantly at the low air control (primary damper) setting. Much variability is shown in the 30 percent tests as secondary combustion, though initiated, could not be sustained nor reproduced easily.

The heat transfer efficiencies for wood heater #5 are shown in Figure 65. The heat transfer efficiencies, not highly dependent upon wood load size or damper setting, ranged from 60 to 73 percent. The highest heat transfer efficiencies for wood heater #5 did not reach values such as 75 percent which is not uncommon for an airtight wood heater. Wood heater #5 did not possess an extensive secondary heat transfer surface area following the secondary combustion zone. The heat transfer efficiency remained at or above 60 percent for even the high burn rate firings.

The summary of the distributed energies for wood heater #5 is presented in Table 32. The thermal efficiency ranged from 49 to 69 percent with the combustion efficiency ranging from 76 to 95 percent. The 95 percent combustion efficiency was obtained when the secondary combustion feature of the wood heater was in optimum operation. The heat transfer efficiency was about 66 percent while the sum of the sensible and latent losses ranged from 27 to 31 percent. The chemical losses were low (5.5 percent) due to effective secondary combustion on all medium and open damper firings.

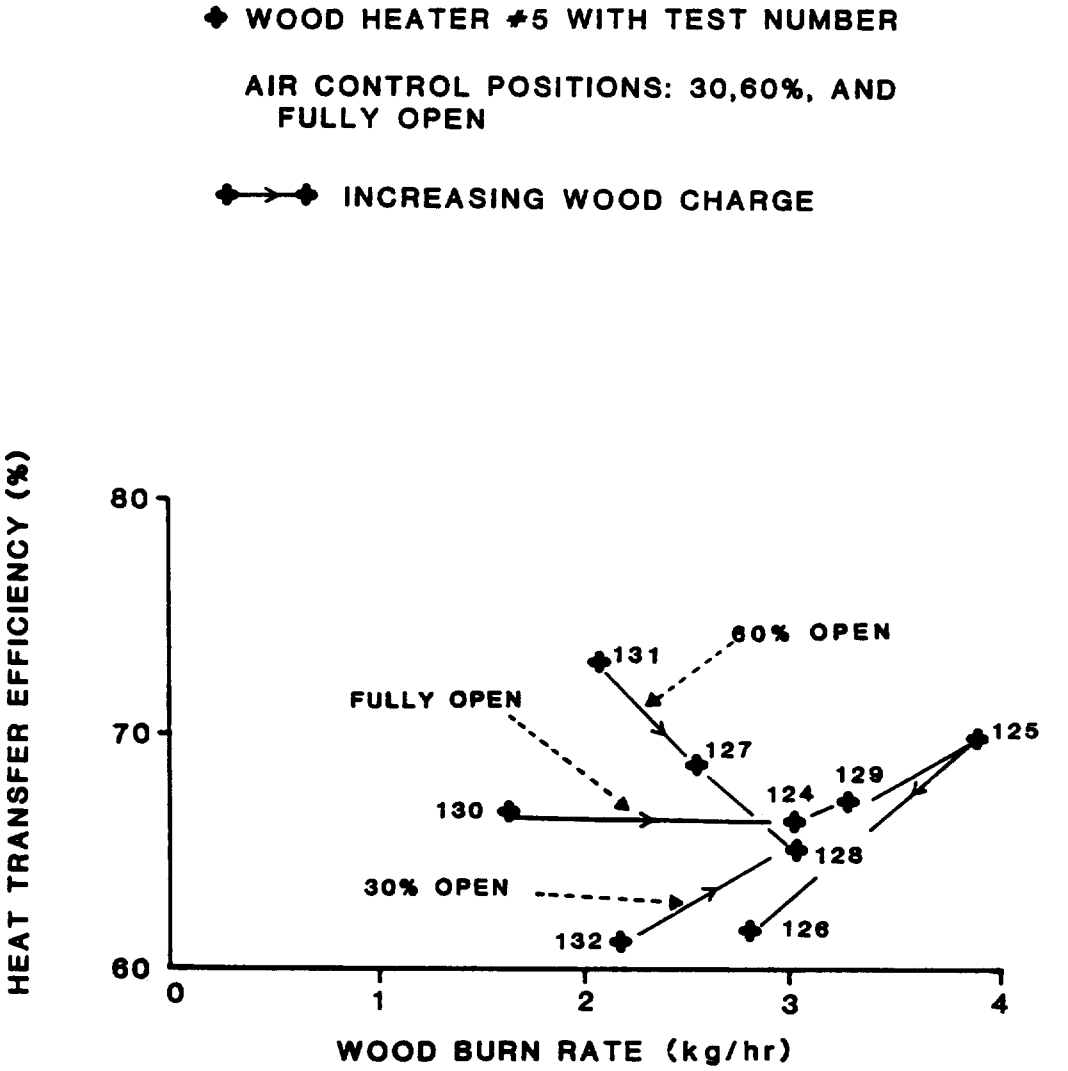


Figure 65. Heat Transfer Efficiency Versus Burn Rate-Wood Heater #5

Table 32. SUMMARY OF DISTRIBUTED ENERGIES[a] (%)
FOR WOOD HEATER #5

Damper Setting	Burn Rate (kg/hr)	Thermal Efficiency	Combustion Efficiency	Heat Transfer Efficiency	Sensible Plus Latent Losses	Chemical Losses
Open	2.7	61.3	91.8	66.8	30.5	8.4
60%	2.5	63.9	94.5	67.6	30.6	5.5
30%	2.9	49.0	75.9	64.3	26.9	24.1
Average	2.7	58.1	87.4	66.2	29.3	12.7

[a]Average of three tests, each having a different cordwood fuel loading size.

Wood Heater #5: Emissions

Carbon monoxide emission factors for wood heater #5 are shown in Figure 66. The CO emission factors increased from 40 to 137 g/kg when secondary combustion was not being sustained. General trends relating emission factors to wood load size and primary damper setting were not as well defined as for other wood heaters due to the highly variable nature of the operation. The operator was able to identify conditions conducive to secondary combustion and make adjustments in the damper to maintain the process. These adjustments took place during a test and produced fluctuations in the instantaneous data. Tests were not conducted on wood heater #5 at burn rates less than 2 kg/hr. At the very low burn rates wood heater #5 performed similar to a generic airtight wood heater since its special secondary combustion features were inactive. The prime combustion chamber was small. Therefore, the largest wood loads possible and damper settings other than closed had to be used to sustain heat outputs typical of residential requirements.

The total hydrocarbon emission factors for wood heater #5 are shown in Table 31. The THC emission factors were directly related to the carbon monoxide emission factors since both resulted from incomplete oxidation of carbon in the wood fuel.

The use of continuous analyzers and strip chart recorders for monitoring the flue gases provided real time experimental data that were used for precise evaluation of secondary combustion. CO and THC flue gas concentrations at the wood heater exit and many other variables were recorded during each test. The operators' decisions and observations used in controlling the secondary combustion were also recorded. After some development testing, the operators were able to visually determine whether secondary combustion was being maintained since the secondary combustion flame color

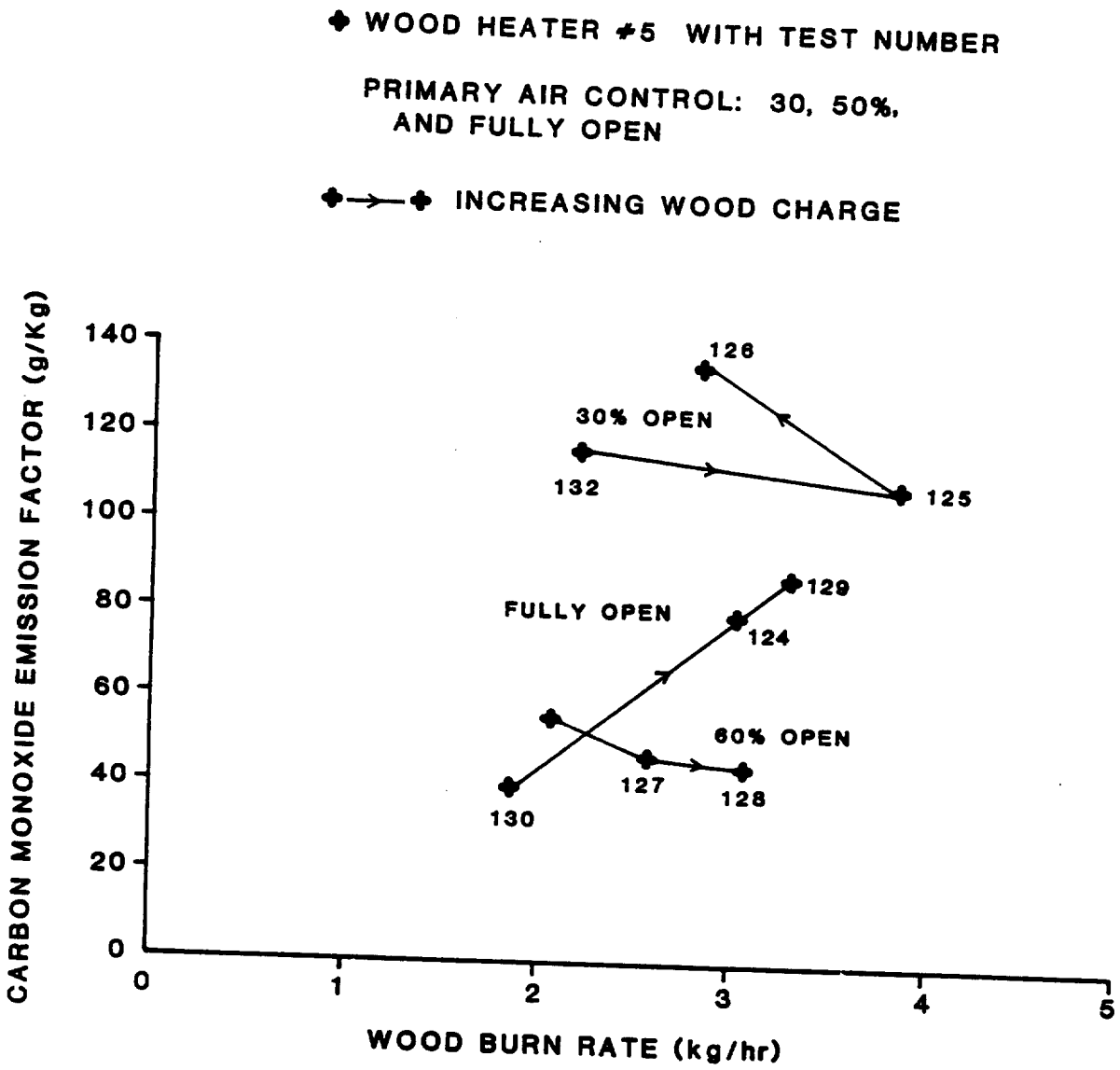


Figure 66. Carbon Monoxide Emission Factor Versus Burn Rate - Wood Heater #5

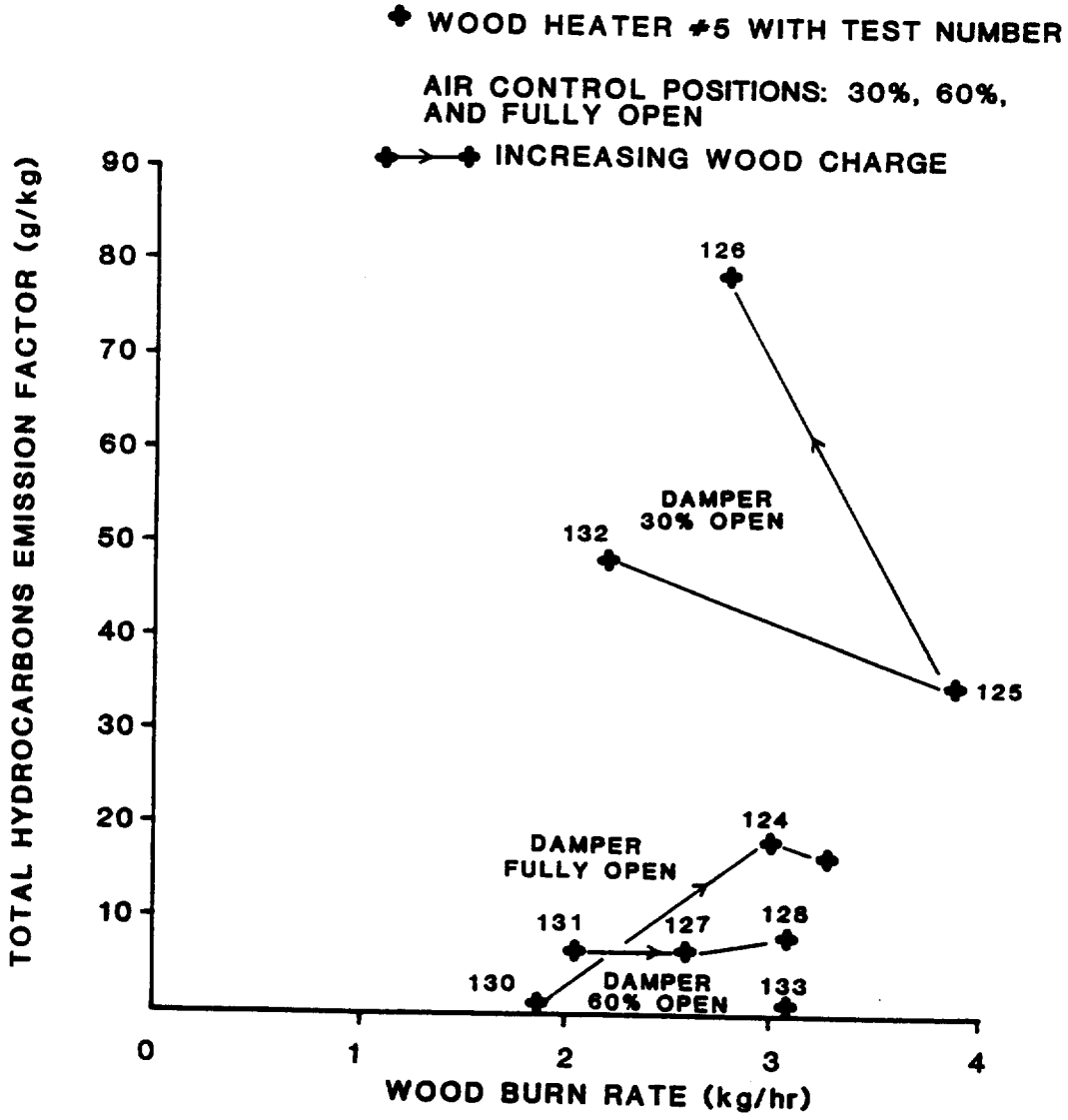


Figure 67. THC Emissions Versus Burn Rate-Wood Heater#5

and radiation intensity correlated directly with reduced CO and THC emissions. Wood heater #5 emission factors are plotted in Volume II and show the rapid changes resulting when the door handle on the front of the heater was fully lowered. This action opened the secondary air damper allowing secondary combustion to begin if the following conditions existed in the secondary region: (1) high flue gas and secondary refractory temperatures and (2) high concentrations of incompletely oxidized CO and THC existing in the flue gases. These required conditions were easily met for the early phase of the 60 percent and fully open damper tests. During the early phase of the combustion process the flue gases contained high CO and THC concentrations and at the end of a burn cycle CO and THC emission factors were diminished. The precise point in time when secondary combustion ended was difficult to ascertain.

The NO_x emission factors for wood heater #5 are shown in Table 31. The NO_x emission factor ranged from 0.85 to 1.50 g/kg over all tests. The lowest NO_x emissions were obtained when the heater was operated at lowest burn rates for partially open primary air supply.

The total PAH emission factors for wood heater #5 are presented in Table 33. The naphthalene component represented less than 63 percent of the total PAH for both tests with phenanthrene being the second largest with less than 20 percent.

The total PAH emission factors for tests 124 and 127 are shown in Figure 68 and decreased with increased wood loading size. Test 124 was conducted with a fully open primary air supply while test 127 was conducted with the primary air supply 60 percent open. Low total PAH emissions were found for the low burn rate test 127 where secondary combustion was observed for more than half of the burn cycle.

Table 33. WOOD HEATER #5
PAH EMISSION FACTORS (g/kg) - OAK CORDWOOD

	Test Number	
	124	127
Naphthalene/Methylnaphthalenes/ Phenylnaphthalenes	0.0273	0.0541
Acenaphthylene	0.0029	0.0112
Acenaphthene	0.0011	0.0036
Fluorene	0.0004	0.0022
Phenanthrene/Anthracene	0.0084	0.0196
Fluoranthene	0.0013	0.0034
Pyrene	0.0009	0.0030
Benzo (g,h,i) fluoranthene	0.0004	0.0021
Chrysene/Benzo (a) anthracene	0.0004	0.0027
Benzo (b) fluoranthene/ benzo (k) fluoranthene	———	0.0017
Benzo (a) pyrene	———	0.0015
Indeno (1,2,3-c,d) pyrene/ Benzo (g,h,i) perylene	———	———
Dibenzo (a,h) anthracene	———	———
Total	0.0431	0.1051

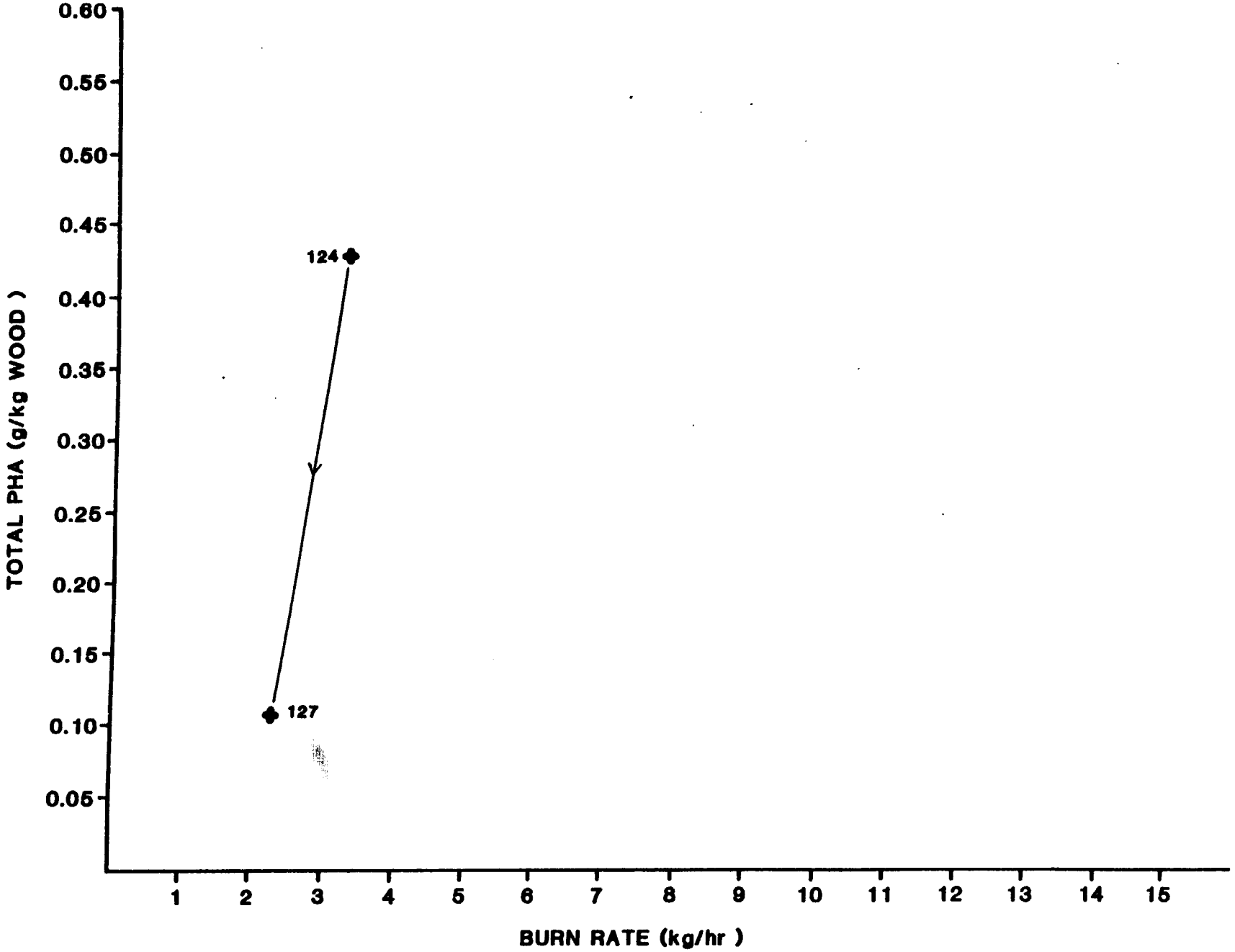


Figure 68. Effect of Burn Rate on PAH Emissions-Wood Heater # 5

Figure 69 shows that wood heater #4 operated with low excess air values typical of high firing tests on conventional airtight wood heaters. The small combustion chamber of wood heater #5 limited its wood burn rate to about 4.2 kg/hr.

Figure 70 shows the total PAH emissions to be independent of wood load charge. The primary air supply, however, as well as duration of secondary combustion were different for the two tests shown in the figure. Secondary combustion was sustained for a much longer period of time in test 127 than test 124.

The exit temperature for tests 127 and 129 are shown in Figure 71. The test having the lowest PAH emissions also had the lowest burn rate. This result seems to conflict with the general rule that PAH increases as the burn rate decreases. It is thought that this anomaly resulted from the complex interaction of conditions required for the primary and secondary phases of combustion. Opening of the secondary air supply supported secondary combustion but reduced the primary air. In contrast, the closing of the secondary air supply eliminated secondary combustion but maintained high primary air and high exit temperatures. With increased secondary combustion, the PAH emissions were reduced and the burn rates were reduced because the secondary air damper was open.

The emission factors for compounds other than PAH that were associated with the integrated sample recovered by the modified Method 5 sampling system are shown in Table 34. The table also contains volatile hydrocarbon emission factors.

Total particulate emission factors less than 3 g/kg were found for two tests as shown in Figure 72. Figure 73 shows the filterable particulate emission factor to be less than 1 g/kg. The ratio of condensible

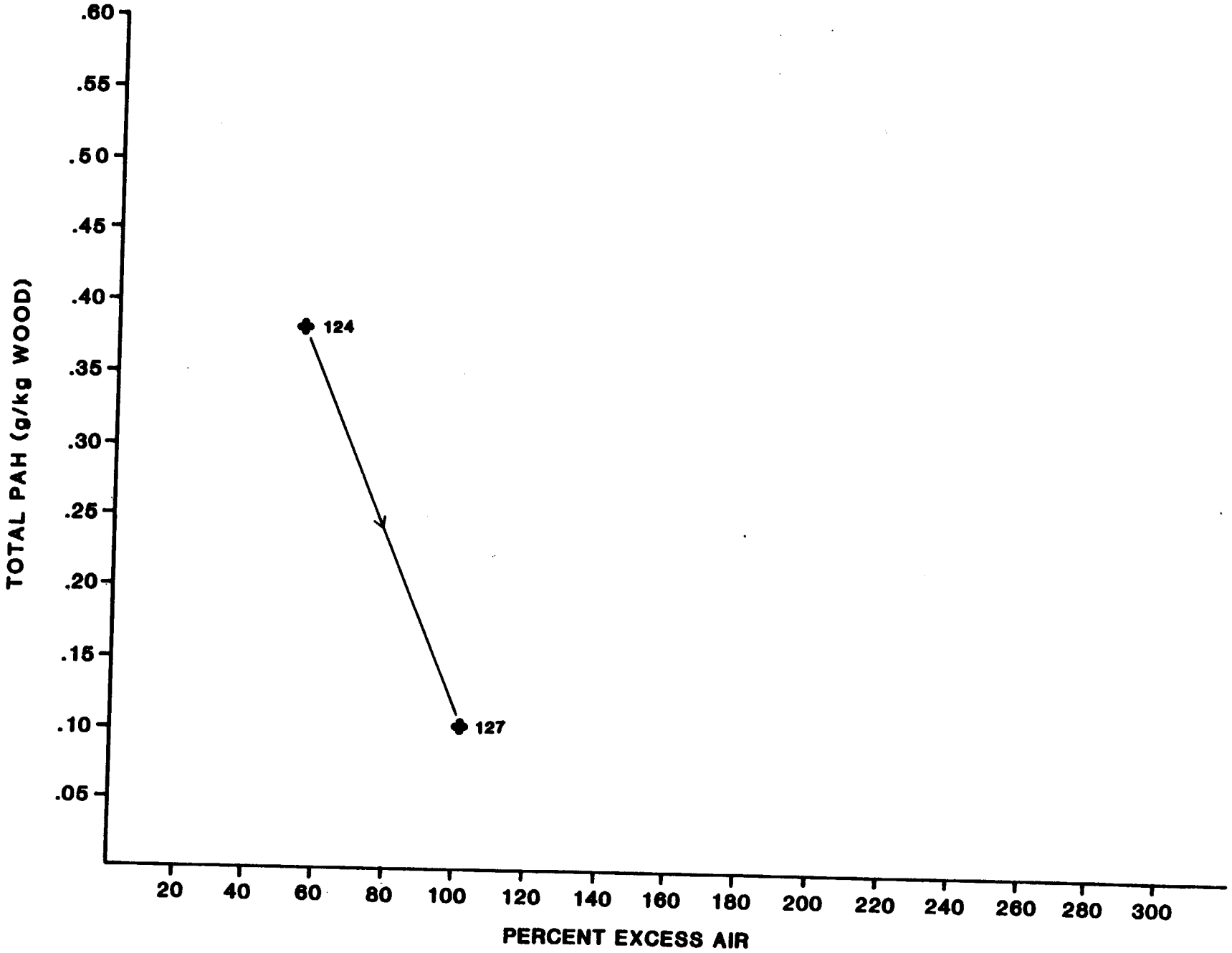


Figure 69. Effect of Percent Excess Air on PAH Emissions- Wood Heater # 5

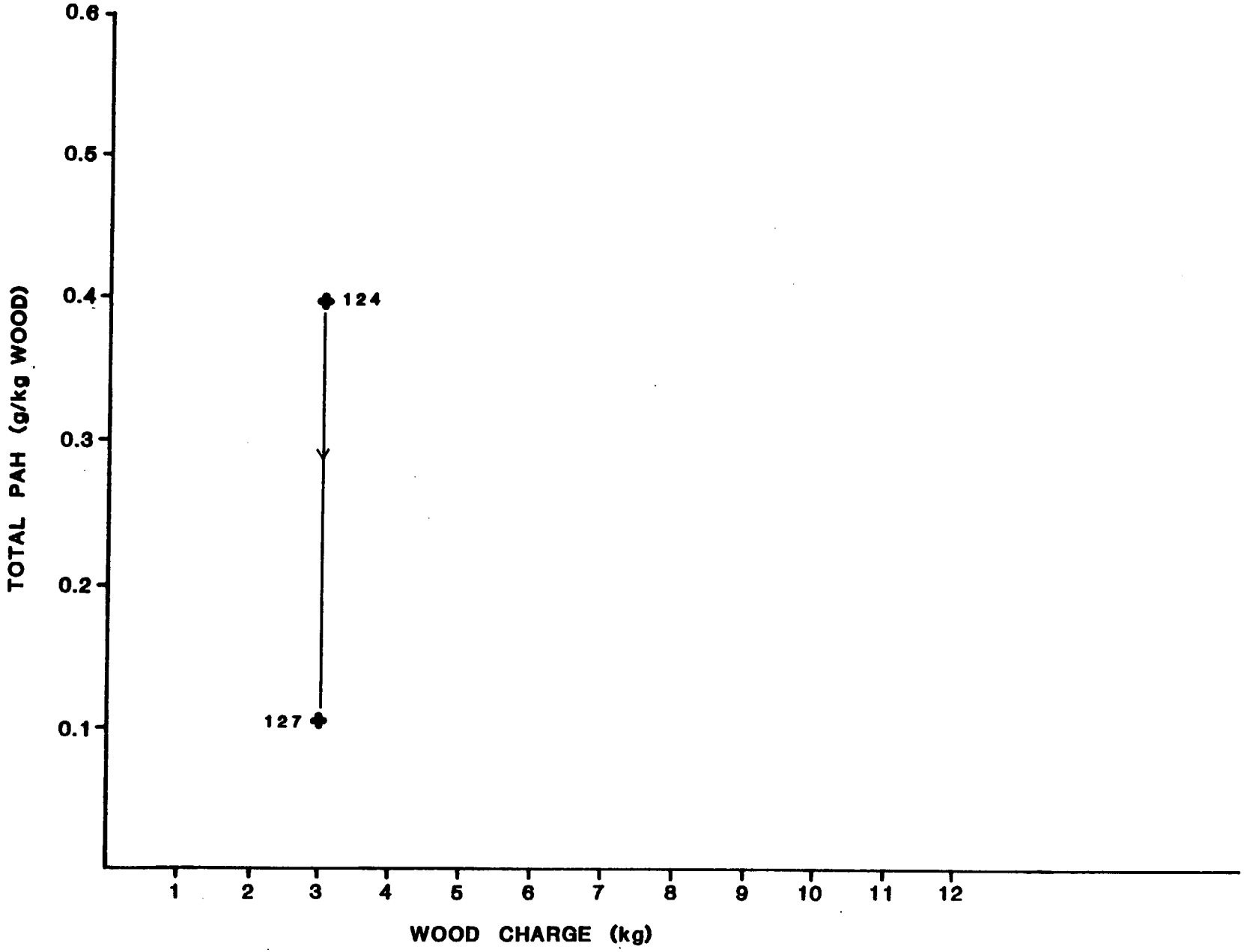


Figure 70. Effect of Wood Charge on PAH Emissions–Wood Heater # 5

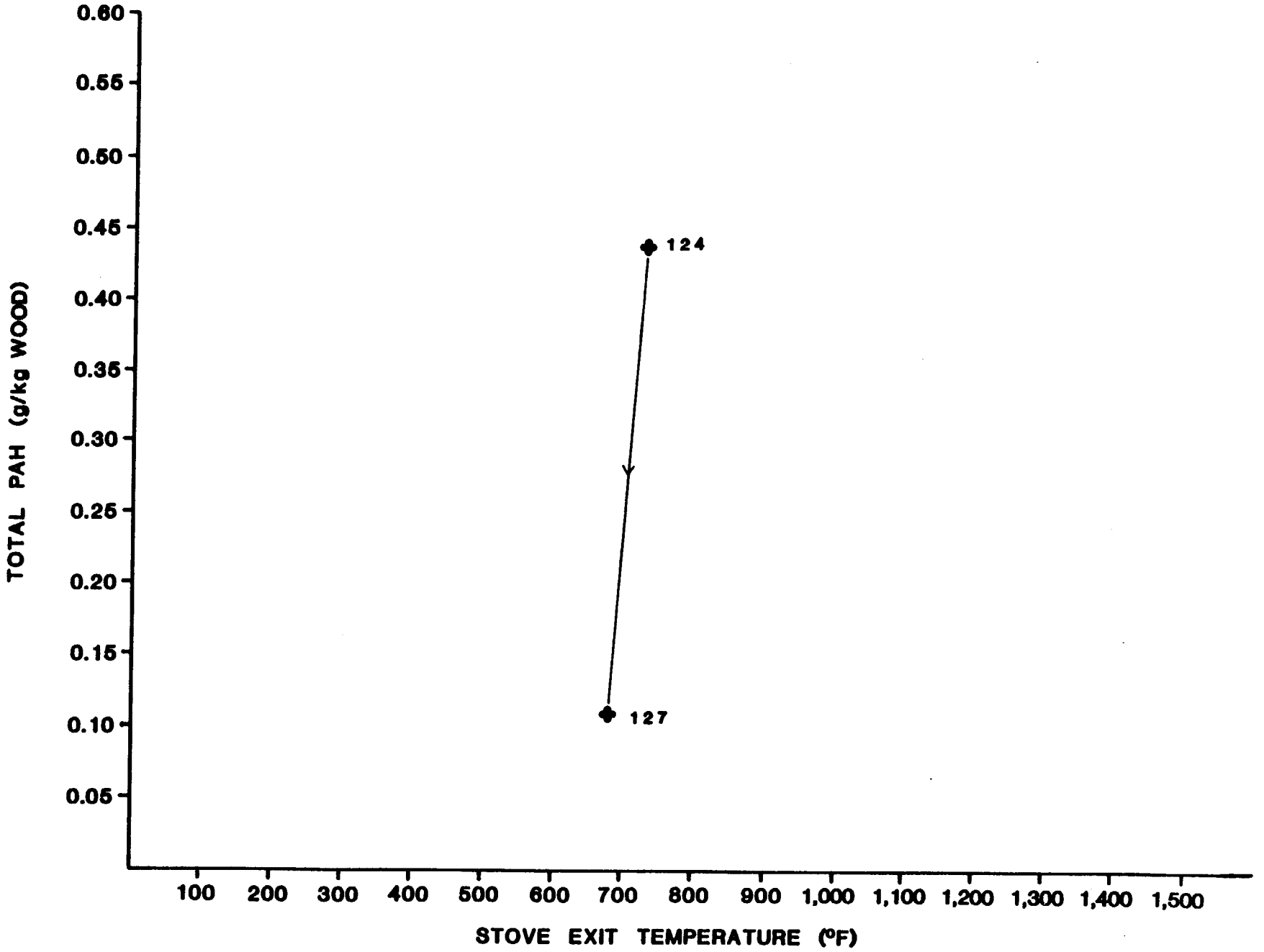


Figure 71. Effect of Stove Exit Temperature on PAH Emissions–Wood Heater # 5

Table 34. WOOD HEATER #5
EMISSION FACTORS FOR COMPOUNDS OTHER THAN PAH (g/kg)

	Test Number	
	124	127
Filterable Particulate[a]	0.1888	0.2871
Front half Gravimetric[b]	0.1264	0.0861
Back half Gravimetric[c]	0.6388	2.4020
Back half TCO[d]	0.0491	0.1723
Total Condensible Organics[e]	0.6879	2.5743
Total Particulates[f]	0.8767	2.8614
Volatile Hydrocarbons (g/kg)	0.057	0.1084
Major Constituents:		
Methane (vol. %)		
Ethylene (vol.%)		

Note: f = a + e
e = c + d

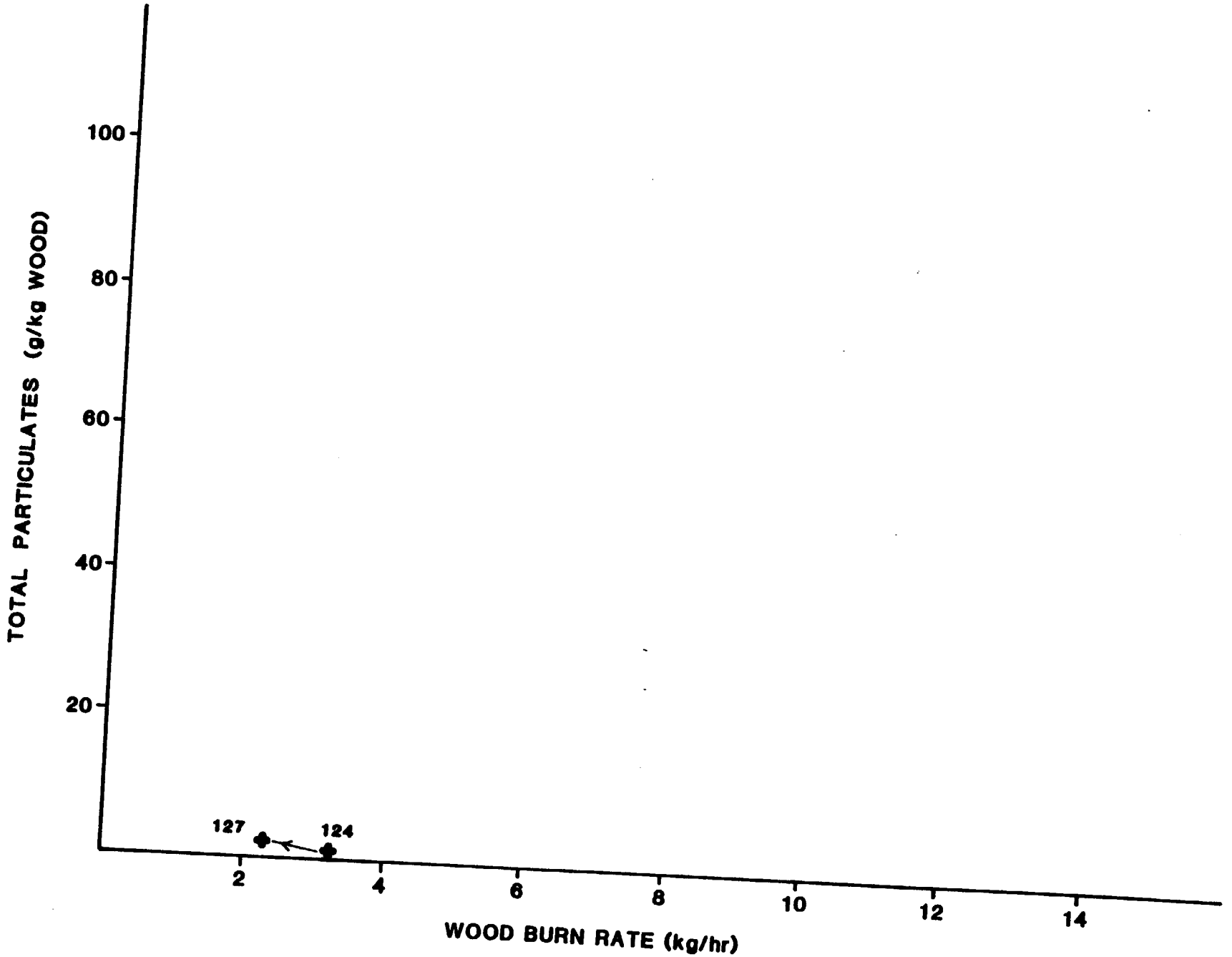


Figure 72. Effect of Burn Rate on Total Particulate Emissions–Wood Heater # 5

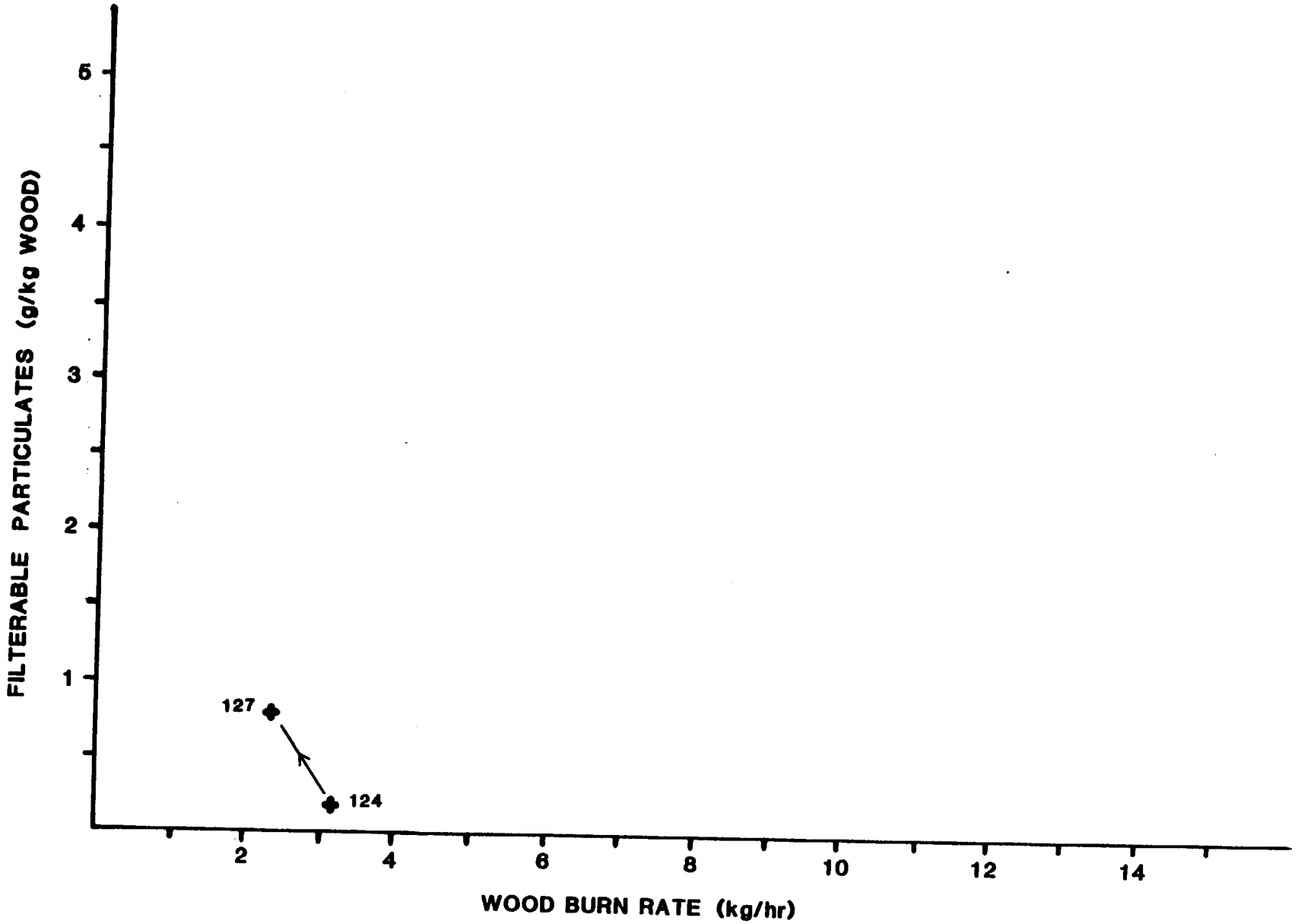


Figure 73. Effect of Burn Rate on Filterable Particulate Emissions–Wood Heater # 5

organics to the filterable particulates is shown in Figure 74. Volatile hydrocarbon emissions are presented in Figure 75.

The detailed comparisons between secondary combustion and wood heater exit paramaters were not made for wood heater #5. Only the exit sample was continuously monitored for wood heater #5.

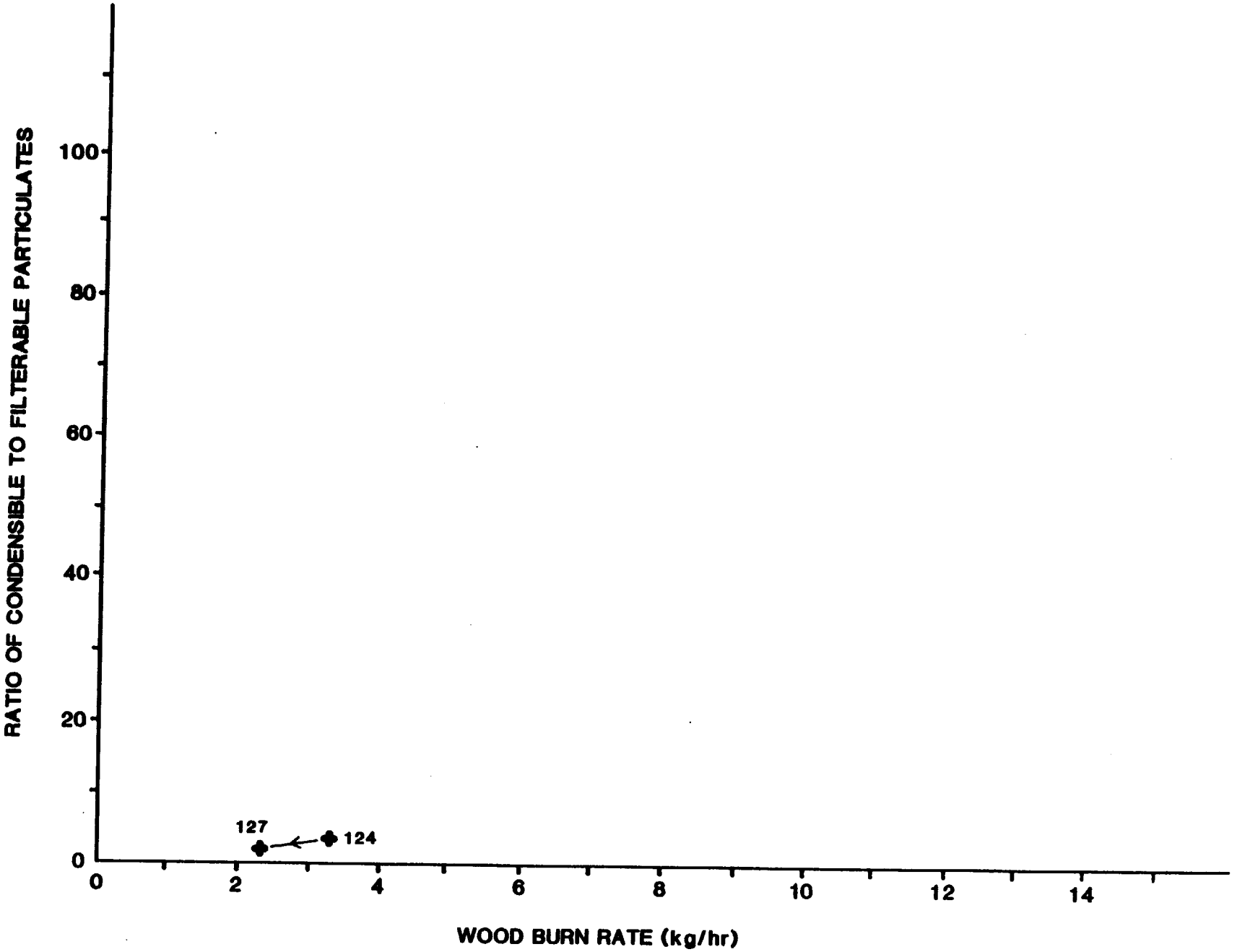


Figure 74. Effect of Burn Rate on the Ratio of Condensible to Filterable Particulates–Wood Heater # 5

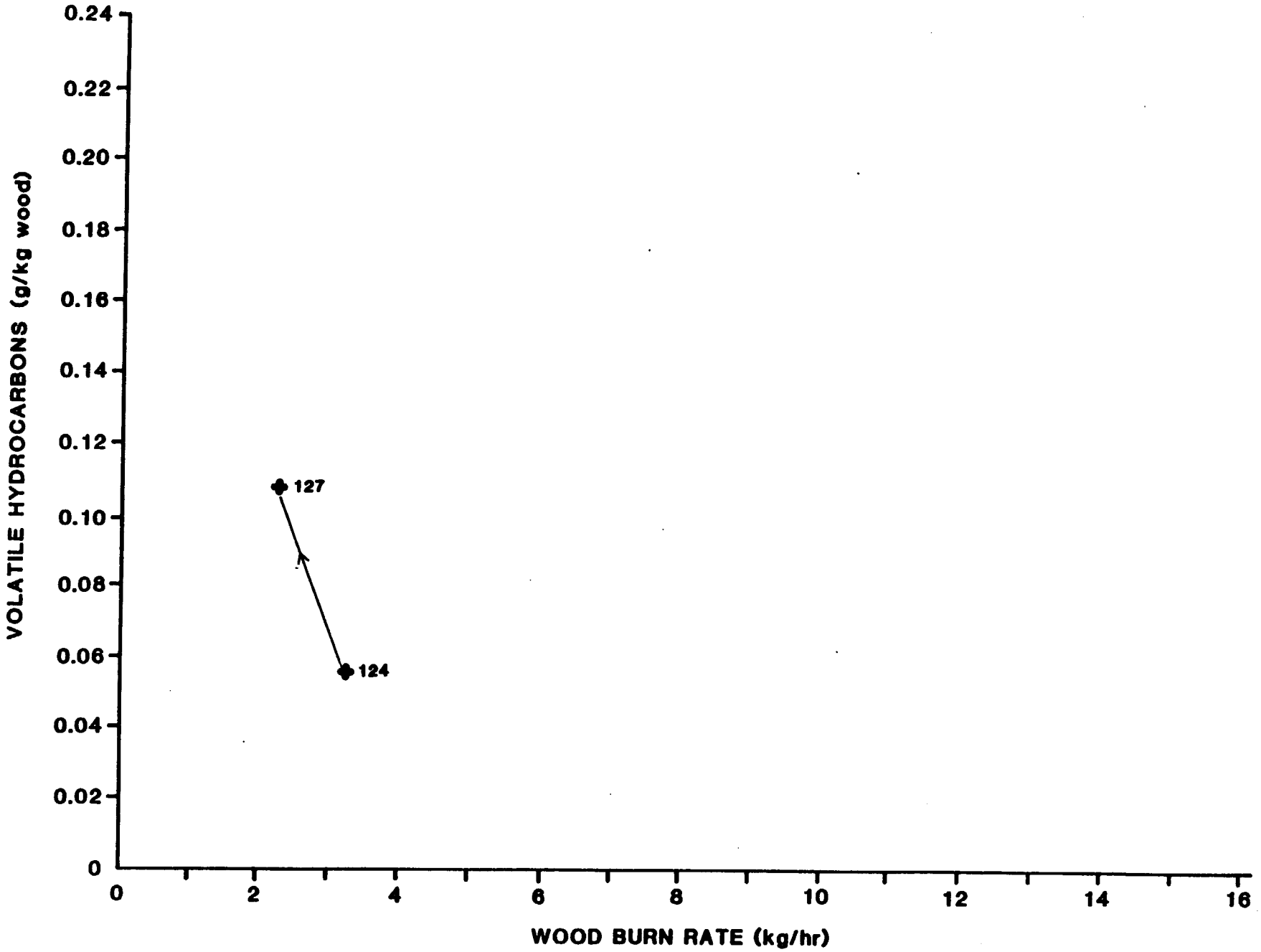


Figure 75. Effect of Wood Burn Rate on Volatile Hydrocarbon Emissions–Wood Heater #5

COMPARATIVE DISCUSSION

Efficiencies

Thermal efficiency comparisons between wood heaters #1, #2, and #4 are presented in Figure 76. The conventional airtight results for wood heater #1 will be used throughout the discussion as a baseline unit to which the other wood heaters possessing new technological combustion concepts will be compared.

The baseline thermal efficiency performance of wood heater #1 was highly variable and had thermal efficiencies of less than 40 percent for the closed damper tests and over 62 percent for medium burn rate tests. The thermal efficiency of wood heater #1 dropped to about 51 percent at the highest burn rates. This highly variable thermal efficiency existed over a wide burn rate range of 2 to 11 kg/hr.

Wood heater #2 thermal efficiencies presented in Figure 76 were higher than those for wood heater #1. The thermal efficiencies reached a high of 78 percent and the lowest thermal efficiency was over 65 percent. Highly reduced thermal efficiencies for wood heater #2 were not found as the manufacturer had limited the closed damper operation of the unit to one-half turn open for both primary air screws. Low thermal efficiencies would probably have been found if the closed damper restriction had been violated. Wood heater #2 had high thermal efficiencies while operating over a burn rate range of 1 to 4.5 kg/hr. The thermal efficiency of wood heater #2 was rather insensitive to damper setting but very dependent upon wood fuel loading size. In contrast wood heater #1 was sensitive to both damper setting and wood fuel loading size, especially so for closed damper tests.

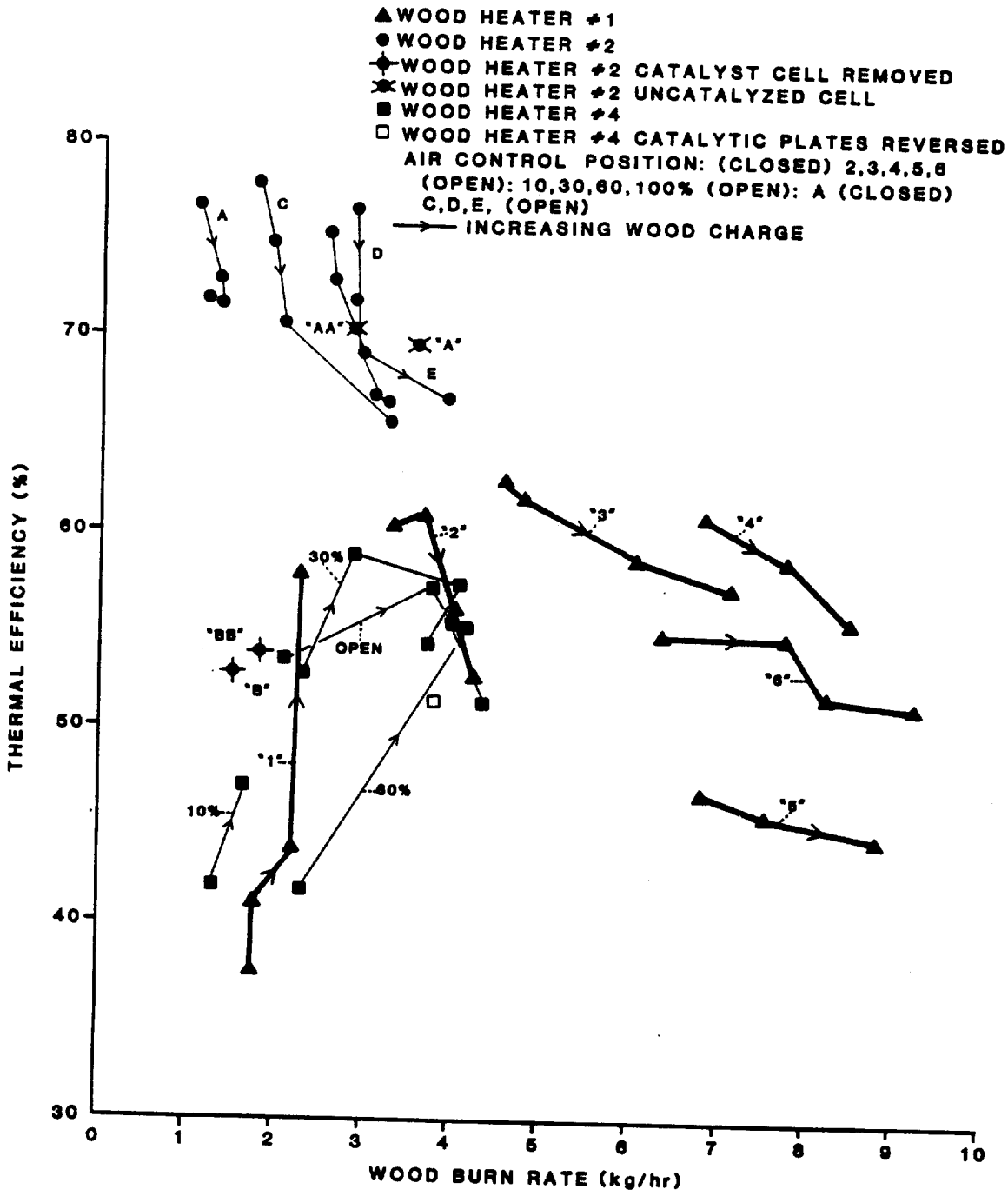


Figure 76. Thermal Efficiency Comparisons (Part I)

In many home uses, a wood heater is forced to operate at the lowest burn rate possible through damper control. Figure 76 shows that wood heater #2 operated with a 30 percent higher thermal efficiency than wood heater #1 for small fuel loadings and 8 percent higher for the larger fuel loadings. Overall, wood heater #2 operated with much higher thermal efficiencies at lower burn rates than could even be sustained for wood heater #1. Wood heater #2 operated with highest thermal efficiencies when fueled by small wood loads. In contrast, Figure 76 shows that the thermal efficiency of wood heater #1 was very sensitive to damper position and burn rate.

Two special tests noted as "A" and "AA" were conducted to determine the effect of reduced catalytic effectiveness which may result from aging or poisoning of the catalyst. Figure 76 shows that the thermal efficiency of wood heater #2 for the two special tests was still 7 percent higher than the highest thermal efficiency for wood heater #1. It is important to point out that the thermal efficiency for the special tests "A" and "AA" remained high due to the heater's very effective secondary heat exchange design. The combustion efficiency declined while the chemical losses in the flue gases associated with incomplete combustion increased for tests "A" and "AA." Tests "B" and "BB" were conducted after the catalytic combustor had been totally removed. During these tests wood heater #2 performed like a traditional airtight wood heater while sustaining thermal efficiencies over 12 percent higher than for wood heater #1 at the same burn rate.

The thermal efficiencies for wood heater #4 are also presented in Figure 76. The thermal efficiencies for wood heater #4 were similar to those of wood heater #1 within the burn rate range of 1 to 4.5 kg/hr.

The thermal efficiencies associated with wood heater #4 were much lower than those associated with wood heater #2 even though both operated over about the same range of burn rates. A special test was conducted by inverting the catalytic plates in wood heater #4. This was intentionally done to make the catalytic assembly inactive. When test 118 (similar in fuel load and damper setting) was compared with special test "A," no significant difference was found in the thermal efficiencies. Hence, the heater performed basically the same relative to thermal efficiency whether or not the catalyst was in place.

Thermal efficiency comparisons for wood heaters #1, #3, and #5 are presented in Figure 77. Wood heater #3, was wood heater #1 with an "add-on" catalytic unit and operated with higher thermal efficiencies at lower burn rates than were obtained for wood heater #1 alone. The lowest burn rates for both wood heaters #1 and #3 were obtained with the damper fully closed. Wood heater #3 operated with higher thermal efficiencies than wood heater #1 alone up to about a 4 kg/hr burn rate. At higher burn rates, wood heater #3 operated with thermal efficiencies similar to wood heater #1. Both wood heaters #1 and #3 showed an inverted parabolic thermal efficiency versus burn rate performance with peak thermal efficiencies of 63 percent at a burn rate of 5 kg/hr and 65 percent at a burn rate of 3 kg/hr, respectively. The "add-on" unit increased the thermal efficiency of wood heater #1 primarily through the addition of secondary heat exchange. However, the catalytic combustor in the "add-on" unit did contribute to the improved emissions performance of wood heater #3 at medium and high burn rates.

Figure 77 also shows that wood heater #5 thermal efficiencies were highly variable with the thermal efficiency varying from 69 to 42 percent

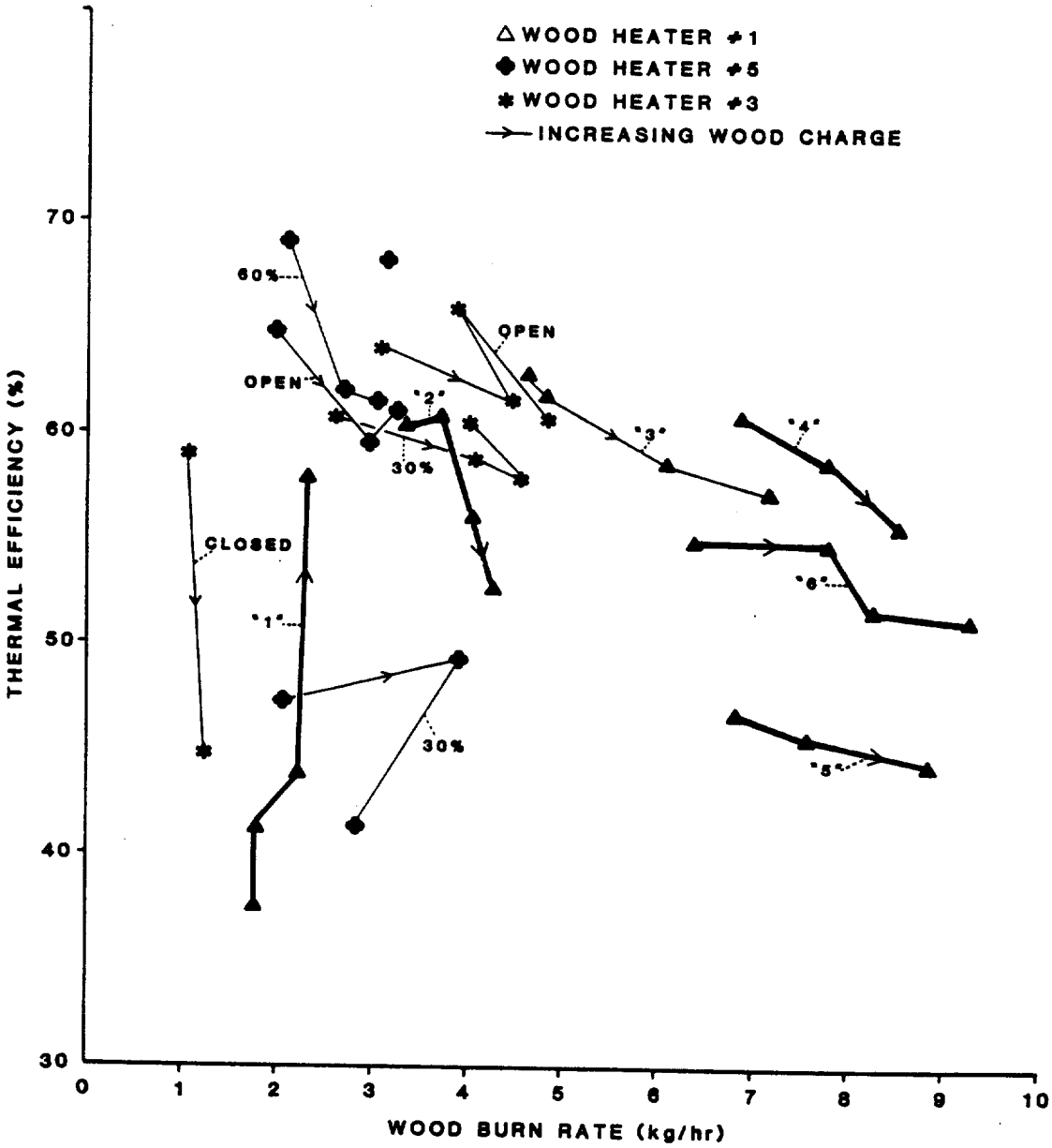


Figure 77. Thermal Efficiency Comparisons (Part II)

at about the same burn rate of 2 kg/hr. This variability in performance resulted from difficulties associated with maintaining active secondary combustion through a full burn cycle. Most of the thermal efficiencies for wood heater #5 were between 58 and 64 percent. Table 30 shows that wood heater #5 operated with rather low heat transfer efficiencies due to high sensible and latent energy flue gas losses which were also typical of wood heater #1. In effect, the ultimate thermal efficiency performance of wood heater #5 was limited by its heat transfer capabilities and the dedicated attention offered by the operator who was responsible for sustaining the secondary combustion through rather frequent wood loadings.

A summary of <u>average</u> distributed energies for all fire wood heaters involved in the test program is presented in Table 35. Wood heater #1 was an airtight, circulator model while wood heaters #2 through #5 are models having so-called "improved" combustion features.

Wood heater #2 operated with the highest thermal efficiency (71.5 percent) while wood heaters #3 and #1 followed with thermal efficiencies of 58.4 and 53.7 percent, respectively. Wood heater #2 also operated with the highest combustion and heat transfer efficiencies and lowest sensible plus latent and chemical losses. Wood heater #2 operated with a combustion efficiency over 6 percent higher than that for wood heaters #3 and #1 due to the activity of the catalytic combustor at the lowest burn rates. The add-on catalytic combustor of wood heater #3 was not effective in increasing the combustion efficiency at the low burn rates. Wood heater #2 contained an "in-top" heat exchanger aft of the catalytic combustor. The serpentine flow design provided heat transfer efficiencies higher than those for wood heaters #3 and #1 by 9 and 14 percent, respectively. Wood heater #2 effectively cooled the flue gases as is shown by

Table 35. SUMMARY OF AVERAGE DISTRIBUTED ENERGIES (%)
ALL FIVE WOOD HEATERS

Wood Heater	Burn Rate (kg/hr)	Thermal Efficiency	Combustion Efficiency	Heat Transfer Efficiency	Sensible Plus Latent Losses	Chemical Losses
#1[a]	5.7	53.8	81.4	66.6	27.7	18.6
#2[b]	2.2	71.5	88.6	80.9	17.0	11.4
#3[c]	2.9	58.4	81.9	71.7	23.8	17.9
#4[d]	3.0	51.0	78.8	65.1	27.9	21.2
#5[e]	2.7	58.1	87.4	66.2	29.3	12.7
[f]	6.2	58.7	86.5	68.3	-	-

[a]Table 5
[b]Table 12
[c]Table 19
[d]Table 26
[e]Table 32
[f]TVA study (8); average for all oak fuel tests on various airtight residential wood heaters.

the low 17 percent sensible plus latent energy loss. The chemical losses were 11.4 percent for wood heater #2 and were 18.0 and 18.6 percent for wood heaters #3 and #1, respectively. This means that the chemical losses were over 60 percent higher for wood heaters #1 and #3.

Wood heater #3 should theoretically have possessed better performance features than wood heater #1 since wood heater #3 was actually wood heater #1 coupled to an "add-on" catalytic combustor. Table 35 shows that wood heater #3 did indeed operate with improved thermal efficiency, combustion efficiency, heat transfer efficiency, and reduced sensible plus latent and chemical losses when compared with wood heater #1. The most significant difference between wood heaters #3 and #1 was shown to be associated with the increased heat transfer efficiency that resulted from the addition of the add-on unit. Wood heater #3 would have been run more effectively if additional heat exchange area had been included to cool the hot gases leaving the exit of the add-on unit. The add-on unit cooled the hot flue gases leaving the back of wood heater #1 but did not effectively extract the thermal energy produced by the catalytic combustor.

Wood heaters #1, #2, and #3 were tested using fully closed to fully open damper settings while wood heaters #4 and #5 were not tested at the closed damper position. Therefore, the results for wood heaters #4 and #5 presented in Table 35 must not be compared rigidly to those for wood heaters #1, #2, and #3.

The combustion efficiency of 87 percent for wood heater #5 was much higher than that shown for wood heater #4. Table 30 shows that wood heater #5 operated with a combustion efficiency over 94 percent for the 60 percent damper setting with chemical losses of 5.5 percent. The 60 percent damper setting firings of wood heater #5 had the highest combustion efficiency

and lowest chemical losses associated with any tests in this program. Low emission factors for CO and total hydrocarbons were also found for these series of tests. During periods when ideal secondary combustion was being maintained, the instantaneous combustion efficiency reached over 98 percent with chemical losses less than 2 percent. But this ideal secondary combustion could not be sustained throughout any test.

Table 35 shows that wood heater #4 performed with the lowest thermal efficiency, combustion efficiency, and heat transfer efficiency but the highest chemical losses. Each of the distributed energies for wood heater #4 was similar to those for wood heater #1. The results show that the catalytic plates as used in wood heater #4 were not effective in reducing the chemical losses associated with products of incomplete combustion. No catalytic activity as indicated by increased temperatures was noted during actual testing of wood heater #4 in which thermocouples were placed in the combustion gases before and after the catalytic section. Such catalytic activity was very evident in wood heaters #2 and #3 since a thermocouple was used to monitor the temperature within the catalytic cell structure.

Wood heaters are operated solely to provide useful heat output. The distributed energies associated with the end use of the fuel with different damper settings are presented in columnar form in Figure 78 to visually compare the heat output among the five wood heaters. The averaged end use of wood energy is graphically shown in Figure 79 where the merits of wood heater #2 are evident.

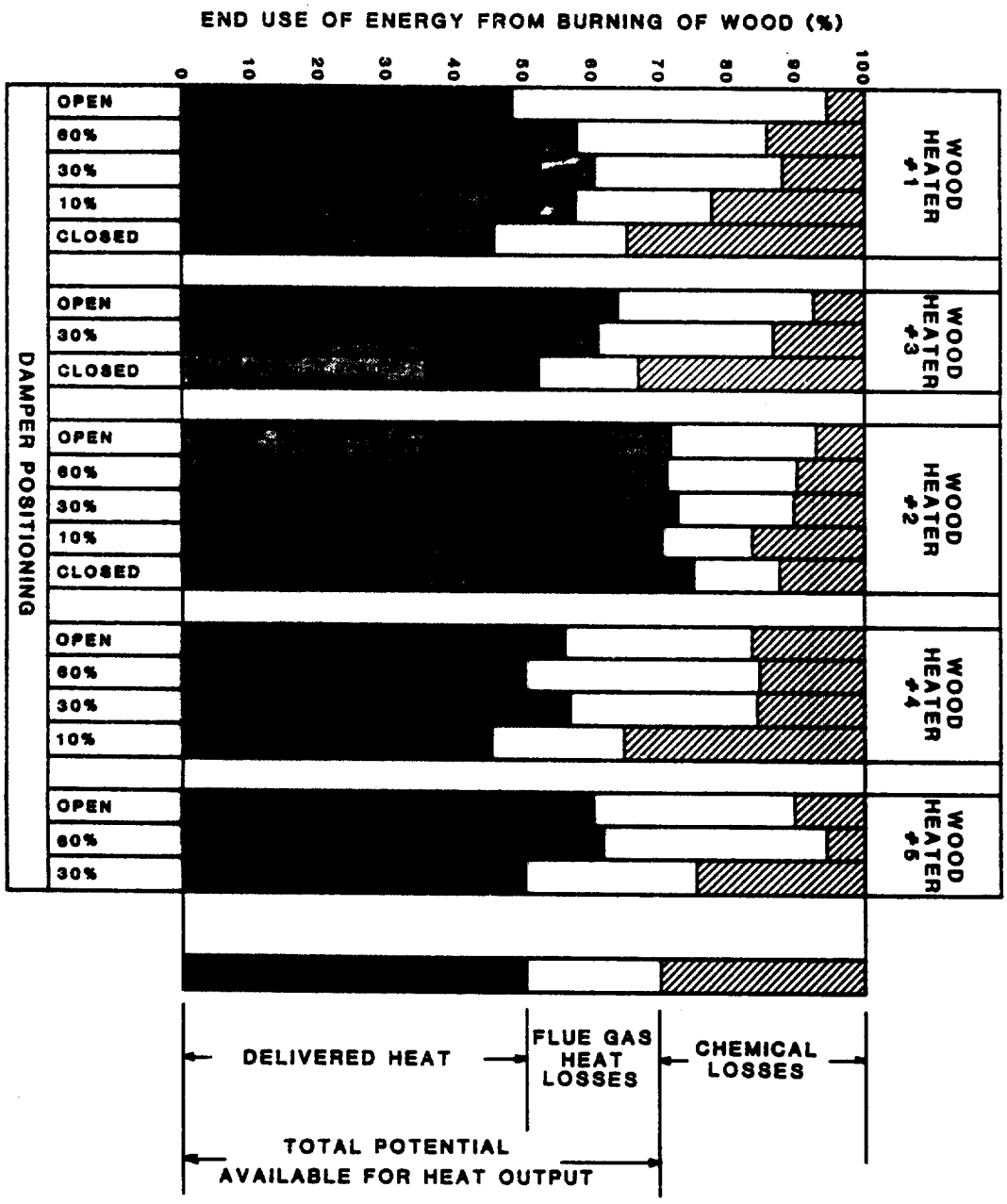
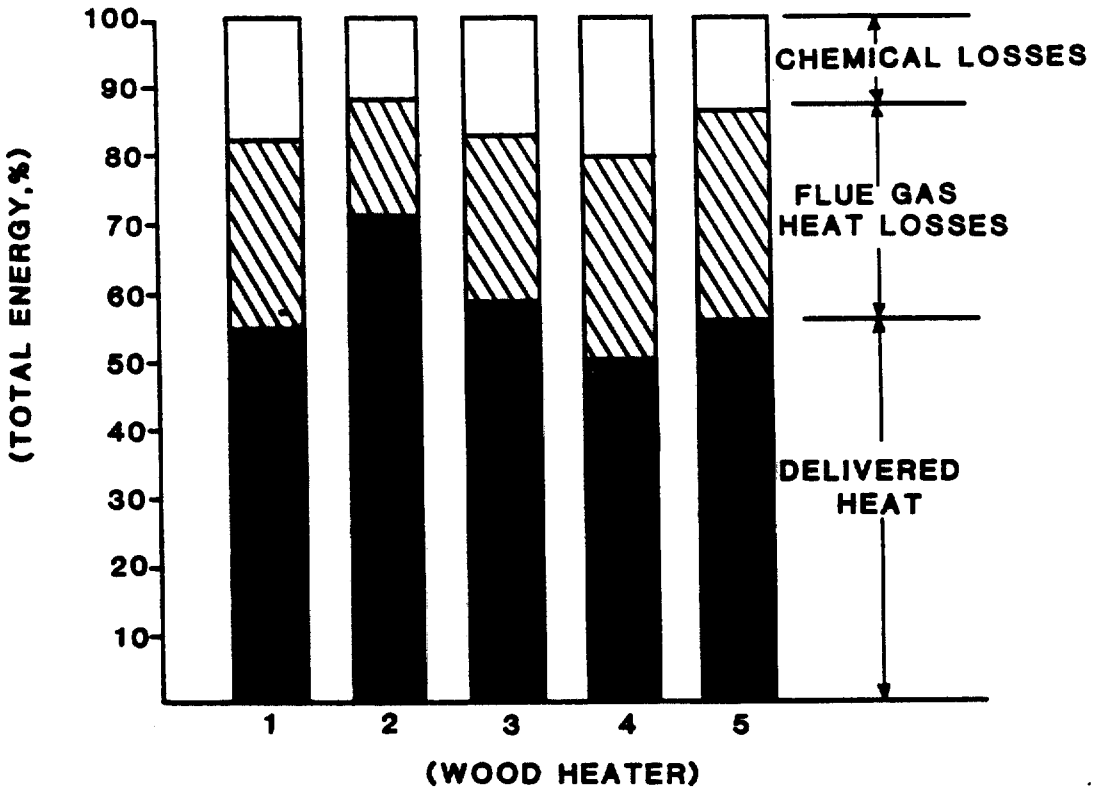


FIGURE 78 DISTRIBUTED ENERGIES

KEY

Wood Heater #1-Airtight Circulator (a)
Wood Heater #2-Ceramic Honeycomb Catalytic (b)
Wood Heater #3-Retro Ceramic Honeycomb Catalytic (c)
Wood Heater #4-Metal Catalytic (d)
Wood Heater #5-Secondary Combustion (e)



Footnote:
a. Average of twenty tests.
b. Average of twenty tests.
c. Average of twelve tests.
d. Average of sixteen tests.
e. Average of twelve tests.

Figure 79.

Carbon Monoxide Emissions

Wood heater #1 carbon monoxide (CO) emission factors are presented in Figure 80 to show baseline CO performance for a conventional airtight wood heater. The improved CO emissions performance of wood heater #2 over either wood heater #1 or #4 was remarkable at low burn rates of 1 to 4 kg/hr. Figure 80 shows that wood heater #2 operated in a completely different domain on the figure. Neither wood heater #1 nor #4 was able to operate with as low CO emission factors at low burn rates as wood heater #2.

Wood heater #4 generated CO emission factors typical of wood heater #1 except at low burn rates where wood heater #4 generated higher CO emissions than wood heater #1. Wood heater #4 generated CO emission factors ranging between 90 and 200 g/kg over a burn rate range of 1.5 to 5 kg/hr. In comparison, wood heater #2 is CO emission factors ranged between 2 and 102 g/kg over a similar burn rate range of 1 to 4 kg/hr.

Wood heater #1 was operated over a broad burn rate range of 2 to 14 kg/hr. At the lower burn rates wood heater #1 generated much higher CO emission factors than wood heater #2. However, as the burn rate increased, wood heater #1 CO emissions decreased to levels typically associated with wood heaters having an active catalytic combustor. Figure 80 shows that the CO emission factors for wood heater #1 were inversely related to burn rate. Carbon monoxide emission factors as low as 7 g/kg were generated by wood heater #1 at the higher burn rates. The data supported the common perception that typical airtight wood heaters operate with reduced CO emission factors at high burn rates for open damper firings.

Wood heaters #3 and #5 CO emission factors are compared with #1 in Figure 81. Both wood heaters #3 and #5 typically generated CO emission

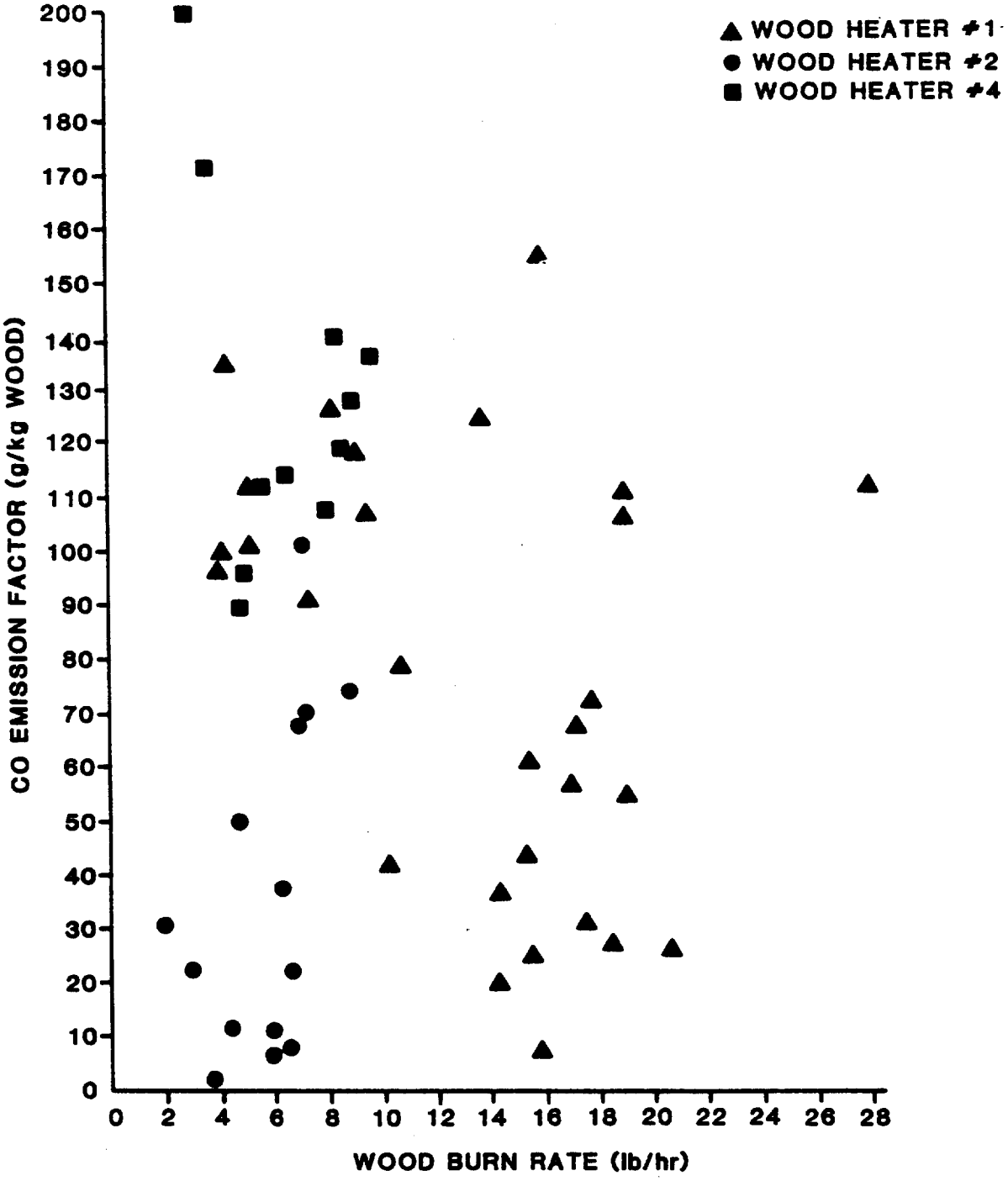


Figure 80. Carbon Monoxide (CO) Emission Factors Versus Wood Burn Rate (l)

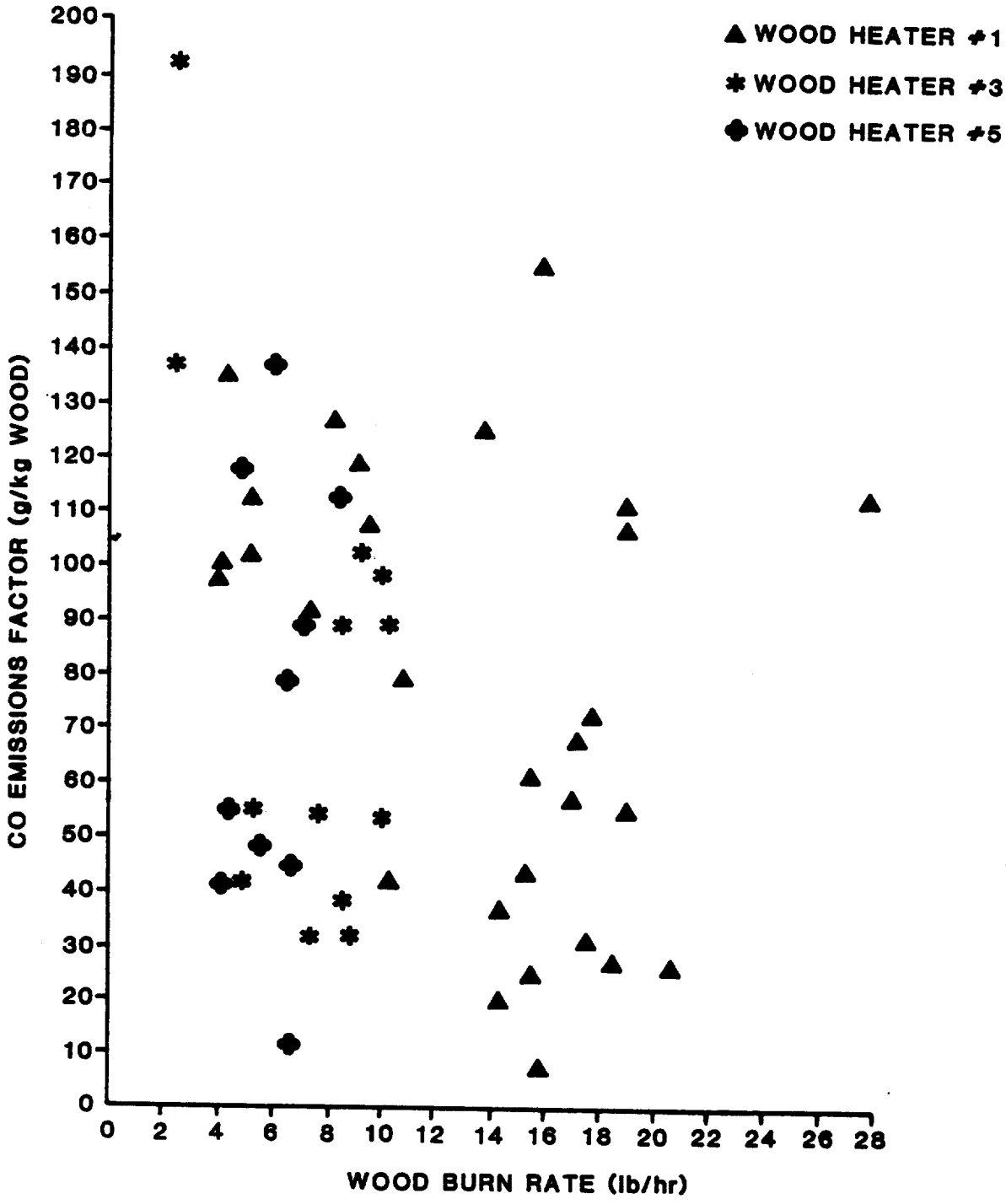


Figure 81. Carbon Monoxide (CO) Emission Factors Versus Wood Burn Rate (II)

factors much lower than those for wood heater #1 at burn rates less than about 5 kg/hr. At higher burn rates (where neither wood heater #3 or #5 could operate) wood heater #1 operated with low CO emission factors.

The CO emission factors for wood heater #5 showed large variability during replicate tests since these tests were hard to complete due to difficulties associated with maintaining real secondary combustion. The lowest CO emission factor found for wood heater #5 was 11 g/kg. Only about ten minutes of experimental data from the most favorable portion of the test was used in generating the emission factor. The details of this test (133) are presented in Table 30.

Wood heaters #2, #3, and #5 showed significant potential for reducing CO emission factors when compared to the airtight wood heater #1. This reduced CO emissions output for the three wood heaters was found to exist at low burn rates typically used by the homeowner. Wood heater #2 showed the lowest CO emission factors. At burn rates in excess of 6 kg/hr, wood heater #1 operated with reduced CO emission factors. Thus, the new technology wood heaters with their low CO emissions at low burn rates contrasted with wood heater #1 which had low CO emissions at high burn rates. This is not to say that CO did not decrease as the burn rate was increased for the new technology heaters. This just means that the levels of CO at low burn rates are lower than those for a conventional airtight wood heater.

Wood heater #1 was considered to be one of the most typical airtight units in the TVA region. Having a rather large combustion volume, wood heater #1 was capable of high burn rates. If other airtight, updraft wood heaters like wood heater #1 had been used, similar CO emissions would have been found but at different burn rates than found for wood heater #1.

An interesting comparison between carbon monoxide and FID-measured total hydrocarbon emission factors is presented in Figure 82. Both THC and CO emissions tended to increase together as both were the result of incomplete combustion. An earlier Battelle study (19) found that the ratio of THC to CO varied between about 1 and 0.2 for several wood heaters with the THC/CO=1 ratio being typical of low burn rate firings and THC/CO=0.2 being typical of high burn rate firings. All wood heaters used in this study, except for wood heater #2, operated typically with THC/CO ratios between 0.7 and 0.18. The catalytic wood heater #2 operated generally with a THC/CO ratio of about 1.5. The low burn rate firings provided the higher THC/CO ratios. Since wood heater #2 was operated at burn rates lower than for any other wood heater, the highest THC/CO ratios would be expected. Figure 82 shows that wood heater #2 was unique from the other four heaters involved in the study. The figure also shows that wood heaters #1 and #4 differ more significantly from catalytic wood heater #2 than do wood heaters #3 and #5. This is consistent with an earlier observation that wood heaters #1 and #4 performed with combustion efficiencies typical of conventional airtight wood heaters.

Filterable Particulate Emissions

The filterable particulate emission factors presented in Figure 83 were associated with the entire front half of the modified EPA Method 5 sampling system. Materials recovered from the probe, filter, and filter assembly were included in the emission factors which are presented as grams of particulate materials per kilogram of actual wood weight consumed. The filterable particulate emission factors were not very dependent on wood load size and remained below 2 g/kg throughout testing of all wood heaters with the exception of one low-burn test for wood heater #1 using a large fuel load.

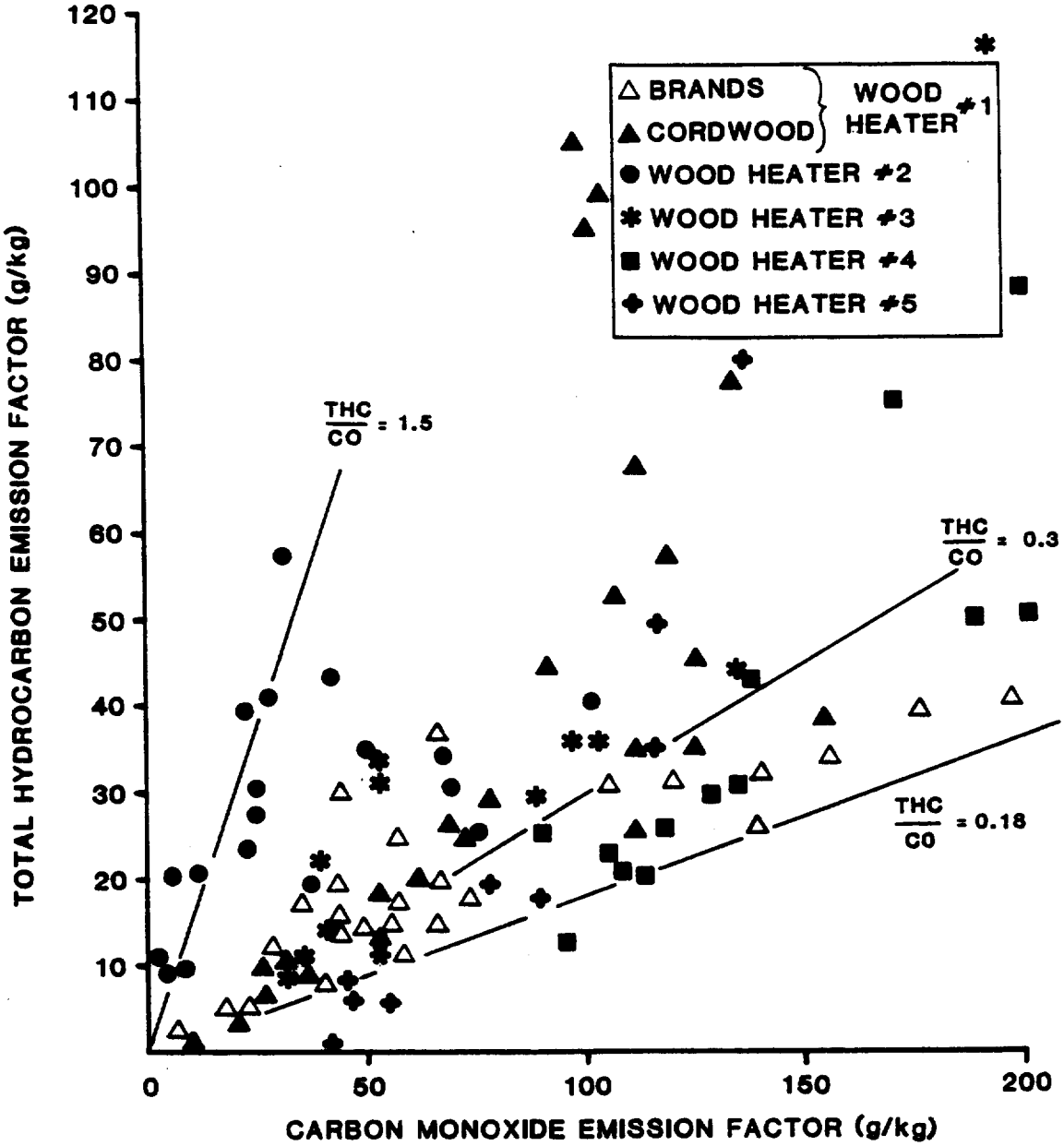


Figure 82. Total Hydrocarbon Versus Carbon Monoxide Emission Factors

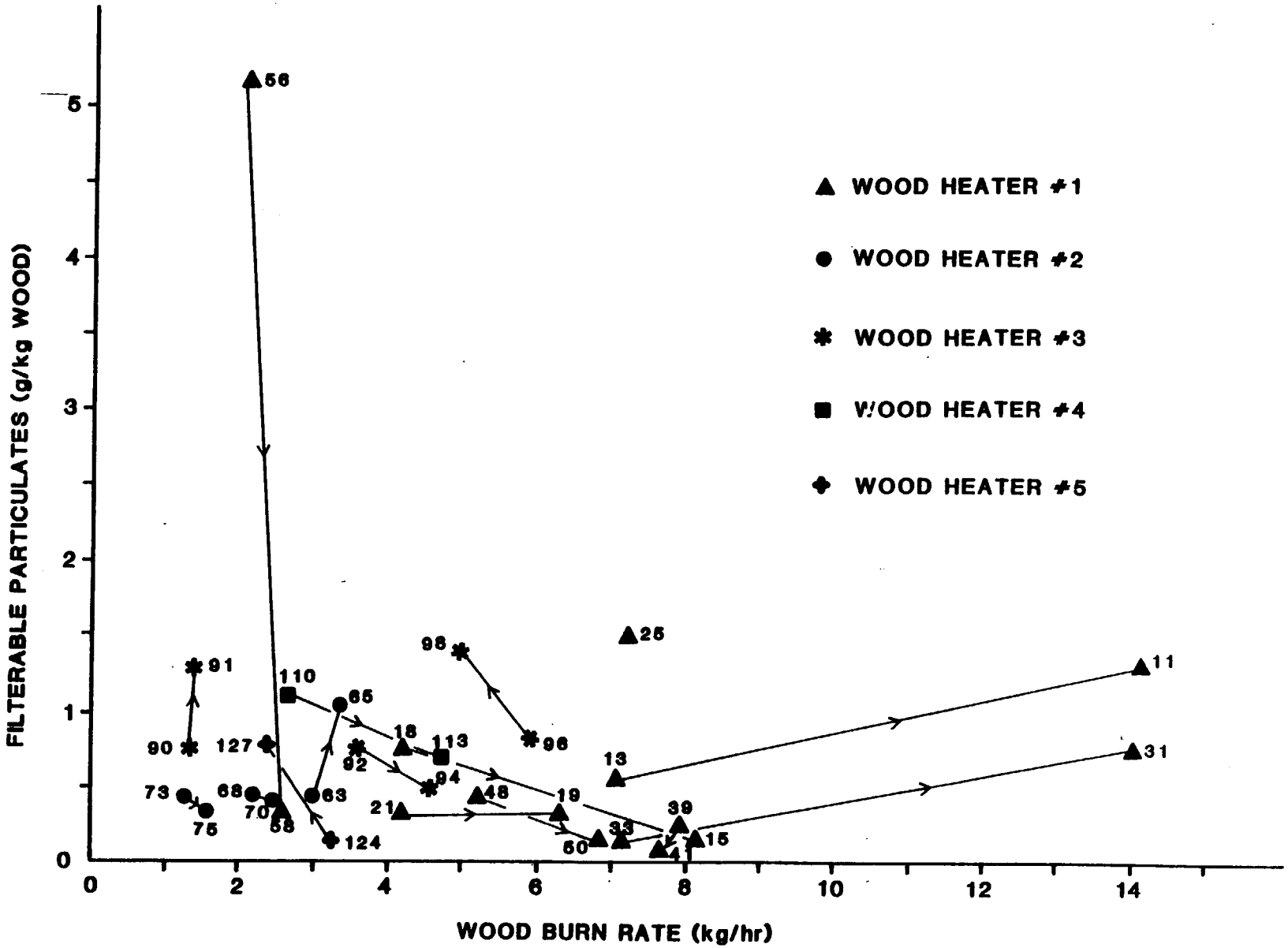


Figure 83. Effect of Burn Rate on Filterable Particulate Emissions

Total Particulate Emissions

The total particulate emission factors presented in Figure 84 were strongly dependent upon the burn rate below some critical burn rate. This critical rate was dependent upon the wood heater design and the nature of the wood load. The curve showing the total particulates of wood heater #1 for a small 7.8 pound wood load agreed with the Argonne results (6) which are also shown in Figure 84. Both curves show results obtained using a fixed wood load weight with the air control damper position reset between tests to control the burn rate. The Argonne study sampled the "stable" part of the burn while TVA sampled throughout the duration of the burn. Wood heater #1 shows higher total particulates at low burn rates than the wood heaters having "so-called" improved combustion features. The TVA total particulate emission factors also compared very favorably with the high burn rate results found by Monsanto (4). A study by the Oregon Department of Environmental Quality (3) also found higher total particulates for the airtight wood heaters than for the catalytic wood heater tested.

The ratio of condensibles to filterable particulates was dependent upon burn rate as shown in Figure 85. But only wood heater #1 showed sharp increases at low burn rates that were directly associated with wood load weight. This increase resulted from an increase in the concentration of intermediate and low molecular weight organics relative to the concentration of the heavier organics in the flue gases.

Volatile Hydrocarbon Emissions

The volatile hydrocarbon emission factors presented in Figure 86 also show the prevalent dependency upon burn rate, with large increases resulting from firings below some critical burn rate. The wood heaters

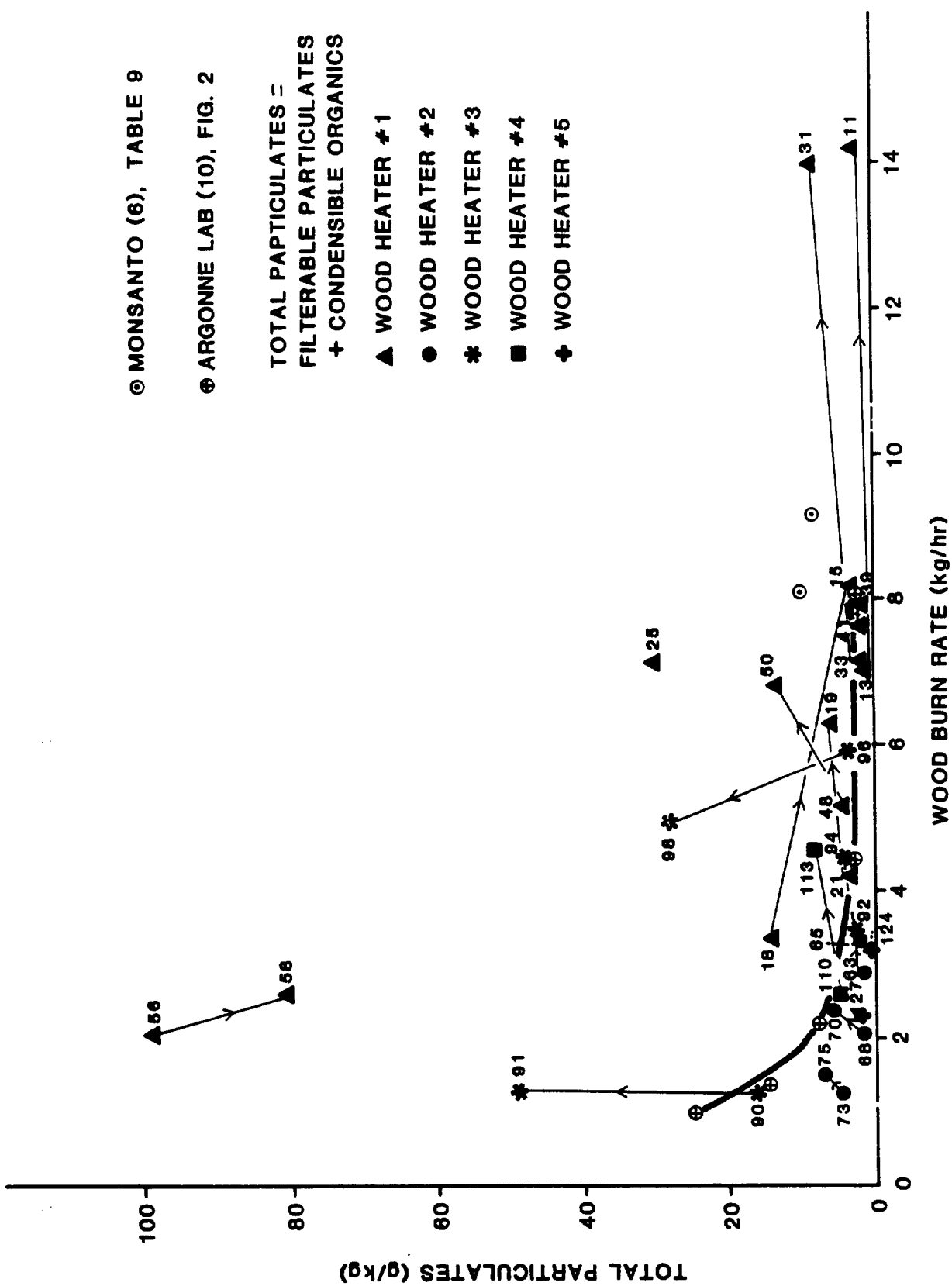


Figure 84. Effect of Burn Rate on Total Particulate Emissions

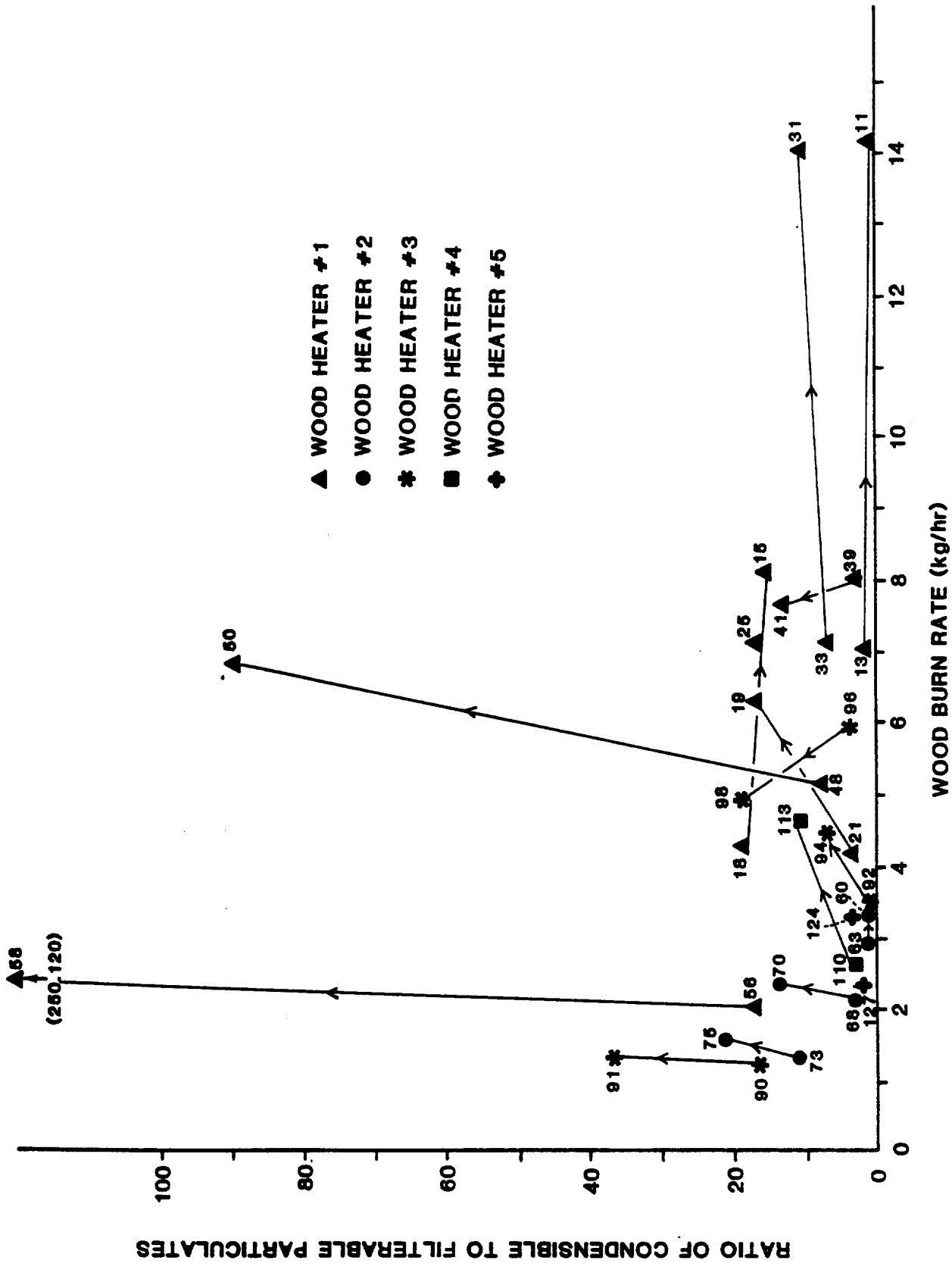


Figure 85. Effect of Burn Rate on the Ratio of Condensible to Filterable Particulates

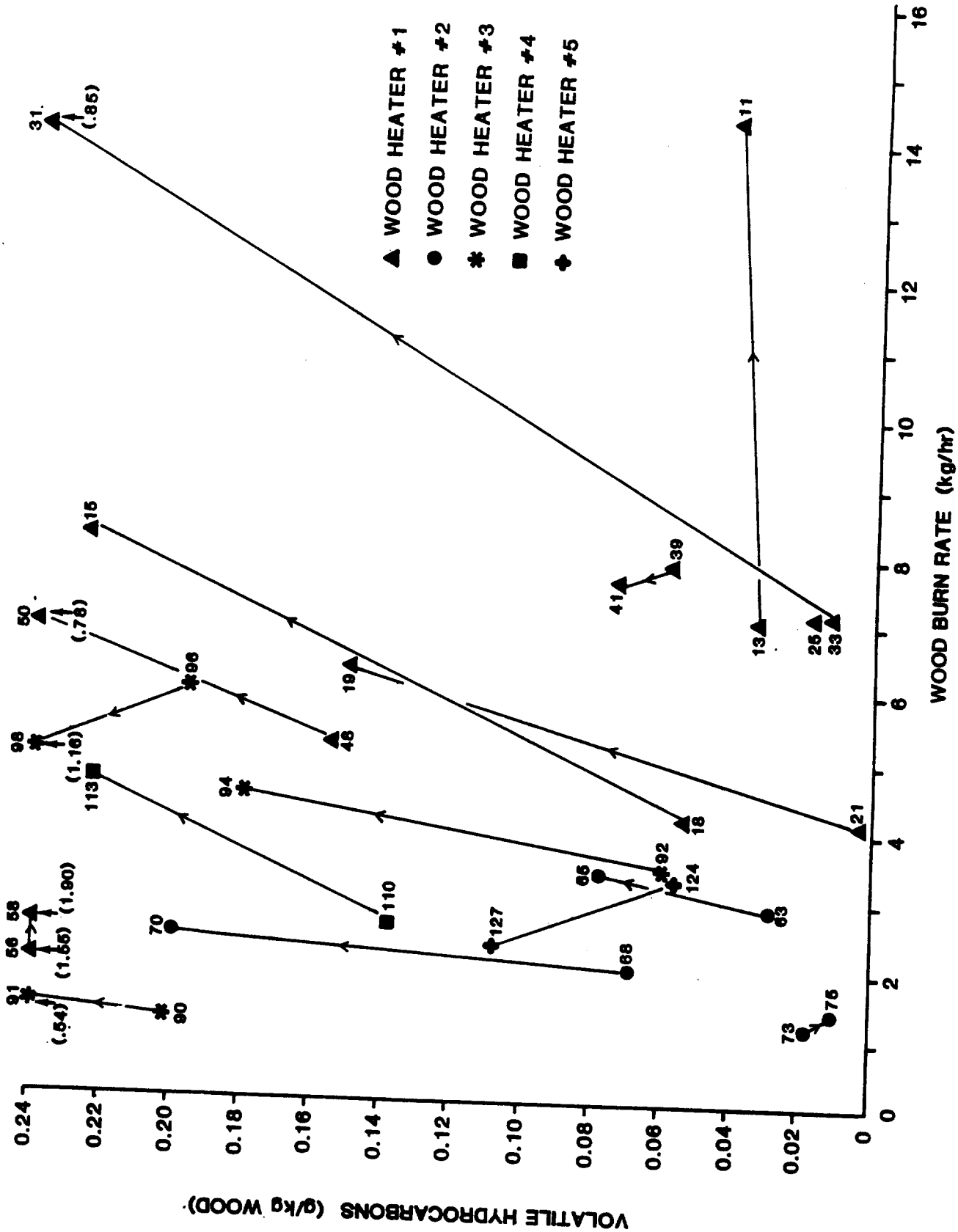


Figure 86. Effect of Wood Burn Rate on Volatile Hydrocarbon Emissions

with advanced combustion features had reduced volatile emissions, especially at the lower burn rates.

Polynuclear Aromatic Hydrocarbon (PAH) Emissions

The interrelationships between excess air and the complex conditions associated with combustion of each wood fuel charge were responsible for the PAH versus excess air trends shown in Figure 87. At high and intermediate burn rates corresponding to flue gas excess air values below about 200 percent, the PAH emission factors increased significantly with increased wood fuel charge. The PAH emission factors decreased with increased wood fuel charge for the very low burn rates corresponding to excess air values over 200. Figure 87 shows that PAH emission factors were significantly reduced when operating the wood heaters with excess air values between approximately 120 and 200. The reduction in PAH emission factors by a factor of approximately three for the catalytically equipped retro heater resulted from the improved flow and thermal conditions conducive to primary and secondary combustion. The temperature (~275°F) of the flue gas entering the add-on catalytic unit during the low burn tests was too low for catalysis activation. In effect, the add-on catalytic unit only provided additional back pressure and heat exchange surface when operating in this inactive mode.

Figure 88 shows the different increases in PAH that resulted from increased wood fuel charge size. Generally, the largest increases in PAH were associated with the higher burn rates and more open air control settings.

Connective test results for PAH emission factors versus wood burn rate are shown in Figure 89. PAH emission factors are again shown to have increased dramatically with increased wood load weight; the largest

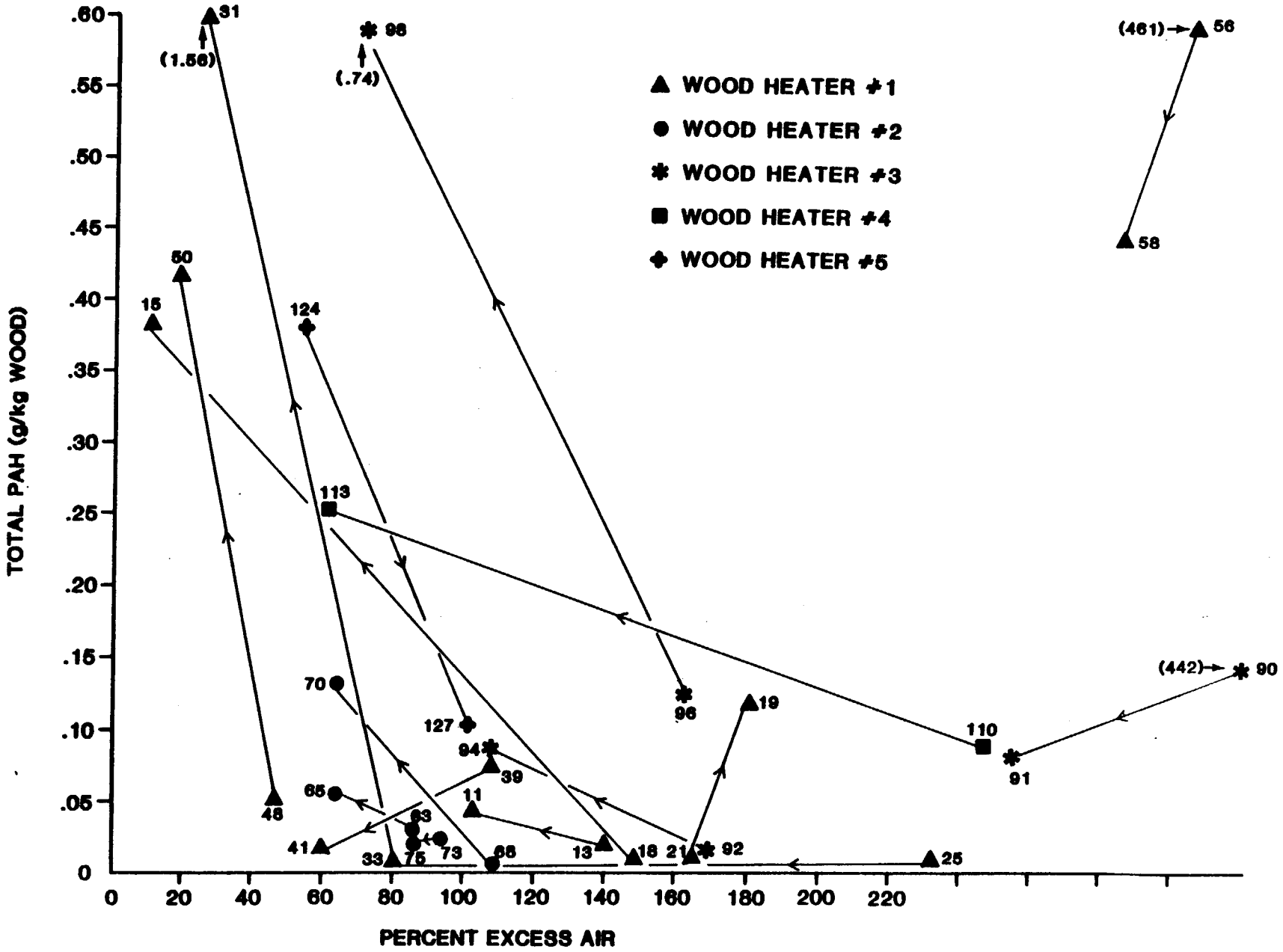


Figure 87. Effect of Percent Excess Air on PAH Emissions

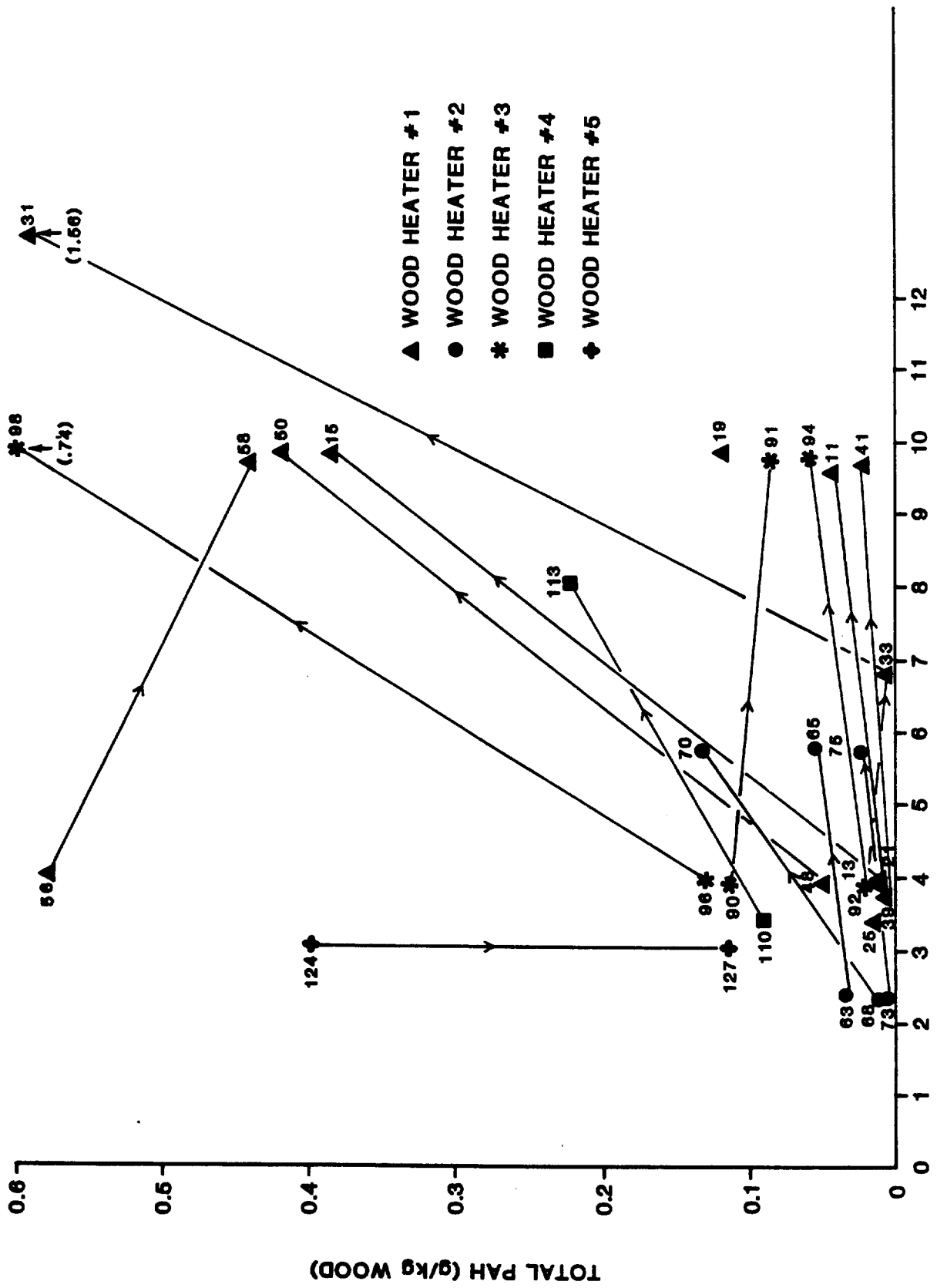


Figure 68. Effect of Wood Charge on PAH Emissions

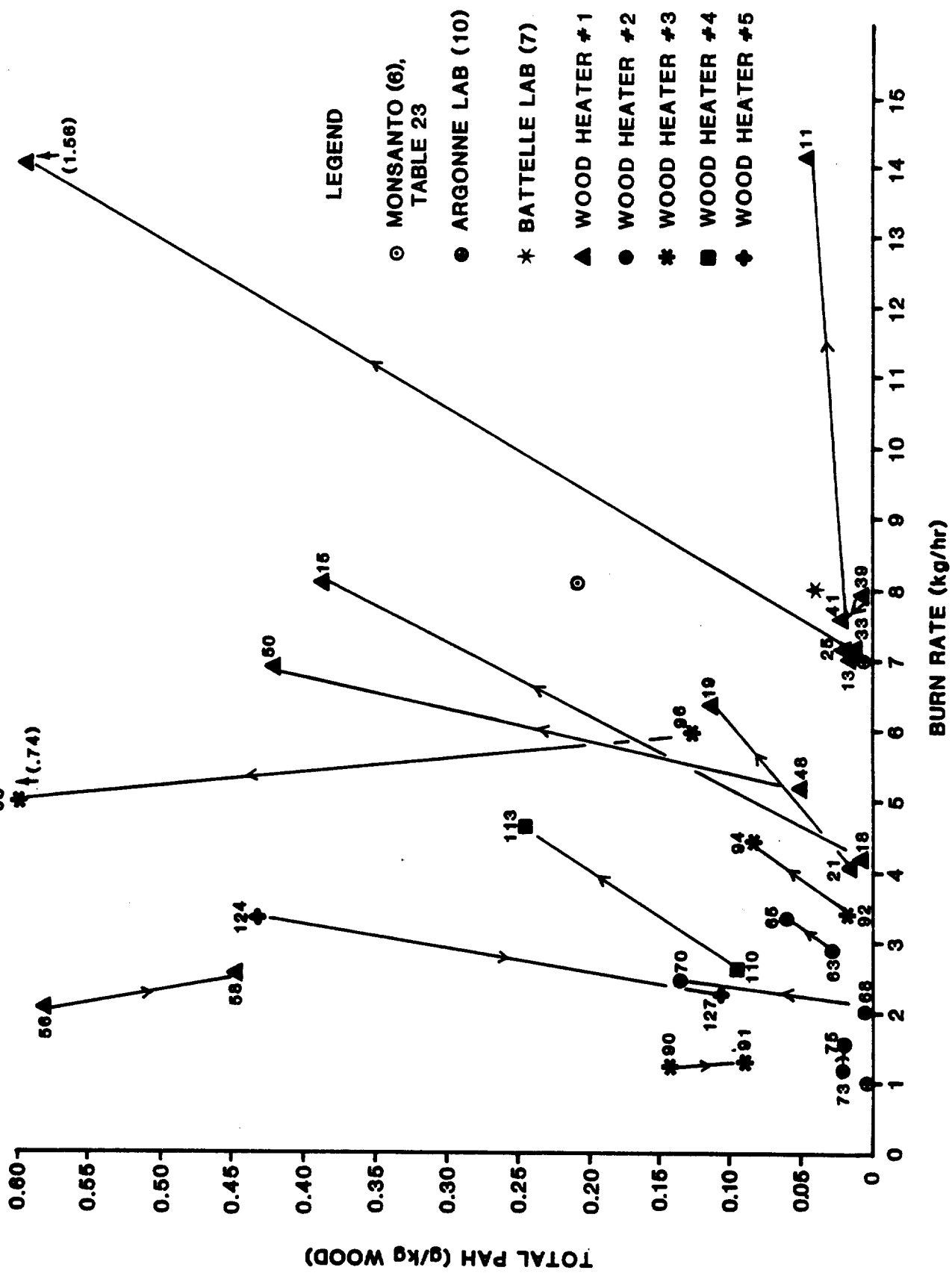


Figure 89. Effect of Burn Rate on PAH Emissions.

differences being for the higher burn rate tests on the airtight wood heater. The basic airtight wood heater had higher PAH emission factors when fueled by the larger wood charges. Generally, the PAH emission factors were similar for small wood loads. However, the catalytic units continued to maintain low PAH emission factors when burning the larger fuel charges with wood heater #2 showing the lowest average PAH emission factor. Wood heaters #2, #3, #4, and #5 possessed relatively low PAH emission factors at low burn rates while airtight wood heater #1 had to operate at much higher burn rates to sustain its comparable low PAH emission factors. At low burn rates, wood heater #1 had PAH emission factors about 15 times as large as catalytic wood heater #2. Figure 89 also shows that the burn rate for each wood heater generally increased with increased wood fuel charge size with the air control (damper) position being held constant.

Figure 89 also shows that PAH emissions decreased dramatically with increased wood burn rate when the smaller wood weights were consumed. Similar PAH emission trends have been reported by the Canadian Combustion Research Laboratory (16). The sharp reduction in PAH emission factors with increased wood burn rates, however, did not result when the larger wood charge weights were consumed. The emission factors dropped to a minimum and then increased dramatically at the highest burn rates. Initially, the high emission factor (1.57) was thought to be due to some error in sampling or analysis. However, no evidence was found that invalidated this highest PAH emission factor. In effect, it appears that PAH emission factors for the conventional airtight wood heater could have been minimized by operating at a burn rates near 12 lb/hr when the larger wood weights were being burned and at the highest burn rate possible for the smallest wood weights.

An Argonne Lab study (6) concluded by using data from only two tests that the PAH emission factor increased with burn rate. The Argonne emission factors are included in Figure 89 to show how low their findings were in comparison with TVA, Monsanto (4), and Battelle Lab (5) PAH emission factors. The TVA PAH emission factors were in general agreement with the Monsanto and Battelle results at higher burn rates. Low burn rate PAH emissions were either not obtained or not reported in the Monsanto and Battelle studies. The small recovery of PAH emission associated with the Argonne test effort may possibly have been associated with the sample recovery system used by Argonne Lab. The TVA, Monsanto, and Battelle studies added an XAD-2 resin trap to the EPA Method 5 sampling system specifically to recover organics from the flue gases. The Argonne study did not use an XAD-2 trap or any specific mechanism designed to trap organics. Differences in the handling procedure and type of gas chromatography used in quantification of PAH may have also contributed to the smaller PAH emission factors reported by the Argonne study.

The flue gas temperature at the exit of the wood heater did not correlate with PAH emissions as shown in Figure 90. The exit temperature did not change significantly with size of the wood fuel charge while the PAH emission factor possibly varied by a factor of 20 or more. This does not support the principle held by some which relates increased PAH emission factors with increased wood heater exit temperature.

Composite averages for PAH emission factors are presented in Table 36. It is important to note that the average PAH emission factor for wood heater #1 was the highest, while that for catalytic wood heater #2 was the lowest. The catalytic wood heater PAH emissions were only about 20 percent of those associated with the conventional, airtight wood heater.

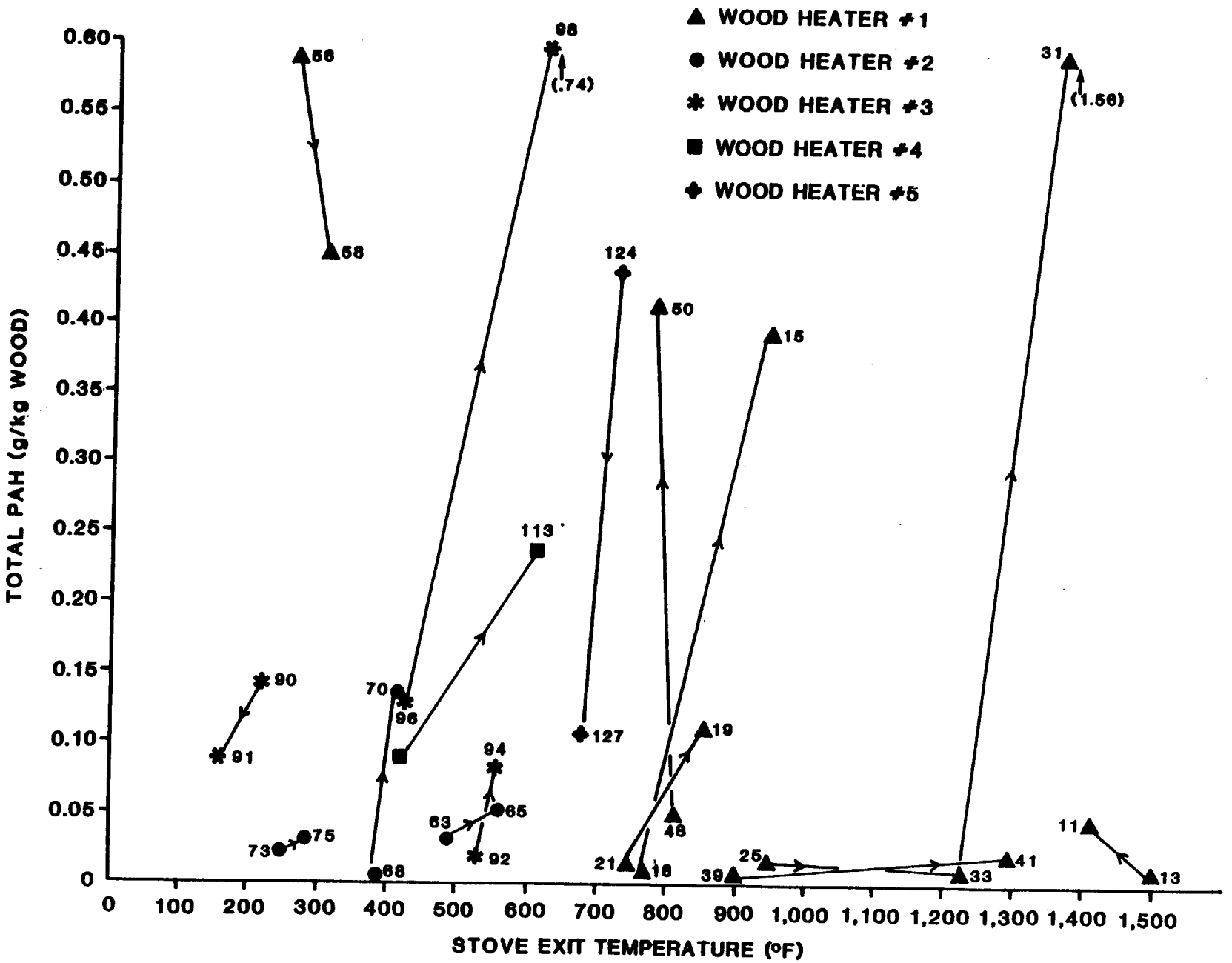


Figure 90. Effect of Stove Exit Temperature on PAH Emissions.

Table 36. SUMMARY OF AVERAGE EMISSION RESULTS FOR CRITERIA POLLUTANTS AND PAH FOR FIVE DIFFERENT WOOD HEATERS - EMISSION FACTORS (g/kg)

Wood Heater #	Fuel	PAH	Filterable Particulates	Condensible Organics	Total Particulates	Volatile Hydrocarbons	MM5 Samples	CO[i]	NO_x[i]
1	a	0.10	0.58	3.52	4.10	0.10	c	77[j]	2.10[j]
1	b	0.25	1.06	31.89	32.95	0.75	d	89	0.31
2	b	0.05	0.60	5.13	5.73	0.07	e	35	0.86
3	b	0.19	0.87	15.96	16.83	0.38	f	95	1.01
4	b	0.16	0.89	5.98	6.87	0.18	g	139	0.82
5	b	0.08	0.23	1.54	1.77	0.08	h	80	1.14
k		0.27	3.60	6.10	9.70	0.20		181	0.50
1	n	0.10	1.48	-	-	-	m	92	2.50

[a]Oak brands, 2" x 4", 11.9% moisture (wet)
[b]Red oak, split cordwood, 10.4% moisture (wet)
[c]Six samples at medium and high burn rates
[d]Eight samples at low, medium, and high burn rates
[e]Six samples at low, medium, and high burn rates
[f]Six samples at low, medium, and high burn rates
[g]Two samples at medium burn rate
[h]Two samples at medium and high burn rates
[i]Average for all tests by continuous analyzers; $\geq$ 90 percent NO (v/v)
[j]All medium and high burn tests
[k]Monsanto Study (4) (average results)
[l]TVA Study (8); heated filter at 350°F as opposed to 405°F for this stucy; PAH quantified using flourescent screening techniques in (8) as apposed to GC/MS in this study
[m]Average for all tests
[n]Red Oak fuel of various configurations

Wood heater #5 had the lowest PAH emissions next to catalytic wood heater #2. This was not surprising since effective secondary combustion was maintained in wood heater #5 during a major portion of the burn cycle. Naphthalene represented about 50 percent of the total PAH for all five wood heaters, while BaP was typically less than 4 percent of the total PAH. Wood heaters #2 and #5 showed reductions in BaP emissions by a factor of eight over wood heater #1.

A Battelle study (5) reported total PAH emission factors of 0.034 and 0.017 g/kg, respectively, for side-draft and up-draft firings of a wood heater using seasoned, triangular oak fuel. High burn rate PAH emission factors for wood heater #1 presented in Table 37 are similar to the Battelle findings. The average value of 0.25 g/kg was higher than that reported by Battelle because it includes results from a broad range of operations. The Monsanto study (4) reported a seasoned oak PAH emission factor of 0.19 g/kg for a medium to high burn rate test on a nonbaffled stove.

The same Battelle study reported BaP emission factors of 0.0005 and 0.00137 g/kg for the side-draft and up-draft firings. An average BaP emission factor of 0.0082 g/kg as shown in Table 37 was found in this study for the airtight wood heater. The BaP emissions for wood heater #1 ranged from 0.0003 to 0.035 g/kg for cordwood fuel.

Summary of Criteria and PAH Emissions

An overall summary of criteria emission factors for wood heaters #1 and #2 is presented in Tables 38 and 39. The emission factors for low, medium, and high burn rates represent the average of two tests in each case. The two tests were conducted at the same damper or air control setting for the wood heater but with two different wood loading sizes.

Table 37. SUMMARY OF AVERAGE PAH EMISSIONS
EMISSION FACTORS, g/kg (% of Total)

WOOD HEATER #1[a]

Firing	Burn Rate (kg/hr)	Tests	BaP	Naphthalene	Phenanthrene	Total
Low	2.2	56,58	0.0142(2.7)	0.264(51.4)	0.039(16.7)	0.514
Medium	5.8	48,50	0.0102(4.2)	0.114(48.7)	0.045(19.4)	0.235
High	8.5	39,41	0.0003(2.2)	0.007(50.7)	0.002(16.2)	0.014
Average	5.4		0.0082	0.128	0.029	0.254
b	7.2		0.0097			0.270

WOOD HEATER #2[a]

Firing	Burn Rate (kg/hr)	Tests	BaP	Naphthalene	Phenanthrene	Total
Low	1.25	73,75	0.0005(2.1)	0.014(58.9)	0.005(19.9)	0.024
Medium	2.04	68,70	0.0008(1.1)	0.039(55.7)	0.015(20.9)	0.070
High	2.87	63,65	0.0007(1.5)	0.021(43.0)	0.011(23.9)	0.048
Average	2.05		0.0007	0.025	0.010	0.047

[a]Red oak cordwood fuel, 10.4% moisture (wet)
[b]Monsanto Study (4), Table 23

Table 38. SUMMARY OF WOOD HEATER #1 EMISSION RESULTS FOR CRITERIA POLLUTANTS EMISSION FACTORS (g/kg) - CORDWOOD FUEL

Firing	Burn Rate (kg/hr)	Filterable Particulates	Condensible Organics	Total Particulates	Volatile Hydrocarbons	CO	NO_x	SO_2
Low[b]	2.2	2.75	86.30	89.05	1.72	103	0.11	0.28
Medium[c]	5.8	0.28	8.42	8.70	0.47	101	0.14	1.21
High[d]	8.5	0.16	0.96	1.12	0.06	41	0.69	0.30
Average	5.4	1.06	31.89	32.95	0.75	89[a]	0.31[a]	0.72[a]
e	7.2	3.60	6.10	9.70	0.20	181	0.50	0.20

[a]Average for all cordwood tests using continuous analyzers
[b]Tests 56 and 58 averaged
[c]Tests 48 and 50 averaged
[d]Tests 39 and 41 averaged
[e]Monsanto Study (4), Table 1

Table 39. SUMMARY OF WOOD HEATER #2 EMISSION RESULTS FOR CRITERIA POLLUTANTS EMISSION FACTORS (g/kg) - CORDWOOD FUEL

Firing	Burn Rate (kg/hr)	Filterable Particulates	Condensible Organics	Total Particulates	Volatile Hydrocarbons	CO	NO_x	
Low[b]	1.25	0.61	10.32	10.93	0.021	27	0.44	
Medium[c]	2.04	0.43	3.86	4.29	0.132	28	1.44	
High[d]	2.87	0.76	1.20	1.96	0.053	15	0.78	
Average	2.05	0.60	5.13	5.73	0.069	35[a]	0.86[a]	

[a]Average for all tests using continuous analyzers
[b]Tests 73 and 75 averaged
[c]Tests 68 and 70 averaged
[d]Tests 63 and 65 averaged

The smaller wood loading was represented by 32 kg per cubic meter of internal combustion volume in each wood heater, while the larger wood loading was represented by 80 kg per cubic meter of combustion volume. The small wood loadings were 3.5 kg (7.8 pounds) and 2.1 kg (4.7 pounds), respectively, for wood heaters #1 and #3. The larger wood loadings were 8.8 kg (19.3 pounds) and 5.3 kg (11.6 pounds), respectively, for wood heaters #1 and #3. The average values were determined by using MM5 results with the exception of CO, NO_x, and SO_2 results, which were obtained by using continuous analyzers. The average emission factors presented for CO, NO_x, and SO_2 are the average for all tests conducted using the cordwood fuels.

The Monsanto results presented in Table 38 were obtained at medium and high burn rate firings for airtight wood heaters. Table 38 shows that the TVA and Monsanto results corresponded at medium and high burn rates for total particulates, NO_x, and SO_2. The disagreement of the separate components of the total particulates with the Monsanto results was possibly due to the operating procedure for the EPA Method 5 sampling system. Both TVA and Monsanto used an XAD-2 resin trap. Monsanto operated their heated filter section at a low temperature of 100°C while TVA operated its front half heated filter section at 205°C. The high temperature allowed most condensing organics to be recovered in the resin trap and impingers of the modified Method 5 system. However, both operating procedures should have recovered the same total sample. Table 38 shows that all criteria emissions except NO_x and SO_2 increased significantly with decrease in burn rate. NO_x emissions decreased due to lower combustion temperatures. The total particulate emission factor increased by a factor of 85 going from high to low firing conditions. Since the burn rate decreased by a

factor of 2.5, the time rate of generation of total particulates increased by a factor of 32.

This increase in the rate of total particulate generation is a very important finding in view of its implications with regard to ambient air quality. The total particulates represent the ultimate potential for creosote formation. Typically, only a small fraction of the total particulates actually become creosote with the remainder becoming total suspended particulates. Table 38 shows that for wood heater #1, larger quantities of creosote should be deposited in flue systems at low burn rate firings than at high firings. A recent Shelton study (7) showed that low firings did result in increased creosote deposits for airtight wood heaters.

Catalytic wood heater #2 emission results presented in Table 39 show reductions in all areas, except NO_x, when compared to wood heater #1 results. At low burn rate firings, the catalytic wood heater total particulate emission factor was lower by a factor of 8 than that for wood heater #1. The average total particulate emission factor for wood heater #2 was lower than the Monsanto average by a factor of nearly 2. The average CO emission factor for wood heater #2 was lower than that found by Monsanto by a factor of 5. Average NO_x emission factors did not differ significantly for wood heaters #1 and #2, although #2 was higher.

The differences in CO emissions found by TVA and Monsanto may possibly be associated with the differences in sampling procedures. Monsanto determined their CO emission factors by using only ten Orsat samples taken during the complete burn, while TVA measured CO flue components at intervals not exceeding 2 minutes throughout tests that sometimes lasted 6 hours.

The summary of average PAH emissions for wood heaters #1 and #2 was presented in Table 37. Total PAH emission factors increased significantly with reduced burn rate for wood heater #1 while wood heater #2 operated with similar PAH emission factors at low and high firing rates. The average total PAH found for wood heater #1 corresponded very closely with Monsanto's findings. Wood heater #2 average PAH emissions were lower by a factor of 5 than those found for wood heater #1.

The benzo(a)pyrene (BaP) component of total PAH was typically less than 2 percent for catalytic wood heater #2 and was less than about 4 percent for wood heater #1. Table 37 shows the average BaP emission factor for wood heater #2 to be less than that for wood heater #1 by a factor of 12. The average BaP emission factor found by TVA for wood heater #1 was very similar to that found by Monsanto.

The two most common components of PAH found by TVA were methyl/phenyl/naphthalene and phenanthrene/anthracene. The naphthalene class typically represented about 50 percent of the total PAH while phenanthrene represented about 20 percent of the total PAH for both wood heaters.

A summary of average emission factors for criteria pollutants and PAH for the five different wood heaters involved in this test program was presented in Table 36. The Monsanto results are also presented again to provide a direct comparison. It is very important to note that MM5 samples were recovered for low, medium, and high burn rates for wood heaters #1, #2, and #3 using the Cordwood fuel while such samples were recovered for medium and high burn rates for wood heaters #4 and #5. Therefore, the emission results presented in Table 36 should not be treated with equal significance since the results for wood heaters #1, #2, and #3 represent the average emissions for the widest spectrum of wood

heater operation. The emission results for wood heaters #4 and #5 are associated with medium and high burn rates where typically such emissions are lower than for low burn rates. The Monsanto results are also associated with medium and high burn rates. The summary of emission factors for all five wood heaters is also presented in Figure 91.

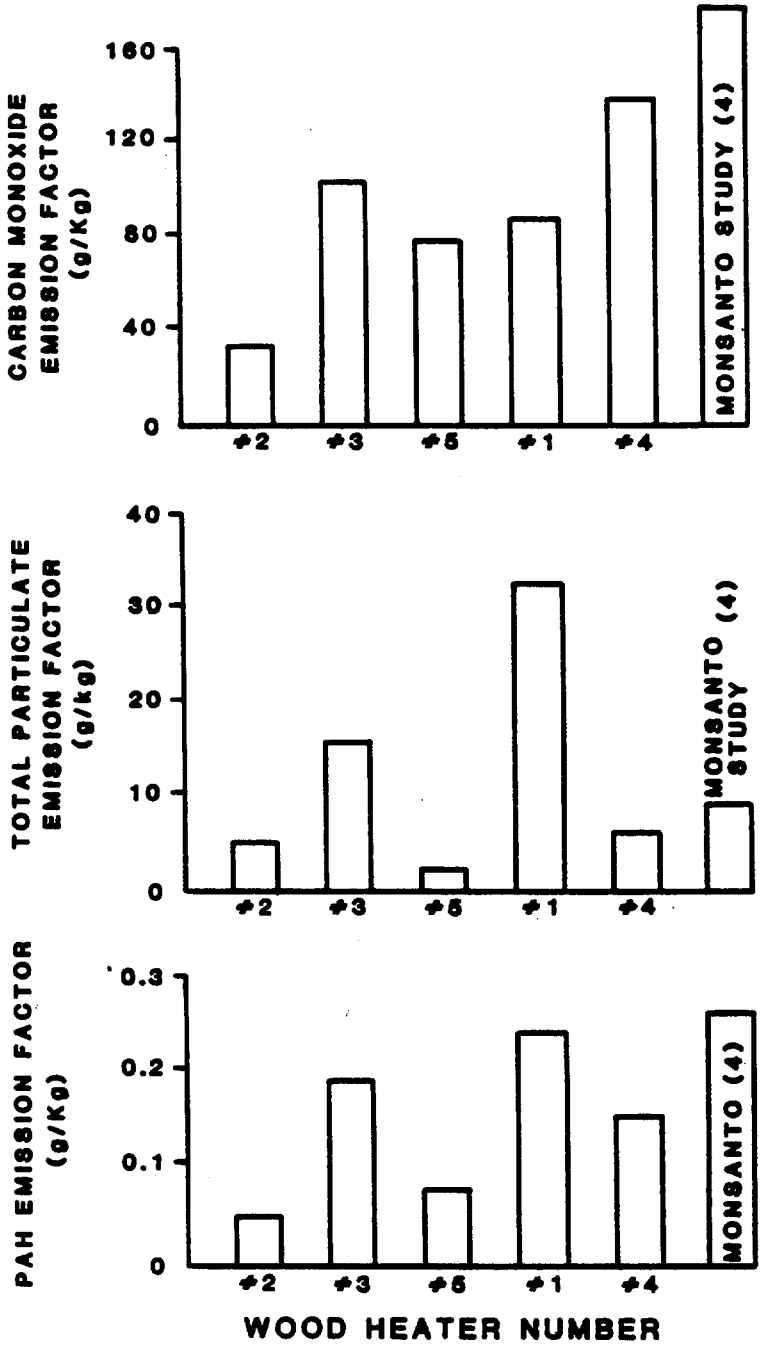


Figure 91 . Summary of Emission Factors

CONCLUSIONS

The thermal efficiency, combustion efficiency, heat transfer efficiency, sensible plus latent losses, and chemical losses as well as emissions generated by wood heaters are dependent upon:

- the wood load composition and size
- the damper or air control setting
- the type of wood heater (catalytic, airtight, etc.).

Catalytic wood heater emissions and thermal performance showed less dependence on wood load size and damper setting than did the airtight wood heater tested.

All wood heaters possessing new technology combustion features did not operate with similar success. Figure 79 shows that the wood heaters using the Corning catalytic combustor operated with the highest thermal efficiency and lowest chemical loss.

Wood heater #5 operated with "active" secondary combustion which enabled it to develop an average thermal efficiency nearly as high as the retrofit ("add-on") wood heater #3. Wood heater #5 has the potential of very high thermal efficiency due to its 87 percent combustion efficiency. However, its low heat transfer efficiency of 60 percent prevented it from realizing the higher thermal efficiency.

Each wood heater tested (except wood heater #2) operated with highly variable thermal efficiencies as shown in Figure 78. Generally speaking, each of the heaters developed its highest thermal efficiency at the fully open damper setting with the major exception being heater #1. The thermal efficiency for wood heater #1 was highest for the 30 percent open damper setting.

Chemical losses associated with the emissions from each wood heater were minimized by operating each heater at an open damper setting. The chemical losses associated with wood heater #2 were the least dependent upon damper setting.

The emissions of catalytic wood heater #2 showed less dependence on wood load size and damper setting than those of the airtight wood heater #1 tested. However, the PAH and associated organic emissions for the airtight wood heater were minimized by using smaller loads of cordwood fuel and medium damper settings.

The five wood heaters involved in this study may be ranked relative to reduced PAH emission factors as follows:

- wood heater #2 (Corning catalytic)
- wood heater #5 (secondary combustion)
- wood heater #4 (metal catalytic)
- wood heater #3 (retro Corning catalytic)
- wood heater #1 (airtight circulator).

GLOSSARY OF TERMS

In the following glossaries, the definitions of the terms used in the model and other parts of this report are given. In Section 1, Instantaneous Efficiency and Emissions Glossary, the terms described are the ones measured at designated time intervals during each test. Section 2, Average Efficiency and Emissions Glossary, includes the average values for the instantaneous values collected over the entire test run. Section 3, Modified Method 5 Data Analysis Glossary, describes the terms used in the Modified Method 5 Data Analysis section of the report.

Section 1 - INSTANTANEOUS EFFICIENCY AND EMISSIONS GLOSSARY

Air/Fuel Ratio - pounds of air supplied per pounds of dry wood burned.

Excess Air - percentage of air available to react that is in excess of the air theoretically required to completely burn the combustible material.

Gas Composition - molar percent (%) of O_2, CO, CO_2, etc., in the flue gases.

Instantaneous Air Flow In - volume of air (ft^3/min) drawn into the stove at any instant of time.

Instantaneous THC Composition - flue gas THC in parts per million (ppm) at any instant of time.

Section 2 - AVERAGE EFFICIENCY AND EMISSION VALUES GLOSSARY

Average Air Flow Rate - average of instantaneous (inst.) air flow in values based on a time weighted average.

Average Air/Fuel Ratio - average of the air/fuel ratios based on a mass weighted average.

Average CO Emission - average of the inst. CO emissions during each inst. time interval based on a mass weighted average.

Average CO Emission Factor - average of the inst. CO emission factors during each inst. time interval based on a mass weighted average.

Average CO_2 Emission - average of the CO_2 emissions of CO_2 in pounds per million Btu's (lb/MBtu) of heat released based on a mass weighted average.

Average CO_2 Emission Factor - average emission of CO_2 in pounds per ton of wood burned (lb/ton) based on a mass weighted average.

Average Combustion Efficiency - average of the inst. combustion efficiency values weighted to the mass of the wood burned during each inst. time interval.

Average Efficiency - average of the inst. efficiency values weighted to the mass of wood being burned during each inst. time interval.

Average Excess Air - average of the excess air values based on a mass weighted average.

Average Flue Gas Temperature - average of the flue gas temperature values based on a mass weighted average during each inst. time interval.

Average Gas Flow Rate - average of the inst. gas flow values based on a time weighted average during each inst. time interval.

Average Heat Output Rate - average rate of heat released into the room based on a mass weighted average during each inst. time interval.

Average Heat Release Efficiency - average of the inst. heat release efficiency values based on a mass weighted average during each inst. time interval.

Average Heat Release Rate - average of the inst. heat release rate values based on a mass weighted average during each inst. time interval.

Average NO Emission - average of the inst. NO emissions during each inst. time interval based on a mass weighted aveage.

Average NO Emission Factor - average of the inst. NO emission factors during each inst. time interval based on a mass weighted average.

Average Percentage of Combustion Losses - average of the inst. percentage of combustion losses values during each inst. time interval based on a mass weighted average.

Average Percentage of Sensible and Latent Heat - average of the inst. percentage of sensible and latent heat values during each inst. time interval based on a mass weighted average.

Average SO_2 Emission - average of the inst. SO_2 emissions during each inst. time interval based on a mass weighted average.

Average SO_2 Emission Factor - average of the inst. SO_2 emission factor values during each inst. time interval based on a mass weighted factor.

Average Stove Gas Temperature - average of the temperature of the gas next to the stove based on a mass weighted average.

Average THC Emission - average of the inst. THC emissions during each inst. time interval based on a mass weighted average.

Average THC Emission Factor - average of the inst. THC emission factor values during each inst. time interval based on a mass weighted average.

Average Wood Burning Rate - average consumption of wood during the test based on a mass weighted average.

Inst. CO mission Factor - (a) emission of CO in pounds per million Btus of heat released at any instant of time (lb/MBtu); (b) emission of CO in pounds per ton of wood burned at any instant of time (lbm/ton); (c) emission of CO in grams per kilogram of wood burned at any instant of time (g/kg).

Inst. Combustion Efficiency - that percentage of the total heat of combustion of the wood (higher heating value - HHV) that is evolved as sensible and latent energy at any instant of time.

Inst. Efficiency - the ratio of heat released by the wood heater to the total energy input.

Inst. Gas Flow Out - volume of exhaust gases (ft^3/hr) at approximately 4 feet from the stove which are being generated by the stove at any instant.

Inst. Heat Release - amount of heat released (Btu/hr) from the wood at any instant of time.

Inst. Heat Release Efficiency - measure of the success by which the wood heater converts the heat developed by combustion into useful heat transfer at any instant of time.

Inst. NO_x Emission - instantaneous parts per million (ppm) of NO_x in the stack gas.

Inst. NO_x Emission Factor - (a) instantaneous pounds of NOx released per million Btu's of heat released (lb/MBtu); (b) instantaneous pounds of NO_x released per ton of wood burned (lbm/ton); (c) instantaneous grams of NO_x released per kilogram of wood burned (g/kg).

Inst. Percentage of Combustion Losses - measure of the combustion losses resulting from incomplete combustion at any instant of time during the test.

Inst. Percentage Sensible and Latent Heat - measure of sensible and latent heat lost at any instant of time.

Inst. SO_2 Emission - emission of SO_2 in parts per million (ppm) at any instant of time.

Inst. SO_2 Emission Factor - (a) emission of SO_2 in pounds per million Btu's of heat released at any instant of time (lb/MBtu); (b) emission of SO_2 in pounds per ton of wood burned at any instant of time (lbm/ton); (c) emission of SO_2 in grams per kilogram of wood burned at any instant of time (g/kg).

Inst. Total Hydrocarbon (THC) Emission - instantaneous parts per million (ppm) of total hydrocarbon (THC) in the stack gas expressed as equivalent methane (CH_4).

Inst. THC Emission Factor - (a) instantaneous pounds of total hydrocarbon released per million Btu's of heat released (lb/MBtu); (b) instantaneous pounds of total hydrocarbon released per ton of wood burned (lbm/ton); (c) instantaneous grams of total hydrocarbon released per kilogram of wood burned (g/kg).

Temperature Gas Out - gas temperature (°F) inside the flue approximately 8 feet from the stove outlet.

Temperature Stove Out - gas temperature (°F) in the stack at approximately 4 feet from the stove outlet.

Time Averaged Stove Gas Temperature - average temperature of the exhaust gas next to the stove, based on a time average.

Time Averaged Ratio, Dry Gas/Wet Gas - the molar balances in the program were used to calculate the moles of H_2O in the stack gas relative to the moles of other emissions measured in the stove. The ratio is that of the emissions without H_2O divided by the total emissions with H_2O, based on a time average.

Section 3: MODIFIED METHOD 5 DATA ANALYSIS GLOSSARY

Volatile Hydrocarbons Emission Factor - pounds of volatile hydrocarbons released per ton of wood burned (lbm/ton or g/kg).

Filterable Particulates Emission Factor - pounds of filterable particulates released per ton of wood burned (lbm/ton or g/kg).

Condensible Organics Emission Factor - pounds of condensible organics released per ton of wood burned (lbm/ton or g/kg).

POM Emission Factor - pound of polycyclic organic materials released per ton of wood burned (lbm/ton or g/kg).

Total Particulates Emission Factor - sum of filterable particulates and condensible organics emission factors.

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Tennessee Valley Authority

Residential Wood Heater Test Report

Phase II Testing, Volume II
Energy Use Test Facility

TENNESSEE VALLEY AUTHORITY

Division of Energy Conservation and Rates

Residential Wood Heater Report

Phase II (1981 - 1983)

Volume II

Energy Use Test Facility

Chattanooga, Tennessee

November 1983

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INTRODUCTION

Volume I of the Phase II test report contains a listing of the test procedures, a description of the TVA WOODSTV efficiency and emissions computer model, discussions of the results of each wood heater, and a comparative discussion of these results. The present volume provides the data release section for Volume I and is composed of three appendices.

Appendix A contains a listing of the TVA WOODSTV efficiency and emissions computer model along with a sample input dataset and a sample of the output generated by the model. The model consists of a main or controlling program and 10 subroutines which instruct the computer to perform the calculations and output necessary to meet the required objectives. Detailed information concerning the subroutines can be found in this section.

Appendix B contains descriptions of the five wood heaters tested during this study. The wood heaters tested in this study included: (1) a conventional nonbaffled airtight circulator typically used in the TVA region, (2) a new nonbaffled airtight catalytic radiant unit, (3) a new retrofit, add-on catalytic combustor connected to the exit of wood heater No. 1, (4) a new baffled airtight catalytic circulator using metal instead of ceramic as a catalyst base, and (5) a new airtight unit specially designed to provide secondary combustion features.

Appendix C contains a graphical display of all instantaneous data recorded during testing. The display for each run includes wood weight vs time, air/fuel ratio vs wood burned, heat release rate vs wood burned, gas flow rate vs wood burned, percent combustion efficiency vs wood burned, percent heat transfer efficiency vs wood burned, percent thermodynamic efficiency vs wood burned, percent carbon dioxide (CO_2) vs wood burned, percent oxygen (O_2) vs wood burned, percent carbon monoxide (CO) vs wood burned, percent total hydrocarbon (THC) vs wood burned, CO emission factor vs wood burned, THC emission factor vs wood burned, sulfur dioxide (SO_2) emission factor vs wood burned, and outlet temperature vs wood burned. In addition to these displays, the catalytic wood heaters also include temperatures before, in, and after the catalyst vs wood burned, CO emission factors before and after the catalyst vs wood burned, THC emission factors before and after the catalyst vs wood burned, and percent thermodynamic efficiency before and after the catalyst vs wood burned.

APPENDIX B

WOOD HEATER DESCRIPTIONS

Wood Heater Number 1

Description

Wood heater number 1 is a circulator-type heater, the walls of which are constructed of sheet metal. The firebox, lined with cast iron plates, is 25 inches long, 12 inches wide, and 22 1/2 inches high. A removable ash pan is located beneath a cast iron grate. The primary air enters through the damper near the top of the heater, is heated, and then added below the cast iron grates. The flow of air is regulated by means of a bimetallic damper. The damper was not allowed to modulate during testing. Internal baffles are absent. Weight: approximately 225 lbs.

Wood Heater Number 2

Description

Wood Heater number 2 is a radiant heater equipped with a catalytic combustor unit. The heater is constructed of welded steel plates and the firebox is lined with fire brick. The firebox is 17 1/2 inches long, 11 inches wide, and 11 inches high. No grate or ash pan is present. Two screw-type primary air controls located on the lower portion of the fire door admit air directly into the fire zone. A bypass damper, located near the fire door, is closed when the fire door is shut. A secondary air supply at the lower front supplies air to the top of the primary combustion zone and the combustor unit. After gases pass through the combustor unit, a large single baffle divides the flow forcing the flue gases to negotiate a complete path that acts as a secondary heat exchanger. Weight: approximately 425 lbs.

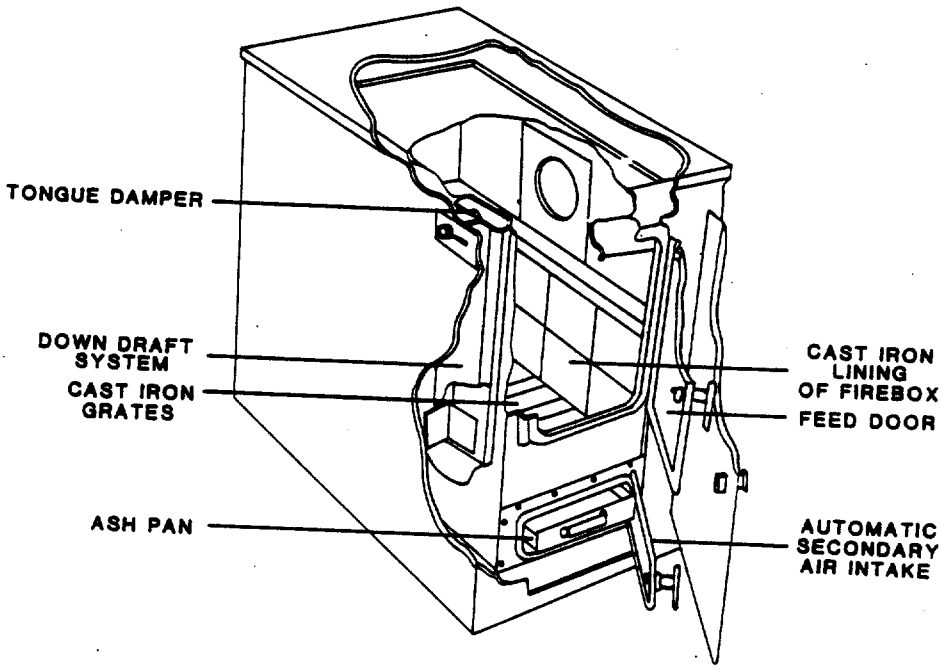

Figure 2. Broken - Out Sectional View Of Wood Heater #1, Showing Interior Detail.

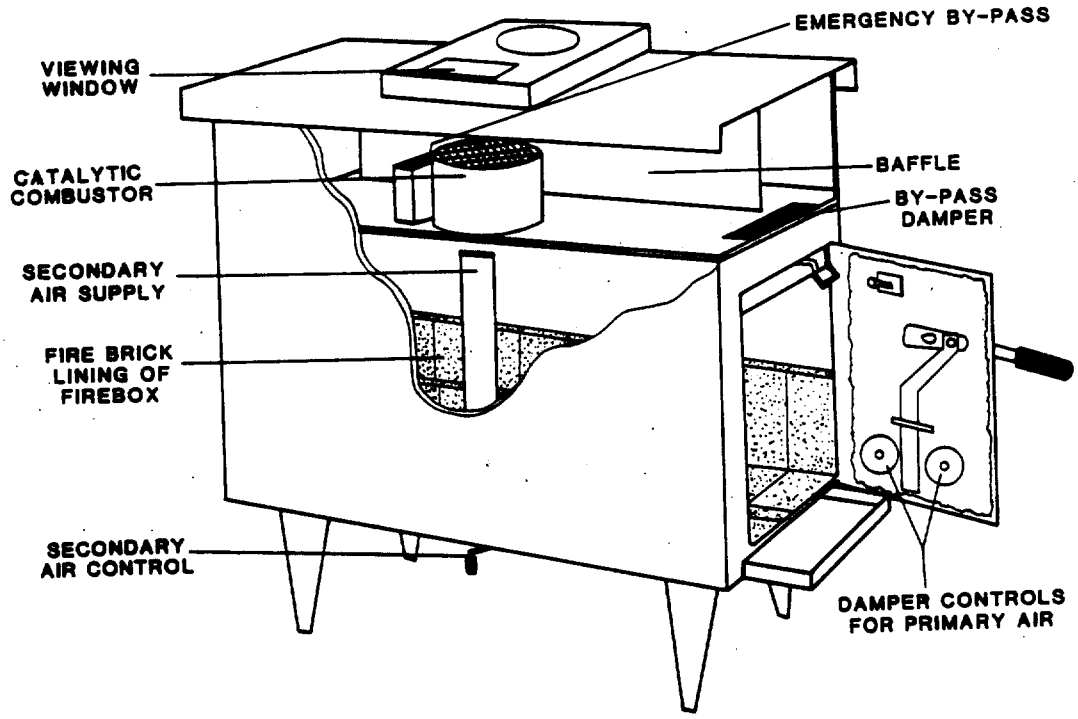

Figure 3. Broken-Out Sectional View Of Wood Heater #2, Showing Interior Detail.

Wood Heater Number 3

Description

Wood heater number 3 is wood heater number 1 plus an exit mounted add-on (retofit) catalytic combustor. This unit, constructed of sheet metal, is approximately 20 inches tall and 10 inches wide. When attached to the wood heater proper, the catalytic combustor is located approximately 3 inches away from the exit of wood heater number 1. A mounted fan aids in the exchange of the generated heat. Bypass of the catalytic combustor during wood loading is completed by the use of an internal damper within the "add-on" unit. Secondary combustion air for the catalyst is provided by a vent across the face of the catalytic combustor. The retrofit stack unit weighs approximately 27 lbs.

Wood Heater Number 4

Description

Wood heater number 4 is a combination radiant and circulator unit, which is also equipped with four catalyst-coated metal plates. Much of the construction is of welded stainless steel. The octagon-shaped firebox is 21 inches long, 18 inches wide, and 15 inches high. A removable ash pan drawer is located beneath a central metal grate. The air supply for catalytic combustion is drawn through variable size openings located just above the ash pan. A series of metal plates (including the catalyst-coated plates) in the upper portion of the stove create a baffled flow path for the flue gases. Weight: approximately 380 lbs.

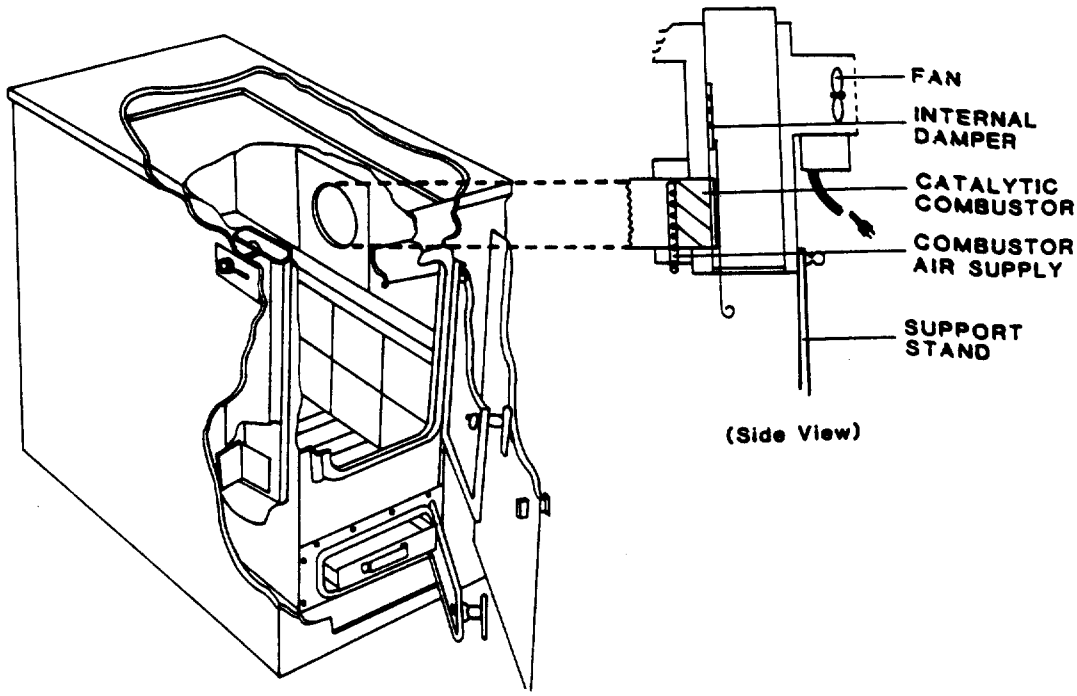

Figure 4. Cross-Sectional View Of Wood Heater #3, Showing Interior Detail.

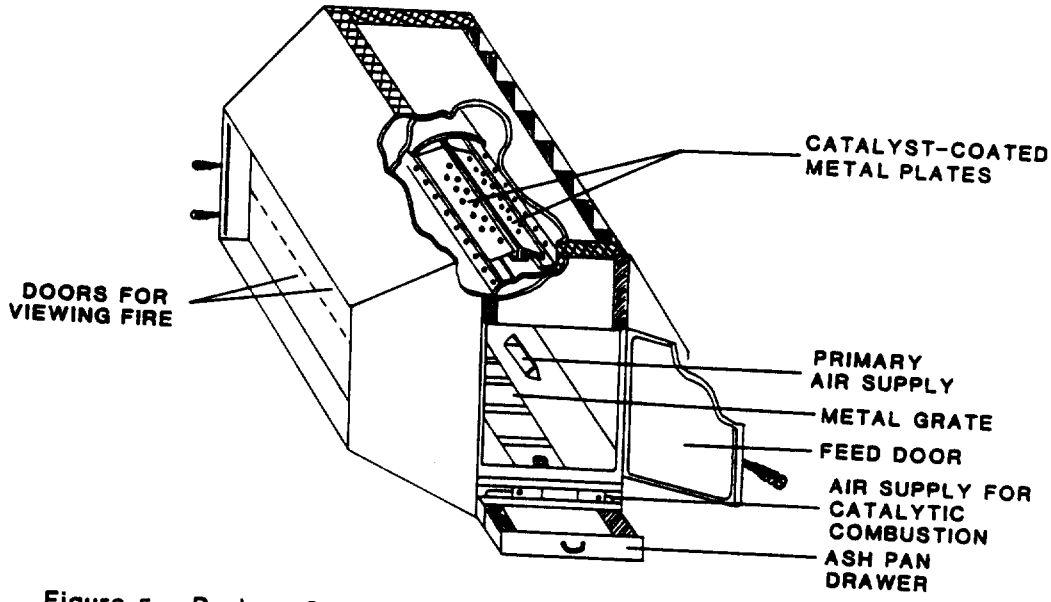

Figure 5. Broken-Out Sectional View Of Wood Heater #4, Showing Interior Detail.

Wood Heater Number 5

Description

Wood heater number 5 is an airtight radiant unit which features secondary combustion. Both the upper and lower combustion chambers are made of cast iron and are lined with fire brick. The primary (lower) firebox is 15 inches long, 12 inches wide, and 8 inches high. Primary air is admitted directly into the fire zone through a single screw control knob located on the fire door. Control for the secondary combustion air is provided by the relative positioning of the fire door handle. Secondary combustion air after being preheated is added in the secondary combustion zone. A grate and an ash pan are present. Weight: approximately 308 lbs.

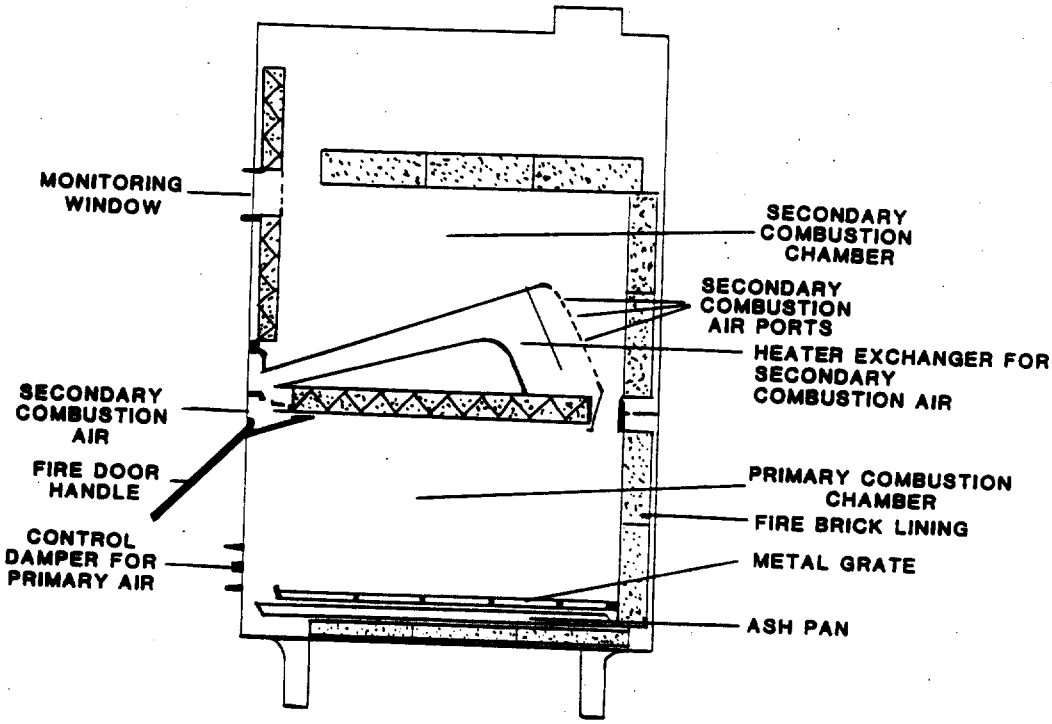

Figure 6. Cross-Sectional View Of Wood Heater #5, Showing Interior Detail.

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C***      WOOD HEATER EFFICIENCY AND EMISSIONS REPORT.  BATCH VERSION   00000010
C***      OF AUBURN UNIVERSITY BASIC PROGRAM WITH EMMISIONS             00000020
C***      CALCULATIONS ADDED.                                           00000030
C***                                                                    00000040
      DIMENSION RDATA(50),DRYWET(300)                                   00000050
C                                                                       00000060
      REAL*8 IWOOD                                                      00000070
      COMMON/BLK1/A,B,C,HHVW,HFCO2,HFCO,HFH2OG,HFCH4,HFH2OL,RBAR,BARHG  00000080
      COMMON/BLK2/ITYPE,IRUN,IDATE(3),ATEMP,IOTM(300),IOTS(300),IWOOD(2)00000090
      COMMON/BLK3/ATEMPR,STEMPR,GTEMPR,OPCH4(300),OPNO(300)             00000100
      COMMON/BLK4/WUSED,TDS,BURNR,WDIFF(300),DELTAT(300)                00000110
C                                                                       00000120
      COMMON/BLK5/WMOLW,WF,HFWOOD,BARPSI,BARPSF,KMOIST,WISP,NFLAG,INUM  00000130
C                                                                       00000140
      COMMON/BLK6/H,DIAM,AEPOM,AEPART,HE,DELTH,AS,ASIGV,BAP,TVS,CHIX    00000150
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     >OPMSO2(300),EQSO2(300),CEQSO2(300),EWSO2(300),CEWSO2(300),OPS(300)00000210
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     >CEWCH4(300),AVGTEM,ORGS,POMBUT,EFPUM,PARBUT,EFPAR                 00000250
C                                                                       00000260
      COMMON/PAGE4/AEF(14),ACO(4),ASO2(4),ANO(4),ACH4(4)                00000270
       COMMON/CO2/ICO2,ACO2(4),OPMCO2(300),EQCO2(300),                  00000280
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     >CHIMAX(6)                                                         00000310
C                                                                       00000320
C                                                                       00000330
C                                                                       00000340
C***                                                                    00000350
C***          DEBUG WRITE FLAG                                          00000360
C***                                                                    00000370
      ICO2=1                                                            00000380
      IDBUG=0                                                           00000390
      DO 811 I=1,50                                                     00000400
      RDATA(I)=0                                                        00000410
  811 CONTINUE                                                          00000420
C                                                                       00000430
C..ZERO ARRAYS USED TO HOLD CALCULATED VALUES                           00000440
      DO 4 I=1,200                                                      00000450
      DRYWET(I)=0                                                       00000460
    4 CONTINUE                                                          00000470
C                                                                       00000480
    1 CALL ZERO                                                         00000490
C                                                                       00000500
C***                                                                    00000510
C    READ DECISION CARD                                                 00000520
C                                                                       00000530
C    DECISION CARD TELLS THE COMPUTER WHICH TYPE OF HEADER CARD         00000540
C     IT IS GOING TO READ                                               00000550
       READ(5,*,END=999) NFLAG                                          00000560
       IF (NFLAG.EQ.1) GO TO 6                                          00000570
      IF (NFLAG.EQ.2) GO TO 7                                           00000580
C                                                                       00000590
C***     READ HEADER CARD:                                              00000600
C***          ITYPE = STOVE TYPE                                        00000610
C***          IRUN = RUN NUMBER                                         00000620
C***          DATE = DATE THIS TEST (MO DAY YR)                         00000630
```