Section 1.9

Ref No. 13



# In-Home Evaluation of Emissions From Masonry Fireplaces and Heaters

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# Executive Summary

While woodstoves have undergone extensive regulation for almost ten years, fireplaces have only recently begun to be regulated. Capitalizing on the woodstove regulatory experience, this project was commissioned by Western States Clay Products to be the first research project to obtain basic baseline emissions data on masonry fireplaces and masonry heaters under real-world conditions in homes. Direct comparison of results with previous field studies of woodstoves and pellet stoves can be made.

The main objective of the current project was to measure particulate and carbon monoxide emissions from a baseline of conventional fireplaces and a group of potentially cleaner-burning fireplace designs and masonry heaters. Additional objectives were to evaluate the effects of wood moisture and altitude on conventional fireplace emissions.

To ensure widespread applicability for the Pacific Northwest and tight scientific control, the Portland, Oregon area was chosen as the field area, Douglas fir was used as the fuel, and fuel moisture content was held constant at 20%. All homeowners burned as they normally did and no instructions on burning techniques were given. Five conventional fireplaces, two Rosin fireplaces, one modified Rumford design, and two masonry heaters were evaluated.

The Automated Woodstove Emissions Sampler (AWES), which has been used extensively in field studies of woodstoves and pellet stoves, was used to measure emissions. The samplers were operated for seven days in each home. Typically each home burned their fireplace once a day. Tests were conducted from December 1990 through March 1991. An additional test on one of the Rosins was conducted in June 1991.

The tests provided information on how homeowners burn their fireplaces. For the conventional fireplaces, the average burn rate was 3.45 dry kg/hr, the average burn cycle length was 4.3 hours, the average number of wood loads per burn cycle was 4.4, and the average wood load weight was 9.4 wet pounds. Of these variables, the only one with a large amount of variation was the average wood load weight, which varied over a range of 3:1.

Masonry heater burn patterns were quite different. Average burn rate for the combustion period was 8.2 kg/hr for the Contraflow and 2.5 kg/hr for the locally built Russian unit.[1] Average burn lengths were 2.2 and 2.3 hours, respectively, and wood loads averaged 47 and 15 wet pounds, respectively. Both heaters were burned only once or twice per day as needed to heat the homes.

Particulate emissions[2] from the conventional fireplaces averaged 24.9 g/kg, 82.7 g/hr, and 14.1 average daily g/hr. These values are near the upper end of the range of results in the literature, which comprises mostly laboratory tests. CO emissions from the conventional fireplaces averaged 107 g/kg, 360 g/hr, and 64.5 average daily g/hr.

[1] This heater was built by a local mason who had no prior experience in masonry heater design.

[2] Particulate emissions in this report are expressed in AWES units which are directly comparable to all previous field woodstove results. Values for EPA Method 5H, the lab certification method, would be 10-20% lower.

Emissions from the Rosin fireplaces were generally less than 50% of those from the conventional fireplaces. A *t*-test indicated that the g/kg difference was significant at the 98% probability level. Particulate emissions averaged 10.4 g/kg, 33.2 g/hr, and 9.9 average daily g/hr. CO emissions averaged 52.5 g/kg, 158 g/hr, and 47.3 average daily g/hr.

Emissions from the Contraflow masonry heater were about half those of the locally designed and built Russian heater. Contraflow particulate emissions were 5.6 g/kg, 45.7 g/hr, and 5.6 normalized average daily g/hr. CO emissions were 41.0 g/kg, 336.8 g/hr, and 31.0 normalized average daily g/hr. Emissions from the locally designed Russian unit were about twice as high.

The format in which emissions results are presented is of great importance. For example, use of different formats can result in as much as an 8:1 difference in comparative emissions results. Grams per hour (which is used for woodstoves) is considered the poorest representation of fireplace/masonry heater emissions because these types of devices are only burned for a few hours each day. Thus, use of g/hr greatly exaggerates emissions contributions to airsheds. A new term, average daily g/hr, is introduced which appears to be more appropriate. This format portrays the total amount of pollution that a given combustion device contributes to an airshed on a daily basis. Average daily g/hr is used rather than grams per day to facilitate a direct and easy comparison with the body of woodstove data which is expressed in grams per hour. Grams per kilogram produces somewhat similar rankings for fireplaces, but is less appropriate to meet the objective of quantifying the amount of pollution per day. It is, however, valuable in calculating the total emissions contribution per burning season for any residential biomass combustion device.

To facilitate direct comparison of masonry heater results with those of woodstoves, the term normalized average daily g/hr is used. This term refers to average daily g/hr at a burn rate of 1.0 kg/hr, the field average for certified woodstoves. This term is equal to g/kg.

The effects of wood moisture (range 15% to 24%) on emissions from a conventional fireplace were significant above 20% moisture. Emissions ranged from 22.1 at 15% moisture to 41.4 g/kg at 24% moisture. The effect of altitude on emissions could not be measured because a second variable—long burns associated with the fireplace being burned only on weekends—was present.

The real-world data collected in this project can be used to negotiate with regulators to develop fair and equitable regulations for all stakeholders. Efforts should be made to ensure that the relatively clean-burning Rosin be acceptable for burning within any of the new regulations.

The data from this project should be used as the foundation for the development of a realistic emissions laboratory standard for masonry fireplaces and heaters[3] and to evaluate candidate laboratory test methods. Considering the large mass and lack of portability of masonry fireplaces and heaters, in-home testing (as conducted in this project) must be considered an acceptable certification procedure.

The Fireplace Emissions Research Coalition (FERC) laboratory test procedure of Virginia Polytechnic Institute (VPI) should be evaluated for applicability to masonry fireplaces by comparing the Brick Institute of America (BIA) results with those of the current project. The VPI masonry heater laboratory procedure

[3] This development process would philosophically follow closely the system currently being used to develop the stress test protocol for woodstoves which will be used to evaluate potential product durability problems.

should be evaluated by comparing Contraflow results with VPI's. The Wood Heating Alliance (WHA) fireplace test procedure, due this fall, should also be evaluated by operating it on the units tested in this project.

Other, potentially more promising, masonry heater designs should be evaluated in the field. Improvements in masonry heater design should also be made. It appears that masonry heater technology holds promise of meeting the strictest of emissions standards.

Rosin and Rumford fireplaces strictly following the original designs should be field-evaluated. Further refinements in the Rosin design should also be made. This technology appears promising.

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# Introduction

The 1980s were a decade of regulation for the woodstove industry. Regulations started in Oregon with new source performance standards (NSPS) in 1983-1984, progressing to Colorado in 1985. In 1986, the EPA formulated its national NSPS for woodstoves. Emissions limits took effect in three progressive stages. The final, toughest EPA emissions levels went into effect in 1990 for so-called Phase II woodstoves. In recent years, regulatory action has also been undertaken by local jurisdictions, who cater their local regulations to their particular problems. Such regulations commonly take the form of progressive burn bans on woodstove usage as air inversions develop and air quality deteriorates. Jurisdictions can also require more stringent emissions requirements on new woodstoves than the EPA requires. It is anticipated that localized regulations will continue to be developed for woodstoves for some time.

Regulation of fireplaces began more recently, during the last one to two years. Regulations have followed a pattern similar to that of woodstove regulations except that the EPA has not become involved. Regulation at the state level was initiated in the State of Washington in 1991, but elsewhere most regulation has been at the local level to date.

The sponsors of the current project, being aware of the woodstove regulatory situation, have attempted to benefit from the woodstove experience, capitalizing on the strengths and building in the areas of weakness. As a result of this analysis, the current study has been designed to gather relevant, independent data early and use it to the sponsors' benefit during the regulatory processes that lie ahead. Specifically, a need exists for a baseline of data on real-world conventional masonry fireplaces to document the magnitude of the pollution problem and to serve as a benchmark for evaluating potentially superior technologies. Studies of this nature have not been undertaken before. Secondly, tests were conducted to identify existing technologies that might produce significantly lower emissions in homes than conventional fireplaces. These improved technologies would have an additional benefit if they could be retrofitted to the existing installed base of conventional fireplaces. Technology that can improve the performance of already installed conventional fireplaces would include retrofitable inserts of masonry materials, etc. that could improve combustion characteristics, and special fuels, such as densified logs, that could burn cleaner than cordwood in existing fireplaces or in concert with inserts. It was decided to evaluate inserts in this project but not special fuels.

It was necessary that real-world rather than laboratory data be collected on fireplaces at this time. Such data are the only type that can document the true magnitude of the emissions problem and accurately evaluate the emissions reduction potential of various improved technologies. The need for real-world data is further underscored because woodstove studies have demonstrated a large discrepancy between in-home and laboratory emissions values.

Real-world data are also needed as a foundation for the development of a realistic laboratory test method for masonry fireplaces and masonry heaters (laboratory standards do not exist) and to evaluate candidate test methods for suitability.

The data collected in this project can be used by Western States Clay Products to negotiate with regulators to ensure the development of regulations which are fair and equitable to all stake holders and which maximize the air quality benefit to the various airsheds.

# Objectives

- To obtain a real-world evaluation of particulate and CO (carbon monoxide) emissions of a baseline of conventional fireplaces.

- To evaluate the effects of wood moisture on conventional fireplace emissions performance.

- To evaluate the effect of altitude on conventional fireplace emissions performance.

- To evaluate potentially cleaner-burning fireplace burning technologies.

- To conduct a controlled before-and-after experiment whereby a conventional fireplace is evaluated, a Rosin fireplace retrofit is inserted in the fireplace and the emissions are again measured.

- To evaluate two types of masonry heaters for potential to meet the very strict standards of emissions (one to two g/hr) which are beginning to be promulgated in certain areas.

# Study Design

This project was designed so that its results would have the widest possible applicability, especially to the Pacific Northwest. Additionally, it was designed to ensure the tightest possible scientific control of the results.

The Portland, Oregon area was chosen as the site for the current study because its climate is representative of the western valleys of both Oregon and Washington, the region where most fireplaces are used in the Pacific Northwest. Douglas fir, the most common fuel used in the Northwest, was chosen for the project. Fuel came from a common source stored at OMNI and all pieces of fuel were measured for moisture content to ensure consistency from house to house. Average moisture content was about 20% dry basis for all tests, except where wood moisture sensitivity analyses were being conducted. Wood length was 16" and diameter ranged from 4" to 8". Over 75% of the wood was split, mostly twice. Stack heights in the homes ranged from 24 to 30 feet high, the height range for $1^1/_2$- and 2-story houses. All homeowners were asked to burn as they normally did. No instructions were given to the homeowners on how to burn their fireplaces. To ensure that enough burn cycles were completed, homeowners were asked wherever possible to burn once a day to obtain seven burn cycles during their one-week-long sampling period. At the end of the testing period, homeowners were given an exit survey in which they were asked to compare the procedures that they used with those that they have normally used in the past (Appendix D). While some fireplaces had glass doors, no glass doors were closed in this project. All fireplaces had grates and used them. All tests were conducted from December 1990 through March 1991, with the exception of the second test on the Rosin F04, which was conducted in June 1991.

Five fireplaces were used to develop the conventional fireplace baseline. One modified Rumford design was evaluated and two Rosin units, one a retrofit and the other an original equipment version, were used. An extra test was conducted on the original equipment Rosin, one following the manufacturer's method of wood placement and the other using the homeowner's own preferred wood placement. Wood moisture effects were evaluated in one conventional fireplace (F01) using 15%, 20%, and 24% moisture fuel. The effect of altitude was evaluated using a fireplace in Government Camp, Oregon at 3500' elevation. Two masonry heaters were evaluated. One was a unit designed by a local mason who had no prior experience in masonry heater design, and the other, a Contraflow, was a manufactured kit.

The automated woodstove emission sampler (AWES) system was used throughout this project. By doing so, a direct comparison can be made to numerous published previous field results from woodstoves and pellet stoves. The AWES sampler was typically operated for seven days in each home and seven burns were typically conducted by the homeowner.

In addition to producing emissions results, the AWES uniquely collects real-time data on stack temperatures, wood load patterns, and stack oxygen values. Such data have proven invaluable to understanding the way homeowners actually burn. This information in turn is useful in designing cleaner-burning units and in developing realistic laboratory standard tests.[d]

The AWES was specially modified for fireplace sampling. Due to the highly dilute nature of fireplace flue gases (stack oxygen averages >20% for fireplaces), a large volume of these gases had to be sampled in order to collect an adequate amount of particulate catch. In this project, 500 or more liters were collected for each sample. This meant that the AWES was operated one minute on and two minutes off throughout the sampling period. Additionally, a Tedlar bag was used to collect an integrated flue gas sample for the week-long sample period so that carbon monoxide and carbon dioxide could be measured. These gases were then used to calculate a carbon balance for use in the emissions equations as well as to calculate the CO emissions themselves. CO emissions were measured along with particulate emissions because CO is regulated in Fresno County, California and could be regulated elsewhere in the future.

Details of how data reduction procedures were modified for masonry heaters are discussed in the section Methodology.

For the sake of completeness, this report contains results of tests conducted on the Zagelow conventional fireplace and the Rosin retrofit that was inserted in that fireplace. These tests were sponsored by Mutual Materials Company in December 1990.

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[d] This type of information is the foundation of an ongoing project to develop the laboratory Stress Test Protocol for Woodstoves to evaluate woodstove durability for the EPA and other governmental agencies.

# Fireplace Descriptions

Detailed drawings of all the fireplaces and masonry heaters are shown in Appendix A. Photos are shown in Appendix B. Table 1 contains dimensional details of the fireplaces.

Table 1. Dimensions of the fireplaces used in this project.

| | Width (in.) | Height (in.) | Depth (in.) | W at Back (in.) | Flue Size (in.) | Stack Ht. (ft) | Location |
|---|---|---|---|---|---|---|---|
| Conventional Fireplaces | | | | | | | |
| Zagelow | 32 | $23^1/_2$ | 23 | 26 | 12×12 | 24 | Vancouver, WA |
| F01 | 26 | $28^1/_2$ | 24 | $26^1/_2$ | 12×12 | 26 | Beaverton, OR |
| F04 (Rumford) | 35 | 29 | $20^1/_2$ | 18 | 12×16 | 25 | Vancouver, WA |
| F06 | 40 | 24 | $22^1/_2$ | 32 | 12×12 | 21 | Beaverton, OR |
| F07 | 36 | 26 | 23 | 27 | 12×12 | 30 | Govt. Camp, OR |
| Rosin Fireplaces | | | | | | | |
| Zagelow Retrofit | 32 | 24 | 17 | 18 | 12×12 | 24 | Vancouver, WA |
| F03 Original Equipment | 32 | 22 | $22^1/_2$ | 14 | 8×12 | 28 | Vancouver, WA |

## Conventional Fireplaces

The Zagelow fireplace (designated Zagelow) has an opening of 23.5" by 32". It is 23" deep and 26" wide at the back. It has a 12" × 12" flue and a stack height of 24 feet. The fireplace is located in Vancouver, Washington. It has glass doors that were not used during testing.

The F01 fireplace has a 28.5" by 36" opening. It is 24" deep and 26.5" wide at the back. The chimney flue is 12" × 12" and has a height of 26 feet. The fireplace is located in Beaverton, Oregon. This fireplace was tested three times to evaluate sensitivity of emissions to varying wood moisture content. The glass doors were not used during testing.

The F06 fireplace has a 24" by 40" opening. It is 22.5" deep and 32" wide at the back. The flue is 12" × 12" and the stack is 21 feet tall. Fireplace F06 is located in Beaverton, Oregon. Glass doors were not present.

The F07 fireplace has a 26" by 36" opening. It is 23" deep and 27" wide at the back. The flue is 12" × 12" and the stack is 30 feet high. It is located in Government Camp, Oregon, at an elevation of approximately 3500 feet. No glass doors were present.

## Rosin Fireplaces

The Zagelow Rosin (designated Zagelow) is a retrofit made by Firecrest that has an opening of 24" by 32". It is 17" deep and 18" wide at the back. It was placed in the Zagelow conventional fireplace after that fireplace had been evaluated for emissions. The glass doors were left open for the test. The homeowner oriented the logs front-to-back and tilted up in the back approximately 45°.

The F03 Rosin (a Heat Force™) has an opening of 32" × 22". It is 20.5" deep and 14" wide at the back. The flue is 8" × 12" and the stack is 28 feet high. It is located in Vancouver, Washington. This unit was installed as original equipment with the house. Two tests were performed on it. One test (F0301) was performed in which the homeowner placed the logs as he preferred: oriented front-to-back, tilted up in the back approximately 45° (see Figure B-10 of Appendix B). (This is the same way Mr. Zagelow placed his logs.) The second test (F0302) was run with most of the wood forming a criss-cross pattern as shown in Figure B-11 of Appendix B. This was the preferred method of the Rosin's manufacturer.

## Modified Rumford Fireplace

Fireplace F04 has an opening of 29" by 35". It is 20.5" deep and 18" wide at the back. The flue is 12" × 12" and the stack is 25 feet high. Glass doors were not present. It was located in Vancouver, Washington. The geometry of this fireplace differed only slightly from the conventional fireplaces studied in this project, in that it had more of a taper from front to back and a slightly higher front opening (see Appendix A). On the other hand, it differed markedly from a true Rumford, which is three times as wide at the front as at the back and is only one-third as deep as it is wide. This fireplace is therefore considered to be a conventional fireplace for purposes of this project.

## Masonry Heaters

F02 is a Russian-style masonry heater installed in a single-story house. It was designed and built by a local mason who had no prior experience in masonry heater design and is located in Clackamas, Oregon. The firebox is an updraft design with combustion air entering on the left side and flue gases exiting on the right. No baffling or secondary air is present. No other form of heat was used in the house during the test.

Masonry heater F05 is a commercial firebox kit manufactured by Contraflow. The masonry surrounding materials were built locally. This firebox has underfire draft air, no secondary air, and no baffling. It is located in a single-story house in Vancouver, Washington. No other form of heat was used during the test.

# Methodology

## Emissions Sampling

### The Modified AWES Emission Sampling System for Fireplaces

Automated Woodstove Emissions Samplers modified for sampling fireplace emissions were used in this project. Figure 1 shows a schematic of the modified AWES/data logger system. For fireplaces, the AWES unit draws flue gases through a 182 to 212 cm (72 to 84 in.) long, 1.0 cm ($^3/_8$ in.) O.D. stainless steel probe which samples from the center of the flue about 212 to 243 cm (84 to 96 in.) above the floor of the fireplace. The sample then travels through a 1.0 cm O.D. Teflon line, and a heated U.S. EPA Method 5-type filter for collection of particulate matter, followed by a sorbent resin (XAD-2) trap for semi-volatile hydrocarbons. Water vapor is removed by a silica gel trap. Flue gas oxygen concentrations, which are used to determine flue gas volume, were measured by an electrochemical cell. The oxygen cell used in the AWES was manufactured by Lynn Instruments. The AWES uses a critical orifice (Millipore #XX500001) to maintain a nominal sampling rate of 1.0 liters per minute (0.035 cfm). Each AWES critical orifice is calibrated to determine the exact sampling rate. For masonry heaters, the sampling probe was inserted in the last stretch of flue as it exited from the house. For the Contraflow, the

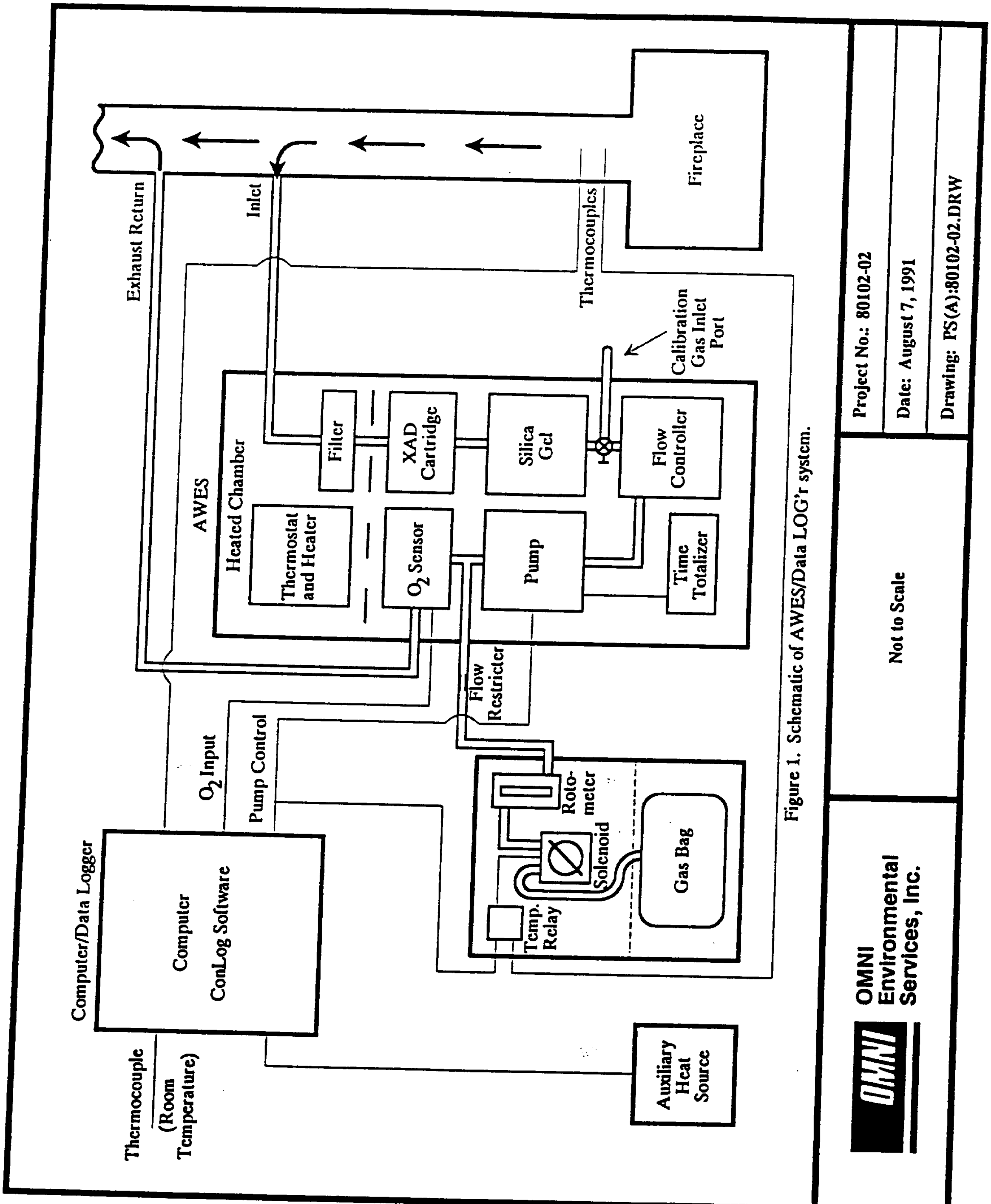

Exhaust Return
Inlet
Thermocouples
Fireplace
Calibration Gas Inlet Port
AWES
Heated Chamber
Filter
XAD Cartridge
Silica Gel
Flow Controller
Thermostat and Heater
$O_2$ Sensor
Pump
Time Totalizer
Flow Restricter
$O_2$ Input
Pump Control
Roto-meter
Solenoid
Gas Bag
Temp. Relay
Computer/Data Logger
Computer
ConLog Software
Thermocouple
(Room Temperature)
Auxiliary Heat Source
Figure 1. Schematic of AWES/Data LOG'r system.
Project No.: 80102-02
Date: August 7, 1991
Drawing: PS(A):80102-02.DRW
Not to Scale
OMNI Environmental Services, Inc.

Figure 1.

probe was located 61 cm (24 in.) above the floor, and for the Rosin unit, 122 cm (48 in.) above the floor.

The AWES unit returns particle-free exhaust gas to the flue via a 0.6 cm ($^1/_4$ in.) Teflon line and a 38 cm (15 in.) stainless steel probe inserted in the flue. Some flue gas exiting the AWES is pumped into a 22-liter Tedlar bag (for later gas analysis) under positive pressure, since the inlet to the bag is on the positive side of the pump. The flow to the bag is controlled by a solenoid valve connected to the pump circuit, a temperature controller, and a rotameter with a flow-controlling orifice. The solenoid valve is open only when the pump is activated and the temperature of the stack exceeds 100° F. The rate of flow into the bag is controlled by the rotameter, which was adjusted to acquire the optimum amount of gas over the entire test without over-pressurizing the bag.

## The Data Logger System

The data logger system, known as the CONLOG data logger system, is a second-generation data logging and emission sampler controlling system developed in 1990 by OMNI. The system (Figure 2) consists of a host personal computer (PC) containing a data processing board, a terminal box, and specialized data acquisition software.

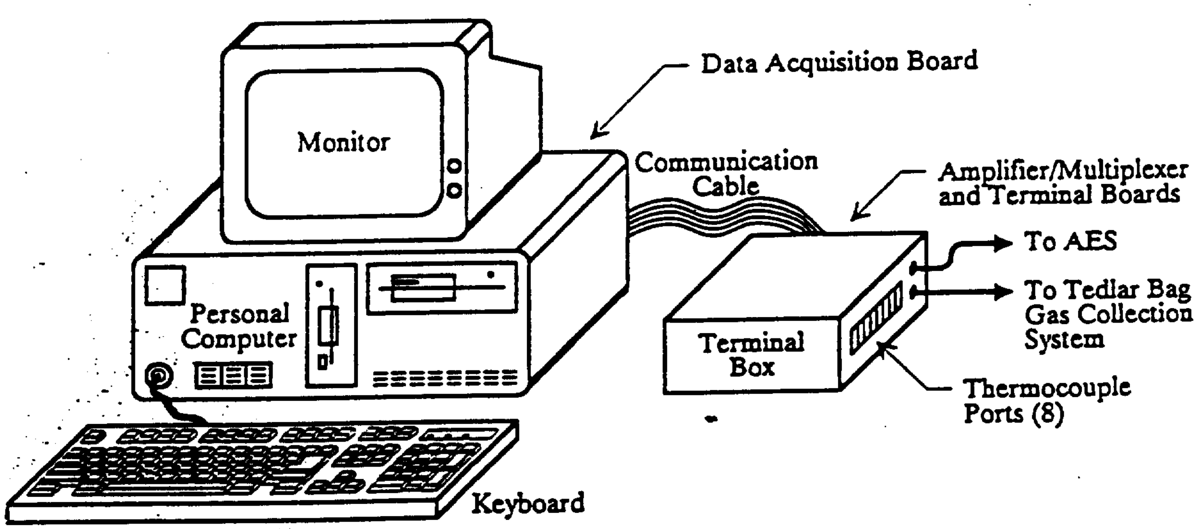



**Figure 2. The ConLog data logger system.**

The CONLOG software is written in a high-level programming language (C) and can be programmed to control, collect, and store the following software settings and data:

- Establish starting and ending date and length of sampling period

- Establish pump cycle length and thermocouple (TC) cycle recording interval
- Record date and time at pre-selected intervals
- Record three temperatures, including flue gas temperature, averaged over pre-selected intervals
- Record ambient temperature (room temperature), averaged over pre-selected intervals
- Record flue gas oxygen measurements, averaged over pre-selected intervals
- Save file as an ASCII file with PRN suffix on 3.5" disk

Instantaneous readings of real-time data are also displayed on the system status screen of date, time, temperature for TCs 1 through 4, and flue gas oxygen percent. The most recent 15 sets of recorded data are also displayed.

The CONLOG system uses external sensors which generate analog voltages that are processed by the PC microprocessor's data acquisition board. For this project, a type K ground-isolated, stainless-steel-sheathed TC (Pyrocom 1K-27-5-U) was used to monitor flue gas temperature at 120 cm (4 ft) above the base of the fireplace in the center of the flue gas stream.

The keyboard and screen were left installed in the home during the sample period. The presence of the display screen's real-time data generated considerable interest on the part of the participants in the project and was a positive experience. The CONLOG program was software-locked to prevent possible interference. However, on a few occasions homeowners were given the password and "walked through" minor program modifications over the telephone to solve a problem that may have occurred during a sampling period. This proved successful and saved considerable field technician time.

## Equipment Preparation and Sample Processing Procedures

Prior to emissions testing, each AWES unit was cleaned and prepared with a new fiberglass filter and XAD-2 sorbent resin cartridge. This was done in OMNI's laboratory facility at Beaverton, Oregon. After each sampling period, the stainless steel sampling probe, Teflon sampling line, filter holder, and XAD-2 cartridges were removed from the home and transported to OMNI's laboratory for processing. The components of the AWES samplers were processed as follows:

1. Filters: The glass fiber filters (102 mm in diameter) were removed from the AWES filter housings and placed in petri dishes for desiccation and gravimetric analysis for particulate catch.

2. XAD-2 sorbent resin: The sorbent resin cartridges were extracted in the Soxhlet extractor with dichloromethane for 24 hours. The extraction solvent was transferred to a tared glass beaker. The solvent was evaporated in an ambient air dryer, the beaker and residue were desiccated, and the extractable residue was weighed on a Mettler AE160 balance.

3. AWES hardware: All hardware which was in the sample stream (stainless steel probe, Teflon sampling line, stainless steel filter housing, and all other Teflon and stainless steel fittings) through the base of the sorbent resin cartridge was rinsed with a 50/50 mixture of dichloromethane and methanol solvents. The solvents were placed in tared glass beakers. The solvents were evaporated in an ambient air dryer, desiccated, and weighed to determine the residue fraction weight.

EPA Method 5 procedures for desiccation and the weighing time schedule were followed for 1 through 3 above. After cleaning, the AWES units were reassembled for field use. The intake port, sampling probe, and sampling line were sealed for transportation to the home and unsealed immediately prior to installation.

OMNI personnel serviced the sampling equipment at the start and end of each sampling period. At the start of each sampling period, the AWES unit was installed; leak checks were performed; the thermocouples, woodbasket/scale unit, and oxygen cell were calibrated; and the data logger was programmed with the proper sampling interval and start/stop times. Data loggers were programmed to activate the AWES units for one minute on and two minutes off for seven consecutive days. At the end of each sampling period, final calibration, and leak-check procedures were performed, and the AWES, sampling line, filter housing, XAD-2 cartridge, and sampling probe were removed and sent to the lab.

## Data Processing and Quality Assurance

Data files stored on the data logger's 3.5" computer diskette were sent to OMNI's lab for computer analysis. Each data file was reviewed immediately to check for proper equipment operation. The data logger data files, log books, and records maintained by field staff were reviewed to ensure sample integrity. Any parameter or calibration objective that did not meet OMNI's in-house quality control criteria was flagged and noted. The data for those emission rate calculations which incorporated a flagged quality assurance parameter were carefully reviewed.

Data logger files were used in conjunction with the AWES particulate sample to calculate particulate emission rates, daily temperature profiles of the various flue temperatures, fireplace operation time, burn rates, etc. In addition, computer program outputs for each file include graphical representations of parameters and parameter interrelationships (see Appendix B for graphical output for all tests for all fireplaces and masonry heaters).

### *Particulate Emissions Calculations*

The basic particulate emissions equation produces grams per dry kilogram of fuel burned (g/kg). This value is multiplied by burn rate, expressed as dry kilograms of fuel per hour (kg/h), to yield g/hr emissions (g/h). The basic g/kg equation includes the following components:

1. Particulate mass: The total mass, in grams, of particulate caught on the filter, XAD-2 resin trap, and in the probe rinse. Particulate mass averages about 0.08 grams but varies considerably.

2. Sample time: The number of minutes the sampler operated during the sampling week when the stack temperature was greater than 38°C (100°F).

3. Sampler's flow rate: This is controlled by the critical orifice in the sampler. Flow values vary slightly for the various samplers and average about one liter per minute.

4. Stoichiometric volume: The volume of smoke produced by combusting one dry kilogram of wood. This value is calculated using a carbon balance for each sample but averages about 4,500-4,700 liters at standard temperature and pressure for fireplaces.

5. Dilution factor: The degree to which the sampled combustion gases have been diluted in the stack by the presence of excess air. The dilution factor is obtained by using the sample period's average oxygen value in the following equation. Dilution factors range from about 20 to 50.

$$\text{Dilution Factor} = ((20.9/(20.9 - \text{Average oxygen}))$$

A second method of obtaining the dilution factor involves the use of carbon balance equations using CO and $CO_2$ readings. Both methods are used for each test as a check. The latter method is preferred for the highly dilute flue gases of fireplaces. The basic emissions equation is expressed as follows using these components:

$$\text{Emissions (g/kg)} = \frac{\text{(Particulates)(Stoich. Vol.)(Dilution Factor)}}{\text{(Sample Time)(Sampler Flow)}}$$

### Uncertainty in Emissions Results

Each measurement used in the emissions calculations has some degree of uncertainty associated with it, and these uncertainties are propagated to determine the amount of uncertainty attached to each calculated particulate emission rate. Within the range of emissions values encountered in this project, uncertainty is generally about $\pm$10 to 15% of the stated value.

## AWES Modifications for Fireplace Emissions Testing

Two fundamental differences between cordwood stoves and fireplaces are (1) higher flue gas oxygen content for fireplaces (more excess air) as compared to conventional cordwood stoves and (2) shorter burn times per week (fireplaces operate eight hours or less per day). Because the AWES (automated woodstove emissions sampler) system was designed for cordwood sampling, small modifications were used to make it completely compatible for fireplace sampling.

A modification in data reduction procedures was made for the masonry heaters. All previous AWES sampling of woodstove used 100 °F stack temperature as the cutoff point to mark the start and end of a combustion cycle. Since masonry heaters maintain high stack temperatures long after combustion ceases, this procedure could not be used. Review of the stack temperature-stack oxygen regression results from computer files of the noncatalytic stoves in the 1988-1989 Northeast Cooperative Woodstove Study[1] and the 1990 Klamath Falls Pacific Energy Project[3] indicated that 100° stack temperature at the end of a burn cycle was associated with 20.6% oxygen in the stack. Therefore, the masonry heater computer program was modified to separate burning from nonburning periods using the 20.6% oxygen criterion rather than 100° stack temperature. A sensitivity analysis using 0.1% increments from 20.5% to 21.5% indicated a low sensitivity to the cutoff setting. All results (g/kg and average daily g/hr) were within a 5% range. Grams per hour were significantly affected, of course, because g/hr - g/kg × burn rate (kg/hr).

The sampling period was modified to accommodate the high excess air and short burn periods of fireplaces. A sampling frequency of one minute of sampling out of every fifteen minutes at a flow rate of one liter per minute has been found to provide optimal sample catches for analysis from clean-burning cordwood stoves during a one-week period. A shorter sampling frequency of one minute out of three minutes at the same flow rate was selected to obtain optimal sample catch from one week of fireplace sampling.

The final modification was the addition of a flue gas Tedlar bag collection system (Figure 3). Carbon dioxide, carbon monoxide, and oxygen data are generated from this collection system, allowing for calculation of carbon monoxide emission factors. Carbon balance equations using carbon dioxide and carbon monoxide were used to calculate the stack dilution factor which is used in the emissions equations. Tedlar bag gases were measured using an NDIR analyzer.

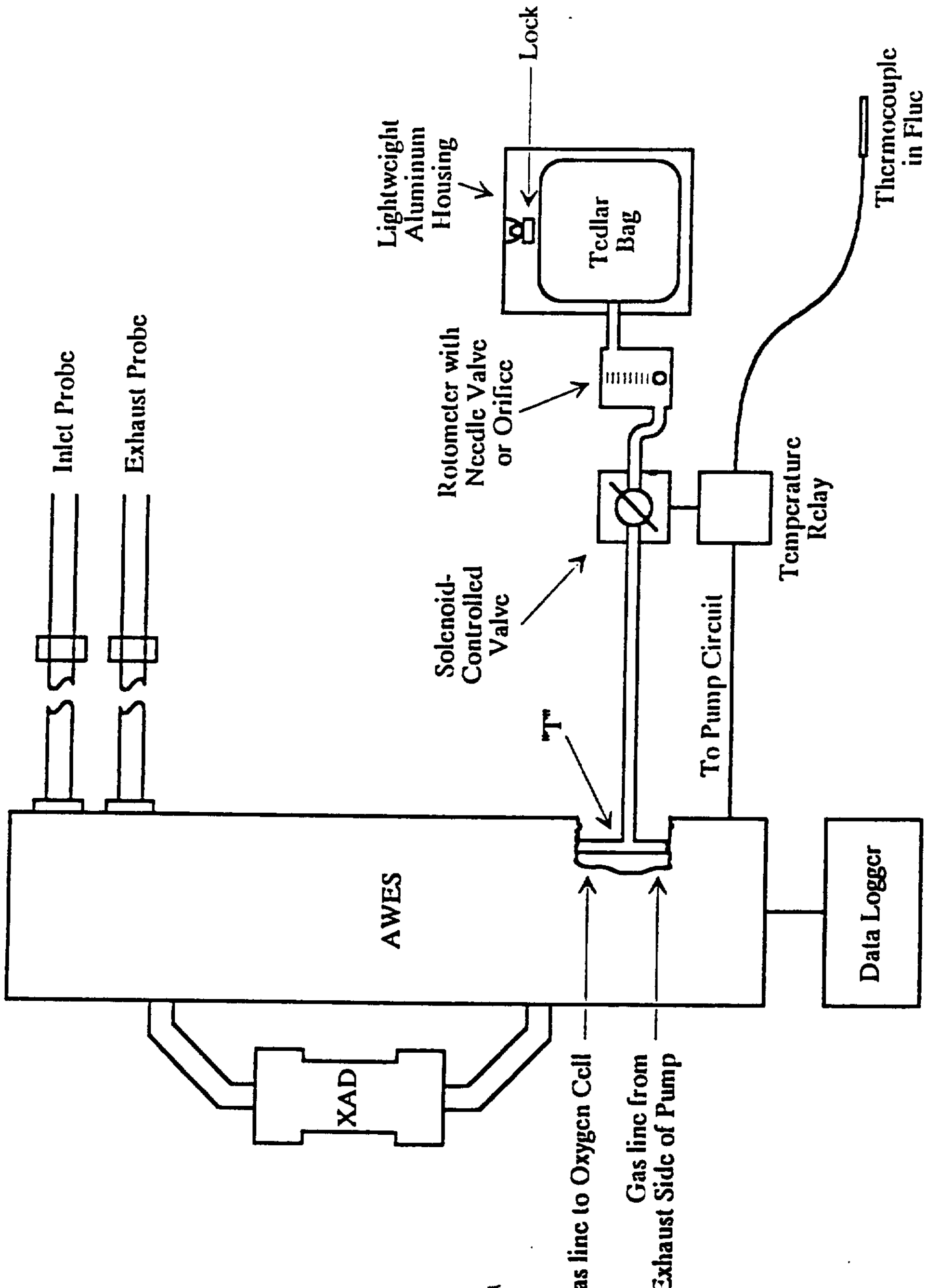



Figure 3. Schematic of AES system modified for fireplace application.

Figure 3.

# Results

## Fireplaces

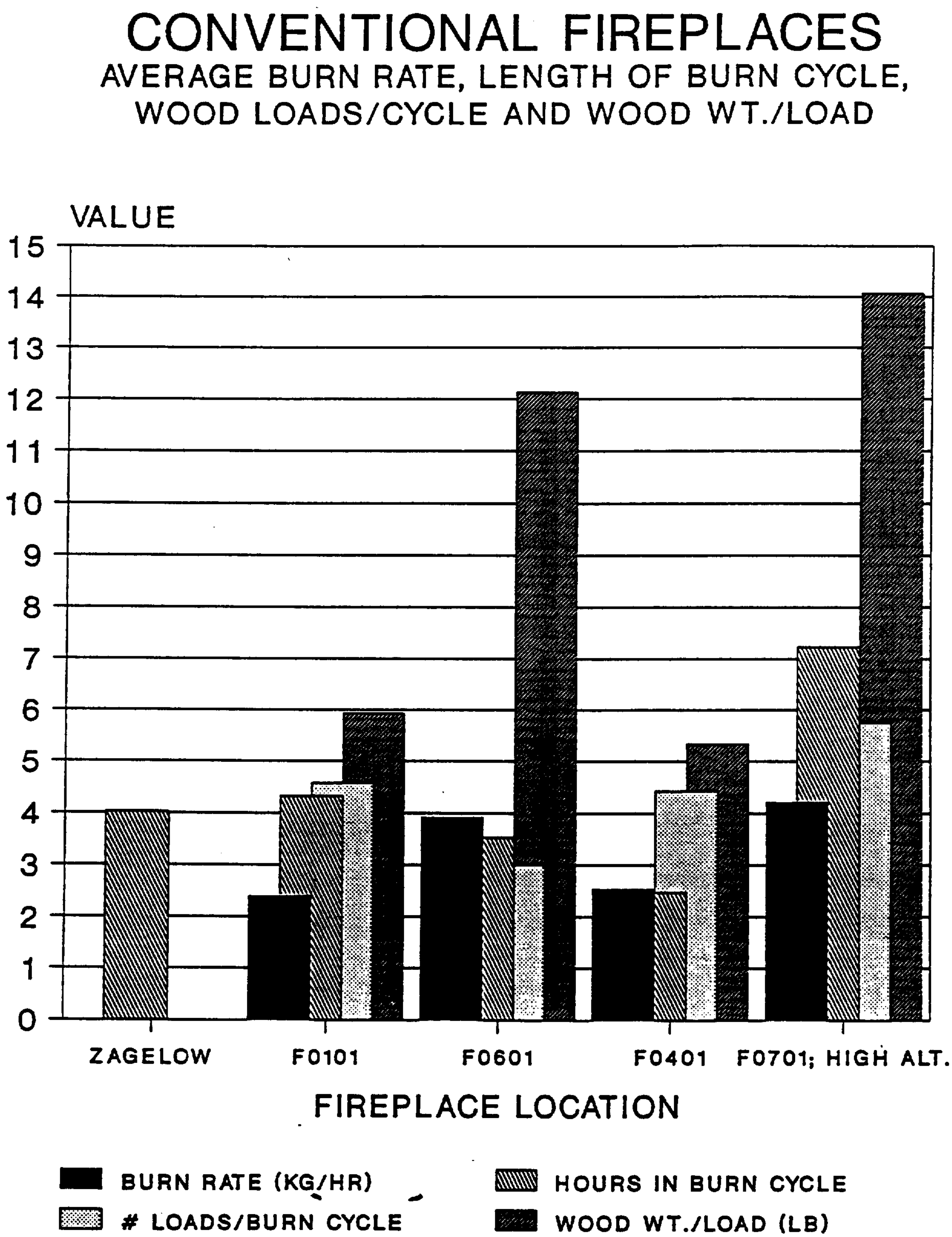
### Burn Conditions - Conventional and Rosin Fireplaces

Figure 4 shows burn conditions results for the conventional fireplaces. Average burn rate, length of burn cycle, number of loads per burn cycle, and wood weight per load are shown. Average burn rate was 3.45 dry kg/hr. Figure 4 indicates that variation in burn rates was rather small. These burn rates are about 3 times as high as woodstoves. The burn rate for the original equipment Rosin, F03, was considerably lower—between 2.1 and 2.2 kilograms per hour. This unit is designed with a smaller cross-sectional area flue pipe which constricts flow, probably causing this reduction in burn rate. The Rosin that was retrofitted in the Zagelow house did not have a special flue pipe, but instead used the original fireplace flue. The burn rate in this fireplace was relatively high: 4.2 kilograms per hour.

The average length of a burn cycle for the conventional fireplaces was 4.3 hours. Figure 4 indicates that there is little variation in length of burn, with one exception: house F07, which averaged 7.3 hours. This fireplace was only burned during the weekends and inspection of the other fireplace temperature data (Appendix C) indicates that during the weekends other fireplaces are burned considerably longer than during the week. This probably explains this discrepancy. Burn length for both Rosin fireplace units were longer than for conventional fireplaces, averaging about 6.8 hours. It is not known why these fireplaces were burned longer than the conventional fireplaces.

The average number of wood loads per burn cycle was 4.4 for the conventional fireplaces. Again, there is not extensive variation, as shown in Figure 4. The number of loads for the original equipment Rosin, F03, was 3.1 per burn cycle and for the Zagelow retrofit Rosin, was 7.7.

The average wood weight per load was 9.4 wet pounds for the conventional fireplaces and 10.5 wet pounds for the Rosins. Of the basic parameters discussed in this section, the variation in wood load weight is the greatest, as shown in Figure 4, ranging from a low of about 5 wet pounds for house F04 to a high of 14 wet pounds for F07.



CONVENTIONAL FIREPLACES
AVERAGE BURN RATE, LENGTH OF BURN CYCLE,
WOOD LOADS/CYCLE AND WOOD WT./LOAD
VALUE
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
ZAGELOW
F0101
F0601
F0401
F0701; HIGH ALT.
FIREPLACE LOCATION
BURN RATE (KG/HR)
HOURS IN BURN CYCLE
# LOADS/BURN CYCLE
WOOD WT./LOAD (LB)


Figure 4

### Burn Conditions - Masonry Heaters

Since masonry heaters burn large loads of wood very rapidly and they are burned infrequently (once or twice daily), their burn conditions are very different from fireplaces. Average burn rate for the Contraflow, F05, was 9.8 kg/hr and 2.3 kg/hr for the Russian unit, F02. Average burn lengths were 1.8 hour and 2.5 hour, respectively. Both heaters only use one load per burn cycle. Average wood loads were 47 wet pounds for the Contraflow and 15 wet pounds for the Russian.

## Emissions Results

### Conventional Fireplaces

Particulate emissions results[5] for the conventional and the Rosin fireplaces are shown in Figure 5 and carbon monoxide (CO) emissions are shown in Figure 6, as well as in Tables 2 and 3. Particulate emissions for the conventional fireplaces averaged 24.9 g/kg, 82.7 g/hr, and 14.1 average daily g/hr.[6] These values are near the upper end of the range of results in the literature. However, none of the previous projects involved in-home testing of fireplaces burned and operated by homeowners. Most were laboratory studies and used various different methods of measuring emissions. Average CO emissions for the conventional fireplaces are 107 g/kg, 360 g/hr, and 64.5 average daily g/hr. As was the case for particulates, CO emissions are near the upper end of the range found in the literature.

Figures 5 and 6 indicate that for both particulates and carbon monoxide, the variation in results is not large. The coefficients of variation are 26% for particulate g/kg and 14% for CO g/kg. Only one house, F07, had distinctly lower emissions than the other fireplaces. It is possible that the use of this fireplace for long, continuous weekend burning may have increased the average combustion efficiency, producing lower emissions.

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[5] Particulate emissions in this report are expressed in AWES units which are directly comparable to all previous field woodstove results. Values for EPA Method 5H, the laboratory certification method, would be 10-20% lower.

[6] See the section on "The Concept of Average Daily g/hr" for explanation of this term.

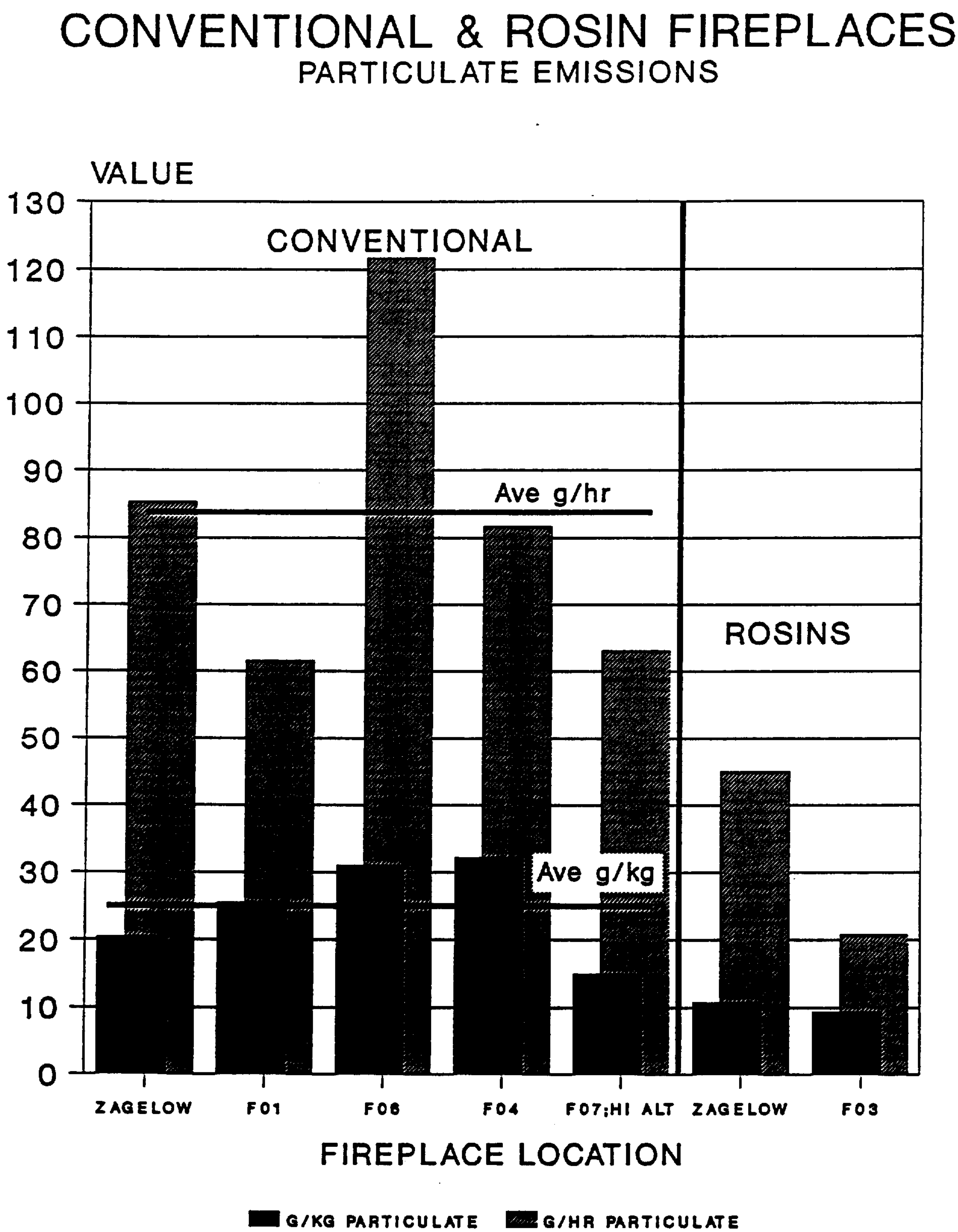

CONVENTIONAL & ROSIN FIREPLACES
PARTICULATE EMISSIONS
VALUE
130
120
110
100
90
80
70
60
50
40
30
20
10
0
CONVENTIONAL
ROSINS
Ave g/hr
Ave g/kg
ZAGELOW
F01
F06
F04
F07;HI ALT
ZAGELOW
F03
FIREPLACE LOCATION
G/KG PARTICULATE
G/HR PARTICULATE

Figure 5

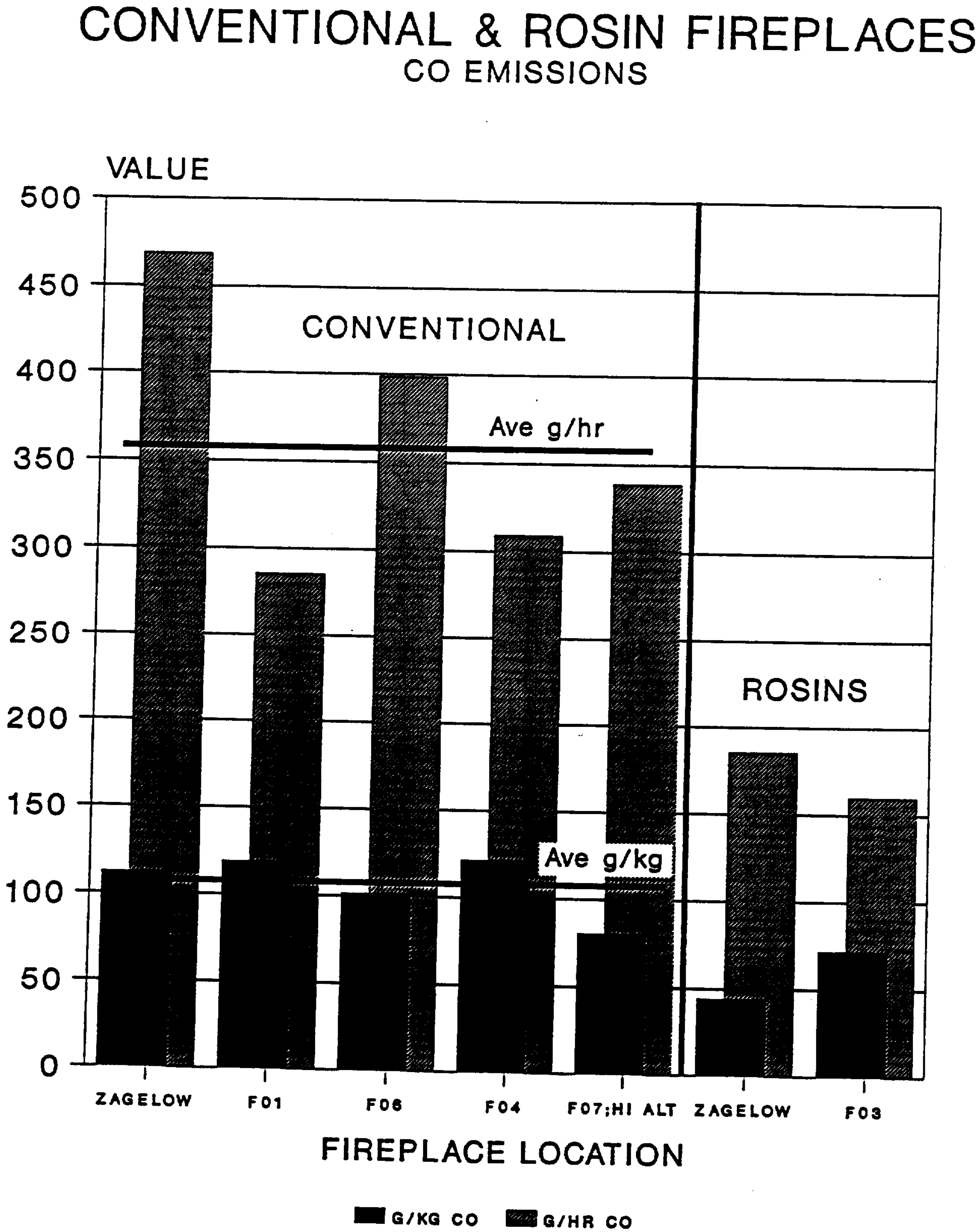

CONVENTIONAL & ROSIN FIREPLACES
CO EMISSIONS
VALUE
500
450
400
350
300
250
200
150
100
50
0
CONVENTIONAL
Ave g/hr
Ave g/kg
ROSINS
ZAGELOW
F01
F06
F04
F07;HI ALT
ZAGELOW
F03
FIREPLACE LOCATION
G/KG CO
G/HR CO

Figure 6

## "IN–HOME" MASONRY CONVENTIONAL FIREPLACES @ 20% WOOD MOISTURE

| HOUSE AND RUN: | ZAG. #1 | F0101 | F0601 | F0401 | F0701 | AVERAGES | |
|---|---|---|---|---|---|---|---|
| SAMPLE DATES: | 12/17– 12/20/90 | 2/6– 2/13/91 | 2/26– 3/07/91 | 2/22– 2/28/91 | 3/2– 3/10/91 | | |
| FIREPLACE TYPE: | CON–VENTIONAL | CON–VENTIONAL | CON–VENTIONAL | MODIFIED RUMFORD | CONV., HIGH ALT. | | |
| FUEL TYPE: | D. FIR | D. FIR | D. FIR | D. FIR | D. FIR | | |
| FUEL MOISTURE: | 20% MOIST | 19% MOIST | 20% MOIST | 20% MOIST | 21% MOIST | | |
| TOTAL STOVE BURNING HOURS= | 28.17 | 30.25 | 24.67 | 24.75 | 28.92 | 27.4 | TOTAL STOVE BURNING HOURS= |
| % OF TIME FIREPLACE BURNED= | 31.07 | 18.16 | 14.63 | 21.48 | 46.80 | 26.5 | % OF TIME FIREPLACE BURNED= |
| AVE. STACK TEMP (DEGREES F.)= | 195 | 203 | 156 | 153 | 302 | 202 | AVE. STACK TEMP (DEGREES F.)= |
| AVE OXYGEN %(STACK>100 DEGREES)= | 20.15 | 20.44 | 20.60 | 20.45 | 19.98 | 20.30 | AVE OXYGEN %(STACK>100 DEGREES)= |
| AVE. OXYGEN % (BAG)= | 20.2 | 20.4 | 20.3 | 20.4 | 19.7 | 20.20 | AVE. OXYGEN % (BAG)= |
| TOTAL WOOD USED (WET LBS.)= | Not determined | 189.8 | 254.9 | 165.6 | 323.6 | 186.8 | TOTAL WOOD USED (WET LBS.)= |
| WOOD MOISTURE (DRY BASIS %)= | 19.50 | 18.90 | 19.90 | 19.70 | 20.80 | 19.8 | WOOD MOISTURE (DRY BASIS %)= |
| AWES FLOW RATE (L./MIN)= | 1.089 | 0.944 | 1.025 | 0.944 | 0.967 | 0.99 | AWES FLOW RATE (L./MIN)= |
| LENGTH OF SAMPLING CYCLE (MIN)= | 2 | 2 | 3 | 3 | 3 | 2.60 | LENGTH OF SAMPLING CYCLE (MIN)= |
| AVERAGE CO % (BAG)= | 0.07 | 0.05 | 0.04 | 0.05 | 0.07 | 0.056 | AVERAGE CO % (BAG)= |
| AVERAGE CO2 % (BAG)= | 0.7 | 0.49 | 0.47 | 0.48 | 0.96 | 0.62 | AVERAGE CO2 % (BAG)= |
| NUMBER OF BURN CYCLES IN TEST= | 7 | 7 | 7 | 10 | 4 | 7.0 | NUMBER OF BURN CYCLES IN TEST= |
| TOTAL PARTICULATES IN MG. | | | | | | | TOTAL PARTICULATES IN MG. |
| RINSE (MG)= | 65.3 | 37.9 | 39.1 | 51.5 | 52.9 | 49.3 | RINSE (MG)= |
| XAD (MG)= | 39.9 | 78.7 | 14.6 | 3.2 | 7.3 | 28.8 | XAD (MG)= |
| FILTER (MG)= | 35.0 | 6.0 | 21.7 | 20.9 | 28.4 | 22.4 | FILTER (MG)= |
| MINUS AVE BLANK | 3.9 | 3.9 | 3.9 | 3.9 | 3.9 | 3.9 | MINUS AVE BLANK |
| TOTAL PARTICULATES (GRAMS)= | 0.136 | 0.107 | 0.072 | 0.072 | 0.085 | 0.0943 | TOTAL PARTICULATES (GRAMS)= |
| TOTAL DRY WOOD USED (KG)= | Not determined | 72.54 | 96.63 | 62.89 | 121.78 | 70.8 | TOTAL DRY WOOD USED (KG)= |
| BURN RATE (DRY KG/HR)= | 4.17 | 2.40 | 3.92 | 2.54 | 4.21 | 3.45 | BURN RATE (DRY KG/HR)= |
| AIR–FUEL RATIO= | 204 | 303 | 321 | 310 | 144 | 256.2 | AIR–FUEL RATIO= |
| PARTICULATE EMISSIONS: | | | | | | | PARTICULATE EMISSIONS: |
| GM/KG= | 20.5 | 25.7 | 31.0 | 32.2 | 15.0 | 24.9 | GM/KG= |
| GM/HR= | 85.4 | 61.6 | 121.6 | 81.7 | 63.1 | 82.7 | GM/HR= |
| AVE. DAILY G/HR= | 14.3 | 11.1 | 17.9 | 8.4 | 19.0 | 14.1 | AVE. DAILY G/HR= |
| CO EMISSIONS: | | | | | | | CO EMISSIONS: |
| GM/KG= | 112.4 | 119.2 | 101.8 | 121.6 | 80.5 | 107.1 | GM/KG= |
| GM/HR= | 468.8 | 285.8 | 398.7 | 309.4 | 338.9 | 360.3 | GM/HR= |
| AVE. DAILY G/HR= | 78.6 | 51.5 | 58.5 | 31.9 | 102.1 | 64.5 | AVE. DAILY G/HR= |
| ADDITIONAL ITEMS: | | | | | | | ADDITIONAL ITEMS: |
| AVE. BURN CYCLE LENGTH (HR)= | 4.02 | 4.32 | 3.52 | 2.48 | 7.23 | 4.31 | AVE. BURN CYCLE LENGTH (HR)= |
| TOTAL PARTICULATES/DAY (G)= | 344 | 266 | 429 | 202 | 456 | 339 | TOTAL PARTICULATES/DAY (G)= |
| TOTAL CO/DAY (G)= | 1887 | 1235 | 1405 | 766 | 2450 | 1548 | TOTAL CO/DAY (G)= |
| WET LBS. USED/ BURN CYCLE= | | 27.1 | 36.4 | 16.6 | 80.9 | 40.2 | WET LBS. USED/ BURN CYCLE= |
| # WOOD LOADS/BURN CYCLE= | | 4.6 | 3.0 | 4.4 | 5.8 | 4.44 | # WOOD LOADS/BURN CYCLE= |
| AVE WOOD LOAD (WET LB.)= | | 5.9 | 12.1 | 5.3 | 14.1 | 9.4 | AVE WOOD LOAD (WET LB.)= |
| AVE. WOOD USAGE/DAY (WET LB)= | | 27.3 | 36.8 | 34.5 | 126.0 | 56.1 | AVE. WOOD USAGE/DAY (WET LB)= |
| AVE. AMBIENT TEMP (DEG.F.)= | | 70.1 | 65.4 | 64.0 | 62.3 | 65.4 | AVE. AMBIENT TEMP (DEG.F.)= |

Table 2. Summary of Conventional Fireplace data.

| | ROSINS | | | | MOISTURE ANALYSIS (CONVENTIONAL FIREPLACE) | | | MASONRY HEATERS | | |
|---|---|---|---|---|---|---|---|---|---|---|
| HOUSE AND RUN: | F0301 | F0302 | ZAG. #2 | ROSIN | F0102 | F0101 | F0103 | F0201 | F0501 | |
| SAMPLE DATES: | 2/22/–3/2/91 | 6/13–6/24/91 | 1/3–1/08/91 | | 2/13–2/20/91 | 2/6–2/13/91 | 2/20–2/27/91 | 2/20–2/27/91 | 2/27–3/06/91 | |
| FIREPLACE TYPE: | ROSIN OR. EQUIP | ROSIN OR. EQUIP | ROSIN RETRO | AVERAGE | CON–VENTIONAL | CON–VENTIONAL | CON–VENTIONAL | RUSSIAN HEATER | CONTRA–FLOW | |
| FUEL TYPE: | D.FIR | D.FIR | D.FIR | | D.FIR | D.FIR | D.FIR | D.FIR | D.FIR | |
| FUEL MOISTURE: | 20% MOIST | 20% MOIST | 17% MOIST | | 15 % MOIST | 20% MOIST | 24% MOIST | 20% MOIST | 18% MOIST | |
| TOTAL STOVE BURNING HOURS= | 50.83 | 39.50 | 37.75 | 41.5 | 27.67 | 30.25 | 25.58 | 29.75 | 15.42 | TOTAL STOVE BURNING HOURS= |
| % OF TIME FIREPLACE BURNED= | 32.85 | 23.52 | 33.07 | 30.6 | 16.47 | 18.16 | 15.33 | 17.77 | 9.19 | % OF TIME FIREPLACE BURNED= |
| AVE. STACK TEMP (DEGREES F.)= | 209 | 190 | 218 | 209 | 206 | 203 | 142 | 350 | 413 | AVE. STACK TEMP (DEGREES F.)= |
| AVE OXYGEN %(STACK>100 DEGREES)= | 20.03 | 20.17 | 20.22 | 20.16 | 20.32 | 20.44 | 20.45 | 18.84 | 16.87 | AVE OXYGEN %(STACK>100 DEGREES)= |
| AVE. OXYGEN % (BAG)= | 20.1 | 20.6 | 20.2 | 20.3 | 20.5 | 20.4 | 20.3 | 19.3 | 16.7 | AVE. OXYGEN % (BAG)= |
| TOTAL WOOD USED (WET LBS.)= | 298.1 | 217.1 | 405.3 | 331.5 | 211.8 | 189.8 | 186.0 | 195.3 | 328.9 | TOTAL WOOD USED (WET LBS.)= |
| WOOD MOISTURE (DRY BASIS %)= | 20.30 | 20 | 16.90 | 18.5 | 15.00 | 18.90 | 24.20 | 19.30 | 17.90 | WOOD MOISTURE (DRY BASIS %)= |
| AWES FLOW RATE (L/MIN)= | 1.054 | 1.067 | 1.044 | 1.1 | 0.944 | 0.944 | 0.967 | 1.067 | 1.084 | AWES FLOW RATE (L/MIN)= |
| LENGTH OF SAMPLING CYCLE (MIN)= | 3 | 3 | 2 | 2.5 | 2 | 2 | 3 | 3 | 3 | LENGTH OF SAMPLING CYCLE (MIN)= |
| AVERAGE CO % (BAG)= | 0.05 | 0.0166 | 0.03 | 0.032 | 0.06 | 0.05 | 0.07 | 0.11 | 0.14 | AVERAGE CO % (BAG)= |
| AVERAGE CO2 % (BAG)= | 0.8 | 0.43 | 0.8 | 0.71 | 0.63 | 0.49 | 0.56 | 1.4 | 4 | AVERAGE CO2 % (BAG)= |
| NUMBER OF BURN CYCLES IN TEST= | 7 | 7 | 5 | 6.00 | 7 | 7 | 7 | 13 | 7 | NUMBER OF BURN CYCLES IN TEST= |
| TOTAL PARTICULATES IN MG. | | | | | | | | | | TOTAL PARTICULATES IN MG. |
| RINSE (MG)= | 40.6 | 41.7 | 64.4 | 52.8 | 30.7 | 37.9 | 78.7 | 50.6 | 47.0 | RINSE (MG)= |
| XAD (MG)= | 36.3 | 12.5 | 16.6 | 20.5 | 33.5 | 78.7 | 6.0 | 27.2 | 20.2 | XAD (MG)= |
| FILTER (MG)= | 7.9 | 15.0 | 23.0 | 17.2 | 50.9 | 6.0 | 37.8 | 48.4 | 8.1 | FILTER (MG)= |
| MINUS AVE BLANK | 3.9 | 3.9 | 3.9 | 3.9 | 3.9 | 3.9 | 3.9 | 3.9 | 3.9 | MINUS AVE BLANK |
| TOTAL PARTICULATES (GRAMS)= | 0.081 | 0.065 | 0.100 | 0.0865 | 0.111 | 0.107 | 0.119 | 0.122 | 0.071 | TOTAL PARTICULATES (GRAMS)= |
| TOTAL DRY WOOD USED (KG)= | 112.64 | 82.23 | 157.59 | 127.5 | 83.70 | 72.54 | 68.07 | 74.39 | 126.79 | TOTAL DRY WOOD USED (KG)= |
| BURN RATE (DRY KG/HR)= | 2.22 | 2.08 | 4.17 | 3.2 | 3.03 | 2.40 | 2.66 | 2.50 | 8.22 | BURN RATE (DRY KG/HR)= |
| AIR–FUEL RATIO= | 180 | 197 | 183 | 185.8 | 229 | 303 | 256 | 98 | 34 | AIR–FUEL RATIO= |
| PARTICULATE EMISSIONS: | | | | | | | | | | PARTICULATE EMISSIONS: |
| GM/KG= | 9.37 | 10.58 | 10.8 | 10.4 | 22.1 | 25.7 | 41.4 | 9.6 | 5.6 | GM/KG= |
| GM/HR= | 20.76 | 22.04 | 45.0 | 33.2 | 66.9 | 61.6 | 110.1 | 24.1 | 45.7 | GM/HR= |
| AVE. DAILY G/HR= | 6.3 | 5.2 | 14.2 | 9.9 | 11.0 | 11.1 | 16.8 | 9.6 | 5.6 | AVE. DAILY G/HR= |
| CO EMISSIONS: | | | | | | | | | | CO EMISSIONS: |
| GM/KG= | 72.12 | 49.26 | 44.4 | 52.5 | 108.7 | 119.2 | 140.3 | 90.7 | 41.0 | GM/KG= |
| GM/HR= | 159.80 | 102.54 | 185.4 | 158.3 | 328.8 | 285.8 | 373.3 | 226.9 | 336.8 | GM/HR= |
| AVE. DAILY G/HR= | 48.4 | 24.1 | 58.3 | 47.3 | 54.2 | 51.5 | 56.6 | 40.2 | 31.0 | AVE. DAILY G/HR= |
| ADDITIONAL ITEMS: | | | | | | | | | | ADDITIONAL ITEMS: |
| AVE. BURN CYCLE LENGTH (HR)= | 7.26 | 5.64 | 7.55 | 7.0 | 3.95 | 4.32 | 3.65 | 2.29 | 2.21 | AVE. BURN CYCLE LENGTH= |
| TOTAL PARTICULATES/DAY (G)= | 0 | 124 | 340 | 201 | 265 | 266 | 402 | 102 | 101 | TOTAL PARTICULATES/DAY (G)= |
| TOTAL CO/DAY (G)= | 7 | 579 | 1400 | 846 | 1300 | 1235 | 1364 | 965 | 743 | TOTAL CO/DAY (G)= |
| WET LBS. USED/ BURN CYCLE= | 42.6 | 31.0 | 81.1 | 50 | 30.3 | 27.1 | 26.6 | 15.0 | 47.0 | WET LBS. USED/ BURN CYCLE= |
| # WOOD LOADS/BURN CYCLE= | 3.1 | 3.0 | 7.7 | 5.4 | 3.6 | 4.6 | 3.3 | 1.0 | 1.0 | # WOOD LOADS/BURN CYCLE= |
| AVE WOOD LOAD (WET LB.)= | 13.6 | 10.3 | 7.5 | 9.7 | 8.5 | 5.9 | 8.1 | 15.0 | 47.0 | AVE WOOD LOAD (WET LB.)= |
| AVE. WOOD USAGE/DAY (WET LB)= | 42.6 | 31.0 | 85.2 | 61.0 | 30.3 | 27.3 | 26.7 | 27.9 | 47.1 | AVE. WOOD USAGE/DAY (WET LB)= |
| AVE. AMBIENT TEMP (DEG.F.)= | 67.9 | 68.7 | 67.0 | 67.6 | 69.3 | 70.1 | 68.4 | 65.3 | 67.9 | AVE. AMBIENT TEMP (DEG.F.)= |

Table 3. Summary of Rosin, Masonry Heater and moisture analysis data.

## Rosin Fireplaces

In contrast to the conventional fireplaces, the emissions from the two Rosins were significantly lower. Particulate emissions averaged 10.4 g/kg, 33.2 g/hr, and 9.9 average daily g/hr.[8] This represents a 60% reduction in g/kg compared to the conventional fireplaces. A *t*-test indicated that the g/kg difference is significant at the 98% probability level. CO emissions averaged 52.5 g/kg, 158.3 g/hr, and 47.3 average daily g/hr. CO g/kg emissions are 50% lower than the conventional fireplaces.

There is a large difference in burn rate and hence g/hr emissions between the two Rosins, although both units had nearly identical g/kg particulate emissions. The original equipment version averaged 21.5 g/hr versus 44.5 g/hr for the retrofit version. Although there is insufficient data to draw a definitive conclusion, it appears that the smaller flue of the original equipment Rosin may cause the burn rate to be lower, thus having the effect of reducing gram-per-hour emissions compared to the retrofit Rosin. Unfortunately, only one unit of each type was tested. It should be noted that the flue damper in F03 was not operated during this project. The manufacturer recommends that it be partially closed during the latter parts of a burn cycle. This could reduce burn rate further. The effect of this action on emissions is not yet known.

Fuel loading geometry differed in the two tests of the original equipment Rosin, F03. In the first test, logs were loaded front-to-back and tilted upward in the back (Figure B-10 in Appendix B ). This loading pattern was used by Mr. Zagelow in his Rosin as well. The second test used a criss-cross pattern recommended by the Rosin manufacturer (Figure B011 in Appendix B). Emissions were very similar for both tests (Table 3), suggesting that the Rosin is quite free of sensitivity to certain wood load patterns.

## Masonry Heaters

Since the two masonry heaters differ significantly from each other, they will be treated separately. The Contraflow, F05, averaged 5.6 g/kg, 45.7 g/hr, and 5.6 normalized average daily g/hr particulate emissions. CO emissions were 41.0 g/kg, 337 g/hr, and 31.0 average daily g/hr. Particulate emissions for the locally designed Russian heater, F02, were 9.6 g/kg, 24.1 g/hr, and 9.6 average daily g/hr. CO emissions were 90.7 g/kg, 227 g/hr, and 40.2 average daily g/hr.

---

[8] See the section on "The Concept of Average Daily g/hr" for explanation of this term.

Since masonry heaters are used primarily to heat homes and have combustion chambers very similar to woodstoves, they should be compared to woodstoves, specifically noncatalytic woodstoves, rather than fireplaces. The Contraflow particulate emissions are about the same as those from field results of the best-performing noncatalytic 1990-certified Phase II woodstoves (6-7 g/hr)[2,3] on a normalized average daily g/kg basis. The Contraflow's CO emissions of 41.0 g/kg are significantly lower than those reported for Phase II noncatalytic stoves[4] (77 g/kg). Since the net delivered efficiencies of woodstoves and the Contraflow are both about 55%, a homeowner would burn a similar amount of fuel to heat his house with either heater.

The potential for masonry heaters appears to be large. Examination of the Contraflow's firebox indicates that it does not possess three major features of clean-burning woodstoves: a baffle, secondary air, and absence of underfire air. If these features were included, the Contraflow could possibly reduce emissions significantly and become one of the cleanest-burning residential biomass forms of heat.

The locally built Russian heater, F02, performs more poorly than the Contraflow. Not only are its g/kg emissions for both particulate and CO about twice as high, but its net delivered efficiency is only 35%. Therefore, a homeowner, to obtain the same amount of heat, would burn about 1.6 times as much wood per day and thus produce three times as much particulate pollution.

The differences in the two masonry heaters underscore two points. To ensure optimal efficiency, heaters should be designed by experts or standardized as kits or designs. Careful attention must be paid not only to increasing combustion efficiency (reducing g/kg emissions) but also heat transfer efficiency, so as to maximize net delivered efficiency and minimize emissions. The subject of heat transfer is discussed at length in the 1990 report on the Pacific Energy noncatalytic woodstoves[3] and in the 1991 report on exempt pellet stoves.[5]

## Effects of Wood Moisture on Conventional Fireplace Emissions

Figures 7 and 8 show the results of burning Douglas fir of various moisture contents of 15%, 20%, and 24% in the conventional fireplace in house F01. While there is little difference between emissions from 15% and 20% wood moisture, 24% moisture wood produced significantly increased particulate emissions (Figure 7, Table 3). Emissions ranged from 22.1 g/kg for the 15% moisture to 47.4 g/kg for the 24% moisture wood. CO emissions shown in Figure 8 display a similar but less pronounced increase with

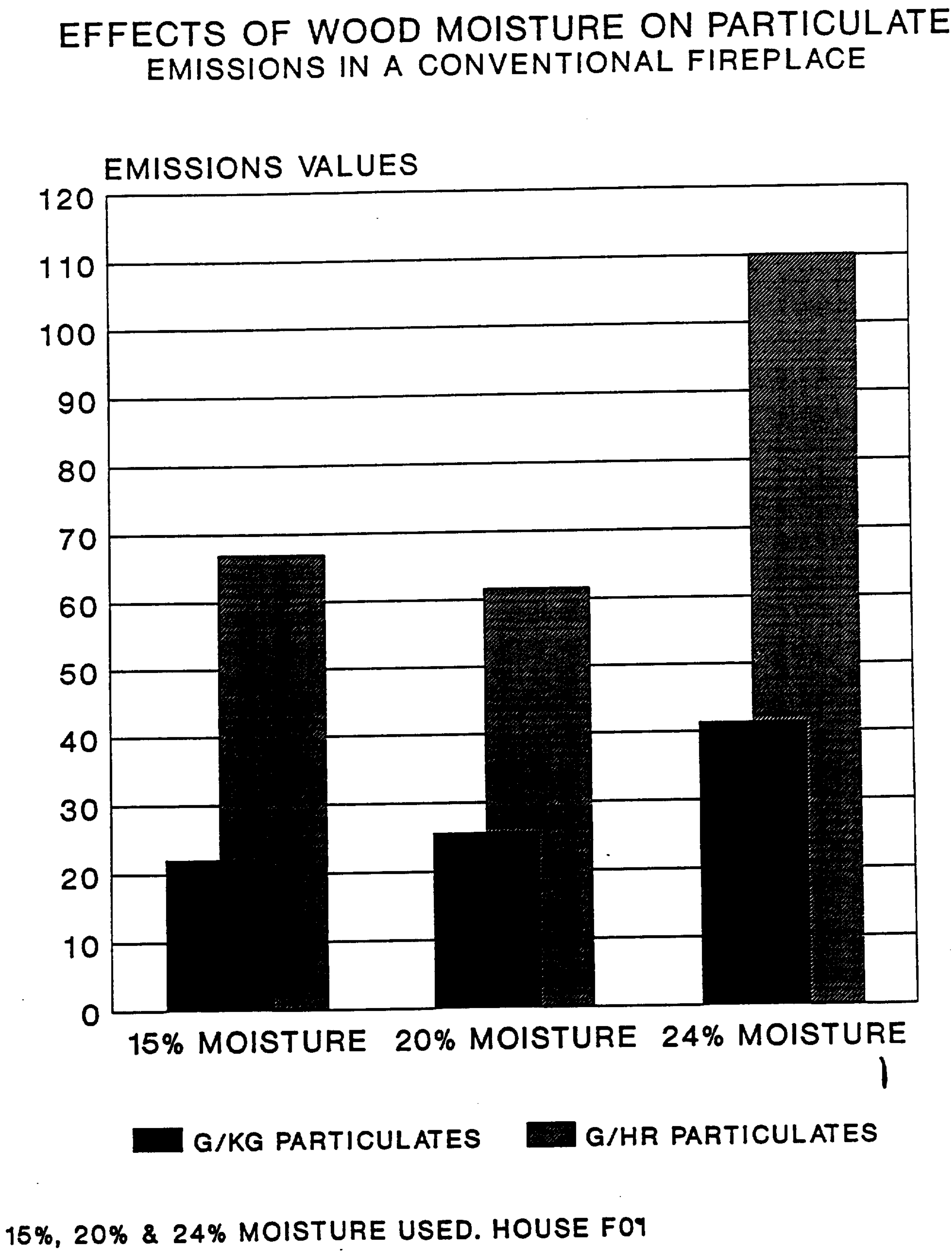
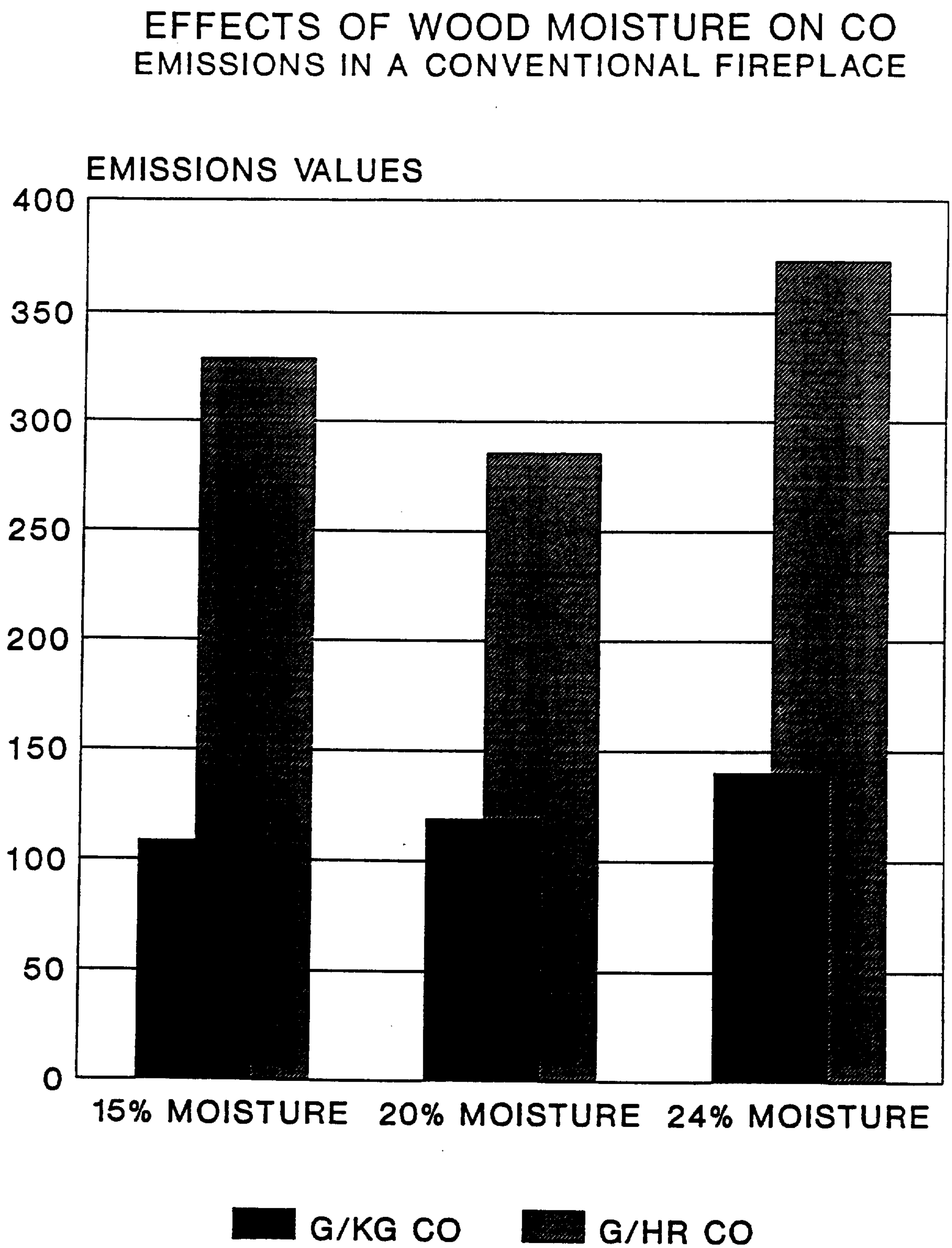

EFFECTS OF WOOD MOISTURE ON PARTICULATE
EMISSIONS IN A CONVENTIONAL FIREPLACE
EMISSIONS VALUES
120
110
100
90
80
70
60
50
40
30
20
10
0
15% MOISTURE
20% MOISTURE
24% MOISTURE
G/KG PARTICULATES
G/HR PARTICULATES
15%, 20% & 24% MOISTURE USED. HOUSE F01

Figure 7




15%, 20% & 24% MOISTURE USED. HOUSE F01

Figure 8

increasing fuel moisture.

The effects of moisture on the emissions performance of this conventional fireplace appear to be similar to those on the noncatalytic 1990-certified Phase II noncatalytic woodstoves studied in Klamath Falls, Oregon and Glens Falls, New York.[1,2,3]

## Effects of Altitude on Emissions from Conventional Fireplace Emissions

Fireplace F07 is located at an altitude of 3,500 feet in Government Camp, Oregon, in the Cascades just south of Mt. Hood, about 3,300 feet higher than the Portland area. It was hoped that this fireplace could be used to evaluate the effects of altitude on emissions. However, this did not turn out to be the case because a second variable was not controlled. While this fireplace is at a relatively high elevation, the fireplace was only burned on weekends. Burning habits on weekends for the other conventional fireplaces in the project are different than during the week: burns are decidedly longer. It is distinctly possible that combustion efficiency is improved by these long burns. Therefore, no definitive conclusion can be drawn at this time about the effect of altitude on conventional fireplace emissions.

## CO—Particulate Emissions Relationship

The relationship between particulates and CO emissions typically displays a moderate level of correlation for woodstoves and pellet stoves. The same situation appears to be the case for the fireplaces and masonry heaters in this project. The 12 test results are plotted in Figure 9. The correlation coefficient (R) of 0.89 is moderately high but the sample is quite small.

The primary pollutant that is regulated for woodstoves and fireplaces is particulates. It is clear from examining Figure 9 that while a relationship exists between CO and particulates, it is not correlated highly enough so that CO can be used to precisely predict particulates. CO can be used to screen a relatively clean-burning fireplace from a highly polluting one, but CO does not have the "resolution" to be used as a tool for evaluating the merits of design changes during fireplace or masonry heater development. CO data is supplemental.

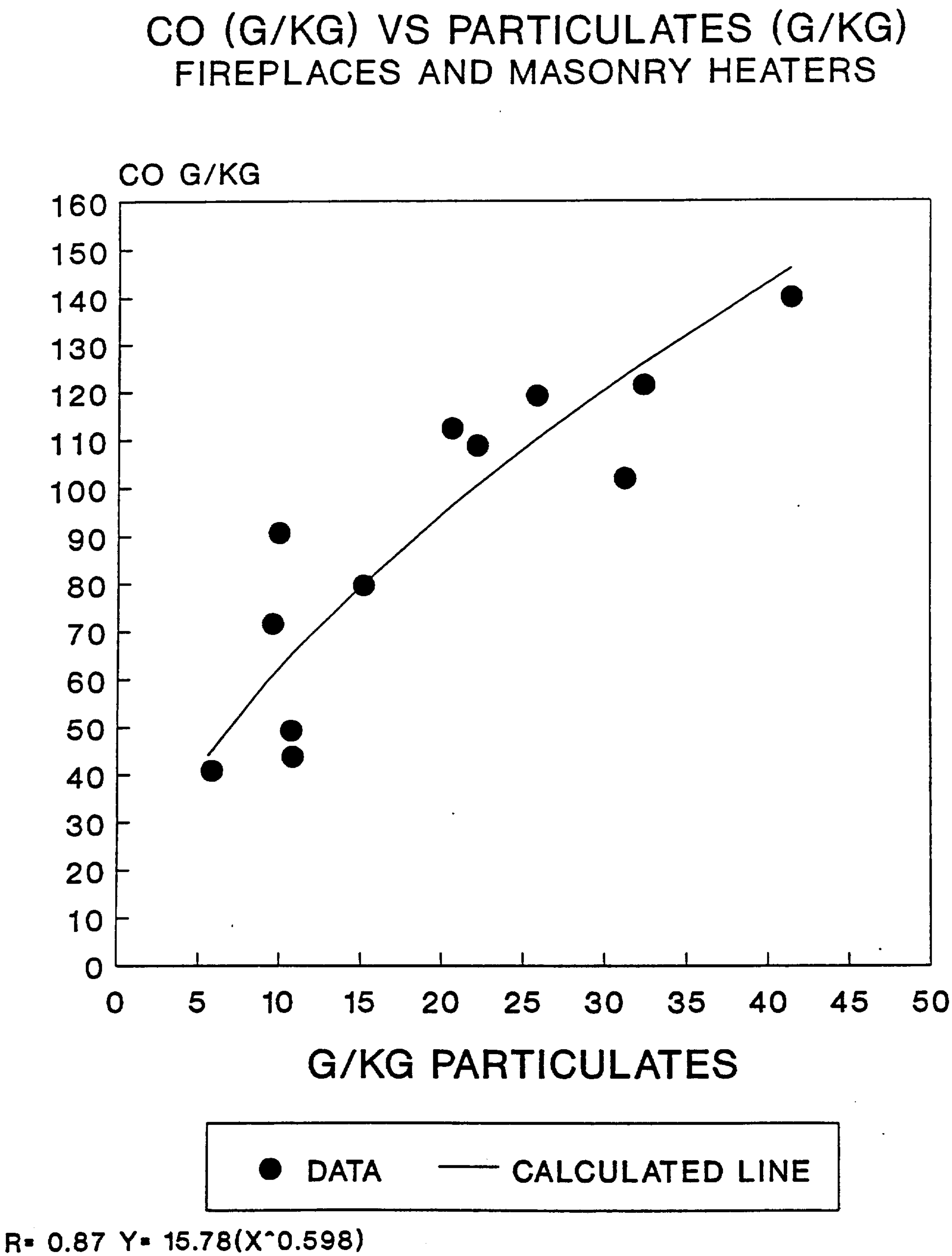

CO (G/KG) VS PARTICULATES (G/KG)
FIREPLACES AND MASONRY HEATERS
CO G/KG
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
0 5 10 15 20 25 30 35 40 45 50
G/KG PARTICULATES
DATA
CALCULATED LINE
R= 0.87 Y= 15.78(X^0.598)

Figure 9

# Discussion

## The Significance of the Format in Which Emissions are Presented

Emissions from combustion devices are usually expressed in either a g/kg or g/hr format. Grams per hour is an emission rate; g/kg is an emission factor. Implicit in the g/hr emissions rate as used in woodstoves is that a particular g/hr emission rate will be continuous over a period of time, usually over a day or more. Grams per kilogram refers to emissions per unit of fuel that is burned. The lower the g/kg, the more efficient the combustion process. The g/hr method of presentation has been adapted for woodstoves and is appropriate because woodstoves are typically burned on a 24-hour or near 24-hour basis to heat homes.

A fundamental question that emissions values attempt to address for residential woodburning is how much pollution is contributed to an airshed on a daily (or yearly) basis, since woodburning particulates and CO remain in the air for days and accumulate. Because most woodstoves are used continuously, g/hr values are appropriate for them. However, when woodstoves are compared to other forms of residential wood combustion that burn discontinuously, then the comparison becomes less meaningful when one uses g/hr. An example of this would be a comparison with masonry heaters. Masonry heaters only burn for a short period during a given day, using one or perhaps two loads of wood. Since their burn rate is many times higher during the combustion process than that of a woodstoves, their g/hr values are correspondingly much higher. The Contraflow masonry heater particulate emissions are 45.7 g/hr compared to about 7 g/hr for Phase II woodstoves. In this case, g/hr does not correctly convey the relative daily contribution of these two heating devices to the airshed. In one day the woodstove would emit about 170 grams (7 g/hr × 24 hour) of particulates and the Contraflow, on the other hand, would actually emit less (101 grams [45 g/hr × 2.21 hr]). If one assumes a population of masonry heaters on average would burn at the same burn rate (1.1 kg/hr) as the noncatalytic woodstoves in the field (both have a similar efficiency of about 55%) then the masonry heaters would emit an amount (135 grams per day) similar to the noncatalytic woodstove. This example illustrates that use of g/hr format distorts emissions from the Contraflow by a factor of 8.

The situation for the fireplace is similar to that of the masonry heater. The average conventional masonry fireplace emits about 82.7 g/hr of particulates compared to only about 21 g/hr for conventional woodstoves and about 7 for Phase II certified stoves. On this basis, the conventional fireplace would appear to be polluting four times as much as the conventional woodstoves. However, the average conventional fireplace in the current study was only burned 4.3 hours a day. On a daily basis, then, the conventional fireplace average was 356 grams of particulate per day and the conventional woodstove is slightly over 500 grams per day. Therefore, the rankings of these two combustion devices actually become reversed when one looks at it from a daily contribution point of view. The g/hr distortion was about six times. Additionally, fireplaces are rarely burned every day, so daily contribution to pollution from fireplaces is actually lower.

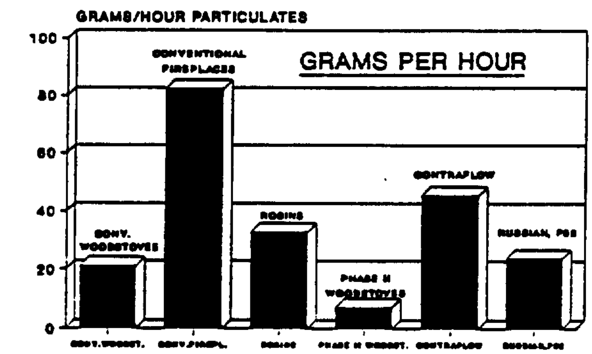
## The Concept of Average Daily g/hr

Because masonry fireplaces and masonry heaters are burned discontinuously, the concept of average daily g/hr is introduced to express their emissions. This term refers to g/hr emissions as averaged over a 24-hour period. Average daily g/hr emissions = g/hr (hours burned/24 hr). Taking the average masonry fireplace as an example: Grams per hour emissions are 82.7 and the fireplaces were burned an average of 4.31 hours per day. Average daily g/hr = 82.7 (4.3/24) = 14.8. It should be noted that average daily g/hr is used instead of grams per day only because the former is readily comparable with the large body of woodstove and pellet stove results.

In the case of masonry heaters, an appropriate means of comparison with woodstoves is to normalize masonry heater results to an average daily burn rate of 1.0 kg/hr, in agreement with certified woodstoves in the field. Thus, the term normalized daily g/hr is proposed for masonry heaters. This term is equivalent to the g/kg value.

The relative rankings of the woodstoves, fireplaces, and masonry heaters are shown in more detail in Figures 10, 11, and 12, which show, respectively, g/hr, average daily g/hr, and g/kg of particulates. In Figure 10 (g/hr), both conventional fireplaces and the Contraflow stand out as apparently the largest polluters of the group, followed by the Rosins and then the conventional woodstoves. When the results are presented in average daily g/hr (Figure 11), the conventional woodstoves have the highest emissions, followed by the conventional fireplaces, the Rosins, and the Russian masonry heater. The cleanest-burning devices of the group are the Phase II woodstoves and the Contraflow, both at approximately the same emissions level.

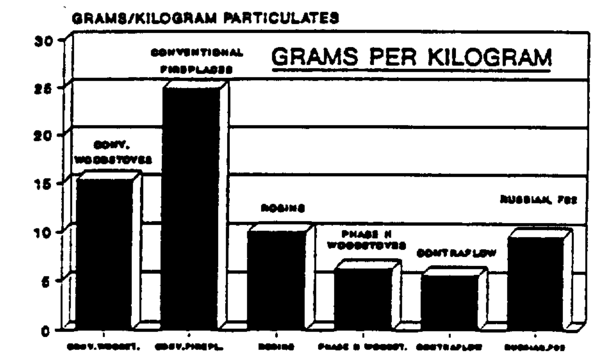
COMPARISON OF PARTICULATES; G/HR
WOODSTOVES, FIREPLACES, MASONRY HEATERS




Conventional woodstoves from EPA's AP-42
Phase II woodstoves are field average.

Figure 10

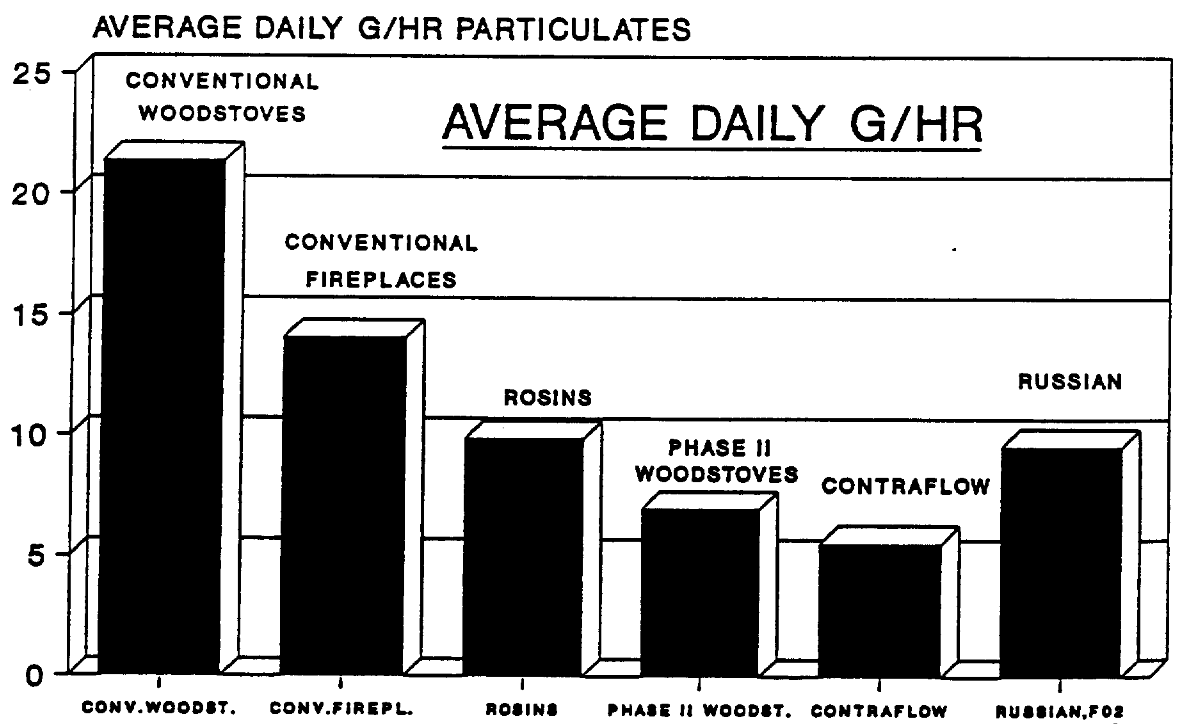
COMPARISON OF PARTICULATES; G/KG
WOODSTOVES, FIREPLACES, MASONRY HEATERS




Conventional woodstoves from EPA's AP-42
Phase II woodstoves are field average.

Figure 12

# AVERAGE DAILY G/HR PARTICULATES FOR WOODSTOVES, FIREPLACES, MASONRY HEATERS




Masonry heater values normalized to a 1.0 kg/hr burn rate, the Phase II woodstove field average.

Figure 11

Figure 12 shows emissions using the g/kg format. The ranking of the various woodburning devices is similar to that of the average daily g/hr and very dissimilar to the g/hr, the only exception being that conventional fireplaces g/kg show higher emissions than conventional woodstoves compared to average daily g/hr. The g/kg format has an advantage in that emissions per burning season can readily be calculated using it. Since many states have taken surveys indicating the amount of wood usage for woodstoves and fireplaces, multiplying this quantity times the g/kg emission factor yields grams per burning season.

# Summary and Conclusions

The emissions tests conducted in this project provide information on how homeowners burn their fireplaces. For the conventional fireplaces, the average burn rate was 3.45 dry kg/hr, the average burn cycle length was 4.3 hours, the average number of wood loads per burn cycle was 4.4, and the average wood load weight was 9.4 wet pounds. Of these variables, the only one with a large amount of variation was the average wood load weight, which varied over a range of 3:1.

Masonry heater burn patterns were quite different. Average burn rate for the combustion period was 8.2 kg/hr for the Contraflow and 2.5 kg/hr for the locally built Russian unit. Average burn lengths were 2.2 and 2.3 hours, respectively, and wood loads averaged 47 and 15 wet pounds, respectively. Both heaters were burned only once or twice per day.

Particulate emissions from the conventional fireplaces averaged 24.9 g/kg, 82.7 g/hr, and 14.8 average daily g/hr. These values are near the upper end of the range of results in the literature, which comprises mostly laboratory tests conducted using various methods of emissions measurement. CO emissions from the conventional fireplaces averaged 107 g/kg, 360 g/hr, and 64.5 average daily g/hr.

Emissions from the Rosin fireplaces were generally less than 50% of those from than the conventional fireplaces. Particulate emissions averaged 10.4 g/kg, 33.2 g/hr, and 9.9 average daily g/hr. CO emissions averaged 52.5 g/kg, 158 g/hr, and 47.3 average daily g/hr.

Emissions from the Contraflow masonry heater were about half those of the locally designed and built Russian heater. Contraflow particulate emissions were 5.6 g/kg, 45.7 g/hr, and 5.6 normalized average daily g/hr. CO emissions were 41.0 g/kg, 336.8 g/hr, and 31.0 normalized average daily g/hr. Emissions from the locally designed Russian unit were about twice as high.

The format in which emissions results are presented is of great importance. For example, use of different formats can result in as much as an 8:1 difference in comparative emissions results. Grams per hour (which is used for woodstoves) is considered the poorest representation of fireplace/masonry heater emissions because these types of devices are only burned for a few hours each day. Thus, use of g/hr greatly exaggerates emissions contributions to airsheds. A new term, average daily g/hr, is introduced which appears to be more appropriate. This format portrays the total amount of pollution that a given combustion device contributes to an airshed on a daily basis. Average daily g/hr is used rather than grams per day to facilitate a direct and easy comparison with the body of woodstove data which is expressed in grams per hour.[h] Grams-per-kilogram produces similar rankings for residential wood combustion burning devices but is somewhat less appropriate to meet the objective of quantifying the amount of pollution per day. Grams per kilogram is valuable in calculating the total emissions contribution per burning season, however.

The effects of wood moisture (range 15% to 24%) on emissions from a conventional fireplace were significant above 20% moisture. Emissions ranged from 22.1 at 15% moisture to 41.4 g/kg at 24% moisture. The effect of altitude on emissions could not be measured because a second variable—long burns associated with the fireplace being burned only on weekends—was present.

# Recommendations

This study has produced a data base that should prove helpful to the masonry heating industry in developing regulations that are fair to all the involved stakeholders. It is important to stress in discussions with the regulators the significance of the format in which emissions results are presented. Large distortions can develop from using a g/hr basis for comparison with other forms of residential biomass combustion. Most preferable is average daily g/hr, followed by g/kg.

[h] For masonry heaters, the term normalized average daily g/hr is most appropriate. In this case, a burn rate of 1.0 kg/hr, the average field value for certified woodstoves, is used. This emissions value is equal to g/kg.

Since the Rosin fireplaces reduce emissions by greater than 50% compared to the conventional fireplaces, efforts should be made to ensure that this type of technology is acceptable to regulators as an improved technology in their regulations.

The clean-burning nature of the Contraflow masonry heater and the potential for this type of heater to perform at extremely low emissions rates should be emphasized. Other, more promising heater designs should be evaluated in the field to document this potential. These types of heaters could produce emissions low enough that they could be allowed to be used in areas where very strict emissions standards are being developed.

Since no standard laboratory test procedure for fireplaces and masonry heaters exists, efforts should be made to establish one. Considering the mass of both fireplaces and masonry heaters, as well as the difficulty of setting up either of these units in a laboratory, it is important that one option that must be reserved as an acceptable method of certification testing be the use of in-home testing itself, following the procedures that were used in this study.

The development of laboratory test standards for masonry fireplaces and heaters should incorporate the data on the burning habits of homeowners that was obtained in this study. An example of the kind of detailed data that is needed is shown in Appendix C, Figure 1. Candidate test methods should be evaluated for comparability and realism by comparing emissions results obtained with a candidate technique with results that were obtained in this field study.

As a first step, the results of the Virginia Polytechnic Institute (VPI) laboratory masonry fireplace study, which tested fireplaces similar to those in the current project, should be evaluated.

A second step should be to evaluate the effectiveness of the VPI masonry heater laboratory testing by comparing their results on the Contraflow with those in this report.

The third step should be to evaluate for effectiveness the fireplace test method of the Wood Heating Alliance (WHA), which should become available in September or October of 1991.

Research should be directed at evaluating other aspects of the pollution from fireplaces and masonry heaters. An example of an important pollutant group to investigate would be polycyclic aromatic hydrocarbons (PAH). This group contains some of the known carcinogens that are produced during residential biomass combustion.

Alternative fuels should be evaluated in fireplaces as potential mitigation measures for the installed base of conventional fireplaces. Compressed logs appear to have promise and they should be evaluated in some of the homes used in the current project.

Promising fireplace designs should be identified and evaluated in homes. Two such designs should include a Rosin and a Rumford[i], both of which have been built strictly following the original designs. Development of improved Rosin and masonry heater technologies should be pursued.

A seminar should be developed to convey to the designers of fireplaces and masonry heaters the results of this project. Also, techniques for measuring emissions by individual fireplace designers at their locations should be taught, and a list of suitable test equipment should be provided. Principles of fireplace and masonry heater design should additionally be conveyed to the participants.

[i] While the commercial Rosins tested in this project are rather close to Professor Rosin's original design, they differ significantly in the lentil area. A true Rumford as designed by Count Rumford is very different from the modified Rumford tested in this project.

# References


1. Barnett, S. G.; Field Performance of Advanced Technology Woodstove in Glens Falls, New York 1988-1989, Final Report, prepared for New York State Energy Research and Development Authority, U.S. Environmental Protection Agency, CONEG Policy Research Center, Inc., Canadian Combustion Research Laboratory, and Wood Heating Alliance, December 1989.

2. Dernbach, S.; Woodstove Field Performance in Klamath Falls, Oregon, prepared for the Wood Heating Alliance, April 18, 1990.

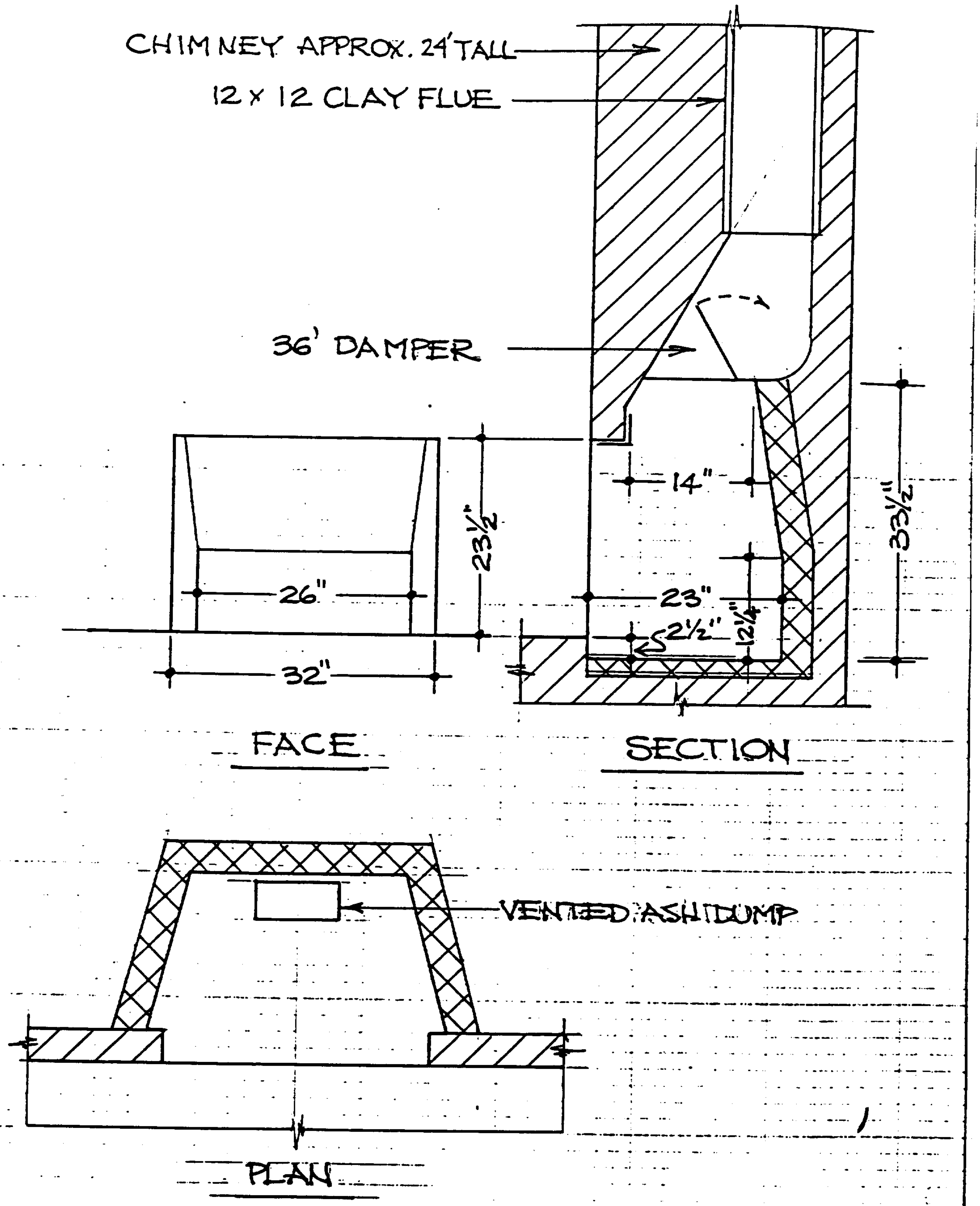
3. Barnett, S. G.; In-Home Evaluation of Emission Characteristics of EPA-Certified High Technology Non-Catalytic Woodstoves in Klamath Falls, Oregon, 1990.

4. McCrillis, Robert C. and Dennis R. Jaasma; Comparability Between Various Field and Laboratory Woodstove Emission Measurement Methods, for presentation at 84th Annual Meeting & Exhibition of Air & Waste Management Association, Vancouver, British Columbia, June 16-21, 1991.

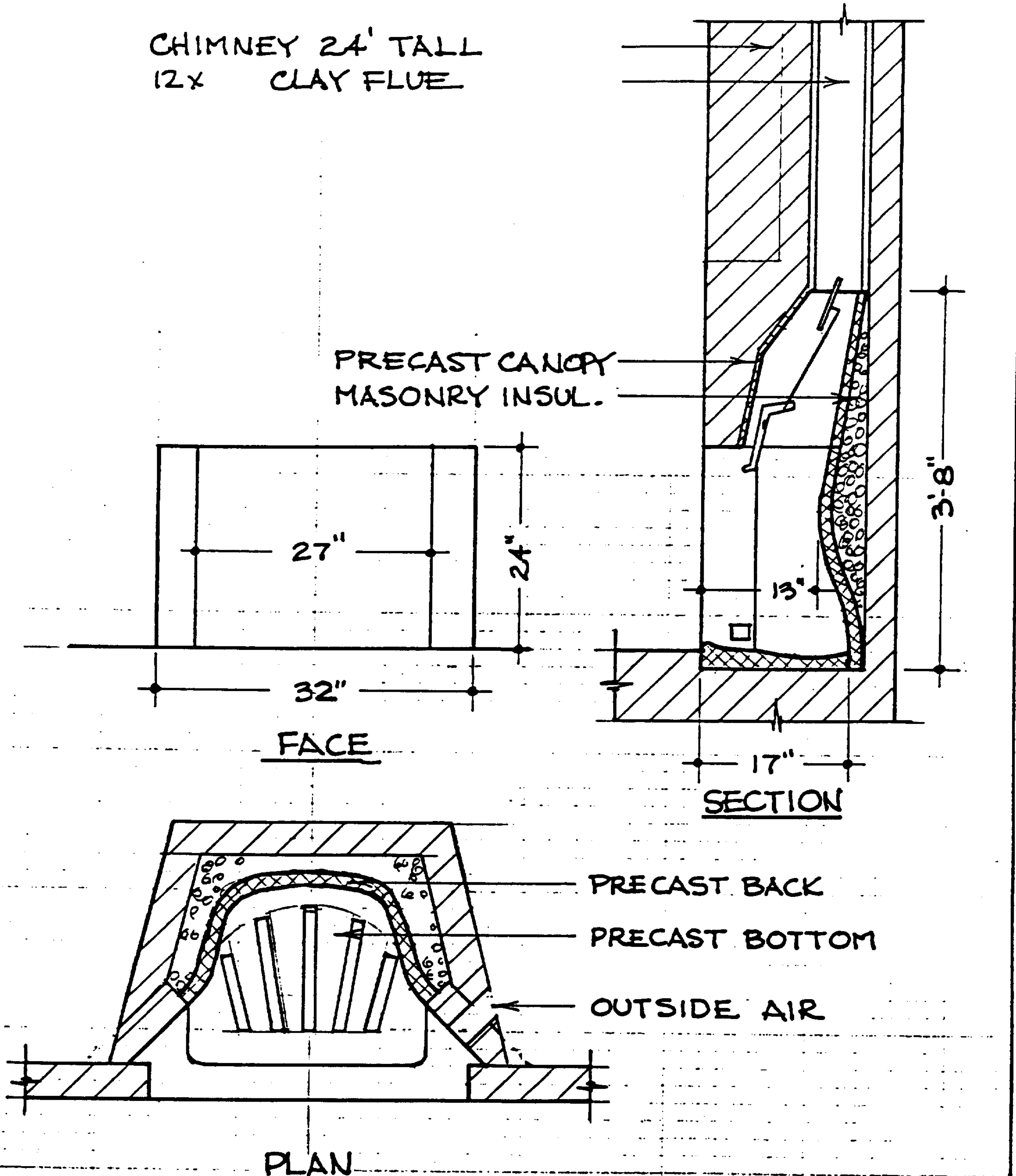
5. Barnett, S. G. and Paula G. Fields; In-Home Performance of Exempt Pellet Stoves in Medford, Oregon, prepared for U.S. Department of Energy, Oregon Department of Energy, Tennessee Valley Authority, and Oregon Department of Environmental Quality, July 1991.

# Appendix A

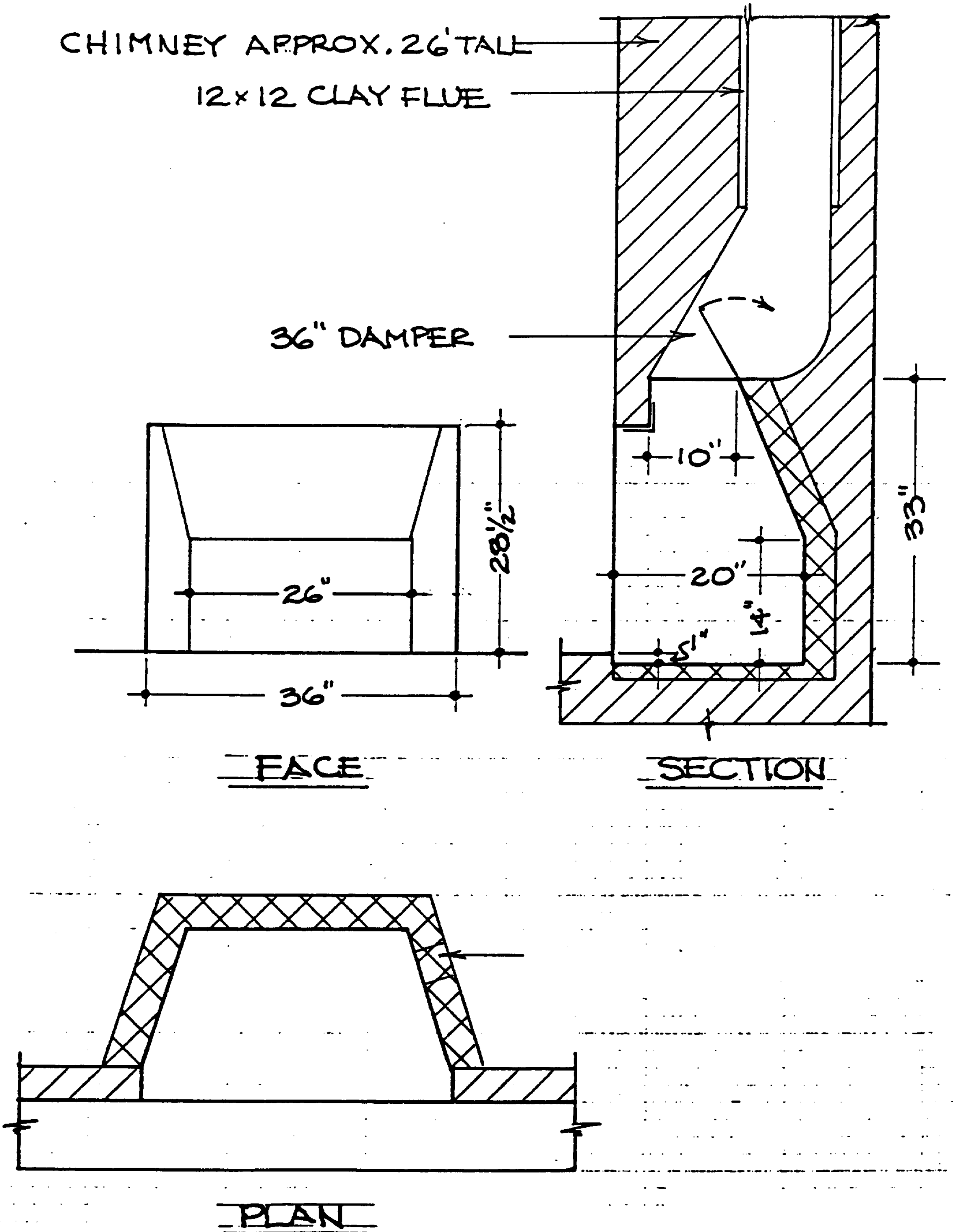
## Diagrams of Fireplaces and Masonry Heaters



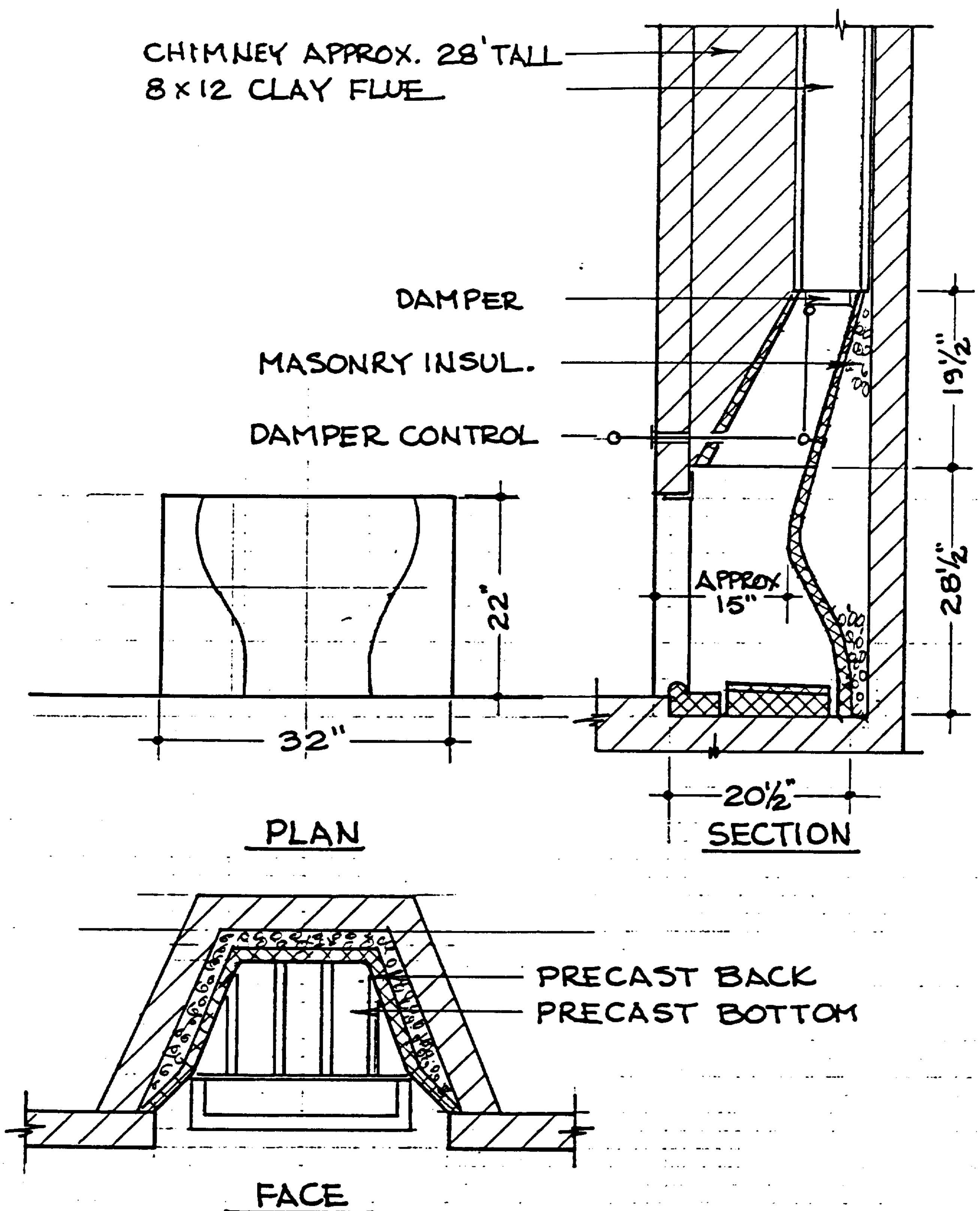

Zagelow, Conventional, Vancouver, Washington



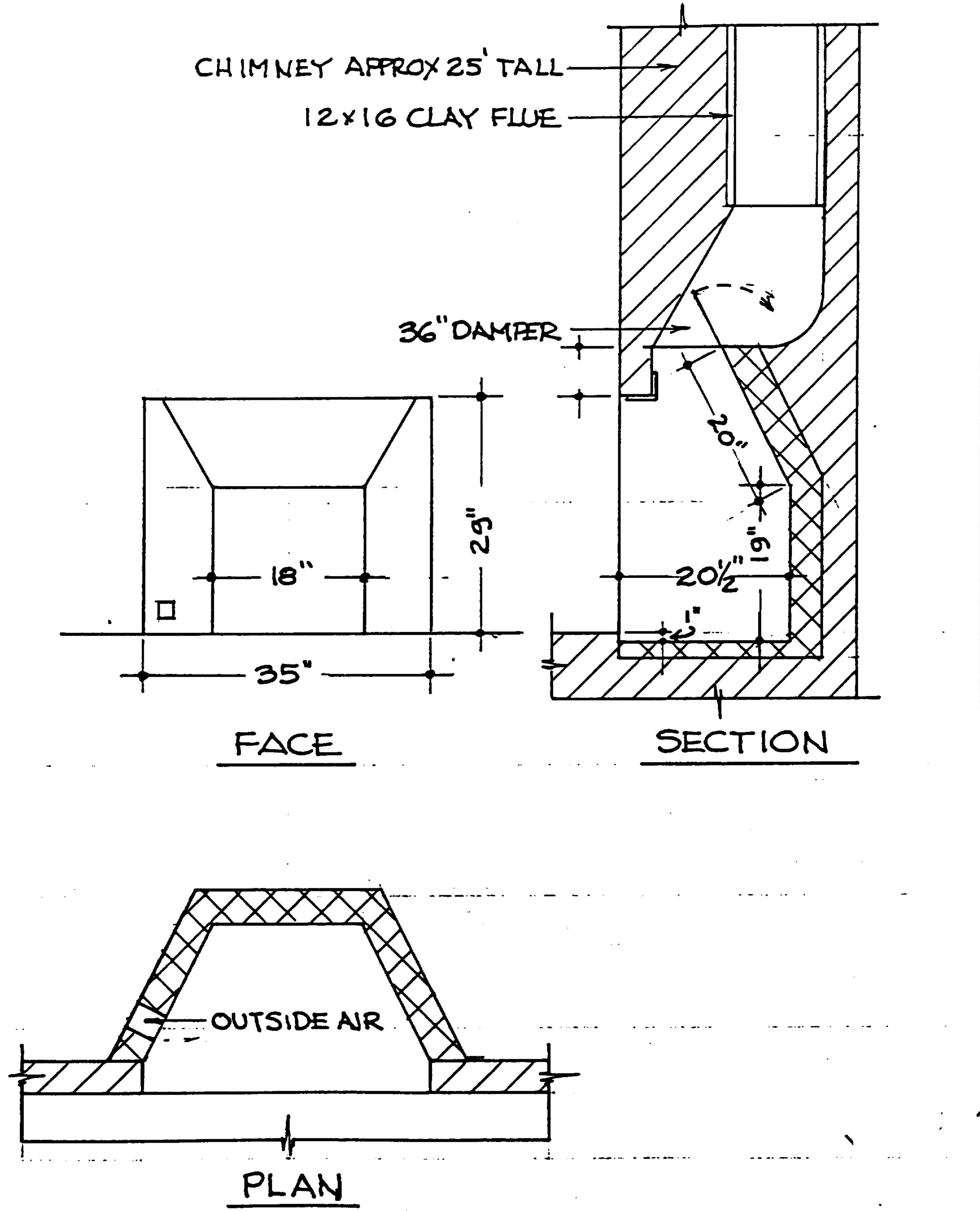

Zagelow, Firecrest Rosin Insert, Vancouver, Washington




F01, Conventional, Beaverton, Oregon

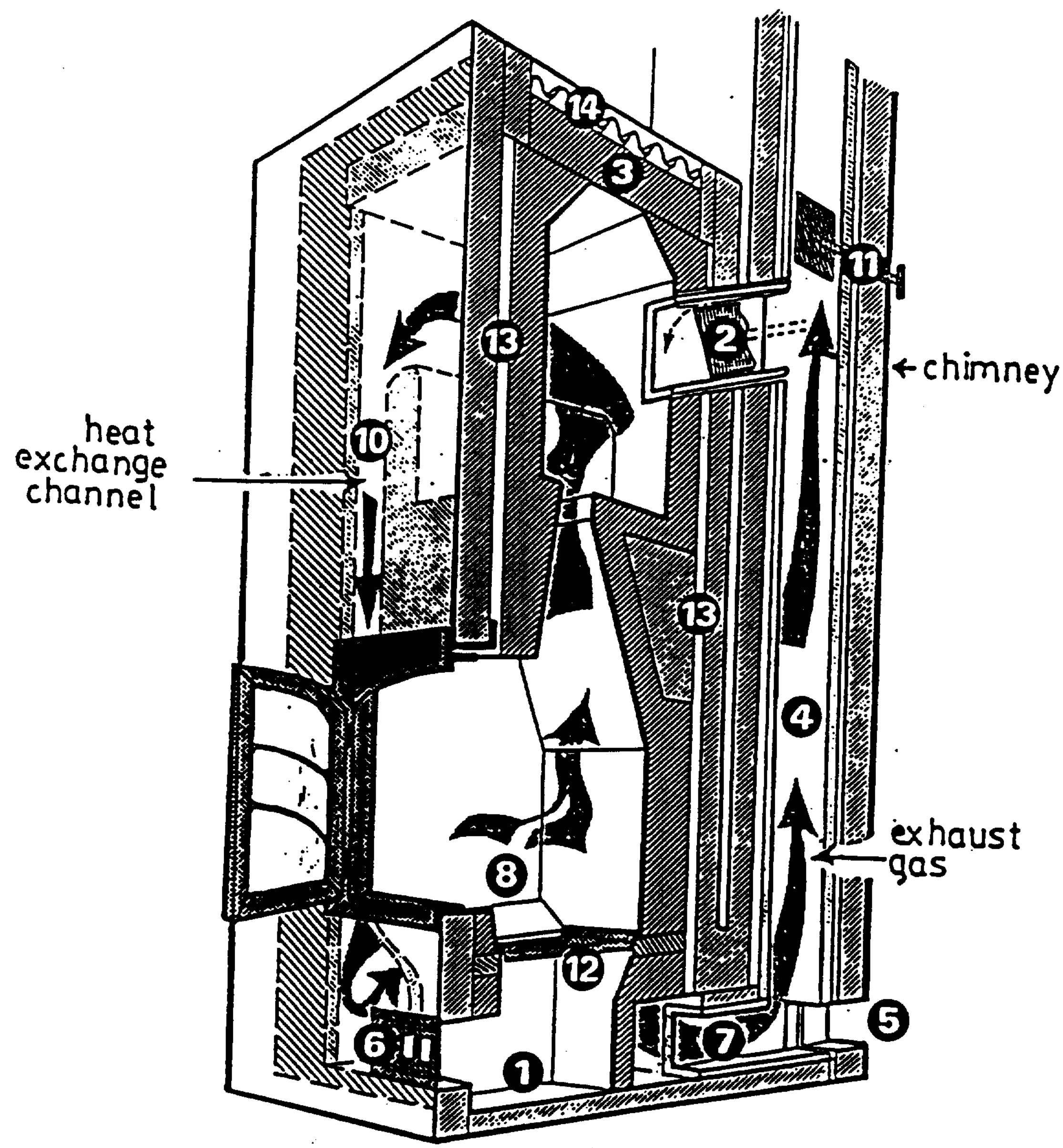



F03, Pedipas Rosin Original Equipment, Vancouver, WA



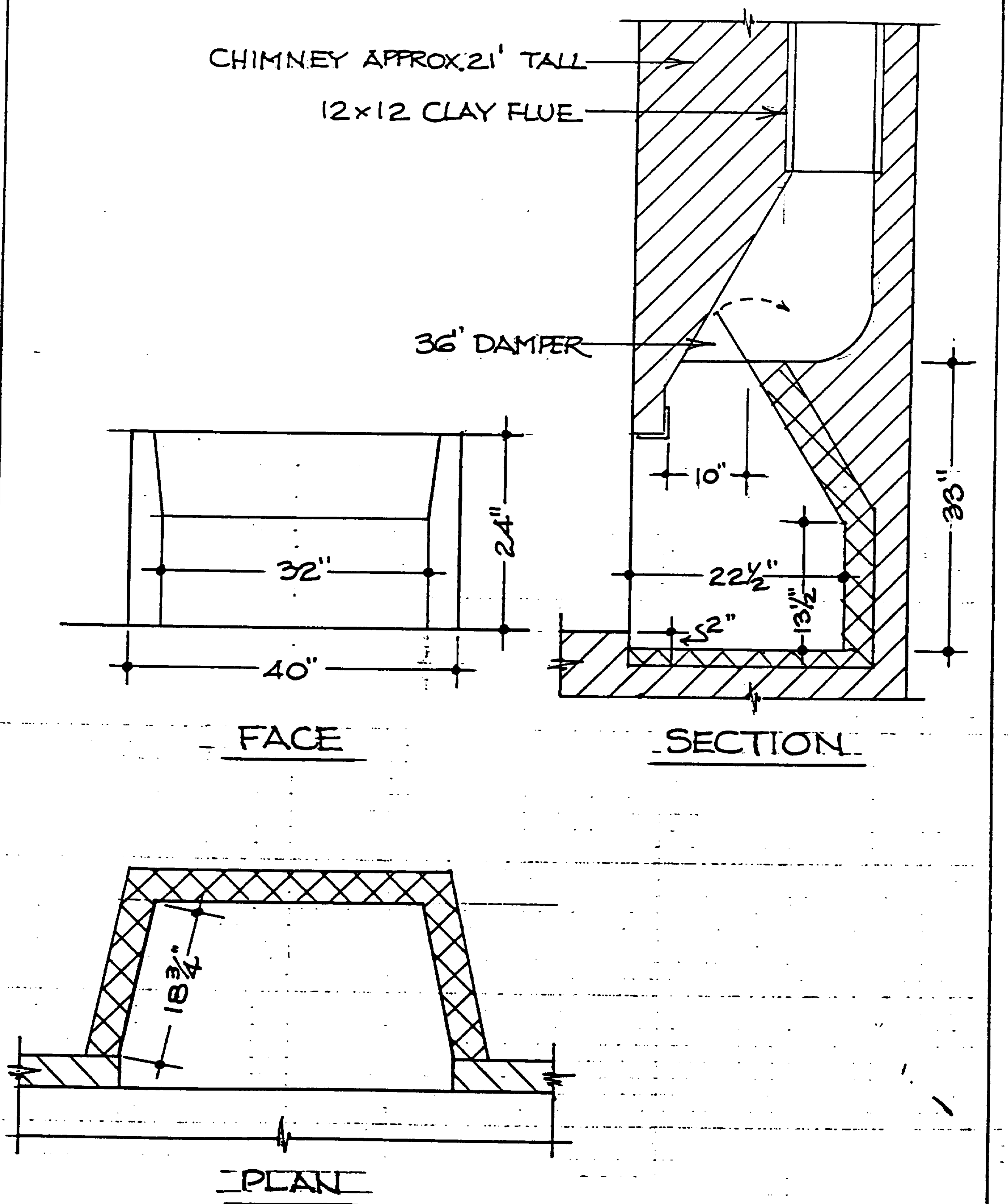

F04, "Modified Rumford", considered Conventional, Vancouver, WA

# Contraflow Masonry Heater
# (F05)

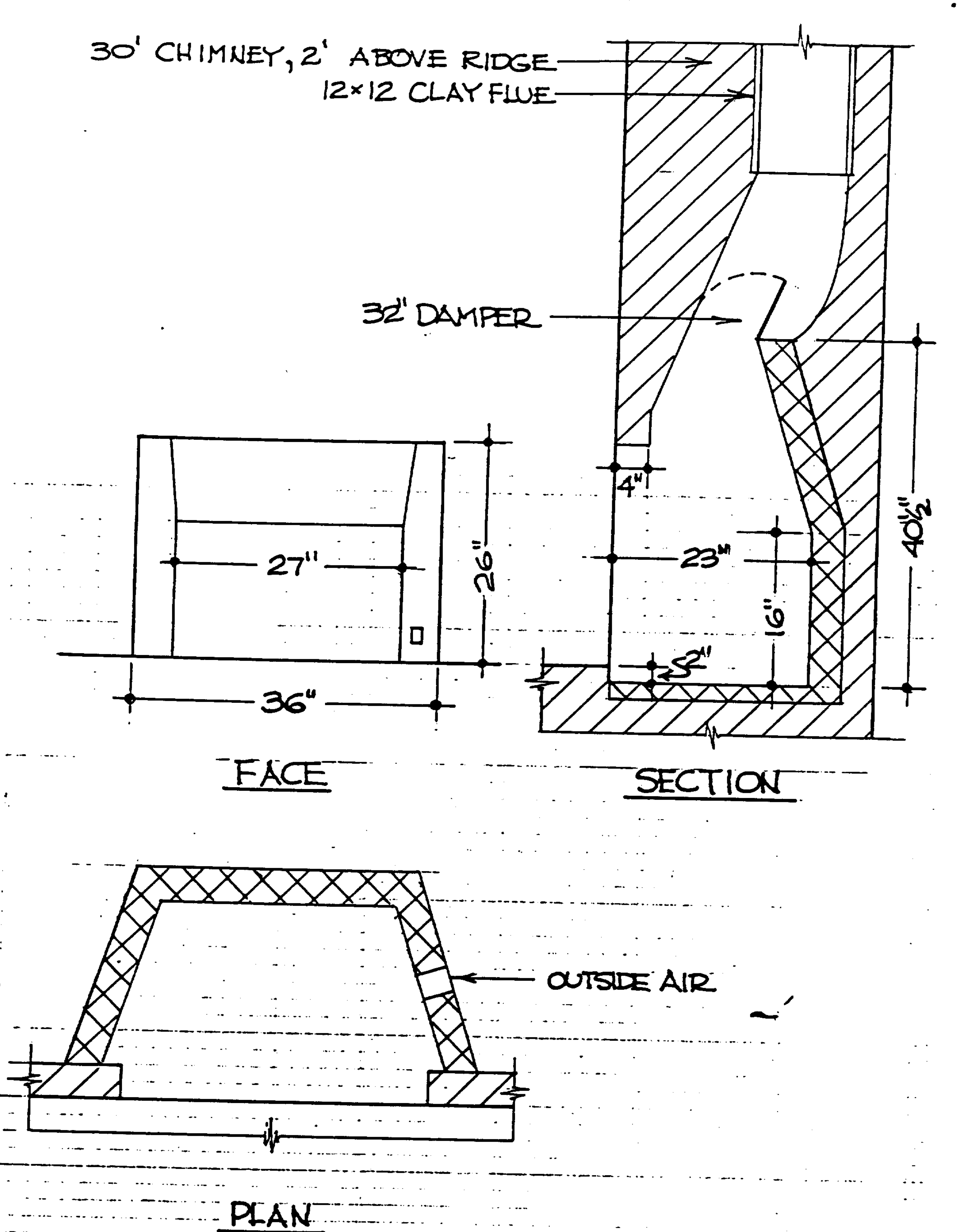



1. ASHBOX
2. BYPASS DAMPER
3. CAPPING SLAB
4. CHIMNEY
5. CLEAN-OUT
6. COMBUSTION AIR
7. EXHAUST GAS
8. FIREBOX
9. FIREBOX DOOR
10. HEAT EXCHANGE ARE
11. SHUT-OFF DAMPER
12. GRATE
13. EXPANSION JOINT
14. INSULATION

HEAT-KIT$^{tm}$ gas flow




F06, Conventional, Beaverton, Oregon




F07, Conventional, Government Camp, Oregon

# Appendix B

## Photos of the Fireplaces and Masonry Heaters

Figure B-1. Conventional fireplace in Zagelow residence.

Figure B-2. The Zagelow residence.

Figure B-3. Firecrest Rosin inserted into Zagelow fireplace.

Figure B-4. Conventional fireplace with AWES equipment in F01 residence.

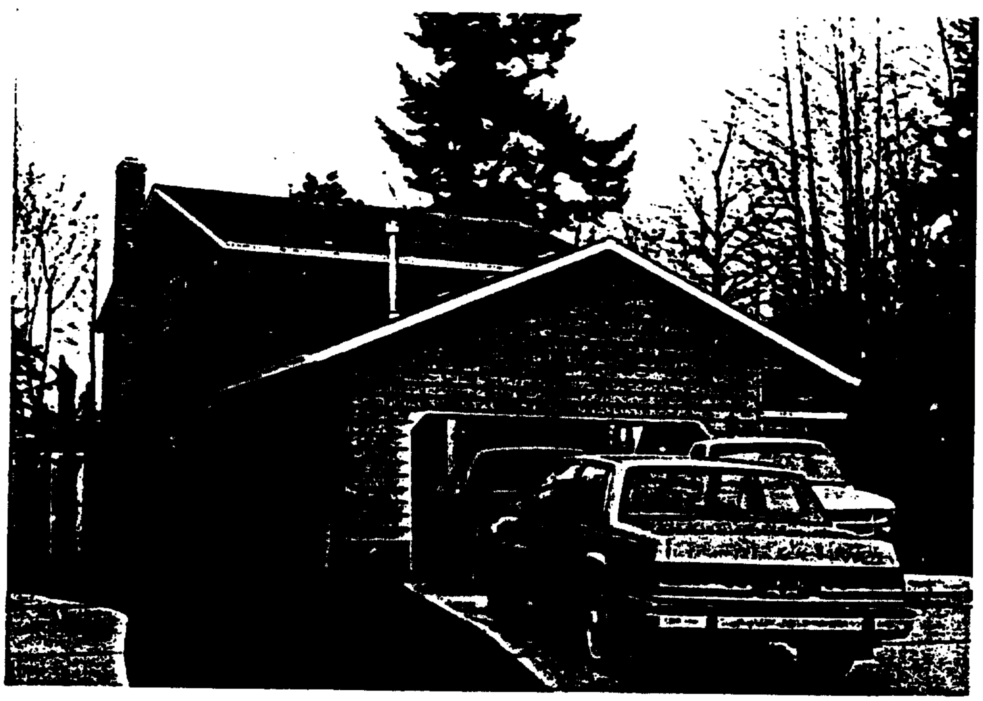


Figure B-5. The F01 residence.

Figure B-6. The Russian heater and AWES equipment in the F02 residence.

Figure B-7. The F02 residence.

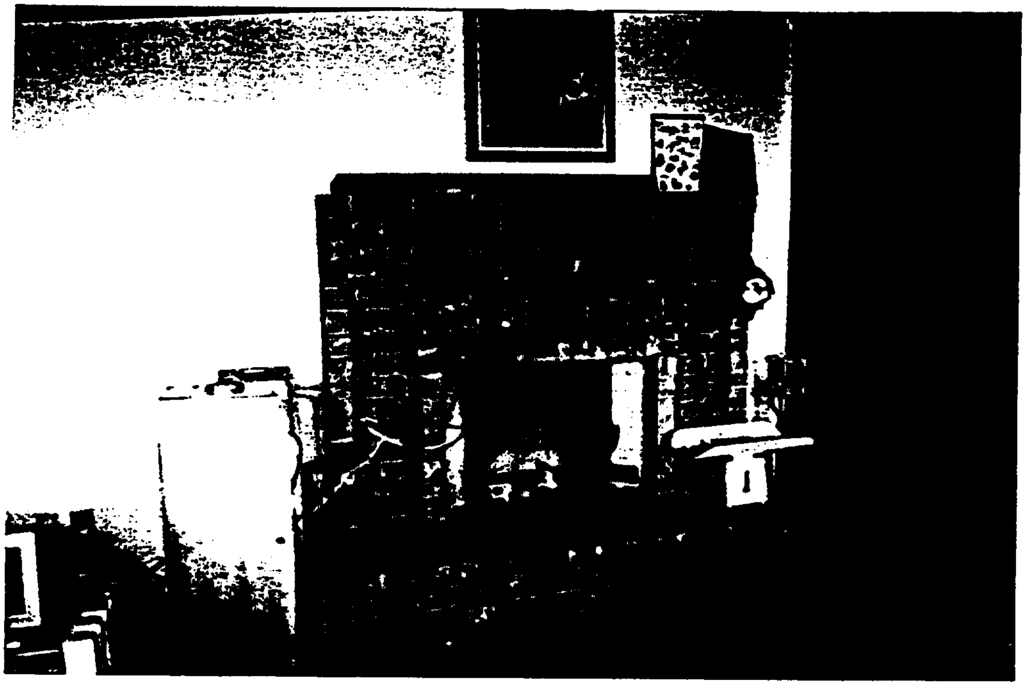


Figure B-8. The Rosin fireplace in the F03 residence.

Figure B-9. The F03 residence.

Figure B-10. Wood oriented in the F03 Rosin for the first test, F0301.

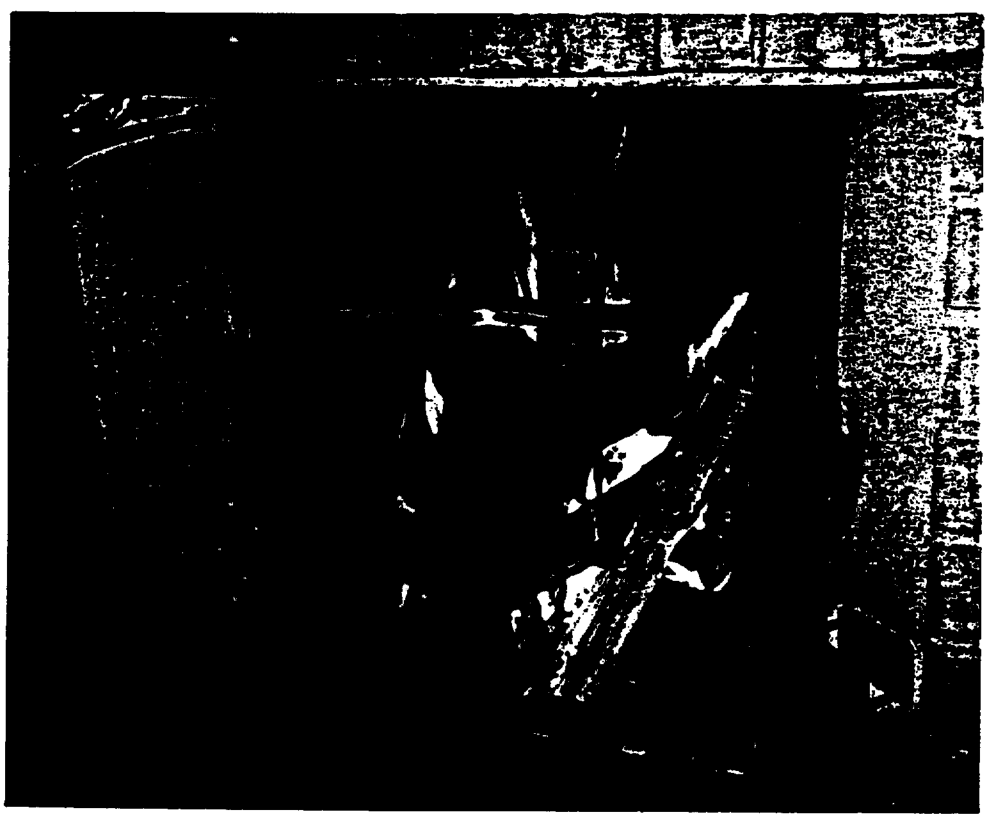


Figure B-11. Wood oriented in the F03 Rosin for the second test, F0302.

Figure B-12. The modified Rumford fireplace in the F04 residence.

Figure B-13. The F04 residence.

Figure B-14. The Contraflow masonry heater with AWES equipment in the F05 residence.

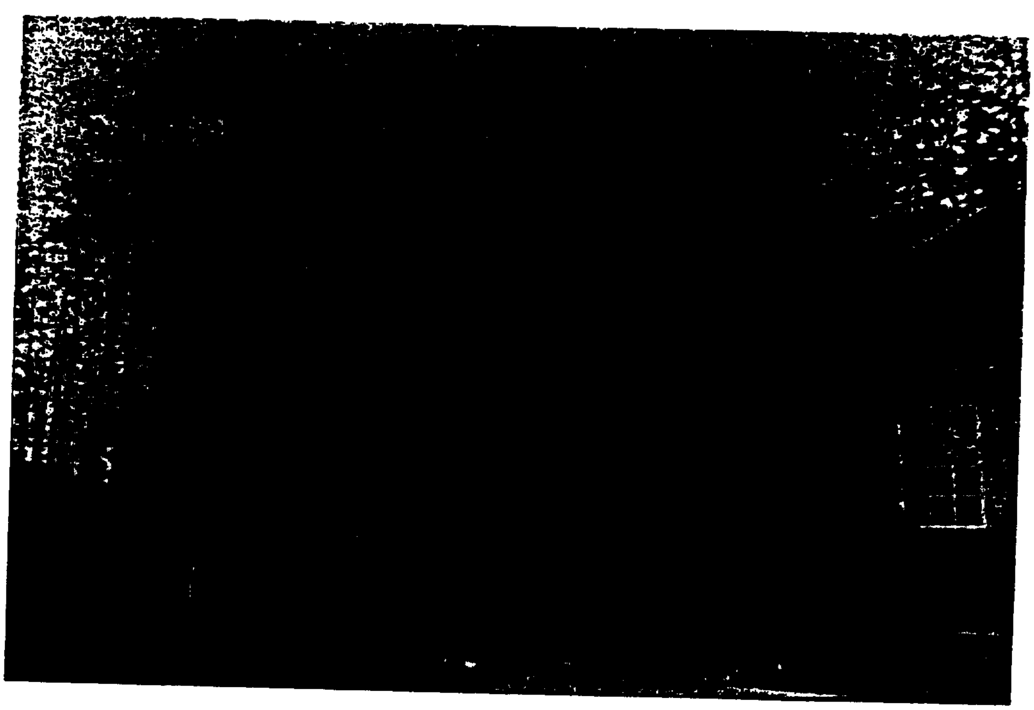


Figure B-15. The F05 residence.

Figure B-16. The conventional fireplace in the F06 residence.

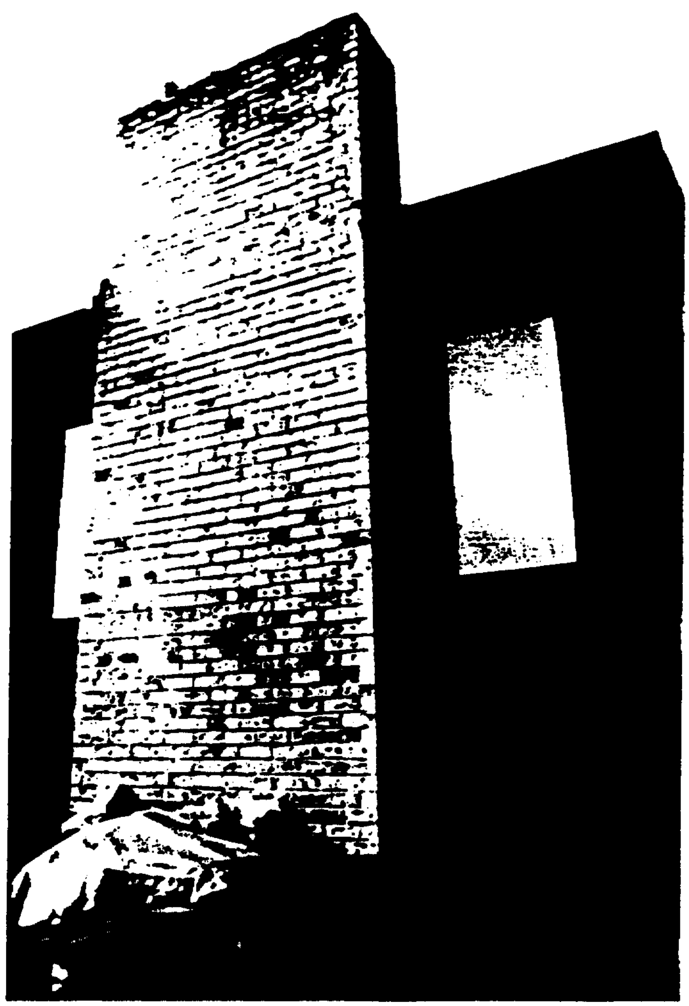


Figure B-17. The F06 residence.

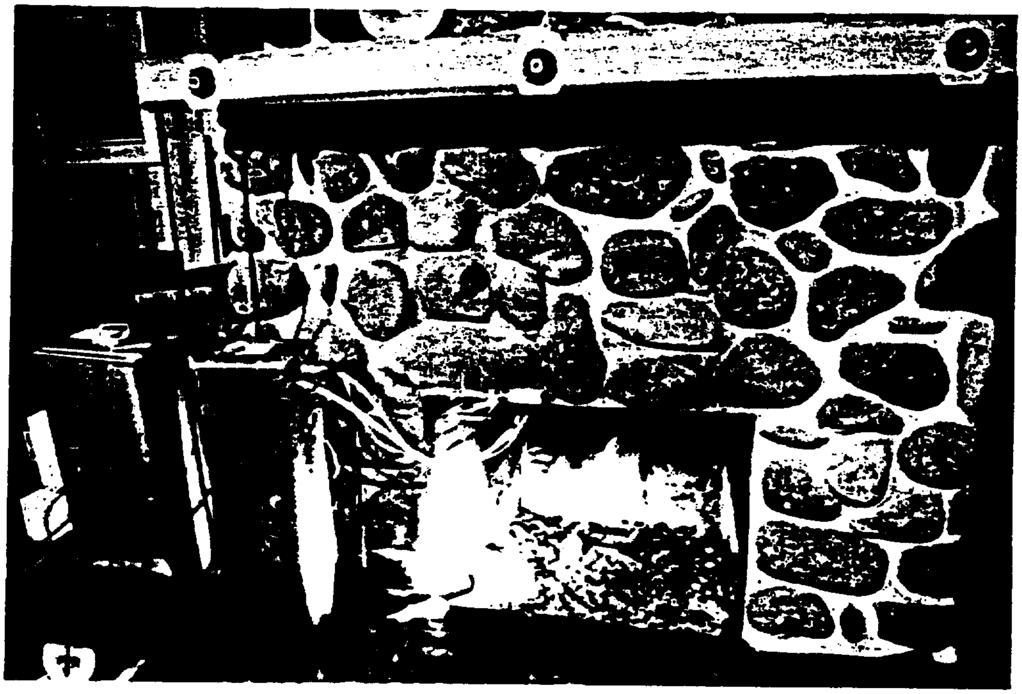


Figure B-18. The conventional fireplace and AWES equipment in the F07 residence.

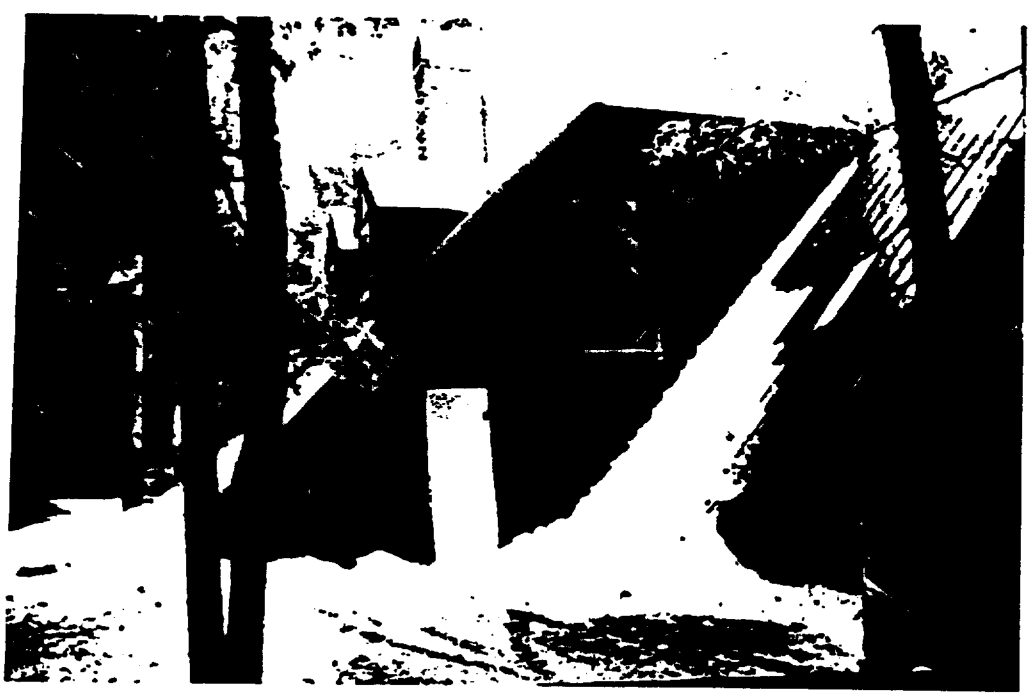
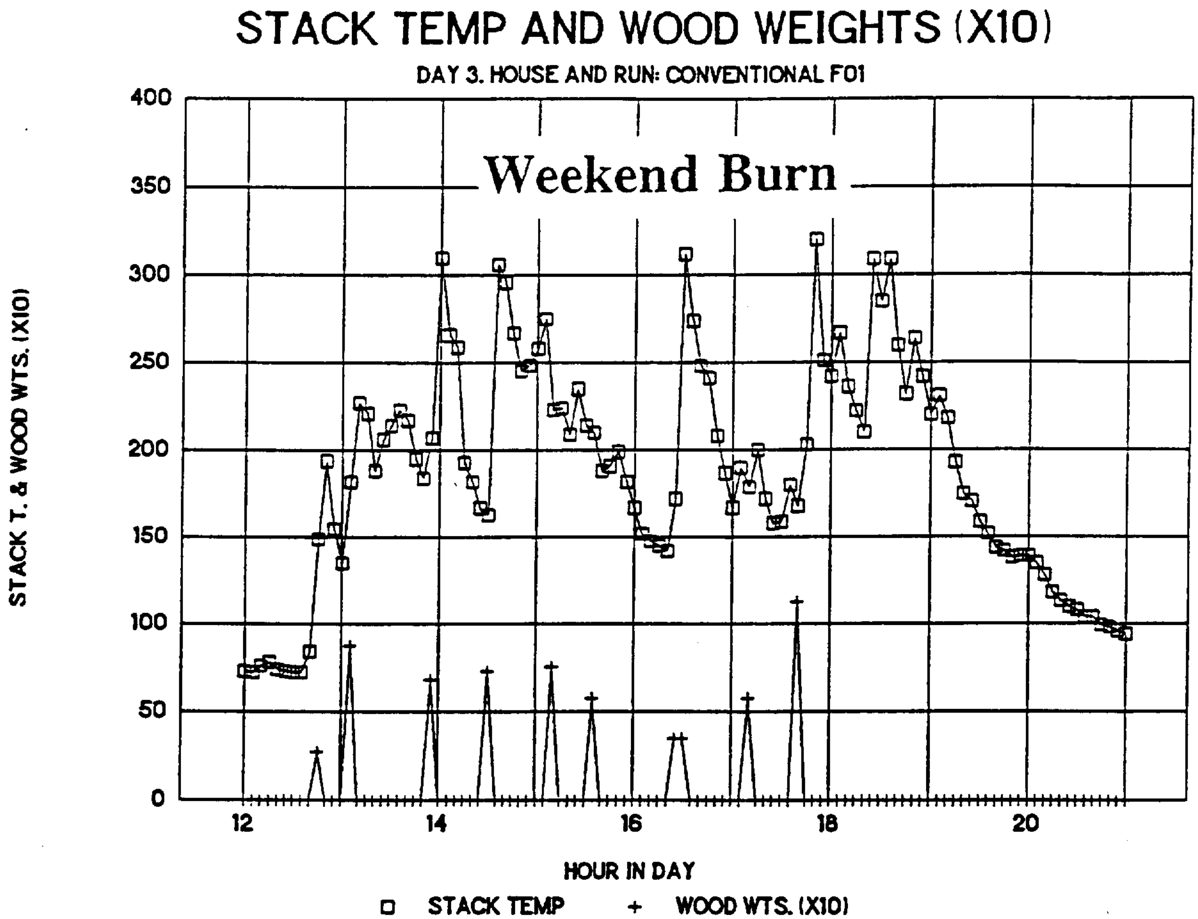


Figure B-19. The F07 residence.

# Appendix C

## Continuous Traces of Stack Temperatures and Wood Loadings



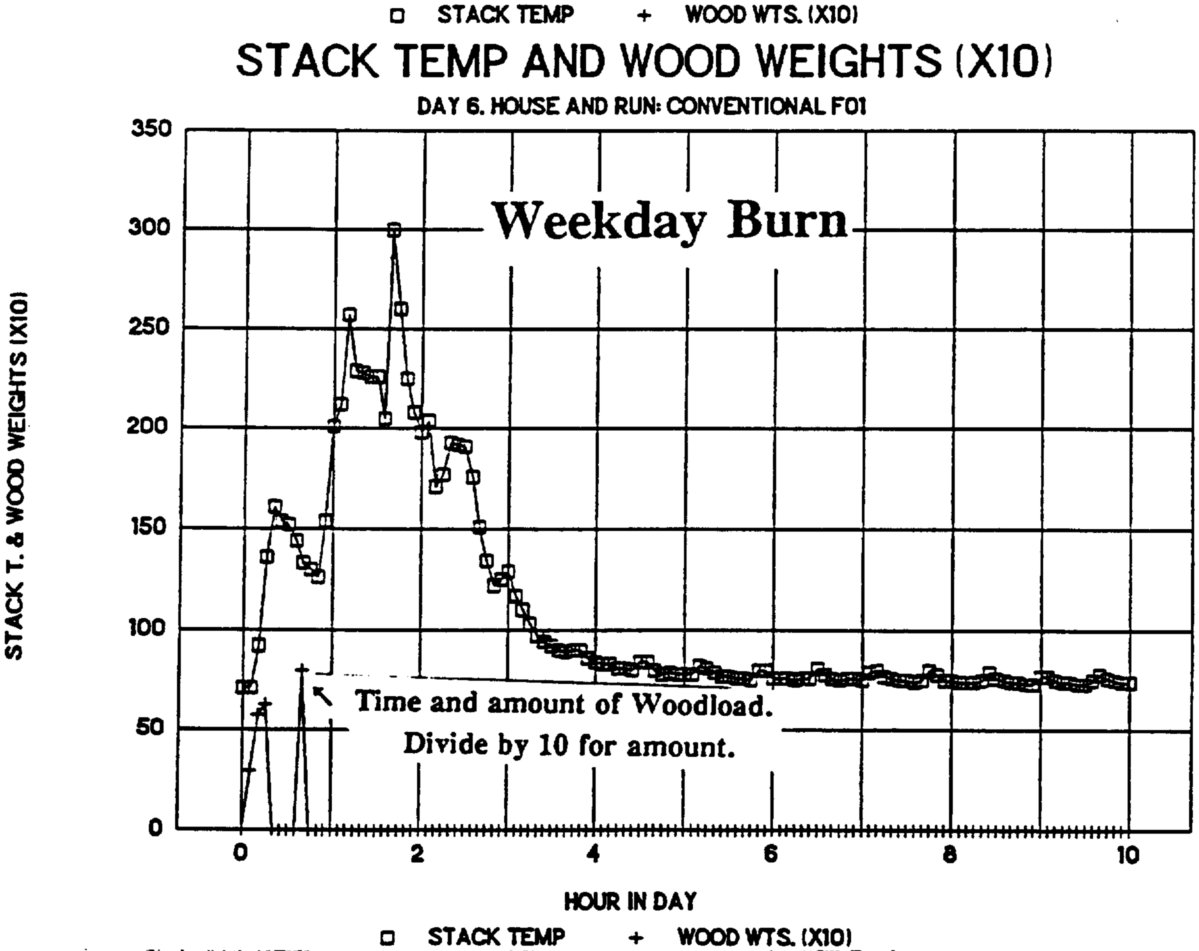
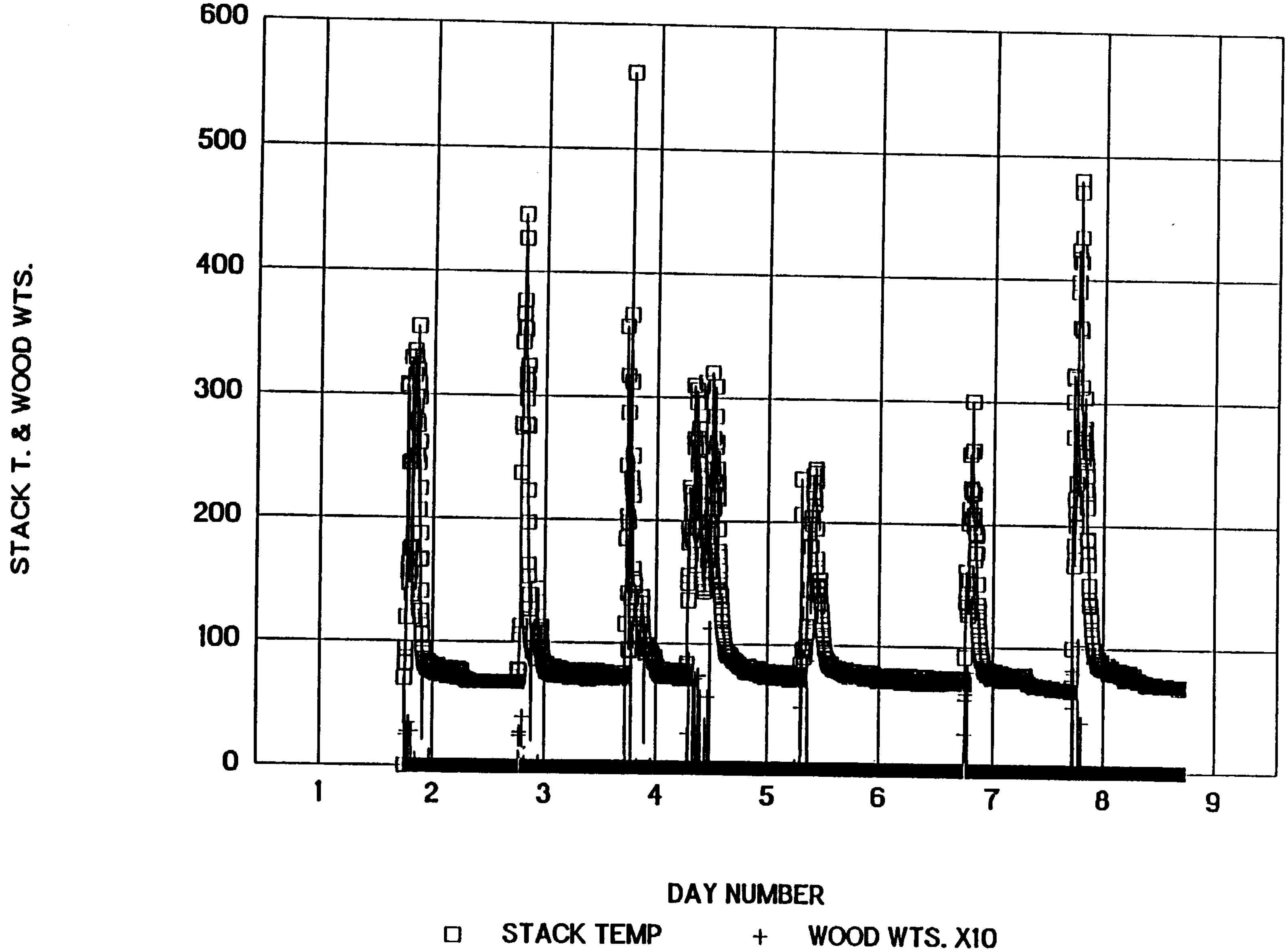




**Figure 1.** Example of stack temperature - wood weight diagram, These are details of a weekend and weekday burn in F01. Note timing relationship between stack temperature and wood loads.

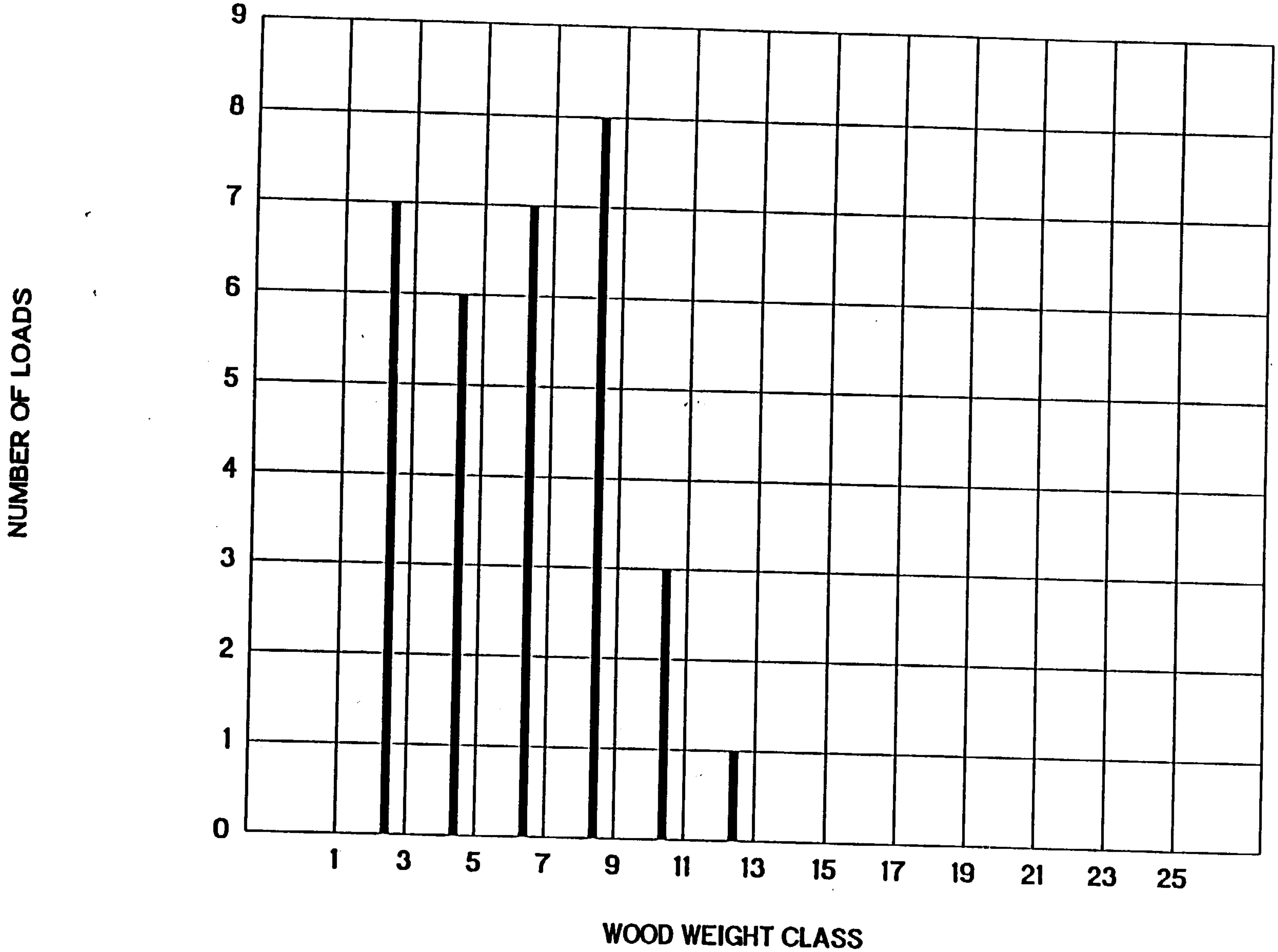
# STACK TEMP AND WOOD WEIGHTS

ALL 7 DAYS. CONVENTIONAL: F0101



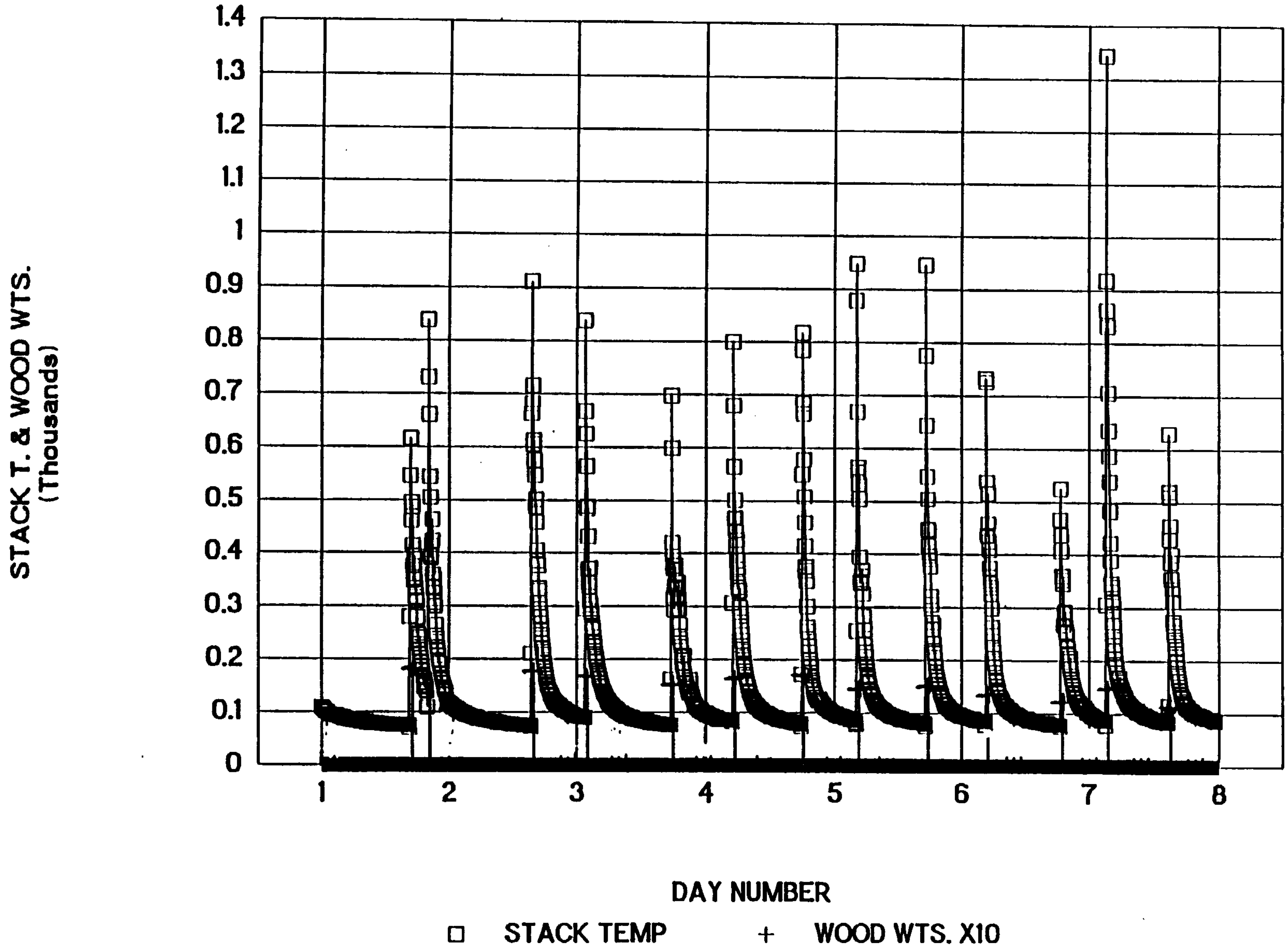
# HISTOGRAM OF WOOD LOADS

CONVENTIONAL: F0101



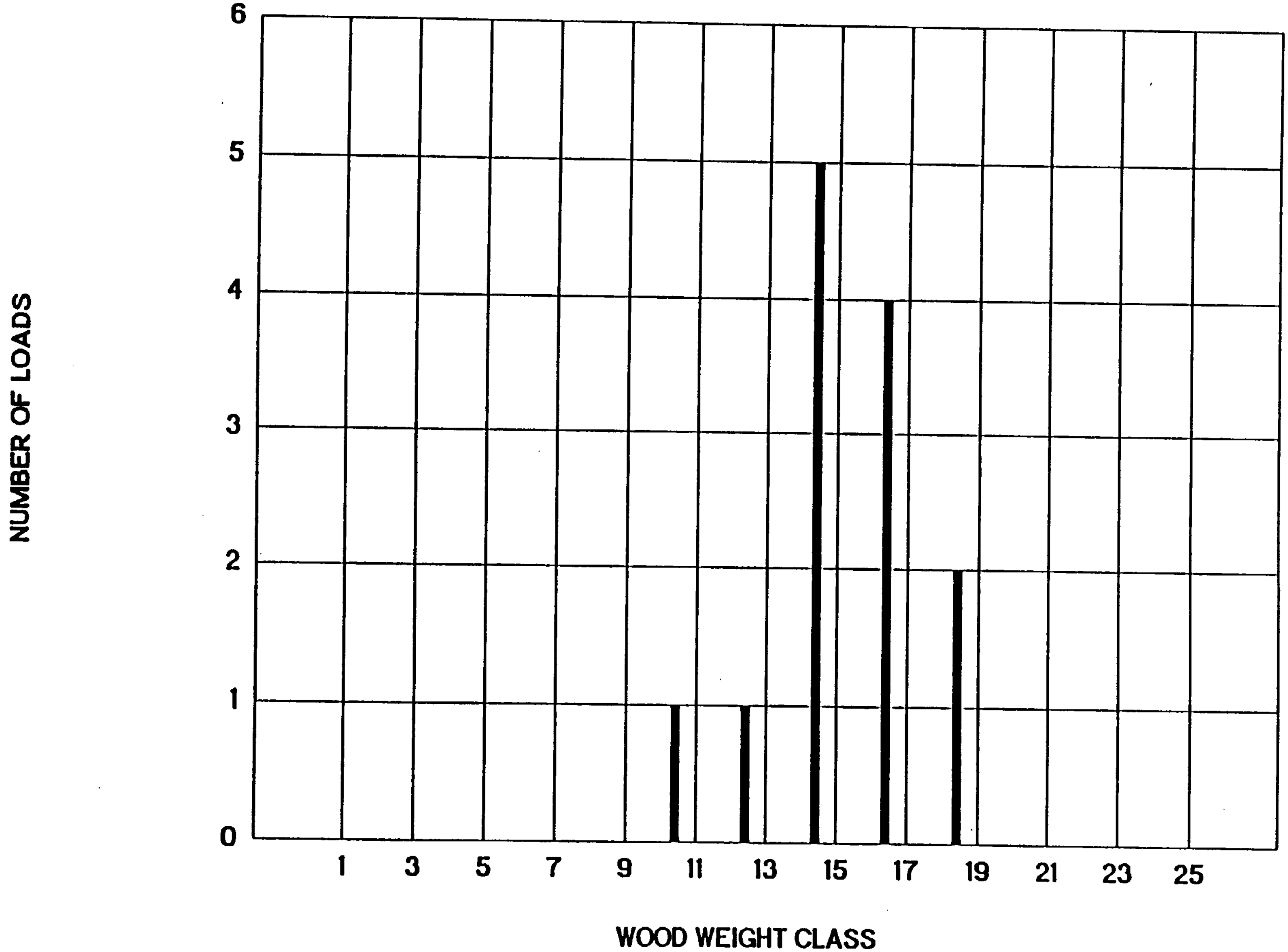
# STACK TEMP AND WOOD WEIGHTS

ALL 7 DAYS. RUSSIAN: F0201



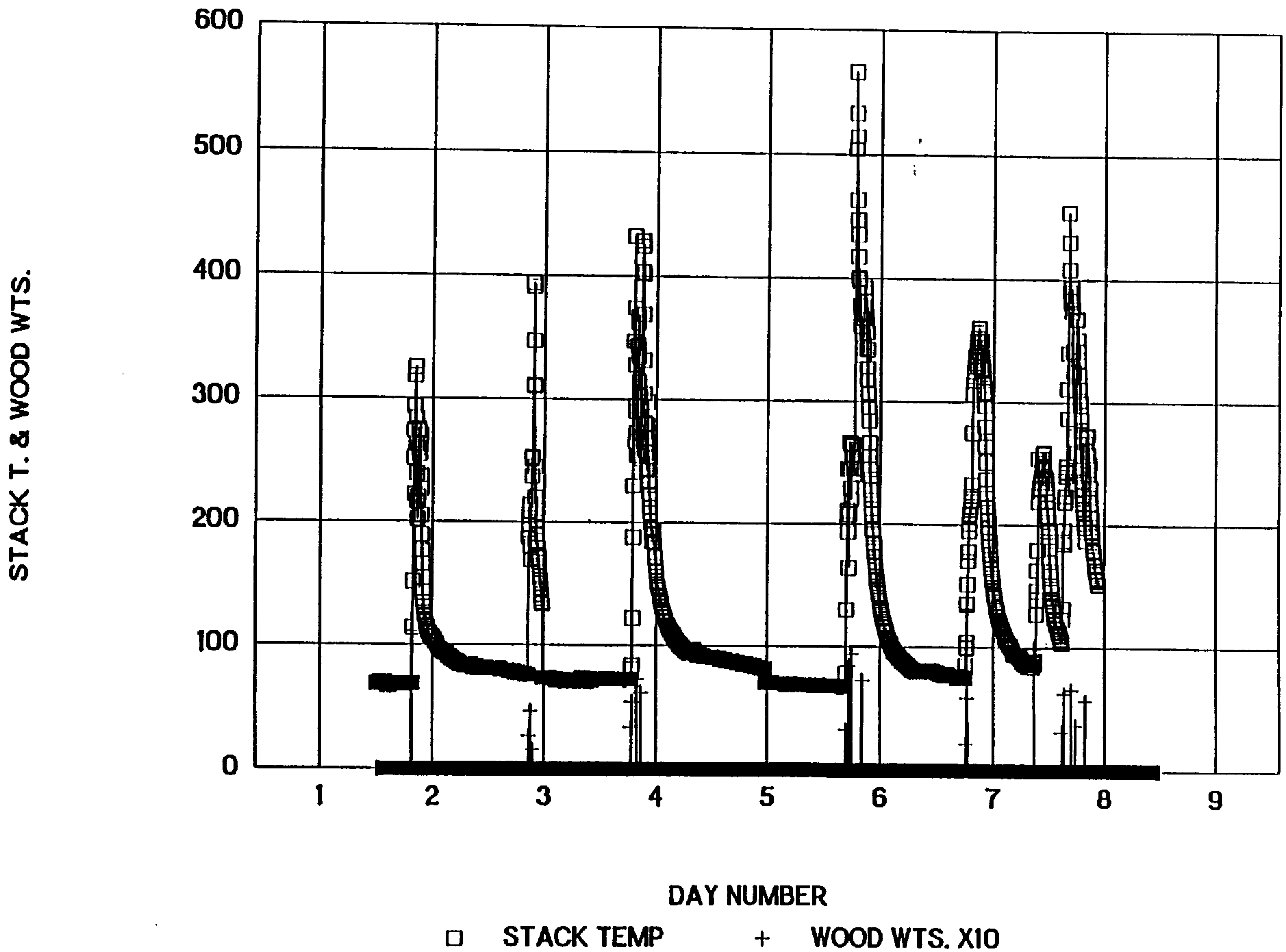
# HISTOGRAM OF WOOD LOADS

RUSSIAN: F0201



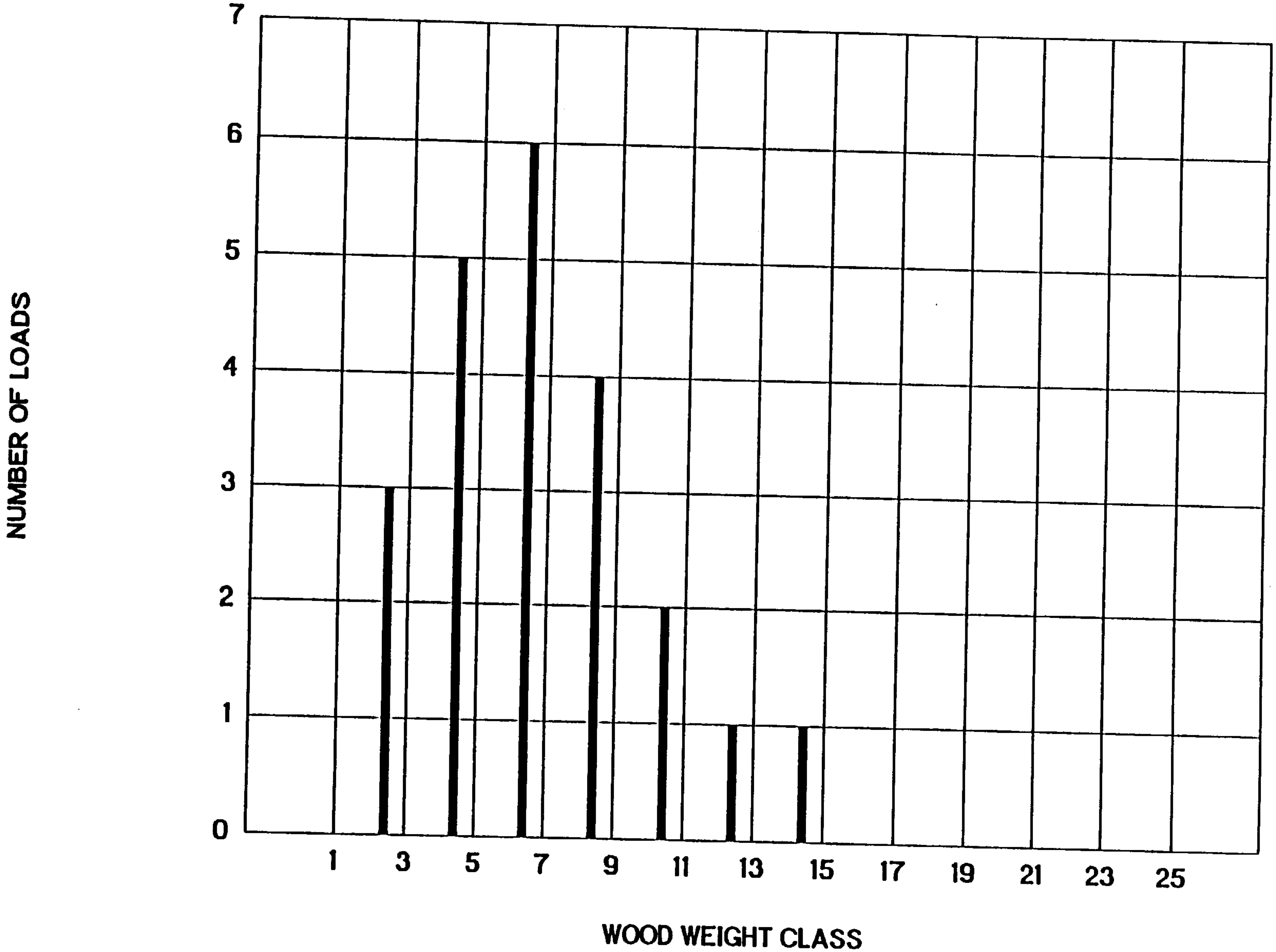
# STACK TEMP AND WOOD WEIGHTS

ALL 7 DAYS. ROSIN OEM: F0301



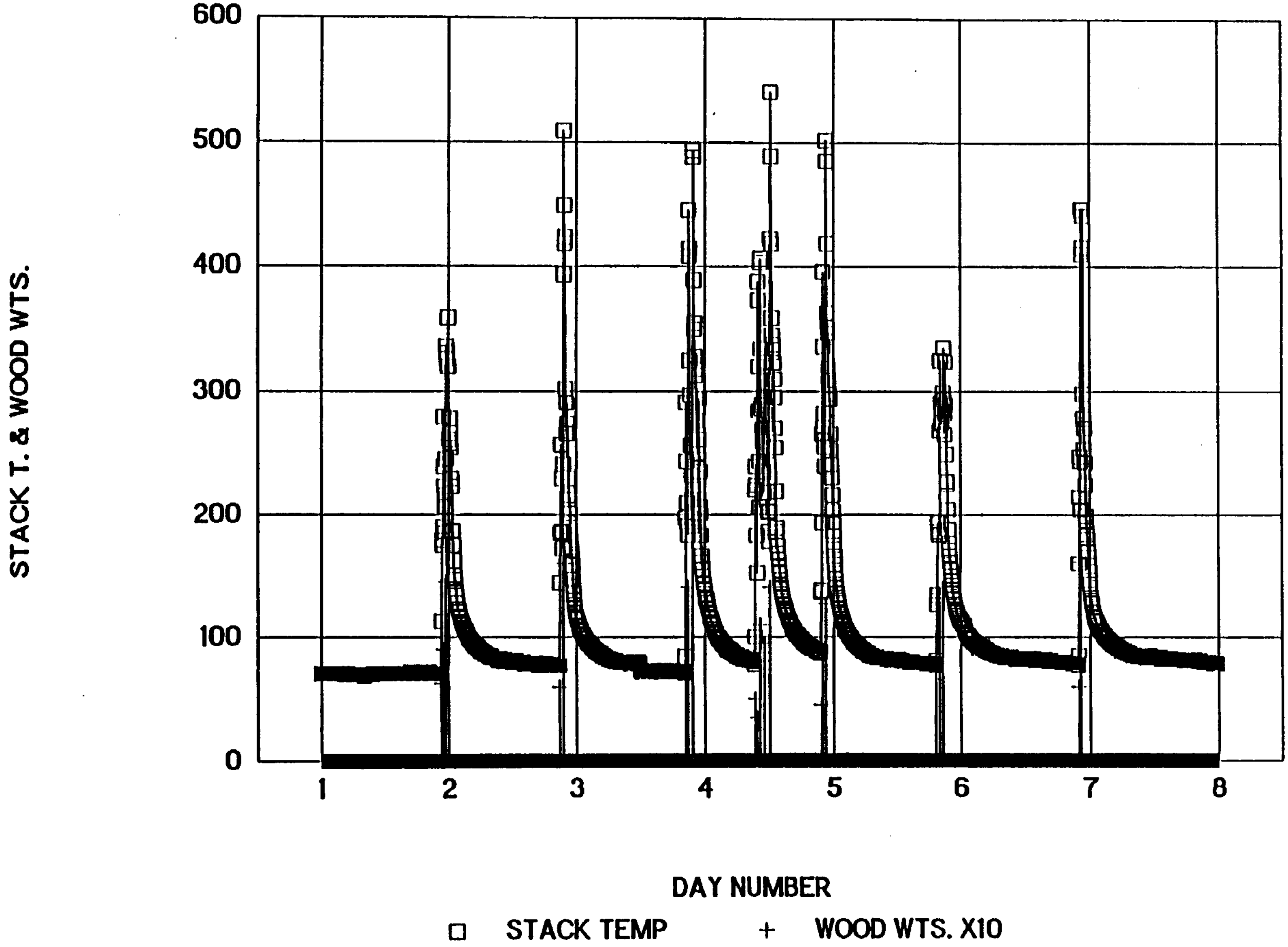
# HISTOGRAM OF WOOD LOADS

ROSIN OEM: F0301



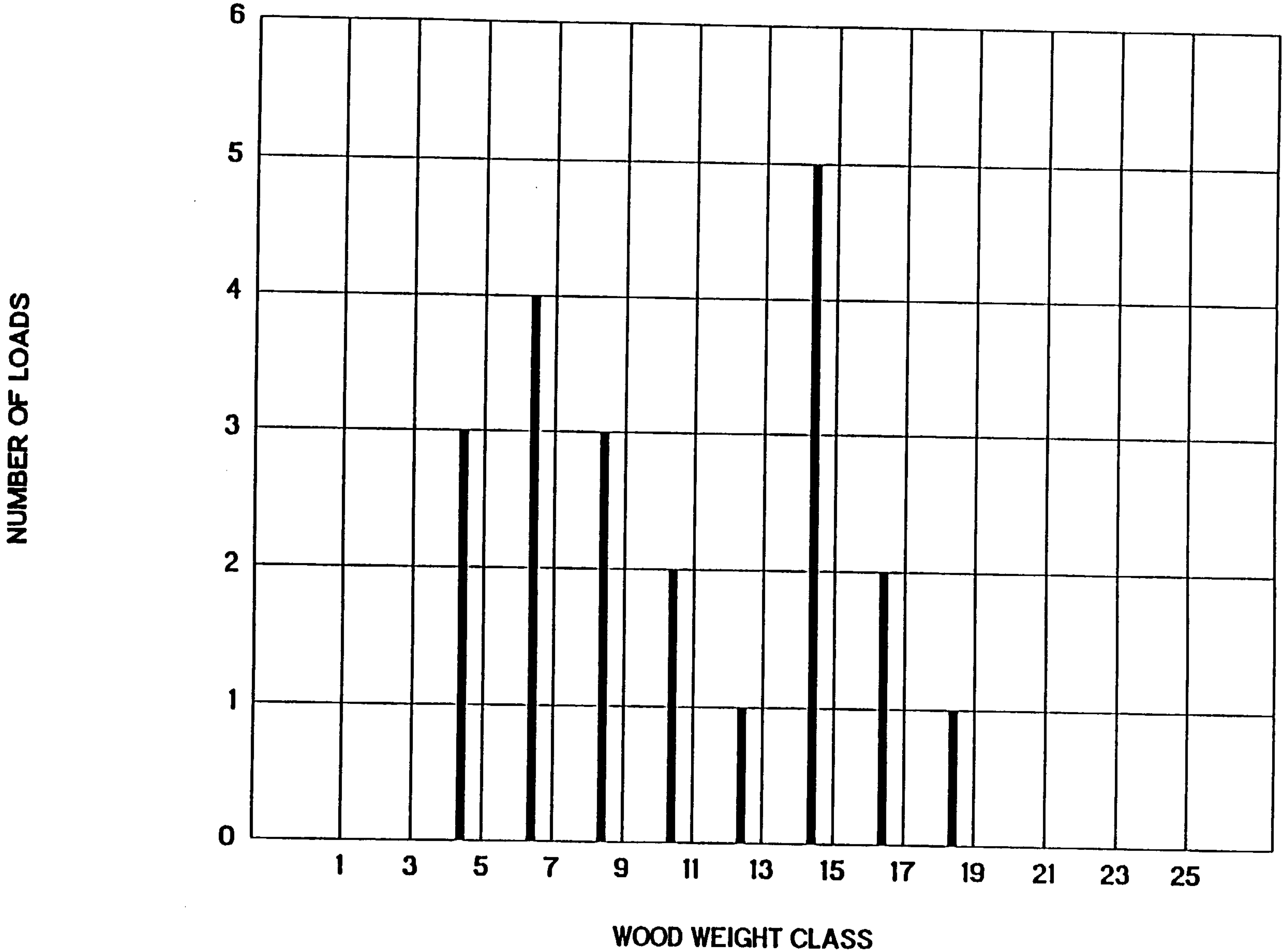
# STACK TEMP AND WOOD WEIGHTS

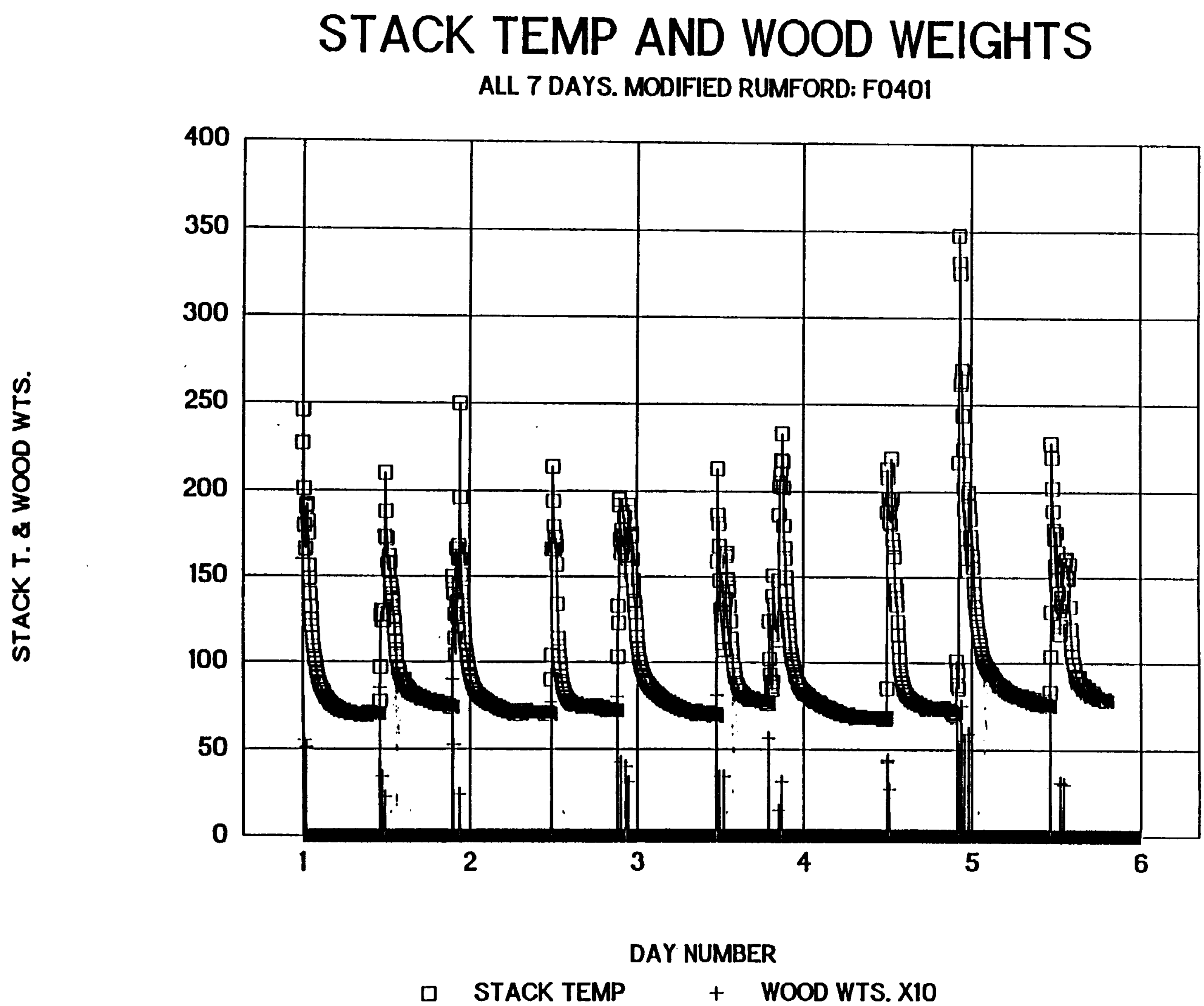
ALL 7 DAYS. ROSIN OEM: F0302



# HISTOGRAM OF WOOD LOADS

ROSIN OEM: F0302

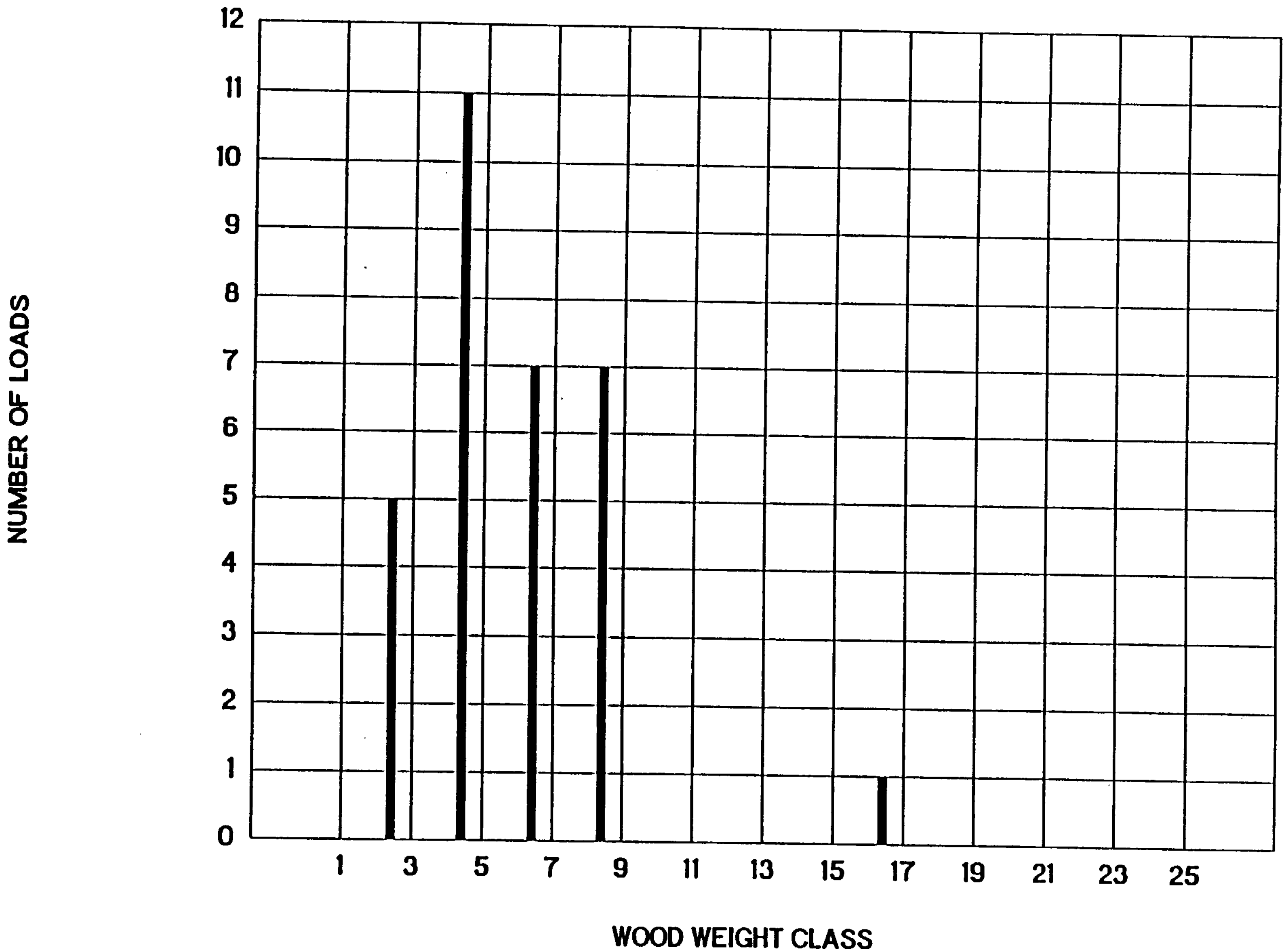


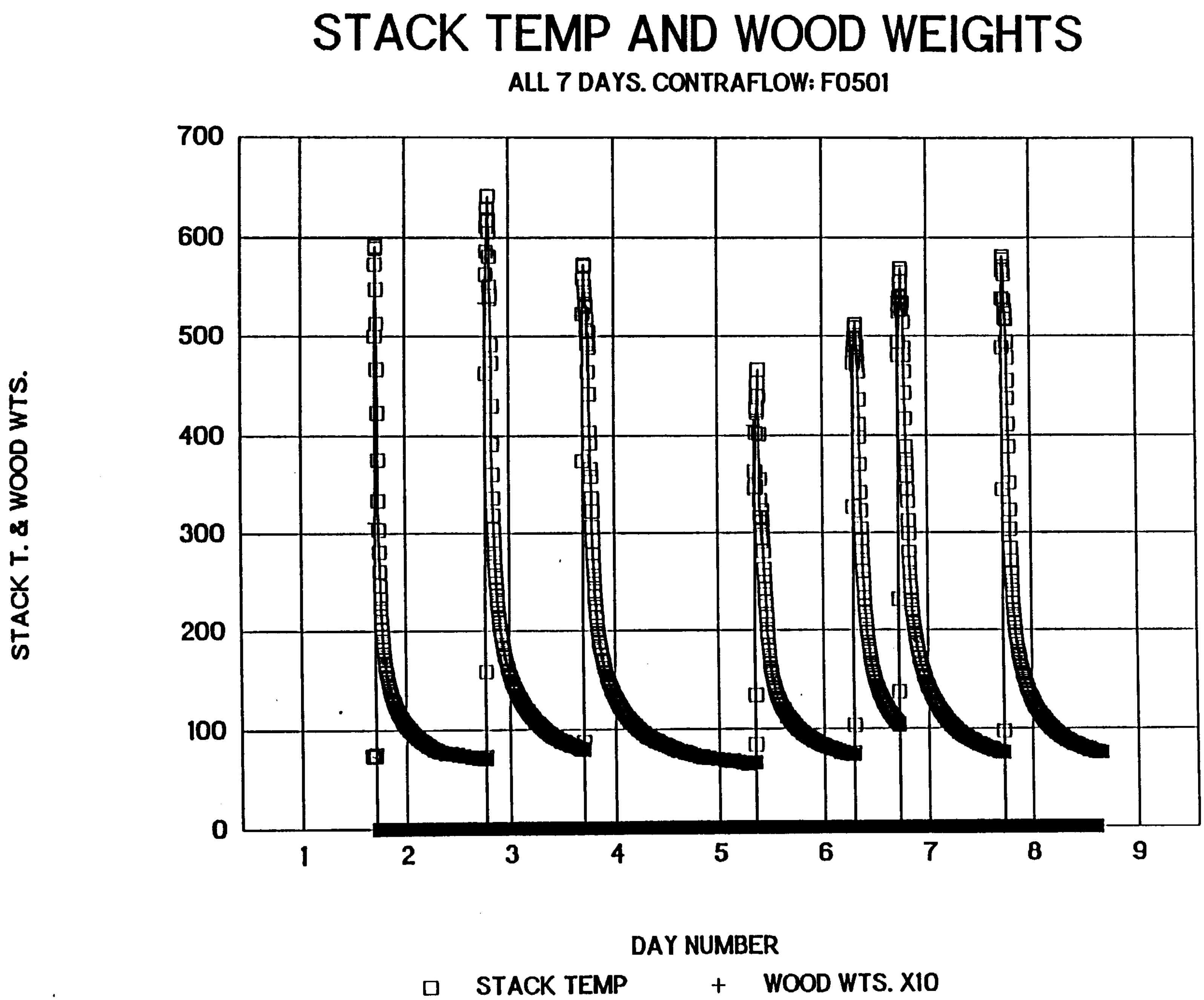


STACK TEMP AND WOOD WEIGHTS
ALL 7 DAYS. MODIFIED RUMFORD: F0401
STACK T. & WOOD WTS.
400
350
300
250
200
150
100
50
0
1
2
3
4
5
6
DAY NUMBER
STACK TEMP
WOOD WTS. X10

# HISTOGRAM OF WOOD LOADS

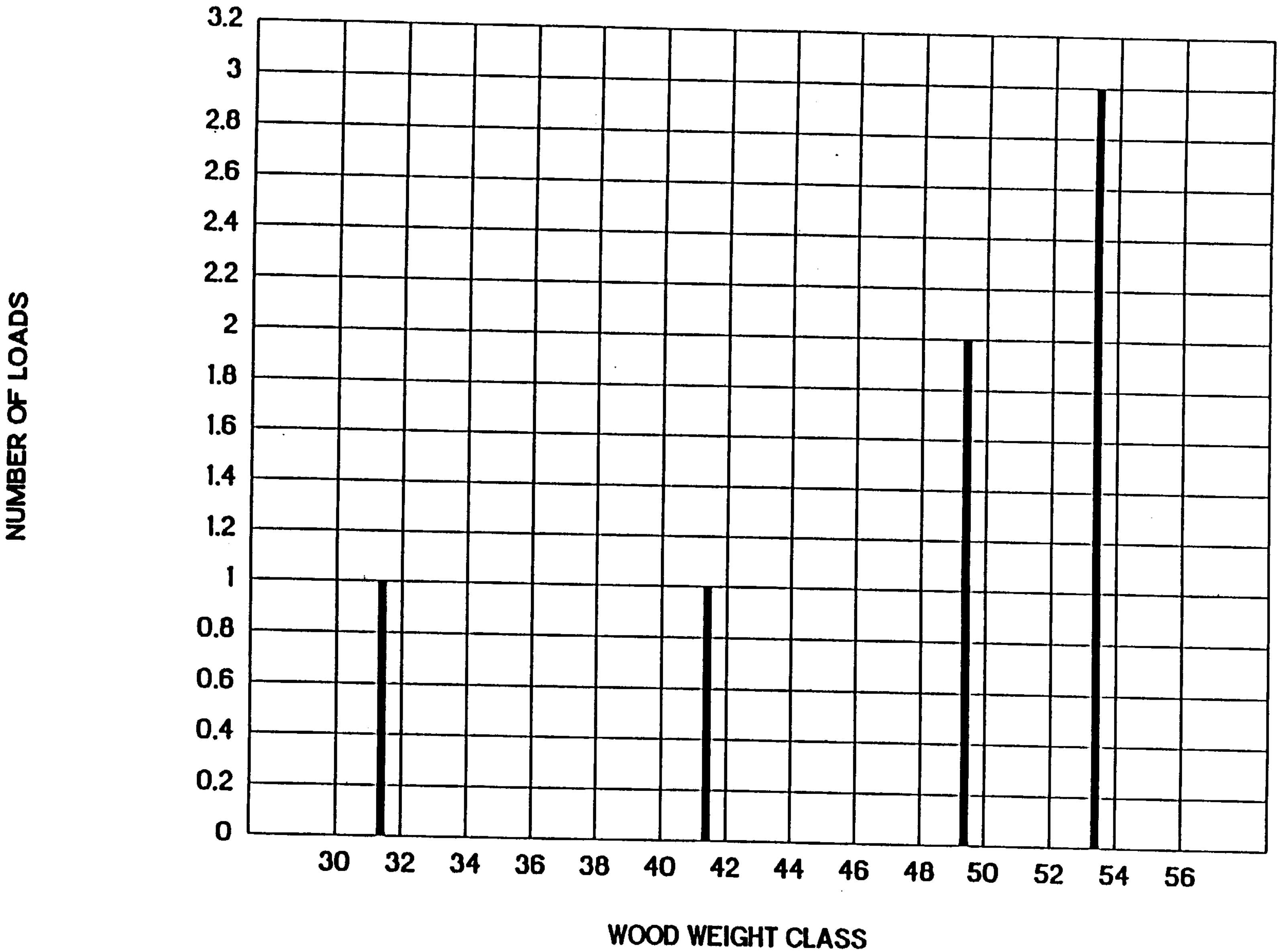
MODIFIED RUMFORD: F0401




STACK TEMP AND WOOD WEIGHTS
ALL 7 DAYS. CONTRAFLOW: F0501
STACK T. & WOOD WTS.
700
600
500
400
300
200
100
0
1
2
3
4
5
6
7
8
9
DAY NUMBER
□ STACK TEMP
+ WOOD WTS. X10

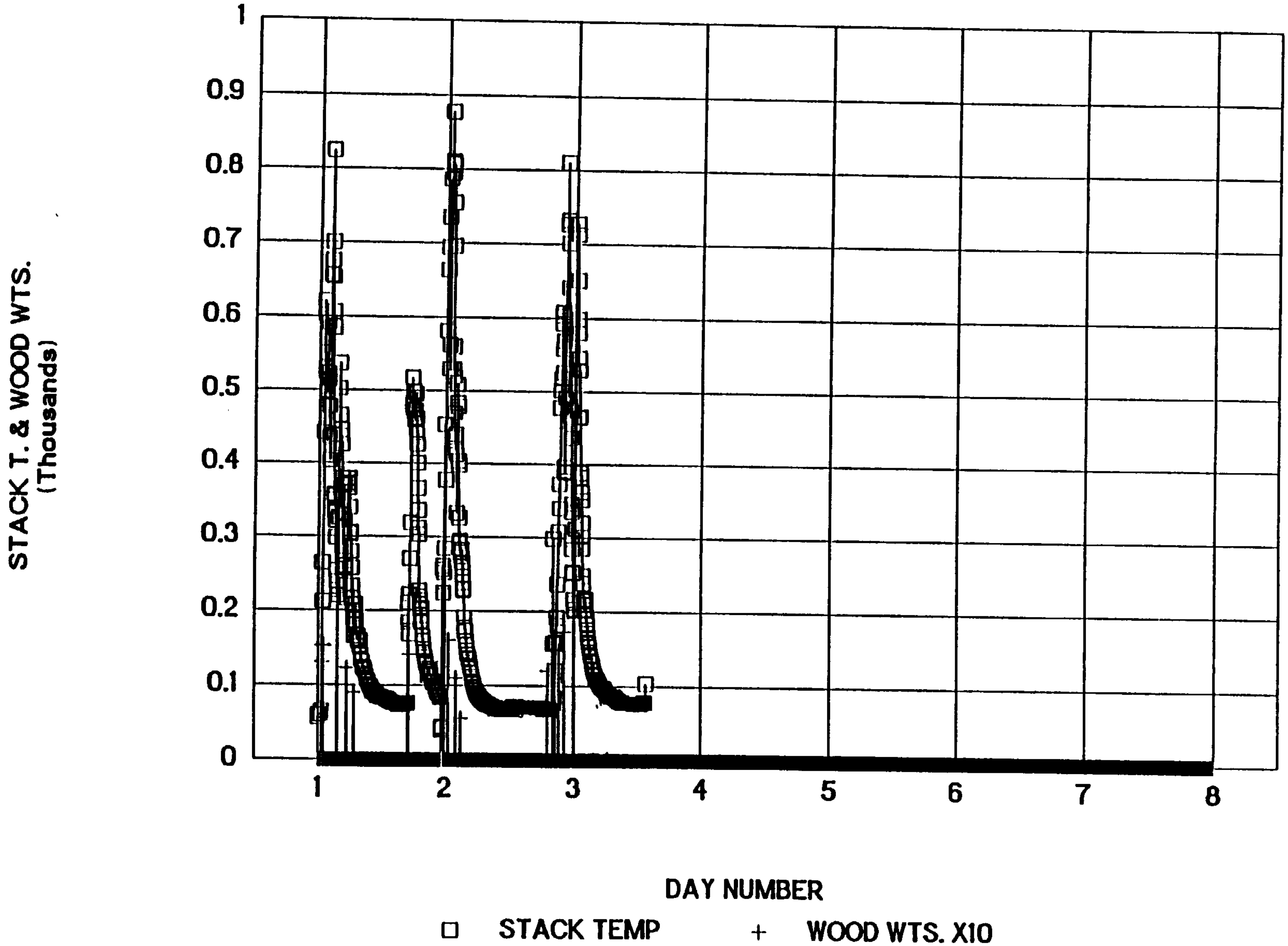
# HISTOGRAM OF WOOD LOADS

## CONTRAFLOW: F0501



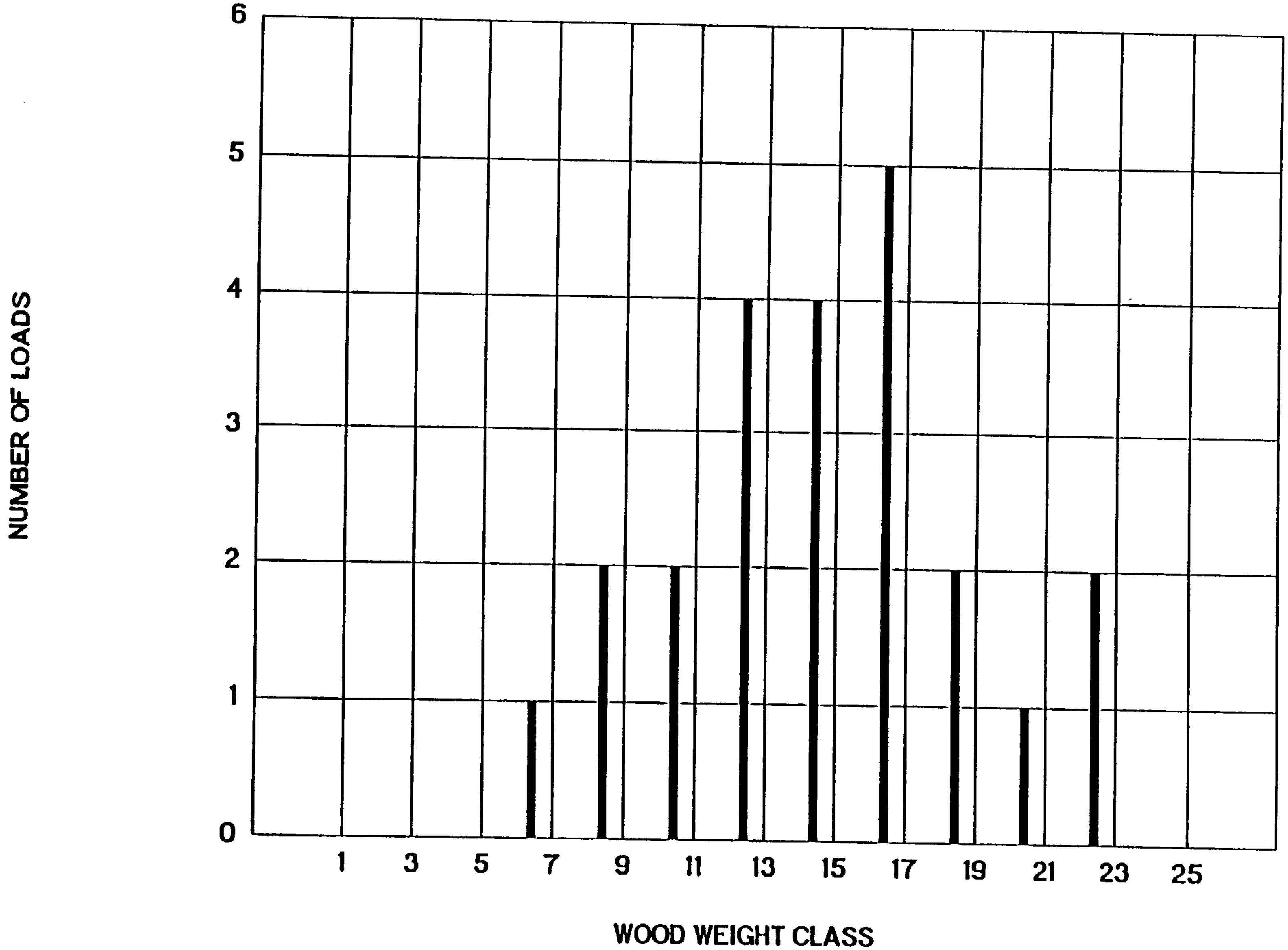
# STACK TEMP AND WOOD WEIGHTS

ALL 7 DAYS. CONVENTIONAL: F0701



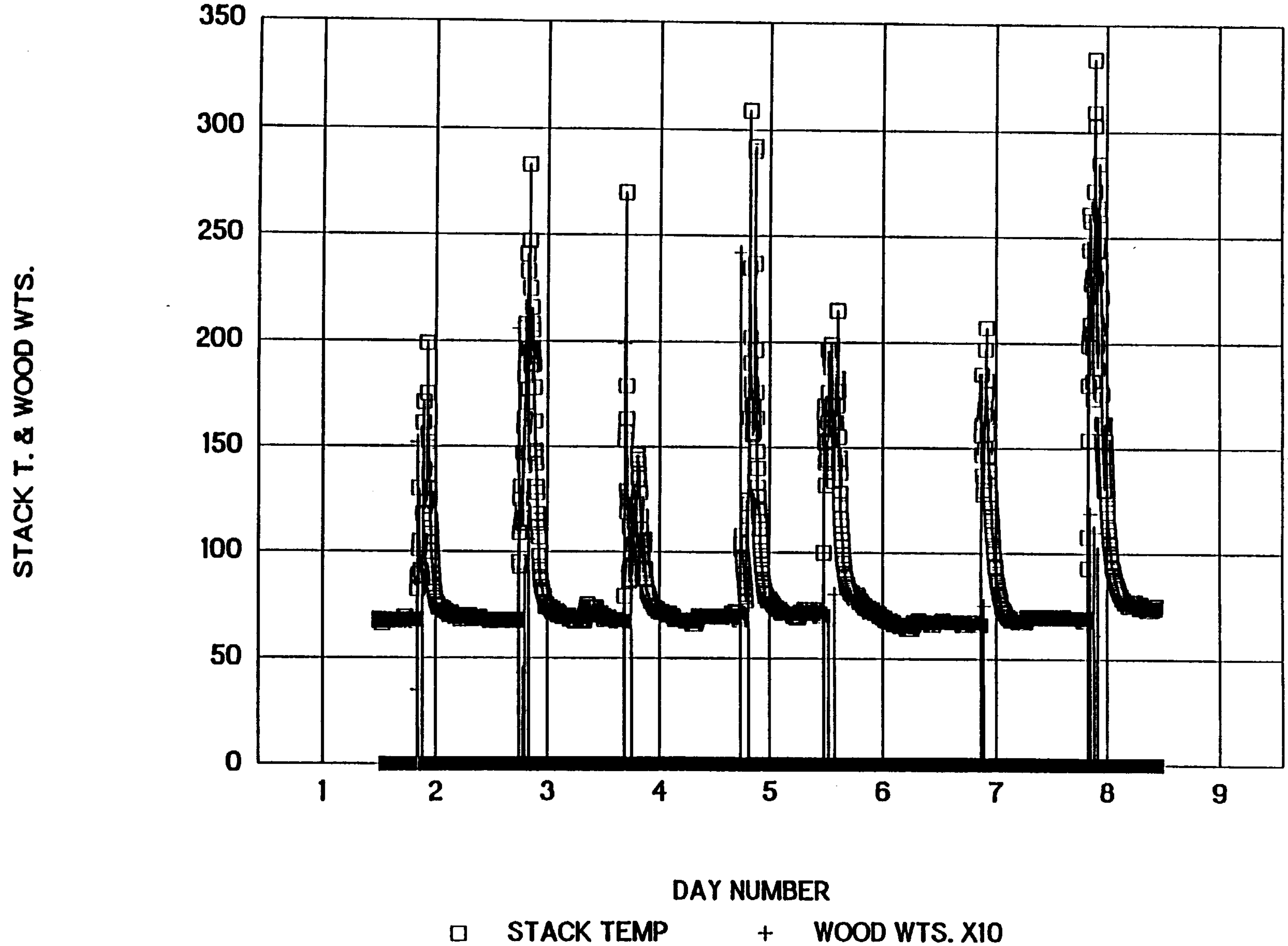
# HISTOGRAM OF WOOD LOADS

CONVENTIONAL: F0701



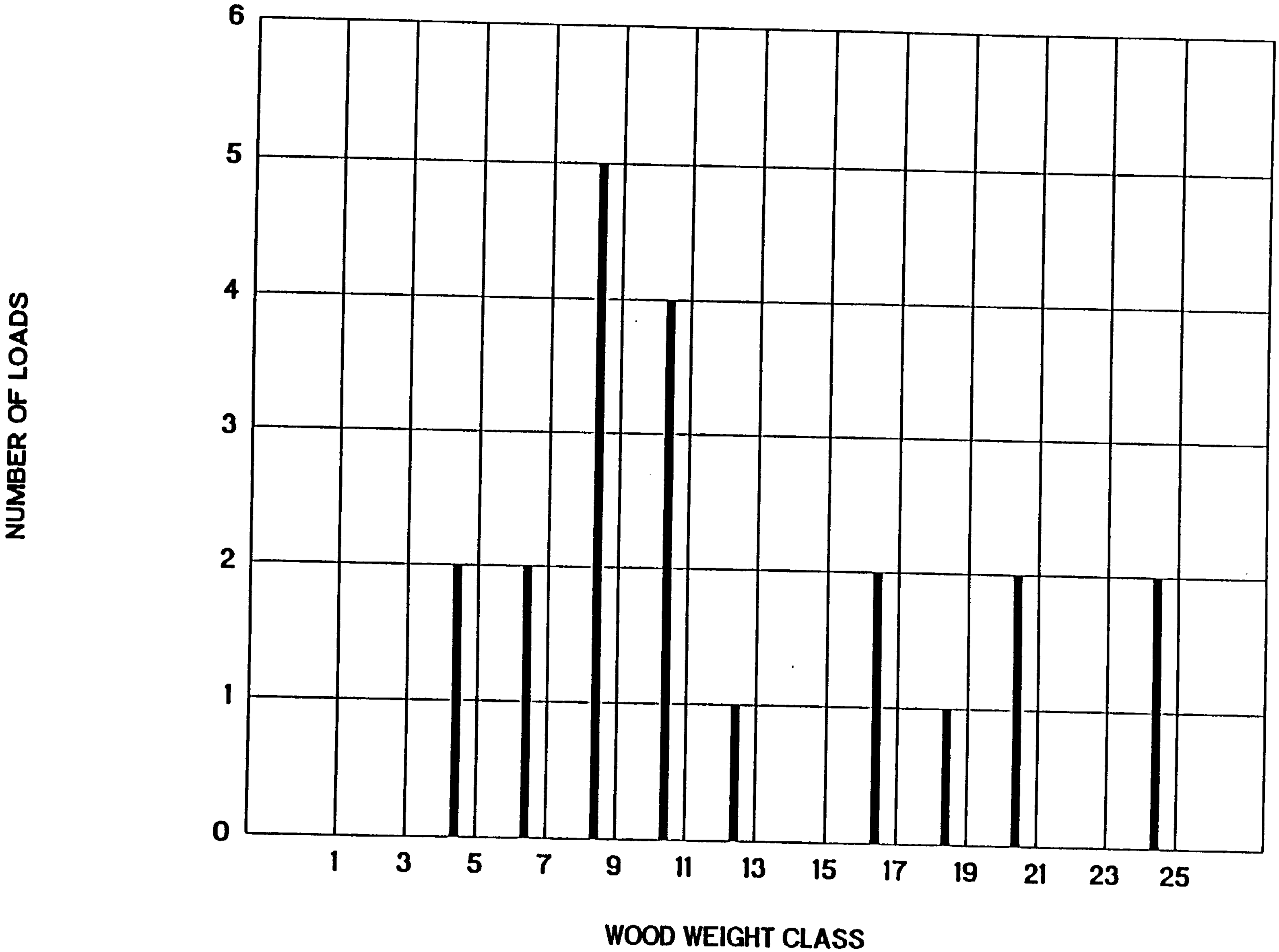
# STACK TEMP AND WOOD WEIGHTS

ALL 7 DAYS. CONVENTIONAL: F0601



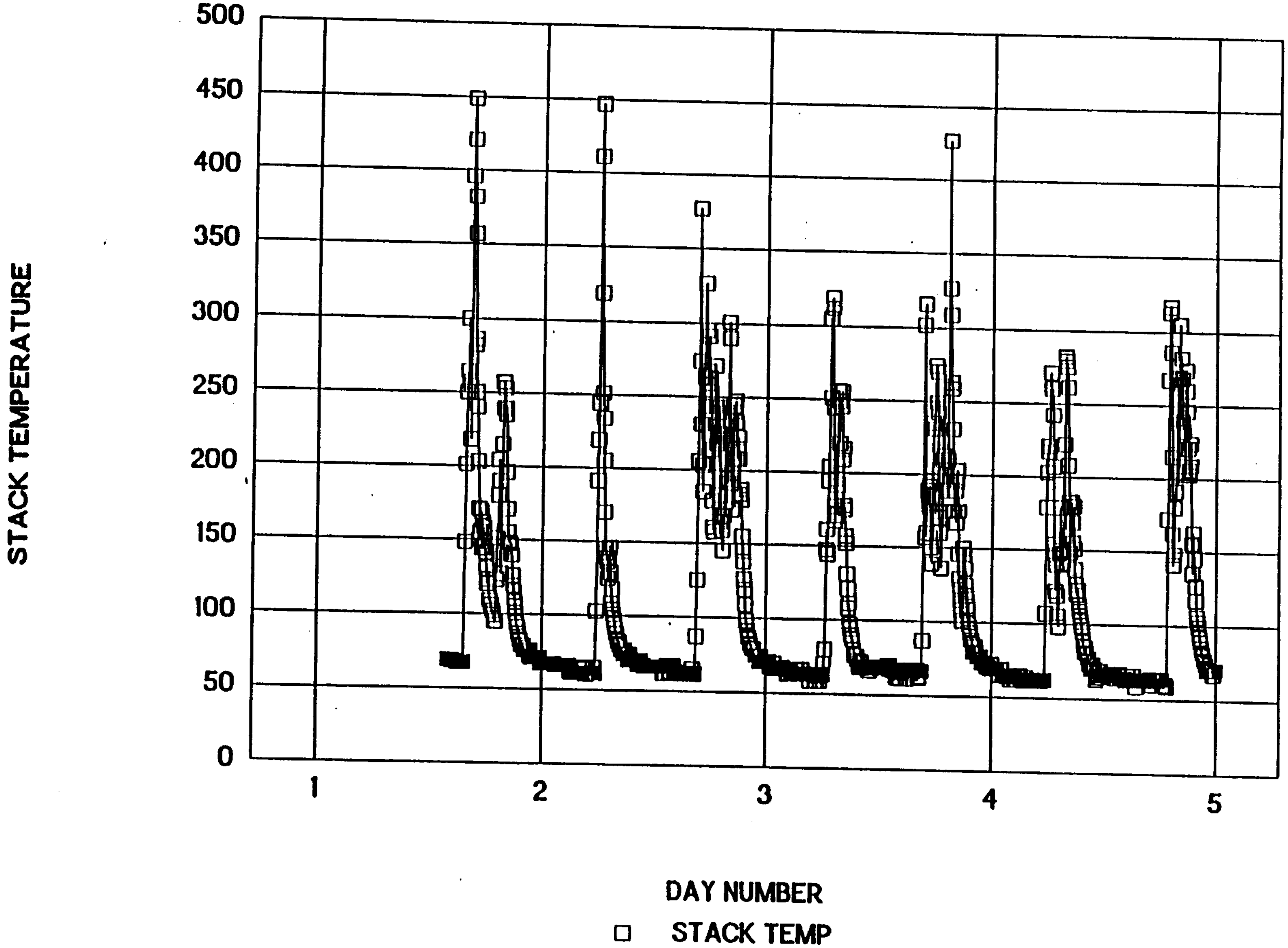
# HISTOGRAM OF WOOD LOADS

CONVENTIONAL: F0601



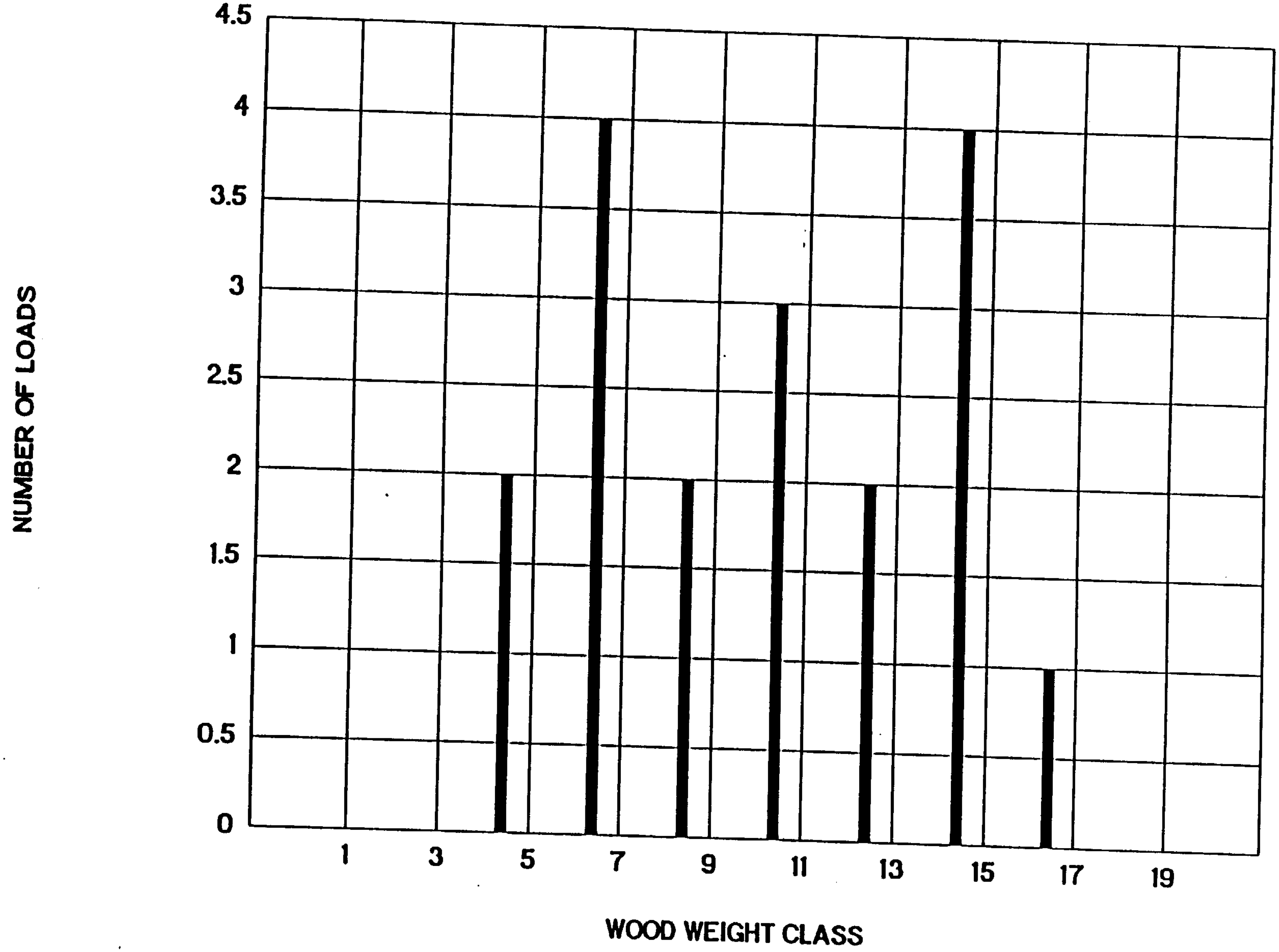
# STACK TEMPERATURES

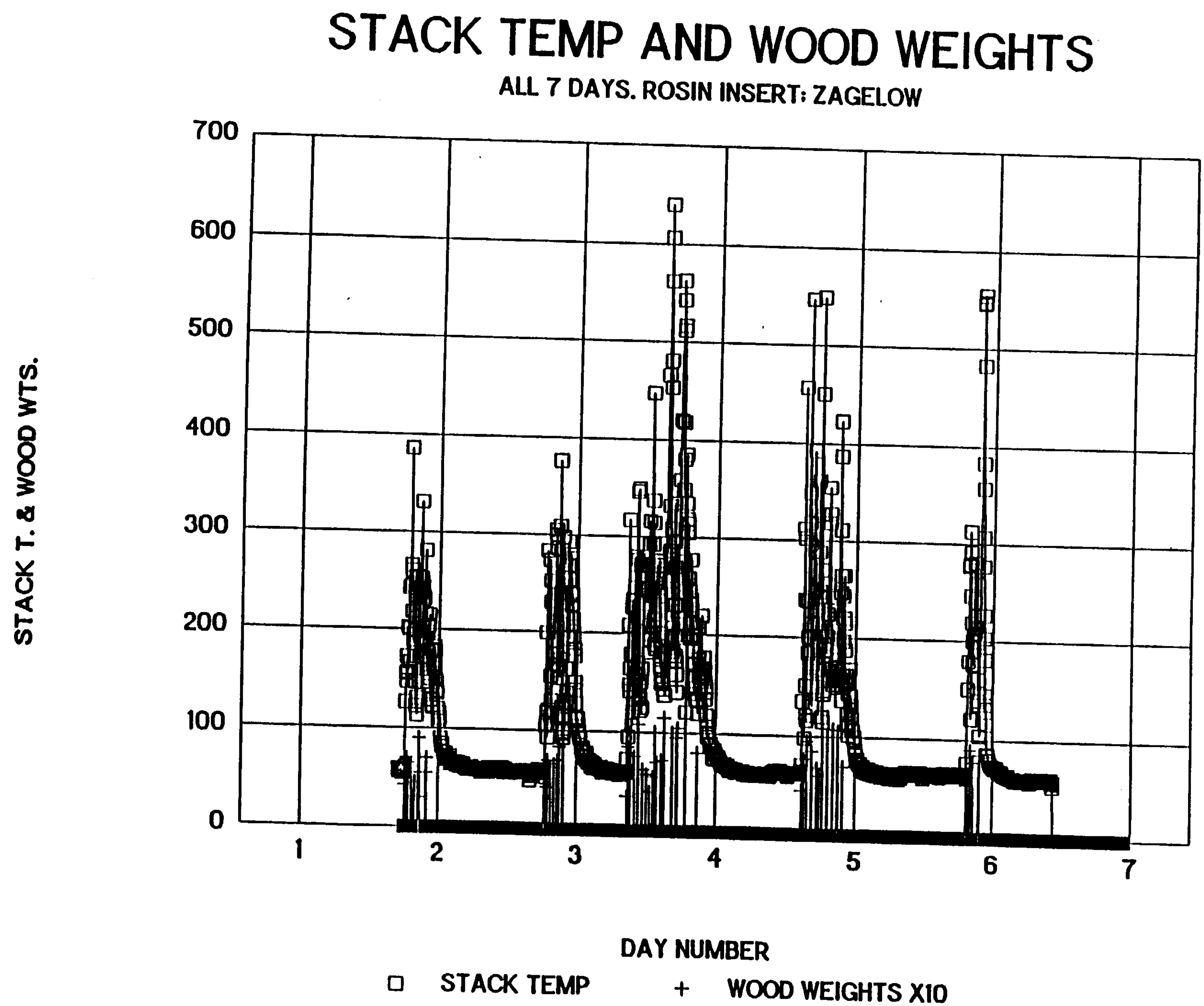
CONVENTIONAL: ZAGELOW



# HISTOGRAM OF WOOD LOADS

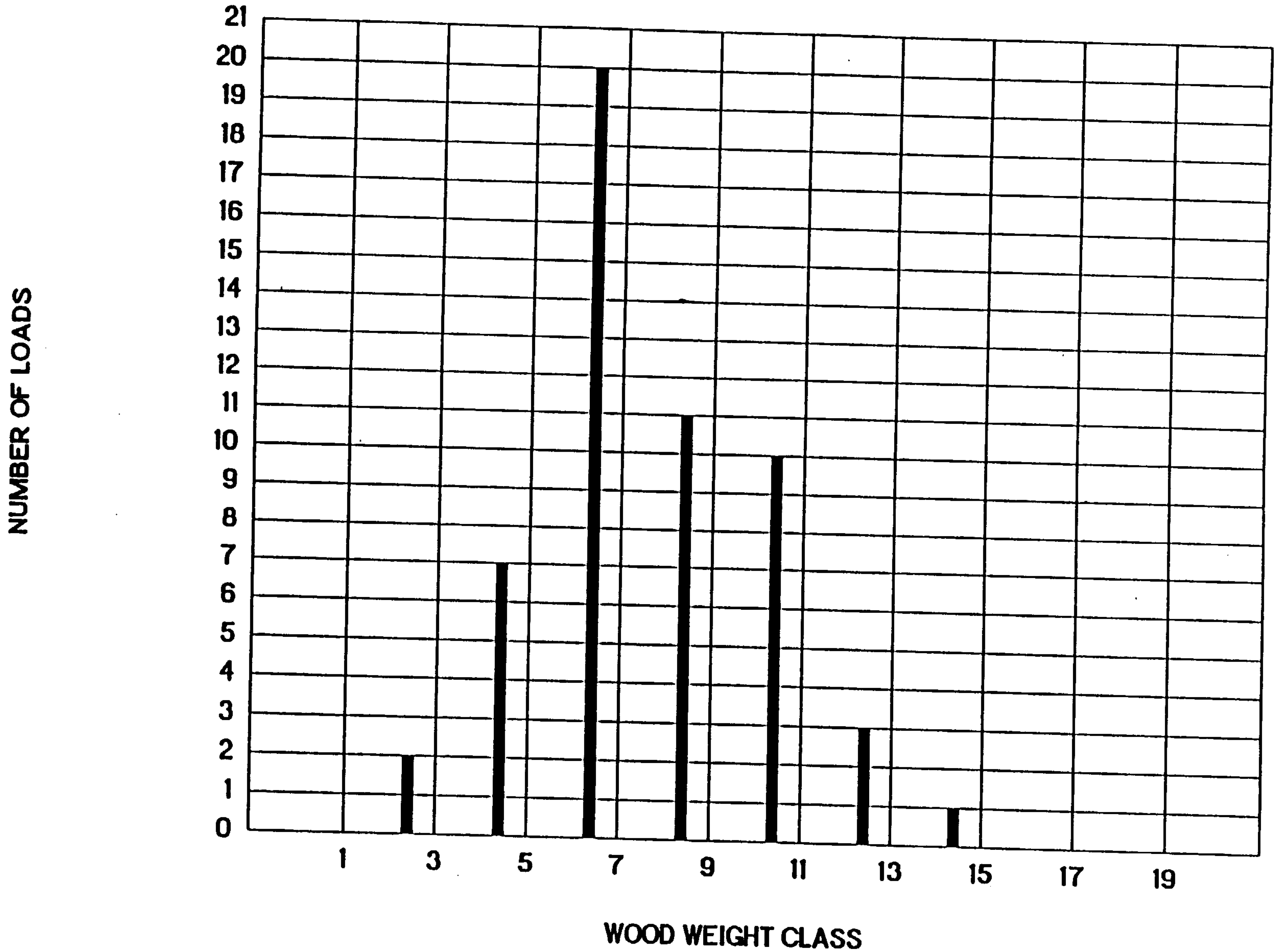
CONVENTIONAL: ZAGELOW




STACK TEMP AND WOOD WEIGHTS
ALL 7 DAYS. ROSIN INSERT: ZAGELOW
STACK T. & WOOD WTS.
700
600
500
400
300
200
100
0
1
2
3
4
5
6
7
DAY NUMBER
STACK TEMP
+ WOOD WEIGHTS X10

# HISTOGRAM OF WOOD LOADS

ROSIN INSERT: ZAGELOW



# Appendix D

## Homeowner Follow-Up Questionnaires

Legend:

Bold = There is a difference between normal and test operation of the fireplace.
N = Normal operation.
T = Operation during test.

# In-Home Fireplace Test Follow-up Questionnaire

Brint, Conventional (F01)

1. It is important to us to know how your burning differed during the test from your *usual* burning. Please comment on the following: indicate your normal situation and then note the difference from during the test.

a. Length of your burns in hours.
N = 5 hrs (normally a weekend burner)
**T = 4 hrs** (our test was daily & weekend)

b. Number of times you load wood during a burn.
N = 12 (very dry, smaller wood)
**T = 6**

c. The # of wood per load.
N = 7#
**T = 10#** wetter, bigger pieces

d. Number of pieces of wood per load at startup.
N = 3
T = same

e. Number of pieces of wood per load when reloading.
N = 2
T = Same

f. The length and diameter of wood you use.
N = 20", 4"
**T = 16", 7"**

g. Poking the wood - describe your usual practice.
N = just before adding wood
T = Same

h. How do you orient the wood in the fireplace? For example: side to side, front to back, inclined against fireplace back or not, tightly packed or not, large logs on bottom or on top.
N = side to side, large pieces in back
T = Same

i. The species of the wood.
**N = Madrona and hazelnut**
**T = Douglas fir and white fir**

j. How did you read our scale, in pounds or kilograms? pounds

k. Moisture of the wood (dry, wet?).
N = dry, dryer than our driest (which was 15%)
**T = not as dry as his**

General

1. How many cords of wood per winter do you burn (account for leftover wood)?
   ½ cord

2. Do you burn this amount every year? How does it vary?
   about the same

3. What percentage of each day of the week do you usually burn per winter season?
   For example: I burn 25% of all Mondays, etc.

| Monday | Tuesday | Wednesday | Thursday | Friday | Saturday | Sunday |
|---|---|---|---|---|---|---|
| 10 | 10 | 10 | 10 | 10 | 45 | 45 |

4. How many hours do you burn each time you burn?

| Monday | Tuesday | Wednesday | Thursday | Friday | Saturday | Sunday |
|---|---|---|---|---|---|---|
| 3 | 3 | 3 | 3 | 3 | 5-6 | 5-6 |

5. How long is your burning season in months? 7

6. Number of fires per year? 35 - 40 (one third to ½ cord)

7. Do you use a grate? Yes

8. Do you use doors (how often?)? Yes, doors are left open

9. What is your criteria for when to reload the fire?
   When flames have died down and most of wood is gone, coals left

10. What is your normal startup technique?
    Small pieces of cedar, 1 small piece of pitch in front; 1 large of wood piece in back; after fire is burning, put in load

Legend:

Bold = There is a difference between normal and test operation of the fireplace.
N = Normal operation.
T = Operation during test.

# In-Home Fireplace Test Follow-up Questionnaire

Linder/Hoevet, Russian (F02)

1. It is important to us to know how your burning differed during the test from your *usual* burning. Please comment on the following: indicate your normal situation and then note the difference from during the test.

a. Length of your burns in hours. **N = 3 hrs (times 2 per day, a.m. & p.m.) adj. dampers on low when fire dies down.**
**T = 2 hrs, left dampers on open**

b. Number of times you load wood during a burn.
N = 1 during a.m., 1 during p.m.
T = Same

c. The # of wood per load. **N = 20#**
**T = 14#**

d. Number of pieces of wood per load at startup.
**N = 6 - 8 pieces, 2×4 scrap or 5" diameter logs**
**T = 3 - 4 pieces of our wood**

e. Number of pieces of wood per load when reloading. N/A

f. The length and diameter of wood you use. N = 20", 5"
T = our wood

g. Poking the wood - describe your usual practice.
N = poke during first part of fire
T = same

h. How do you orient the wood in the fireplace? For example: side to side, front to back, inclined against fireplace back or not, tightly packed or not, large logs on bottom or on top.
N = criss-cross
T = same

i. The species of the wood. **N = 2×4 scrap, pallets, cherry wood, oak, poplar**
**T = ours**

j. How did you read our scale, in pounds or kilograms? pounds

k. Moisture of the wood (dry, wet?).
N = dry

General

1. How many cords of wood per winter do you burn (account for leftover wood)?
   Hard to tell due to type of wood. Guess about 1 cord

2. Do you burn this amount every year? How does it vary?
   Last year used less - gone a lot

3. What percentage of each day of the week do you usually burn per winter season?
   For example: I burn 25% of all Mondays, etc.

| Monday | Tuesday | Wednesday | Thursday | Friday | Saturday | Sunday |
|---|---|---|---|---|---|---|
| 75 | 75 | 75 | 75 | 75 | 75 | 75 |

4. How many hours do you burn each time you burn?

| Monday | Tuesday | Wednesday | Thursday | Friday | Saturday | Sunday |
|---|---|---|---|---|---|---|
| 6 | 6 | 6 | 6 | 6 | 6 | 6 |

5. How long is your burning season in months? Nov. - Dec., Mar

6. Number of fires per year? 180

7. Do you use a grate? No

8. Do you use doors (how often?)? Yes, always

9. What is your criteria for when to reload the fire?
   NA - if heat is low will add

10. What is your normal startup technique?
    4 full sheets of newspaper, 6 - 7 pieces of kindling, big wood at angle

Legend:

Bold = There is a difference between normal and test operation of the fireplace.
N = Normal operation.
T = Operation during test.

# In-Home Fireplace Test Follow-up Questionnaire

Halsey, Original Equipment Rosin (F03)

1. It is important to us to know how your burning differed during the test from your *usual* burning. Please comment on the following: indicate your normal situation and then note the difference from during the test.

a. Length of your burns in hours. N = 2.5 hrs
T = Same

b. Number of times you load wood during a burn.
N = 3 - 4 times
T = Same

c. The pounds of wood per load. N = 4#
T = Same

d. Number of pieces of wood per load at startup.
N = 3
T = Same

e. Number of pieces of wood per load when reloading. N = 4
T = Same

f. The length and diameter of wood you use. N = 18" × 4"
T = Same

g. Poking the wood - describe your usual practice.
N = Just in the beginning when adding material

h. How do you orient the wood in the fireplace? For example: side to side, front to back, inclined against fireplace back or not, tightly packed or not, large logs on bottom or on top.
N = inclined from front to back, moves charred wood to back and places side-to-side under new wood.
T = Same

**i. The species of the wood. N = Douglas fir**
**T = Douglas fir and pine**

**j. How did you read our scale, in pounds or kilograms? kg**

**k. Moisture of the wood (dry, wet?).**
**N = between**
**T = dry?**

General

1. How many cords of wood per winter do you burn (account for leftover wood)?
   past season, about 1 cord

2. Do you burn this amount every year? How does it vary?
   NA - only in house since August 1990

3. What percentage of each day of the week do you usually burn per winter season? For example: I burn 25% of all Mondays, etc.

| Monday | Tuesday | Wednesday | Thursday | Friday | Saturday | Sunday |
|---|---|---|---|---|---|---|
| 50 | 50 | 50 | 50 | 50 | 70 | 70 |

4. How many hours do you burn each time you burn?

| Monday | Tuesday | Wednesday | Thursday | Friday | Saturday | Sunday |
|---|---|---|---|---|---|---|
| 4 | 4 | 4 | 4 | 4 | 5 | 5 |

5. How long is your burning season in months? Nov - Feb

6. Number of fires per year? 120

7. Do you use a grate? No

8. Do you use doors (how often?)? No

9. What is your criteria for when to reload the fire?
   Visual inspection - no more flames

10. What is your normal startup technique?
   2 - 3 pieces of newspaper, kindling, split wood of species being used, start fire, add load

Legend:

Bold = There is a difference between normal and test operation of the fireplace.
N = Normal operation.
T = Operation during test.

# In-Home Fireplace Test Follow-up Questionnaire

## Strong, Modified Rumford (F04)

1. It is important to us to know how your burning differed during the test from your *usual* burning. Please comment on the following: indicate your normal situation and then note the difference from during the test.

a. Length of your burns in hours. N = 2.5 hrs
T = Same

b. Number of times you load wood during a burn.
N = 2
T = Same

c. The # of wood per load. N = 3 lg pieces, 15#
T = Same

d. Number of pieces of wood per load at startup.
N = 3 - 4
T = Same

e. Number of pieces of wood per load when reloading. N = 2
T = 2

f. The length and diameter of wood you use. N = 18", 6 - 8 "
T = Same

g. Poking the wood - describe your usual practice.
N = no poking
T = Same

h. How do you orient the wood in the fireplace? For example: side to side, front to back, inclined against fireplace back or not, tightly packed or not, large logs on bottom or on top.
N = side to side
T = same

i. The species of the wood. N = ?? doesn't know

j. How did you read our scale, in pounds or kilograms?
pounds

k. Moisture of the wood (dry, wet?).
N = in between
T = dry

General

1. How many cords of wood per winter do you burn (account for leftover wood)?
   1 cord

2. Do you burn this amount every year? How does it vary?
   Every year, but only in house one year

3. What percentage of each day of the week do you usually burn per winter season? For example: I burn 25% of all Mondays, etc.

| Monday | Tuesday | Wednesday | Thursday | Friday | Saturday | Sunday |
|---|---|---|---|---|---|---|
| 2 | 2 | 2 | 2 | 50 | 50 | 50 |

4. How many hours do you burn each time you burn?

| Monday | Tuesday | Wednesday | Thursday | Friday | Saturday | Sunday |
|---|---|---|---|---|---|---|
| 2.5 | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 |

5. How long is your burning season in months? November - February (4)

6. Number of fires per year? 35

7. Do you use a grate? Yes

8. Do you use doors (how often?)? No

9. What is your criteria for when to reload the fire?
   When fire appears to be dying

10. What is your normal startup technique?
    Newspaper - 5-6 wadded up pieces and kindling

Legend:

Bold = There is a difference between normal and test operation of the fireplace.
N = Normal operation.
T = Operation during test.

# In-Home Fireplace Test Follow-up Questionnaire

## Halme, Contraflow (F05)

1. It is important to us to know how your burning differed during the test from your *usual* burning. Please comment on the following: indicate your normal situation and then note the difference from during the test.

a. Length of your burns in hours. N = 2 hrs
T = Same

b. Number of times you load wood during a burn.
N = 1 time
T = same

c. The # of wood per load. N = 40-50#
T = same

d. Number of pieces of wood per load at startup.
The only load = 10 pieces

e. Number of pieces of wood per load when reloading. NA

f. The length and diameter of wood you use. N = 18", 4-6"
T = ours

g. Poking the wood - describe your usual practice.
N = only occasionally at end of burn to scatter ashes
T = None

h. How do you orient the wood in the fireplace? For example: side to side, front to back, inclined against fireplace back or not, tightly packed or not, large logs on bottom or on top.
N = F to back, occasionally criss-cross
T = Same

i. The species of the wood. N = Douglas fir
T = fir and lodgepole pine

j. How did you read our scale, in pounds or kilograms?
pounds

k. Moisture of the wood (dry, wet?).
N = dry (covered shed)

General

1. How many cords of wood per winter do you burn (account for leftover wood)?

   2 cords

2. Do you burn this amount every year? How does it vary?

   Burned less last year, no time to cut wood

3. What percentage of each day of the week do you usually burn per winter season? For example: I burn 25% of all Mondays, etc.

| Monday | Tuesday | Wednesday | Thursday | Friday | Saturday | Sunday |
|---|---|---|---|---|---|---|
| 50 | 50 | 50 | 50 | 50 | 100 | 100 |

4. How many hours do you burn each time you burn?

| Monday | Tuesday | Wednesday | Thursday | Friday | Saturday | Sunday |
|---|---|---|---|---|---|---|
| 2 | 2 | 2 | 2 | 2 | 2 | 2 |

5. How long is your burning season in months? Nov - Feb

6. Number of fires per year? 100

7. Do you use a grate? Yes

8. Do you use doors (how often?)? Yes, always

9. What is your criteria for when to reload the fire?

   NA

10. What is your normal startup technique?

    3 - 4 pieces, crumbled, cedar kindling, put load on then light

Legend:

Bold = Difference between normal and test operation.
N = Normal operation.
T = Operation during test.

# In-Home Fireplace Test Follow-up Questionnaire

Andoniadas, Conventional (F06)

1. It is important to us to know how your burning differed during the test from your *usual* burning. Please comment on the following: indicate your normal situation and then note the difference from during the test.

a. Length of your burns in hours.
N = 3-4 hrs
**T = 3 hrs**

b. Number of times you load wood during a burn.
N = 3-4 times
**T = 2-3 times**

c. The # of wood per load.
N = unknown
T = 8# or so

d. Number of pieces of wood per load at startup.
N = 3
T = same

e. Number of pieces of wood per load when reloading.
N = 1
T = same, except last burn, may have used more

f. The length and diameter of wood you use.
N = 18", 4-5"
T = 18", 4-5"

g. Poking the wood - describe your usual practice.
N = poke when loaded & in order to keep flame
T = same

h. How do you orient the wood in the fireplace? For example: side to side, front to back, inclined against fireplace back or not, tightly packed or not, large logs on bottom or on top.
N = side to side
T = same

i. The species of the wood.
**N = oak**
**T = Douglas fir**

j. How did you read our scale, in pounds or kilograms?
pounds

k. Moisture of the wood (dry, wet?).
N = dry

Legend:

Bold = Difference between normal and test operation.
N = Normal operation.
T = Operation during test.

## General

1. How many cords of wood per winter do you burn (account for leftover wood)?
   less than 1

2. Do you burn this amount every year? How does it vary?
   about the same

3. What percentage of each day of the week do you usually burn per winter season? For example: I burn 25% of all Mondays, etc.

| Monday | Tuesday | Wednesday | Thursday | Friday | Saturday | Sunday |
|---|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 20 | 60 | 20 |

4. How many hours do you burn each time you burn?

| Monday | Tuesday | Wednesday | Thursday | Friday | Saturday | Sunday |
|---|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 3-4 | 5-6 | 3-4 |

5. How long is your burning season in months? Whenever it's cool

6. Number of fires per year? 40-50

7. Do you use a grate? Yes

8. Do you use doors (how often?)? No, screen only

9. What is your criteria for when to reload the fire?
   Low flame, wood is burned up

10. What is your normal startup technique?
    Kindling at bottom, stack load on top, natural gas starter for 2 min C ±1 min

Legend:

Bold = Difference between normal and test operation.
N = Normal operation.
T = Operation during test.

# In-Home Fireplace Test Follow-up Questionnaire

## McGinnis/Ackerman, Conventional, High Altitude (3400') (F07)

1. It is important to us to know how your burning differed during the test from your *usual* burning. Please comment on the following: indicate your normal situation and then note the difference from during the test.

a. Length of your burns in hours.
N = 6 hrs
T = Same

b. Number of times you load wood during a burn.
N = Builds up to first load, lets burn down, then reloads ~4 - 6
T = Same

c. The # of wood per load.
N = 15# - 20#
T = Same

d. Number of pieces of wood per load at startup.
N = Kindling plus 2, 1 on each side, build up to first load
T = Same

e. Number of pieces of wood per load when reloading.
N = 2 - 3
T = Same

f. The length and diameter of wood you use.
**N = 16" × 10 - 12"**
**T = 16" × 8 - 11"**

g. Poking the wood - describe your usual practice.
N = If it's not burning well, will rearrange
T = Same

h. How do you orient the wood in the fireplace? For example: side to side, front to back, inclined against fireplace back or not, tightly packed or not, large logs on bottom or on top.
N = Front to back unless ash accumulates, contributing to an incline, occasionally criss-crosses
T = Same

i. The species of the wood.
N = D.F. W. Hemlock, Mtn. Hemlock, Spruce, White Pine, lodgepole, cedar (to start)
T = Burned what we gave him.

j. How did you read our scale, in pounds or kilograms? pounds

k. Moisture of the wood (dry, wet?).
N = Seasoned, criss-cross stacked until dry then puts in shed

Legend:

Bold = Difference between normal and test operation.
N = Normal operation.
T = Operation during test.

## General

1. How many cords of wood per winter do you burn (account for leftover wood)?
   $^3/_4$ cord - 1 cord

2. Do you burn this amount every year? How does it vary?
   Yes, only there for two years

3. What percentage of each day of the week do you usually burn per winter season?
   For example: I burn 25% of all Mondays, etc.

| Monday | Tuesday | Wednesday | Thursday | Friday | Saturday | Sunday |
|---|---|---|---|---|---|---|
| 4 | 4 | 4 | 4 | 80 | 80 | 4 |

4. How many hours do you burn each time you burn?

| Monday | Tuesday | Wednesday | Thursday | Friday | Saturday | Sunday |
|---|---|---|---|---|---|---|
| 6 | 6 | 6 | 6 | 6 | 6 | 6 |

5. How long is your burning season in months? 11 months

6. Number of fires per year? See #3 (M, T, W, Th, S) × 2 = 10
   (Sat, Sun) × 42 = 84 Total: 94

7. Do you use a grate? No

8. Do you use doors (how often?)? No

9. What is your criteria for when to reload the fire?
   When it's not "blasting out heat" or <6" of wood (depth) across bottom

10. What is your normal startup technique?
    1 piece on each side (large); paper in middle; cedar kindling on top

Legend:

Bold = Difference between normal and test operation.
N = Normal operation.
T = Operation during test.

# In-Home Fireplace Test Follow-up Questionnaire

## Zagelow, Conventional then Rosin Retrofit (Mutual 1)

1. It is important to us to know how your burning differed during the test from your *usual* burning. Please comment on the following: indicate your normal situation and then note the difference from during the test.

a. Length of your burns in hours. N = 3 hrs
**T = 5 hrs, to obtain sufficient total burn time**

b. Number of times you load wood during a burn.
**N = 4 - 5 times**
**T = 5 - 6 times**

c. The # of wood per load. N = 3
T = same

d. Number of pieces of wood per load at startup.
N = 2 - 3 small
T = Same

e. Number of pieces of wood per load when reloading. N = 2 - 3
T = 2 - 3 (just smaller)

f. The length and diameter of wood you use. **N - 16 - 20", 4 - 5"**
**T = 16", 2 - 3"**

(Used smaller pieces for Rosin to fit smaller firebox)

g. Poking the wood - describe your usual practice.
N = just before reloading
T = Same

h. How do you orient the wood in the fireplace? For example: side to side, front to back, inclined against fireplace back or not, tightly packed or not, large logs on bottom or on top.
**Conventional - side to side and criss-cross**
**Rosin - front to back against back inclined 45°, put old charred pieces side to side under new wood**

i. The species of the wood. N = Douglas fir, alder
T = Same

j. How did you read our scale, in pounds or kilograms? pounds

k. Moisture of the wood (dry, wet?).
**N = between wet and dry**
**T = dry**

Legend:

Bold = Difference between normal and test operation.
N = Normal operation.
T = Operation during test.

## General

1. How many cords of wood per winter do you burn (account for leftover wood)?
   ½ cord

2. Do you burn this amount every year? How does it vary?
   Same

3. What percentage of each day of the week do you usually burn per winter season?
   For example: I burn 25% of all Mondays, etc.

| Monday | Tuesday | Wednesday | Thursday | Friday | Saturday | Sunday |
|---|---|---|---|---|---|---|
| 25 | 25 | 25 | 25 | 25 | 25 | 25 |

4. How many hours do you burn each time you burn?

| Monday | Tuesday | Wednesday | Thursday | Friday | Saturday | Sunday |
|---|---|---|---|---|---|---|
| 3 | 3 | 3 | 3 | 3 | 5-6 | 5-6 |

5. How long is your burning season in months? Nov - Feb: 4 months

6. Number of fires per year? 20

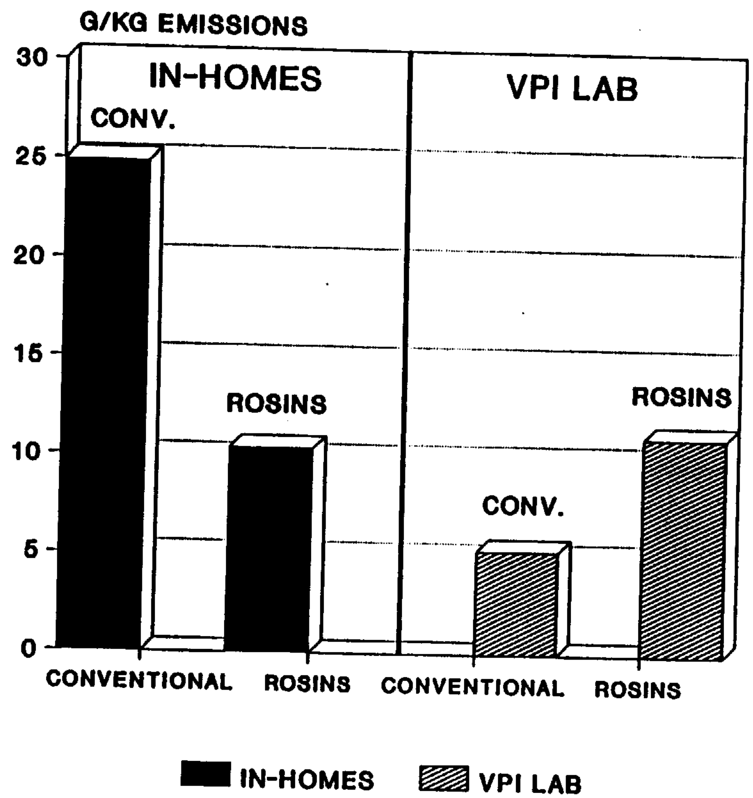
7. Do you use a grate? Yes, before insert; no, after insert

8. Do you use doors (how often?)? Yes, but normally leave doors open

9. What is your criteria for when to reload the fire?
   How much wood is left; when low, reload

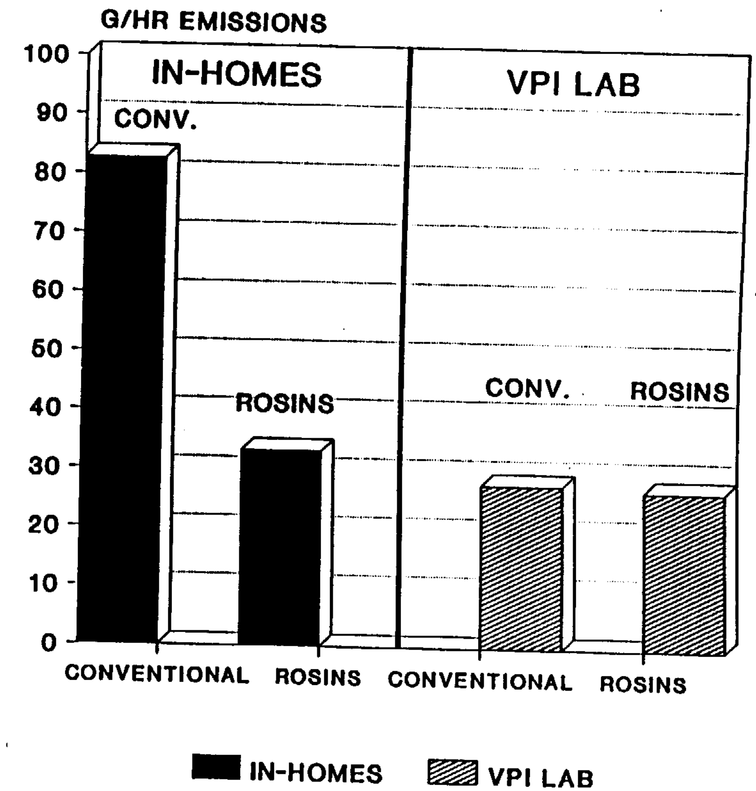
10. What is your normal startup technique?
    2 - 3 pieces full-size sheets newspaper; kindling, same species; 2 - 3 of full size; light, close door until it gets going.

## COMPARISON OF IN-HOME VS VPI LAB TEST
## CONVENTIONAL AND ROSIN FIREPLACES.
### G/KG PARTICULATE EMISSIONS




•In-home ave. of 5 conv; VPI was one.
••Ave. of same 2 Rosins In-homes & VPI.

## COMPARISON OF IN-HOME VS VPI LAB TEST
## CONVENTIONAL AND ROSIN FIREPLACES.
### G/HR PARTICULATE EMISSIONS




•In-home ave. of 5 conv; VPI was one.
••Ave. of same 2 Rosins In-homes & VPI.