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Source Assessment: Residential Combustion of Wood

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Source Assessment: Residential Combustion of Wood

by

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PREFACE

The Industrial Environmental Research Laboratory (IERL) of the U.S. Environmental Protection Agency (EPA) has the responsibility for insuring that pollution control technology is available for stationary sources to meet the requirements of the Clean Air Act, the Federal Water Pollution Control Act, and solid waste legislation. If control technology is unavailable, inadequate, or uneconomical, financial support is provided for the development of the needed control techniques for industrial and extractive process industries. All types of techniques are considered: process modifications, feedstock modifications, add-on control devices, and complete process substitution. The scale of the control technology programs ranges from bench studies to full-scale demonstration plants.

To support the control technology development program, IERL also conducts extensive environmental assessment programs for the purpose of identifying and prioritizing those sources of pollution in need of control. This is a determination which should not be made on superficial information; consequently, each major source category is being evaluated in detail to determine if there is, in EPA's judgment, sufficient need for emission reduction. This report contains data that will be useful in making a more objective decision with respect to the air emissions from the residential combustion of wood.

Monsanto Research Corporation has contracted with EPA to investigate the environmental impact of various source categories which represent sources of pollution in accordance with EPA's responsibility as outlined above. Dr. Robert C. Binning serves as Program Manager in this overall program, entitled "Source Assessment," which includes the investigation of sources in each of four categories: combustion, organic materials, inorganic materials, and open sources. Dr. Dale A. Denny of the Industrial Processes Division at Research Triangle Park serves as EPA Project Officer. In this study of the residential combustion of wood, Dr. Ronald A. Venezia of the Chemical Processes Branch, Warren Peters of the Process Technology Branch, and John O. Milliken of the Special Studies Branch served as EPA Task Officers.

ABSTRACT

The potential environmental impact from the residential combustion of wood has been estimated. An estimated 16.6 million metric tons of wood were burned in the residential sector in 1976. ABout 30% of this was burned for primary heating in an estimated 912,000 housing units. Georgraphic distribution of wood-fired heating devices is related to the natural forest regions in the United States. By 1985 it is estimated that over 10 million homes will be using some wood fuel.

Emissions from wood-fired residential heating devices include particulate matter, sulfur oxides, nitrogen oxides, carbon monoxide, hydrocarbons, and polycyclic organic matter (POM). The estimated impact of these emissions has been assessed by the method of source severities. This method involves estimating maximum ground level concentrations of pollutants from an average source and comparing these concentrations to a National Ambient Air Quality Standard for criteria pollutants or to a reduced threshold limit value for noncriteria pollutants. Source severities were found to be highest for POM emissions. The potential impact of this source was also evaluated by calculating total state and national emissions. Particulates, hydrocarbons, and carbon monoxide emissions from all residential wood-fired sources were estimated to contribute 1.0%, 1.5% and 3.8%, respectively, of the total national emission burden for those species in 1976. In addition, this source was determined to be a major national source of POM emissions.

This report was submitted in partial fullfillment of Contract No. 68-02-1874 by Monsanto Research Corporation under the sponsorship of the U.S. Environmental Protection Agency. The study described in the report covers the period November 1976 to February 1980.

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SECTION 1

INTRODUCTION

Residential combustion of wood for space heating has found renewed interest in this country due to the rising cost of oil and natural gas and their uncertain future availability. Existing knowledge of the emissions from wood combustion indicate that this trend poses a potential environmental problem. It is generally assumed that residential combustion of wood produces significant emissions because of the high level of smoke produced. No major effort has been made in the past to reduce these emissions, however, design changes to improve combustion efficiency may have also reduced smoke and emission levels.

By 1960 residential combustion of wood for home heating had almost been eliminated. This decline is now being reversed, and it is uncertain how rapidly this form of residential heating will grow. It is also unclear what environmental problems would be created by large scale residential combustion of wood. For example, it is suspected that long term exposure to relatively low concentrations of certain organic compounds (e.g., polycyclic organic matter) can have serious health effects. Some of these compounds are known to be emitted by wood combustion sources.

This report presents a review of characterization data for emissions from residential wood combustion and an evaluation of their potential environmental effects. It describes several types of residential wood combustion equipment, the 1976 geographic distribution of wood-fired equipment, fuel characteristics, and combustion chemistry. Primary and secondary wood heating, as well as wood burning for aesthetic purposes, are all covered in the report. Emission control technology and possible future trends of the source are also discussed.

SECTION 2

SUMMARY

This report assesses the environmental impact of air emissions produced by the residential combustion of wood. It encompasses wood burned for primary home heating, wood burned for auxiliary home heating and wood burned in fireplaces for aesthetic purposes.

Residential consumption of wood for primary heating in 1976 was estimated to be 5,122,000 metric tons, burned in 912,000 housing units. The large wood-producing areas in the West and South have the highest number of homes heated by wood. On the basis of 1976 data the six-state region of Alabama, Georgia, North Carolina, South Carolina, Tennessee and Virginia contains about 39% of the nation's total wood-fired primary heating devices, and accounts for 32% of the wood burned for that purpose. Large quantities of wood are also burned in homes either for auxiliary heat or for aesthetic purposes. It is estimated that wood burned for these purposes is greater than that burned for primary heating. In 1976 an estimated 28,000,000 fireplaces and 7,600,000 auxiliary wood stoves burned 2,700,000 metric tons and 8,800,000 metric tons of wood, respectively, per year. Fireplaces are more predominant in the Northeast and West regions of the country, while auxiliary wood heating is more prevalent in the South and Northeast regions.

Residential combustion of wood produces emissions of particulate matter, sulfur oxides (SO_x), nitrogen oxides (NO_x), hydrocarbons, carbon monoxide (CO), and a wide variety of organic compounds including polycyclic organic matter (POM). Uncontrolled mass emissions and emission factors are listed in Tables 1 and 2. Also presented is the contribution of wood-fired residential combustion to the national level of criteria emissions (i.e., particulate matter, SO_x, NO_x, CO, and hydrocarbons). All criteria emissions from residential wood combustion except SO_x and NO_x exceed 1% of the national level of criteria pollutant emissions. On a state basis, criteria emisssions from residential wood combustion exceed 1% of the state total of at least one criteria pollutant in 49 states.

Emission factors for hydrocarbons, CO, and POM are higher than those for most other combustion sources and reflect the imperfect combustion conditions typical of residential wood burning. The composition of the particulate emissions (50% to 80% carbon) also

TABLE 1. CRITERIA EMISSIONS FROM WOOD-FIRED RESIDENTIAL HEATING EQUIPMENT

Emission species	Emission factor,[a] g/kg		Source severity		Affected population[b]				Percent of national emissions from all stationary sources
					$\bar{\chi}/F \geq 1.0$		$\bar{\chi}/F \geq 0.05$		
	Wood stove	Fire-place	Wood stove	Fire-place	Wood stove	Fire-place	Wood stove	Fire-place	
Particulate	9.1	13	0.02	0.08	0	0	0	1	1.0
SO_x	0.2	0.2[c]	<0.001	<0.001	0	0	0	0	<0.01
NO_x	0.49	2.0	0.004	0.05	0	0	0	0	0.05
Hydrocarbons	13	74	0.063	1.0	0	0	0	10	1.5
CO	180	67	0.004	0.005	0	0	0	0	3.3

[a] Based on kg wood burned, as received.

[b] Based on an average population density of 21 persons/km².

[c] Based on data from wood stoves.

TABLE 2. NONCRITERIA EMISSIONS FROM WOOD-FIRED RESIDENTIAL COMBUSTION

Emission species[c]	Emission factor,[a] g/kg		Source severity		Affected population[b]			
					$\bar{\chi}/F \geq 1.0$		$\bar{\chi}/F \geq 0.05$	
	Wood stove	Fire-place	Wood stove	Fire-place	Wood stove	Fire-place	Wood stove	Fire-place
Condensable organics	5.5	10	d	d	d	d	d	d
POM	0.27	0.029	46	14	32	9	730	210
Formaldehyde	0.23	1.5	0.013	0.23	0	0	0	3
Total carbonyls		4.4		d		d		d
Phenol		1.0		0.03		0		0

Note: Blanks indicate no data available.

[a] Based on kg wood burned, as received.

[b] Based on an average population density of 21 persons/km².

[c] Only major species are listed. An extensive listing of other organic species is given in Section 4.

[d] These species are evaluated for source severity and affected population under the criteria pollutant categories of particulates and hydrocarbons.

shows the incomplete nature of the combustion process. It is estimated that total national POM emissions from this source represent approximately 80% of total national POM emissions from all sources (excluding natural and mobile sources).

The extent of potential environmental and health effects was addressed in this study on the basis of bioassay testing of combustion emissions and by means of certain evaluation criteria established under the Source Assessment program. Bioassay tests on a series of stack samples collected from three wood-burning units firing different types of wood showed that solvent extracts of all the samples were mutagenic (Ames test) and cytotoxic (CHO cytotoxicity test).

Potential environmental impact was also evaluated by determining the parameters of source severity and affected population. Because the parameters are based on average source parameters and employ certain assumptions and approximations, they are not intended to provide an absolute measure of environmental impact. Rather, they are to be used in conjunction with other studies to set priorities for sources where emissions reduction may be required. For assessment purposes an average wood stove was assumed to burn wood at the rate of 3.0 kg/hr during a 24-hr period of the heating season. An average fireplace burns wood at the rate of 8.5 kg/hr. It is assumed that both units have chimneys 5.2 m high and are located in areas with a population density of 21 persons/km^2.

Source severity is defined as the ratio of the time-averaged maximum gound level concentrations ($\overline{\chi}_{max}$) of species emitted from the source to a hazard factor (F), i.e., $S = \overline{\chi}_{max}/F$. For criteria emissions, F is the primary ambient air quality standard (PAAQS), while for noncriteria emissions, it is a reduced threshold limit value (TLV®/300). Tables 1 and 2 give the severities for the average wood-burning sources.

Severities for individual residential sources may differ greatly from the values given in Tables 1 and 2 because of the variability found in the population. Those parameters that significantly affect severity include emission factors[a], wood consumption rates[a], duration of burning[a], stack heights, and wind speeds. In addition, the hazard factors for noncriteria pollutants and the equations used to calculate $\overline{\chi}_{max}$ contain a number of assumptions. An in-depth study of all these factors would be necessary to define the actual dimensions of the potential environmental impact. However, these results together with the bioassay results do indicate that there is reason for concern, especially when the possible effects of multiple sources are considered.

[a] These factors depend in turn on the type of combustion equipment, the type and condition of wood, and the method of burning.

Another measure of potential environmental effect is the affected population, defined as the number of persons around an average source who are exposed to a specified average ground level concentration ($\bar{\chi}$). These values are given in Tables 1 and 2 for $\bar{\chi}/F \geq 0.05$ and $\bar{\chi}/F \geq 1.0$. The largest value is for POM emissions from wood stoves, and equals 32 persons for $\bar{\chi}/F \geq 1.0$ and 732 persons for $\bar{\chi}/F \geq 0.05$. Again, these numbers would increase if multiple sources were considered.

Emissions from residential combustion systems are not typically controlled with add-on equipment; however, proper operation of each unit can significantly reduce emissions. Factors influencing emission levels include fuel properties, fuel type, firing rate, firing equipment design, cyclic operation of automatic equipment, and excess air ratio.

Residential combustion of wood for primary heating had shown a steady decline since the 1940's. Even from 1970 to 1974, wood combustion for primary heating decreased about 25%. However, interest in this form of heating has revived since 1974. U.S. Bureau of Census data up to 1976 indicate that primary residential heating with wood increased from 1974 to 1976, with the Northeast and West experiencing the greatest increase. Shipments of wood-fired heating equipment decreased until 1973, when the trend reversed. From 1962 to 1972, sales decreased by about 60%; but from 1972 to 1975 sales increased by 130%. Increased sales have been in the area of domestic heating stoves. Primary heating devices such as stoker furnaces began to show an increase in sales in 1976.

It is difficult to predict the impact the current shortage of oil and natural gas will have on the volume of wood combustion in the residential sector. The resurgence in residential wood combustion is expected to continue in the near term as the cost of wood fuel becomes even more competitive with distillate oil and electric resistance space heating.

SECTION 3

SOURCE DESCRIPTION

Only 1% of U.S. housing units with primary heating devices in 1976 burned wood for primary heating. Natural gas, the most popular heating fuel, was used in about 56% of the housing units (1). Emissions from the small fraction of housing units burning wood are major contributors to total national emissions from residential combustion. For example, a study done in 1973 (2) estimated that particulate emissions from wood-fired residential combustion contributed 11% of the total particulate emissions from all residential sources. By comparison, the analogous fractions of particulate emissions from coal, petroleum, and gas residential combustion were estimated to be 30%, 36% and 23%, respectively (in 1973). Particulate emissions from residential combustion sources accounted for 0.7% of total national particulate emissions from all man-made sources.

Table 3 gives the breakdown of units heated by different fuel types in 1976 (1). As discussed later in Section 6, the number of homes heating with wood has been increasing rapidly in recent years. Another home heating method that is once more gaining in popularity is residential coal combustion. A separate environmental assessment report on this source type has been published (3).

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(1) Current Housing Reports; Bureau of the Census Final Report H-150-76; Annual Housing Survey: 1976, Part A; General Housing Characteristics for the United States and Regions. U.S. Department of Commerce, Washington, D.C., February 1978 179 pp.

(2) Surprenant, N., R. Hall, S. Slater, T. Susa, M. Sussman, and C. Young. Preliminary Emissions Assessment of Conventional Stationary Combustion Systems; Volume II - Final Report. EPA-600/2-76-046b, PB 252 175, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina, March 1976. 557 pp.

(3) DeAngelis, D. G., and R. B. Reznik. Source Assessment: Residential Combustion of Coal. EPA-600/2-79-019a, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina, January 1979. 143 pp.

TABLE 3. HOUSING UNITS HEATED BY A PARTICULAR FUEL IN 1976 (1)

	Rural	Urban	Total units
Utility gas	6,286,000	34,932,000	41,219,000
Bottled, tanked or liquefied petroleum gas	3,712,000	527,000	4,239,000
Fuel oil, kerosene	5,785,000	10,666,000	16,451,000
Electricity	3,954,000	6,197,000	10,151,000
Coke or coal	311,000	174,000	484,000
Wood	820,000	92,000	912,000
Other fuels	8,000	78,000	86,000
Total	20,860,000	52,666,000	73,542,000

SOURCE DEFINITION

Wood-fired residential combustion sources include all equipment that burns wood for household heat or aesthetic purposes. These devices produce up to 530 MJ/hr of heat in occupied structures containing one or two housing units although under typical operating conditions, most units produce well under 100 MJ/hr. Wood burned for primary or auxiliary heating (primarily in wood stoves) and wood burned aesthetically (primarily in fireplaces) are all included in the source population.

A negligible amount of wood is burned for cooking and hot water heating. Discussions with manufacturers have indicated that very few persons use wood for hot water heating. In 1976 approximately 208,000 housing units, or 23% of the units heating with wood (1), used wood for cooking. It is estimated that cooking requires about 10% of the energy used for heating (4, 5). Therefore, the amount of wood used for cooking is approximately 2% of that used for heating with those fuels.

Also excluded from this source type are wood-fired devices located in large multiunit structures since they represent only a small portion of the total wood combustion for residential heating. In

(4) Patterns of Energy Consumption in the United States. Prepared by Stanford Research Institute for Office of Science and Technology, Executive Office of the President, Washington, D.C., January 1972. 221 pp.

(5) Wells, R. M., and W. E. Corbett. Electrical Energy as an Alternate to Clean Fuels for Stationary Sources: Volume I. Contract 68-02-1319, Task 13, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina, March 1976. 181 pp.

1970, approximately 99% of all housing units heated by wood were located in structures having fewer than 3 housing units (6).

EQUIPMENT DESCRIPTION AND OPERATION

A wide variety of wood-fired combustion equipment is available for residential usage. The most popular devices are masonry or prefabricated metal fireplaces, and radiating or circulating metal stoves. Larger forced air furnaces and boilers are also used in the United States, but to a much lesser extent (7, 8).

Fireplaces and stoves operate in essentially the same manner. Wood is manually placed on a metal grate in the unit and ignited. A natural draft of room air passes over the wood and escapes up the chimney, providing combustion air to maintain the fire. Energy released by the fire heats the room by radiation, conduction, and convection. Ash removal is also performed manually. Residential wood-fired furnaces and boilers operate in a similar fashion where combustion air may be provided by blowers or natural draft.

Despite these similarities, there are substantial differences between the various types of residential combustion units. These differences are primarily related to equipment configuration and combustion efficiency, as described in the following subsections.

Fireplaces

A typical wood-burning, masonry fireplace is shown in Figure 1. These devices are commonly used for secondary heating and aesthetic purposes, but rarely for primary heating due to their poor thermal efficiencies. Regular masonry fireplaces have efficiencies of no greater than 10% in cold weather (7). When used in conjunction with another form of heating, they can actually result in an overall loss of heat, because of the large volume of heated room air going up the chimney.

The intake air rate of an open fireplace has been measured at 0.04 m^3/s to 0.16 m^3/s, which is considerably greater than the air intake rate needed to maintain combustion (8). An average

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(6) Census of Housing: 1970 Subject Reports; Bureau of the Census Final Report HC(7)-4; Structural Characteristics the Housing INventory. U.S. Department of Commerce, Washington, D.C., June 1973. 450 pp.

(7) The Old Wood Stove is in Demand Again. Dayton Journal Herald, 170(27):19, 1977.

(8) Soderstrom, N. Heating Your Home with Wood. Times Mirror Magazines, Inc., Harper & Row, New York, New York, 1978. 207 pp.

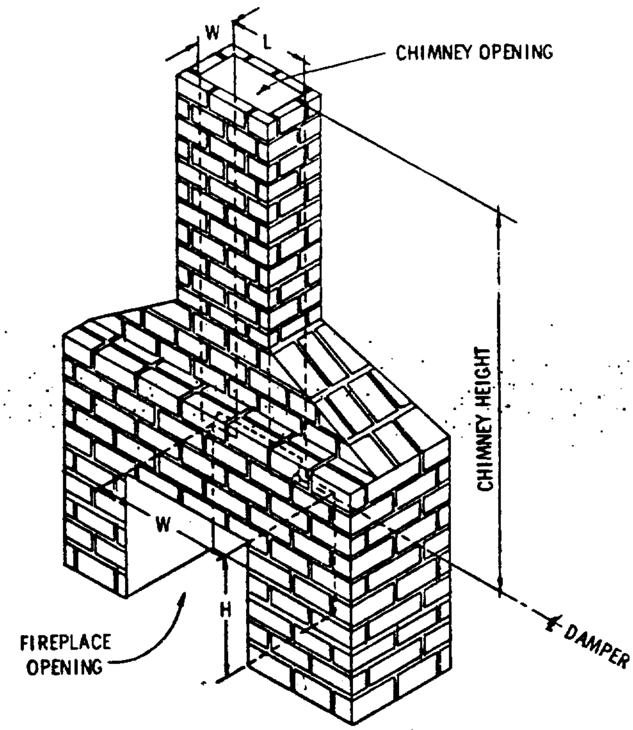

Figure 1. Typical masonry wood-burning fireplace (9).

insulated house with ∿270 m^3 of living space will normally undergo a complete exchange with outdoors air approximately every hour. A fireplace, taking in air at a rate of 0.09 m^3/s, causes the air exchange rate to more than double. Thus, the radiant heating effect of the fire is partially or wholly negated by increased infiltration of cold air from outdoors.

The options for minimizing air exchange are limited. The fireplace opening can be covered with a glass screen or a metal damper can be placed in the fireplace throat. The first option minimizes air exchange at the expense of heat loss up the chimney. The radiant energy transmitted by the fire is partially absorbed or reflected by the glass screen.

A more practical approach to minimizing air exchange is the installation of a metal damper in the throat of the fireplace. A damper controls the intake of room air, reduces the wood consumption rate and eliminates the escape of warm air when there is no fire. Several other mechanical devices are available on the market to increase radiant heat yields from fireplaces; however, these devices do not eliminate the intake of heated room air (9, 10).

The efficiency of masonry fireplaces can be improved by using outside air rather than room air for combustion purposes. Unfortunately, most fireplaces are not equipped in this fashion (10).

Various types of prefabricated metal fireplaces are available on the market. These include stovelike fireboxes designed for installation in existing masonry fireplaces, "zero clearance"[a] fireplaces which physically resemble their masonry counterparts, and free standing fireplaces (8).

Prefabricated fireboxes are normally equipped with glass doors and louvers to regulate the intake of combustion air from the room. In addition, these units are surrounded by a duct through which floor-level air is drawn by natural convection, heated, and returned to the room. Although the glass doors reduce radiant heat transfer from the fire, prefabricated fireboxes tend to be more efficient than open masonry fireplaces due to the reduction in room air losses up the chimney and the return of heated convection air to the room.

Zero-clearance fireplaces consist of a heavy-gauge steel firebox lined with firebrick on the inside and surrounded by multiple steel walls spaced for air circulation. In operating principle, they are very similar to the prefabricated metal fireboxes described above. Some models are also equipped with combustion air inlets that draw cool air from other rooms or from outdoors to avoid the loss of heated air up the chimney. In general, zero-clearance fireplaces are somewhat more efficient than open masonry fireplaces.

The most common freestanding fireplace models consist of an inverted sheet-metal funnel and stovepipe directly above the firebed and grate. However, units such as the Ben Franklin stove may also be considered freestanding fireplaces when operated with

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[a] Zero-clearance fireplaces are so-named because the insulative value of the walls and bottom allow placement directly adjacent to combustible walls or floors.

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(9) Snowden, W. D., D. A. Alguard, G. A. Swanson, and W. E. Stolberg. Source Sampling Residential Fireplaces for Emission Factor Development. EPA-450/3-76-010, U.S. Environmental Proteciton Agency, Research Triangle Park, North Carolina, November 1975. 173 pp.

(10) Manufacturers Brochure. Bolap, Inc., of Colorado, Fort Collins, Colorado.

the doors open. Like masonry fireplaces, these units are inherently inefficient due to the large volumes of heated room air drawn up the chimney. Freestanding fireplaces may be slightly more efficient than masonry fireplaces, however, since all sides of the fire chamber are exposed to the room.

Stoves

The wood-burning stove is a freestanding, cast iron or sheet steel unit similar to a metal fireplace. The major difference is that stoves are equipped with doors through which wood is loaded into the firebox. During operation, these doors are closed and the combustion air intake rate is controlled by movable air inlets. In comparison to the 0.04 m^3/s to 0.16 m^3/s air intake rates for fireplaces, stoves normally draw only 0.01 m^3/s to 0.05 m^3/s (8). Thus, stoves are inherently more efficient than fireplaces due to the reduction in heated room air losses.

Two basic types of stoves are available on the market: radiating stoves, such as the Ben Franklin model, and circulatory stoves (8). A radiating stove consists of a single cast iron or heavy-gauge sheet steel shell lined with firebrick which serves as the firebox and heat radiator. Most radiating stoves are also equipped with burners for cooking. In general, a maximum thermal efficiency of approximately 60% is attainable with radiating stoves.

Circulating stoves consist of an inner firebox enclosed by a decorative steel jacket (resembling an oil space heater) which absorbs radiant energy from the walls of the fire chamber and releases heat to air circulating both inside and outside the jacket. Air flow through the annulus may be provided by natural convection or automatic blowers, depending upon the model. Many circulating stoves are also equipped with thermostats and automatically-controlled dampers to regulate combustion air intake and thus, heat output. With this regulated combustion air rate, wood may only need to be charged to the stove every 6 hr to 12 hr, depending on the type of wood burned.

One practical advantage of the circulatory stove over the radiating stove is a reduction in the severity of the burn received if the stove is accidentally touched. On the negative side, circulatory stoves are not designed for cooking.

The completeness of combustion and the amount of heat transferred from a stove, regardless of whether it is a radiating or circulatory model, depends heavily upon the air flow pattern through the unit. The size and number of combustion air inlets and internal channels that direct flow are the major factors that affect air flow.

The basic combustion air flow patterns are updraft, diagonal and s-flow. In the updraft air flow type of stove, air enters at the base of the stove and passes through the wood to the stove pipe at the top. Secondary air enters above the wood to assist in igniting unburned volatiles in the combustion gases. This type air flow usually results in flames reaching the stove pipe, and the combustion process is fairly complete. However, updraft stoves provide very little gas-phase residence time, which is needed for efficient transfer of heat from the gases to the walls of the stove and stovepipe. Thus, thermal efficiency is limited to some extent.

Stoves designed for diagonal air flow are equipped with an air inlet in the front, but do not have an inlet for secondary air. Air enters at the lower vent and travels diagonally upward through the wood and out of the stovepipe at the upper back. It has been suggested that this stove type does not allow hot volatiles in the combustion gases to mix sufficiently with air to insure complete combustion. Gas-phase residence times in diagonal flow units are also very short, which limits heat transfer and thermal efficiency in itself.

The s-flow type stove is currently the most popular design in the United States. This type of stove is equipped with both a primary and a secondary air inlet like the updraft stove. However, gases are not allowed to exit directly up the flue because a metal baffle plate is located several inches above the burning wood to lengthen the retention time. The baffle plate absorbs a considerable amount of heat and reflects and radiates much of it back to the firebox. This longer gas-phase residence time results in improved combustion when the proper amounts of air are provided, and enhances heat transfer from the gas phase. Ironically, the major problem with this type of stove is that the gases are often cooled below creosote condensing temperatures, creating deposits in the flue.

Forced-Air Furnaces and Boilers

Larger forced air furnaces and boilers are also being used in the U.S., although to a much lesser extent than stoves or fireplaces. Figure 2 shows a schematic of a typical forced air furnace (11). These units are essentially large circulating stoves, the major differences relating to heating capacity and heat delivery system configuration. While stoves are usually intended to heat a single room or area, furnaces are designed to heat entire houses through

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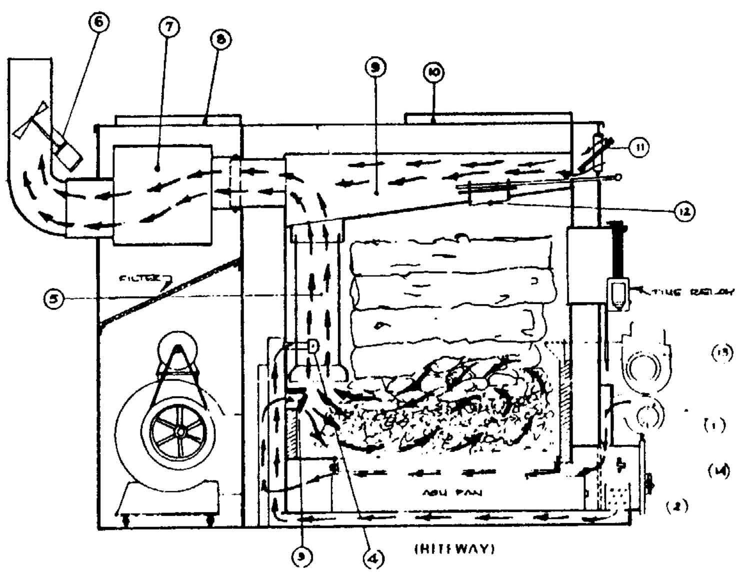
(11) Riteway, The Quality Name in Energy Innovations (manufacturers brochure). Riteway Manufacturing Co., Harrisonburg, Virginia. 12 pp.



(1) ASH PIT BLOWER CONTROLLED BY ROOM THERMOSTAT CREATES FORCED DRAFT IN THE COMBUSTION CHAMBER. AIR ENTERS THROUGH TWO PORTS (3) LOCATED ON EITHER SIDE OF THE GAS COMBUSTION FLUE (5).
(2) SECONDARY AIR ENTERS HERE, IS PREHEATED AS IT PASSES THROUGH SPACE UNDER THE FURNACE AND UPWARD THROUGH A SMALL DUCT INTO THE GAS COMBUSTION FLUE (4).
(3) AIR PORTS WHICH DIRECT THE FLOW OF PRIMARY AIR FROM THE BACK TOWARD THE FRONT OF THE COMBUSTION CHAMBER.
(4) SECONDARY AIR DUCT.
(5) GAS COMBUSTION FLUE LOCATED COMPLETELY INSIDE COMBUSTION CHAMBER, INSURING HIGH TEMPERATURE NECESSARY TO BURN THE GASES.
(6) DRAFT INDUCER OPERATES CONSTANTLY TO GUARANTEE SUFFICIENT SECONDARY AIR UNDER ALL DRAFT CONDITIONS.
(7) RETURN AIR IS PREHEATED AT THE HEAT EXCHANGER BEFORE PASSING THROUGH THE FILTER AND INTO THE BLOWER, WHICH IN TURN FORCES IT OVER THE FURNACE BODY.
(8) OPENING FOR RETURN AIR PLENUM IN TOP OF FAN CHAMBER.
(9) BYPASS AIR FLUE IN TOP OF FURNACE.
(10) OPENING IN TOP OF FURNACE FOR WARM AIR PLENUM.
(11) BAROMETRIC DAMPER PERMITS A CONTINUAL FLOW OF AIR INTO THE BYPASS AIR FLUE. THE DRY WARM AIR IS MIXED WITH FLUE GASES AND HELPS IN PREVENTING THE SMOKEPIPE AND CHIMNEY FROM SWEATING.
(12) DIRECT DRAFT DAMPER LOCATED NEAR TOP OF FUEL DOOR. OPEN ONLY WHEN ADDING FUEL TO PREVENT SMOKE FROM ESCAPING INTO THE FURNACE ROOM.
(13) OPTIONAL OIL OR GAS BURNER. DAMPER OPERATED BY A SOLENOID ISOLATES BURNER FROM THE COMBUSTION CHAMBER WHEN BURNER IS NOT IN OPERATION. IF WOOD FAILS TO MAINTAIN THE DESIRED TEMPERATURE, A ROOM THERMOSTAT CAN AUTOMATICALLY ENERGIZE THE SOLENOID AND OIL BURNER TO SUPPLY REQUIRED HEAT UNTIL WOOD SUPPLY IS REPLINISHED.
(14) GRATE BARS

Figure 2. Wood-fired forced air furnace (11). (Wood-fired boiler is similar in design and operation except furnace jacket is water-filled).

a system of ductwork. Most of these furnaces are thermostatically controlled and require little attention by the user. The thermostat is set at the desired temperature and wood is supplied as necessary, or every 2 to 12 hours, depending on the type of wood burned and the heating requirements. When the furnace is activated by the thermostat, a damper automatically admits air for combustion (other units have combustion air fans). When the demand for heat is satisfied, the damper closes automatically; however, enough air is passed through the system to keep the firebed burning slowly. In this type of unit, ash is collected in an ash pan which must be dumped every week to every 2 weeks.

Return air for the heating system is provided by a blower, which is activated and deactivated in conjunction with a damper. When the blower is activated, air is forced over the furnace body through a system of heat exchangers and into the ductwork system.

Hot water boiler systems currently available on the market are analogous to forced air furnace systems except that water, rather than air, is used as the heat transfer medium (12). Hot combustion gases from the firebox pass through firetubes around which water is circulated. The heated water is then pumped through a series of baseboard heat exchangers to heat the building.

Wood-fired furnaces and boilers can be used as the sole source of heating, or they can be used in tandem with conventional heating systems. In the latter case, the systems are designed so that the conventional heating source is automatically activated if the fire in the wood combustor is extinguished.

FUEL CHARACTERISTICS

Hardwoods and softwoods are the two basic types of wood. When air-dry, most hardwoods weigh over 400 kg/m^3 and have a maximum heating value of 20 MJ/kg. Softwoods weigh less than 400 kg/m^3, air-dry. The most resinous softwoods have a maximum heating value of 21 MJ/kg. Resins and a higher lignin content account for this higher heating value (8). Because of their higher density, hardwoods have a higher heating value than softwoods on a volume basis.

Although softwoods have a higher heating value, hardwoods are favored for use as fuel for various reasons. Because the cells of softwoods are larger and lighter, they tend to burn faster which results in more frequent charges and the handling of more logs in the process. In addition to this disadvantage, the unburned and partially combusted resins of softwoods tend to

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(12) Introducing Tritherm® (manufacturers brochure). Meyer Company, Glenwood Springs, Colorado. 2 pp.

condense in flues and form a creosote that is very difficult to remove. Softwoods ignite more easily and have an extremely hot burn. For these reasons, they are used in many cases for kindling and then hardwoods are added to sustain the burn.

The composition of wood plays an important role in residential combustion and resulting emissions. Wood composition can vary from one type to another or within a wood type, depending upon geographical location.

The materials present in woods include carbohydrates, phenolic substances (lignin), terpenes, aliphatic acids, alcohols, proteins, and inorganic constituents. Cellulose, a carbohydrate, and lignin, a phenolic compound, make up more than 90% of wood substance, with lignin composition ranging from 15% to 30% (13). Chemically, all hardwoods and all softwoods are similar except for the resin and lignin content.

The elemental composition of wood, regardless of species, is approximately 50% carbon, 6% hydrogen, and 44% oxygen on an ash- and moisture-free basis (14). Sulfur content is often undetectable and nitrogen content is typically less than 0.5%. Ash content of wood is also low, rarely exceeding 5% on a dry weight basis (15).

Mineral constituents of wood vary greatly between species and between trees within a species. The most prominent minerals in wood are calcium, potassium, magnesium, phosphates, and silicates.

Volatile content of wood is high, ranging from 60% to 80% on a dry weight basis. Because of this, wood has a low ignition temperature and rapid heat release. Heating value of wood ranges from about 18.1 MJ/kg to about 24.7 MJ/kg on a dry weight basis (16).

Moisture content of wood burned in residential units can vary greatly because the wood is stored outdoors exposed to the weather. Dry wood has a higher heating value than an equal

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(13) Koch, P. Utilization of the Southern Pines. Agriculture Handbook No. 420, U.S. Department of Agriculture Forest Service, Washington, D.C., August 1972. 1662 pp.

(14) Rieck, H. G., Jr., E. G. Locke, and E. Tower. Charcoal, Industrial Fuel from Controlled Pyrolysis of Sawmill Wastes. The Timberman, 46127:49-54, 1944.

(15) Schorger, A. W. Chemistry of Cellulose and Wood. McGraw-Hill Book Company, New York, New York, 1926. p. 51.

(16) Fernandez, J. H. Why Not Burn Wood? Chemical Engineering, 84(11):159-164, 1977.

volume of green wood of the identical type. Approximately 8% of a hardwood's heating value is lost at 12% moisture content (8). It is difficult to maintain temperatures high enough to drive off water and generate the gases necessary for ignition of green woods. If green woods must be burned, better results are obtained by burning them in combination with dry woods.

Moisture content can range from 10% to 50% and averages approximately 20% (17). Tables 4 and 5 list typical analyses of several woods used for residential combustion (15, 16). An average mineral composition of wood is given in Table 6 (15, 18).

COMBUSTION PROCESS

General Description

Because of the varied nature of wood, a precise quantification of combustion chemistry is difficult to determine. The oxidation of hydrocarbons to carbon dioxide and water is only part of the reaction chemistry. Solid fuels contain a variety of chemical constituents that may participate to some extent in reactions at high temperatures. Mineral substances such as silicates and sulfides oxidize in the flame during combustion to form ash that is either retained in the fuel bed or entrained in the flue gas.

The processes involved in the combustion of wood are illustrated in Figure 3 (19). Solid fuels burn in diffusion flames because the solid phase cannot be mixed with oxidants on a molecular scale. With the addition of radiant energy from an ignition device or the combustion zone, volatile components are vaporized and flow away from the solid surface while the solid portion of the fuel begins to pyrolyze. At this point, no oxidation of the fuel at the surface occurs due to lack of intimate contact with the oxidant. A diffusion flame is established where the mixing of combustibles and oxidant forms a combustable mixture. This is noted as the primary combustion zone. Additional transfer of heat results in additional vaporization of volatiles, pyrolysis, and a rise in surface temperature of the solid. After the depletion of volatiles, oxidation of the solid materials commences.

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(17) Panshin, A. J., E. S. Harrar, J. S. Bethel and W. J. Baker. Forest Products, Their Sources, Production, and Utilization. McGraw-Hill Book Company, New York, New York, 1953.

(18) Mingle, J. G., and R. W. Boubel. Proximate Fuel Analysis of Some Western Wood and Bark. Wood Science, 1(1);29-36, 1968.

(19) Edwards, J. B. Combustion, Formation, and Emission of Trace Species. Ann Arbor Science, Ann Arbor, Michigan, 1974. 240 pp.

TABLE 4. COMPOSITION AND FUEL PROPERTIES OF TYPICAL GRADES OF DRY WOOD (16)[a]

	Ultimate analysis, wt %						Fuel properties: Heating value, MJ/kg		Fuel properties
	Carbon	Hydrogen	Sulfur	Oxygen	Nitrogen	Ash	Higher	Lower	Atmos. air required at zero excess air, kg/MJ
Softwoods:									
Cedar, white	48.80	6.37		44.46		0.37	19.5[b]	18.1	0.305
Cypress	54.98	6.54		38.08		0.40	23.0[b]	21.5	0.306
Fir, Douglas	52.3	6.3		40.5	0.1	0.8	21.1	19.6	0.310
Hemlock, western	50.4	5.8	0.1	41.4	0.1	2.2	20.1	18.7	0.304
Pine:									
Pitch	59.00	7.19		32.68		1.13	26.3[b]	24.7	0.302
White	52.55	6.08		41.25		0.12	20.7[b]	19.5	0.311
Yellow	52.60	7.02		40.07		0.31	22.4[b]	20.8	0.306
Redwood	53.5	5.9		40.3	0.1	0.2	21.0	19.8	0.311
Hardwoods:									
Ash, white	49.73	6.93		43.04		0.30	20.7[b]	19.1	0.305
Beech	51.64	6.26		41.45		0.65	20.4[b]	19.0	0.314
Birch, white	49.77	6.49		43.45		0.29	20.1[b]	18.7	0.307
Elm	50.35	6.57		42.34		0.74	20.4[b]	19.0	0.308
Hickory	49.67	6.49		43.11		0.73	20.2[b]	18.7	0.306
Maple	50.64	6.02		41.74	0.25	1.35	20.0	18.6	0.310
Oak:									
Black	48.78	6.09		44.98		0.15	19.0[b]	17.6	0.308
Red	49.49	6.62		43.74		0.15	20.2[b]	18.7	0.305
White	50.44	6.59		42.73		0.24	20.5[b]	19.0	0.308
Poplar	51.64	6.26		41.45		0.65	20.7[b]	19.3	0.308

[a] Blanks indicate no data reported.

[b] Calculated from reported higher heating value of kiln-dried wood assumed to originally contain 80% moisture (i.e., 80 g water per 100 g of dry wood).

TABLE 5. COMPOSITION OF ASH FROM TYPICAL GRADES OF WOOD (15)

Wood grade	Weight percent of ash											
	Ash[a]	K_2O	Na_2O	CaO	MgO	P_2O_5	SO_3	Cl	SiO_2	Fe_2O_3	C	CO_2
Mockernut hickory	0.73	18.93	3.38	25.21	6.66	7.98	2.06	0.28	1.80	0.25	1.20	32.44
Red oak	0.85	16.41	3.68	32.25	3.58	7.04	2.29	0.68	0.97	0.21	1.38	31.85
White oak	0.37	29.90	1.94	21.21	2.43	6.72	4.11	1.00	3.20	0.50	3.87	25.16
Water oak	1.09	15.46	7.22	32.67	4.84	6.38	0.38	0.77	1.00	0.37	0.65	28.86
Shortleaf pine	0.35	12.97	1.18	43.31	2.11	2.75	0.86	0.67	2.35	0.18	0.74	33.26
Dogwood	0.95	20.03	7.65	27.81	4.92	1.02	2.72	0.74	2.00	0.12	0.40	28.16
White ash	0.43	34.74	0.94	17.68	0.45	2.69	8.58	0.26	7.05	2.92	1.14	23.65
Chestnut	0.22	13.33	7.67	36.43	1.56	5.00	2.68	0.88	4.17	2.65	1.19	24.82
Sycamore	0.99	18.24	5.92	24.98	0.49	9.65	5.73	0.45	9.66	4.13	2.14	19.01
Longleaf pine	0.49	10.34	2.34	37.24	4.21	2.65	4.32	0.21	3.41	2.76	1.11	31.47
Evergreen magnolia	0.60	11.87	2.52	23.64	4.89	5.31	3.46	0.23	7.32	1.60	17.22	22.66

[a]Percent ash in wood based on wood with 10% moisture.

TABLE 6. ELEMENTAL COMPOSITION OF WOOD (15,18)

Constituent formula	Mean concentration, g/kg	Number of samples	Reference
Al_2O_3	0.4	4	18
CaO	3.1	15	15, 18
Cl	0.04	11	15
Fe_2O_3	0.2	15	15, 18
K_2O	1.1	15	15, 18
MgO	0.6	15	15, 18
MnO	0.5	4	18
P_2O_5	0.3	15	15, 18
SiO_2	0.5	15	15, 18
Na_2O	0.2	11	15
TiO_2	0.005	4	18

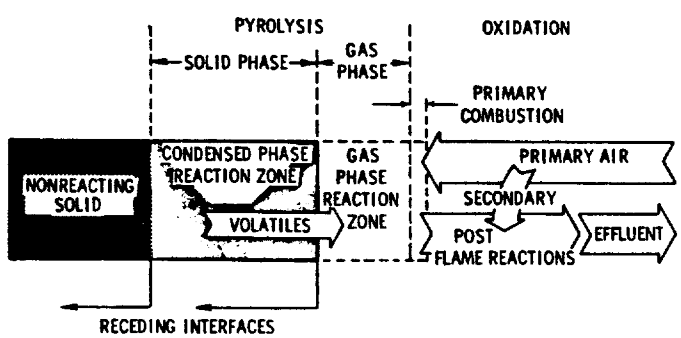

Figure 3. Combustion of a solid (19).

Oxygen diffuses to the solid surface where oxidation of the nonvolatiles occurs, resulting in the release of more heat. Carbon monoxide and dioxide, water, hydrogen, nitrogen oxides, sulfur oxides, carbonaceous particulates from noncombusted vapors, and metallic oxides from the noncombustible constituents may form or begin to form in the combustion zone.

The postflame region is that region directly downstream of the combustion zone. Many chemical and physical processes may occur in the postflame region because the reactants may be both gaseous and solid. Radical recombination reactions such as the recombination of atomic oxygen and the formation of water from atomic hydrogen and the hydroxyl radical occur as the combustion gases cool. Carbon dioxide and atomic hydrogen are formed by the combination of carbon monoxide and the hydroxyl radical. Pyrolytic reactions such as the reaction of fuel species and their products with other hydrocarbons, hydrogenation of hydrocarbons to species of greater saturation, and the cracking of hydrocarbons are among the postflame reactions. Finally, nonash particulates may be formed by both condensation and agglomeration (19).

The high moisture content typical of most woods must be driven off before ignition can take place. The heat needed for this can reduce the potential heat recovery from the wood by as much as 15% (13, 16). The general course of thermal degradation of wood can be described in terms of four reaction zones that develop parallel to the wood surface (13):

Reaction zone	Description
Zone A, to 200°C	Water vapor, formic acid, acetic acid, and possibly carbon dioxide are evolved. Charring may eventually occur at temperatures as low as 95°C.
Zone B, 200°C to 280°C	Reaction becomes exothermic between 150°C and 260°C. With sufficient time - and under favorable conditions - ignition is possible.
Zone C, 280°C to 500°C	Ignitable gases are evolved and block oxygen from the wood surface, thereby preventing ignition. Charcoal is formed with a lower thermal conductivity than wood; thus heat conduction to the center of the wood - and therefore attainment of the exothermic reaction point - is delayed. Surface temperatures high enough for spontaneous combustion have been reported over the entire range of Zone C.
Zone D, above 500°C	Charcoal glows.

During these combustion processes more than 200 compounds can potentially be distilled from the wood (20). Under efficient combustion conditions, these compounds are decomposed; however, residential wood-fired combustion is often not efficient. Creosote, a major constituent of wood distillation, can partially escape combustion and condense in the chimney. Chimney fires can be traced to the build up and ignition of this creosote.

During residential combustion fresh wood is placed on top of a burning fuel bed, as illustrated in Figure 4.

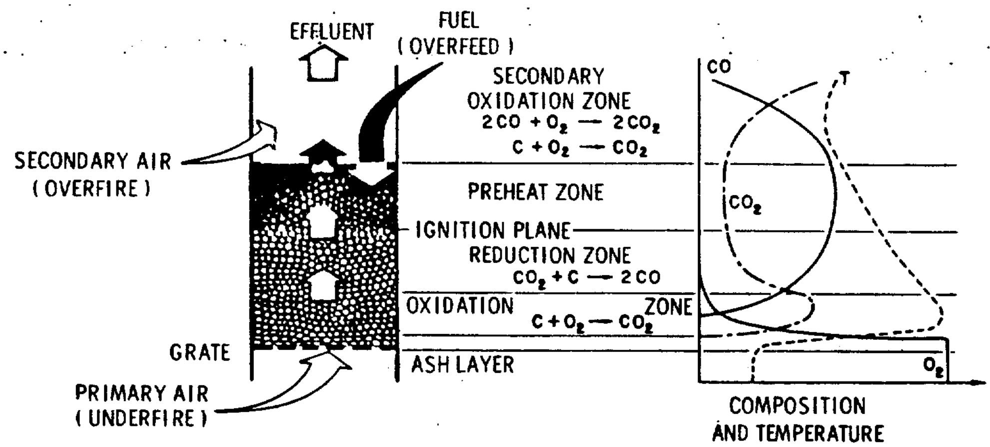

Figure 4. Overfeed arrangement of a solid fuel bed (19).

Reprinted from The Formation and Emission of Trace Species by J. B. Edwards, p. 151, by permission of Ann Arbor Science Publishers, Inc.

The air supply is divided between primary air fed under the bed (or grate) and secondary air introduced above the fuel bed. Primary air controls the rate of combustion since the wood cannot be consumed at a rate greater than the available oxygen permits. A deficiency or excess of primary air will reduce the bed temperature and the rate of combustion. Secondary air controls the overall combustion efficiency by oxidizing unburned or partially oxidized combustible materials emitted from the fuel bed. Overfeed firing has a major problem: as fresh fuel is supplied to the top of the bed, it is preheated with hot combustion gases, and its volatile components are driven off. Because little or no oxygen is present in this region, these volatile organics can only undergo pyrolytic reactions. Therefore, secondary air must be supplied for oxidation to take place above the fuel bed. However, excess secondary air can quench the reactions and produce partial

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(20) Wood Chemistry, Second Edition, Volume 2. Wise, L. E., and E. C. Jahn, eds. Reinhold Publishing Co., New York, New York, 1974. pp. 475-479.

oxidation products. Usually 30% to 50% total excess air is sufficient to compensate for incomplete mixing and permits optimal combustion of the wood, although complete combustion is never attained in residential combustion equipment. Overall excess air levels for combustion of wood in fireplaces have been measured as high as 2,000% excess air (9).

Another characteristic of overfeed firing of wood is that combustion gases flow through the fuel bed in channels resulting in localized areas of high velocity. This high velocity gas entrains smaller particles of partially combusted material carrying them away from the combustion zone.

Most residential wood combustion is batch-fed. When fresh fuel is placed on top of the fuel bed, a number of process steps are upset. At this stage of combustion, the flue gas contains the greatest load of combustible species, and the overall combustion process is least efficient (19).

SOURCE POPULATION AND GEOGRAPHICAL DISTRIBUTION

Wood-fired residential combustion equipment is used throughout the United States and is concentrated in heavily forested areas of the nation as shown in Figures 5 and 6 (21). This distribution pattern reflects the desire of homeowners to burn fuel that is readily available and inexpensive.

The number of residential housing units heated with wood is compiled by the U.S. Bureau of Census. However, detailed state by state compilations are only conducted every ten years at the time of the census. Housing surveys are conducted annually and give estimated statistics on a regional basis. In addition, statistical data are only reported for primary heating with wood, not for auxiliary heating or aesthetic use. In this assessment, two reports from the 1970 U.S. Census of Housing (6, 22) were used in conjunction with the 1976 annual Housing Survey (1) to estimate the actual population of wood-fired heating devices used in homes. Details are presented in Appendix A, and the results are given in Table 7.

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(21) Diller, D. Forest Conservation. In: McGraw-Hill Encyclopedia of Science and Technology, Volume 5. McGraw-Hill Book Company, New York, New York, June 1960. p. 445.

(22) Census of Housing: 1970, Volume 1, Housing Characteristics for States, Cities, and Counties, Part 1; United States Summary. U.S. Department of Commerce, Washington, D.C., December 1972. 512 pp.

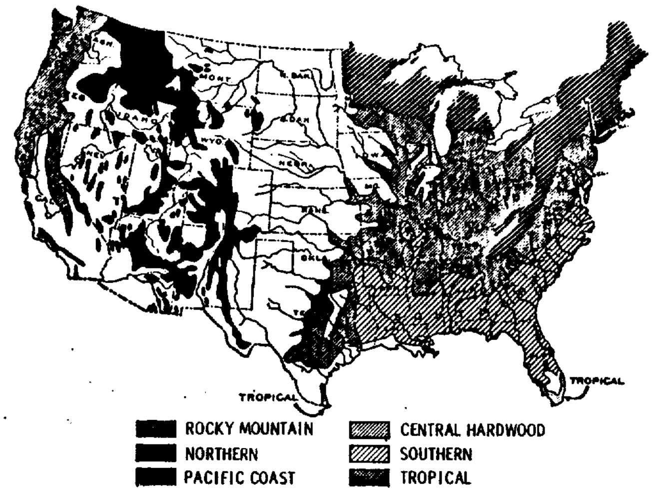

Figure 5. The natural forest regions of the United States (21).

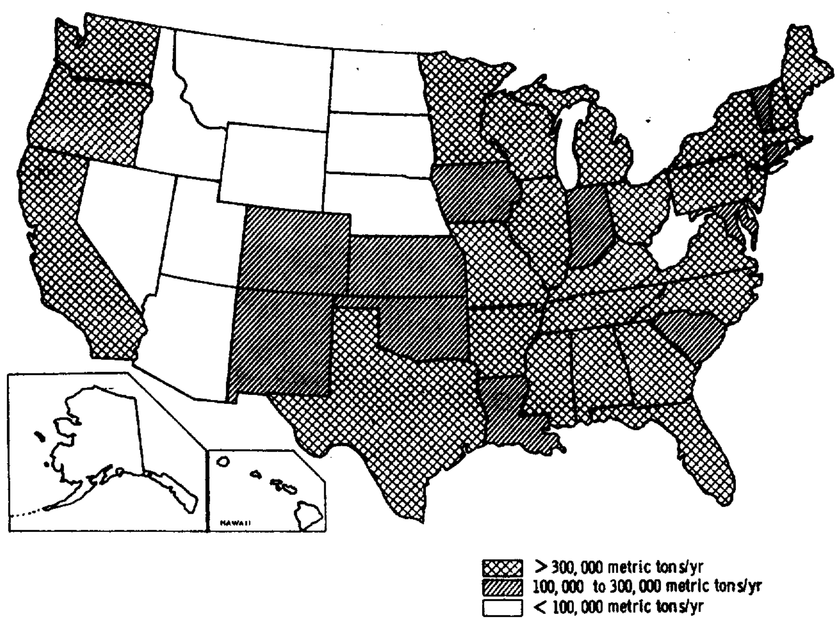

Figure 6. Estimated residential wood consumption by state in 1976.

Wood consumption by the residential sector in 1976 was determined from the source population and the annual heating degree-days per state. This methodology has been discussed in other reports (23-25), and detailed calculations are presented in Appendix A. Results appear in Table 7.

All 50 states have housing units that are heated by wood. The greatest concentration is in the Southeast where the heating season is shorter and milder. Of the approximately 912,000 residential wood-fired primary heating devices, approximately 39% are located in the states of Alabama, Georgia, North Carolina, South Carolina, Tennessee, and Virginia, and about 90% are located in rural housing.

There is no exact information available on the population of wood-fired combustion equipment used for auxiliary heat or aesthetic purposes. However, data on sales of wood stoves and new homes built with fireplaces indicate that this population is much larger than the population of primary heating devices. Estimated secondary wood consumption is also greater. The assumptions and rationale used in arriving at the estimates given in Table 7 are presented in Appendix A.

In order to characterize the source population and evaluate the potential environmental impact of residential wood combustion, operating parameters were determined for the average wood stove and fireplace. It must be recognized that this source exhibits a high degree of variability that is not reflected in the use of average parameters. Details are given in Appendix B. The average wood stove is located in the South region of the United States. It was estimated that the average wood stove consumes wood at the rate of 3 kg/hr during the coldest months of the year, and that the average fireplace consumes wood at the rate of 8.5 kg/hr. Additional assumptions were (1): Both units have emission heights of 5.2 m; (2) The population density around the average source is 21 persons/km^2 (55 persons/mile^2).

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(23) 1973 NEDS Fuel Use Report. EPA-450/2-76-004, PB 253 908, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina, April 1976. 124 pp.

(24) Guide for Compiling a Comprehensive Emission Inventory (Revised). Publication No. APTD-1135, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina, March 1973. 204 pp.

(25) Myers, J. P., and F. Benesh. Methodology for Countywide Estimation of Coal, Gas, and Organic Solvent Consumption. EPA-450/3-75-086, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina, December 1975. 152 pp.

TABLE 7. ESTIMATED POPULATION OF WOOD-FIRED RESIDENTIAL COMBUSTION EQUIPMENT AND WOOD CONSUMED BY THE RESIDENTIAL SECTOR, 1976

State	Number of housing units burning wood[a]		Fuel consumption, metric tons/yr	
	Primary	Auxiliary or aesthetic	Primary	Auxiliary or aesthetic
Alabama	59,200	586,000	150,000	390,000
Alaska	3,600	64,500	50,000	43,000
Arizona	15,200	414,500	36,000	60,000
Arkansas	53,500	278,300	280,000	120,000
California	54,000	4,329,900	190,000	620,000
Colorado	2,000	492,100	18,000	100,000
Connecticutt	2,300	589,200	22,000	190,000
Delaware	700	73,300	5,000	19,000
Florida	25,200	1,180,300	30,000	300,000
Georgia	70,700	618,800	340,000	270,000
Hawaii	2,600	143,400	1,000	21,000
Idaho	6,700	151,100	60,000	31,000
Illinois	3,100	1,608,400	29,000	390,000
Indiana	6,800	753,600	58,000	180,000
Iowa	1,600	421,300	17,000	100,000
Kansas	3,400	344,100	25,000	82,000
Kentucky	26,700	557,100	190,000	200,000
Louisiana	17,000	469,100	38,000	120,000
Maine	15,900[b]	284,800	180,000	460,000
Maryland	6,500	520,300	47,000	130,000
Massachusetts	3,000	1,103,200	26,000	360,000
Michigan	6,300	1,258,900	76,000	510,000
Minnesota	7,700	559,600	110,000	410,000
Missippi	56,700	362,100	200,000	130,000
Missouri	45,100	711,000	330,000	290,000
Montana	5,100	144,000	60,000	30,000
Nebraska	1,300	227,700	12,000	54,000
Nevada	1,600	120,300	15,000	17,000
New Hampshire	5,000[b]	220,800	57,000	350,000
New Jersey	2,500	1,380,800	19,000	280,000
New Mexico	18,500	736,100	120,000	94,000
New York	15,900	3,577,100	150,000	1,200,000
North Carolina	65,000	684,100	340,000	170,000
North Dakota	200	89,000	3,000	21,000
Ohio	5,400	1,515,600	47,000	360,000
Oklahoma	13,700	379,500	78,000	62,000
Oregon	39,900	556,400	290,000	290,000
Pennsylvania	14,100	2,271,600	120,000	460,000
Rhode Island	500	179,200	5,000	76,000
South Carolina	48,800	342,000	200,000	87,000

(continued)

TABLE 7 (continued)

State	Number of housing units burning wood[a]		Fuel consumption, metric tons/yr	
	Primary	Auxiliary or aesthetic	Primary	Auxiliary or aesthetic
South Dakota	1,700	96,100	21,000	23,000
Tennessee	60,500	697,800	320,000	890,000
Texas	26,500	1,000,200	87,000	410,000
Utah	1,200	204,100	11,000	42,000
Vermont	2,700[b]	125,600	33,000	200,000
Virginia	48,200	635,600	280,000	160,000
Washington	22,200	853,400	210,000	450,000
West Virginia	5,100	237,800	36,000	60,000
Wisconsin	7,900	644,800	90,000	260,000
Wyoming	900	73,400	10,000	15,000
Total	912,000	35,467,900	5,100,000	11,500,000

[a] Each housing unit was assumed to contain only one wood-fired combustion device.

[b] A dramatic increase has been noted since 1976 in primary heating with wood in New England because of rising fuel costs. Recent estimates indicate 20% of the homes in Maine and New Hampshire and 18% of the homes in Vermont employ wood for primary heating (26-28).

(26) Vermont Surveys Wood Stove Use. Wood'N Energy, 3(2):8, September 1978.

(27) Turner, A. Personal communication. Vermont Energy Office, Montpelier, Vermont, October 1979.

(28) Shapiro, A. Personal communication. Wood Energy Research Corporation, Camden, Maine, October 1979.

SECTION 4

EMISSIONS

SELECTED POLLUTANTS

Residential combustion of wood produces a number of atmospheric emissions and a solid residue. Atmospheric emissions include particulates, sulfur oxides, nitrogen oxides, carbon monoxide, organic materials including POM's, and mineral constituents. The solid residue is composed of inert materials in the fuel (ash), unburned or partially burned fuel, and materials formed during combustion.

Organic species, carbon monoxide, and to a large extent the particulate matter emissions result from incomplete combustion of the fuel. Sulfur oxides arise from oxidation of fuel sulfur, while nitrogen oxides are formed both from fuel nitrogen and by the combination of atmospheric nitrogen with oxygen in the combustion zone. Mineral constituents in the particulate emissions result from minerals in the wood that are released from the wood matrix during combustion and entrained in the combustion gases.

Polycyclic organic materials result from the combination of free radical species formed in the flame. The synthesis of these molecules is dependent on many combustion variables, including the presence of a chemically reducing atmosphere. Under reducing conditions, radical chain propagation is enhanced, allowing the buildup of a complex organic molecule such as a POM compound. A list of POM species encountered during sampling is presented later in Table 9. Because POM compounds melt/sublime at about 200°C, which is approximately 100°C higher than exhaust gas temperatures for this source (29), they should be in the condensed phase when emitted.

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(29) Preliminary Characterization of Emissions from Wood-fired Residential Combustion Equipment. EPA-600/7-80-040, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina, March 1980. 153 pp.

EMISSIONS DATA

Little work has been done to characterize the emissions from wood-fired residential combustion sources. A few measurements of emissions from wood-fired combustion units have been reported within the past ten years. The limited amount of emissions data available on the residential combustion of wood is attributed to the increasingly small role that wood played in the primary heating of homes in the past.

The 1973 oil embargo and the current energy crisis have created a renewed interest in wood-fired residential combustion. As a result, characterization studies have been undertaken on the local, State, and Federal levels. As a part of this effort, a special sampling project was conducted under the Source Assessment program to better quantify criteria pollutant emissions and characterize other types of emissions from this source. Three wood-burning units - a zero clearance fireplace, a baffled stove, and a non-baffled stove - and four wood types - oak and pine, both seasoned and green - were tested. A complete description of the sampling project and test results appears in a separate report (29).

Emissions data from all available sources are compiled for reference in Appendix C. Average emission factors based on this data are presented in Table 8 (9, 29-33). In some cases test results were reported as pollutant concentrations in the exhaust gas instead of as emission factors, and material balance considerations were needed to convert from one to the other. These calculations and the averaging procedures used in arriving at Table 8 are also included in Appendix C.

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(30) Clayton, L., G. Karels, C. Ong, and T. Ping. Emissions from Residential Type Fireplaces. Source Tests 24C67, 26C, 29C67, 40C67, 41C67, 65C67, and 66C67, Bay Area Air Pollution Control District, San Francisco, California, January 31, 1968. 6 pp.

(31) Butcher, S. S., and D. I. Buckley. A Preliminary Study of Particulate Emissions from Small Wood Stoves. Journal of the Air Pollution Control Association, 27(4):346-347, April 1977.

(32) Source Testing for Fireplaces, Stoves, and Restaurant Grills in Vail, Colorado. Contract 68-01-1999, U.S. Environmental Protection Agency, Region VIII, Denver, Colorado. (Draft document submitted to the EPA by PEDCo-Environmental, Inc., December 1977.) 29 pp.

(33) Butcher, S. S., and E. M. Sorenson. A Study of Wood Stove Particulate Emissions. Journal of the Air Pollution Control Association, 29(7):724-728, 1979.

TABLE 8. AVERAGE EMISSION FACTORS FOR WOOD-FIRED RESIDENTIAL COMBUSTION[a]

Emission species	Emission factor, g/kg		Emission factor range, g/kg		Reference
	Wood stove	Fire-place	Wood stove	Fire-place	
Total particulates	9.1	13	1.0 - 28	2.4 - 26	9, 29-33
Filterable particulates	3.6	2.8	1.8 - 7.0	1.8 - 4.8	9, 29
Condensable organics	5.5	10	3.3 - 12.0	5.9 - 9.1	29
SO_x	0.2		0.16 - 0.24		29
NO_x	0.49	2.0	0.2 - 0.8	0.84 - 4.3	29, 30
CO	180	67	91 - 370	15 - 140	9, 29, 30, 32
Hydrocarbons	13	74	0.3 - 44	2.1 - 300	9, 29, 32
POM	0.27	0.029	0.19 - 0.37	0.017 - 0.044	9, 29
Major organic species	1.6	0.55	1.1 - 2.6	0.46 - 0.64	29
Pentanol	0.07		0.03 - 0.1		29
Acetaldhyde	0.11	0.70	0.03 - 0.2	0.29 - 1.3	29, 30
Isobutyraldehyde	1.5	1.4	0.1 - 4.3		29
Formaldehyde	0.23	1.5	0.1 - 0.3	0.4 - 1.6	29, 30
Propionaldehyde	0.15		0.1 - 0.2		29
n-Butyraldehyde	0.47	0.2	0.2 - 0.6		29
Phenols		1.0		<0.02 - 2.4	30
Total carbonyls (as CHOH)		4.4		1.6 - 9.4	30
Organic acids (as CH_3COOH)		6.4		<0.02 - 15	30
Additional organics (including CH_4)		27		9.6 - 44	30

[a]The data used in obtaining these average emission factors, as well as the procedure for averaging them, can be found in Appendix C.

Distinct average emission factors were calculated for wood-burning stoves and fireplaces because emissions from the two kinds of units have been shown to differ significantly (9, 29-33). All emissions data are for uncontrolled emissions, because no emission control devices are used in the residential sector. A discussion of the emissions data for individual emission species follows. When possible, the effect of various operating parameters (e.g., wood type, combustion equipment, or burning cycle) on emissions is indicated.

Particulate Material

Interpretation of particulate emissions data is difficult because of the large amount of condensable organic material present in the exhaust gas. Test results are strongly dependent on the methods used to collect samples, and different studies have employed different methods. The standard method recognized by EPA for collection of particulate samples, EPA Method 5, consists of a sampling probe connected to a filter held at >100°C, followed by a series of impingers in an ice bath, a sampling pump, and a dry gas meter (34). Normally everything collected on or before the filter in the front half of the sampling train is considered the particulate catch. However, during sampling tests on residential wood combustion a significant quantity of organic material passes through the filter in the vapor phase and condenses in the impingers. This material generally weighs more than the particulate catch from the front half of the train. Because this organic material would normally condense in the atmosphere (some of it may in fact condense within the chimney), it can be considered as a part of the total particulate emissions.

In order to reduce ambiguity, the following terminology has been employed in evaluating particulate emission test data.

- Filterable particulates - All material collected on or before the filter of the sampling train. This includes organic material not in the vapor phase that is collected on the filter.

- Condensable organics - Organic material that condenses in the impingers of a sampling train.

- Total particulates - The sum of filterable particulates and condensed organics.

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(34) Environmental Protection Agency - Part II - Standards of Performance for New Stationary Sources - Revision to Reference Method 1-8. Method 5 - Determination of Particulate Emissions from Stationary Sources. Federal Register, 42(160):41776-41782, August 1977.

Five previous studies have characterized particulate emissions from wood-fired residential combustion sources. These studies indicate that there is no significant difference between the emissions from fireplaces and wood stoves. Average particulate emission factors range from 1.0 g/kg to 28 g/kg. Although the methods of collection and quantification are not consistent, each study indicates a degree of variability in emission factors which can be attributed to the variable nature of the combustion process. Factors such as the addition of fresh wood charges, fuel bed configuration, size of fuel charge, etc., all have some effect on emissions generated from fireplaces and wood burning stoves.

Analysis of particulates for carbon, hydrogen and nitrogen indicated a composition similar to that of wood. The composition remained unchanged upon extraction with methylene chloride. The particulates were a dark brown or black sooty, carbon-black-like material which exhibited some resinous qualities (29).

Sulfur Oxides

Sulfur oxides are formed during combustion by the oxidation of sulfur in the fuel. They are not released to any great extent in residential wood combustion because the sulfur content of wood is low, typically <0.1% in branches and wood components (35).

Only one study has examined emissions of sulfur oxides during residential wood combustion, and that study was limited to two tests using EPA Method 6. Results were close to the detection limit for the method, and gave emission factors of 0.16 g/kg and 0.24 g/kg (29). These values are nearly equal to those expected based on material balance considerations, assuming 100% conversion of fuel sulfur to SO_2.

Recent work with burning of wood bark suggests a substantially lower conversion rate (approximately 5%) of bark sulfur to SO_2, with the balance accounted for in the bottom ash combustion products (36). This study employed a more sensitive measurement technique and also determined the sulfur content of the ash. Most of the fuel sulfur was recovered in the ash, confirming the low sulfur levels found in the stack gas.

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(35) Shriner, D. A., and G. S. Henderson. Sulfur Distribution and Cycling in Dedicuous Forest Watershed. Journal of Environmental Quality, 7(3):392-397, 1978.

(36) Oglesby, H. S., and R. O. Blosser. Information on the Sulfur Content of Bark and Its Contributions to SO_2 Emissions When Burned as Fuel. Paper 79-6.2, Presented at the 72nd Annual Meeting of the Air Pollution Control Association, Cincinnati, Ohio, June 24-29, 1979.

Nitrogen Oxides

Nitrogen oxide formation depends primarily on fuel nitrogen content, amount of excess air used, combustion temperature and design of combustion equipment. Average emission factors have been found to range from 0.2 g/kg to 0.8 g/kg for wood stoves and from 0.8 g/kg to 4 g/kg for fireplaces (29, 30).

Based on average emission factors, fireplaces emit about four times as much NO_x as stoves per unit of wood burned. Increased NO_x emissions are generally associated with higher combustion temperatures. This is consistent with the lower CO and POM emissions (products of incomplete combustion) associated with fireplaces since higher combustion temperatures are indicative of greater combustion efficiency. A possible explanation for this may be the higher combustion air velocities associated with the fireplace which cause more rapid burning and thus higher temperatures.

Carbon Monoxide

Carbon monoxide is a product of incomplete combustion and is a major pollutant emitted from wood-burning fireplaces and stoves. Average emissions of carbon monoxide are highly variable, ranging from 91 g/kg to 370 g/kg for wood stoves and from 15 g/kg to 140 g/kg for fireplaces. Although emission factors for the wood-burning stoves appear higher, a statistical analysis showed no significant difference. According to this analysis an unaccounted for variable exerted significant influence on the CO emission factors. This same study also indicated that CO formation is very sensitive to changing fuel bed conditions which may account for the variability between replicate test results (29).

Condensable Organics

Condensable organic emissions are usually determined by measuring the mass of material collected in the back of the EPA Method 5 particulate train. The back half of this train consists of impingers containing distilled water and a back-up filter which collects most of the materials passing through the front-half filter. This material is often considered as part of the particulate emissions.

Average emission factors range from 3.3 g/kg to 12 g/kg, with no significant difference between fireplace and wood stove emissions. However, emissions are over two times higher when burning green pine than when burning other wood types tested. It has been shown that the condensable organics account for 54% to 76% of the total mass collected by the EPA Method 5 train (29).

Volatile Hydrocarbons

Low-molecular-weight volatile hydrocarbon emissions have been measured in three studies (9, 29, 32). Two of the studies (9, 32) measured total volatile hydrocarbon emissions from fireplaces while the remaining study (29) measured volatile hydrocarbon species in the C_1 to C_6 range from a fireplace and two wood-burning stoves.

Measurement of volatile hydrocarbons was accomplished by collection of a gas sample in an inert gas sampling bag and subsequent injection into a gas chromatograph with a flame ionization detector (GC/FID). The resultant emission data demonstrates a high degree of variability in volatile hydrocarbon emissions ranging from 0.3 g/kg to 3.0 g/kg from wood-burning stoves and from 2 g/kg to 400 g/kg from fireplaces.

Major Organic Species

Four studies have been conducted to quantify and characterize organic species present in the emissions of wood-fired combustion equipment (9, 29, 30, 33). Preliminary analyses of total particulate matter (33) indicated that benzene extractables range from 42% to 67% of the total particulate mass. About 45% of the mass of benzene extractables appeared in the neutral fraction of acid base extractions. Polycyclic aromatic hydrocarbons are expected to be included in this neutral fraction. Other fractions included carboxylic acid fraction (15%), phenol fraction (40%) and organic base fraction (∿1%) (33).

Another study to characterize major organic species was conducted on four fireplaces in the San Francisco area (9). Emissions of organic acids, phenols, formaldehyde, and acetaldehydes were quantified while burning eucalyptus, oak and madrone. Emission data for this study are presented in Appendix C and range from <0.03 g/kg to 29 g/kg for organic acids, <0.04 g/kg to 4.8 g/kg for phenols, 0.3 g/kg to 11 g/kg for formaldehyde and 0.4 g/kg to 2.5 g/kg for acetaldehyde.

A more extensive characterization of organic emission was accomplished as part of the Source Assessment program (29). Major organic species were collected using the Source Assessment Sampling System (SASS) train and a modified Method 5 train equipped with an XAD-2 resin trap. This study found that a significant quantity of organic matter was trapped in the aqueous impingers after passing through the filter and XAD-2 resin trap. That which was recovered from the resin and the particulate fractions would only partially dissolve in hexane during the sample workup. A portion of this insoluble material was soluble in methylene chloride, but there remained an insoluble solid white residue.

It was found that the hexane-soluble fraction was totally chromatographable by GC/MS, while the methylene chloride fraction of hexane-insoluble material was largely nonchromatographable. The chromatographable fraction, however, did contain approximately 50% of the POM compounds recovered from the total system. The nonchromatographable portion was found to contain a variety of high molecular weight fused-ring aromatics (e.g., POM's, MW greater than 302).

The organic material recovered from the aqueous portion of the sampling train was for the most part nonchromatographable. Ions associated with organic acids were found and determined to be of molecular weight greater than 284, e.g., stearic acid. The detection limit of GC/MS for organic acids is quite high and their presence may go undetected.

Over 50 organic species were identified, in addition to POM compounds, in the flue gas from wood-burning stoves and fireplaces. Specific organic acids (i.e., acetic acid, formic acid, etc.) were not identified because of the very high detection limit, but their presence was substantiated as mentioned earlier. The organic species emitted were dominated by the naphthalenes, furans, phenols, cresols, and aldehydes. Total organic emission factors, except POM's, based on individual speciation for each condition ranged from 1.1 g/kg to 2.6 g/kg for wood stoves and 0.46 g/kg to 0.64 g/kg for fireplaces. A list of the organic compounds detected is given in Table 9.

Emission factors for POM compounds and total POM's were also generated during this study. The average emission factors for fireplace emissions range from 0.025 g/kg to 0.036 g/kg. This range is an order of magnitude lower than the total POM emissions from wood stoves which range from 0.19 g/kg to 0.37 g/kg. This is consistent with the CO and NO_x results, which indicate more efficient combustion and/or higher combustion temperatures in the fireplace. The total POM emissions from fireplaces are in agreement with results from another study (9). The average emission factors for fireplace emissions from this earlier study range from 0.017 g/kg to 0.044 g/kg. A list of POM compounds detected during sampling is also given in Table 9.

Trace Elements

One study to date has characterized trace element emissions from wood-fired residential heating equipment (29). Table 10 presents emission factors for 29 elements identified in the analysis of samples taken while burning green pine in the nonbaffled stove. The emission factors determined during this study range from 1.4×10^{-7} g/kg to 4.2×10^{-2} g/kg. The highest values measured (1.8×10^{-2} g/kg for silver and 4.2×10^{-2} g/kg for zinc) are believed to be in error. The analytical procedure tends to give high readings at low concentrations for silver, and many of the

TABLE 9. MAJOR ORGANIC SPECIES AND POM COMPOUNDS DETECTED IN EMISSIONS FROM WOOD-FIRED RESIDENTIAL COMBUSTION EQUIPMENT (9, 29)

Major organic species	POM compounds
Ethyl benzene/xylenes	Anthracene/phenanthrene
Indane	Methyl-anthracenes/-phenanthrenes
Indene	C_2-alkyl-anthracenes/-phenanthrenes
Methyl indanes	Cyclopenta-anthracenes/-phenanthrenes
Methyl indenes	Fluoroanthene
Naphthalene	Pyrene
Methyl-naphthalenes	Methyl-fluoranthenes/-pyrenes
C_2-alkyl-naphthalenes	Benzo(ghi)fluoranthene
Biphenyl	Cyclopenta[ed]pyrene
Acenaphthylene	Benzo(c)phenanthrene
Acenaphthene	Benz(a)anthracene/chrysene
Benzo furan	Methyl-benzanthracenes -benzphenanthrenes/-chrysenes
Dibenzo furan	C_2-alkyl-benzanthracenes/ -benzophenanthrenes/ -chrysenes
Fluorene	Benzofluoranthenes
Anthracene/phenanthrene	Benzopyrenes/perylene
Phenol	Methyl cholanthrene
Cresols	Indeno(1,2,3-ed)pyrene
C_2-alkyl phenols	Benzo(ghi)perylene
C_3-alkyl phenols	Anthanthrene
C_4-alkyl phenols	Dibenzanthracenes/-phenanthrenes
Benzaldehyde	Dibenzopyrenes
C_1-alkyl benzaldehyde	
C_2-alkyl benzaldehyde	
C_3-alkyl benzaldehyde	
Methyl furans	
C_2-alkyl-furans/furfural	
C_3-alkyl-furans/methylfurfural	
C_4-alkyl-furans/C_2-alkylfurfural/ methoxy phenols	
Catechol	
Naphthol	
Methoxy phenols	
Methyl methoxy phenols	
C_2-alkyl methoxy phenols	
C_3-alkyl methoxy phenols	
C_4-alkyl methoxy phenols	
C_5-alkyl methoxy phenols	
Fluorenone	
Fluorenone isomer	
Anthrone	
Benzanthrone	
Dimethoxy phenol	
Hydroxy methoxy benzaldehyde	
Hydroxy methoxy acetophenone	
Hydroxy methoxy benzoic acid	
Hydroxy dimethoxy benzaldehyde	
Hydroxy dimethoxy acetophenone	
Hydroxy dimethoxy cinnamaldehyde	
C_2-alkyl biphenyls (or isomers)	
C_3-alkyl biphenyls (or isomers)	
C_4-alkyl biphenyls (or isomers)	
Di-C_8-alkyl-phthalate	

elements (including silver) were near their detection limits in this analysis. The high reading for zinc may result from volatilization of zinc from the galvanized stack.

The ash composition of wood can range from 0.2% to 2.2%, with calcium, potassium, phosphorus, sodium, and magnesium being the predominant elements (15, 18). These same elements have relatively high emission factors in Table 10 (on the order of 10^{-3} g/kg), but the absolute value of the emission factors is two or three orders of magnitude lower than their typical concentration in wood. Thus, only a small fraction of the trace element content of wood is emitted to the atmosphere, with the majority remaining as a component of bottom ash.

TABLE 10. ELEMENTAL EMISSIONS FROM A NONBAFFLED WOODBURNING STOVE (29)

Emission species	Emission factor, g/kg	Emission species	Emission factor, g/kg
Aluminum	1.5×10^{-3}	Mercury	1.3×10^{-4}
Antimony	2.3×10^{-5}	Molybdenum	2.3×10^{-4}
Arsenic	1.3×10^{-4}	Nickel	1.7×10^{-3}
Barium	2.0×10^{-4}	Phosphorus	7.0×10^{-5}
Beryllium	1.4×10^{-7}	Selenium	1.3×10^{-4}
Boron	7.3×10^{-4}	Silicon	2.7×10^{-3}
Cadmium	3.6×10^{-5}	Silver	1.8×10^{-2}
Calcium	4.7×10^{-3}	Sodium	3.0×10^{-3}
Chromium	9.0×10^{-4}	Strontium	1.1×10^{-5}
Cobalt	6.0×10^{-5}	Tin	3.8×10^{-5}
Copper	1.7×10^{-4}	Titanium	1.0×10^{-5}
Iron	3.1×10^{-3}	Vanadium	1.5×10^{-5}
Lead	4.8×10^{-4}	Yttrium	9.3×10^{-5}
Magnesium	2.9×10^{-4}	Zinc	4.2×10^{-2}
Manganese	1.9×10^{-4}		

POTENTIAL ENVIRONMENTAL EFFECTS

Of significant concern in residential wood combustion are the possible environmental and health effects. These were addressed in this study through bioassay testing of combustion emissions and by means of certain evaluation criteria established under the Source Assessment program.

Bioassay Testing

Bioassay tests were conducted on stack emission and bottom ash samples from residential wood-fired combustion equipment (29, 37). Results of these tests are presented in Table 11.

Discussions of the results observed for each bioassay test are given in the following subsections. Specific test procedures can be found in a report prepared by Litton Bionetics, Inc., (LBI) for the EPA under a separate contract (37).

Ames Mutagenicity Assay--

The Ames Mutagenicity Assay test evaluates samples for genetic activity in the *Salmonella*/microsome plate assays with and without the addition of mammalian metabolic activation preparations. The genetic activity of a sample is measured in these assays by its ability to revert the *Salmonella* indicator strains from histidine dependence to histidine independence. The degree of genetic activity of a sample is reflected in the number of revertants that are observed on the histidine free medium.

The results shown in Table 11 show that all of the emission samples (twenty-four) tested exhibited mutagenic activitiy. None of the four samples of combustion residue showed mutagenic activity (37).

CHO Clonal Toxicity Assays--

This test determined the cytotoxicities of twenty-four residential wood combustion emission samples to cultured Chinese hamster cells (CHO-K1 cell line). The measure of cytotoxicity was the reduction in colony-forming ability after a 24-hour exposure to the test material. After a period of recovery and growth, the number of colonies that developed in treated cultures was compared to the colony number in unexposed vehicle control cultures. The concentration of test material that reduced the colony number by 50% was estimated graphically and referred to as the EC_{50} value (effective concentration for 50% survival). The toxicity of the test materials is evaluated as high, moderate, low, or nondetectable according to the range of EC_{50} values (Table 12).

The cytotoxicity results indicated that the combined organic module rinse plus SAD-2 resin extracts were, as a group, more toxic than the particulate catch extracts. Within each group,

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(37) Level I Bioassays on Thirty-two Residential Wood Combustion Residue Samples. Contract 68-02-2681, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina. (Final report submitted to the EPA by Litton Bionetics, Inc. November 1979). 211 pp.

TABLE 11. RESULTS OF BIOASSAYS PERFORMED ON SASS AND COMBUSTION RESIDUE SAMPLES (29, 37)

			Bioassay test				
Sample code[a]	Combustion equipment	Wood type	Ames mutagenicity[b]	CHO clonal toxicity[c]	RAM[c]	Acute rodent quantal[c]	Freshwater daphnia[c]
A-1 (1)	Fireplace	Seasoned oak	+	H			
A-1 (2)	Fireplace	Seasoned oak	+	H			
A-1 (3)	Fireplace	Seasoned oak	-		L		
A-2 (1)	Fireplace	Green oak	+	H			
A-2 (2)	Fireplace	Green oak	+	H			
A-2 (3)	Fireplace	Green oak					ND
A-3 (1)	Fireplace	Seasoned pine	+	H/M			
A-3 (2)	Fireplace	Seasoned pine	+	H			
A-3 (3)	Fireplace	Seasoned pine				NT	
A-4 (1)	Fireplace	Green pine	+	H			
A-4 (2)	Fireplace	Green pine	+	H			
B-1 (1)	Baffled stove	Seasoned oak	+	M			
B-1 (2)	Baffled stove	Seasoned oak	+	H			
B-2 (1)	Baffled stove	Green oak	+	H			
B-2 (2)	Baffled stove	Green oak	+	H			
B-2 (3)	Baffled stove	Green oak	-		L		
B-3 (1)	Baffled stove	Seasoned pine	+	H			
B-3 (2)	Baffled stove	Seasoned pine	+	H			
B-3 (3)	Baffled stove	Seasoned pine	-		L		
B-4 (1)	Baffled stove	Green pine	+	H/M			
B-4 (2)	Baffled stove	Green pine	+	H			
C-1 (1)	Nonbaffled stove	Seasoned oak	+	H			
C-1 (2)	Nonbaffled stove	Seasoned oak	+	H			
C-2 (1)	Nonbaffled stove	Green oak	+	H			
C-2 (2)	Nonbaffled stove	Green oak	+	H			
C-2 (3)	Nonbaffled stove	Green oak				NT	
C-3 (1)	Nonbaffled stove	Seasoned pine	+	H			
C-3 (2)	Nonbaffled stove	Seasoned pine	+	H			
C-3 (3)	Nonbaffled stove	Seasoned pine					ND
C-4 (1)	Nonbaffled stove	Green pine	+	H			
C-4 (2)	Nonbaffled stove	Green pine	+	H			
C-4 (3)	Nonbaffled stove	Green pine	-				

Note: Blanks indicate samples were not submitted for testing.

[a]Corresponds to the following sample fractions: (1) particulate catch extract, supplied to LBI as methylene chloride solutions; (2) combined organic module rinse and XAD-2 extract, supplied to LBI as dimethyl sulfoxide solutions; (3) combustion residue (bottom ash), supplied to LBI as dry ash.

[b]"+" designates mutagenic activity; "-" designates no mutagenic activity.

[c]ND, no detectable toxicity; NT, not tested; L, low toxicity; M, moderate toxicity; H, high toxicity.

TABLE 12. DEFINITION OF RANGE OF EC_{50} VALUES

Toxicity[a]	EC_{50} values, μg/L
High	<10
Moderate	10 to 100
Low	100 to 1,000
Nondetectable	>1,000

[a]Formulated by Litton Bionetics, Inc., under EPA Contract 68-02-2581, Technical Directive No. 301.

the fireplace samples were either the least toxic or in the least toxic half of the test samples, and the nonbaffled stove extracts were generally the most toxic. No generalizations regarding the fuel source were apparent. Twenty-one of the twenty-four samples tested were considered highly toxic, the others were described as moderately toxic, or at the moderate-to-high toxicity borderline. These results are given in Table 11 (37).

Rabbit Alveolar Macrophage (RAM) Cytotoxicity Assays--
This assay determined the cytotoxicities of four bottom ash samples to rabbit alveolar macrophages in short term culture. The cells were exposed to the test material for 20 hours and the following five cellular variables were measured: percent viability index, total protein, total ATP, and ATP content per 10^6 cells. Each parameter was compared to the corresponding value obtained for untreated control cell cultures. Then the concentrations of test material that reduced each parameter by 50% were estimated graphically and referred to as the EC_{50} values. This assay was limited to applied concentrations in the 3 μg/L to 1,000 μg/L range.

All four test materials (bottom ashes) were evaluated as having low toxicity to RAM cells because the most sensitive assay parameter (usually ATP content) yielded EC_{50} values in the 100 to 1,000 μg/L concentration range (37).

Level I Rodent Toxicity--
The Level I rodent toxicity test evaluates the acute toxicity of the test materials when administered orally to male and female rats. Attempts were made to test two combustion residue (ash) samples. This test was abandoned when it proved impossible to prepare a liquefied form of the combustion residue (37).

Freshwater Toxicity Assays--

Freshwater toxicity assay determines the toxicity of the combustion residue samples during 48-hour static exposure. The acute toxicities of two of the combustion residue samples were determined for the freshwater invertebrate *Daphnia magna*.

The toxicity of the test materials is evaluated as high, moderate, low, or nondetectable according to the range of EC_{50} values (Table 12). Both samples tested had nondetectable toxicity (37).

Environmental Evaluation Criteria

A series of evaluation criteria (source severity, affected population, state emissions burden, and national emissions burden) was established under the Source Assessment program to provide a uniform basis for comparing the relative environmental effects of different source types. Because these criteria are generally based on average source parameters and employ certain assumptions and approximations, they are not intended to provide an absolute measure of environmental impact. Rather, they are to be used in conjunction with other similar studies to set priorities for sources where emissions reduction may be required.

In this program source severity and affected population are used as measures of local environmental impact. Severity is defined as:

$$S = \frac{\bar{\chi}_{max}}{F} \quad (1)$$

where $\bar{\chi}_{max}$ = the time-averaged maximum ground level concentration for each emission species.

F = hazard factor

= primary ambient air quality standard (PAAQS) for criteria pollutants (particulates, hydrocarbons, NO_x, SO_x, and CO)

= a reduced threshold limit value (TLV®) for noncriteria pollutants (i.e., TLV x 8/24 x 1/100)[a]

[a] 8/24 = correction factor to adjust the TLV to a 24-hr exposure level. 1/100 = arbitrary safety factor.

Values of $\overline{\chi}_{max}$ were computed for an average residential source (as described at the end of Section 3) using the equation suggested by Turner (38):

$$\overline{\chi}_{max} = \chi_{max} \left(\frac{t_o}{t}\right)^{0.17} \tag{2}$$

where χ_{max} is the "instantaneous" (i.e., 3-min average) maximum ground level concentration as determined from the equation:

$$\chi_{max} = \frac{2\ Q}{\pi e u H^2} \tag{3}$$

where Q = emission rate, g/s
H = stack height, m
π = 3.14
e = 2.72
u = wind speed, m/s
= 4.5 m/s (national average)
t_o = 3 min
t = averaging time, min

Averaging times used in the calculation of $\overline{\chi}_{max}$ for the criteria pollutants were the same as those specified in the corresponding primary ambient air quality standards (PAAQS). For noncriteria pollutants, a 24-hour averaging time was employed.

Average emission rates were calculated from the average emission factors in Table 8 and the wood consumption rate of the average source (3 kg/hr for wood stoves and 8.5 kg/hr for fireplaces). The average stack height was taken to be 5.2 m (Appendix B). Further details on the derivations of the severity equations are given in the literature (3).

Table 13 presents the values of source severity for the average source. TLV's (39) for noncriteria pollutants and ambient air quality standards for criteria pollutants (40-42) are also listed.

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(38) Turner, D. B. Workbook of Atmospheric Dispersion Estimates. Public Health Service Publication No. 999-AP-26, U.S. Department of Health, Education, and Welfare, Cincinnati, Ohio, May 1970. 84 pp.

(39) TLVs® Threshold Limit Values of Chemical Substances and Physical Agents in the Workroom Environment with Intended Changes for 1976. American Conference of Governmental Industrial Hygienists, Cincinnati, Ohio, 1976. 94 pp.

(40) Federal Register, 36:22384, November 25, 1971.

(41) Federal Register, 43:46258, October 5, 1978.

(42) Federal Register, 44:8220, February 8, 1979.

TABLE 13. SOURCE SEVERITY FOR AVERAGE WOOD-FIRED RESIDENTIAL COMBUSTION UNITS[a]

Emission species	PAAQS, mg/m^3	TLV, mg/m^3	Source severity[b]	
			Wood stove	Fire-place
Total particulates	0.260		0.02	0.08
Filterable particulates	0.260		0.008	0.02
SO_x	0.365		0.0003	
NO_x	0.100		0.004	0.05
Hydrocarbons	0.160[c]		0.063	1.1
CO	40.0		0.004	0.005
POM		0.001	46	14
Formaldehyde		3.0	0.013	0.23
Acetaldehyde		180	0.0001	0.002
Phenols		19		0.03

[a]Blanks indicate no data available.

[b]Emissions assumed constant over a 24-hr period during the heating season.

[c]There is no primary ambient air quality standard for hydrocarbons. The value of 160 $\mu g/m^3$ used for hydrocarbons in this report is a recommended guideline for meeting the primary ambient air quality standard for oxidants.

Because EPA, in this program, assigned the low TLV of 1 $\mu g/m^3$ to potential carcinogens, POM emissions have the highest severities.[a]

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[a]The Source Assessment program has utilized an estimated "TLV" for carcinogens of 1 $\mu g/m^3$. The basis for this value is found in Reference 43. According to the data presented in Figure 13 on page 90 of Reference 43, the ambient level of carcinogens is 4.9 ng/m^3, which was adopted as an approximate hazard factor, F, in the source severity equation. The "TLV" was devised by multiplying 4.9 ng/m^3 by the safety factor of 300 to arrive at 1.47 $\mu g/m^3$, which was rounded off to 1 $\mu g/m^3$ for use in the Source Assessment program. Use of 1 $\mu g/m^3$ yields a hazard factor which approximately corresponds to the carcinogen exposure experienced by nonsmokers.

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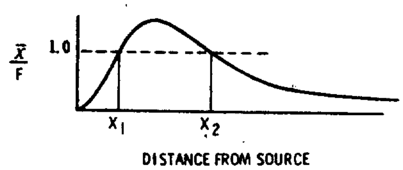
(43) Handy, R. and A. Schindler. Estimation of Permissible Concentrations of Pollutants for Continuous Exposure. EPA-600/2-76-155, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina, June 1976. 148 pp.

Severities for individual residential sources may differ greatly from the values given in Table 13 because of the variability found in the population. Those parameters that significantly affect severity include emission factors,[a] wood consumption rates,[a] duration of burning,[a] stack heights, and wind speeds. In addition, the hazard factors for noncriteria pollutants and the equations used to calculate $\overline{\chi}_{max}$ contain a number of assumptions. An in-depth study of all these factors would be necessary to define the actual dimensions of the potential environmental impact. However, the data in Table 13 together with the bioassay results do indicate that there is reason for concern, especially when the possible effects of multiple sources are considered. [A similar study on residential coal combustion indicated that emissions from an array of 100 houses caused a 30-fold increase in severity (3)].

In addition to source severity it is important to know how many people around an average residential combustion unit are exposed to high ground level concentrations. Dispersion equations predict that the average ground level concentration ($\overline{\chi}$) varies with the distance, x, away from a source. For elevated sources, $\overline{\chi}$ is zero at the source, increases to some maximum value, $\overline{\chi}_{max}$, as x increases, and then falls back to zero as x approaches infinity. Therefore a plot of $\overline{\chi}/F$ versus x will have the following appearance:



The affected population is defined as the number of persons living in the area around an average source where $\overline{\chi}/F$ is greater than 0.05 or 1.0. The mathematical derivation of the affected population can be found in Reference 3. The affected population for wood-fired residential combustion emissions is presented in Table 14. Emissions from an individual wood-fired combustion source affect few people, except in the case of POM emissions, where the maximum affected population is 700 persons for $\overline{\chi}/F > 0.05$ and 30 persons for $\overline{\chi}/F > 1.0$. The affected population varies with population density and will be greater in urban areas.

Another measure of the regional (as opposed to local) impact on the environment is the total annual emissions of each criteria pollutant. Estimated annual emissions from wood-fired residential combustion equipment on a state-by-state basis are derived and tabulated in Appendix D. These were calculated using emission

[a]These factors depend in turn on the type of combustion equipment, the type and condition of wood, and the method of burning.

TABLE 14. AFFECTED POPULATION FOR WOOD-FIRED RESIDENTIAL COMBUSTION (number of persons)

Emission species	Affected population[a]			
	$\bar{\chi}/F \geq 0.05$		$\bar{\chi}/F \geq 1.0$	
	Wood stove	Fire-place	Wood stove	Fire-place
Particulate	0	1	0	0
Hydrocarbons	0	10	0	0
POM	730	210	30	9
Formaldehyde	0	3	0	0

[a]Based on an average population density of 21 persons/km².

factors and fuel usage estimates. The appendix also shows the percent contribution of each source type to the total state emission burden from all stationary sources. In 1976 residential combustion of wood had emissions exceeding 1% of the total state emissions for at least one of the criteria pollutants in 49 states, as shown in Table 15.

Total national criteria emissions from this source and corresponding national emission burdens are given in Table 16. National emissions of criteria pollutants from wood-fired residential combustion can also be compared to emissions from other forms of residential combustion (Table 17). The data show that wood combustion contributes between 0.2% and 95% of the total from the residential sector.

Another emission species worthy of comparing on a national scale are POM's, because of their potential carcinogenicity. Table 18 gives a recent inventory of source types that emit more than 1 metric ton/year of POM's, nationwide (44). Data for certain sources have been revised based on more recent information. Total POM emissions from residential wood combustion, as determined in this report, are: primary wood heating, 1,400 metric tons; auxiliary heating, 2,400 metric tons; and fireplaces, 78 metric tons; for a total of 3,800 metric tons. This represents a substantial increase over the value reported in Reference 44 of 217 metric tons.

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(44) Eimutis, E. C., R. P. Quill, and G. M. Rinaldi. Source Assessment: Noncriteria Pollutant Emissions (1978 Update). EPA-600/2-78-044t, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina, July 1978. 149 pp.

TABLE 15. STATE LISTING OF RESIDENTIAL WOOD CRITERIA EMISSIONS THAT EXCEED 1% OF TOTAL STATE CRITERIA EMISSIONS

State	Residential wood criteria emissions as a percent of total state criteria emissions		
	Particulates	Hydrocarbons	CO
Alabama		1.4	5.0
Alaska	5.9	5.0	9.1
Arizona	1.4	1.7	1.7
Arkansas	2.7	3.2	8.3
California		1.5	1.3
Colorado		2.0	2.0
Connecticut	5.4	2.5	3.8
Delaware		1.0	1.9
Florida	1.5	1.6	1.8
Georgia	1.4	2.2	5.1
Hawaii		1.1	
Idaho	1.6	2.3	4.3
Illinois			
Indiana		1.1	1.2
Iowa		1.2	1.2
Kansas			1.6
Kentucky		2.1	5.7
Louisiana			
Maine	11.9	7.4	30.5
Maryland			2.2
Massachusetts	4.0	2.3	3.6
Michigan		1.8	2.9
Minnesota	1.8	2.2	4.0
Mississippi	1.9	2.8	7.0
Missouri	2.8	2.7	5.8
Montana	1.3		2.4
Nebraska		1.5	1.8
Nevada		1.9	2.1
New Hampshire	25.3	6.8	28.4
New Jersey	2.1	1.3	1.5
New Mexico	2.2	4.6	6.2
New York	8.3	3.0	4.2
North Carolina	1.0	2.0	5.0
North Dakota		1.0	1.1
Ohio		1.0	1.2
Oklahoma	1.5	1.0	1.5
Oregon	3.2	4.2	10.9
Pennsylvania		2.2	2.2
Rhode Island	3.3	2.2	2.0
South Carolina	1.4		1.1
South Dakota		1.1	1.8
Tennessee	2.7	4.9	14.7
Texas			1.1
Utah		1.7	1.9
Vermont	14.8	8.1	27.5
Virginia		2.3	4.7
Washington	3.8	2.5	6.6
West Virginia		2.0	3.1
Wisconsin		1.4	3.6
Wyoming		1.2	1.2

TABLE 16. ESTIMATED ANNUAL CRITERIA EMISSIONS AND NATIONAL EMISSION BURDEN FROM WOOD-FIRED RESIDENTIAL COMBUSTION FOR 1976

Emission species	Total annual emissions, metric tons/yr			National emission burden, % of total of all stationary sources		
	Primary heating	Auxiliary heating	Fireplaces	Primary heating	Auxiliary heating	Fireplaces
Particulate	7,000	80,000	36,000	0.3	0.5	0.2
SO_x	1,000	1,800		<0.01	<0.01	
NO_x	2,500	4,300	5,500	0.01	0.02	0.02
Hydrocarbons	65,000	110,000	200,000	0.3	0.4	0.8
CO	930,000	2,000,000	190,000	1.0	2.1	0.2

TABLE 17. TOTAL ANNUAL EMISSIONS FROM RESIDENTIAL COMBUSTION SOURCES[a]

Fuel type	Emissions, metric tons/yr (percentage of total)				
	Particulates	SO_x	NO_x	Hydrocarbons	CO
Utility, bottled, tank, or L.P. gas (2)	47,000 (16)	1,400 (0.1)	190,000 (63)	19,000 (4)	49,000 (2)
Fuel oil, kerosene, etc. (2)	74,000 (25)	1,100,000 (92)	89,000 (30)	23,000 (5)	37,000 (1)
Coal (3)	17,000 (6)	81,000 (7)	6,900 (2)	7,600 (2)	72,000 (2)
Wood	160,000 (53)	2,800 (0.2)	12,000 (4)	380,000 (88)	3,100,000 (94)
Total	300,000	1,200,000	300,000	430,000	3,300,000

[a] Wood emissions were determined in this report; others are from References 2 and 3.

TABLE 18. LISTING OF SOURCE TYPES THAT EMIT POM'S IN QUANTITIES GREATER THAN 1 METRIC TON/YEAR (44)

Source type[a]	Annual POM emissions, metric tons	Percent of total POM emissions from all sources
Residential combustion of wood	3,800[b]	80
Coke manufacturing	632	13
Residential combustion of bituminous coal	100[c]	2
Dry bottom industrial boilers firing pulverized bituminous coal	41	0.9
Prescribed burning	40	0.8
Coal refuse piles	28[d]	0.6
Abandoned mines and outcrops	28[d]	0.6
Asphalt roofing	15	0.3
Dry bottom utility boilers firing pulverized lignite coal	14	0.3
Stoker-fired industrial boilers firing bituminous coal	7	0.1
Dry bottom utility boilers firing pulverized bituminous coal	7	0.1
Residential combustion of gas	6	0.1
Residential combustion of distillate oil	5	0.1
Asphalt paving - hot mix	4	0.1
Wet bottom utility boilers firing pulverized lignite coal	4	0.1
Cyclone-fired utility boilers firing lignite coal	3	0.1
Carbon black -furnace process	3	0.1
Stoker-fired utility boilers firing lignite coal	2	<0.1
Commercial/institutional combustion of bituminous coal in stokers	2	<0.1
Industrial boilers firing gas	2	<0.1
Wet bottom industrial boilers firing pulverized bituminous coal	1	<0.1
Wet bottom utility boilers firing pulverized bituminous coal	1	<0.1
Cyclone-fired utility boilers firing bituminous coal	1	<0.1
Commercial/institutional combustion of anthracite coal in stokers	1	<0.1
Commercial/institutional combustion of gas	1	<0.1
Total	4,748	

[a]Natural and mobile sources are not included in this listing.

[b]Revised data based on this report.

[c]Revised data from Reference 3.

[d]Revised data from Reference 45.

Two other recent reports give new data on POM emissions from coal refuse piles (45) and residential coal combustion (3). Based on the first report, annual POM emissions from coal refuse piles amount to only 28 metric tons. Data were not given for abandoned mines and outcrops, but they are likely to be similar in magnitude. Annual POM emissions from residential coal combustion have been estimated at 100 metric tons. On the basis of these revised values, residential wood combustion accounts for 80% of national POM emissions from stationary sources.

(45) Chalekode, P. K., and T. R. Blackwood. Source Assessment: Coal Refuse Piles, Abandoned Mines and Outcrops, State of the Art. EPA-600/2-78-004v, U.S. Environmental Protection Agency, Cincinnati, Ohio, July 1978. 51 pp.

SECTION 5

CONTROL TECHNOLOGY

Because of the past decline of solid fuel-fired residential heating systems, there has been little interest in controlling emissions from these sources. No add-on emission control devices are currently on the market; however, any improvement in combustion efficiency will usually result in some improvement of emission levels.

A study was performed to evaluate emission reduction techniques in oil- and gas-fired residential furnaces (46), which, in some areas, can apply to wood-fired units. Table 19 summarizes those control strategies that may apply to wood-fired equipment.

TABLE 19. COMBUSTION CONTROL STRATEGIES FOR REDUCING AIR POLLUTANTS FROM RESIDENTIAL HEATING EQUIPMENT (46)

Control strategy	Impacted pollutant emission	Comments
Excess air level adjustment	NO CO HC	As excess air is increased, CO, HC, and smoke pass through a minimum, but NO passes through a maximum Optimum pollutant and thermal efficiency level occurs at a stoichiometric ratio greater than one
Combustion chamber design	NO CO Hydrocarbons Smoke/particulate	Combustion chamber design affording long residence time at high temperature minimizes smoke, particulates, CO, HC, but may increase NO Refractory-lined chamber affords better combustion and lower emissions
Service and maintenance	NO CO Hydrocarbons Smoke/particulate	Equipment state-of-repair very important for providing breadth for reducing emissions by other methods

(46) Brown, R. A., C. B. Moyer, and R. J. Schreiber. Feasibility of a Heat and Emission Loss Prevention System for Area Source Furnaces. EPA-600/2-76-097, PB 253945, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina, April 1976. 187 pp.

SECTION 6

GROWTH AND NATURE OF THE SOURCE

Before the twentieth century, coal and wood were the predominant fuels available for residential heating in the United States. The last thirty years saw the decline in the use of wood and coal for residential heating in favor of the cleaner, more efficient and convenient oil and gas fuels. This substitution took place at a time when supplies of these new fuels seemed abundant, cheap, and, to many, inexhaustible. Recent history has shown that not only were reserves limited, they were grossly undervalued at current prices. As prices rose rapidly following the Arab oil embargo of 1973 to more truly reflect the value of energy, the displaced, unattractive fuels such as wood and coal once again gained appeal for large numbers of people. Since increased usage of wood has been easier to accomplish individually, the number of households supplementing and converting their residential heating to wood has risen rapidly and dramatically.

PRESENT TECHNOLOGY

The technology of residential wood heating follows a curious historical phenomenon: knowledge is discovered, used, and lost, over and over again. The Romans, who were excellent engineers as shown by their roads and aqueducts which still stand today, developed heating systems under their tiled floors (using wood as fuel) that were modern both in concept and execution (47). With the fall of Rome, wood heating technology disappeared and did not revive until after the Dark Ages.

The earliest records of cast-iron stoves in Europe date from around the end of the fifteenth century, when they began to assume their present form. They were built with rectangular plates and the number of plates gave the stove its basic designation.

By colonial times heating had once again become sophisticated; the Dutch, German, Scandinavian, and French heating units were impressively efficient and satisfactory. The English, however,

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(47) Harrington, G. The Wood-Burning Stove Book. MacMillan Publishing Company, Inc., New York, New York, 1977. 175 pp.

stubbornly stuck to the open fireplace of which they were so fond, and froze in their frame houses from Vermont to Virginia. Eventually, thanks to Ben Franklin and Count Rumford, fireplaces became smaller - and developed smoke shelves, dampers, and other useful devices (47).

As cities grew and forests receded, it became more difficult and expensive to feed the enormous appetite of inefficient colonial fireplaces. By the middle of the eighteenth century there was a real shortage of wood in Philadelphia, and Ben Franklin set his inventive genius to the problem. The result was "The Pennsylvania Fire-place," which he designed in 1744 and described in a published account, complete with diagrams, measurements, and instructions for building and installing. Made of cast iron, the stove was designed to fit into an existing fireplace. It was an open box, joined together with screws and mortared to seal the seams. The front opening was fitted with a solid iron plate, or "shutter," which could be moved up and down to create or control draft while tending the fire, or closed completely when no fire was wanted. The floor of the box curved up in front "to keep coals and ashes from coming to the floor". Although it looks simple at first glance, the construction was fairly complicated. A false back of from two to four inches was constructed so that "no air may pass into the chimney but what goes under the false back, and up behind it." This, to some extent, cut down on drafts, since no air was drawn into the chimney except through the fire (47).

Few people realize that practically all of the technical features of Franklin's Pennsylvania stove were copied from earlier inventors. Louis Savat's heat circulating fireplace, installed in the Louvre around 1600, had a preheated draft which was employed by Franklin with little change in design. The descending flue was also copied: smoke rose in front of a hollow metal back, passed over the top and down the opposite side. Finally, at the same level as the hearth, the smoke ascended the flue. Savat also surrounded the grate with 2 metal air chambers which had warm air outlets above the fire opening. He also supplied the fire with air from under the floor, thereby reducing room drafts and improving combustion efficiency (48).

Franklin had spurned the efficient Dutch and German stoves in favor of an open stove which would allow the fire to be viewed. By 1786 Franklin had lived abroad for some years and become acquainted with European heating devices. Although he never lost

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(48) Stoner, C. Producing Your Own Power. Rodale Press, Inc., Emmaus, Pennsylvania, 1974. 322 pp.

his love of an open wood fire, he reluctantly came to the conclusion that it was not the most efficient method of heating. However, none of the existing heating devices met with his complete approval, and he set about devising one that would be more satisfactory. The result was described in considerable detail in a paper entitled: "Description of a new Stove for burning Pitcoal, and consuming all its Smoke," which was presented to the American Philosophical Society on January 28, 1786. Although described as a stove for pitcoal, it was equally suitable for burning wood, and Franklin's directions cover both fuels (47).

Although Franklin preferred the open fire to the Dutch or Holland stoves, he did so in the face of his own common sense. As he says in another paper (47): "An English farmer in America, who makes great fires in large open chimneys, needs the constant employment of one man to cut and haul wood for supplying them; and the draft of cold air to them is so strong, that the heels of his family are frozen, while they are scorching their faces, and the room is never warm, so that little sedentary work can be done by them in winter. The difference in this article alone of economy shall, in a course of years, enable the German to buy out the Englishman, and take possession of his plantation."

The Franklin fire-place proved immensely popular and was soon being manufactured throughout the colonies. Since Franklin did not believe in patents, he placed no restriction on his inventions, and the Franklin stove was soon being manufactured both to his design and with alterations of which he did not approve. His name was used freely, as it is today, to adorn stoves far removed from the principles on which his original fireplace stove was based.

The first Franklin stove of that name was patented in 1816 and subsequent patents were issued for Slide-Door Franklin Stoves, Closed Franklin Stoves, Pipe Franklin Stoves, and Fold-Door Franklin Stoves, among others. It was soon found that the stove, whatever its variation in design, would heat more effectively if installed outside - rather than within - the fireplace, with a pipe leading to the fireplace chimney. This variation is found to this day, although there are also modern Franklin stoves that still nestle within the fireplace.

Thus the technology of wood heating today is much the same as it always has been, and as diverse: efficient freestanding wood stoves with baffled plate design; fireplaces with heat-circulating chambers, combustion air brought from outside; wood furnace designs which collect heated air and transport it under floors and through ducts; parlor stoves, potbelly stoves and box stoves; and fireplaces which rob a home of heat but afford the charm of an ornamental fire. The reluctance through the ages to give up the viewing of the open fire demonstrates how much a fire means to people. Whether it is due to some atavistic need, or just to aesthetic appreciation, fire has always been a symbol of home.

INDUSTRY TRENDS

Residential heating with wood is increasing rapidly after bottoming out in the early 1970's. In 1850 wood supplied approximately 90% of the energy needs of this nation. Its use declined rapidly to about 75% by 1875 and 20% by 1900 (49).

Near the turn of the century gas and oil entered the home heating market. However, these fuels were only available to a small number of homes near the source. Developments around 1920 made it possible to deliver large quantities of these fuels to distant markets and signalled the decline of coal and wood use for home heating. Wood remained a major home heating fuel in 1940, when 8,000,000 occupied housing units burned wood for primary heating purposes (50). This was about 23% of the total number of occupied housing units in the United States. From that point, however, the decline was rapid. By 1970, housing units burning wood for heat numbered only about 800,000 units (6) and made up 2% of the total number of occupied housing units. By 1974, wood-fired heating dropped by almost 20% to 660,000 housing units (51). Figure 7 shows the decline in primary wood-fired residential heating from 1940 to 1974, followed by slight upturn to 1976 when 912,000 housing units were heated primarily with wood (1, 50, 51). Table 20 gives the distribution of structures built with primary wood heating by decade (6).

Primary wood heating is predominately a rural phenomenon, and tends to occur where the seasonal heating load of a residence is less than 4,000 degree days. The rural nature of heating with wood is because of easy accessibility to supplies of wood fuel and short transportation distances. Table 21 illustrates the distribution of households with primary wood heat by region and shows that the Southern, mountain states have over 50% of the

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(49) Zerbe, J. I. Wood in the Energy Crisis. Forest Farmer, 37(2):13-15, November-December, 1977.

(50) Statistical Abstracts of the United States 1975. U.S. Department of Commerce, Washington, D.C., July 1975. 1,050 pp.

(51) Current Housing Reports; Bureau of the Census Final Report H-150-74; Annual Housing Survey: 1974, Part A; General Housing Characteristics for the United States and Regions. U.S. Department of Commerce, Washington, D.C., August 1976. 179 pp.

total U.S. population which heat in this manner, followed by the Pacific northwest region (6). All these areas have an abundance of forest regions. Table 22 gives the breakdown between urban and rural use of wood fuel as primary heat and illustrates that it is predominately the non-farm household in a rural region (1).

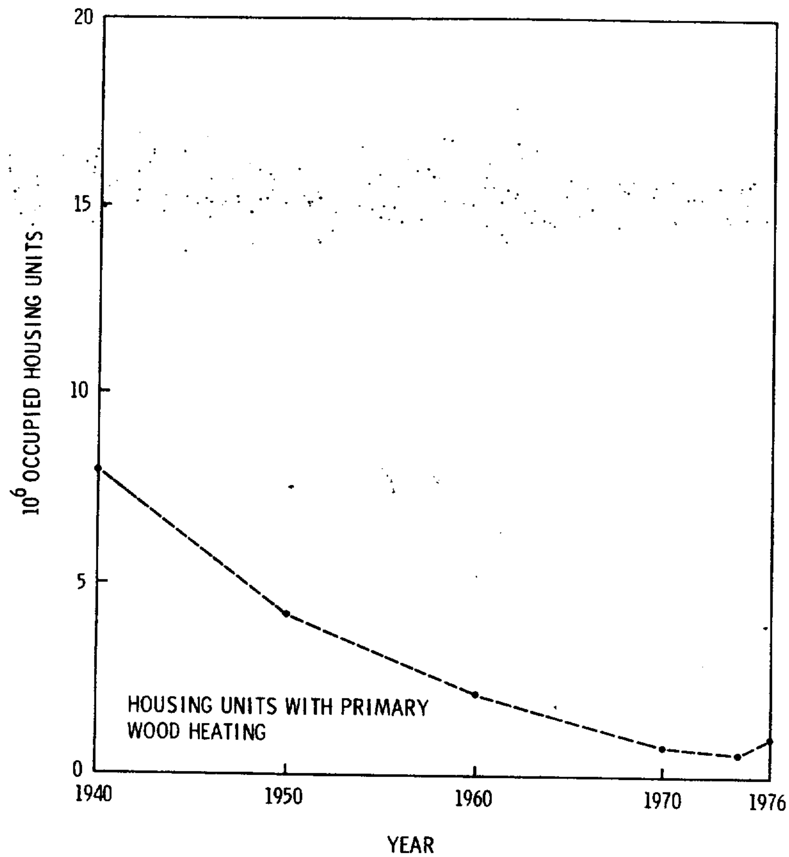

Figure 7. Residential wood-firing heating trends (1, 50, 51).

TABLE 20. STRUCTURES BUILT WITH PRIMARY WOOD HEATING (6)

Decade	Units
1960 - 1970	92,000
1950 - 1959	103,000
1940 - 1949	126,400
1939 and earlier	472,500
Total	793,900

TABLE 21. HOUSING UNITS WITH PRIMARY WOOD HEAT BY REGION, 1970 (6)

Region	Number	Percent of total
U.S. Total	794,000	100
New England	12,500	1.6 (CT, RI, MA, VT, NH, ME)
Middle Atlantic	12,800	1.6 (PA, NY, NJ)
E. North Central	25,400	3.2 (WI, MI, IL, IN, OH)
W. North Central	52,400	6.6 (MO, KS, NE, IA, MN, SD, ND)
South Atlantic	254,600	32.1 (MD, DE, WV, VA, NC, SC, GA)
E. South Atlantic	191,400	24.1 (KY, TN, MS, AL)
W. South Atlantic	104,400	13.1 (TX, OK, AR, LA)
Mountain	41,400	5.2 (MT, ID, WY, NV, UT, CO, AZ, NM)
Pacific	99,000	12.5 (CA, OR, WA)

TABLE 22. REGIONAL DISTRIBUTION OF HOUSING UNITS WITH PRIMARY WOOD HEAT, 1976 (1)

Region	Total	Urban	Rural	Percent non-farm	Percent farm
U.S.	912,000	92,000	820,000	73.5	26.5
Northeast Region	63,000	5,000	58,000	86.2	13.8
North Central Region	91,000	0	91,000	72.5	27.5
South Region	584,000	64,000	520,000	70.4	29.6
West Region	173,000	23,000	150,000	81.3	18.7

The largest increase in wood heating is occurring in supplemental or auxiliary heating. In spite of high utility bills, most people are not willing to rely on wood alone for heat. Particularly in Northern New England, recent surveys have shown that substantial amounts of indigenous fuel wood are being used to supplement conventional energy sources (oil or electricity) for residential space heating. These surveys indicate that 6.5%, 16.5%, and 21.8% of the heating loads per residence were maintained by wood combustion for the winters of 1975-76, 1976-77, and 1977-78, respectively (33).

Statistics on the shipment of wood-fired heating equipment indicate a sudden demand for stove type heating devices, starting around 1973 when the retail price index of #2 fuel oil jumped 58% (50). In 1972, total stove type residential heating equipment shipped was about 197,000 units. In 1975, the number had jumped to about 407,000 units (52-54). Figure 8 shows the trends in shipments for both airtight and nonairtight wood heating stoves (52-63).

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(52) Current Industrial Reports, Heating and Cooking Equipment. Bureau of the Census, MA-34N(72)-1, U.S. Department of Commerce, Washington, D.C., November 1973. 9 pp.

(53) Current Industrial Reports, Selected Heating Equipment. Bureau of the Census MA-34N(75)-1, U.S. Department of Commerce, Washington, D.C., July 1976. 6 pp.

(54) Current Industrial Reports, Air Conditioning and Refrigeration Equipment Including Warm Air Furnaces. Bureau of the Census, MA-35M(75)-1, U.S. Department of Commerce, Washington, D.C., October 1976. 14 pp.

(55) Current Industrial Reports, Heating and Cooking Equipment. Bureau of the Census M34N(60)-13, U.S. Department of Commerce, Washington, D.C., August 1961. 7 pp.

(56) Current Industrial Reports, Heating and Cooking Equipment. Bureau of the Census M34N(64)-13, U.S. Department of Commerce, Washington, D. C., July 1966. 9 pp.

(57) Current Industrial Reports, Heating and Cooking Equipment. Bureau of the Census M34N(65)-13, U.S. Department of Commerce, Washington, D.C., July 1966. 9 pp.

(58) Current Industrial Reports, Heating and Cooking Equipment. Bureau of the Census M34N(66)-13, U.S. Department of Commerce, Washington, D.C., February 1968. 9 pp.

(59) Current Industrial Reports, Heating and Cooking Equipment. Bureau of the Census M34N(67)-13, U.S. Department of Commerce, Washington, D.C., January, 1969. 7 pp.

(60) Current Industrial Reports, Heating and Cooking Equipment. Bureau of the Census M34N(69)-13, U.S. Department of Commerce, Washington, D.C., February 1971. 7 pp.

(61) Current Industrial Reports, Heating and Cooking Equipment. Bureau of the Census M34N(70)-13, U.S. Department of Commerce, Washington, D.C., December 1972. 9 pp.

(62) Current Industrial Reports, Selected Heating Equipment. Bureau of the Census MA-34N(76)-1, U.S. Department of Commerce, Washington, D. C., August 1977. 7 pp.

(63) Current Industrial Reports, Selected Heating Equipment. Bureau of the Census MA-34N(77)-1, U.S. Department of Commerce, Washington, D.C., August 1978. 7 pp.

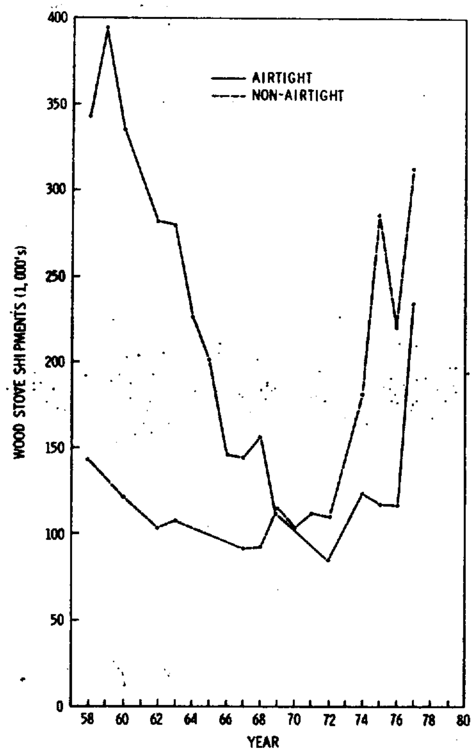

Figure 8. United States production of wood burning stoves (52-63).

The residential use of fireplaces for wood burning is also increasing. Figure 9 illustrates that 36% of new houses completed in 1971 were constructed with one or more fireplaces; this number increased to 58% in 1976, of which 5% had more than one fireplace (64). Fireplaces in American homes are used primarily for aesthetic purposes. Table 23 illustrates the percent distribution of fireplaces in new housing by sales price of the housing unit (50).

Primary residential wood combustion accounts for 5% of total timber usage in the United States. Total timber production in 1977 was estimated at 3.2×10^8 m^3, roundwood equivalent, or 2.5×10^8 m^3 of wood allowing for the packing factor (65). Based on a typical density of 400 kg/m^3 (at 12% moisture), the total production level was approximately 100×10^6 metric tons. This can be compared with the estimated consumption figures for primary residential wood combustion in 1976 of 5×10^6 metric tons.

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(64) Construction Report; Bureau of the Census-Series C25; Characteristics of New Housing: 1976. U.S. Department of Commerce, Washington, D.C., July 1977. 77 pp.

(65) Statistical Abstracts of the United States 1978. U.S. Department of Commerce, Washington, D.C., September 1978. 1,081 pp.

These data indicate that increased consumption of wood by the residential sector could have a substantial impact on forest utilization. By way of example, an increase in the percent of homes in the U.S. heated primarily by wood from 1% to 10% would mean that timber harvesting would have to be increased by 45%, if other wood demand areas remained unchanged.

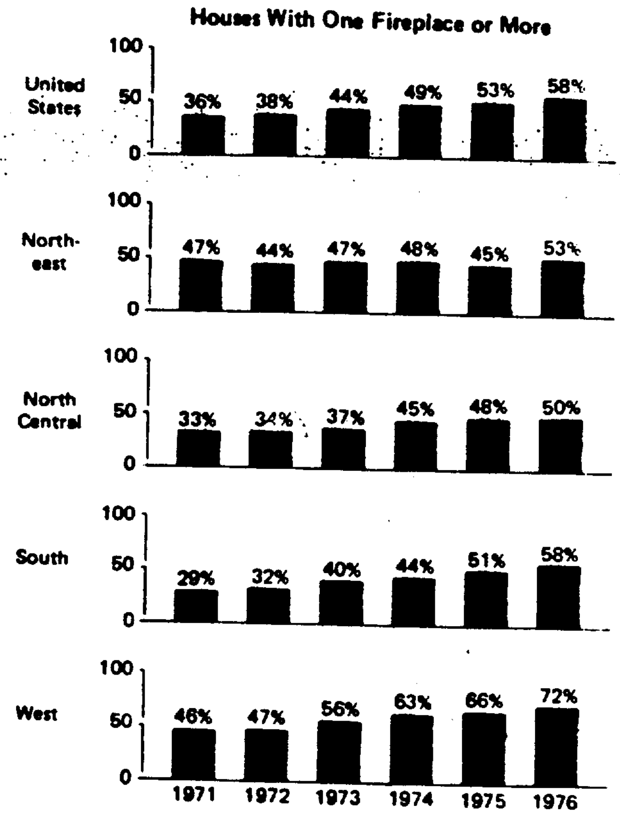

Figure 9. New housing completed, 1971-1976 (64).

TABLE 23. PERCENT DISTRIBUTION OF FIREPLACES IN NEW HOUSING BY SALES PRICE IN 1976 (64).

	Sale price of house						
Number of fireplaces	Under $30,000	$30,000 to $39,999	$40,000 to $49,999	$50,000 to $59,999	$60,000 to $69,999	$70,000 and over	Total
No fireplace	87	55	32	20	12	8	39
1 fireplace	13	44	64	75	81	77	57
2 fireplaces or more	0	1	3	5	7	15	4

When the pioneers began to clear land in the New World for their homes, farms, and cities, they marveled at the apparently endless forests. By the eighteenth century, Ben Franklin was turning his inventive skills to a stove that would help ease the shortage of wood around Philadelphia. Today, two centuries later, the United States still has almost 75% as much forest land as existed in the time of the pioneers - 754 million acres, or one third of the United States, is still forest. Of that acreage, 254 million acres have been set apart for parks and recreation areas and cannot be commercially cut for lumber, but they are still available to those gathering wood by permit. The remaining 500 million acres are classified as commercial forest land, i.e., forests which may be harvested. In the state of Maine, for example, 90% of the land is forest but Maine is also the site of some of the largest paper manufacturers in the country, and 86% of the forest land is commercial acreage (47).

From commercial forest land comes plywood, paper, wood pulp, building lumber, and other wood products, supporting some of the largest and most essential industries in the country; yet even today more wood is grown than harvested. This is due largely to good forest management by industrial users. In most instances where wood has proven an economically desirable product, forest productivity has been increased.

Future trends in residential wood heating are dependent on comparative costs of other residential heating fuels - gas, oil and electricity. Particularly fuel oil and electricity appear currently unattractive as residential fuels, and states which have a high dependence on these fuels coupled with abundant forest regions will see residents supplementing with or switching to wood-fired equipment. Table 24 notes several key states with a large proportion of households dependent on fuel oil or electricity as primary heat (22). If natural gas prices were to rise rapidly as did fuel oil many other states would experience large increases in supplemental heating by wood.

Also, should tax credits be provided to U.S. taxpayers under the Energy Tax Act of 1978 (PL 618) to give eligible wood-burning equipment the same or similar treatment now afforded to wind and geothermal energy equipment, a sharp increase in wood-fired equipment usage might follow. Most solar and wind energy equipment are just beyond the pocketbooks of most Americans; wood heating is a necessity for many rural poor. Yet, six million Americans filed for some type of energy tax credit in 1978 - some 7% of the tax paying public (66); a tax credit for wood would see much greater usage.

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(66) Mueller, S. Federal Tax Credits: The Ultimate "Accounting" for Solar Sales. Solar Heating & Cooling, 4(6):7, 1979.

TABLE 24. STATES WHICH DEPEND HIGHLY ON FUEL AND/OR ELECTRICITY AS PRIMARY HEAT (1970) (22)

State	Wood	Fuel oil	Electricity	Bottled gas
	Percent housing units which heat primarily with:			
Alabama	5.4			
Arkansas	8.2			21.1
Florida		29.2	32.3	
Georgia	4.9		10.7	18.3
Indiana		26.9		
Iowa		20.7		12.5
Maine	2.1	91.8		
Maryland		43.8		
Massachusetts		65.8		
Mississippi	8.4			26.6
Missouri	2.5			16.7
New Hampshire		80.5		
New York		56.8		
North Carolina		61.9	10.8	
Oregon	4.7	37.8	29.8	
Pennsylvania		35.0		
Rhode Island		69.7		
South Carolina	6.3	44.6		
Tennessee	4.7		40.4	
Vermont	1.4	80.4		
Virginia	3.3	48.6		
Washington	1.6	40.8	30.4	
Wisconsin		39.2		

As long as the governments and information media convey the idea that saving on oil imports is a national priority, households will add or switch to wood-burning equipment, often at a substantial cost; so that they can voluntarily contribute to saving on our massive national oil import bill and reduce their own heating bills.

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APPENDIX A

ESTIMATION OF THE SOURCE POPULATION AND FUEL CONSUMPTION

The most recent published data on the population of wood-fired heating equipment is the 1976 Annual Housing Survey published by the Bureau of Census. However, this report is based on data collected from a sample population; it lacks the detail necessary to adequately characterize the whole population. The 1970 Census of Housing surveyed the total population and is much more detailed than the 1976 Housing Survey. To obtain a better estimate of the 1976 population this appendix employs certain relationships and trends observed in various tables from both surveys.

Residential combustion of wood was divided into three categories: 1) primary heating, done primarily with wood-fired furnaces and airtight stoves; 2) auxiliary heating, done with airtight stoves, nonairtight wood stoves (Franklin stoves, box stoves, laundry stoves, parlor stoves), and converted fireplace stoves; and 3) fireplaces, from the heat-circulating type with glass doors to those used for ornamental or aesthetic wood burning.

Table A-1 shows the number of housing units burning wood as their primary source of heat in 1970 and 1976 by region. The table also gives the percent growth from 1970 to 1976. It is assumed that each housing unit noted contains one wood-burning device. Although some multi-unit structures may contain only one heating device, some single unit structures will contain more than one. Thus, possible errors in determining the population of primary heating equipment will tend to cancel out.

TABLE A-1. NUMBER OF HOUSING UNITS BURNING WOOD FOR PRIMARY HEATING, 1970 and 1976 (1, 21)

Region	Number of housing units		Percentage increase from 1970 to 1976	Percentage of national units	
	1970	1976		1970	1976
North East	25,000	63,000	152	3	7
North Central	78,000	91,000	16.7	10	10
South	550,000	584,000	6.2	69	64
West	140,000	173,000	23.6	18	19
United States	794,000	912,000	14.9	-	-

Table A-2 lists the population of housing units burning wood by state as obtained from the 1970 Census of Housing. The estimated 1976 population is obtained by applying the regional growth percentages from Table A-1 to the 1970 state-by-state data. Wood consumption for primary heating was calculated based on the annual heating degree-days in each state and a wood consumption rate of 1.54 kg/degree-day per dwelling unit (23). Results are given in Table A-3.

Estimates of the number of fireplaces burning wood are not available from published surveys. However, a report on the number of new housing units constructed gives the percentage which contain one or more fireplaces (58). Using 1971 as a baseline (since the percentage with fireplaces is increasing), an estimate of the percentage of homes by region was obtained and applied to all housing units in each region. These figures are: South region - 29% of all housing units have one or more fireplaces; West region - 46%; North East region - 47%; and North Central region - 33%.

An estimate of the amount of wood consumed in fireplaces was conservatively assumed to equal the average U.S. wood fuel consumption per capita (65) (2.9 ft^3), in lieu of any published estimate. At 2.9 persons per household, the average wood fuel consumption in fireplaces becomes 98.3 kg per housing unit. This estimate should balance wood consumption between the households with heat-circulating fireplaces who burn wood often during cooler autumn and spring evenings and those households that burn wood rarely for aesthetic reasons. Many households never utilize their fireplace, realizing that it may rob the house of heated air and due to unavailability of sources of firewood. The estimated amount of wood consumed in fireplaces on a state-by-state basis is given in Table A-4.

The largest area of uncertainty and greatest lack of published data are in the category of auxiliary heating by wood stoves. Increasing numbers of homeowners and renters are installing and using wood stoves as an alternative to the high price and uncertain availability of fuel oil. Homes with electric resistance heating are also turning to wood as a supplement in order to hold down heating costs. The best source of information from which to estimate the number of wood stoves are the U.S. Bureau of Census Current Industrial Reports (52-62). Taking the last fifteen years' output (1961-1976) as an estimate of the number of wood stoves which are in use shows that 2,300,000 airtight-type stoves were manufactured and shipped, and 4,300,000 nonairtight stoves (includes kitchen heaters, caboose, woodbox, laundry stoves) were shipped. It was also assumed that an additional 15% over the total number of U.S. made stoves were imported. It is known that wood stoves are manufactured in Taiwan, Korea,

TABLE A-2. NUMBER OF HOUSING UNITS BURNING WOOD FOR PRIMARY HEATING BY STATE, 1970 AND 1976 (1, 21)

State	Number of housing units burning wood for primary heating, 1970	Estimated number of housing units burning wood for primary heating, 1976
Alabama	55,800	59,200
Alaska	2,900	3,600
Arizona	12,300	15,200
Arkansas	50,400	53,500
California	43,700	54,000
Colorado	1,600	2,000
Connecticut	900	2,300
Delaware	700	700
Florida	23,700	25,200
Georgia	66,600	70,700
Hawaii	2,100	2,600
Idaho	5,400	6,700
Illinois	2,700	3,100
Indiana	5,800	6,800
Iowa	1,400	1,600
Kansas	2,900	3,400
Kentucky	25,100	26,700
Louisiana	16,000	17,000
Maine	6,300	15,900
Maryland	6,100	6,500
Massachusetts	1,200	3,000
Michigan	5,400	6,300
Minnesota	6,600	7,700
Mississippi	53,400	56,700
Missouri	38,700	45,100
Montana	4,100	5,100
Nebraska	1,100	1,300
Nevada	1,300	1,600
New Hampshire	2,000	5,000
New Jersey	1,000	2,500
New Mexico	15,000	18,500
New York	6,300	15,900
North Carolina	61,200	65,000
North Dakota	200	200
Ohio	4,600	5,400
Oklahoma	12,900	13,700
Oregon	32,300	39,900
Pennsylvania	5,600	14,100
Rhode Island	200	500
South Carolina	46,000	48,800
South Dakota	1,500	1,700
Tennessee	57,000	60,500
Texas	25,000	26,500
Utah	1,000	1,200
Vermont	1,900	2,700
Virginia	45,400	48,200
Washington	18,000	22,200
West Virginia	4,800	5,100
Wisconsin	6,800	7,900
Wyoming	700	900
United States	794,000	912,000

TABLE A-3. ESTIMATED ANNUAL HEATING DEGREE-DAYS AND WOOD CONSUMPTION FOR PRIMARY HEATING BY STATE, 1976

State	Degree days[a]	Wood consumed for primary heating, metric tons
Alabama	1,684	150,000
Alaska	9,007	50,000
Arizona	1,552	36,000
Arkansas	3,354	280,000
California	2,331	190,000
Colorado	6,016	18,000
Connecticut	6,350	22,000
Delaware	4,940	5,000
Florida	767	30,000
Georgia	3,095	340,000
Hawaii	0	1,000
Idaho	5,833	60,000
Illinois	6,113	29,000
Indiana	5,577	58,000
Iowa	6,710	16,000
Kansas	4,687	24,000
Kentucky	4,640	190,000
Louisiana	1,465	38,000
Maine	7,498	180,000
Maryland	4,729	47,000
Massachusetts	5,621	26,000
Michigan	7,806	76,000
Minnesota	9,034	110,000
Mississippi	2,300	200,000
Missouri	4,956	330,000
Montana	7,652	60,000
Nebraska	6,049	12,000
Nevada	6,022	15,000
New Hampshire	7,360	57,000
New Jersey	4,946	19,000
New Mexico	4,292	120,000
New York	6,221	150,000
North Carolina	3,366	340,000
North Dakota	9,044	3,000
Ohio	5,642	47,000
Oklahoma	3,695	78,000
Oregon	4,792	290,000
Pennsylvania	5,398	120,000
Rhode Island	5,972	5,000
South Carolina	2,598	190,000
South Dakota	7,838	20,000
Tennessee	3,462	320,000
Texas	2,134	87,000
Utah	5,983	11,000
Vermont	7,876	33,000
Virginia	3,714	280,000
Washington	6,010	210,000
West Virginia	4,590	36,000
Wisconsin	7,444	91,000
Wyoming	7,255	10,000
Total		5,100,000

[a] Data in Reference 55 is given for major cities in each state. For this study, it was assumed that these numbers approximated state averages.

[b] Assumed 200 degree days.

TABLE A-4. ESTIMATED WOOD CONSUMPTION IN FIREPLACES AND IN AUXILIARY HEATING BY WOOD STOVES BY STATE, 1976

State	Estimated number of homes with fireplaces	Wood consumed in fireplaces, metric tons	Estimated number of homes with auxiliary heat by wood stove	Wood consumed in auxiliary wood stoves, metric tons (cords)[a]
Alabama	346,800	34,000	239,200	360,000 (1)
Alaska	53,800	5,000	10,700	32,000 (2)
Arizona	346,400	34,000	69,100	26,000 (¼)
Arkansas	211,400	21,000	66,900	100,000 (1)
California	3,610,100	360,000	719,800	270,000 (¼)
Colorado	410,300	40,000	81,800	61,000 (½)
Connecticut	493,000	49,000	96,200	140,000 (1)
Delaware	55,700	5,000	17,600	13,000 (½)
Florida	896,700	88,200	283,600	210,000 (½)
Georgia	470,100	46,000	148,700	220,000 (1)
Hawaii	119,600	12,000	23,800	9,000 (¼)
Idaho	126,000	12,000	25,100	19,000 (½)
Illinois	1,258,600	120,000	349,800	260,000 (½)
Indiana	589,700	58,000	163,900	120,000 (½)
Iowa	329,700	32,000	91,600	68,000 (½)
Kansas	269,300	26,000	74,800	56,000 (½)
Kentucky	329,700	32,000	227,400	170,000 (½)
Louisiana	356,400	35,000	112,100	84,000 (½)
Maine	167,300	16,000	117,500	440,000 (2.5)
Maryland	395,300	39,000	125,000	94,000 (½)
Massachusetts	923,100	91,000	180,100	270,000 (1)
Michigan	985,100	97,000	273,800	410,000 (1)
Minnesota	437,900	43,000	121,700	360,000 (2)
Mississippi	214,300	21,000	147,800	110,000 (½)
Missouri	556,400	55,000	154,600	230,000 (1)
Montana	120,100	12,000	23,900	18,000 (½)
Nebraska	178,200	18,000	49,500	38,000 (½)
Nevada	100,300	10,000	20,000	8,000 (¼)
New Hampshire	129,700	13,000	91,100	340,000 (2.5)
New Jersey	1,155,300	114,000	225,500	170,000 (½)
New Mexico	702,100	69,000	34,000	25,000 (½)
New York	2,993,000	290,000	584,100	870,000 (1)
North Carolina	519,700	51,000	164,400	120,000 (½)
North Dakota	69,600	7,000	19,400	14,000 (½)
Ohio	1,186,000	120,000	329,600	250,000 (½)
Oklahoma	288,300	28,000	91,200	34,000 (¼)
Oregon	387,800	38,000	168,600	250,000 (1)
Pennsylvania	1,900,700	190,000	370,900	280,000 (½)
Rhode Island	149,900	15,000	29,300	22,000 (½)
South Carolina	259,800	26,000	82,200	62,000 (½)
South Dakota	75,200	7,000	20,900	16,000 (½)
Tennessee	413,000	41,000	284,800	850,000 (2)
Texas	1,215,700	120,000	384,500	290,000 (¼)
Utah	170,200	18,000	33,900	25,000 (¼)
Vermont	73,800	7,000	51,800	190,000 (2.5)
Virginia	482,900	48,000	152,700	110,000 (½)
Washington	594,800	58,000	258,600	390,000 (1)
West Virginia	180,700	18,000	57,100	43,000 (½)
Wisconsin	504,600	50,000	140,200	210,000 (1)
Wyoming	61,200	6,000	12,200	9,000 (½)
Total	27,865,300	2,700,000	7,603,000	8,500,000

[a]Number in parentheses is estimated number of cords used per household.

Canada, South America, as well as several European countries (67). These additional 990,000 stoves give a U.S. total wood stove population of 7,600,000 stoves used for auxiliary heating.

The states in which wood heating has become prevalent are assumed to have higher percentages of households which utilize wood stoves as auxiliary heating. It was assumed that 33% of the households in northern New England (VT, NH, and ME) have auxiliary wood stoves, 20% of the households in the East South Central region (KY, AL, TN, and MS) and 20% of the households in Washington and Oregon. That leaves 6,042,300 stoves for the remaining 65,876,000 households of the U.S., or 9.17% of all households for all the other states. Average wood fuel usage for auxiliary wood stoves in each state was estimated based on average state degree days and forest availability, and ranged from one-fourth of a cord to 2.5 cords (374 kg to 3,740 kg). The estimated number of housing units with auxiliary heat by wood stoves and auxiliary wood fuel consumption by state are given in Table A-4.

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(67) Jøtul: A Resource Book on the Art of Heating with Wood (1978 Revision). Kristia Associates, Portland, Maine, 1978. 64 pp.

APPENDIX B

DETERMINATION OF THE REPRESENTATIVE SOURCE

Due to the heterogeneous nature of residential wood combustion, two representative sources were chosen for source severity calculations: 1) a wood-burning stove used for primary or auxiliary heating, and 2) a fireplace used for aesthetic burning.

Data from the 1976 Housing Survey indicate that the representative wood stove is located in the South region of the U.S., within a rural area in a non-farm dwelling, as shown in Table B-1 and Table B-2. Within the South region the wooded hills and mountains comprising Appalachia are the location of most wood-derived home heating.

TABLE B-1. DISTRIBUTION BY REGION OF HOUSEHOLDS WHICH HEAT PRIMARILY WITH WOOD (1)

Region	1976,[a] %	1970,[a] %
South	64.0	69.3
Northeast	6.9	3.1
North Central	10.0	9.8
West	19.0	17.6

[a]Numbers do not add up to 100% due to rounding.

TABLE B-2. DISTRIBUTION WITHIN REGIONS OF HOUSEHOLDS WHICH HEAT PRIMARILY WITH WOOD, 1976 (1)

Region	Urban, %	Rural, %	
		Farm	Non-farm
South	11.0	26.3	62.7
Northeast	7.9	12.7	79.4
North Central	0	27.5	72.5
West	13.3	16.2	70.5
U.S.	10.1	23.8	66.1

Excellent data is available from the Tennessee Valley Authority (TVA) concerning individual household wood stove usage rates in the South (68). In the fall of 1977 TVA embarked on a project to study the practicality of wood-burning stoves as an alternate source of residential heating to electricity. Benefits to the TVA were expected to be energy conservation by households and reduction in peak hourly loads. Ninety (90) households participated in the study, with 59 installing Ashley stoves and 31 installing Riteway stoves. In return for a reduced cost from the manufacturer they agreed to provide TVA a monthly report for two years on the stove's operation and their past and present electric utility bills. Data from 36 households for the months of January and February 1978 are presented in Tables B-3 and B-4, respectively (68).

The average household during the most severe heating load months (January and February) loaded the stove 3.69 times per day with dry hardwood. At an average hardwood density of 640.6 kg/m^3, each household averaged 0.113 m^3 (4.0 ft^3) of wood burned, or 3 kg/hr.

The average fireplace burning rate was determined by averaging the data from all published source tests on fireplaces (9, 29, 30 and 32), giving a value of 8.5 kg/hr.

Emission heights of residential combustion equipment will vary with building height and placement within a building. Chimney heights for a total of 38 wood-burning fireplaces average 4.3 m above the firebox (9, 29). Assuming the top of the firebox to be about 0.9 m above the floor and these fireplaces to be all at ground level, the average emission height is 5.2 m above ground. This figure will be used for all wood-burning equipment.

To determine the affected population for a pollutant from an emission source, the population density around the source must be known. For the representative wood stove emission source the average population density of the non-urban counties of Tennessee will be assumed in this case, or 21 $persons/km^2$ (55 $persons/mi^2$).

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(68) Project Plan: North Georgia Wood Heater Demonstration Project. Preliminary Report. Tennessee Valley Authority, Chattanooga, Tennessee, October 1978. 18 pp.

TABLE B-3. TVA WOOD FOR ENERGY HEATING DEMONSTRATION - JANUARY 1978 DATA (68)

ID number	Where wood obtained, January	How wood obtained, January	Cost of wood, $	Condition of wood, January	Type wood	Times loaded per day	Wood used in January, ft³	Utility bill, 1978, $	Kwh, 1978	Utility bill 1977, $	Kwh, 1977
0007	TVA LAND	NOT PURCHASED		GREEN	HARD	3	171	56.79	2,204	97.88	4,796
0008	OTHER PUBLIC	NOT PURCHASED		DRY	HARC	4	10	63.70	2,484	67.48	2,595
0010	OTHER PUBLIC	NOT PURCHASED		GREEN	HARD	4	96	54.80	2,000	99.28	4,712
0012	OTHER PUBLIC	NOT PURCHASED		DRY	HARC	4	122	66.37	2,554	77.67	3,820
0018	TVA LAND	NOT PURCHASED		GREEN	HARD	4	278	19.83	708	55.10	2,219
0022	TVA LAND	NOT PURCHASED		GREEN	SOFT	2	120	113.52	4,500	112.89	5,566
0032	YOUR LAND	NOT PURCHASED		DRY	HARD	3	210	40.00	1,400	63.00	2,420
0033	OTHER PUBLIC	NOT PURCHASED		DRY	HARD	3	150	53.80	2,052	98.10	3,773
0034	TVA LAND	NOT PURCHASED		GREEN	HARD	7	128	38.65	1,510	150.40	7,764
0036	OTHER PUBLIC	NOT PURCHASED		DRY	HARD	4	116	46.95	1,806	68.58	3,294
0037	YOUR LAND	NOT PURCHASED		DRY	HARD	4	81	57.05	2,104	81.44	3,828
0044	OTHER PUBLIC	NOT PURCHASED		GREEN	HARD	2	120	23.97	876	61.88	2,380
0045	OTHER PRIVATE	PURCHASED & DELIVERED	75	GREEN	HARD	5	72	21.88	842	67.30	2,588
0051	YOUR LAND	NOT PURCHASED		GREEN	HARD	4	121	49.19	1,896	81.65	3,964
0052	YOUR LAND	NOT PURCHASED		DRY	HARD	4	60	86.23	3,568	163.00	6,278
0053	YOUR LAND	NOT PURCHASEC		DRY	50/50	4	180	49.83	1,922	94.49	3,700
0055	YOUR LAND	NOT PURCHASED		GREEN	HARD	3	190	18.40	650	43.19	1,660
0058	OTHER PRIVATE	PURCHASED & CUT/YOU HAUL		GREEN	HARD	3	96	34.61	1,306	67.48	3,238
0063	YOUR LAND	NOT PURCHASED		GREEN	HARD	3	128	68.16	2,664	135.00	5,204
0065	DO NOT KNOW	PURCHASED & DELIVERED	50	GREEN	HARC	4	78	45.36	1,722	75.62	3,534
0066	YOUR LAND	NOT PURCHASED		DRY	HARD	3	62	28.06	1,000	21.76	820
0077	DO NOT KNOW	NOT PURCHASED		DRY	HARD	4	128	32.00	1,185	84.99	4,026
0078	TVA LAND	NOT PURCHASED		DRY	HARD	3	184	65.18	2,542	125.54	6,214
0108	OTHER PUBLIC	NOT PURCHASED		DRY	HARD	4	160	13.50	518	52.00	2,000
0109	TVA LAND	PURCHASED & DELIVERED	75	GREEN	HARD	2	90	45.87	1,762	45.00	1,730
0111	OTHER PRIVATE	PURCHASED & DELIVERED	90	GREEN	HARD	3	125	66.08	2,580	145.21	7,222
0112	YOUR LAND	NOT PURCHASED		DRY	HARD	5	200	45.52	1,758	72.39	3,426
0114	YOUR LAND	NOT PURCHASED		GREEN	HARD	5	80	73.19	2,868	97.60	4,782
0115	OTHER PRIVATE	NOT PURCHASED		DRY	HARD	3	224	47.51	1,734	117.00	4,502
0116	YOUR LAND	NOT PURCHASED		DRY	HARD	2	75	44.63	1,712	36.62	1,656
0119	OTHER PUBLIC	NOT PURCHASED		DRY	HARD	7	160	57.58	2,236	90.23	4,404
0123	OTHER PRIVATE	PURCHASED & DELIVERED	50	GREEN	HARD	4	160	91.03	3,528	90.14	3,467
0124	OTHER PUBLIC	NOT PURCHASED		GREEN	HARD	3	128	24.92	914	62.42	2,401
0125	OTHER PRIVATE	PURCHASED & CUT/YOU HAUL	30	GREEN	HARD	6	27	34.86	1,334	44.73	1,720
0126	OTHER PRIVATE	PURCHASED & DELIVERED	75	GREEN	HARD		100	39.43	1,480	71.66	2,756
0127	YOUR LAND	NOT PURCHASED		DRY	HARD	4	128	63.13	1,920	81.50	3,140
FINAL TOTALS			445				4,558	1,779.56	67,839	3,000.22	131,581

TABLE B-4. TVA WOOD FOR ENERGY HEATING DEMONSTRATION - FEBRUARY 1978 DATA (68)

ID number	Where wood obtained, February	How wood obtained, February	Cost of wood, $	Condition of wood, February	Type wood	Times loaded per day	Wood used in February, ft³	Utility bill 1978, $	Kwh, 1978	Utility bill 1977, $	Kwh, 1977
0007	TVA LAND	NOT PURCHASED		GREEN.	HARD	4	182	40.55	1,572	70.87	3,510
0008	OTHER PUBLIC	NOT PURCHASED		DRY	HARD	4	69	47.50	1,852	51.52	2,490
0010	OTHER PUBLIC	NOT PURCHASED		50/50	HARD	5	128	81.89	3,160	82.00	3,936
0012	OTHER PUBLIC	NOT PURCHASED		DRY	HARD	4	94	61.23	2,468	67.35	3,378
0020	OTHER PUBLIC	NOT PURCHASED		GREEN.	HARD	3	80	65.96	2,626	65.85	3,246
0021	YOUR LAND	NOT PURCHASED		DRY	HARD	3	102	167.98	6,856	150.70	7,800
0033	OTHER PUBLIC	PURCH & CUT/YOU HAUL		DRY	HARD	3	150	48.50	1,884	95.36	3,668
0034	TVA LAND	NOT PURCHASED		DRY	HARD	4	130	71.27	3,267	101.77	5,100
0036	OTHER PUBLIC	NOT PURCHASED		DRY	HARD	4	104	50.48	1,984	75.41	3,750
0037	YOUR LAND	NOT PURCHASED		DRY	HARD	4	137	49.12	1,878	96.48	4,724
0044	OTHER PUBLIC	NOT PURCHASED		DRY	HARD	2	81	17.47	626	47.63	1,832
0045	OTHER PRIVATE	PURCH & DELIVERED	75	GREEN.	HARD	4	60	21.83	796	60.52	2,241
0046	YOUR LAND	NOT PURCHASED		DRY	HARD	2	56	47.00	1,754	60.52	2,241
0051	YOUR LAND	NOT PURCHASED		GREEN.	50/50	4	110	40.49	1,570	59.91	2,304
0052	YOUR LAND	NOT PURCHASED		DRY	HARD	4	30	73.81	3,112	124.00	4,772
0053	YOUR LAND	NOT PURCHASED		DRY	HARD	4	200	59.56	2,360	100.88	3,880
0055	YOUR LAND	NOT PURCHASED		GREEN.	HARD	3	120	15.09	526	68.42	2,632
0060	YOUR LAND	NOT PURCHASED		GREEN.	HARD	4	120	51.78	2,074	121.50	4,672
0063	YOUR LAND	NOT PURCHASED		GREEN.	HARD	3	128	68.16	2,664	123.41	4,762
0065	OTHER PRIVATE	NOT PURCHASED		DRY	HARD	4	89	49.16	1,910	73.33	3,538
0066	YOUR LAND	NOT PURCHASED		DRY	HARD	3	62	27.37	984	37.05	1,678
0077	DO NOT KNOW	NOT PURCHASED		DRY	HARD	4	112	39.44	1,532	110.36	5,436
0078	OTHER PRIVATE	NOT PURCHASED		GREEN.	HARD	3	166	38.66	1,494	102.60	5,184
0108	OTHER PRIVATE	NOT PURCHASED		DRY	HARD	3	110	9.70	373	56.00	2,154
0109	TVA LAND	NOT PURCHASED		50/50.	HARD	2	25	47.87	1,876	40.00	1,538
0111	OTHER PRIVATE	PURCH & DELIVERED	75	GREEN.	HARD	3	107	51.30	2,018	92.67	4,660
0112	YOUR LAND	NOT PURCHASED		DRY	HARD	3	50	53.34	2,040	76.90	3,780
0113	OTHER PRIVATE	NOT PURCHASED		DRY	HARD	2	112	27.59	1,052	88.55	3,406
0114	YOUR LAND	NOT PURCHASED		GREEN.	HARD	4	105	66.16	2,634	89.03	4,468
0115	OTHER PRIVATE	NOT PURCHASED		DRY	HARD	3	128	36.29	1,310	88.00	3,386
0116	YOUR LAND	NOT PURCHASED		DRY	HARD	2	75	39.59	1,532	24.37	1,058
0119	OTHER PUBLIC	NOT PURCHASED		DRY	HARD	7	132	55.98	2,212	60.97	2,988
0123	DO NOT KNOW	PURCH & DELIVERED	55	GREEN.	50/50	4	155	101.60	4,036	87.40	3,361
0124	OTHER PUBLIC	NOT PURCHASED		GREEN'	HARD	3	140	16.81	588	65.00	2,501
0125	OTHER PRIVATE	PURCH/YOU CUT & HAUL	30	GREEN.	HARD	5	43	29.70	1,098	58.00	2,231
0126	OTHER PRIVATE	PURCH & DELIVERED	30	GREEN.	HARD	3	100	41.02	1,570	62.64	2,009
0127	YOUR LAND	NOT PURCHASED		DRY	HARD	4	128	42.98	1,260	64.91	2,500
FINAL TOTALS			265				3,920	1,854.23	72,548	2,902.28	127,290

APPENDIX C

DERIVATION OF EMISSION FACTORS

Some calculations in this appendix have been made using nonmetric units; however, all final emission factors were converted to metric form in this appendix and in the text.

Source test measurements from six studies, summarized in Tables C-1 to C-6, were used to derive average emissions factors.

Emission data were presented in one study (3) for particulates, CO, hydrocarbons and POM from wood combustion in fireplaces under three conditions: startup, stable burning, and smoldering. Only stable burning emissions are considered here, because startup and smoldering are assumed to be small segments of the total combustion time.

Because the results of some studies were reported as concentration of stack gas, it was necessary to calculate the emission factors. The following examples illustrate the methods used in converting concentrations to emission factors in g/kg.

For run number 6 (Table C-1), CO is expressed as 280 ppm. The emission factor calculation is:

$$\frac{280 \text{ std m}^3 \text{ CO}}{10^6 \text{ std m}^3 \text{ flue gas}} \times \frac{12.771 \text{ std m}^3 \text{ flue gas}}{\text{min}} \times \frac{44.62 \text{ g - mole}}{\text{std m}^3}$$

$$\times \frac{28 \text{ g CO}}{\text{g - mole CO}} \times \frac{\text{hr}}{6.2 \text{ kg wood}} \times \frac{60 \text{ min}}{\text{hr}} = 43.2 \text{ g CO/kg wood}$$

For run number 6 (Table C-1), POM's are expressed as 5,746 ng/std ft^3. The Emission factor calculation is:

$$\frac{5{,}746 \text{ ng}}{\text{std ft}^3 \text{ flue gas}} \times \frac{10^{-9} \text{ g}}{1 \text{ ng}} \times \frac{12.771 \text{ std m}^3 \text{ flue gas}}{\text{min}}$$

$$\times \frac{\text{hr}}{6.2 \text{ kg wood}} \times \frac{60 \text{ min}}{\text{hr}} = 0.025 \text{ g POM/kg wood}$$

TABLE C-1. EMISSIONS DATA FOR WOOD COMBUSTION IN FIREPLACES UNDER STABLE CONDITIONS (9)

Fuel type	Run no. from Ref. 7	Burning rate, kg/hr	Stack gas flow rate, std m^3/min	Particulate emission factor, g/kg	POM, ng/std ft^3 (g/kg)	CO, ppm (g/kg)	Nonmethane volatile hydrocarbons, ppm (g/kg)
Alder	2	7.8	10.513	5.9			
	6	6.2	12.771		5,746 (0.025)	280 (43)	4.5 (2.1)
Douglas Fir	7	5.7	12.139	11.5			
	8	4.1	11.715	14.4		405 (87)	4.7 (3.1)
	10	6.7	11.814	13.5			
	11	4.3	11.737		7,444 (0.044)		
Locust	15	6.2	11.414	12.7		440 (61)	5.3 (2.2)
	18	5.5	12.709	15.3			
Pine	20	14.0	10.986	6.5			
	21	10.0	10.539		7,647 (0.017)		
	23	9.1	10.727	8.1			

Note.-Blanks indicate data not available.

TABLE C-2. EMISSIONS DATA FOR WOOD COMBUSTION (30)

Test code from Ref. 25	Wood type	Burning rate, lb/hr (kg/hr)	Emissions, lb/ton[a] CO	NO_x[b] (as NO_2) (g/kg)	Organic acids (as acetic acid)	Phenols	Formaldehyde	Acetaldehyde	Organics	Particulate
A1	Eucalyptus	22 (10	64 to 111	12 (1.3)	20.2 to 16.2	1.5 to 2.2	3.3 to 2.2		41 to 40	∿13.2
A2	Eucalyptus and oak	69 (31)	25.8	35 (0.8)	<0.03	<0.04	0.27	0.45	5.4	
A3	Eucalyptus and oak	5 (2.3)	438	22 (7.8)	<0.03	<0.04	4.3	1.21	82.9	
A4	Oak	13 (5.9)	268 to 166	16 (2.1)	∿7.7	∿4.6	1.4 to 1.2		∿32.8	25.2 to 6.9
B2	Oak	12 (5.5)	96.7		11.8	0.83	10.5		44.5	26.7
C1	Oak	19 (8.6)	114		17.5	1.6	1.2	1.3	39.3	26.3
C2	Oak	15 (6.8)	171		17.9	2.8	1.5	1.9	48.8	44.0
C3	Madrone	10 (4.5)	168		29.3	4.8	3.2	2.5	66.3	48.0
D1	Oak	25 (11)	55.1	11 (0.9)	3.4	0.2	0.59	0.36	11.9	10.4
D2	Oak	20 (9.1)	52.6	8 (0.8)	5.3	0.48	1.03	0.78	15.1	16.0

Note.-Blanks indicate data not available.

[a] 1 lb/ton = 0.5 g/kg.

[b] ppm.

TABLE C-3. PARTICULATE EMISSIONS DATA FOR WOOD COMBUSTION (31)

Stove	Wood	Draft setting	Number of runs	Emission factor, g/kg Average	Standard Deviation	Range
Jotul	Pine	1/2 open	6	4.5	1.0	2.9 to 5.6
Jotul	Pine	1/4 open	5	10	8	4.5 to 25
Jotul	Oak	1/2 open	6	1.7	0.9	0.7 to 2.8
Jotul	Oak	open	2	1.17	0.01	1.16 to 1.18
Jotul	Birch	1/2 open	2	2.3	1.7	1.1 to 3.5
Franklin	Oak	-[a]	15	2.8	1.0	1.2 to 4.4
Franklin	Very dry oak	-[a]	3	1.02	0.10	0.91 to 1.08

[a] Not applicable.

TABLE C-4. EMISSIONS DATA FOR WOOD COMBUSTION, STABLE CONDITIONS (32)

Test code from Ref. 32	Sampling location	Type fuel	Burning rate, kg/hr	Flow rate, std m^3/min	Particulates,[a] g/kg	CO, ppm (g/kg)	CO_2, ppm	Hydrocarbons,[b] ppm (g/kg)
2	Condominium fireplace	Dry pine	8.2	12.1	16.6	269(28)	10,634	222(13)
4	Condominium fireplace	Dry pine	11.5	9.3	15.3	1,308(74)	12,571	2,575(83)
5	Condominium fireplace	Dry pine	10.1	10.9	16.7	1,117(81)	8,419	1,337(18)
8	Condominium fireplace	Green aspen	7.1	13.1	19.1	1,111(144)	6,004	4,023(297)
10	Condominium fireplace	Dry aspen	8.1	12.2	15.8	659(75)	7,383	1,042(63)
13	Condominium fireplace	Green pine	7.1	10.6	20.0	1,033(108)	4,840	920(55)
16	Residential fireplace	Dry pine	3.2	7.4	20.8	647(105)	8,085	4,162(385)
17	Residential fireplace	Dry pine	3.2	7.5	23.1	670(110)	10,883	1,507(141)
18	Residential fireplace	Green pine	4.6	6.8	26.3	1,001(104)	7,523	451(27)
19	Stove	Dry pine	6.2	2.2	28.3	8,194(204)	115,007	3,130(44)

[a] The particulate emission factors were calculated using both the front-half and back-half catch. The condensable portion on back half averaged 75% of the total particulate loadings.

[b] Hydrocarbons reported as methane equivalents.

TABLE C-5. EMISSIONS DATA FOR WOOD COMBUSTION (29)

Wood burning device	Wood type	Wood burning rate,[a] kg/min	Flow rate[b] Nm^3/min	Emission factor, g/kg (g/MJ)						
				Particulates[c]	Condensable organics[d]	Volatile hydrocarbons[e]	NO_x[f]	SO_x[g]	CO[h]	POM[i]
Fireplace	Seasoned oak	0.18	6.5	2.3 (0.13)	6.3 (0.35)	19 (1.1)	2.4 (0.13)	j	30 (1.7)	0.025 (0.0014)
Fireplace	Green oak	0.17	6.4	2.5 (0.19)	5.4 (0.40)	j	1.9 (0.14)	j	22 (1.6)	j
Fireplace	Seasoned pine	0.19	6.5	1.8 (0.10)	5.9 (0.32)	j	1.4 (0.08)	j	21 (1.2)	j
Fireplace	Green pine	0.16	6.5	2.9 (0.21)	9.1 (0.67)	j	1.7 (0.13)	j	15 (1.1)	0.036 (0.0026)
Baffled stove	Seasoned oak	0.14	1.5	3.0 (0.17)	4.0 (0.22)	j	0.4 (0.02)	j	110 (6.2)	0.21 (0.012)
Baffled stove	Green oak	0.11	0.9	2.5 (0.19)	3.8 (0.28)	j	0.7 (0.05)	j	120 (9.0)	j
Baffled stove	Seasoned pine	0.12	1.0	3.9 (0.21)	4.1 (0.23)	2.8 (0.15)	0.5 (0.03)	j	270 (15)	0.37 (0.020)
Baffled stove	Green pine	0.10	2.0	7.0 (0.51)	12.0 (0.88)	j	0.8 (0.06)	j	220 (16)	j
Nonbaffled stove	Seasoned oak	0.13	0.9	2.5 (0.14)	6.0 (0.34)	j	0.4 (0.02)	0.16 (0.01)	370 (21)	0.19 (0.011)
Nonbaffled stove	Green oak	0.11	0.9	1.8 (0.13)	3.3 (0.25)	0.3 (0.02)	0.5 (0.04)	j	91 (6.8)	j
Nonbaffled stove	Seasoned pine	0.12	0.9	2.0 (0.11)	5.6 (0.31)	j	0.2 (0.01)	0.24 (0.02)	150 (8.2)	j
Nonbaffled stove	Green pine	0.13	0.8	6.3 (0.46)	10.0 (0.74)	3.0 (0.22)	0.4 (0.03)	j	97 (7.1)	0.32 (0.024)

[a] Average burning rate during EPA Method 5, POM, and SASS train operation.

[b] Determined from average EPA Method 5 data.

[c] Front half of EPA Method 5 and POM train. Averaged when two values available.

[d] Back half of EPA Method 5. Averaged when two values available.

[e] GC/FID

[f] EPA Method 7. Average of 6 grab samples.

[g] EPA Method 6.

[h] EPA Method 3 (ORSAT) for stoves; average of 10 samples. Dräger tube for fireplace; 15 to 30 minute composite.

[i] POM train (EPA Method 5 modified with XAD resin trap).

[j] No data obtained.

TABLE C-6. PARTICULATE EMISSIONS DATA FOR WOOD COMBUSTION (33)

Stove	Wood	% moisture	Draft	Fuel load (kg)	Length of burn (hr)	Emission factor (g/kg)
Jotul	Oak	23.8	1	2.15	1.72	13.31
Jotul	Oak	23.8	1	2.66	0.67	2.31
Jotul	Oak	23.8	½	2.75	1.55	9.40
Jotul	Oak	23.8	½	3.18	1.56	5.21
Jotul	Oak	23.8	¼	2.32	1.42	10.39
Jotul	Oak	23.8	¼	2.69	1.23	10.14
Jotul	Oak	23.8	¼	2.69	1.77	8.24
Jotul	Oak	23.8	¼	2.27	1.05	6.75
Jotul	Oak	22.8	¼	1.42	0.48	2.46
Jotul	Oak	22.8	¼	3.40	1.38	3.36
Jotul	Oak	22.8	¼	1.28	0.62	2.52
Jotul	Oak	19.8	¼	0.49[a]	0.26[a]	1.82[a]
Jotul	Oak	8.7	¼	2.69	0.87	4.85
Jotul	Oak	8.7	¼	1.22	0.65	4.90
Jotul	Oak	8.7	¼	1.05	0.45	1.27
Jotul	Oak	8.7	¼	2.72	1.10	10.87
Jotul	Oak	23.8	<¼	2.07	1.70	15.72
Jotul	Oak	23.8	<¼	2.01	1.95	24.35
Jotul	Oak	23.8	<¼	1.67	1.80	12.82
Jotul	Pine	42.4	¼	2.04	0.98	10.37
Jotul	Pine	42.4	¼	3.23	1.40	10.79
Jotul	Pine	42.4	<¼	1.67	1.33	18.52
Jotul	Pine	42.4	<¼	1.50	1.52	15.33
Jotul	Pine	42.4	<¼	1.39	0.73	9.60
Rite-way	Oak	22.8	b	5.23	1.52	11.85
Rite-way	Pine	42.8	c	4.10	1.20	13.26

[a]These figures are averages for a burn in which 3.94 kg of fuel, divided into eight portions, was burned in 2.05 hours.

[b]These figures are averages for a burn in which the thermostat setting remained fixed and 15.71 kg of fuel, in three portions, was burned in 4.58 hours.

[c]These figures are averages for a burn in which the thermostat setting remained fixed and 12.30 kg of fuel, in three portions, was burned in 3.59 hours.

In cases where emission data was reported as lb/ton, the following conversion factor was used: 1 lb/ton = 0.5 g/kg.

Average emission factors (Table 8) were determined by considering the average of tests conducted on one piece of combustion equipment and test condition. Replicate runs with a specific wood type were treated as one separate test. For example, Reference 30 reports two tests burning oak and one burning madrone in fireplace C. The madrone test is considered as a separate test in calculating the overall emission factor. The oak tests were first averaged and then considered as one test.

APPENDIX D

TOTAL WOOD-FIRED RESIDENTIAL COMBUSTION EMISSIONS

Total criteria emissions from wood-fired residential combustion equipment were compared on a state and national basis to emissions from all stationary sources. State emissions were calculated by multiplying the emission factors presented in Section 4 by the estimated fuel usage in each state for wood-fired residential combustion. Tables D-1, D-2, and D-3 give the percent contribution to total state and national criteria emissions for primary heating with stoves, auxiliary heating with wood stoves, and aesthetic burning in fireplaces, respectively. Total state emissions were taken from the NEDS inventory (69) which is shown in Table D-4.

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(69) 1972 National Emissions Report. EPA 450/2-74-012, Environmental Protection Agency, research Triangle Park, North Carolina, June 1974. 422 pp.

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TABLE D-2. PERCENTAGE OF TOTAL STATE CRITERIA EMISSIONS DUE TO AUXILIARY RESIDENTIAL HEATING WITH WOOD

State	Percent of total state emissions				
	Particulates	SO_x	NO_x	Hydrocarbons	CO
Alabama	0.28	<0.01	0.06	0.7	3.44
Alaska	2.09	0.11	0.05	1.4	3.47
Arizona	0.32	<0.01	0.01	0.2	0.57
Arkansas	0.66	0.05	0.03	0.6	2.15
California	0.24	0.01	<0.01	0.2	0.59
Colorado	0.28	0.02	0.02	0.4	1.27
Connecticut	3.27	0.02	0.05	0.8	2.91
Delaware	0.33	<0.01	0.01	0.3	1.17
Florida	0.85	<0.01	0.02	0.4	1.43
Georgia	0.50	0.01	0.03	0.6	1.98
Hawaii	0.13	<0.01	<0.01	0.1	0.59
Idaho	0.31	0.01	<0.01	0.3	0.99
Illinois	0.21	<0.01	0.01	0.2	0.74
Indiana	0.15	<0.01	<0.01	0.3	0.76
Iowa	0.29	<0.01	0.01	0.3	0.86
Kansas	0.15	0.01	0.01	0.2	1.01
Kentucky	0.28	<0.01	0.02	0.7	2.59
Louisiana	0.20	0.01	<0.01	0.06	0.27
Maine	8.14	0.06	0.3	4.51	21.18
Maryland	0.17	<0.01	0.02	0.40	1.34
Massachusetts	2.55	0.01	0.04	0.77	2.90
Michigan	0.53	0.01	<0.01	0.72	2.29
Minnesota	1.24	0.02	0.06	1.12	3.75
Mississippi	0.60	0.04	0.03	0.71	2.42
Missouri	1.04	0.02	0.03	0.71	2.26
Montana	0.06	<0.01	<0.01	0.08	0.53
Nebraska	0.35	0.01	0.02	0.36	1.18
Nevada	0.07	<0.01	<0.01	0.18	0.63
New Hampshire	20.78	0.1	0.3	4.85	24.09
New Jersey	1.01	0.01	0.02	0.26	1.06
New Mexico	0.22	<0.01	<0.01	0.21	0.91
New York	4.99	0.05	0.07	1.10	3.25
North Carolina	0.23	<0.01	0.01	0.35	1.29
North Dakota	0.17	<0.01	<0.01	0.26	0.82
Ohio	0.12	<0.01	0.01	0.27	0.86
Oklahoma	0.33	<0.01	<0.01	0.13	0.42
Oregon	1.35	0.1	0.09	1.35	4.92
Pennsylvania	0.14	<0.01	<0.01	0.39	1.35
Rhode Island	1.52	<0.01	0.02	0.42	1.40
South Carolina	0.28	<0.01	<0.01	0.09	0.26
South Dakota	0.27	0.02	0.02	0.22	0.73
Tennessee	1.89	0.01	0.1	2.96	10.52
Texas	0.48	<0.01	0.01	0.16	0.76
Utah	0.32	<0.01	0.02	0.33	1.14
Vermont	12.08	0.2	0.4	5.81	23.33
Virginia	0.22	<0.01	0.02	0.39	1.34
Washington	2.17	0.03	0.10	1.41	4.23
West Virginia	0.18	<0.01	<0.01	0.46	1.57
Wisconsin	0.46	<0.01	0.03	0.50	2.40
Wyoming	0.11	<0.01	<0.01	0.21	0.54
Total	0.5	<0.01	0.2	0.4	2.1

TABLE D-3. PERCENTAGE OF TOTAL STATE CRITERIA EMISSIONS DUE TO RESIDENTIAL WOOD BURNING IN FIREPLACES

State	Percent of total state emissions			
	Particulates	NO_x	Hydrocarbons	CO
Alabama	0.04	0.02	0.4	0.1
Alaska	0.5	0.04	1.4	0.2
Arizona	0.6	0.06	1.3	0.3
Arkansas	0.2	0.02	0.80	0.2
California	0.5	0.04	1.2	0.3
Colorado	0.3	0.06	1.5	0.3
Connecticut	1.6	0.06	1.6	0.4
Delaware	0.2	0.02	0.6	0.2
Florida	0.5	0.03	1.1	0.2
Georgia	0.1	0.02	0.7	0.1
Hawaii	0.2	0.05	1.0	0.3
Idaho	0.3	0.05	1.1	0.2
Illinois	0.1	0.02	0.5	0.1
Indiana	0.1	<0.01	0.7	0.1
Iowa	0.2	0.03	0.8	0.1
Kansas	0.1	0.02	0.6	0.2
Kentucky	0.1	0.02	0.7	0.2
Louisiana	0.1	0.02	0.1	0.04
Maine	0.4	0.04	1.0	0.3
Maryland	0.1	0.03	<0.01	0.2
Massachusetts	1.2	0.05	1.5	0.4
Michigan	0.2	<0.01	1.0	0.2
Minnesota	0.2	0.03	0.8	0.2
Mississippi	0.2	0.02	0.8	0.2
Missouri	0.3	0.02	1.0	0.2
Montana	0.1	0.02	0.3	0.1
Nebraska	0.2	0.03	1.0	0.2
Nevada	0.1	0.02	1.4	0.3
New Hampshire	1.1	0.04	1.1	0.3
New Jersey	1.0	0.05	1.0	0.3
New Mexico	0.9	0.07	3.4	0.9
New York	2.4	0.1	1.7	0.4
North Carolina	0.1	0.03	0.8	0.2
North Dakota	0.1	0.02	0.7	0.1
Ohio	0.1	0.02	0.7	0.1
Oklahoma	0.4	0.02	0.6	0.1
Oregon	0.3	0.06	1.2	0.3
Pennsylvania	0.1	0.01	1.6	0.3
Rhode Island	1.5	0.06	1.7	0.3
South Carolina	0.2	<0.01	0.2	0.04
South Dakota	0.2	0.03	0.6	0.1
Tennessee	0.1	0.02	0.8	0.2
Texas	0.3	0.02	0.4	0.1
Utah	0.3	0.04	1.3	0.3
Vermont	0.7	0.06	1.3	0.3
Virginia	0.1	0.03	1.0	0.2
Washington	0.5	0.06	1.3	0.2
West Virginia	0.02	0.01	1.1	0.2
Wisconsin	0.2	0.02	0.7	0.2
Wyoming	0.1	0.02	0.8	0.1
Total	0.2	0.02	0.8	0.2

TABLE D-4. NEDS EMISSION SUMMARY BY STATE (69)
(metric tons)

State	Particulates	SO_x	NO_x	Hydrocarbons	CO
Alabama	1,178,643	882,731	397,068	643,410	1,885,657
Alaska	13,913	5,874	32,757	28,389	167,357
Arizona	72,685	1,679,768	123,871	189,981	815,454
Arkansas	137,817	39,923	168,989	195,538	843,204
California	1,006,452	393,326	1,663,139	2,160,710	8,237,667
Colorado	201,166	49,188	147,496	193,456	875,781
Connecticut	40,074	168,068	155,832	219,661	897,580
Delaware	36,808	209,310	58,407	63,886	204,227
Dist. Columbia	19,451	60,630	46,824	41,789	190,834
Florida	226,460	897,381	644,794	619,872	2,695,817
Georgia	404,574	472,418	369,817	458,010	2,036,010
Hawaii	61,621	45,981	44,221	89,530	275,566
Idaho	55,499	54,387	48,552	84,230	343,720
Illinois	1,143,027	2,043,020	974,372	1,825,913	6,412,718
Indiana	748,405	2,050,541	1,371,233	600,477	2,933,780
Iowa	216,493	283,416	242,524	316,617	1,440,621
Kansas	348,351	86,974	233,987	309,633	1,002,375
Kentucky	546,214	1,202,827	419,142	326,265	1,189,932
Louisiana	380,551	166,664	442,817	1,919,662	5,633,827
Maine	49,155	144,887	76,741	122,918	376,196
Maryland	494,921	420,037	265,204	295,867	1,261,804
Massachusetts	96,160	636,466	334,379	440,481	1,682,218
Michigan	705,921	1,466,935	2,222,438	717,891	3,243,526
Minnesota	266,230	391,633	311,834	410,674	1,760,749
Mississippi	168,355	50,591	172,519	195,950	829,094
Missouri	202,435	1,152,373	448,300	413,130	1,854,901
Montana	272,688	871,235	148,405	271,824	611,061
Nebraska	95,338	58,014	101,948	127,821	569,522
Nevada	94,040	304,851	88,933	53,673	215,751
New Hampshire	14,920	86,596	67,309	88,469	256,380
New Jersey	151,768	463,736	489,216	819,482	2,877,319
New Mexico	102,785	444,310	199,181	152,057	504,249
New York	160,044	345,979	572,451	1,262,206	4,881,922
North Carolina	481,017	473,020	412,599	447,238	1,734,398
North Dakota	78,978	78,537	85,708	70,289	318,679
Ohio	1,766,056	2,980,333	1,101,470	1,153,493	5,205,719
Oklahoma	93,595	130,705	222,687	341,358	1,456,627
Oregon	169,449	36,776	135,748	234,669	929,247
Pennsylvania	1,810,598	2,929,137	3,017,345	891,763	3,729,830
Rhode Island	13,073	65,761	46,921	65,833	283,650
South Carolina	198,767	247,833	521,544	907,833	4,222,168
South Dakota	52,336	17,354	49,490	90,478	387,356
Tennessee	409,704	1,179,982	426,454	362,928	1,469,253
Texas	549,399	753,098	1,303,801	2,218,891	6,897,748
Utah	71,692	152,526	80,998	98,282	402,527
Vermont	14,587	17,751	24,286	41,980	150,510
Virginia	477,494	447,394	329,308	369,416	1,548,031
Washington	161,934	272,991	187,923	344,643	1,659,117
West Virginia	213,715	678,348	229,598	116,155	494,214
Wisconsin	411,558	712,393	408,525	523,930	1,582,869
Wyoming	75,427	69,394	72,572	55,319	303,297

ADJUSTMENTS TO GRAND TOTAL

The United States summary does not include certain source categories. The following additions should be considered part of the United States grand total for a more accurate picture of nationwide emissions

New York pt. sources	311,000	993,000	382,000	127,000	44,000
Forest wild fires	375,000	0	88,000	529,000	3,089,000
Agricultural burning	272,000	15,000	29,000	272,000	1,451,000
Structural fires	52,000	0	6,000	61,000	200,000
Coal refuse piles	100,000	128,000	31,000	62,000	308,000
Total	1,110,000	1,076,000	536,000	1,051,000	5,086,000
U.S. subtotal (above)	16,762,000	28,873,000	21,722,000	23,994,000	91,782,000
U.S. grand total	17,872,000	29,949,000	22,258,000	25,045,000	96,868,000

GLOSSARY

affected population: Number of persons around an average source who are exposed to a source severity greater than 0.05 or 1.0 as specified.

average source: Wood-fired residential combustion source defined for use in calculating source severity.

boiler: Closed vessel in which fuel is burned to generate steam or heat water.

criteria emissions: Those for which air quality standards have been established.

damper: Valve or plate used to regulate the flow of air to a combustion process.

draft: Pressure difference causing flow of a fluid, usually applied to convection flow as in chimneys.

emission factor: Quantity of emission per quantity of fuel burned.

flue: Enclosed passage for conveying combustion gases to the atmosphere.

housing unit: Apartment, group of rooms, or a single room occupied or intended for occupancy as separate living quarters.

national emission burden: Ratio of annual emissions from a specific source to the total national emissions from all stationary sources.

overfeed: Method of feeding solid fuel to a fuel bed where the fresh fuel is charged to the top of the fuel bed.

overfire: Portion of the combustion air which enters the combustion zone over the fuel bed to provide turbulence for smoke reduction in hand- and stoker-fed coal combustion equipment.

plenum: Air space or chamber under pressure.

pyrolysis: Chemical decomposition by the application of heat.

source severity: Indication of the hazard potential of an emission source.

state emission burden: Ratio of annual emissions from a specific source in any state to the total state emissions from all stationary sources.

threshold limit value (TLV®): Airborne concentrations of substances to which it is believed that nearly all workers may be exposed day after day without adverse effect.

underfire: Method of providing combustion air to a fuel bed by forcing the air through the fuel bed from underneath.

warm air furnace: Closed vessel in which fuel is burned to heat room air.

wind box: Enclosure around a stoker which directs combustion air through the retort.

CONVERSION FACTORS AND METRIC PREFIXES (70)

CONVERSION FACTORS

To convert from	To	Multiply by
Degree Celsius (°C)	Degree Fahrenheit (°F)	$t^\circ_F = 1.8\, t^\circ_C + 32$
Degree Kelvin (°K)	Degree Celsius (°C)	$t^\circ_C = t^\circ_K - 273.15$
Gram (g)	Pound-mass	2.205×10^{-3}
Gram/second (g/s)	Pounds/hour	7.930
Joule (J)	British thermal unit (Btu)	9.479×10^{-4}
Kilogram (kg)	Pound mass (avoirdupois)	2.204
Kilogram (kg)	Ton (short, 2,000 lb mass)	1.102×10^{-3}
Kilogram/meter^3 (kg/m^3)	Lb mass/foot^3	6.243×10^{-2}
Kilometer^2 (km^2)	Mile^2	2.591
Meter (m)	Foot	3.281
Meter (m)	Inch	3.937×10^{1}
Meter^3 (m^3)	Foot^3	3.531×10^{1}
Metric ton	Pound-mass	2.205×10^{3}
Pascal (Pa)	Pound-force/inch^2 (psi)	1.450×10^{-4}

METRIC PREFIXES

Prefix	Symbol	Multiplication factor	Example
Giga	G	10^9	1 Gg = 1×10^9 grams
Mega	M	10^6	1 MJ = 1×10^6 joules
Kilo	k	10^3	1 kPa = 1×10^3 pascals
Milli	m	10^{-3}	1 mg = 1×10^{-3} gram
Micro	μ	10^{-6}	1 μm = 1×10^{-6} meter

(70) Standard for Metric Practice. ANSI/ASTM Designation E 380-76$^{\epsilon}$, IEEE Std 268-1976, American Society for Testing and Materials, Philadelphia, Pennsylvania, February 1976. 37 pp.

TECHNICAL REPORT DATA

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16. ABSTRACT The report gives results of an estimate of the potential environmental impact of the residential combustion of wood. About 16.6 million metric tons of wood was burned in the residential section in 1976. About 30% of this was burned for primary heating in about 912,000 residential units. Geographic distribution of wood-fired heaters is related to the natural forest regions in the U.S. By 1985, over 10 million homes will be using some wood fuel. Emissions from wood-fired residential heaters include particulates, SOx, NOx, CO, hydrocarbons (HC), and polycyclic organic material (POM). The impact of these emissions has been assessed by source severity, involving estimating maximum ground level concentrations of pollutants and comparing these concentrations to a National Ambient Air Quality Standard for criteria pollutants or to a reduced threshold limit value for non-criteria pollutants. A comparative analysis of source severities for residential wood combustion with other stationary sources indicates that residential wood combustion is a major source of POM. Particulate, HC, and CO emissions from all residential wood-fired sources were estimated to contribute 1.0, 1.5, and 3.8%, respectively, of the total national emission burden for those species in 1976.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group	
Pollution	Sulfur Oxides	Pollution Control	13B	07B
Combustion	Nitrogen Oxides	Stationary Sources	21B	
Wood	Carbon Monoxide	Residential Heaters	11L	
Residential Buildings	Hydrocarbons	Source Assessment	13M	07C
Heating Equipment	Polycyclic Compounds	Particulate	13A	
Assessments		Polycyclic Organic Material	14B	
Dust			11G	

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