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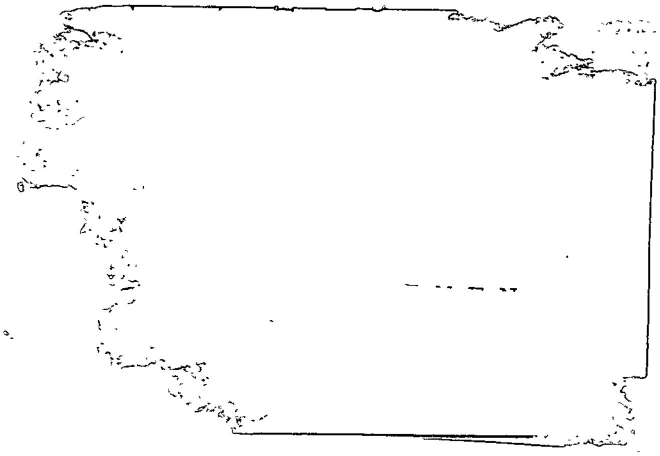
Air Pollution Emissions and Control Techniques: Residential Heating Units



Economic and Technical Review
Report EPS 3-AP-79-3

Pollution Control Directorate

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AIR POLLUTION EMISSIONS AND CONTROL TECHNIQUES: RESIDENTIAL HEATING UNITS

by

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ABSTRACT

The principal air contaminant emissions attributable to fuel-fired residential heating units are particulates, sulphur oxides, unburnt hydrocarbons, nitrogen oxides and carbon monoxide.

Although domestic heating units account for only 11% of emissions from stationary sources, seasonal variations, geomorphology and meteorology can combine to intensify greatly the adverse effects of these emissions.

This report shows that the reduction of emissions from heating systems is compatible with the present goal of energy conservation in that the best conservation strategies can reduce overall emissions. One strategy is burner modifications such as the addition of retention heads and the reduction of nozzle sizes. Another is adjustments to furnaces and their controls to decrease cycle frequency and reduce flue gas losses. Further emission reductions could be effected by better quality control of fuel oil. Control over fuel oil sulphur content and the nature of the hydrocarbon constitutents would ensure better combustion and a reduction of overall emission levels.

Recent substantial increases in fuel costs and concern about future supply have placed new pressures on the heating industry and precipitated the development of new, more efficient burners and furnaces. While this new equipment has not gained wide distribution as yet, the continuing escalation of fuel prices will virtually guarantee it. Another response to this situation has been a resurgence in the popularity of wood-fired heating. Although much less convenient, wood heating can be economical, particularly in rural areas where wood is cheap and plentiful. This trend may warrant further scrutiny as air pollution from wood used in residential heating exceeds that from liquid or gaseous fuels.

RÉSUMÉ

Les principaux polluants atmosphériques libérés par les appareils de chauffage au mazout ou au gaz dans les résidences sont les particules, les oxydes de soufre et d'azote, les hydrocarbures imbrûlés et le monoxyde de carbone.

Cette pollution ne représente que 11% des émissions provenant de sources fixes, mais l'action combinée des variations saisonnières, de la géomorphologie et des conditions météorologiques peut en augmenter considérablement les effets nocifs.

Le présent rapport démontre que la réduction de ces émissions répond au besoin actuel d'économie de l'énergie, car de meilleures méthodes de conservation permettent de diminuer le volume des émissions. Parmi ces méthodes, on suggère l'ajout de têtes de rétention aux brûleurs et la réduction de la taille des gicleurs, le réglage des chaudières et de leurs commandes pour diminuer la fréquence des cycles de chauffage et les pertes des gaz de combustion, ainsi qu'un contrôle plus serré de la qualité du mazout, notamment de sa teneur en soufre et de ses composants en hydrocarbures, ce qui assure une combustion améliorée et plus propre.

Les fortes hausses qui sont survenues dernièrement dans les coûts du mazout et les inquiétudes que suscite l'avenir de nos réserves exercent de nouvelles pressions auprès de l'industrie du chauffage et accélèrent la mise au point de nouveaux brûleurs et de nouvelles chaudières plus efficaces. Ce nouveau matériel n'est pas encore très répandu, mais il le sera très certainement à cause de la montée des prix du mazout. Une autre réaction à cette situation est le regain de popularité du chauffage au bois. Même s'il est beaucoup moins commode, le chauffage au bois peut être économique, surtout dans les régions rurales où l'on peut se procurer ce combustible facilement et à bon compte. Il faudra peut-être examiner de plus près cette nouvelle tendance étant donné que le chauffage résidentiel au bois pollue davantage l'air que celui au mazout ou au gaz.

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1 INTRODUCTION

1.1 Purpose

This report was prepared to review the state-of-the-art in fuel-fired residential heating and to assess the magnitude of the emissions produced. By summarizing some fundamentals of combustion and pollutant formation as well as presenting an inventory of equipment and fuels used, the report identifies and quantifies problems and evaluates trends.

1.2 General

Residential heating with natural gas and light oils accounts for roughly 11% of the emissions attributable to stationary sources in Canada. These fuels are consumed in units classified as warm air furnaces or boilers depending on whether the working fluid is air or water. Heat energy is transferred from the fuel by controlled combustion and subsequent radiation, convection and conduction to the heating medium and ultimately the living environment.

The major differences between boilers and furnaces are in the heat exchange configurations, with some associated minor differences in the combustion chamber. Since these differences do not substantially alter combustion, boilers and furnaces are essentially identical emission sources. This report deals with residential sizes only, that is, those with a capacity below 410 000 Joules/h (400 000 Btu/h). Typical configurations are illustrated in Figures 1 and 2.

The burner and combustion chamber are the main elements affecting atmospheric emissions. Although the burner plays a predominant role in emission reduction, the choice of combustion chamber can strongly influence both the type and amount of emissions and a compatible burner-combustion chamber system is needed for proper performance.

The two most widely used fuels for residential heating are natural gas and No. 2 fuel oil. Most of the natural gas supply originates in Western Canada and is distributed through transmission lines owned and operated by Trans Canada Pipelines Limited. A typical analysis of this fuel is given in Table 1.

Fuel oil is generally restricted to No. 2 fuel oil and is defined by the Canadian Government Specifications Board 3-GP-2E, March 1977. A typical analysis is given in Table 2.

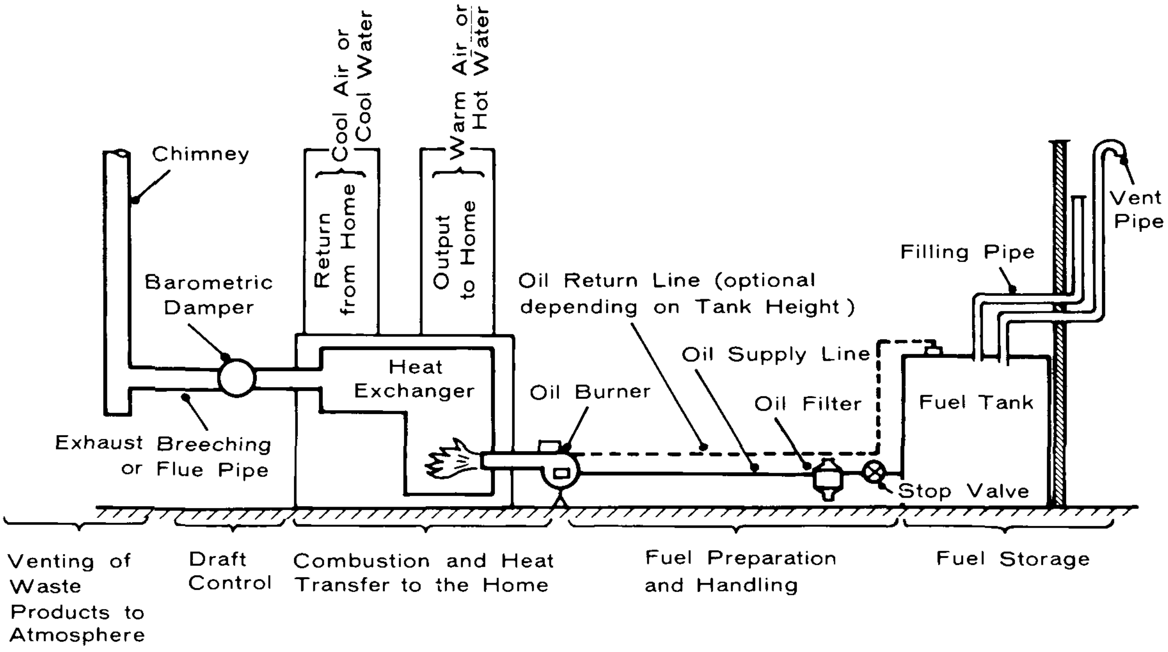

FIGURE 1 SCHEMATIC ILLUSTRATION OF THE COMPONENTS OF AN OIL-FIRED RESIDENTIAL HEATING SYSTEM

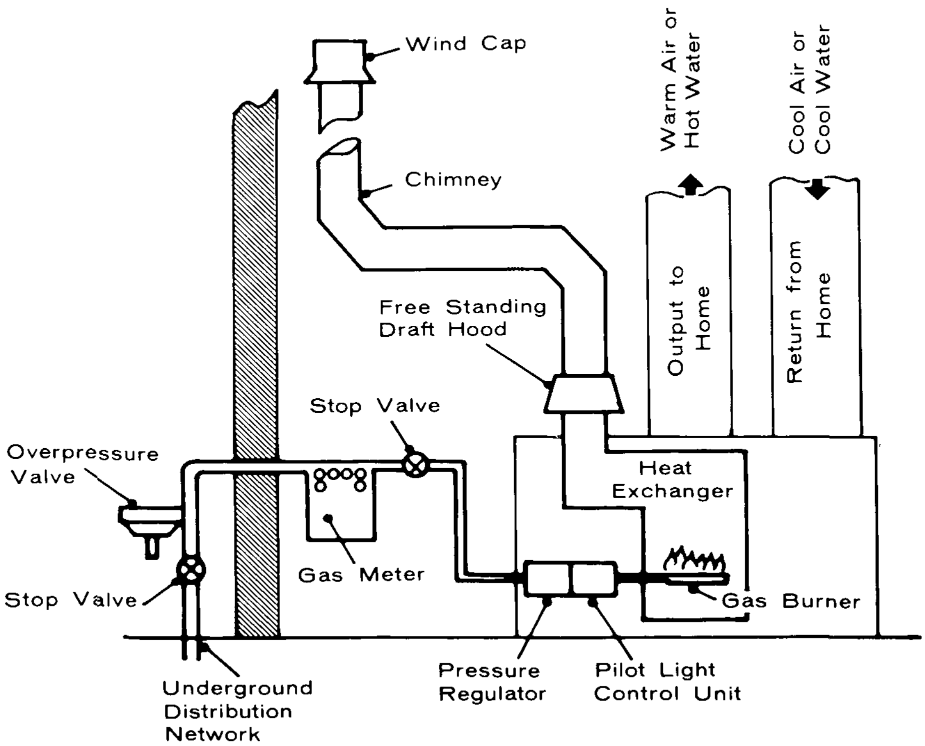

FIGURE 2 SCHEMATIC ILLUSTRATION OF THE COMPONENTS OF A GAS-FIRED RESIDENTIAL HEATING SYSTEM

(Figures 1 and 2 reproduced with permission of Energy, Mines and Resources Canada)

TABLE 1 TYPICAL ANALYSIS OF CANADIAN NATURAL GAS

Constituent	Volume Percent
Methane (CH_4)	91.50
Ethane (C_2H_6)	5.01
Propane (C_3H_8)	0.25
Butane (C_4H_{10})	0.10
Pentane (C_5H_{12})	Trace
Hexanes plus ($C_6H_{14}+$)	-
Nitrogen (N_2)	2.65
Carbon Dioxide (CO_2)	0.49
Oxygen (O_2)	-
Hydrogen (H_2)	-
Hydrogen Sulphide (H_2S)	-
	100.00%
Total Sulphur	5.26 mg/m^3
Calorific Value	37.5 x 10^6 Joules/m^3 (1 007 Btu/scf)
Specific Gravity	0.598 (air = 1.0)

Source: A Combustion Handbook for Canadian Fuels 1973, Vol. 2, Energy, Mines and Resources Canada. Monograph 879.

TABLE 2 TYPICAL ANALYSIS OF NO. 2 HEATING OIL

Constituent	Weight Percent
Carbon (C)	86.00
Hydrogen (H_2)	13.30
Sulphur (S)	0.70
Nitrogen (N_2)	-
Oxygen (O_2)	-
Ash	-
Moisture	-
	100.00%
Calorific Value	45.6×10^6 Joules/kg (19 590 Btu/lb)
Specific Gravity	0.850 (water = 1.0)

Source: A Combustion Handbook for Canadian Fuels 1969, Vol. 1, Energy, Mines and Resources Canada. Monograph 877.

2 EQUIPMENT INVENTORY

The following inventory of heating equipment is based on data from a Statistics Canada survey conducted in May, 1976, entitled "Household Facilities and Equipment" (12). In other cases, 1971 census data are used (1). Table 3 shows that emission sources in Canada are highly concentrated in urban areas.

TABLE 3 URBAN CONCENTRATION OF RESIDENTIAL HEATING UNITS

Province/Territory	% Urban
Newfoundland	58.7
Prince Edward Island	39.9
Nova Scotia	57.5
New Brunswick	59.7
Quebec	83.9
Ontario	83.8
Manitoba	72.7
Saskatchewan	55.7
Alberta	76.1
British Columbia	78.1
Yukon and NWT	59.1
CANADA	78.5

Source: Statistics Canada, Census of Canada 1971.

In the following tables heating equipment is classified by both system type and fuel used.* It is apparent that the large majority of the units are central systems of either hot water-steam or forced warm air, with stoves and space heaters negligible. Since, from the emissions standpoint, there is no appreciable difference between system types, the main classification criterion will be fuel use.

The following tables and figures contain a summary of Canadian heating statistics for various years up to 1976.

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*Electric heating is not considered in this report, because the pollutants involved are emitted by large generating stations.

TABLE 4 RESIDENTIAL HEATING EQUIPMENT BY TYPE AND ENERGY SOURCE, CANADA 1976 (%)

Type	Oil	Gas	Electricity	Wood and Coal	Total
Hot Water	77.5	21.4	Negligible	1.1	100
Warm Air	50	49.1	Negligible	0.9	100
Electric (Radiant)	NA	17.8	100	NA	100
Other*	57.9	17.8	Negligible	24.3	100
No. of Units (thousands)	2 224	1 794	505	121	4 644

*Other: stoves, fireplaces and other free-standing heaters

NA: not applicable

Source: Statistics Canada

TABLE 5 RESIDENTIAL HEATING EQUIPMENT BY PROVINCE, CANADA 1976 (%)

Province	Oil	Gas	Electricity	Wood and Coal	Total
Newfoundland	77.7	NA	22.3	Neg.	100
Prince Edward Island	100	Neg.	Neg.	Neg.	100
Nova Scotia	84.4	Neg.	6.9	8.7	100
New Brunswick	81.2	Neg.	12.7	6.1	100
Quebec	71.1	4.1	20.5	4.3	100
Ontario	46.4	43.2	9.4	1.0	100
Manitoba	27.5	62.7	9.8	Neg.	100
Saskatchewan	27.6	72.4	Neg.	Neg.	100
Alberta	6.7	93.3	Neg.	Neg.	100
British Columbia	38.7	47.5	11.6	2.2	100
CANADA	47.9	38.6	11.0	2.5	100

NA: not applicable

Source: Statistics Canada

TABLE 6 ENERGY CONSUMPTION IN HEATING, DOMESTIC AND FARM, CANADA 1975

Fuel	Quantity	Joules	Btu
Oil	85.8 million bbls	5.3×10^{17}	5.0×10^{14}
Gas	3.0×10^{11} scf	3.2×10^{17}	3.0×10^{14}
Electricity	64×10^{9} kW-h	2.3×10^{17}	2.2×10^{14}
Solid	242 000 tons	5.1×10^{15}	4.8×10^{12}

Source: Statistics Canada

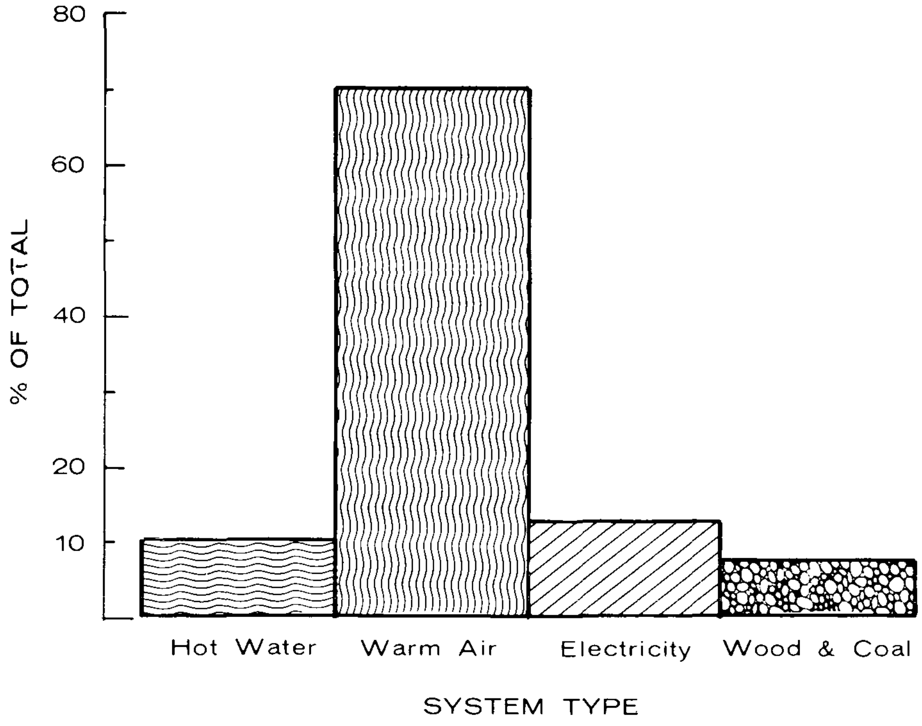


FIGURE 3 HEATING EQUIPMENT BY SYSTEM TYPE

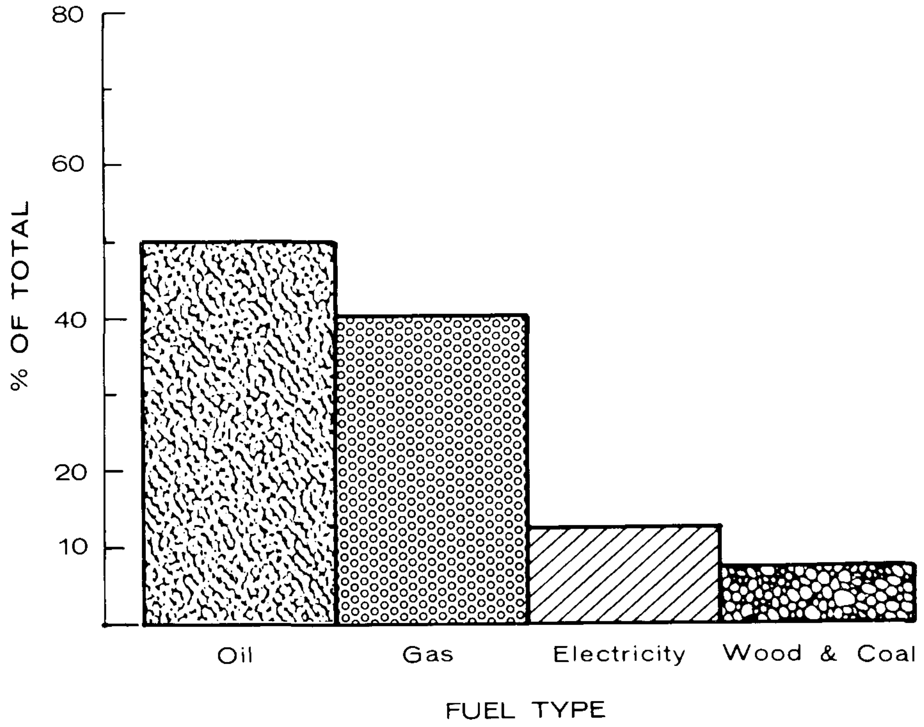


FIGURE 4 HEATING EQUIPMENT BY FUEL TYPE

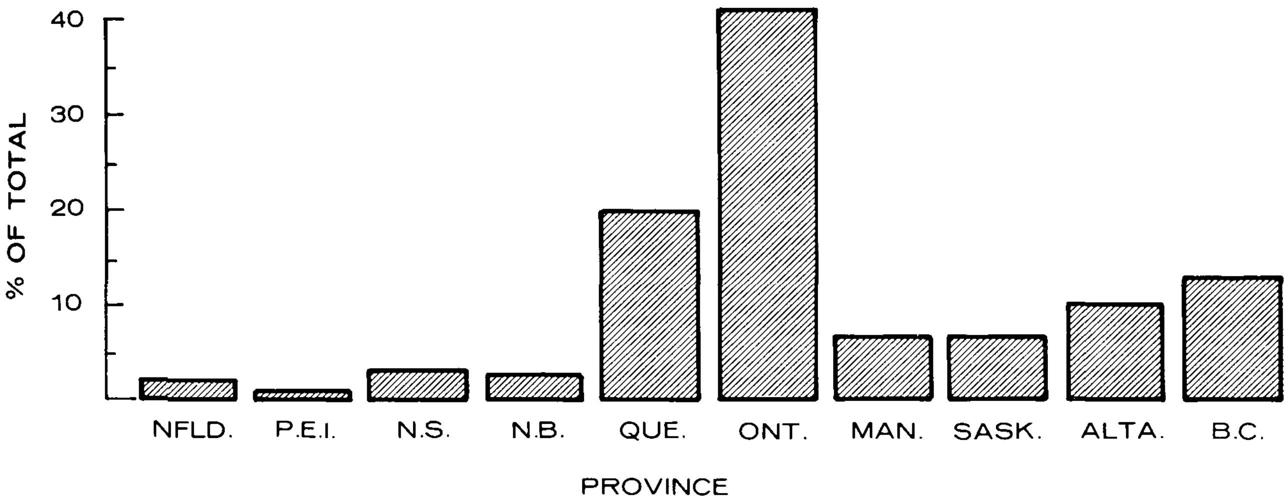


FIGURE 5 DISTRIBUTION OF HEATING SYSTEMS IN CANADA

Figure 6 shows the trends in heating over the past 35 years. The decline of coal and wood and the increased use of oil, gas and electricity are evident. The change has been one to fuels that are more convenient, clean and until recently, economical. Higher fossil fuel prices have triggered a renewed interest in coal and wood which, to many, seem cheap and plentiful.

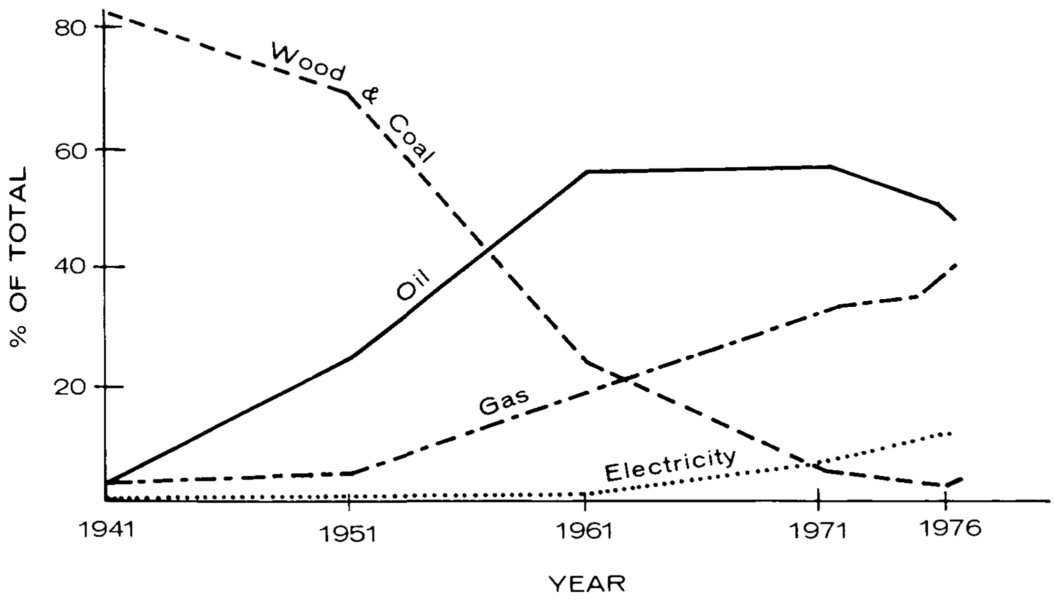


FIGURE 6 PERCENTAGE DISTRIBUTION OF OCCUPIED DWELLINGS BY PRINCIPAL HEATING FUEL, 1941–76

3 EMISSIONS INVENTORY

3.1 Emission Factors

Emission factors have been developed in order to estimate the emissions from residential heating units, because it is impractical to monitor all the units individually. An emission factor can be defined as an average estimate of the rate at which a pollutant is released as a result of some activity, divided by the level of that activity. In the case of residential heating, they are usually given as a mass of pollutant generated per unit of fuel or energy consumed. Because they are averages, these factors should only be used when applied to a large number of sources. To obtain an estimate of total emissions in a given area, these factors are multiplied by the number of sources involved.

Although several sets of emission factors from different studies have been published, the most widely accepted are those listed by the United States Environmental Protection Agency (EPA) (Table 7) (2). Accordingly they are used in this report.

Several things influence emissions and emission factors. One of these is the cycling rate of the furnace. As most emissions are produced at the beginning and end of each cycle, variations in the cycling rate will induce errors in emission estimates (section 6). Another is the recent shift by refineries to heavier crude oil feedstocks and thus a higher production of catalytically cracked oils. This means that the No. 2 fuel oils have larger aromatic hydrocarbon fractions. These less volatile fuels tend to produce smoky flames especially at the low excess air levels required for efficient combustion.

Most of the domestic heating capacity in Canada is provided by oil- and gas-fired furnaces. For this reason the report will deal principally with these units.

TABLE 7 EPA EMISSION FACTORS FOR NO. 2 OIL AND NATURAL GAS

Fuel	Units	Particulates	SO_2	HC	NO_x	CO
No. 2 Oil	$lb/10^6$ Btu	0.057	1.024 (S)*	0.036	0.056	0.036
	$g/10^6$ Joules	0.024	0.44 (S)*	0.015	0.024	0.015
Natural Gas	$lb/10^6$ Btu	0.019	0.000596	0.0079	0.079	0.02
	$g/10^6$ Joules	0.0082	0.00026	0.0034	0.034	0.0086

* Numerical constant. The SO_2 emission factor is calculated by multiplying the weight percentage of sulphur in the fuel by this numerical constant.

3.2 Total Emissions

Numerous variables such as equipment inventory and distribution, local fuel composition and quality of servicing can affect the accuracy of emission estimates. Previously reported estimates of emissions (2) (3) differ for some pollutants but are in close agreement for others. An estimate using both fuel consumption and equipment statistics (4) and the EPA emission factors is given in Table 8. The relative importance of each emission is shown in Table 9.

TABLE 8 MAJOR AIR CONTAMINANT EMISSIONS FROM RESIDENTIAL HEATING

Contaminant	kg/yr	tons/yr
Particulates	1.75×10^7	19 300
Hydrocarbons	5.53×10^6	6 100
Carbon Monoxide	1.02×10^7	11 200
Nitrogen Oxides	2.85×10^7	31 400
Sulphur Dioxide*	1.06×10^8	117 200

* Based on an average sulphur content of 0.5% by weight.

TABLE 9 RELATIVE IMPORTANCE OF AIR CONTAMINANT EMISSIONS FROM RESIDENTIAL HEATING

Contaminant	% of Canadian Total
Particulates	1.3
Hydrocarbons	0.5
Carbon Monoxide	0.3
Nitrogen Oxides	2.2
Sulphur Oxides	2.4

A three- to five-percent annual growth rate for residential construction has been experienced for the past five years, with a somewhat lower growth rate expected in the next few years.

As shown in Figure 6 this projection cannot entirely be extended to emissions as the trend is to using the cleaner-burning natural gas in new units as well as to developing more efficient equipment for oil combustion. So while a continuing increase in the total number of units is anticipated, the widespread use of more efficient, cleaner-burning equipment as well as the retrofitting of new devices in older units could initially lead to a net reduction in the total emissions from this source.

3.3 Pertinence of Emissions

Despite the relatively small volume of emissions from domestic heating sources, several factors act to concentrate these pollutants.

Residential heating is seasonal, extending over a six- to eight-month period. This has the effect of concentrating the yearly emission into a shorter time.

Approximately 80% of all heating equipment is located in heavily populated urban areas. Emissions from these units are usually released at low elevations, near buildings and other structures. Also, most operate on natural draft, with low stack exit velocities. These factors combine to favour stack downwash and accumulation of pollutants in building cavities where eddy currents entrain them. The net effect is the release of pollutants at ground level where the dispersive action of wind is often at a minimum.

4 COMBUSTION PARAMETERS

Several interdependent parameters govern the combustion process as it applies to residential heating. Since they determine the main operating characteristics of combustion units they provide a logical approach to emission reduction and efficiency enhancement. They are briefly discussed below.

4.1 Air-Fuel Mixing

Combustion is a rapid oxidation of the carbon and hydrogen in the fuel, releasing energy in the form of heat.

This process ideally takes place between two gases -- oxygen and fuel vapour. Intimate mixing of these reactants is of prime importance in achieving complete combustion. With oil, vapourization is either approximated by spraying the fuel through a special nozzle or by evaporation in a heated container. The first is by far the most common method, while evaporation is usually reserved for stoves and small space heaters. Air for combustion is then pumped into the fine spray where mixing, ignition and combustion take place.

With gas, vapourization is of no concern. Burner designs are simpler, usually using natural draft to supply air for combustion.

4.2 Air-Fuel Ratio

The air-fuel ratio is defined as a ratio of the mass of air to the mass of fuel in a given mixture. An air-fuel ratio of 4:1, then, would imply that there are 4 kilograms of air for every kilogram of fuel in the mixture.

4.3 Stoichiometric Air

Simply stated, the combustion of hydrocarbons takes place essentially as follows:

$$C + O_2 \rightarrow CO_2 + \text{heat energy}$$
$$2H_2 + O_2 \rightarrow 2H_2O + \text{heat energy}$$

In such combustion reactions, stoichiometric air is the chemically exact amount of air required to supply the oxygen to oxidize all of the carbon and hydrogen in a given fuel. An air supply less than stoichiometric will result in incomplete combustion with its inherent loss of combustion efficiency and emission of unburnt fuel as particulates, carbon monoxide and hydrocarbons. Greater than stoichiometric air will tend in the extreme to impede efficient combustion by over-diluting the reaction and its products.

A good estimate of this value can be calculated knowing the weight content of reactants in the fuel (from analysis or reference) and the weight content of oxygen in air (approximately 23%). A more exact value would include secondary reactions and consideration of impurities not listed above.

4.4 Excess Air

The stoichiometric air described above is a theoretical determination of air required for complete combustion. This value would apply for air and fuel which are "perfectly" mixed.

The physical limitations of burner designs prevent perfect mixing. To compensate for this, some air in excess of stoichiometric requirements must be fed to the process to ensure complete combustion.

This excess air is expressed as a percentage above the stoichiometric air. (A mixture containing 125% of the stoichiometric air would have 25% excess air). Expressed as a ratio (as in the example, 1.25), this is called the stoichiometric ratio.

Just as too little air results in decreased performance, so does too much excess air. These relationships are subjectively illustrated by Figure 7.

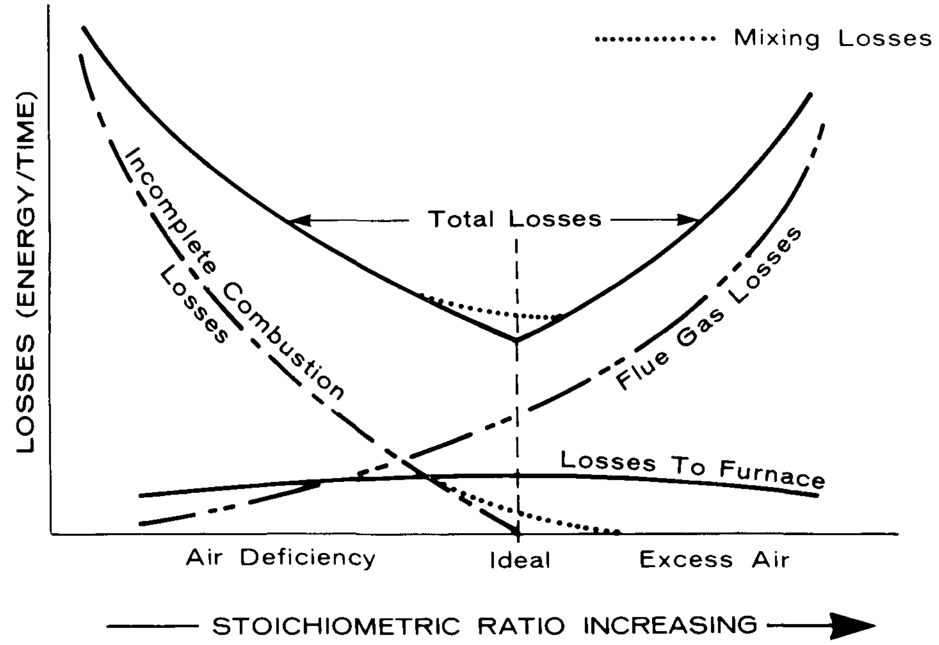


FIGURE 7 VARIATION OF FURNACE LOSSES WITH STOICHIOMETRIC RATIO

The effect of excess air is to increase the throughput of gases in combustion. Since the firing rate remains constant, the effect is essentially one of dilution. The quantity of heat produced is constant but is contained in a larger volume of gases. This is illustrated in Figure 7 by the 'flue gas losses' line. As excess air increases, so does the velocity of flow through the heat exchanger. This faster moving, cooler exhaust is less capable of transmitting heat to the heat exchange surfaces, resulting in lower performance.

4.5 Flue Gas Concentrations of CO_2 and O_2

It is evident from the previous discussion that since the concentration of combustion products varies with variations in excess air, pollutant emission measures for these gases are meaningless unless supplied at a specified excess air level.

Assuming complete combustion, a fixed mass of a given fuel will always produce the same mass of CO_2. The actual percentage of CO_2, usually expressed as volume percentage dry in the flue gas, then will depend on the amount of excess air. By the same token all of the O_2 present in the flue gas can be attributed to the excess air which has not been involved in the oxidation reaction. It is evident that as excess air is increased, the percentage of O_2 in the flue gas increases and the percentage of CO_2 decreases. Typical curves for these relationships can be seen in Figure 8.

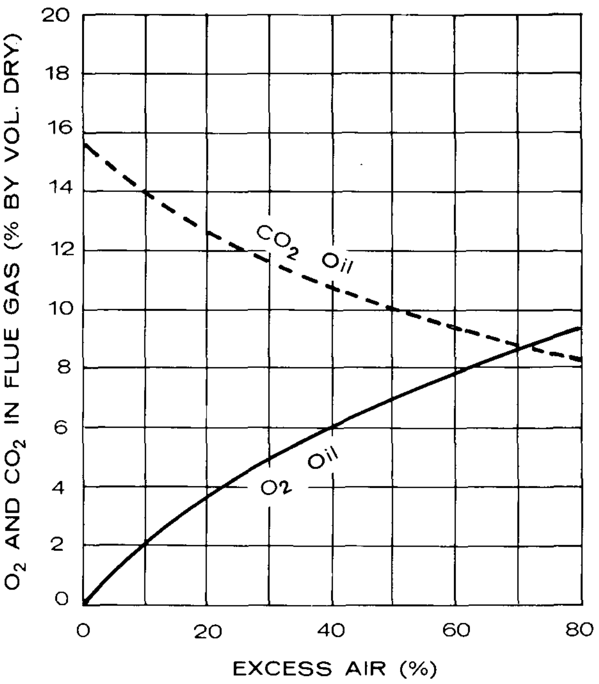


FIGURE 8 RELATIONSHIP BETWEEN EXCESS AIR AND FLUE GAS O_2 AND CO_2 CONTENT

It should be noted, however, that the percentage of CO_2 at a given excess air level (or the amount of CO_2 produced) is dependent on the carbon content of the fuel used. The curves in Figure 8 therefore do not give exact information for all fuels, but show the relationships that exist.

It can be seen that an analysis of the flue gas gives a good determination of the excess air used in the combustion chamber.

4.6 Thermal Efficiency

The thermal efficiency of a heating unit is defined as the ratio of gross heat available (heating value of fuel) minus all losses, divided by the gross heat.

$$\text{Efficiency} = \frac{\text{Gross Heat - Losses}}{\text{Gross Heat}} \times 100\%$$

These total losses, as shown in Figure 7, are a combination of radiation and wall losses, incomplete combustion losses and flue gas losses. Flue gas losses are particularly important in efficiency improvement.

In practice, the thermal efficiency of a household furnace is estimated by taking a flue gas temperature measurement and a CO_2 content measurement. As illustrated in Figure 9, the lower the exhaust temperature and the higher the CO_2, the better the efficiency.

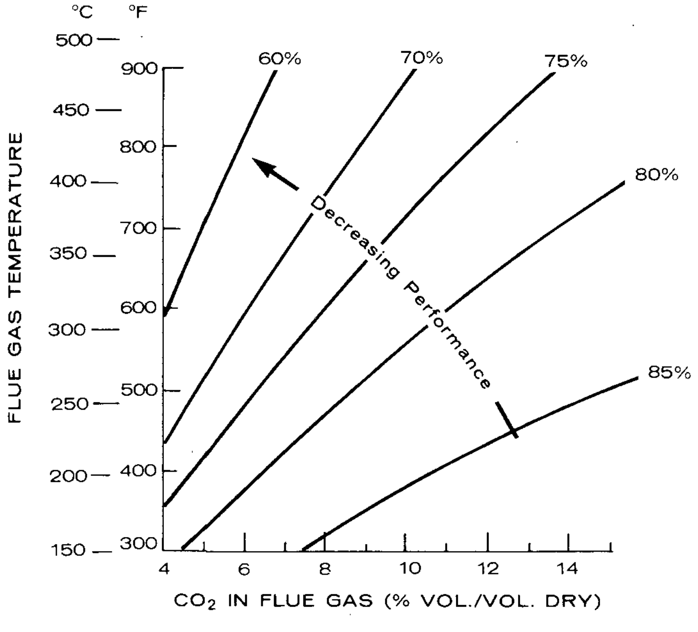


FIGURE 9 EFFICIENCY VERSUS CARBON DIOXIDE AND FLUE GAS TEMPERATURE

5 DESCRIPTION OF UNITS AND FUNCTIONAL COMPONENTS

5.1 Oil Combustion System

Residential burners use No. 1 or No. 2 fuel oil and often combine two principal methods to prepare the oil for combustion. The methods are atomization (spraying) and vapourization (heating). There are a number of different types of oil burners on the market, but each one can be identified as primarily employing one of the above methods for fuel preparation.

5.1.1 **Burners.** Most oil burners in use or on the market in Canada are classified as high-pressure atomizing burners (Figure 10). These units pressurize the oil to 7.03 kg/cm^2 (approximately 100 psi) by pump and atomize the fuel using specially designed and calibrated nozzles. This spray is then mixed with combustion air which has been pumped by a fan down the blast tube and through the head. The air and fuel mix in the combustion chamber and are ignited by an electric spark. This type of burner, because of its popularity and high degree of standardization, is now the subject of research aimed at enhancing its performance. These efforts and other recent developments discussed in the following pages ensure that this type of unit will be popular for some time yet.

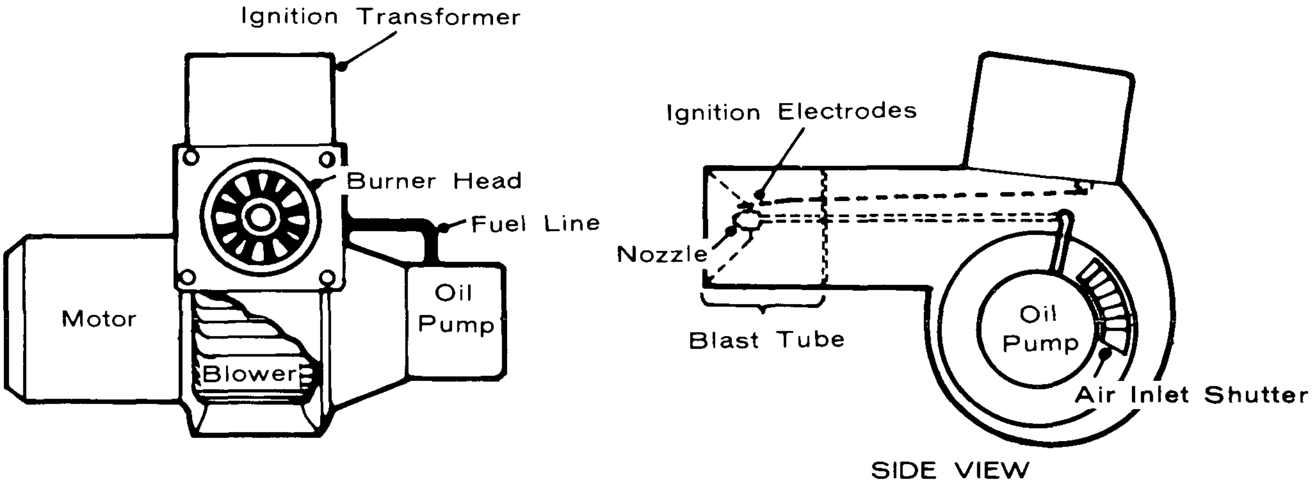
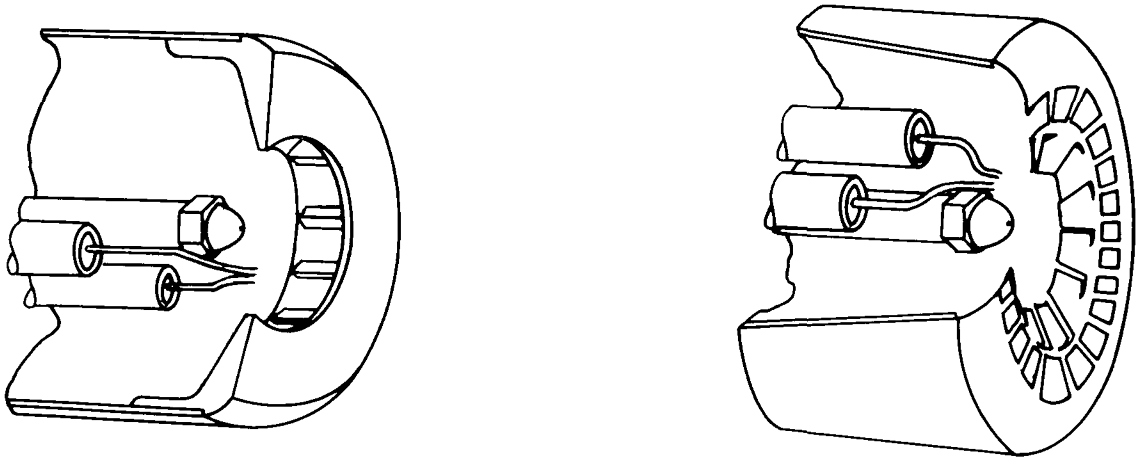


FIGURE 10 TYPICAL CONFIGURATION OF HIGH-PRESSURE ATOMIZING BURNER

The fan or blower is an integral part of the burner housing and is generally driven by the same shaft that drives the oil pump. Air leaving the fan moves down the blast tube without any initially imparted rotational motion. If the air were allowed to approach the oil spray in this fashion, a very inefficient flame (unstable and smoky) would be produced. Devices must be used to give the air further energy, velocity and direction, thereby creating enough turbulence to ensure the thorough mixing of air and oil mist. The devices used force the air through a restricted, specially designed section which gives a swirling, turbulent, high-speed motion to the air stream. They yield increased efficiency by producing more stable, bushy and intense flames at lower excess air levels, permitting more complete combustion and corresponding reductions in soot and hydrocarbon emissions.

Typical burner heads are shown in Figure 11.



STANDARD BURNER HEAD

RETENTION HEAD

FIGURE 11 TYPICAL BURNER HEADS

The last few years have been ones of intense research and development activity in this field and new trends are beginning to emerge. Perhaps one of the most significant ones has been the development and marketing in the United States of a Blue Flame Burner-Furnace System (15) (Figure 12). In this system, combustion products are partially recycled into the flame zone producing a blue flame of relatively low temperature, as is produced in natural gas burners. Preliminary indications are that such a unit is capable of operating with excess air levels of under 20% with CO_2 well in excess of 13%. The lower temperatures reduce NO_x production and the complete combustion is virtually smokeless. Efforts are underway to obtain Canadian certification.

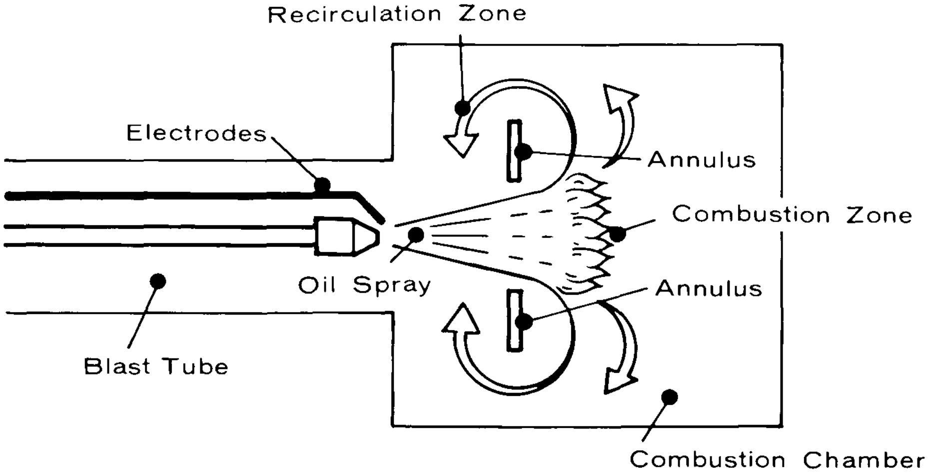


FIGURE 12 SCHEMATIC ILLUSTRATION OF INTERNAL RECIRCULATION OIL BURNER

5.1.2 **Nozzles.** The three basic functions of an oil burner nozzle are: atomization, metering and patterning.

1) Atomization: This process initiates vapourization by swirling the pressurized oil through a calibrated orifice into fine droplets. Small droplets are necessary for quiet, complete ignition and for establishing a flame front close to the burner head. Large droplets take longer to burn and, depending on the configuration, may cause problems by impinging on the back wall of the combustion chamber. Furthermore, large droplets have a lower vapour pressure than small ones. They therefore do not evaporate as rapidly and when heated, rather than vapourize, they polymerize to produce soot.

   The trend is to faster vapourization and, through enhanced atomization and turbulent mixing, correspondingly shorter flames and combustion chambers.
2) Metering: A nozzle is designed to deliver a fixed amount of atomized fuel to the combustion chamber for a given pressure within 5% of rated capacity. For this reason, a large range of capacities is available to satisfy a wide range of needs.
3) Patterning: A nozzle delivers the atomized fuel to the combustion chamber in a uniform spray pattern and at a spray angle best suited to the requirements of the burner/combustion chamber.

High-pressure type nozzles come in various sizes from 0.5 gallons per hour to 35 gallons per hour*. Spray angles vary from 30° to 90° and the spray may be hollow, semi-hollow or solid (Figure 13).

5.1.3 **Combustion Chambers.** Once the oil is broken up into tiny droplets, efficient, clean combustion is dependent upon the combustion chamber. The function of the combustion chamber is to ensure that:

1) all oil is burnt in suspension;
2) enough heat is given to the burning oil to speed up vapourization and maintain a high enough surrounding temperature to prevent any oil from escaping unburnt.

Oil particles require the high temperatures furnished by the fire itself to complete combustion. The tips and sides of the flame are filled with droplets and are

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U.S. gallons. Sizes not yet metric.

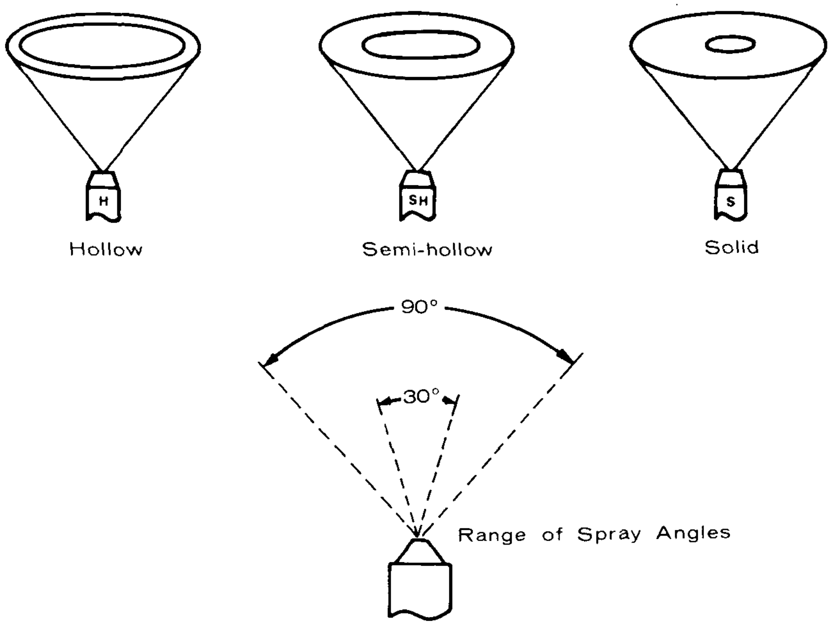


FIGURE 13 AVAILABLE SPRAY PATTERNS AND ANGLES
(From "Domestic and Commercial Oil Burners," by Charles H. Burkhardt. c 1969, McGraw-Hill. Used with permission of McGraw-Hill Book Company)

more susceptible to a decline in temperature. If the flame tips brush against cold surfaces the burning oil particles are rapidly chilled, cease combustion and freeze as deposits of oily soot. Such flame impingement is usually accompanied by increased smoke emissions.

For optimum combustion the combustion chamber design must be matched with the oil flow and flame pattern. It must provide sufficient space to prevent impingement of the partially burned oil on the surrounding walls and also provide an area of intense heat that can be radiated back upon the fire itself (Figure 14).

Refractory brick or other suitable material is used to line the combustion chamber. The most suitable material for domestic oil burner operations is lightweight insulating fire brick. This brick, which is highly porous, heats up quickly and radiates heat back into the flame. This type suits the numerous on-off cycles of domestic burners in which the burner and combustion chamber are relatively cold during starting conditions (Figure 15).

Recent advancements in high-temperature insulating materials have led to the development of "cerafelt" (Figure 15) which is used as a wrap-around blanket with a stainless steel outer support to either line an existing unit or form a new combustion chamber. This material offers similar properties to lightweight refractories and is lower in cost, simpler to install and easily used to retrofit existing units.

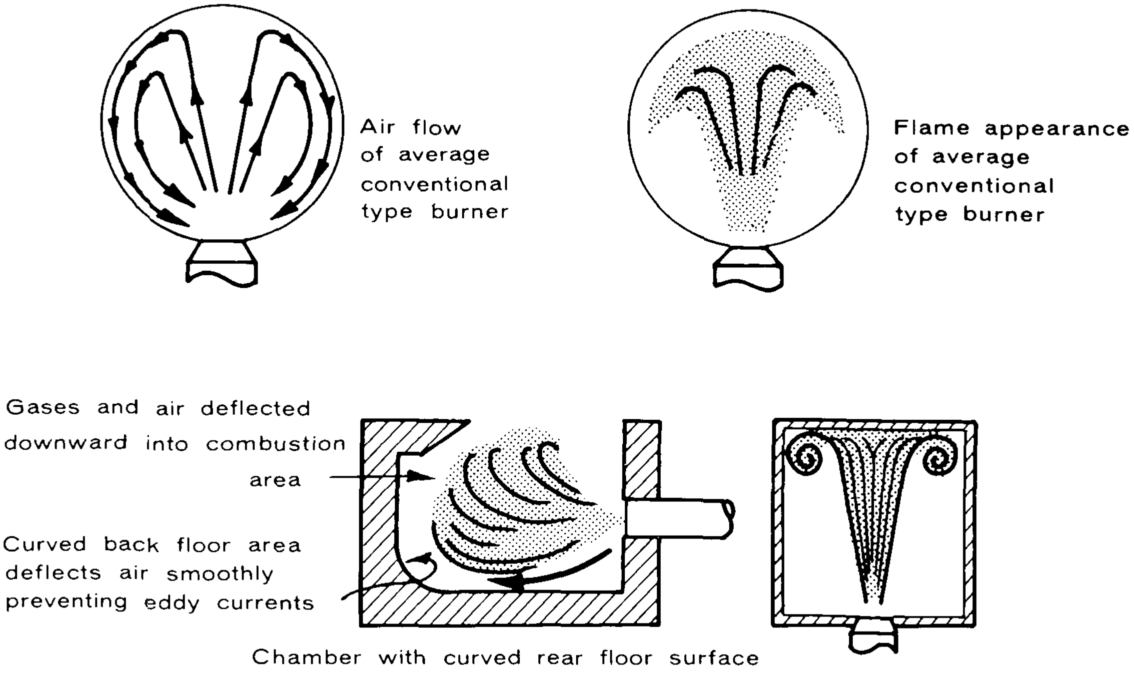
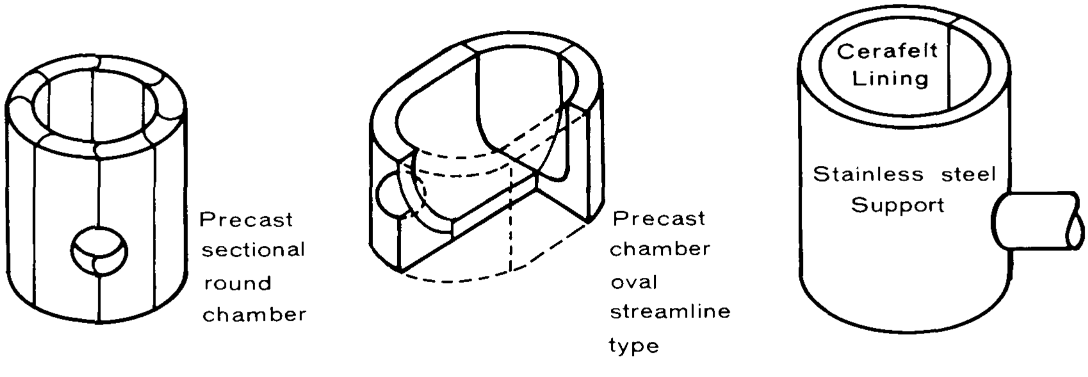


FIGURE 14 TYPICAL FLOW IN COMBUSTION CHAMBERS
(From "Domestic and Commercial Oil Burners," by Charles H. Burkhardt. c 1969, McGraw-Hill. Used with permission of McGraw-Hill Book Company)



LIGHTWEIGHT CAST REFRACTORY

CERAFELT LINED

FIGURE 15 TYPICAL REFRACTORY COMBUSTION CHAMBERS
(Lightweight cast refractory types from "Domestic and Commercial Oil Burners," by Charles H. Burkhardt. c 1969, McGraw-Hill. Used with permission of McGraw-Hill Book Company)

5.2 Gas Burners

5.2.1 **Burners.** Practically all domestic gas heating equipment employs atmospheric gas burners in low-pressure systems (up to 35 g/cm^2, 14 in. water gauge). In these burners, the momentum of the jet of gas entrains from the atmosphere a portion or all of the air required for combustion. Air premixed with the gas is designated as primary air and the remainder around the flame as secondary air.

Several basic designs of atmospheric burners are illustrated in Figures 16 and 17. Most residential units now being installed are of the multiple-port type. With these, the gas, premixed with some combustion air, is released through drilled holes (ports) arranged on an array of tubes. Because of the flexibility in configuration, these are often closely mated to the heat exchanger giving increased performance.

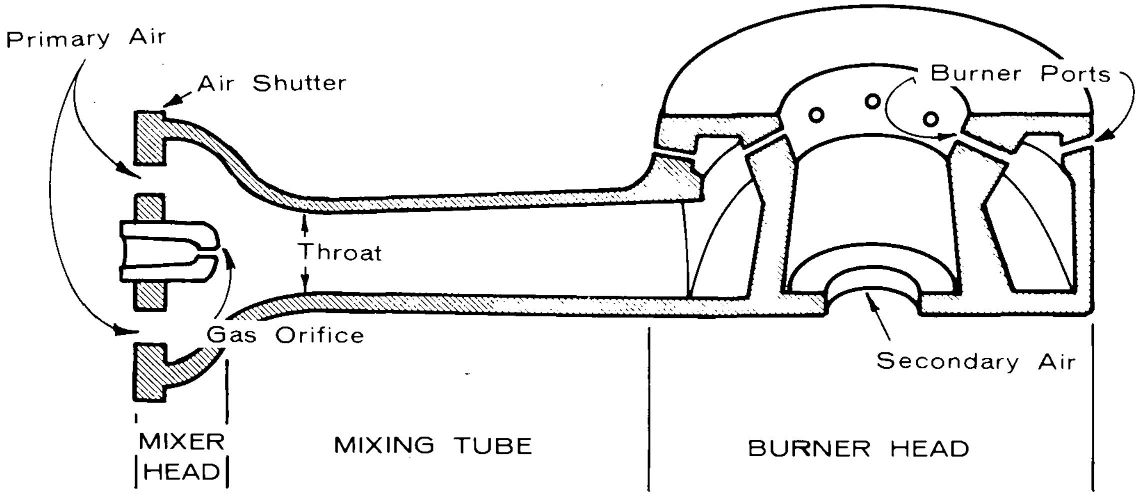
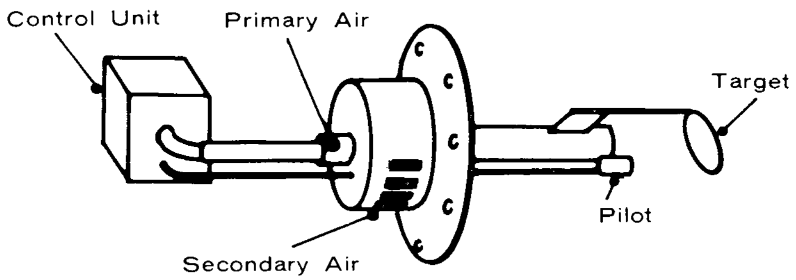
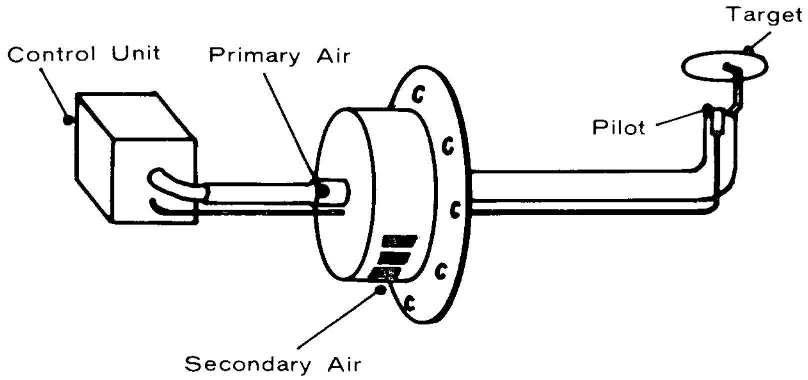


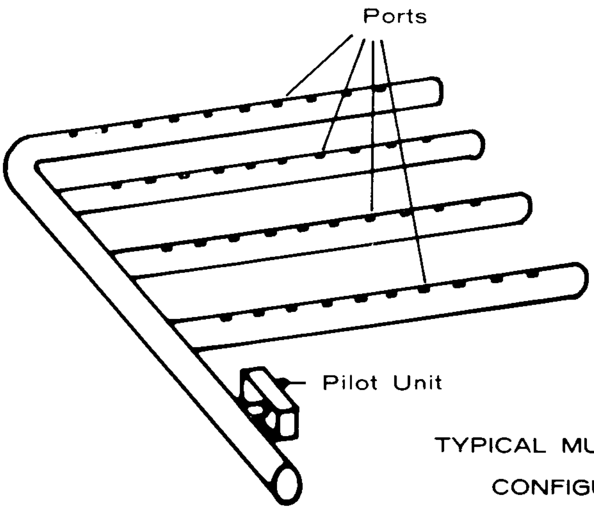
FIGURE 16 RING MULTIPLE-PORT ATMOSPHERIC GAS BURNER



INSHOT TYPE



UPSHOT TYPE



TYPICAL MULTIPLE-PORT CONFIGURATION

FIGURE 17 SINGLE- AND MULTIPLE-PORT GAS BURNERS

5.2.2 Ports. As mentioned previously, atmospheric gas burners are subdivided into single-port or multiple-port burner head arrangements. The single port is either of two basic designs, the upshot or inshot type, depending upon the orientation of the port. Both these types have "targets" to help stabilize the burner flame.

An advantage of single-port burners is their simplicity of design. However, as the range of adjustment for primary air and gas input rate is narrow, their operation is less flexible than drilled multiple-port burners. This results in limited use for residential heating.

Residential heating with gaseous fuels is primarily accomplished with drilled multiple-port burners. This ensures uniform heat distribution over the burner head, complete burning of the gas, ready ignition with flame travelling from port to port, and quiet, efficient ignition, combustion and extinction. The burner mixing tube is designed to entrain in the order of 35% to 60% primary air with the remainder of the air required for combustion being aspirated by the gas flow through the drilled ports. Ports and mixing tube are both designed to obtain the desired firing rate. They are both sized to provide minimum flame lifting, flashback and yellow tipping. Variations in port size and gas pressure control the height of the secondary combustion zone or outer flame mantle.

5.2.3 Combustion Chambers. The function, size and shape of combustion chambers in gas-fired residential heating units often differ from those of their oil-fired counterparts. They are, in fact, a little less critical in their role of providing for clean combustion than those of oil-burning units because of the different nature of the two fuels. However, the non-luminous, small gas flames produced in multiple-port burners necessitate that for good heat exchange to take place, the burner be closely mated to the heat exchanger. This combustion chamber is often nothing more than the lower section of the heat exchanger. Single-port upshot or inshot type burners, because they produce a single large flame, use the same combustion chambers as comparable oil burners. For this reason they are the preferred burner style for retrofitting oil-fired units.

6 AIR CONTAMINANT EMISSION FORMATION

Air contaminant emissions from residential heating combustion include particulate matter, sulphur oxides, nitrogen oxides, carbon monoxide and, to a lesser extent, organic compounds. Some accepted emission factors are the Scott, the Battelle, and the previously listed EPA emission factors. While it is too cumbersome to present them here, some idea of the values and variations involved can be gained from Table 10. In general, the kinetics of formation for these pollutants during the combustion process are still not widely understood, but include such variables as time, temperature, aerodynamics and the concentration of reactants in the specific fuel being used (3,9,14).

The wide variation in emission levels of all types of pollutants can possibly be explained by the range in age and type of units being tested, as well as the different testing conditions used.

TABLE 10 SUMMARY OF RESIDENTIAL HEATING EMISSION FACTORS

		Particulates	SO_2	NO_x	CO	HC
Average Factor	g/kg fuel	1.40	12.33	1.27	1.00	0.26
	$lb/10^6$ Btu	0.069	0.63	0.064	0.051	0.013
Variation	± %	78%	26%	45%	60%	64%

6.1 Formation by Emission Type

6.1.1 Particulate Matter and Products of Incomplete Combustion. Smoke consists mostly of carbon particles and other products of incomplete combustion. Quite apart from detrimental environmental effects, this emission can play a major role in reducing furnace efficiency. This happens when soot and ash deposits form on heat exchange surfaces, effectively acting as an insulator. Evidence that this may be taking place is an increase in flue gas temperature as the heating season progresses.

Residential heating units account for but a small percentage of particulates emitted in Canada. The installation of control devices, if available, would be of marginal value; more emission reduction can be achieved through improvements in fuel quality and burner maintenance. With oil combustion, a small portion of the particulate matter originates from non-combustibles in the fuel, but as the ash content of No. 2 fuel oil is very low, this source can be ignored. To some extent particulates can be eliminated by tuning and by slight burner modifications to decrease the start-up and shut-down times when most particulates are formed.

6.1.2 Sulphur Oxides (SO_x). SO_x are formed when chemically bonded sulphur reacts with oxygen during the combustion process. SO_x are present as SO_2 and SO_3, but at the combustion temperatures encountered in residential heating units the SO_2/SO_x ratio can reach 0.98. Because of this high conversion to SO_2 , the level of these oxides can be readily calculated without measurements being necessary. The sulphur not emitted as a gas is emitted mainly with the particulate matter as a condensed acid. Although SO_2 is one of the more troublesome emissions from domestic heating equipment, the quantity is relatively low compared with other sources (Table 9).

6.1.3 Nitrogen Oxides (NO_x). NO_x represents the combination of NO and NO_2, and is formed from both the free nitrogen in the atmosphere at high temperatures, and from bonded nitrogen in the fuel. Atmospheric nitrogen reacts with oxygen at elevated temperatures to form NO and, to a much lesser degree, NO_2. Nitrogen bonded in the fuel reacts as part of the fuel and is not as temperature dependent.

6.1.4 Carbon Monoxide (CO) and Hydrocarbons (HC). Both CO and HC are products of incomplete combustion. If combustion were complete, the carbon in the fuel would be oxidized to CO_2 and the hydrogen to H_2O. Again, proper maintenance and tuning help reduce these emissions.

6.2 Emission Formation

Residential heating emission characteristics are dictated by the local climate and the equipment used. The wind speed, gustiness, solar radiation, temperature and humidity are the variables of the climate that affect the demands made on heating equipment. Automatic control of each heating unit is accomplished predominantly by an indoor space thermostat which is adjusted to a set point. The heating unit firing is controlled by this set point, with the unit cycling "on" or "off" depending on whether the temperature of the space to be heated is above or below this set point. The above variables of climate control the rate of heat loss from the space and the heating unit operation fluctuates in order to keep the space temperature in equilibrium with the temperature selected as the control set point. This on-off operation is by far the simplest space heating control system and the most commonly used; more sophisticated methods, such as indoor-outdoor compensation and temperature differential control, are adaptable to variable firing but are usually reserved for commercial heating.

This operational cycling of a heating unit produces on-off cycles of varying duration. The average operation for heating units as a consequence of the firing rate and heat load is about one third "on" and two thirds "off". During a representative heating cycle of ten minutes "on" and twenty minutes "off", the air contaminant emission formation characteristics vary as shown in EPA-650/2-74-003 "A Study of Air Pollutant Emissions from Residential Heating Systems" (9). Most of the emissions in question have sizeable peaks during ignition and/or shut-down (Figures 18 to 21).

CO and gaseous HC emissions both peak during ignition and after burner shut-off. HC emissions return to near zero after the initial peak and remain low until the burner goes off. A similar response is apparent for the CO emissions. These variable conditions could be accounted for by a slow build-up of air flow as the fuel is injected into the combustion chamber, resulting in an imbalance of the air-fuel mixture and/or low flame temperature, delayed ignition or incomplete combustion. Both of these emissions tend to reach a measurable equilibrium during the "on" part of the cycle.

Both the smoke and particulate matter emissions peak during ignition, taper off continuously during the cycle, and peak again upon extinction. Imbalance of the air-fuel ratio and/or incomplete combustion due to the relatively cool combustion chamber and its lack of re-radiated heat account for the peaks on burner start-up and extinction.

NO emissions do not peak like those of the other pollutants. After the initial NO peak, the emission level rises at a fairly steady rate because of the increase in temperature in the combustion chamber and would eventually level off at an equilibrium point if the average "on" cycle for residential units were of longer duration.

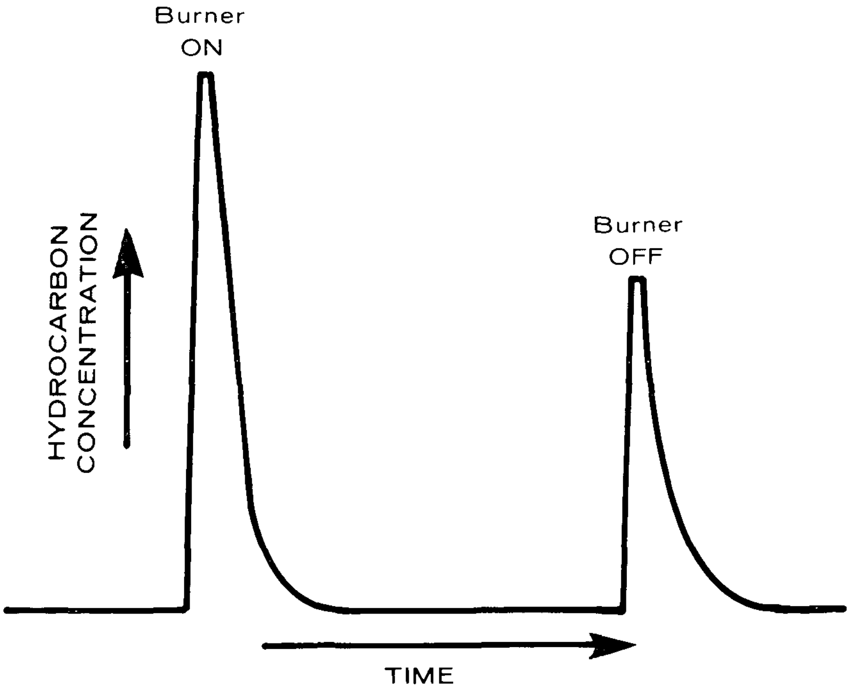


FIGURE 18 HYDROCARBON TREND DURING CYCLE

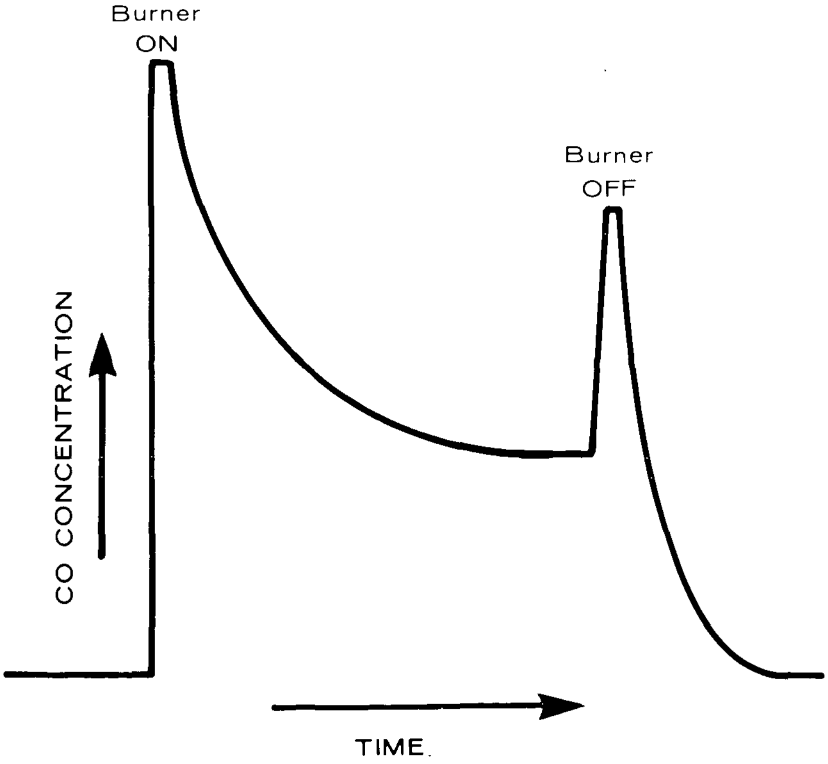


FIGURE 19 CARBON MONOXIDE TREND DURING CYCLE

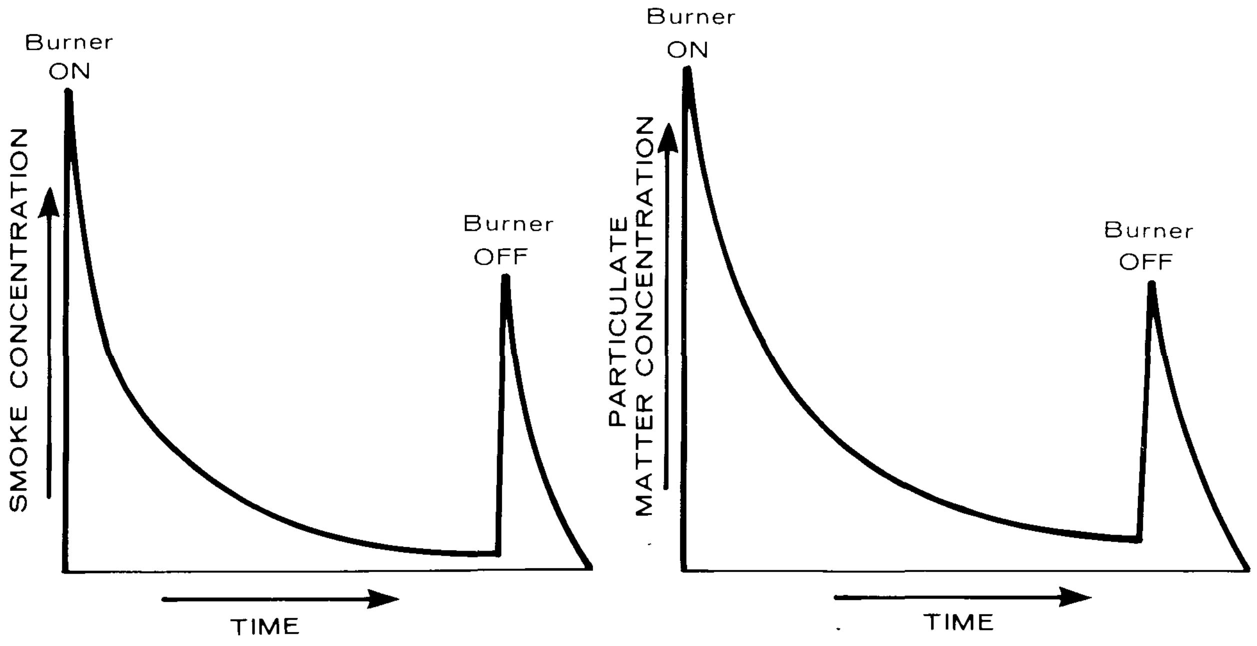


FIGURE 20 SMOKE AND PARTICULATE MATTER TRENDS DURING CYCLE

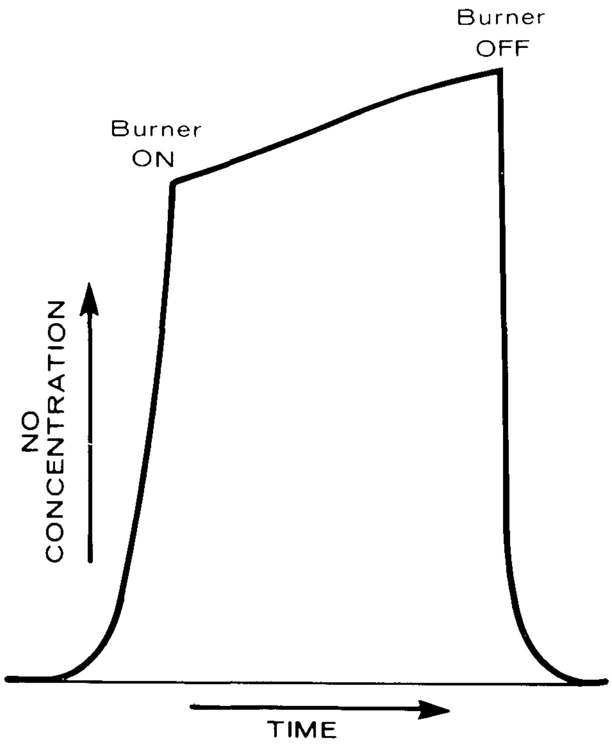


FIGURE 21 NITRIC OXIDE TREND DURING CYCLE

7 EMISSION TESTING

Testing emissions from residential heating furnaces poses several problems. One of the major problems is that, as shown in section 6, operation of these units is highly cyclical, and within any cycle concentrations of any given pollutant may vary by several hundred percent. Other problems are related to difficulties in sampling. In gas units, undiluted combustion products are not readily accessible and bends and poor ductwork often make sampling in the field difficult. Draft is usually unassisted and varies to some extent with outside temperature and wind speed and thus volumetric flow rates are not constant. Obtaining representative samples of gases often highly stratified in flues typically six inches in diameter requires special care.

For these reasons the standard steady-state procedures for stack testing cannot be relied upon to yield representative samples. They require sampling times often in excess of the complete cycling time of the furnace and thus cannot yield important information contained in start-up and shut-down peaks. Special techniques have been successfully employed for measurement of emissions from these sources but require expensive equipment and skilled technical operators and thus are not readily applicable to field testing.

7.1 Sulphur Oxides

As previously mentioned, SO_x emissions are directly related to the sulphur content of the fuel used. As the oxidation of the sulphur in the fuel to sulphur dioxide is almost complete, for all intents and purposes a simple calculation of this value based on fuel sulphur content is sufficient.

7.2 Nitrogen Oxides

NO_x emissions can be continuously monitored with standard laboratory equipment, using the standard reference phenoldisulphonic acid (PDSA) method. Recent work (10) has shown that ultra-violet (UV) methods (Dupone 411) are also satisfactory, as the variance between these two methods is minimal (standard error = 0% for NO and 2.9% for NO_2). Direct probing of the flue gas breeching will give reliable results by UV if particulate matter is removed from the sample gas stream to eliminate interference in the instrument. A sintered metal filter placed between the probe and the monitor is effective.

7.3 Carbon Monoxide and Carbon Dioxide

CO and CO_2 emissions from residential units can be conveniently measured continuously with long-path non-dispersive infra-red (NDIR) analyzers (9). As in the case of NO_x, suitable precautions must be taken to ensure against interference from particulate matter and moisture in the sample. EPA (9) has successfully achieved this with the use of molecular sieves, water impingers and particulate filters.

CO_2 emissions from residential sources are sufficiently high (8% - 12%) that spot checks with an Orsat analyzer are reliable. It has been stated that CO_2 measurements made using an Orsat analysis are within 5% of the standard NDIR reference method (10). Fyrite and similar devices give readings comparable to Orsat analysis.

The reliability of an Orsat is questionable with low CO emission levels from combustion sources.

7.4 Smoke and Particulate Matter

Particulate matter emissions from residential heating units burning No. 2 fuel oil are so variable that determination of short-term emission levels by standard reference methods is difficult. Emissions from gas burning, because of their low levels, pose even greater difficulties.

No exact correlation between particulate emission levels and smoke number has been found, but Bacharach smoke values are a good indication of emissions of fine particles.

Standard reference laboratory methods cannot be used to determine emissions from residential heating units because of:

1) poor accessibility of flues;
2) wide variations in over-fire draft;
3) wide variations in emissions within each cycle;
4) difficulty obtaining representative samples, particularly of particulates;
5) a lack of sufficient time to perform certain operations within relatively short cycle times.

8 MINIMIZING EMISSIONS AND OPTIMIZING BURNER DESIGN

In the last few years, mainly because of rapidly escalating fuel costs, a great deal of attention has been placed on improving the operating efficiency of domestic furnaces, particularly the oil-fired type. Because the combustion of light fuels in this equipment accounts for but a small percentage of Canada's total emissions and because no simple method for at-source control of these emissions exists, it is likely that the more efficient use of cleaner fuels will, to a large extent, reduce or eliminate this problem.

The work done to date indicates that, in general, increased efficiency can be compatible with reducing emissions. This can be achieved in two ways.

One is the reduction in total emissions by lowering total fuel consumption through conservation and the use of more efficient equipment. Tests have shown (9) that lowering excess air in a given burner can increase efficiency to some degree but at the cost of increased emissions, particularly those related to inefficient or incomplete combustion. However, burners designed to achieve complete combustion at low excess air levels, especially those using turbulator or retention heads, when properly matched to a combustion chamber, give both better efficiencies and lower emissions. Other fuel conservation strategies such as nighttime thermostat set-back, and increased thermal insulation also reduce emissions by lowering fuel consumption.

The second is the reduction of the emissions generated during the start-up and shut-down phases of the burner cycle. Increasing the cycle length by using lower firing rates or increasing the null band of the thermostat set point thus minimizing the number of cycles are two methods. Here, care must be taken not to underfire the unit to such a degree that the combustion process deteriorates or that the ability to cope with peak loads is affected. The tendency has been to oversize home heating equipment and so some leeway is available. Thermostat adjustment is limited both by the constraints of maintaining indoor comfort as well as the limitations imposed by the thermostat itself.

Another method of achieving this end is the use of devices to aid in clean start-ups and shut-downs. These are the solenoid valve and the clutch coupling. They allow the burner air fan to start before the fuel is admitted and to run on after the fuel supply has stopped as well as providing for 'instantaneous' "on" and "off" control of the oil supply.

Combustion-improving devices such as special heads, will generally reduce total emissions, but they also alter the nature of the emissions. Burners equipped with such heads, combined with smaller refractory-lined steel combustion chambers, produce more intense flames which, while eliminating unburnt hydrocarbons, increase the production of NO_x. Tests have demonstrated (14) that by lowering the flame temperature by quenching to an intermediate level which minimizes NO_x levels, a good compromise is attainable -- a low level of unburnt hydrocarbons with little or no increase in NO_x as well as lower fuel consumption.

Other significant sources of emissions exist. Some ignition systems are capable of producing small amounts of NO_x. Faulty nozzles can cause unnecessary emissions, but this problem can usually be corrected by replacing the nozzle and subsequently adjusting the burner.

With the present equipment, short-term measures are available to abate emissions in those areas where the problem is acute.

Emissions from existing domestic furnaces could be reduced significantly by proper maintenance. This would include careful servicing by an authorized serviceman at least once each heating season, and replacing poorly designed or obsolete units. The nozzle in an oil burner should be replaced each season and the burner should be readjusted by using proper equipment for measuring smoke and CO_2. The furnace air filters should be replaced or serviced several times during the heating season to avoid appreciable reduction in heating efficiency.

The greatest loss is convection of heat up the flue. Flue gas sensible heat losses may be reduced by lowering either excess air or flue gas temperature.

When the burner is not being fired, a natural draft flow of air through the burner, firebox, etc., cools furnace components and continues to convect heat up the flue. Draft air loss can be reduced by having the burner fire more continuously or by incorporating in the flue a damper interlocked with the burner safety circuit. These are not yet available in Canada.

All residential heating units approved by CSA in the last fifteen years are capable of 75% steady-state efficiency. State-of-the-art equipment is capable of efficiencies in excess of 80%, as are many old units if properly retrofitted with efficiency-increasing devices such as flame retention heads.

Potentially, these measures combined with other conservation methods are capable of reducing fuel consumption by up to 30%. This represents a corresponding reduction in emissions from this source. In the short run, efficiency and conservation are the key to lower residential heating emissions.

A recent trend has been the extensive marketing of wood-burning heating equipment. These units include fireplaces, stoves and sophisticated refractory-lined wood-oil combination furnaces. Wood combustion is a relatively crude process and is commonly a heavy producer of smoke, particulates, carbon monoxide, nitrogen oxides and aromatic hydrocarbons. As fossil fuel costs continue escalating, it is possible that wood will continue gaining popularity as a heating fuel, primarily in those rural areas where it is cheap and plentiful. Very little reliable information is available on this re-emerging source. If the present rise in wood use continues, further studies will have to be undertaken.

REFERENCES

1. Statistics Canada, Catalogue 93-733, Vol. 2, Part 3, Housing - Principal Fuels and Heating Equipment, 1971.

2. U.S. EPA, Compilation of Air Pollution Emission Factors, AP-42, 1976.

3. Cauley, S.P. and Siegmund, C.W., Updating Emission Factors for Space Heating with Fuel Oil, API Meeting, May 1972.

4. Statistics Canada, 55-002, Gas Utilities, Dec. 1974;
   Statistics Canada, 45-208, Refined Petroleum Products, Vol. 2, 1974;
   Statistics Canada, 57-207, Detailed Energy Supply and Demand in Canada, 1975.

5. National Academy of Sciences/National Research Council, Combustion Equipment and Related Facilities for Non-Residential Heating Boilers, Publication 1294, 1974.

6. Burkhardt, C.H., Domestic and Commercial Oil Burners, McGraw-Hill, 1969.

7. Segeler, G., "Gas Engineers Handbook", The Industrial Press, 1965.

8. Inventories of National and Individual Air Pollution, Canadian Combustion Research Laboratory, Fuels Research Centre, June 1971.

9. U.S. EPA, A Study of Air Pollutant Emissions from Residential Heating Systems, EPA-650/2-74-003, Jan. 1974.

10. Private communications with Environment Canada personnel.

11. Standards for Fuel Oil: Heating (3-Gp-2c), Canadian Government Specifications Board, 1977.

12. Statistics Canada, 64-202, Household Facilities and Equipment, 1976.

13. A Nationwide Inventory of Air Pollutant Emissions, Environment Canada, EPS 3-AP-77-2, March 1977.

14. U.S. EPA, Residential Oil Furnace System Optimization, Phase II, PB264-202, Jan. 1977.

15. Fuel and Oil Heat, May 1977, The Blueray System.