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Introduction

In a national fuel efficiency program, fuel conservation in oil-fired residential heating equipment is one area where absolute savings of a significant magnitude can be made and where direct effects are immediately perceived by the homeowner as dollar savings. Perhaps more important is the knowledge of a personal contribution to a national conservation program.

There is a need to identify side benefits in pollutant emission characteristics due to the fuel conservation strategies which are being recommended to the homeowner. Reduced fuel consumption almost invariably leads to reduced emissions. The extent of these emission reductions will, in many cases, be responsive to the technique which is used to achieve the fuel reduction. Selection of fuel conservation strategies should be made to optimize the extent of both the emission reduction and the fuel conservation.

This paper describes part of a continuing research program carried out at the Canadian Combustion Research Laboratory (CCRL) in support of the National Fuel Conservation Policy and is devoted to conservation in oil-fired residential heating equipment. The early results from this program established, in field experiments, the relative merits of several well-publicized fuel conservation strategies (1). This paper has the specific purpose of relating these fuel conservation strategies to their emission control potential.

The experimental work has all been carried out in Ottawa where the typical winter amounts to over 4000 Celsius degree days (below 18°C) with a minimum temperature of -30°C, a winter average temperature of -2°C and a typical snowfall of 250 cm.

Fuel Consumption Studies

Records of the daily fuel consumption in the test homes selected for these systems analyses have been accumulated over three consecutive winters.

The fuel consumption and cyclic operation of the heating system in each home was monitored with three digital-display meters as follows:

1. a volumetric fuel-oil meter (± 0.01 Imperial gallons) which was installed in the oil supply line to the burner;
2. a total elapsed-time indicator (± 0.1 hr) which was connected across the power supply to the burner and which displayed total burner operating time;

3. an event counter, which was connected across the power supply to the burner and displayed the number of burner operating cycles.

The homeowners were provided with data sheets on which the displays from the three meters were recorded twice daily (generally at 07.00 and 19.00 hrs), together with any additional commentary on disturbances to the normal domestic routine. Throughout the course of the experiment, periods of time were designated as representing "normal" operation for each home; during these periods each control thermostat remained at a constant set-point of the homeowner's choice. The time periods were chosen to give fuel consumption data across the complete range of external (outdoor) temperatures which might be encountered in an Ottawa winter. Weather data provided by the Atmospheric Environment Service at Ottawa International Airport included hourly temperature readings which allowed the accurate calculation of a mean temperature for any selected time period. The studies were restricted to the period between October 1st and April 30th.

The data from the monthly log sheets was matched with the hourly temperature readings to give an average external air temperature for the time period between recorded data points. This average temperature was then converted to degree days below 18°C and used as the abscissa in graphical presentations, with ordinates such as fuel consumption (Imperial gallons/hr), burner "on" time (hr/hr) and cycles/hr.

Using this simple data recording and reduction technique, the following variations in furnace operation and burner hardware were studied during the course of the three test winters:-

Thermostat Operation : Moderate overnight cut-back
Severe overnight cut-back
Increased thermostat anticipator

Reduced "off" cycle losses: Positive chimney damper
Reduced firing rate

Burner Performance : Retention-heat burner
Prototype blue-flame burner.

Emission Studies

Measurement Techniques

Measurement of steady-state and cyclic emission characteristics of the oil fired equipment in the test homes and in the laboratory was carried out by laboratory staff using conventional measuring techniques. The emissions nominated for study together with the appropriate continuous measuring techniques were as follows:

Particulate Emissions These were measured as filterable solid material using an iso-kinetic sampling and collecting system developed at CCRL. The measurements consisted of systematic sampling of the flue gases over extended periods of steady and cyclic running of a control furnace. Using the Von Brand apparatus, continuous tape sampling of the smoke emissions showed that cyclic particulate emission measurements should be extended for 30 seconds after the end of a burner operating cycle. The total emission was, therefore, a function of both the concentration-time profile and the flow-time profile.

Sulphur Dioxide Emissions These were measured during the cyclic operation of a control furnace using both a modified West-Gaeke methodology and a pulsed U.V. technique. As anticipated, the SO_2 emission was a function of excess combustion-air level and the fuel sulphur content.

Nitric Oxide Emissions An extensive series of measurements of nitric oxide emissions was made using a chemiluminescent analyzer. These measurements, which established nitric oxide emission levels as a function of furnace type, burner type and firing rate were made at CCRL as part of a joint research program with the Ontario Petroleum Association (2).

Carbon Monoxide Emissions These measurements were made during cyclic operation of control furnaces using a continuous recording non-dispersive infra-red system. Transient peak concentrations of CO at both the start and end of a burner operating cycle were measured for several burner types over a range of firing rates and excess-air levels.

In all cases typical steady running conditions produced CO concentrations in the range of 15-26 ppm, with transient peaks which existed for approximately 1½ minutes at the start and end of the burner operating cycle. The peak concentration, although indubitably a function of the system design, was generally in the range of 50-75 ppm on start-up and 250-350 ppm on shutdown. The total carbon monoxide emission was, therefore, a function of both the concentration-time profile and the flow-time profile.

Using inputs of fuel consumption, cycling frequency and cyclic emissions obtained as described above, the seasonal emissions for each of the homes and each of the conservation strategies were determined numerically.

Calculation of Seasonal Emissions

Particulate Emissions All of the experimental furnaces in the conservation study were operating at a Bacharach smoke number of 1. Measurement of the fuel characteristics, excess-air level, fuel consumption and particulate mass concentration at Smoke No. = 1 allowed calculation of the steady running emissions.

Continuous smoke traces using the Von Brand continuous tape sampler showed that start-up and shutdown peaks in smoke concentration were essentially the same in each home.

The increased emissions due to cycling were calculated from particulate emission measurements at test conditions corresponding to the operating conditions at each test home.

The incremental mass emission per cycle was calculated for each test home. Fuel consumption data and cyclic frequency data allowed calculation of the mass emission over the heating season profile as the total of the steady-running emission and the incremental cyclic emission.

Sulphur Dioxide Emissions All measurements made at CCRL for this and other programs indicated that SO_2 mass emissions from No. 2 oil combustion are a function only of the sulphur content of the fuel. SO_3 formation (1%) can be neglected. The sulphur dioxide emission was calculated from fuel consumption assuming an average fuel sulphur content of 0.36% by weight, as supplied to the Ottawa area during the test periods.

Nitric Oxide Emissions All measurements made at CCRL in this and other research programs indicate the nitrogen oxide emissions from No. 2 oil combustion occur as nitric oxide. From the series of tests described in Reference 2, an empirical correlation between NO concentration (ppm) and excess-air level at a Bacharach smoke number of 1 was developed.

For excess-air levels above 30%

$$\text{NO ppm} = 140.64 - 35.66 \left[1 + \frac{\text{Excess-air Level}}{100} \right]$$

Within the thermal input range of these experiments no significant effect due to firing rate was detected.

No cyclic factor was built into the calculation of nitric oxide emissions since it was observed that these emissions averaged very closely a step function, for burner "on-off" operation.

Carbon Monoxide Emissions These are analogous to particulate emissions in that they are composed of cyclic and steady running components. For the calculation of carbon monoxide emissions, a steady running concentration of 20 ppm was nominated on the basis of previous experience (2) and verified by measurment on the field units. The steady running CO emission for each test home and conservation strategy was then calculated from the operating excess-air level, fuel consumption and fuel characteristics. The contribution from cyclic operation due to the CO peaks at start-up and shutdown was measured separately.

Previous measurements (2) showed that the form of the cyclic CO-time profile was unchanged for a large number of furnace-burner combinations; the major difference was the magnitude of the peak concentration. At both start-up and shutdown, the duration of the emission was approximately 1.3 minutes and average values for the peak concentration were 60 ppm and 297 ppm respectively. The shapes of both concentration time profiles (start-up and shutdown) were identical and were represented by a linear-growth exponential-decay function.

The cyclic contribution to mass CO emission on start-up was calculated by integration of the growth-decay function at constant total volumetric flow rate and peak CO concentration of 60 ppm.

The cyclic contribution to mass CO emission on shutdown was calculated by simultaneous integration of the growth-decay function with a peak CO concentration of 297 ppm, and an exponentially decaying volumetric flow rate.

A knowledge of the firing rate and operating and excess-air level for each test unit along with the heating season profile, allowed the calculation of the individual CO cyclic mass emission levels, which were then added to the steady running emission levels to obtain the seasonal emissions reported in subsequent sections of this paper.

Performance Deterioration Studies

As a support to the detailed studies of fuel consumption and emission characteristics, an investigation of a wider sample of residential equipment was carried out with the support of a community organization, Pollution Probe Kanata. The investigation had simple objectives: firstly, to determine the magnitude of performance deterioration due to soot deposition during a heating season and secondly, to determine the applicability of the fuel conservation strategies under investigation in the parallel fuel consumption studies. The volunteer community is of recent construction and the heating systems equipment can be considered typical of units manufactured during the past ten years.

Throughout one heating season, measurements of steady running flue-gas temperature were made in 124 homes at monthly (or more frequent) intervals by trained volunteer personnel. In addition, measurements of the steady running efficiency and smoke number were made in 35 homes at monthly intervals by CCRL staff.

The Effect of Fuel Conservation Techniques on Consumption

The homes used in the fuel consumption studies, which were all of timber-frame construction in suburban locations, are listed in Table I. The effects of the fuel conservation techniques applied in these homes are presented in Table II. The most effective fuel conservation technique was the installation of a high efficiency burner; this was closely followed in effectiveness by severe overnight thermostat cut-back. Reduced firing rate, moderate thermostat cut-back, and the use of a positive chimney damper all produced similar percentage fuel savings at a lower level than the severe thermostat cut-back.

The Effect of Conservation Techniques on Emissions

The effect of the conservation techniques on the cycling frequency of the heating unit is an important factor in establishing effect on emissions. This applies specifically to carbon monoxide and particulate emissions. In the case of SO_2, the emission is dependent only on fuel consumption and fuel sulphur content; in the case of NO, the emission is dependent on fuel consumption, fuel nitrogen content and operating excess-air level.

The effects of the conservation techniques on cycling frequency for a nominal winter of 4260 degree days below 18°C are shown in Table III. It is apparent that the hot-water heating systems (Homes D and F) operate at significantly higher cycling frequencies than the warm-air heating systems; this behavior is inherent in the nature and sequencing of the controls. In general, overnight thermostat cut-back reduced the cycling frequency. The exceptional case, the poorly insulated home (Home B), was one where the furnace capacity was undersized relative to the overnight heating load at low temperatures; the furnace therefore ran continuously without cut-back. Severe thermostat cut-back eliminated continuous overnight operation and increased cycling frequency.

Improved burner performance led in one case to a small decrease in cycling frequency and in the second case to a significant increase. The second case is considered to be more general; improved efficiency should allow a more rapid satisfaction of the heating demand while the heat loss characteristics of the home should remain constant.

The use of a positive chimney damper also gave divergent effects on cyclic frequency for the two homes investigated. The difference is due to the two types of heating systems. The use of a chimney damper with the hot-water heating system produced significantly improved thermal storage in the boiler and reduced burner cycles actuated by the boiler aquastat. The use of a chimney damper with the warm-air heating system produced an increase in cycling frequency of 2½%. This increase is not thought to be significant.

Reduced firing rate, as could be expected, increased the duration of individual burner cycles without having a major effect on the cycling frequency.

Increased thermostat anticipator setting, which was examined only in the two homes with hot-water heating systems, resulted in significant reductions in cycling frequency.

The cycling data presented in Table III was used, in conjunction with the cyclic emission levels and the total fuel consumption levels, to calculate the emission characteristics of each conservation technique.

The Effect of Overnight Thermostat Cut-back on Seasonal Emissions

Table IV shows that overnight thermostat cut-back produced nearly similar reductions in NO and SO_2 emissions. The reductions in particulate and CO emissions were also similar but at higher levels. This reflects the fact that SO_2 and NO emissions are fuel-consumption-dependent at constant excess-air level whereas particulate and CO emissions are dependent on both fuel consumption and cycling frequency.

The Effect of Improved Burner Performance on Seasonal Emissions

Table V shows that, in the homes investigated, improvements in burner performance produced major reductions in all emissions. SO_2 emissions responded only to fuel consumption whereas NO responded to both fuel consumption and the decreased excess-air level. CO and particulate emission reductions responded to the decrease in cyclic efficiency in the case of Home C. In the case of Home E (where an increase in cyclic frequency occurred), the emission increases due to cyclic frequency were outweighed by the savings in the steady-running emissions and by the reduced excess-air level, yielding a reduction in seasonal emissions.

The Effect of a Positive Chimney Damper on Seasonal Emissions

The action of a positive chimney damper in reducing fuel consumption is to reduce the "off" cycle losses from the home by elimination of both convective heat losses from the furnace structure and ventilation loss in the venting system due to the difference between indoor and outdoor temperatures. The results presented in Table VI again show that, at constant excess-air level, both the SO_2 and NO emission reductions are a direct consequence of fuel consumption reductions. The use of the chimney damper in Home C produced a 2½% increase in cycling frequency, emission increases of CO and particulates due to cycling were outweighed by the decreases in steady running emissions and a seasonal reduction in these emissions was recorded. The use of the chimney damper in Home D was accompanied by a reduction in cyclic frequency which in turn reduced the cyclic component of the emissions. In this case both the cyclic and the steady-running components of the seasonal emissions were reduced.

The Effect of Reduced Firing Rate on Seasonal Emissions

Table VII shows the effect of reduced firing rate on emissions from the one home where reduced firing rate was used as a conservation technique. The fuel consumption saving of 9% was directly reflected in the reduced SO_2 and NO emissions. The longer burner operating cycles and slight reduction in cycling frequency produced relatively small reductions in CO and particulate emissions.

The Effect of Increased Thermostat Anticipator Setting on Seasonal Emissions

Table VIII shows the small effect which this conservation technique had on fuel savings and hence on SO_2 and NO emissions. On the other hand, the effect on cycling frequency and consequent seasonal emissions of CO and particulate material was dramatic. The reductions of >30% in CO emissions and >40% in particulate emissions are indicative of the importance of the cyclic contribution to the total seasonal emission. The effect may be somewhat exaggerated in the two homes considered since both had extremely high cycling frequencies. For a home with a lower cycling frequency, e.g., Home A, reductions in the number of cycles by 25% without any change in fuel consumption would result in a reduction of seasonal CO emissions by 13% and of seasonal particulate emissions by 6%.

A summary of the effectiveness of each conservation technique in reducing seasonal emissions has been compiled in Table IX, where each pollutant has been given equal weighting. The emission reduction is, therefore, the mean reduction for SO_2, CO, NO and particulates.

Improved burner performance is clearly the most effective technique for conserving fuel and reducing emissions. To the homeowner it is among the most expensive alternatives presented here. Severe overnight thermostat cut-back, although less effective in conserving fuel and reducing emissions, may be the most attractive alternative to the homeowner since it can be done at no expense. Reduced firing rate is also attractive because the cost can be included in annual maintenance charges. An annual nozzle change should, in the authors' view, be part of the annual maintenance operation. Increased thermostat anticipator setting does not offer any fuel economy and is unlikely to gain any widespread homeowner acceptance as a contribution to emission control since it can lead to unacceptable swings in internal temperature.

The installation charges for a positive chimney damper are similar to those for a new high performance burner and the benefits are smaller. In Canada, the fail-safe requirements of the installation codes have not yet been satisfied by the commercially available units although there does not appear to be any technical barrier to an acceptable design.

Results from the Performance Deterioration Studies

Table X shows the distribution of gross flue-gas temperature for the 124 homes included in the field survey. The distribution is skewed to temperatures above 280°C. Significant fuel savings (10%) and reductions of SO_2 and NO emissions would result if the heat transfer within these systems were improved. This could certainly be achieved without any deterioration in the natural draft generated by the venting and chimney system. Comparable reductions (10%) in CO and particulate emissions would result.

Particulate material (soot) formed in the flame is consistently held responsible for reductions in heating system efficiency during a heating season. The results presented in Table XI show that this seasonal reduction is small. It is apparent that operation of heating systems in the smoke number range 1-3 in preference to a smoke number of zero offers a significant fuel saving with a negligible penalty in seasonal deterioration. For smoke numbers between 4 and 6, further gains in efficiency are small and the penalty in seasonal deterioration becomes perceptible. None of the heating systems in the survey operated at smoke numbers above 6 and the suggestion that operation at this level would lead to rapid deterioration could not be documented.

Conclusions

At this stage of the investigation the data must be regarded as specific to the homes investigated. Extrapolation to alternative locations in continental North America has been carried out to establish the fuel savings from the selected conservation techniques. Extrapolation of the emission reductions requires a detailed analysis of the combined effects of total degree days and winter temperature profile on cyclic frequency. This analysis forms part of the continuing effort of CCRL in the residential heating field.

The present study leads to the following conclusions:

1. Reductions in sulphur dioxide emissions are a direct consequence of reduced fuel consumption.
2. Reductions in nitric oxide emissions are chiefly a consequence of reduced fuel consumption with only secondary reductions due to changes in excess-air level. Improved burner performance is the only conservation technique which offers NO reductions by both mechanisms.
3. Seasonal emissions of carbon monoxide and particulates are equally due to cyclic emissions and steady running emissions at smoke numbers close to one. The potential for reduction of these emissions is a combined effect of a reduced fuel consumption and a reduced cycling frequency.
4. The most effective strategy for both fuel conservation and emission reduction is the use of a high efficiency low excess-air burner with satisfactory long term stability. However, to the homeowner the most attractive (cost-effective) strategies will be severe overnight thermostat cut-back and reduced firing rate.
5. Field studies indicate that operation of oil-fired heating systems at measurable smoke numbers up to 3 offer significant efficiency improvements without the danger of excessively rapid performance deterioration over a heating season.

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References

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2. "Comparative Performance Characteristics of Typical Oil Fired Domestic Space and Water Heating Applicances". Published by the Ontario Petroleum Association, 1976.

Table I. The experimental homes

Description	Type	Floor Area of Heated Space	Type of Heating	Standard of Insulation
Home A	Two storey	230 m^2	Warm-air	High
Home B	Two storey	230 m^2	Warm-air	Poor
Home C	Two storey	160 m^2	Warm-air	Average
Home D	Bungalow	110 m^2	Hot-water	Average
Home E	Bungalow	170 m^2	Warm-air	Average
Home F	Two storey	135 m^2	Hot-water	Average

Table II. A comparison of the fuel conservation techniques over a typical winter (4260 degree days below 18°C)

Conservation Technique	Fuel Consumption, kilograms					
	Home A	Home B	Home C	Home D	Home E	Home F
None	3042	5326	2762	3399	3675	2875
Thermostat Cut-back						
Moderate	2761			3116	3420	
Severe		4518				
Improved Burner Performance			2229		3157	
Positive Chimney Damper			2540	3078		
Reduced Firing Rate	2759					
Increased Thermostat Anticipator				3390		2817

Table III. Effect of fuel conservation techniques on furnace cycling over a typical winter

Conservation Technique	Number of Cycles					
	Home A	Home B	Home C	Home D	Home E	Home F
None	3406	3594	5872	21929	6403	11757
Thermostat Cut-back						
Moderate	2667			14996	4928	
Severe		3842				
Improved Burner Performance			5682			
Positive Chimney Damper			6010	17241		
Reduced Firing Rate	3301					
Increased Thermostat Anticipator				10811		4560

Table IV. Effect of thermostat cut-back on seasonal pollutant emissions

Pollutant	Percentage Emission Reduction			
	Home A[a]	Home D[a]	Home E[a]	Home B[b]
SO_2	9.2	8.3	6.9	15.2
NO	9.2	8.3	6.9	15.2
CO	15.7	27.2	16.3	9.1
Particulates	12.3	23.6	12.4	11.5

[a] Moderate overnight cut-back of 3°C.

[b] Severe overnight cut-back of 5°C.

Table V. Effect of improved burner performance on seasonal pollutant emissions

Pollutant	Percentage Emission Reduction	
	Home C	Home E
SO_2	19.3	14.1
NO	23.5	12.5
CO	46.8	35.6
Particulates	45.5	26.3

Table VI. Effect of positive chimney damper on seasonal pollutant emissions

Pollutant	Percentage Emission Reduction	
	Home C	Home D
SO_2	8.1	9.4
NO	8.1	9.4
CO	2.4	19.1
Particulates	2.2	17.2

Table VII. Effect of reduced firing rate on seasonal pollutant emissions

Pollutant	Percentage Emission Reduction
	Home A
SO_2	9.3
NO	8.8
CO	14.2
Particulates	3.7

Table VIII. Effect of increased thermostat anticipator setting on seasonal pollutant emissions

Pollutant	Percentage Emission Reduction	
	Home D	Home F
SO_2	0.3	2.0
NO	0.3	2.0
CO	41.0	45.2
Particulates	31.5	33.4

Table IX. Relative effectiveness of various techniques on fuel conservation and pollutant emissions

Conservation Technique	Fuel Saving %	Emission Reduction %
Improved Burner Performance	14 - 20	28
Thermostat Cut-back	7 - 15	13
Reduced Firing Rate	9	9
Positive Chimney Damper	3 - 9	12
Increased Thermostat Anticipator	0 - 2	3 - 19

Table X. Distribution of stack temperatures in large-scale sample

Stack Temperature Interval, °C	220 -249	250 -279	280 -309	310 -339	340 -369	370 -399
Number of Homes	2	12	36	37	24	13

Table XI. Deterioration in stack temperature and furnace efficiency over heating season for large-scale field sample, for different smoke numbers

Smoke	Parameter	November	January	April	Seasonal Deterioration
0	Temperature, °C	326.4	330.6	340.9	14.5°C
	Efficiency	74.0	73.7	73.0	1.0%
1 - 3	Temperature, °C	291.4	303.6	306.8	15.4°C
	Efficiency	77.4	76.7	76.5	0.9%
4 - 6	Temperature, °C	305.8	329.8	333.3	27.5°C
	Efficiency	77.8	76.7	76.3	1.5%