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COAL-FIRED TILE STOVES —EFFICIENCY AND EMISSIONS

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ABSTRACT

Coal-fired tile stoves are widely used in Poland for domestic heating. These massive stoves are fired for short periods once or twice each day, and the stored heat is slowly released into the room by natural convection. Low-quality coal is typically used, and these stoves are therefore a major source of air pollution. A facility has been constructed to study the efficiency and emissions characteristics of these stoves. Stove exhaust gas is directed into a dilution tunnel in which pollutant concentrations and emission rates are measured. Efficiency is determined using a heat loss method.

In baseline tests, stove efficiencies were found to be higher than expected—60% to 65%. Emission factors are high for particulates, carbon monoxide (CO), and organics. Low-volatility "smokeless fuels" were tested as an alternative to the normal fuels. Using the normal operating procedure, these were found to yield a factor of 10 reduction in particulate emissions but a 50% increase in CO emissions. A new operating procedure was developed with these fuels in which CO levels were lower than with the normal fuel and efficiency increased to 70%. These smokeless fuels are seen as attractive options for improving regional air quality, partly because their use does not require capital investment by residents.

INTRODUCTION

Most of the city of Kraków, Poland, is heated by either the central district heating system or single-building gas- or coal-fired boilers. In addition, concentrated in the older central part of the city, there are many traditional coal-fired tile stoves. It is currently estimated that there are 100,000 such stoves in Kraków, with an annual coal consumption of 130,000 metric tons. These are felt to be important contributors to Kraków's air quality problems. It has been estimated that there are about 7 million of these stoves throughout Poland (Lipka et al. 1991).

These are very large masonry stoves with ornate tile exteriors. They are built in place by specialized craftsmen, and often two or more stoves will be used to heat a single flat. During the heating season, these stoves are fired once or twice each day. For each firing, the owner will carry a bucket of coal up from a basement storage area, light a new fire, and then tend it occasionally for about one hour. During this time, the masonry is heated and this stored heat keeps the flat warm for the next 12 hours. Traditionally, stoves in apartment buildings are common-vented.

A testing effort on these tile stoves has recently been completed. One of the objectives of this testing program was to provide baseline thermal efficiency and emissions data as input to evaluations of costs and benefits of alternative options for heating these flats. The second primary objective was to provide at least a preliminary assessment of the possibility of reducing emissions by using improved fuels in these stoves.

TEST PROGRAM

Description of the Stove Tested

The masonry tile stove tested during this program is typical of those used in Kraków. It was built specifically for these tests by local craftsmen in a laboratory at a local university. During construction, great care was taken to record dimensions and the types of materials used. A series of thermocouples was installed in selected locations within the stove mass to monitor heat storage during the firing cycle. A vertical cross-sectional drawing of the tile stove tested is shown in Figure 1. The stove has three flue gas passes. The first and largest vertical pass acts as the combustion chamber and is full-width across the front of the stove. The second (down) and third (up) passes are half-width across the back. There is an ash clean-out port at the bottom of the second pass. The section in Figure 1 is through the center of the second pass and the left side of the first pass.

Test Methodology

A facility for studying the emissions and efficiency of home coal stoves has been built at a university in Kraków with guidance and test equipment provided by U.S. partici-

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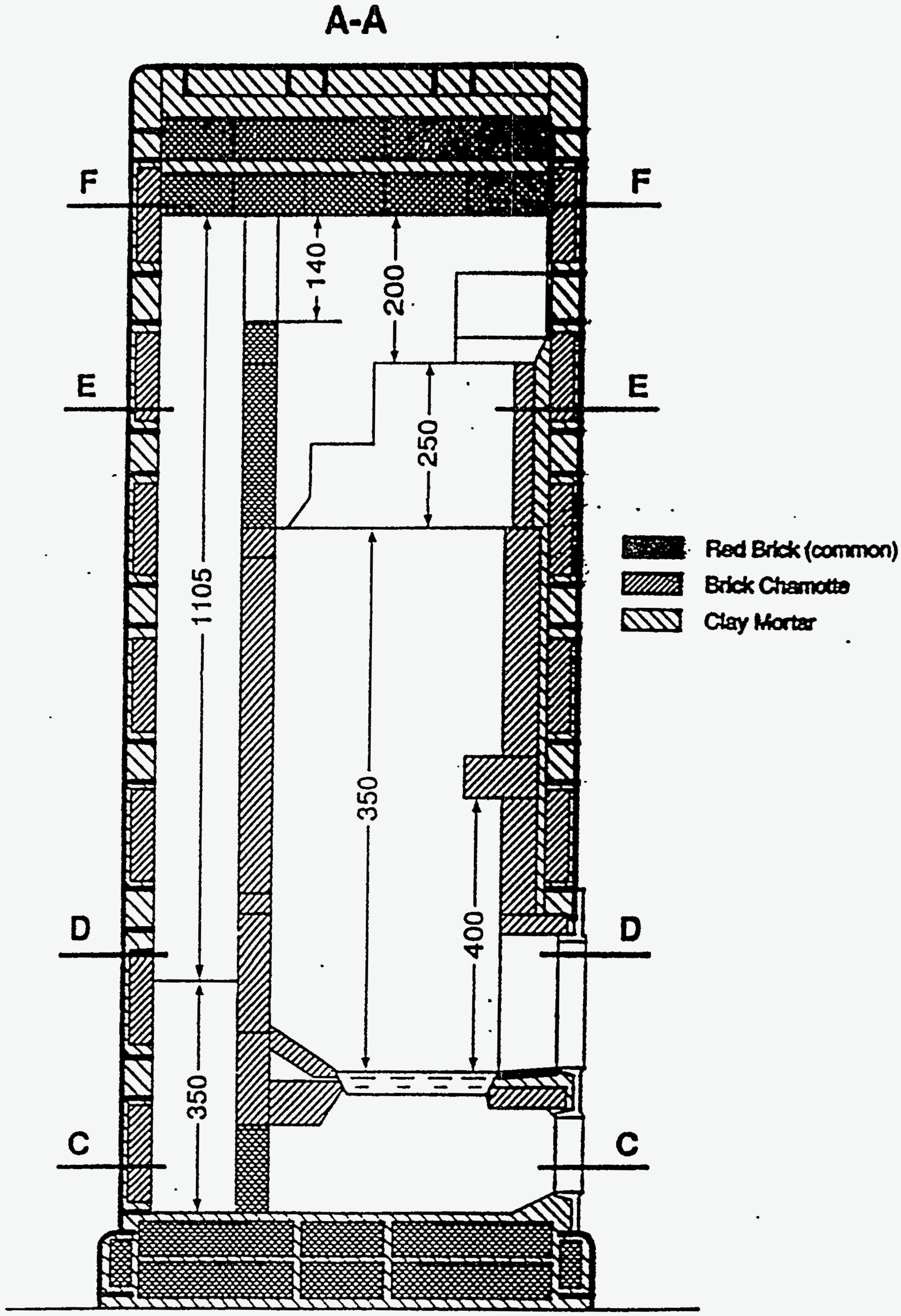

Figure 1 *Vertical cross section of Polish tile stove showing first and second passes (dimensions in millimeters).*

DISCLAIMER

pants. The system uses a dilution tunnel method (Macumber and Jaasma 1981; EPA 1990) to determine gaseous pollutant emission rates and flue gas sensible energy loss on a continuous basis. Particulate emissions are averaged over firing cycles.

The dilution tunnel system is illustrated in Figure 2. All of the combustion products leaving the stove enter the dilution tunnel along with air from the room. The flue gas flow at the stove exit varies greatly during a firing cycle and is often too low to measure practically. In contrast, the flow in the dilution tunnel is steady and can be easily measured using the orifice-type flowmeter shown. The emission rate of any gaseous pollutant is simply the product of the dilution tunnel concentration and the dilution tunnel flow rate.

Particulates are measured by sampling from the dilution tunnel using a heated filter. Beyond the filter, semivolatile organics are condensed in ice-bath impingers. These organics are later extracted and total mass determined.

The active part of the normal firing cycle lasts about one and one-half hours. During this time, infrared analyzers are used to continuously monitor carbon dioxide (CO_2) content in both the stove exhaust and the dilution tunnel. These measurements, along with dilution tunnel flow, allow calculation of the mass flow of gas leaving the stove. The concentration of CO, nitrogen oxides (NO_x), dioxide (O_2), and sulfur dioxide (SO_2) in the dilution tunnel is monitored continuously during the active part of the firing cycle using an analyzer with electrochemical cells. The concentration of gas-phase hydrocarbons is also measured continuously in the dilution tunnel using a flame ionization detector-based analyzer. All of the gas concentration data, the flow orifice pressure drop, gas temperatures at the stove exit and in the dilution tunnel, draft, and temperatures throughout the stove mass were logged continuously during the cycle using a computer-based data-acquisition system.

For any measured gaseous pollutant, the instantaneous emission rate can be simply calculated as

$$M_i = [x_i]_3 \cdot \left(\frac{MW_i}{MW_2}\right) \cdot Mg_3 \qquad (1)$$

where

M_i = total mass flow rate in dilution tunnel,
MW_i = molecular weight of general pollutant i,
MW_2 = average molecular weight of gas in dilution tunnel, and
$[x_i]_3$ = molar concentration of general pollutant i in the dilution tunnel.

The total amount of general pollutant i emitted during a firing cycle can be determined simply by integrating M_i over the cycle.

The efficiency of the stove has been determined as 100% minus the sum of all losses, including

- loss due to sensible heat in flue gas leaving the stove,
- loss due to latent heat of flue gas,
- loss due to chemical energy in CO and CH_4 in flue gas, and
- loss due to chemical energy in unburned carbon.

To calculate the sensible heat loss, the mass flow of gas leaving the stove is first calculated from the measured flow rate in the dilution tunnel and the CO_2 measurements made before and after dilution. A dilution ratio can be defined as

$$R = \frac{[CO_2]_2}{[CO_2]_3} \qquad (2)$$

where

R = dilution ratio,
$[CO_2]_2$ = molar concentration of CO_2 at the stove exit, and
$[CO_2]_3$ = molar concentration of CO_2 in the dilution tunnel.

Using this equation, the mass flow rate of gas leaving the stove can be calculated as

$$Mg_2 = \frac{Mg_3}{R} \cdot \frac{MW_{g2}}{MW_{g3}} \qquad (3)$$

where

Mg_2 = total mass flow rate of gas at the stove exit,
Mg_3 = total mass flow rate in dilution tunnel,
MW_{g2} = flue gas average molecular weight at the stove exit, and
MW_{g3} = gas average molecular weight in the dilution tunnel.

To determine the flue gas average molecular weight at the stove exit and for the sensible heat loss calculation, it is necessary to calculate gas composition at the stove exit. The CO_2 concentration at the stove exit is, of course, directly measured. The concentrations of CO, NO_x, and SO_2 are simply the product of their concentration in the dilution tunnel and the dilution ratio defined above. The oxygen concentration at the stove exit can be calculated as

$$[O_2]_2 = ([O_2]_3 \cdot R) - 0.21 \cdot (R-1) \qquad (4)$$

where

$[O_2]_2$ = molar concentration of O_2 at the stove exit and
$[O_2]_3$ = molar concentration of O_2 in the dilution tunnel.

The water vapor concentration at the stove exit has been estimated based on fuel composition and the concentration

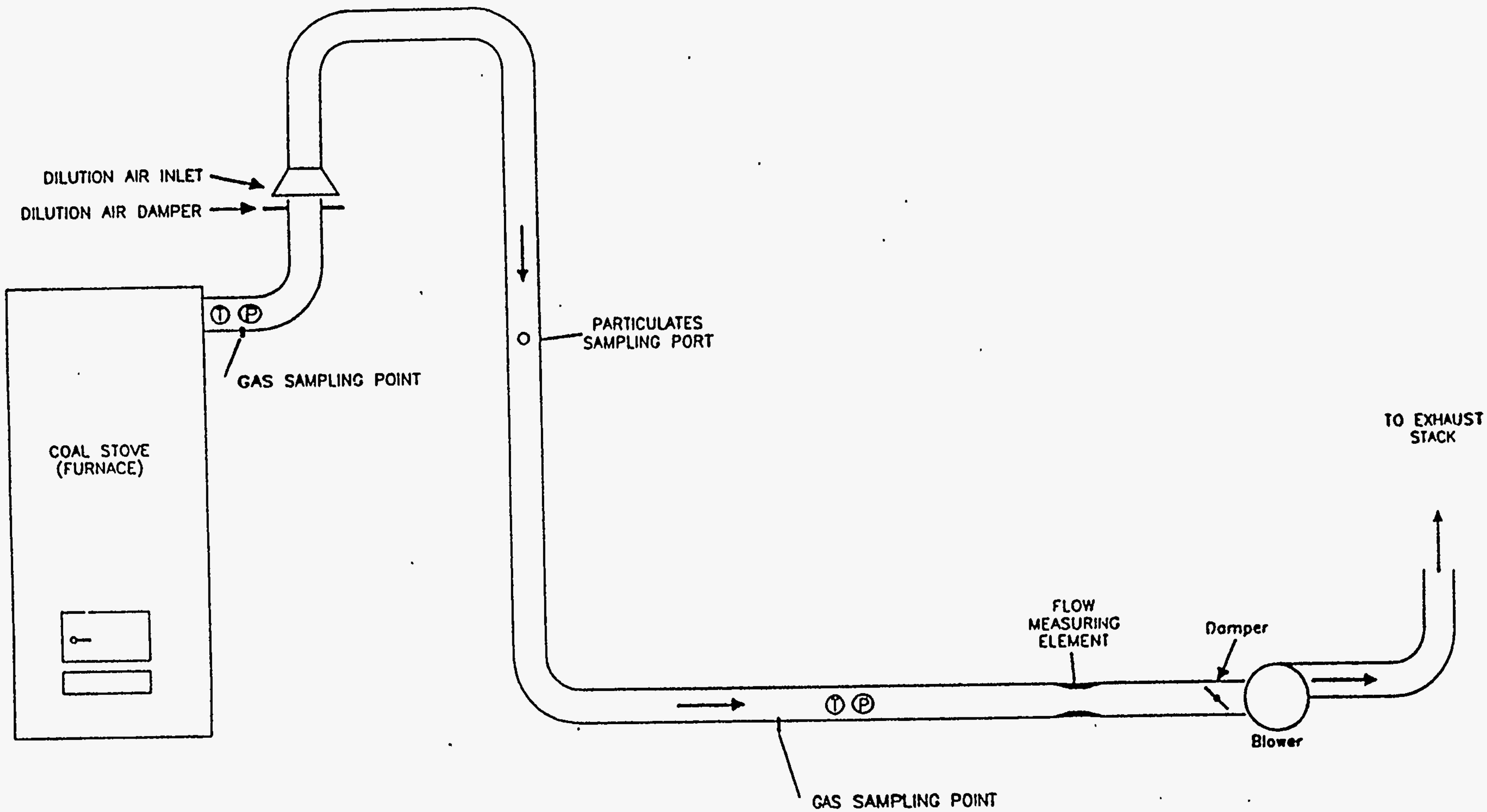

Figure 2 *Illustration of dilution tunnel system for stove emissions and efficiency measurements.*

of other components. Given the concentration of all other components at the stove exit, the balance is assumed to be N_2. The instantaneous sensible heat loss rate can be calculated as

$$L_s = Mg_2 \cdot \Sigma [x_i]_2 \cdot \frac{MW_i}{MW_{g2}} \cdot Cp_i \cdot (T_2 - T_0) \qquad (5)$$

where

L_s	=	instantaneous heat loss rate;
Cp_i	=	specific heat of component i, averaged between T_0 and T_2;
MW_i	=	molecular weight of component i;
T_0	=	ambient temperature;
T_2	=	gas temperature at the stove exit; and
$[x_i]_2$	=	molar concentration of component i at the stove exit.

The total sensible heat loss can be calculated by numerically integrating L_s over the entire firing cycle. The total sensible heat loss can be divided by fuel energy content to obtain sensible loss as a fraction of input.

The loss due to latent heat on the flue gas is calculated simply from the total amount of water vapor produced during combustion based on fuel water and hydrogen content. This loss is obviously calculated for the entire firing cycle rather than instantaneously. The instantaneous loss rate can be approximated (if desired) by assuming, for example, that the rate of water vapor emission is proportional to the CO_2 emission rate. In fact, the water vapor emission rate during the early part of the firing cycle is likely to be higher as fuel moisture is evaporated.

The instantaneous loss due to CO and CH_4 emissions is simply the product of their instantaneous emission rate (see Equation 1) and heating value. The loss due to chemical energy in unburned carbon includes carbon in particulates emitted with the flue gas and carbon removed with the ash when the stove is cleaned at the end of each firing cycle. These quantities are determined only for the entire cycle. At the end of each firing cycle, only ash that has fallen through the grate is collected and analyzed for carbon loss. The mixture of coke and ash that remains on the top of the grate is not removed, but is left for the next firing cycle.

Test Procedures

Test procedures were planned so that the stoves would operate in a manner as close to typical as possible. In the case of the tile stoves, each "firing" cycle lasted about 24 hours and a total of five cycles was used to evaluate each fuel. Before each such test series, the combustion chamber, ash pit, and dilution tunnel were carefully cleaned to remove the remains of the previous series. After each firing cycle, ash that has fallen through the grate was removed for analysis but the char was left for the next run. The mass of fuel, char, kindling, and ash were all carefully measured for each run.

In lighting the fire in the tile stoves for baseline procedures, the fuel charge was added in two stages, following normal practice. The first part (one-third of total) was added initially with the kindling. The remainder was added 15 minutes later.

During the main part of the combustion in the tile stove, the top and bottom (ash pit) doors are both partially ajar. The top door is normally closed after "degasification" is complete ("long flame disappears"), about one hour. The ash-pit door is closed completely when the "glow is dark red," about 30 minutes later. In baseline tests, the doors were closed tightly after combustion ended. In this case, measurements showed the total stove flow to be zero; there were no off-cycle flue energy losses.

In typical home installations, stoves from different floors are common-vented. Stove draft varies considerably over a firing cycle and will depend on the number of stoves firing into the chimney at a given time. To develop a typical draft/time profile, field measurements were made before the test program started. Based on these, a target profile was developed and implemented by adjusting the dilution air damper position during the firing. After the firing part of the cycle, the dilution air damper was closed completely and the tunnel blower was turned off. Natural draft from the fan exhaust stack provided the desired draft level for the remainder of the test period.

It is interesting to note that the practice of common-venting floors has led to building codes that prohibit the use of stoves with fan-assisted combustion airflow. This could impede the replacement of existing tile stoves with some advanced designs.

Test Fuels

Properties of the fuels evaluated during this testing program are listed in Table 1. The two coals listed represent the best and worst fuels currently used in Kraków. Coal from the Boleslaw Smiaty mine is high in ash content and low in heating value and currently sells for about $60/metric ton. Wujek coal is much better in quality and higher in price—about $80/ton. The "Zabrze" briquettes have been produced in Zabrze, Poland, in a pilot-scale facility. In this process, hot char from a fluid-bed gasifier is combined with a preheated coking coal. The mixture feeds into a roll press, forming the egg-shaped briquettes (Zielinski et al. 1991). These briquettes are termed "smokeless" because of their reduced volatiles content.

The wood briquettes listed in Table 1 are made from wood waste and have recently been proposed as an option for the tile stoves. A principal advantage of these is price—currently about half the price of coal (on a per-ton basis). Even considering the low heating value of these briquettes, they may be attractive to apartment owners. The final fuel

TABLE 1
Coal Stove Test Fuels

fuel properties as-fired		Boleslaw Smialy Coal	Wujek Coal	Zabrze Briquettes	Wood Briquettes	Coke
Water	%	2.11	2.72	3.30	5.6	0.1
Ash	%	21.7	3.20	10.9	1.8	8.7
Volatiles	%	30.3	32.1	8.1	71.6	1.0
Sulfur	%	.28	0.29	0.22	0.0	0.5
Higher Heating Value	Btu/lb (kJ/kg)	10950 (25450)	13960 (32440)	12060 (28030)	8400 (19520)	13150 (30560)

listed is a semi-coke, which has also recently been offered as a possible option for the home stoves.

TEST PROGRAM RESULTS

Normal Operating Procedures

Some example results illustrating the general nature of the operation of the tile stove and the dilution tunnel system are shown in Figures 3 through 5. All of these data were obtained using Wujek coal and the normal stove operating procedures described earlier. The emission rate of CO_2 shown in Figure 3 can be used as a measure of the combustion rate. Initially the coal volatiles burn giving high combustion rates as well as high emission rates of CO. After about 0.3 hour, much of the volatiles are burned off; the combustion rate remains fairly high, but the CO emission rate decreases. In addition to the lost volatiles, it is likely that the higher temperatures of the combustion chamber and the masonry flue passages also help keep the CO down from about 0.4 to 0.9 hours. At the one-hour point, the top door of the stove was closed, leading to a gradual reduction in the combustion rate but a dramatic increase in the CO emission rate. A significant part of the total CO emission rate clearly occurs after this top door has been closed. When the lower ash-pit door is finally closed at about 1.3 hours, the combustion process clearly stops. Figure 4 shows the stove exit temperature and the loss rate in percent per hour. This energy loss includes only the loss due to sensible heat in the flue gas and the loss due to latent heat in the flue gas. As discussed earlier, in including the latent heat loss it was necessary to make an assumption about the distribution of the combustion-zone water emission rate during the firing period. A selected group of flow parameters is presented in Figure 5, including the stove mass flow, the dilution ratio, and the dilution tunnel flow. As flue gas flow varies during the firing cycle, the dilution ratio varies from about 3 to 7 but the dilution tunnel velocity (and flow) remain quite steady. Temperatures of the stove interior masonry peak about one hour after combustion is started and then cool slowly during the next 20 hours. The peak internal temperatures range from 440°F to 840°F (225°C to 450°C).

Performance of the tile stove with the fuels tested using the normal operating procedure is summarized in Table 2. Generally, the efficiency of the tile stove was found to be higher than expected. Both efficiency and emissions with the coals tested are roughly similar to results that have been obtained by others with more modern stove designs (Waslo and Jaasma 1983). A dramatic reduction in particulate emissions is obtained by substituting the smokeless briquettes for the coal. Carbon monoxide emissions, however, were found to increase sharply with this fuel, and this result is unacceptable.

With the smokeless briquettes, combustion was very slow, leading to the low values of NO_x emissions with this fuel. Also, the increase in stove mass temperature during firing was considerably lower with the briquettes. This is consistent with the lower stove efficiency listed in Table 2.

Tests Under Poor Operating Conditions

All of the tests for which results are reported in Table 2 were performed under ideal operating conditions. In many cases, however, stoves are not operated correctly and, in addition, many stoves have cracks and other flaws that lead to air leaks. These air leaks could lead to efficiency loss as room air is heated and then escapes through the chimney. Additional tests were carried out to quantify the influence of incorrect operating procedures commonly used and the effects of leaks. In this program, the following two "incorrect" procedures were evaluated:

- leaving the two doors fully, rather than partially, open during the active part of the combustion process and
- shutting the doors one hour later than in the normal case.

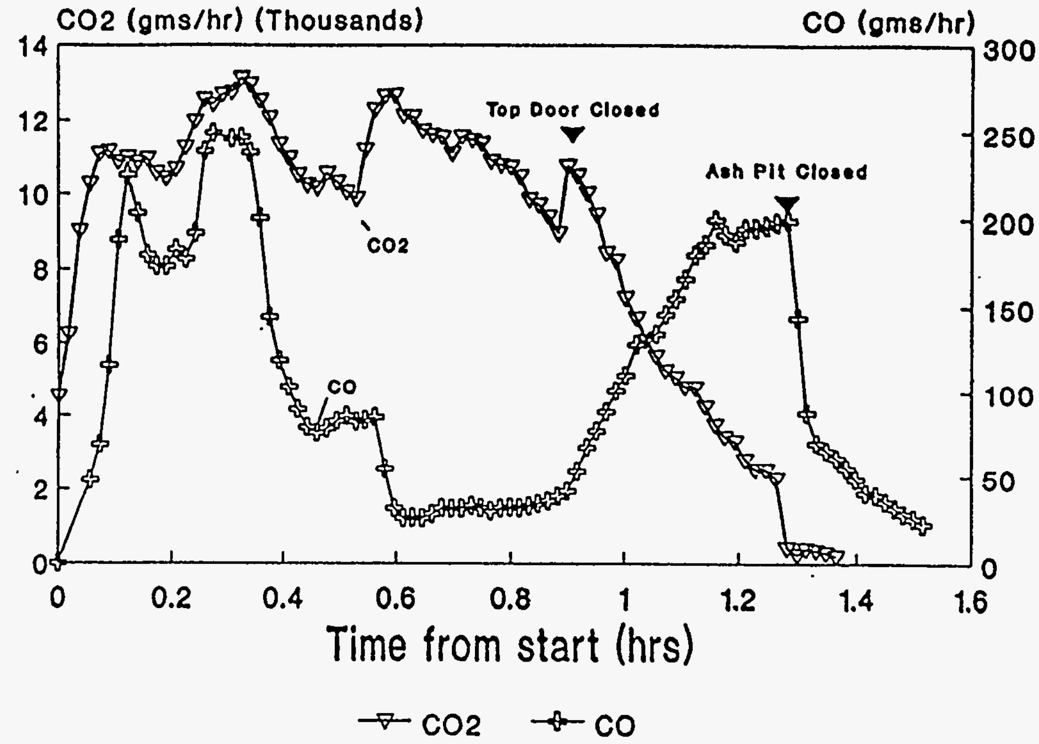

Figure 3 *Rate of emission of CO_2 and CO from tile stove during a typical firing cycle.*

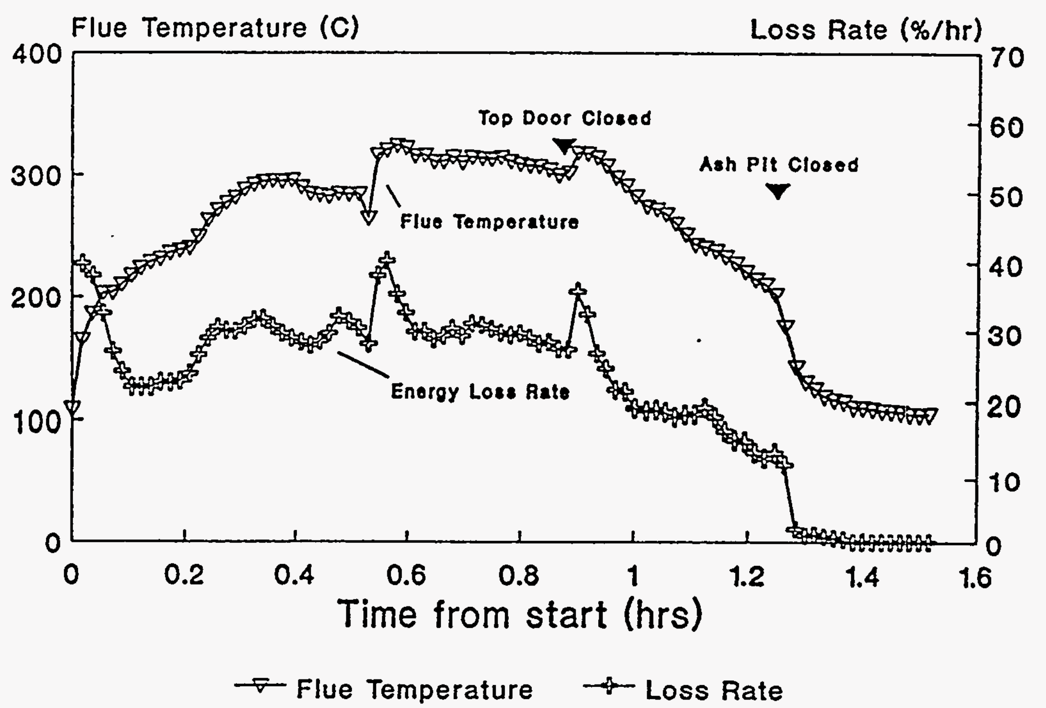

Figure 4 *Stove exit temperature and energy loss rate (sensible and latent) during a typical firing cycle.*

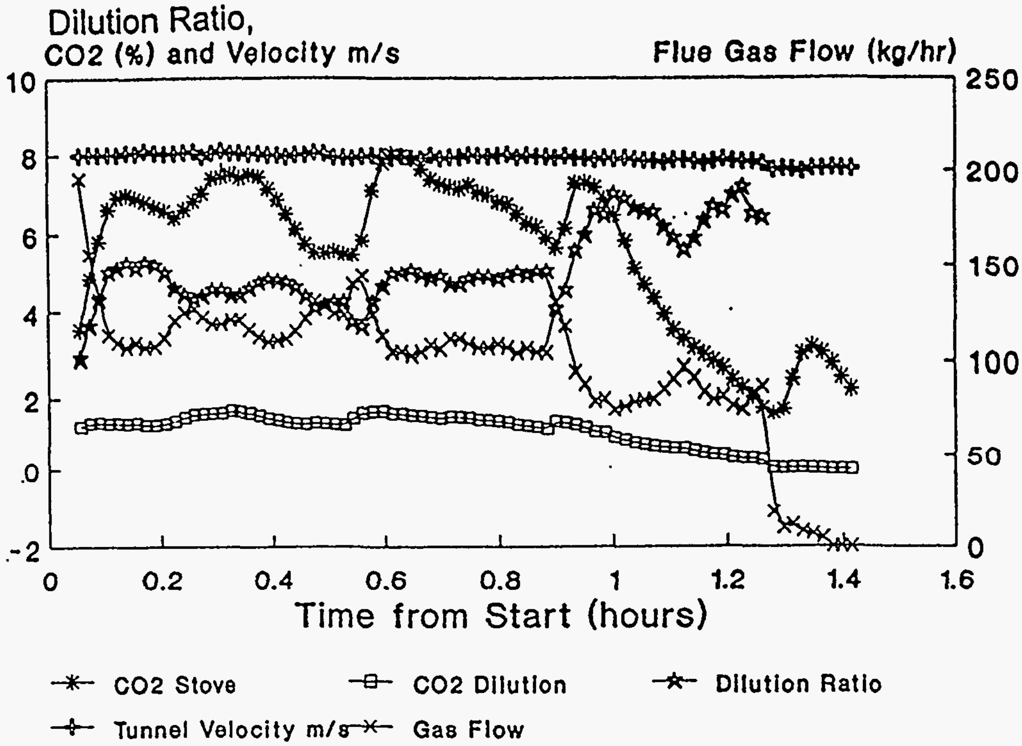

Figure 5 Stove and dilution tunnel flow parameters during a typical firing cycle.

To evaluate the effects of air leaks, the doors were left open a very small and carefully set amount after the end of the normal combustion process. The door opening to be used in this case was determined through a set of field tests in which actual leakage rates with older stoves were measured. In these field measurements, a metal flow hood was constructed and sealed to the stove front face, completely covering the doors. All airflow leaking into the stove through and around the door set passed through a duct at the opposite end of the flow hood. A hot-wire anemometer was used to measure this flow rate. During the laboratory tests of leakage rates, the door opening after the end of the active combustion process was set to give the same leakage rates.

Table 3 summarizes the results of all of the tests done under poor conditions with the Wujek coal. In all cases, the efficiency was lower than under normal operating procedures (Table 2); the worst case was when the door was left open for an extra hour. The efficiency penalty due to leaks was found to be fairly small. Stove temperature measurements made with and without leaks showed that the rate of cooling of the bricks after the end of the combustion process was about the same in both cases. This confirms that the rate of energy loss due to the leaks is not significant. When the doors were fully open for the entire combustion process, CO was reduced. Volatile organics, however, increased. In all other cases, effects on emissions could be considered rather small.

Tests with Modified Operating Procedures

In the baseline tests, the results with the smokeless briquettes were very encouraging for the possibility of reducing particulate emissions. The increased CO emissions with this fuel, however, are not acceptable, even considering the order-of-magnitude reduction in particulates. Based on the long burning time and the low stove mass temperatures observed with the smokeless briquettes, it was felt that the high CO was primarily due to the low temperature of the combustion zone. Several methods of increasing the burning-zone temperature were then evaluated, including the use of two types of metal inserts designed to increase airflow through and reduce heat loss from the fuel bed and packaging the briquettes in combustible containers. These efforts were essentially not successful. During the course of the investigations, however, an improved operating procedure was developed that was successful in improving performance. This new procedure involved the following:

- feeding the fuel onto the grate in three equal parts—one was used during the ignition and the other two were added during the process of combustion;
- reducing the overall excess air and, at the same time, supplying all of the combustion air through the lower ash-pit door (obviously except when adding fuel or grooming the bed);

TABLE 2
Baseline Test Results

		Boleslaw Smialy Coal	Wujek Coal	Zabrze Briquettes	Wood Briquettes
Efficiency	%	59	65	54	71
Emissions per mass of fuel:					
Particulates	g/kg	14	17	0.8	6.4
CO	g/kg	20	27	49	48
Semivolatile Organics	g/kg	0.9	0.9	0.4	2.2
Volatile Organics	g/kg	3.4	1.8	2.4	6.0
NOx	g/kg	3.3	6.9	2.4	0.5
SO2	g/kg	5.6	5.1	3.3	0.07
Emissions per unit of heat input:					
Particulates	lb/MMBtu (g/GJ)	1.3 (560)	1.2 (520)	0.07 (30.)	0.76 (330)
CO	lb/MMBtu (g/GJ)	1.8 (770)	1.9 (820)	4.1 (1800)	5.8 (2500)
Semivolatile Organics	lb/MMBtu (g/GJ)	0.08 (34.)	0.65 (280)	0.32 (140)	0.24 (100)
Volatile Organics	lb/MMBtu (g/GJ)	0.31 (130)	0.12 (52.)	0.20 (86.)	0.72 (310)
NOx	lb/MMBtu (g/GJ)	0.30 (129)	0.49 (210)	0.20 (86.)	0.06 (26.)
SO2	lb/MMBtu (g/GJ)	0.51 (220)	0.37 (160)	0.27 (120)	0 (0)

- more frequent poking of the bed; and
- closing the bottom door, effectively ending combustion, earlier. Specifically, the bottom door was closed just after the stove mass reached its peak temperature.

The last part of the procedure is important because CO emissions always increase dramatically at the end of the normal operating procedure. Closing the door earlier may lead to higher amounts of unburned coke remaining on the grate. However, this coke is burned during the next firing cycle and does not lead to an efficiency loss. It should be noted that as part of the test procedures used during this program, efficiency was evaluated during multiple cycles, not just a single firing.

Testing with the improved operating procedure was done with three selected fuels—Wujek coal, the smokeless briquettes, and semi-coke. Results are listed in Table 4. Relative to the baseline tests, the new procedure gave dramatic improvements in thermal efficiency and reductions in CO with the low-volatile-content briquettes. Using this procedure with smokeless fuels leads to clear reductions in emissions.

DISCUSSION

Standard emission factors for Kraków's boiler population have been presented (Cyklis et al. 1995) and used to compare total emissions from different categories of boilers.

TABLE 3
Results of Tests with Poor Operating Conditions with Wujek Coal

		Doors Fully Open for Entire Firing Cycle	Doors Open Extra Hour	Simulated Leaky Stove	Doors Open Fully for Firing Cycle and Leaky Stove
Efficiency	%	52	44	51	50
Emissions per mass of fuel					
Particulates	g/kg	17	20	17	15
CO	g/kg	20	25	29	27
Semivolatile Organics	g/kg	0.69	0.62	0.54	0.73
Volatile Organics	g/kg	2.6	3.1	2.7	2.8
NOx	g/kg	4.2	4.1	4.4	5.0
SO2	g/kg	5.1	5.5	4.4	4.9
Emissions per unit of heat input					
Particulates	lb/MMBtu (g/GJ)	1.2 (520)	1.4 (600)	1.2 (520)	1.0 (430)
CO	lb/MMBtu (g/GJ)	1.4 (600)	1.8 (770)	2.1 (900)	1.9 (820)
Semivolatile Organics	lb/MMBtu (g/GJ)	0.05 (22.)	0.04 (17.)	0.04 (17.)	0.004 (1.7)
Volatile Organics	lb/MMBtu (g/GJ)	0.19 (82)	0.23 (100)	0.19 (82)	.20 (86)
NOx	lb/MMBtu (g/GJ)	0.30 (130)	0.30 (130)	0.32 (140)	.36 (150)
SO2	lb/MMBtu (g/GJ)	0.36 (155)	0.39 (170)	0.32 (138)	0.35 (150)

With the stove test results in this paper, this can be extended to include the home stoves. For this purpose, the emissions factor developed for Wujek coal with normal operating procedures (Table 2) was adopted. Results are shown in Table 5. Among the categories listed, the home stoves do not consume the most coal. They are, however, by far the most important single source of particulates and semivolatile organics. They are, in addition, important sources of both volatile organics and CO. Changing the fuel to briquettes or semi-coke would greatly reduce the total production of particulates by Kraków's low-emission sources.

CONCLUSIONS

As part of this work, a coal stove testing laboratory has been established in Kraków and some important data on the behavior of these stoves have been produced. Properly operated, these stoves have fairly high thermal efficiency. They also, however, have very high emission factors for particulates, CO, and organics. These stoves are clearly an important source of particulate pollution in the city. Changing the fuel used from coal to semi-coke or briquettes combined with the use of improved operating procedures developed

TABLE 4
Results of Tests with Modified Operating Procedure

		Wujek	Zabrze Briquettes	Semi-Coke
Efficiency	%	72	71	70
Emissions per mass of fuel:				
Particulates	g/kg	15	1.2	1.8
CO	g/kg	32	21	28
Semivolatile Organics	g/kg	1.9	0.54	0.55
Volatile Organics	g/kg	3.9	1.4	1.8
NOx	g/kg	2.8	1.8	1.6
SO2	g/kg	2.7	4.1	2.8
Emissions per unit of heat input				
Particulates	lb/MMBtu (g/GJ)	1.1 (470)	0.10 (43)	0.13 (56.)
CO	lb/MMBtu (g/GJ)	2.3 (990)	1.7 (730)	2.1 (900)
Semivolatile Organics	lb/MMBtu (g/GJ)	0.14 (60.)	0.05 (22.)	0.42 (180)
Volatile Organics	lb/MMBtu (g/GJ)	0.28 (120)	0.11 (47.)	0.13 (56.)
NOx	lb/MMBtu (g/GJ)	0.20 (86.)	0.15 (65.)	0.12 (52)
SO2	lb/MMBtu (g/GJ)	0.20 (86)	0.34 (150)	0.22 (95)

during this work would have a great impact on total particulate emissions in Kraków. This change would require no capital investment by Kraków residents.

ACKNOWLEDGMENTS

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TABLE 5
Comparison of Contribution of Boilers and Home Stove to Kraków Emissions

	fuel use (metric tons per year)	Annual Emissons (metric tons per year)					
		Particulates	CO	Semivolatile Organics	Volatile Organics	NOx	SO2
Stoker without cyclones	34984	539	290	1	0	77	1030
Stokers with cyclones	198240	427	1650	6	0	436	5810
Hand-Fired Boilers-coke	59107	118	5470	4	41	112	1050
Hand-Fired Boilers-coal/coke mixtures	52023	281	3870	57	328	62	930
Hand-Fired Boilers - coal	26012	520	1170	42	75	60	471
Home Stoves - coal fired	130000	2160	3520	117	221	455	663

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