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Project Summary

Control of Wood Stove Emissions Using Improved Secondary Combustion

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Self-initiating secondary combustion in wood stoves is encouraged by designs that introduce additional heated air and turbulence to the primary combustion products. This can be very effective in reducing carbon monoxide (CO) and hydrocarbon emissions at high burning rates. At low burning rates the effectiveness is limited by low temperatures, inadequate mixing, and thermal quenching by the primary air which bypasses the wood. Two stoves were operated in the laboratory with simultaneous on-line chemical analysis of the gases entering the secondary combustion zone and the gases leaving the stove. Stove modifications providing increased temperatures and improved mixing in the secondary combustion zone in a small box stove resulted in minor improvements in secondary burning. The continued burning of CO in the secondary zone was not greatly affected. In a large side-draft stove, with effective secondary burning at high burning rates, the secondary burning at low rates was not effective at any air flow distribution available to the operator.

This Project Summary was developed by EPA's Industrial Environmental Research Laboratory, Research Triangle Park, NC, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

Increased use of wood as a residential heating fuel has resulted from the rising prices of other fuels and public skepticism of the reliability of normal fuel supplies. Government agencies, equipment manufacturers, and many environmentalists are supporting the use of wood as an alternate fuel. With increased use is also the widespread impression that wood burning is environmentally clean. Unfortunately, technology characterizing the objectionable emissions from wood stoves is limited, and few experiments have been performed to try to effectively reduce emissions. Often, residential stove manufacturers and operators are adopting stove designs and operating practices that increase emissions. This accentuates the environmental significance of the increasing use of wood as residential heating fuel.

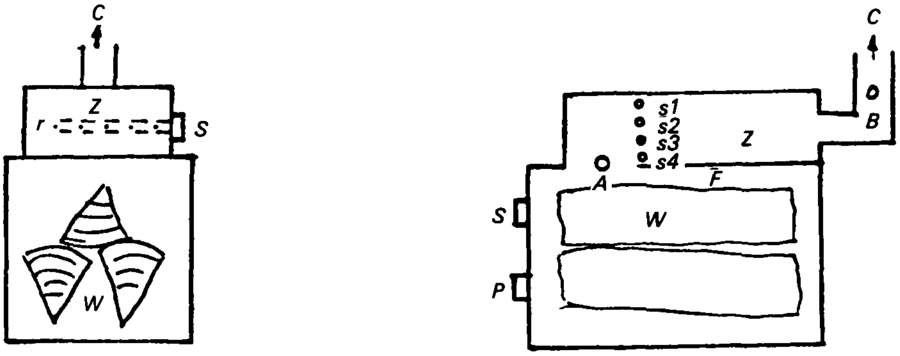
There are at least five ways to reduce objectionable emissions from residential wood stoves: (1) prevent or reduce emissions formed in the fuel magazine in the stove; (2) prevent or reduce emissions formed in the primary combustion zone; (3) destroy emissions in the primary combustion zone; (4) destroy emissions in a secondary combustion zone; and (5) add systems or devices that will reduce emissions.

Of the five, the first three can be accomplished by burning well seasoned wood at a relatively high rate. Recently introduced stoves with catalytic afterburners employ Method 5, so it is not discussed here. Method 4 was the focus of this study; to investigate the effects of various modifications of commercial stoves as a way to improve the effectiveness of secondary combustion.

Secondary combustion is the combustion of fuel materials that are not completely burned in the primary combustion zone; i.e., in the immediate vicinity of the wood. These materials can result from quenching the primary combustion products or from pyrolysis of wood without complete combustion in the primary combustion zone. Secondary combustion can be achieved by mixing the gases from the wood and from the primary combustion with suitable oxygen at a temperature sufficient to ignite the mixture or sustain burning. Sometimes secondary combustion is an extension or continuation of primary combustion, and specific secondary ignition may not be required. In some stoves, secondary combustion takes place directly above the burning wood. In other stoves, the secondary zone is separated from the primary zone by a baffle or barrier; the primary and secondary air are supplied at different locations. For secondary combustion to take place the gas composition must be within the flammability limits of the gases. Adding secondary air can sometimes dilute the combustion gases below these limits or cool the mixture below ignition temperatures.

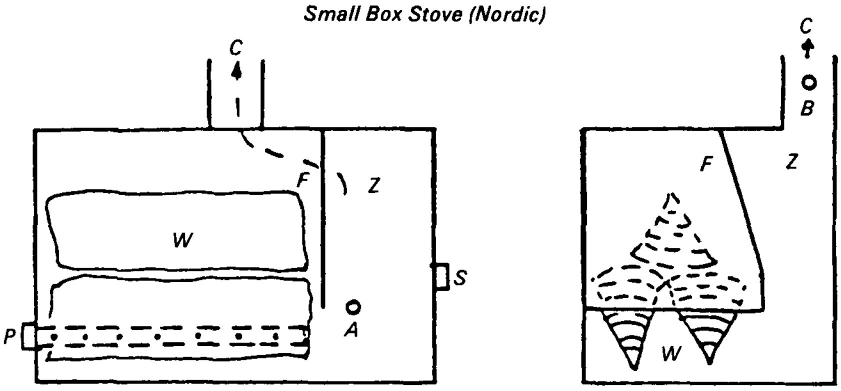
In actual practice, secondary combustion is hindered by: (1) limited mixing rate and turbulence due to low air velocities available in natural draft stoves, and (2) low temperatures in the secondary zone due to excess air and wall quenching.

As a result, in many conventional stoves secondary combustion is often not sustained for any significant length of time. Just after a charge of new wood has been added, the temperature of the secondary air and the combustion products may be too low to initiate or maintain secondary combustion. In mid-period burning, the gases from pyrolysis tend to be hotter and contain more combustible matter, thus satisfying the conditions for continued burning. Later in the burning cycle, when gas evolution is reduced as the wood becomes char, there may be insufficient combustible gas to sustain secondary burning.



Front View *Side View*

Small Box Stove (Nordic)



Front View *Side View*

Large Side-Draft Stove (Defiant)

Legend

Alternative secondary air inlets

s1	*upper inlet*
s2	*No. 2 inlet*
s3	*No. 3 inlet*
s4	*Bottom inlet*

P	*primary air inlet*
S	*secondary air inlet*
C	*outlet to chimney*
F	*baffle*
W	*wood*
A	*primary combustion gas sample*
B	*secondary combustion gas sample*
Z	*secondary combustion zone*

Figure 1. *Schematic diagram of stoves.*

Procedure

Two basic stove designs were investigated in an experimental laboratory study: the Nordic, a small box stove with a horizontal baffle; and the Defiant, a larger side-draft stove with a vertical baffle. Figure 1 shows schematic diagrams of both stoves. The Nordic was modified extensively during this study, but the Defiant was used only in the form received from the manufacturer.

Each stove was mounted on a platform that permitted weight loss (burning rate) measurement during operation. The stoves were equipped with shielded aspirated thermocouples (at the inlet and outlet of the secondary combustion zone) to measure gas temperatures and withdraw a representative gas sample for analysis by on-line instrumentation to determine gas composition. Each gas sample was supplied to both a heated line leading to a heated Total Hydrocarbon (THC) Analyzer and an unheated line leading to a cooling/trapping system which in turn led to inorganic gas analyzers. The gas analyses, weights, and temperatures were machine-processed with an on-line computer (to determine emission factors and other engineering calculations) and recorded on magnetic tape.

The computer program for data reduction developed by Battelle provided continuous 1-minute parameter checks and emission calculations. All data were stored in engineering terms for subsequent computer graphic presentations.

A total of 32 test burns were performed in the box stove. The first 10 were background tests to check supporting equipment and determine operating characteristics. The remaining 22 included: 6 baseline tests that established typical and also some atypical characteristics of the unmodified stove; and 16 tests to examine the effect of various modifications on the stove flue gas emissions. Six tests were also conducted in a large-side draft stove to demonstrate effects of secondary air control in a large stove.

The wood for these tests was all triangular split, seasoned white oak. Two different lots were used: one contained about 10 percent moisture, and the second, about 18 percent (determined by average weight loss after drying in a 105°C laboratory oven). For each, the appropriate moisture value was entered in the computer data reduction program.

Design Modifications

Several modifications were made in a Nordic box stove, and the emission factors calculated and averaged. The modifications were:

- The stove body was sealed, eliminating extensive air leaks, and making the stove airtight.
- A diverter plate was installed on the inside of the door to direct the primary air flow down toward the wood, and the secondary air up toward the secondary combustion chamber. (Both primary and secondary air normally enter through dampered holes in the door.)
- An independent secondary air distributor with multiple outlets was installed at the inlet to the secondary combustion chamber, to control the rate and distribution of secondary air, and improve mixing.
- A bypass of the secondary combustion chamber was installed by the manufacturer, permitting primary combustion products to pass directly out of the stove.
- The exterior of the secondary chamber was insulated to reduce heat loss and thus increase gas temperatures.
- The interior of the primary combustion chamber was insulated to reduce heat loss.
- The hearth was lined with firebrick, spaced to permit primary air to flow up between the bricks, into the burning wood.
- The interior of the secondary combustion chamber was insulated with firebrick to reduce the flow passage area, thus increasing gas velocity and improving mixing.

Effects of Design Modifications on Small Box Stove

Table 1 shows representative emission factors calculated from emissions measured during the experimental operation of the small Nordic box stove.

The conventional baffled box stove was first operated as purchased and subsequently operated with modifications intended to improve the effectiveness of secondary combustion. Dispersed and uncontrolled secondary air infiltration (by leakage) resulted in stove emission factors that were at least as low as those obtained with any of several restricted and controlled secondary air introduction systems. However, the burning rate was not easily controlled until the stove was made airtight. The reduction in emission factors obtained in the secondary combustion chamber by the controlled introduction of secondary air was generally greater than that obtained in the same upper chamber of the stove with the uncontrolled, secondary air supply. These observations are consistent with the generally recognized characteristics of airtight stoves.

A mild degree of turbulence and mixing was introduced into the inlet of the secondary combustion zone by injecting secondary air into the stove through small jets. Only when the jets were directed counter to the primary flue gas stream was there evidence of turbulence-induced continued combustion. At best, the emission factors for CO and hydrocarbons were reduced 40 percent.

Thermal insulation was applied to the small box stove in several places to attempt to increase significantly the temperature of the combustion gases at the point where secondary air was supplied. Reductions of up to 46 percent of the emission factors of CO and hydrocarbons were then obtained in the secondary combustion. Extensive insulation was apparently not sufficient to maintain the gases at high enough temperatures to complete the combustion process during low rates of burning. Only when the burning rate was increased appreciably and gas temperatures in the secondary combustion chamber were above 425°C were reductions in emission factors more significant.

Under all operating conditions, CO continued to oxidize slowly during the gas transit through the secondary combustion zone, whether the hydrocarbons were oxidized significantly or not. Although the lower temperatures may have impeded the oxidation of CO, it was not completely quenched. Secondary (or continued) combustion of the hydrocarbons was less evident and more erratic than CO combustion. The technique used to analyze hydrocarbons (flame ionization detection) is known to be inexact for the many gases released from wood, but this possible discrepancy is not considered to be significant. At these low burning rates, combustion of split wood in a stove becomes inherently variable, and the emission factors may not be reproduced exactly with repeated tests.

Effects of Operating Techniques on Side-Draft Stove

In previous tests, the Defiant side-draft stove achieved very distinct and effective secondary combustion at high burning rates (i.e., 9 kg/hr). This stove incorporates several features that promote secondary combustion. More than a ten-fold reduction in CO and hydrocarbon concentrations in the flue gas was obtained with active secondary burning at the high burning rates.

Table 1. *Emission Factors for Modified Box Stove*

		Average Emission Factors, g/kg			
		Carbon Monoxide		*Total Hydrocarbons*	
Test No.	*Wood Burn Rate, kg/hr*	*Leaving Primary Chamber*	*Leaving Stove*	*Leaving Primary Chamber*	*Leaving Stove*
	Unsealed stove with uncontrolled air infiltration				
3	*3.0*	*76*	*35*	*6*	*6*
	Secondary air supplied in controlled manner and location				
10	*2.7*	*100*	*64*	*31*	*18*
	External insulation of secondary combustion chamber				
12	*2.3*	*143*	*114*	*43*	*43*
	Both chambers insulated, primary chamber internally				
16	*2.0*	*84*	*45*	*17*	*19*
	Firebrick installed in secondary combustion chamber				
20	*2.6*	*85*	*65*	*24*	*17*

Lower burning rates, which are more typical of residential use, were used in this program. Air control settings on the unaltered stove were changed to determine their effects at these lower rates. Distinct secondary burning was not easily identified, either by gas analysis or by gas temperature readings. Several test runs using thoroughly dried split oak were conducted with the Defiant stove.

Table 2 summarizes the emission factors obtained in these tests. The first four tests were run with similar settings of the air-flow controls and in the same manner. The emission factors were consistently reduced by the continued burning in the secondary combustion zone. However, the reductions were relatively small, and the emission factors varied considerably.

Table 2. *Emission Factor Averages for Different Air Supply Control Settings on a Large Side-Draft Stove*

				Average Emission Factors, g/kg Wood Burned			
				Carbon Monoxide		*Total Hydrocarbons*	
		Air Supply[a]					
Test No.	*Dry Wood Burn Rate, kg/hr*	*Primary*	*Secondary*	*Primary Zone*	*Secondary Zone*	*Primary Zone*	*Secondary Zone*
4	*2.0*	*1/3*	*Full*	*167*	*135*	*41*	*31*
5	*2.5*	*1/3*	*Shut*	*153*	*114*	*21*	*13*
6	*2.0*	*Shut*	*Full*	*171*	*122*	*75*	*53*

[a] *Fraction of full open damper.*

In Test 5, the secondary air supply was shut, and in Test 6, the primary air supply was shut. Leakage air was available in both tests, because neither flow control system was airtight. With the secondary air supply damper shut, the primary combustion products were relatively hot, and the hydrocarbon emissions were relatively low. When the primary air supply damper was shut, the primary combustion product temperatures were lower, and the hydrocarbon emissions were significantly higher. In neither extreme of air distribution was there a large effect on emission factors which could be related to effective burning in the secondary combustion zone.

As in the smaller box stove, the low gas temperatures associated with low burning rates apparently precluded complete burning of the flue gases. In the larger stove, effective distribution of heated secondary air by tuyeres did not result in large-scale reductions in emission factors at low burning rates.

Advanced Stove Design

The Tennessee Valley Authority (TVA) recently tested several wood stoves incorporating advanced technologies for efficient and clean burning of wood. A new European-built stove evaluated in that program is designed to optimize non-catalytic secondary combustion. This advanced design introduces heated secondary air through several small holes into the primary combustion products as they leave the primary combustion chamber through a ceramic-lined passageway. TVA found that this design provided equal or higher combustion efficiency compared to a typical airtight stove at medium and high burning rates (above 2.5 kg/hr), but not as high as with a catalytic stove. Emission factors for CO, particulates, and polycyclic aromatic hydrocarbons were found to be lower than for the conventional airtight stove. However, the advanced secondary combustion stove required more operator attention to maintain the effective secondary combustion at the medium burning rates. Effective secondary combustion in the stove could not be obtained at low burning rates, so the stove was not tested at those rates.

TVA's observations of effective secondary combustion at high burning rates, but not at low burning rates, agree with observations from this program and those from a previous Battelle study.

Conclusions

This program has demonstrated that secondary (or continued) combustion supported by an independent secondary air supply is very difficult to attain at low burning rates in wood stoves. An almost universal characteristic of wood stoves at low burning rates is the abundance of excess air in the combustion products leaving the primary combustion zone. At these low burning rates, the pyrolysis and immediate partial burning of the wood result in some unburned fuel gases (CO and hydrocarbons), which leave the wood with the combustion products. The combustible concentration range of these fuel gases is limited by both low temperature and the concentration of inert compounds (residual nitrogen and reaction products of completed burning). Requirements of a minimum temperature and an acceptable mixture of fuel, air, and the diluent inerts are seldom met.

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***Robert E. Hall** is the EPA Project Officer (see below).*

The complete report, entitled "Control of Wood Stove Emissions Using Improved Secondary Combustion," (Order No. PB 84-199 033; Cost: $8.50, subject to change) will be available only from:
National Technical Information Service
5285 Port Royal Road
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