PB91-223156

Advancing Woodstove Secondary Combustion State-of-the-Art

(U.S.) Environmental Protection Agency, Research Triangle Park, NC

1991

AEERL-P-780

TECHNICAL REPORT DATA

(Please read Instructions on the reverse before completing)

1. REPORT NO.
EPA/600/D-91/145

2.

3.
PB91-221156

4. TITLE AND SUBTITLE
Advancing Woodstove Secondary Combustion State-of-the-Art

5. REPORT DATE

6. PERFORMING ORGANIZATION CODE

7. AUTHOR(S)
Robert C. McCrillis and Nelson L. Butts

8. PERFORMING ORGANIZATION REPORT NO.

9. PERFORMING ORGANIZATION NAME AND ADDRESS
See Block 12

10. PROGRAM ELEMENT NO.

11. CONTRACT/GRANT NO.
NA (Inhouse)

12. SPONSORING AGENCY NAME AND ADDRESS
EPA, Office of Research and Development
Air and Energy Engineering Research Laboratory
Research Triangle Park, North Carolina 27711

13. TYPE OF REPORT AND PERIOD COVERED
Published paper; 7/89-2/91

14. SPONSORING AGENCY CODE
EPA/600/13

15. SUPPLEMENTARY NOTES AEERL project officer is Robert C. McCrillis, Mail Drop 61, 919/541-2733. Presented at 84th Annual Meeting, AWMA, Vancouver, B.C. 6/16-21/91.

16. ABSTRACT The paper summarizes work performed by EPA/AEERL at its in-house woodstove test laboratory over the past several years, including investigations into the effects of augmenting the secondary combustion process with electric glowplugs and extensive tests on two EPA 1990 certified stoves, directed at achieving lower emissions by retuning the primary and secondary air controls. Most emission tests have been done while burning split oak cordwood. This work, termed noncatalytic technology, involves maintaining gas temperatures above the ignition point even at low burnrates without using a catalyst, by restricting heat transfer in an insulated secondary combustion chamber, and by providing adequate fresh preheated air to the secondary combustion zone. This represents one of two basic approaches to reducing emissions from residential woodstoves by enhancing the secondary combustion process. All cordwood-burning woodstoves operate in an air-starved mode which promotes the generation of products of incomplete combustion (PICs), including CO and a wide range of organic compounds. The heavier molecular weight organics condense into a fine aerosol upon entering the atmosphere, producing visible smoke. A large percent of these PICs must be oxidized to CO2 and water by enhancing the combustion process outside of the primary combustion zone.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group	
Pollution	Organic Compounds	Pollution Control	13B	07C
Combustion	Carbon Monoxide	Stationary Sources	21B	
Wood	Igniters	Woodstoves	11L	19A
Smoke		Glowplugs		
Aerosols		Secondary Combustion	07D	
Carbon Dioxide			07B	

18. DISTRIBUTION STATEMENT
Release to Public

19. SECURITY CLASS (This Report)
Unclassified

20. SECURITY CLASS (This page)
Unclassified

21. NO. OF PAGES
13

22. PRICE

EPA Form 2220-1 (9-73)

REPRODUCED BY
U.S. DEPARTMENT OF COMMERCE
NATIONAL TECHNICAL
INFORMATION SERVICE
SPRINGFIELD, VA 22161

PB91-223156

EPA/600/D-91/145

91-129.6

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Robert C. McCrillis
and
Nelson L. Betts

U.S. Environmental Protection Agency
Air and Energy Engineering Research Laboratory
Research Triangle Park, North Carolina 277

ABSTRACT

All cordwood-burning woodstoves operate in an air starved mode which promotes the generation of products of incomplete combustion (PICs), including carbon monoxide (CO) and a wide range of organic compounds. The heavier molecular weight organics condense into a fine aerosol upon entering the atmosphere producing visible smoke. Reducing woodstove emissions requires that a large percent of these PICs be oxidized to carbon dioxide (CO_2) and water by enhancing the combustion process outside of the primary combustion zone. There are two basic approaches to reducing emissions from residential woodstoves through enhancing the secondary combustion process. One approach utilizes a noble metal catalyst to reduce the ignition temperature of the combustible gases leaving the primary combustion zone, thus facilitating further oxidation at the low heat output rates commonly found. The other approach attempts to maintain gas temperatures above the ignition point even at low burnrates without using a catalyst, by restricting heat transfer in an insulated secondary combustion chamber and by providing adequate fresh, preheated air to the secondary combustion zone. The subject of this paper is the latter approach, not surprisingly called noncatalytic technology. The paper focuses on work performed by the U.S. Environmental Protection Agency (EPA) at its in-house woodstove test laboratory. The paper summarizes work performed over the past several years, including investigations into the effects of augmenting the secondary combustion process with electric glowplugs and extensive tests on two EPA 1990 certified stoves directed at achieving lower emissions through retuning the primary and secondary air controls. Most emission testing has been done while burning split oak cordwood.

INTRODUCTION

The promulgation by EPA of the Residential Wood Heater New Source Performance Standard on February 26, 1988[1], established separate particulate emission standards for stoves employing a catalyst (called catalytics) and for those which do not employ a catalyst (called noncatalytics) to promote destruction of the PICs produced in the primary combustion zone. The principal advantage of the catalyst is that it lowers the ignition temperature of the

CO and hydrocarbons leaving the primary combustion zone, thereby promoting their destruction. A disadvantage is that the catalyst may lose its effectiveness but not be replaced by the woodstove user. Periodic replacement of the catalyst was anticipated during development of the regulation.

The noncatalytic technology requires that the stove be operated hot enough, during the high particulate emission phase of the burn, to ensure meeting the emission standard. This has resulted in noncatalytic stoves being smaller and having to be run hotter, leading to the disadvantage that they must be refueled more frequently. Manufacturers have attacked this weakness vigorously over the past few years. Noncatalytic stoves now being certified are capable of overnight burns. Because of the high temperatures in the combustion zone, the secondary combustion baffle and air distribution manifolds must be constructed of suitable materials to avoid premature mechanical failure and loss of the stove's low emission capabilities. Even in the most rugged designs, periodic replacement of some parts may be necessary to maintain low emissions throughout the life of the appliance.

The Air and Energy Engineering Research Laboratory (AEERL) has had a program underway since 1984 to investigate the problems associated with achieving clean-burning noncatalytic technology. This paper summarizes that program to date and provides some thoughts on its future direction.

DISCUSSION

Jotul 201

AEERL's onsite woodstove program dates back to the late 1970s. Early testing was centered on conventional, uncontrolled stove emission characteristics. In the early 1980s several new stoves were purchased including a Jotul 201, at the time one of the most advanced noncatalytic stoves on the market. In spite of the extensive development effort, however, the Jotul 201 did not meet the Oregon 1986 standard of 15 g/hr weighted average particulates. Testing on the Jotul by AEERL started in 1984. These tests showed that the stove did not achieve low emissions at the low burnrates (0.9 - 1.2 dry kg/hr) commonly measured in the field[2,3,4,5]. For several years, tests were run on the Jotul 201 to explore the benefits, at low burnrates, of adding energy to the secondary combustion zone, first via a gas flame and, later, electric glowplugs. Two papers were presented on this early work[6,7], which showed that secondary air temperature and flowrate had an effect on CO emission concentration, there appearing to be an optimum combination of 2 m^3/hr (70 scfh) and 371 °C (700 °F) while using two 400 W glowplugs. Particulate emissions were not quantified during the reported tests.

All runs on the Jotul 201 followed a fixed procedure. Each run started with the placement of the fuel charge into a hot stove on a bed of coals. The fuel charge consisted of seasoned, split oak cordwood purchased locally. During much of the early work, a test was stopped when the fuel weight dropped to 0.45 kg (1.0 lb). During the tests described below, runs continued until the weight dropped to zero. The stove draft was set for the desired burnrate when the fuel charge was placed in the stove and was not adjusted during the run. Continuous measurements were made of the concentrations of CO, CO_2, oxygen, and total hydrocarbons (THCs) (as measured by a hot flame ionization detector). The stove and flue were supported on a weigh scale. Except for the fuel charge, tests were run according to EPA Method 28[1].

Further analysis of these data raised questions as to whether or not the effects being attributed to secondary air flowrate and temperature were not, in fact, due to some interaction with each other and/or with burnrate. Throughout these tests, every effort was made to hold consistent burnrates; however, woodstoves and wood being what they are, there were variations in burnrate. There was also the fact that there were no simultaneous particulate emission measurements. A statistical analysis revealed that the variation in burnrates within a burnrate category could have masked any effect of the glowplugs. Another way of saying this is that burnrate has such a strong influence on emissions that it can overshadow other effects. The outgrowth of this review was a decision to perform additional tests to pin down these effects and to obtain particulate emission measurements.

In August 1989, an experiment was designed to investigate the effects of glowplug power rating, number of glowplugs, secondary air temperature, and secondary air flowrate on particulate emission rate. Each of the four variables was to be investigated at three levels as shown in Table I. The proposed experiment consisted of a 1/3 fraction of a 3^4 factorial, a total of 27 tests. A copy of the matrix is included as Table II. All tests were to be run at a nominal burnrate of 2.00 lb (wet)/hr (0.8 kg (dry)/hr). The test series was initiated on October 10, 1989, with the final test completed on December 13, 1989. Table III summarizes the results. Four tests (6, 15, 17, and 27) were not run due to equipment limitations/malfunctions. Runs 8 and 26 were replicated.

Figure 1, an overall summary of the data, is a plot of particulate emissions as a function of glowplug power input. There was a statistically significant improvement in particulate emission rate as glowplug power was increased. Secondary airflow and secondary air temperature seemed to have an effect but the interaction was too strong to separate the individual effects. As can be seen in Table III, particulate emissions were lowered from as high as 78.6 g/hr to as low as 1.8 g/hr with 0.8 kW electric

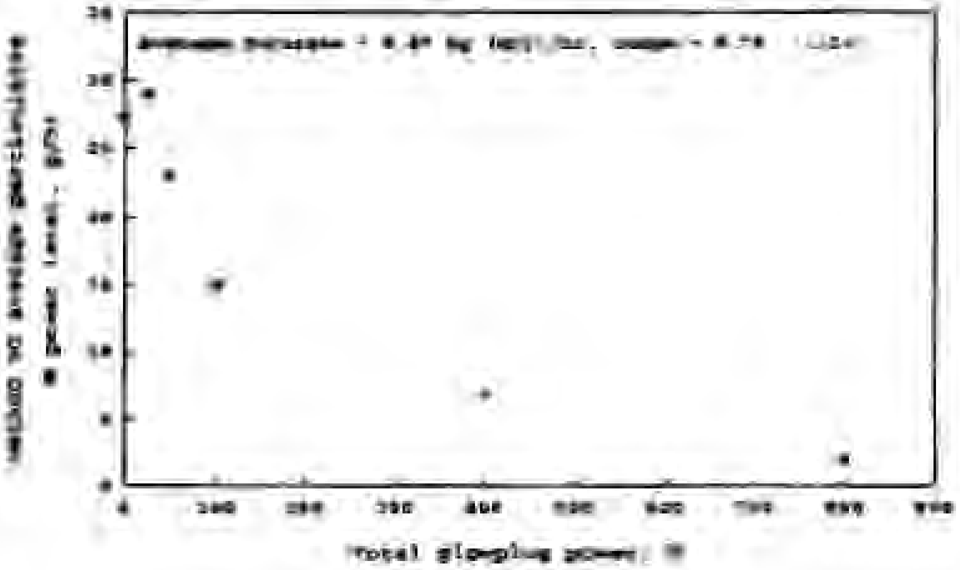

Figure 1. Effect of glowplug power input on particulate emissions.

power input. The statistical analysis also showed that there was little correlation between particulate emissions and average CO for each run. Thus the earlier work, while showing effects on CO, did not prove as useful for predicting the effect on particulates.

Pacific Energy Super 27

In late 1989, it was decided to move on to more advanced technology stoves, representative of the new noncatalytic technology entering the market. The first to be tested was the Pacific Energy Super 27, which is EPA 1990-certified at 3.4 g/hr. This stove has an approximately 0.056 m^3 (2 ft^3) firebox and has dampers controlling primary and secondary air flowrate. Both dampers are connected to a single control knob on the front of the stove. This stove was tested in three Klamath Falls, OR, houses during the 1989-90 winter under Canadian sponsorship (the Super 27 is manufactured in British Columbia). Overall average particulate emission rate for the three houses was 6.2 g/hr at an average burnrate of 0.96 kg (dry)/hr[4].

Between February 20 and October 19, 1990, a total of 26 tests were run in AESRL's laboratory on the Super 27. The test procedure followed that used on the Jotul 201, with an initial wood charge of about 7 kg. The results are summarized in Table IV. The break from April 30 to August 27 resulted from the relocation of the laboratory to another area within the Environmental Research Center. After relocation, it was found to be necessary to recharacterize the stove. It appears that stoves tested in the old laboratory were affected by the heating/ventilation/air-conditioning (HVAC) system. The old laboratory space was within the HVAC zone while the new laboratory is not. The effect of the HVAC appears to have been significant. There were several tests in the old laboratory at burnrates at or below 1.0 kg/hr (Runs 2-3, 5-6) with both primary and secondary draft dampers at minimum (0) settings where the emission rate was less than 5 g/hr. In the new laboratory, running with the same minimum draft settings (Run 20) resulted in high emissions. Settings of 1 on both primary and secondary generally produced good, low emission data in the new laboratory (Runs 22-23), but start-up is critical as shown by high emissions in Run 24. One suspects that the HVAC imposed very small but nevertheless significant pressure differentials across the stove-flue system. These pressure differentials may have varied depending on whether the system was heating or cooling, whether outside doors were open, and what other test equipment in the facility was in operation. It is assumed that the relative effects of test variables in all work performed in the old laboratory were consistent with one another even though the absolute magnitude of the effects may have been influenced by the HVAC.

One initial finding on the Super 27 was that CO emissions were quite high at the low burnrate even though particulates were at or below certification level. (EPA does not regulate CO from woodstoves so there is no emphasis on CO by the manufacturers.) Since it was noted that oxygen levels were very low during times of high CO, it was reasoned that more secondary air might help. The primary and secondary air dampers were decoupled and run with the primary at the low burnrate setting and the secondary at the high setting. Runs 15-18 were run in this configuration. The results are rather mixed although it looks like there may have been about a 45% CO reduction <u>in tests run in the old laboratory</u>. In the new laboratory, comparing Runs 25 and 26 versus their baseline (Runs 22 and 23) shows no significant difference. In the new laboratory, decoupling the primary and secondary draft dampers seems to have no impact on CO and has the adverse impact of increasing particulates by 80%. These data also show that there is no correlation between the CO and particulate emission rates.

Quadra-Fire 3100

The second 1990-certified stove to be tested was the Quadra-Fire 3100 which, at 2.1 g/hr, has the lowest EPA-certification value for noncatalytic stoves. This stove is equipped with separate primary and secondary air controls. For most operations, the primary control is kept at the minimum air setting with burnrate varied by adjusting the secondary air control. A total of 22 runs have been completed on Quadra-Fire 3100, which are summarized in Table V. Runs 1 - 8 followed the same procedure used for the Jotul 201 and the Super 27. Run 2 was the first attempt to operate the stove at a burnrate < 1.0 kg/hr. As can be seen, particulate emissions were high (25.4 g/hr). By careful adjustment of the secondary air, an emission rate of 6.7 g/hr was achieved at a burnrate of 0.91 kg/hr (Run 5). Run 6, an attempt to duplicate Run 5, came in at a lower burnrate and resulted in much higher emissions. These runs illustrate that low emission operation at low burnrates is possible but difficult to achieve consistently.

Runs 9 - 15 and 22 followed the owner's manual start-up procedure which states that both primary and secondary dampers be full open each time wood is added. The secondary is to be adjusted to the desired setting 15 minutes after adding wood, and the primary closed 20 minutes after adding wood. This start-up procedure helped to achieve lower emissions but still did not guarantee low emissions. Runs 9-11 prove this fact. Runs 9 and 10 were performed while burning oak as before. As can be seen, Runs 9 and 10 (especially Run 9) showed good, low emission performance with burnrates at or below 1 kg/hr. Run 11 was to be a repeat, using western larch, a soft wood common to the location (western Washington State) where the stove was developed. The test gave disappointing results (particulates = 9.6 g/hr), because the secondary combustion flame went out a few minutes into the burn. This stove had been run many times on this fuel, following this procedure, during its development. These results prove that low emissions at low burnrates are not consistently achievable.

Following the owner's manual start-up procedure helps to achieve low emissions at the low burnrates commonly found in field studies. On the negative side, the initial high burnrate period, before the dampers are adjusted, produces a great deal of heat, with as much as 33% of the fuel weight being consumed during the first 20 minutes of a test. Since this high heat output may be objectionable to many users, several runs were made to ascertain the possibility of reducing the high burn time period while still achieving low emissions. The results from Runs 16 - 21 show that low emissions can still be achieved (Runs 16 and 18) but there is increasing likelihood that high emissions will result (Runs 17, 19-21). The owner's manual procedure also results in very low heat output for the last hour or two of a run, which might be just as objectionable as being too hot during start-up.

Future work on the Quadra-Fire 3100 will focus on finding ways to even out the heat output without sacrificing low emissions. Since low emissions and operating procedure go hand in hand with certification, it may be that the certification test needs to be revised to more accurately reflect user requirements. This would drive the technology toward a more even heat output.

SUMMARY AND CONCLUSIONS

Results to date show that the key to low emission operation of current noncatalytic woodstoves lies in the first 30 minutes or so of the burn. One can watch the CO concentration during this period and predict the end result fairly accurately. Overall CO emission rate seems to have little or no correlation with particulates. Low CO concentration during the first portion of the burn, however, will forecast low particulates for the whole run. CO concentration during the first half hour in Run 2 was much higher than the corresponding time interval in Run 9. Particulate levels were markedly different, 25.4 and 1.5 g/hr, respectively, whereas CO emission rates were not that different (126.3 vs 99.9 g/hr, respectively). That low CO during the early part of a run results in low particulates is easily understood since most of the volatile matter in the wood is distilled off in the beginning of the run as the wood becomes heated. Woodstove particulate emissions are these unburned organic compounds, condensed into fine droplets. After the initial volatile burning period, the stove enters the charcoal burning phase where little particulate matter is produced. Thus high CO during the charcoal phase can dominate the CO picture, whereas low CO in the beginning means high temperatures and adequate oxygen for much more complete combustion of all the PICs, including the organics that would be particulate if not burned. In all low burnrate tests, the secondary fire extinguishes within the first hour.

Tests on the Jotul 201, Super 27, and Quadra-Fire 3100 stoves point out the major weakness of current technology: The inability to consistently achieve low emissions at burnrates below 1 kg/hr. This is the same general problem which has historically plagued noncatalytic woodstoves. The only difference now is that the minimum burnrate for clean burning has been pushed down to about 1 kg/hr through aggressive development by industry. The focus of AEERL's in-house woodstove program will continue to be to lower the minimum clean-burn burnrate, with the goal of achieving consistent, clean operation at dry burnrates of about 0.9 kg/hr. This must be achieved without requiring the user to follow a procedure which produces heat in a highly cyclic pattern. Rather than follow such a procedure, most users will operate the stove to suit their needs, irrespective of the emissions being generated.

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Table I. 4x3 test matrix on Jotul 201.

Variable	Level	Setting	Code
Secondary air flow	0	2.12 cmh	A0
	1	4.25 cmh	A1
	2	8.49 cmh	A2
Secondary air temp.	0	204°C	B0
	1	371°C	B1
	2	538°C	B2
Number of glowplugs	0	0	C0
	1	1	C1
	2	2	C2
Glowplug rating	0	400W	D0
	1	50W	D1
	2	25W	D2

Table II. Matrix of 1/3 of a full 3^4 factorial (27 tests).

Test #1 A0/B0/C0/D0	Test #4 A0/B1/C0/D2	Test #7 A0/B2/C0/D1
Test #2 A1/B2/C1/D2	Test #5 A1/B0/C1/D1	Test #8 A1/B1/C1/D0
Test #3 A2/B1/C2/D1	Test #6 A2/B2/C2/D0	Test #9 A2/B0/C2/D2
Test #10 A0/B0/C2/D1	Test #13 A0/B1/C2/D0	Test #16 A0/B2/C2/D2
Test #11 A1/B2/C0/D0	Test #14 A2/B2/C1/D1	Test #17 A1/B1/C0/D1
Test #12 A2/B1/C1/D2	Test #15 A2/B2/C1/D1	Test #18 A2/B0/C1/D0
Test #19 A0/B0/C1/D2	Test #22 A0/B1/C1/D1	Test #25 A0/B2/C1/D0
Test #20 A1/B2/C2/D1	Test #23 A1/B0/C2/D0	Test #26 A1/B1/C2/D2
Test #21 A2/B1/C0/D0	Test #24 A2/B2/C0/D2	Test #27 A2/B0/C0/D1

Table III. Test results of 4 x 3 matrix series on Jotul 201.

Run No.	Burn-rate kg (dry)/hr	Particulate (g/hr)	CO corrected to 0% O_2 (ppm*E-3)	CO actual (ppm*E-3)
1	0.79	9.0	37.8	9.78
2	0.89	14.9	22.2	2.52
3	0.92	22.7	35.3	3.36
4	0.75	24.3	39.6	8.72
5	0.78	16.6	26.0	5.46
6	----	----	----	----
7	0.74	32.6	----	----
8	0.90	13.3	31.1	5.87
8	0.79	9.5	----	----[a]
9	0.87	16.6	38.7	2.65
10	0.87	7.1	32.0	7.34
11	0.81	37.3	40.3	6.63
12	0.94	61.7	39.6	2.52
13	1.11	1.9	29.2	11.80
14	0.85	56.6	33.8	5.16
15	----	----	----	----
16	0.81	28.8	36.2	5.89
17	----	----	30.1	4.57
18	0.74	3.1	18.2	2.48
19	1.05	10.2	28.0	9.28
20	0.99	----	22.7	4.27
21	0.79	9.2	56.1	4.10
22	0.70	21.7	31.8	4.31
23	1.14	2.0	6.1	2.08
24	0.83	78.6	31.9	2.22
25	0.88	3.8	23.2	6.32
26	0.75	11.5	20.7	3.36
26	1.08	12.9	----	----[a]
27	----	----	----	----

(a) means replicate runs

Table IV. Pacific Energy Super 27 test data summary.

Date (1990)	Run No.	Burnrate -kg/hr dry basis	Particulate emissions		CO	THC	Draft setting primary/ secondary 0-100%	Wood moisture -% dry basis
			g/hr	g/kg	g/hr	g/hr		
02/20	1	0.88	9.7	11.2	(a)		0/0	29
02/22	2	1.00	2.2	2.2			0/0	29
02/26	3	0.91	2.4	2.6	75.4	5.9	0/0	27
02/28	4	0.88	7.3	8.3			0/0	29
03/05	5	0.85	4.3	5.1			0/0	29
03/07	6	0.88	2.6	3.0			0/0	29
03/08	7	1.60	3.8	2.4			50/50	29
03/12	8	2.00	3.4	1.7			50/50	27
03/15	9	1.13	19.2	17.0			40/40	22
03/19	10	2.74	1.7	0.6			80/80	20
03/20	11	1.70	2.7	1.6			80/80	20
03/22	12	2.59	10.6	4.1			80/80	22
04/03	13	2.40	2.5	1.0			80/80	26
04/04	14	1.65	1.2	0.7			50/50	26
04/11	15	0.77	5.7	7.4	34.6	33.5	0/100	25
04/19	16	1.10	3.0	2.7	7.6	23.8	0/100	25
04/30	17	0.89	3.0	3.4	84.4	17.5	0/100	25
08/27	18	1.13	14.3	12.6			0/100	17
08/28	19	no data						18
08/29	20	0.87	19.3	22.2			0/0	17
09/04	21	1.00	1.5	1.5			30/30	17
09/05	22	0.89	1.0	1.1	95.4	ND	20/20	17
09/20	23	1.32	1.4	1.1	92.8	1.6	20/20	17
10/17	24	1.53	24.4	16.0	120.5	ND	20/20	20
10/18	25	1.10	2.3	2.1	90.4	9.1	20/100	20
10/19	26	1.32	2.1	1.6	90.6	2.2	20/100	20

(a) Blank space = data not reduced unless otherwise noted.

Table V. Quadra-Fire 3100 test data summary.

Test date	Run No.	Burnrate -kg/hr dry basis	Particulate emissions g/hr	Particulate emissions g/kg	CO g/hr	THC g/hr	Draft setting pri/sec 0-100%	Draft control start schedule pri/sec min/min[a]	Wood moist, -% dry basis
10/31/90	1	1.91	1.7	0.89	33.1	ND	0/50	0/0	18
11/01/90	2	0.92	25.4	27.6	126.5	17.7	0/0	0/0	18
11/05/90	3	1.23	1.2	0.98	105.8	8.9	0/20	0/0	18
11/06/90	4	1.37	1.0	0.73	81.2	1.6	0/25	0/0	18
11/07/90	5	0.91	6.7	7.4	110.1	2.7	0/5	0/0	18
11/08/90	6	0.84	19.5	23.2	112.8	0.5	0/5	0/0	17
11/13/90	7	2.25	1.3	0.52	80.8	1.7	0/100	0/0	16
11/14/90	8	2.17	2.0	0.81	115.4	2.2	0/100	0/0	16
11/15/90	9	1.00	1.5	1.5	99.9	3.2	0/0	20/15	13
11/19/90	10	0.82	6.0	7.3	95.5	6.8	0/0	20/15	17
11/20/90	11	1.00	9.6	9.6	142.2	11.0	0/0	20/15	17[b]
11/26/90	12	1.14	0.9	0.79	129.8	2.3	0/10	20/15	17[b]
11/27/90	13	1.24	2.1	1.70	125.8	4.3	0/10	20/15	17[b]
11/28/90	14	0.90	0.86	0.95	87.5	2.5	0/0	20/15	15
12/03/90	15	0.76	4.35	5.70	89.1	0.53	0/0	20/15	15
12/13/90	16	1.07	0.72	0.68	103.1	ND	0/0	15/10	15
12/17/90	17	0.90	1.49	13.92	90.7	5.16	0/0	15/10	15
01/16/91	18	0.80	2.8	3.5	101.1	5.29	0/0	15/10	16
01/22/91	19	0.83	12.9	15.5	113.4	11.5	0/0	15/10	18
01/24/91	20	0.81	15.8	19.6	119.6	13.6	0/0	15/10	18
01/28/91	21	0.75	17.0	22.6	103.7	15.5	0/0	15/10	18
01/31/91	22	0.77	4.7	6.1	117.6	2.0	0/0	20/15	18

(a) Length of time (in minutes) that the primary and secondary draft dampers are left on full open, after loading fuel charge, before dampers are adjusted to desired setting for test run target burnrate.

(b) Western larch (tamarack) used for Runs 11-13. All other runs used eastern oak.