COMBUSTION GENERATED PARTICULATE EMISSIONS

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ABSTRACT

This paper addresses the generation of particulate emissions during combustion of wood waste fuels in spreader-stoker boilers. The purpose is to bring the results of research in wood wastes to the attention of users of all solid waste fuels. The scope is limited to reporting results of research conducted on the Oregon State University Pilot spreader-stoker test facility sponsored by the U.S. Department of Energy. This paper reports the experiments the author has been involved in; it reviews the results and conclusions that have been reported; states applications of results to commercial wood fired boilers that have been made; finally, this paper reports the analysis of steady-state data which was beyond the scope of the original experiment. The applicability of this research on wood wastes to solid wastes is discussed in general.

NOMENCLATURE

g/m³ (SD 12% CO_2) (grains/SDCF) = standardized particulate mass emission rate; Mass emitted per standard, dry unit volume corrected to 12% CO_2

kg/h·m² (lb/hr ft²) = combustion rate is the fuel mass flow per unit area of grate

mass mean diameter = fuel particle size, average size of second largest dimension of fuel particles, measured in mm (in.)

UF A/F = ratio of underfire air mass flow rate to fuel mass flow rate, does not include overfire air flow rate

SOLID WASTE COMBUSTION

Combustion of solid wastes will probably continue to grow in popularity as a means of disposal and as a source of energy. Burning solid fuels on grates is only one way, although an important way, to burn them. Boilers that have grates, such as spreader-stoker boilers, are in widespread use and are an effective way to burn many different solid fuels.

One of the more difficult fuels to burn is solid wastes. Although municipal solid wastes are different in many ways from wood wastes, they may have enough characteristics in common with wood wastes to allow research on wood wastes to be applicable. The validity of the research results to be presented has been demonstrated only for wood wastes in spreader-stoker boilers.

This paper addresses the generation of particulate emissions during combustion rather than the collection of those particles. With wood wastes, improving combustion has been proven to be as effective or more effective than improving collection efficiency [3].

Intuition may suggest that increasing fuel particle size is the wrong way to go. That would be correct for suspension burners. It was once commonly accepted that wood-fired spreader-stoker boilers should be designed to burn a substantial fraction of the fuel particles in suspension. Recent research has shown why that is not true [3]. Grate fired boilers, as in Fig. 1, burnout wood fuel particles better if combustion occurs on the grate [3]. Increasing fuel particle size is important in spreader-stoker boilers. Evidence of that will be presented in Fig. 2. The emissions from smaller fuel particles are consistently higher.

Some wood-fired spreader-stoker boilers supply all of the combustion air through the grate. However, the need for overfire air to reduce particulate emissions and improve combustion efficiency has been clearly demonstrated [1–4]. As more air is provided overfire, less air need be provided underfire, through the grate. With less air passing through the grate and through the fuel bed, the fuel particles are less likely to be blown off the grate, entrained by the gases and carried out of the combustion chamber [3]. The effect that reducing underfire air has on particulate emissions can be seen in Fig. 2. The emissions when higher underfire air ratios are used are consistently higher.

Combustion rate, the rate at which fuel is burned per unit area of grate, is almost universally accepted as having an effect on particulate emissions. This is because combustion rate is the one variable that is normally varied through a wide range by boiler operators. An increase in emissions at higher combustion rates has been observed by many. This effect has been reported consistently [1–4], and Fig. 2 consistently shows an increase in emissions as combustion rate increases in all four experiments.

RESEARCH EFFORTS

The research to be presented was initiated in 1975 by Junge [1]. Funding was provided by the U. S. Department of Energy to develop a pilot plant test facility at Oregon State University. A small spreader-stoker boiler was used to test various waste wood fuels. A schematic of the facility is presented in Fig. 1. Experiments were conducted at the facility until 1980.

In addition to Junge's work, early results were presented in a doctoral dissertation by Tuttle [3]. That research resulted in Patent No. 4,241,672 being awarded for a method of burning wood to control particulate emissions. The early results were reported in the *Journal of the Air Pollution Control Association* [4]. The process was later useful in a commercial application of biomass gasification [5]. The results of this research have been applied (Tuttle) to commercial boilers to pass emissions compliance tests.

Three hypotheses were tested during the doctoral research and their effects shown to be statistically significant [3].

(a) The original hypothesis was that the velocity of the air passing through the fuel bed would have a substantial effect on particulate emissions.

(b) It was also hypothesized that reducing amount of underfire air proportional to fuel flow rate would develop a deeper fuel bed.

(c) A third hypothesis was that a deeper fuel bed would tend to trap easily entrained particles.

In 1978 more comprehensive research was conducted in the Oregon State University test facility [2]. The main objective was to determine whether load swings increased emissions. The effects of slugs of wet fuel and of changing fuel particle size was also of interest. Nine independent variables and ten dependent variables were tested. Three large fractional factorial experiments were designed using computerized statistical programs. The largest experiment, designed to test load swings is shown in detail in Tables 1 and 2. Only the unsteady-state data points are shown. Data taken at the steady-state condition on either side of each unsteady-state test run are still being analyzed. Some of the steady-state data were analyzed by Kester [6].

TEST DESIGN

The tests were planned in two phases: Phase I—to determine the levels of factors used in Phase II; and Phase II—to answer the stated test objectives.

Phase I was used to provide information on the facility operation, to establish baseline data, and to determine the levels of factors to be used in Phase II. During the test, the project team became familiar with the boiler's operation and test equipment. The data logger and data reduction program were operated and verified.

Phase II experiments tested for measurable effects of step changes in fuel size, moisture, and feed rate on completeness of combustion and stack opacity.

Description of Components

(1) Screw Conveyor With Fuel Feed Hopper
(2) Vibrating Fuel Conveyor
(3) Fuel Spreader Roll
(4) Water Wall Lined, Spreader Stoker Combustion Chamber (1x1x3 m)
(5) High-Temperature Cumbustion Gas Duct
(6) Inlet Air Duct - Underfire Air
(7) Inlet Air Duct - Overfire Air
(8) Air Preheater - Triple Pass, Plate Type
(9) Stack Gas Duct
(10) Stack Gas Sample Port
(11) Cyclone Separator (Dia=2m)
(12) Stack Gas to Atmosphere
(13) Forced Draft Fan
(14) Mass Emission Monitor
(15) Particulate Metering
(16) Lear-Siegler Transmissometer

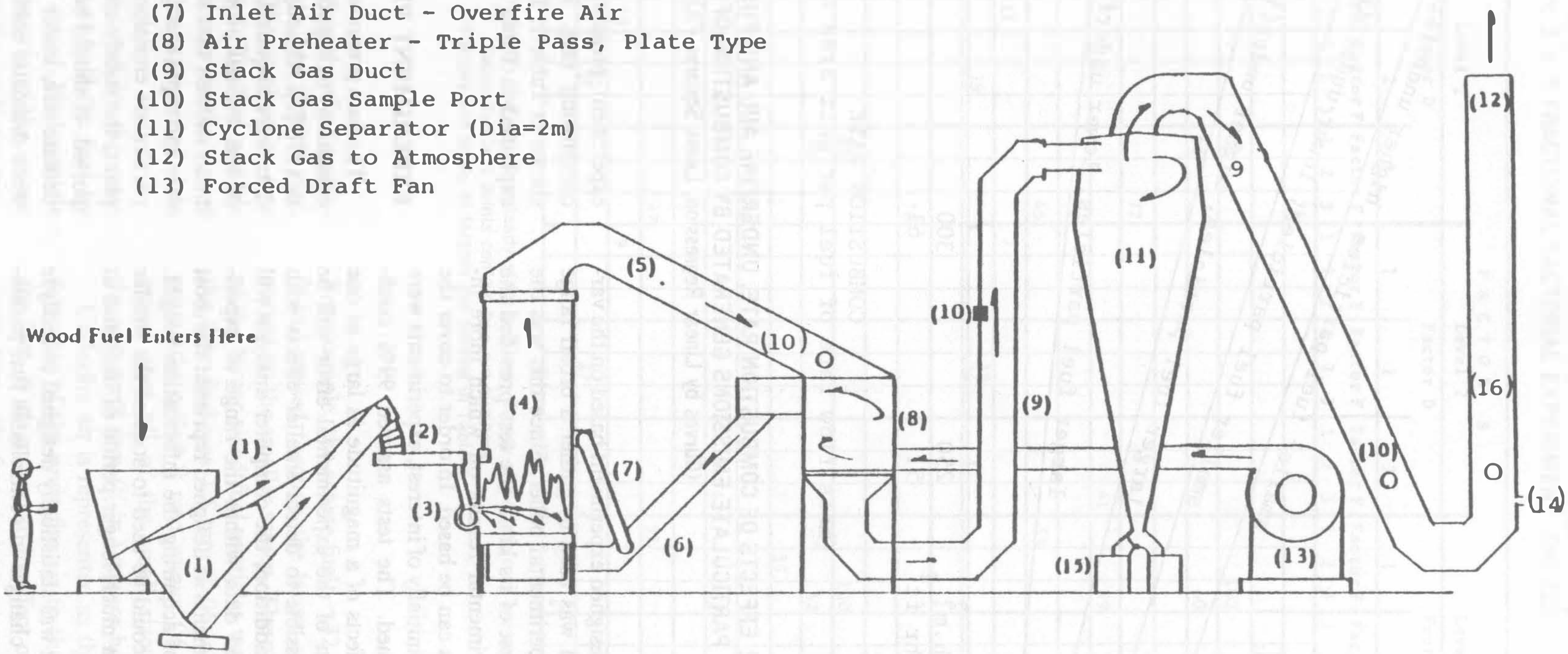

FIG. 1 SCHEMATIC ILLUSTRATION OF THE MODIFIED OREGON STATE UNIVERSITY WOOD COMBUSTION TEST FACILITY (Ref. [2])

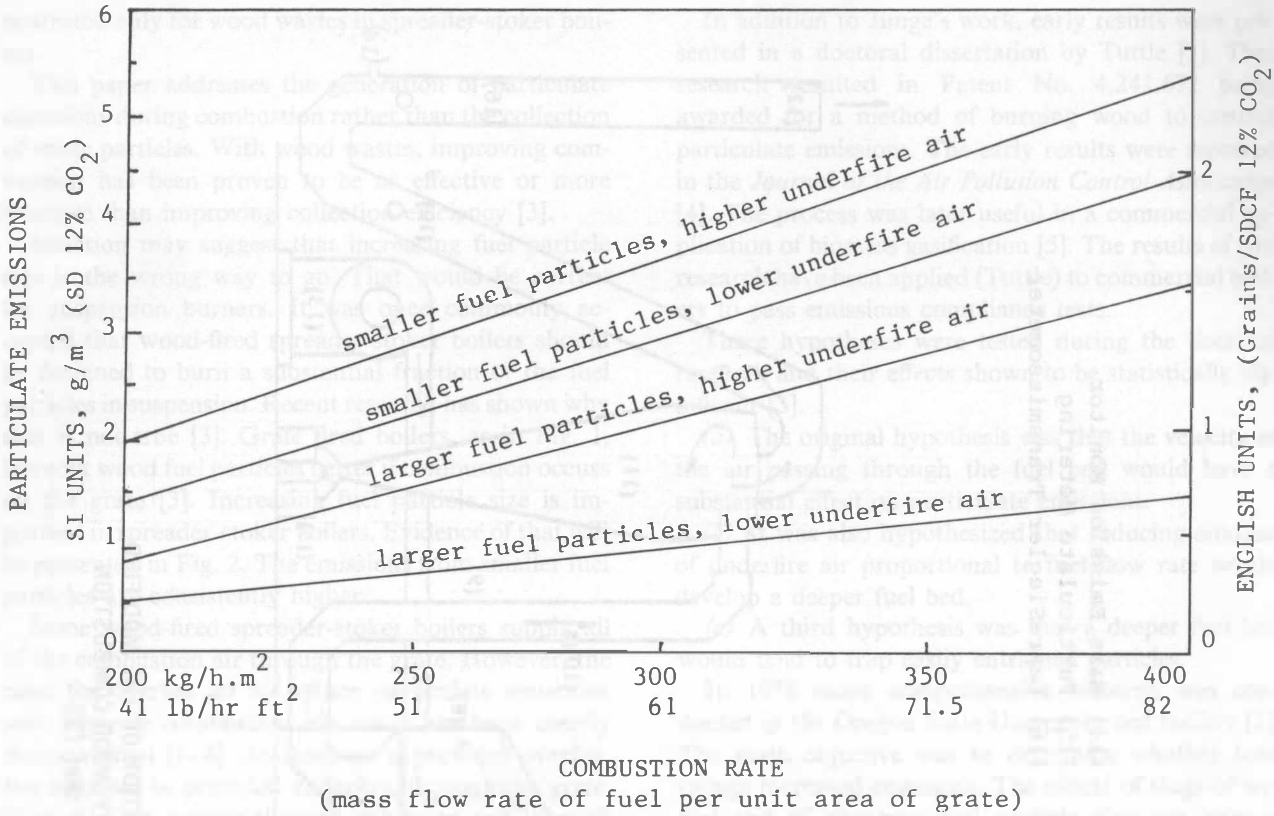

FIG. 2 EFFECTS OF COMBUSTION RATE, UNDERFIRE AIR, AND FUEL PARTICLE SIZE ON PARTICULATE EMISSIONS GENERATED BY COMBUSTION OF WOOD WASTES
(Curves by Linear Regression, Least Squares Fit)

A statistically designed experiment based on the variables to be tested was used to gather a broad range of data on the experimental boiler. Since this was the first pilot boiler test of its kind, the test provided the preliminary experimental results on which more indepth experiments can be based. In order to cover the range of variables initially of interest, experiments were statistically designed. The tests assured 99% confidence that any effects of a magnitude as large as one standard deviation of the experimental error will be detected. It is possible to detect smaller effects with less certainty. In addition, the computer analysis will supply interpolated data within the range of experiments. The experiments as designed represent the most efficient method of acquiring the information sought. Key experiments could be used to acquire the similar information over a much longer period of time and at increased expense.

One experiment was statistically designed to analyze the effects of step changes in controllable fuel parameters. The experiment required 23 trials. The largest experiment measured the effects of step changes in combustion rate. The experiment took 50 trials as shown in Table 1. The factors and levels of factors are explained in Table 2.

EXPERIMENT RESULTS

The data presented are the data taken at steady-state conditions to support the unsteady-state data analyses in 1978 [2]. Although substantial valuable steady-state data were acquired, its analysis was beyond the scope of the original project. Although the original experiment showed that load swings, rapid changes in moisture and rapid changes in fuel size did not affect average particulate emissions in the manually controlled pilot plant, the steady-state data were not analysed and reported. It should be noted that the effects of fuel particulate size, under air/fuel ratio and combustion rate were dramatic enough to be noticed during the data collection.

TABLE 1 STEP-CHANGE IN COMBUSTION RATE EXPERIMENT, A STATISTICALLY DESIGNED $2 \times 3 \times 2 \times 3 \times 2 \times 3 \times 3$ FRACTIONAL FACTORIAL EXPERIMENT (Ref. [2])

Factor A	Factor C	Factor E	Factor G	FACTOR B																										
				Level 1									Level 2									Level 3								
				Factor D									Factor D									Factor D								
				1			2			3			1			2			3			1			2			3		
				Factor F			Factor F			Factor F			Factor F			Factor F			Factor F			Factor F			Factor F			Factor F		
				1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
Level 1	Level 1	1	1	98								76																84		
			2																							94/104				
			3							80														102						
		2	1							68														60						88
			2																											
			3	64								72																		
	Level 2	1	1																		41			49				37		
			2																											
			3									45										53								
		2	1			11							7																	23
			2					19								15/34														
			3																					2				27		
Level 2	Level 1	1	1	96								78																86		
			2																							92				
			3							82														100						90
		2	1							70														62						
			2																				57							
			3	66								74																		
	Level 2	1	1																		43			51				39		
			2																											
			3									47										55								
		2	1			13							9																	25
			2					21/31								17														
			3																					4				29		

Numbered spaces in matrix signify the actual unsteady-state test run. Steady-state test runs are not shown.
Replicated test points contain two run numbers.
Factors and levels of factors are defined in Table 2.

The three variables which significantly affect particulate emissions are combustion rate, fuel particle size, and the amount of underfire air. The combustion rate is shown along the abscissa in Fig. 2. The fuel particle size and underfire air effects are shown by the curves from least squares fit through the represented data points.

Fuel particle size can be represented by the mass mean diameters, which means that half the fuel by mass is smaller than the diameter stated. Fuel particle size can also be represented by the size of the screen openings through which the fuel will or will not pass. For example, the coarse fuel, $-32 + 8$ mm ($-1\frac{1}{4} + \frac{3}{8}$ in.) passed through the larger screen opening and stayed on the smaller screen. The mass mean diameter of the larger sized fuel particles was 20 mm (0.8 in.); the finer fuel was 1.5 mm (0.06 in). The finer fuel is popularly called 8 mm minus ($\frac{3}{8}$ in. minus), which means that all of the small sized fuel would pass through an 8 mm ($\frac{3}{8}$ in.) square hole.

Underfire air is represented as the ratio of the mass flow rate of the underfire air to the mass flow rate of the fuel. With respect to its effect on particulate emissions, the underfire air is most precisely represented

TABLE 2 DEFINITION OF FACTORS AND LEVELS OF FACTORS IN THE STEP CHANGE IN COMBUSTION RATE EXPERIMENT (Ref. [2])

Factor A. Direction of Combustion Rate Change

Level 1. Increase in Rate
Level 2. Decrease in Rate

Factor B. Size of Combustion Rate Step Change

Level 1. Step change of 4.5 kilograms (10 lb) of dry fuel per hour, equals 4.9 kilograms of fuel per hour per square meter of grate (1 lb/hr ft^2)
Level 2. Step change of 22.7 kilograms (50 lb) of dry fuel per hour, equals 24.4 kilograms of fuel per hour per square meter of grate (5 lb/hr ft^2)
Level 3. Step change of 45 kilograms (100 lb) of dry fuel per hour, equals 24.4 kilograms of fuel per hour per square meter (10 lb.hr ft^2)

Factor C. Moisture Content of Fuel

Level 1. 40 percent by weight, 66.7 percent by dry basis
Level 2. 50 percent by weight, 100 percent by dry basis

Factor D. Combustion Rate

Level 1. 227 kilograms of dry fuel per hour, equals 244 kilograms per hour per square meter of grate, equals 4.7 GJ/h. m^2, equals 0.95 to 1.50 GJ/h. m^3 (60 lb/hr ft^2, 0.41 million Btu/hr ft^2, 20 to 30 thousand Btu/hr ft^3)
Level 2. 273 kilograms of dry fuel per hour, equals 294 kilograms per hour per square meter of grate, equals 6.6 GJ/h. m^2, equals 0.95 to 1.50 GJ/h. m^3 (60 lb/hr ft^2, 0.49 million Btu/hr ft^2, 25 to 40 thousand Btu/hr ft^3)
Level 3. 318 kilograms of dry fuel per hour, equals 342 kilograms per hour per square meter of grate, equals 6.5 GJ/h. m^2, equals 1.1 to 1.7 GJ/h. m^3 (70 lb/hr ft^2, 0.57 million Btu/hr ft^2, 30 to 45 thousand Btu/hr ft^3)

Factor E. Size Distribution of Fuel

Level 1. Fines, Eight millimeter minus, -8 mm Douglas fir bark (3/8 inch minus)
Level 2. Coarse, Thirty-two millimeter minus, eight millimeter plus, -32+8 mm Douglas fir bark (11/4 inch minus, 3/8 inch plus)

Factor F. Underfire Air/Fuel Ratio

Level 1. Four mass units of Underfire Air per unit of dry fuel
Level 2. Six mass units of Underfire Air per unit of dry fuel
Level 3. Eight mass units of Underfire Air per unit of dry fuel

Factor G. Excess Air Percent

Level 1. 30 percent in excess of chemically correct amount for complete combustion
Level 2. 55 percent in excess of chemically correct amount for complete combustion
Level 3. 80 percent in excess of chemically correct amount for complete combustion

in this ratio [2–5]. Another way to express air is as the overfire air/underfire air ratio [1].

The effect that increasing the combustion rate has on particulate emissions can be seen on every curve in Fig 2, as well as in the data points taken as a whole. In these data the effect of underfire air is comparable to that of combustion rate. Figure 2 shows that doubling the underfire/air to fuel ratio has about the same tendency to increase emissions as does doubling the combustion rate. The slopes of the curves imply a possible interaction between underfire air and combustion rate. The effect of underfire air on emissions clearly exists in Fig. 2 for both fine fuel and coarse as well as across the entire range of combustion rates. The emissions from finer fuel are consistently higher in Fig. 2 than the emissions from the coarser fuel. The size of the fuel particles shows a much greater effect on the generation of particulate emissions than either underfire air or combustion rate at the levels these variables were tested. At underfire air/fuel ratios of less than 4:1, particulate emissions have been found to be even more strongly affected [3, 4].

Three other independent variables exist in these data. They are moisture content, excess air, and load swings. They account for some of the scatter in the data. In addition, experimental error is a large contributor to the scatter. Substantial experimental error may have been introduced by combining the steady state data with the unsteady state data. Statistical significance of the effects of fluctuating fuel conditions is based mainly on multiple regression analysis and the null hypothesis using the Student's T test [2]. Two way analysis of variance was used for statistical significance of main effects and interactions for combustion rate and underfire air in earlier tests [3, 4].

It should be noted that fuel moisture content indirectly affects particulate emissions. To generate equal steam flow rates in a boiler, wetter fuel must be burned at a higher combustion rate to release the same net energy as drier fuel. Burning the wetter fuel at a higher combustion rate would result in greater emissions. The effect of combustion rate on particulate emissions has long been recognized by boiler operators. These research efforts merely quantified that effect [1–4].

There are several reasons why application of these research findings to other solid wastes can be expected to improve efficiency and reduce particulate emissions. Most importantly, spreader-stoker boiler operation is one of the main results of the research. Any solid fuel burned in a spreader-stoker is expected to respond to the combustion rate variable and the need for overfire air. Although the actual ratios of air to fuel are fuel dependent, the effect of high air flow rates through the fuel bed and the trapping effect [3] of deeper fuel beds are expected to affect all fuel beds the same way.

Those solid wastes which are cellulose are similar chemically to wood wastes. Physically solid waste fuel particles will differ in size and shape from wood fuel particles. However, the more easily a fuel becomes entrained in the combustion gases the more important it is to keep the fuel particles on the grate. Both larger fuel particle size and lower underfire air/fuel ratios help to keep fuel particles on the grate.

Fuel particle size and underfire air effects may be important only if a solid fuel produces solid carbon during pyrolysis. Fuels which produce little or no charcoal may burn well in suspension regardless of size. However, carbon particles which are produced do not have time to burn out in suspension unless they are similar in size to pulverized coal particles.

CONCLUSIONS

Three variables have been shown to have a substantial effect on the rate at which particulate emissions are produced by combustion on grates:

(a) Combustion rate has a significant effect on the rate of particulate emissions. Higher heat release rates result in higher levels of emissions [1, 3]. This effect can also be seen in Fig. 2.

(b) Fuel partial size has a substantial effect, as seen in Fig. 2, on the production of particulate emissions. Fuel smaller that 8 mm (3/8 in.) has greater emissions that fuel screened to larger than 8 mm (3/8 in.).

(c) The amount of underfire air has a significant effect on particulate emissions. As the ratio of underfire air to fuel flow rate increases, the rate of particulate emissions increases [1, 3]. This effect can also be seen in Fig. 2.

A number of parameters have been shown to not have a significant effect on particulate emissions [2]. Increases in emissions caused by upward load swings were nullified by decreases in emission caused by downward load swings [2]. Based on the results of these tests [2], the following statements can be made:

(a) Fuel moisture step changes in the range tested, 50–100% dry basis, did not directly effect the rate of total particulate emission [2].

(b) Load swings in the range tested did not have a significant effect on particulate emissions. Load swings were simulated by step changes in the fuel feed rate and air flow rate [2].

There are three variables which can be controlled to reduce the generation of particulate emissions generated by combustion of wood wastes. Combustion of most solid wastes in spreader-stokers are expected to respond to these variables.

(a) Reducing the combustion rate, i.e., decreasing the unit's capacity is known to be effective. The cost may prove to be exorbitant in many cases.

(b) Increasing fuel particle size is effective and may be economical if efforts are limited to keeping larger fuel from being pulverized.

(c) Reducing underfire air may require operator training or capital expenditure for retrofits. It has been the author's experience on wood fired boilers that implementation of reduced underfire air technology to existing boilers has required training of the operators and engineers involved. Capital expenditures could automate the process and reduce or eliminate training requirements.

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