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THE EFFECTS OF OVERFIRE AIR AND LOW EXCESS AIR ON NO_x EMISSIONS AND ASH FOULING POTENTIAL FOR A LIGNITE-FIRED BOILER

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INTRODUCTION

Federal standards were established on March 2, 1978 [1] for limiting NO_x emissions from new pulverized coal-fired stationary sources burning lignites to 0.6 lb/10^6 Btu. Some uncertainties remain as to the effect on the operation of lignite-fired power plants of efforts to reduce NO_x emissions using currently available technology. The uncertainties are greatest for units burning high-sodium Northern Great Plains lignites. These units experience aggravated boiler-tube ash fouling problems during periods of high sodium content coal. In an effort to study the effects of NO_x control on ash fouling potential, the Grand Forks Energy Research Center (GFERC) of the Department of Energy conducted two weeks of testing on a tangentially-fired boiler burning a high-fouling North Dakota lignite. Ash fouling rates were studied under conditions of both overfire air and low excess air.

TEST PROGRAM

Tests were run at the Hoot Lake Station of the Otter Tail Power Company located at Fergus Falls, Minnesota, in August of 1977. The Hoot Lake No. 2 unit was selected for these tests since it is the only tangentially-fired boiler in current operation utilizing high-fouling North Dakota lignite as fuel. The boiler is shown in cross-section elevation in Fig. 1. The unit has a steam capacity of 400,000 lb/h at 1450 psig and 1000 F and is rated at 53.5 MW.

The fuel used at the Hoot Lake Station is North Dakota lignite supplied from the Beulah Mine. Typical properties of this lignite include a higher heating value of 7000 Btu/lb, with 36 percent moisture and 7 percent ash content. The sodium content (Na_2O in ash) varies from less than 1.5 percent to greater than 8.5 percent. Coal used during testing was chosen to have a sodium content close to 5 percent.

The arrangement of the inlet ducts and nozzles for the lignite and primary air and for the secondary air are indicated in Fig. 2. This arrangement is typical for each corner of Hoot Lake Unit 2. The lignite/air nozzles are slanted to provide the tangential swirl flame pattern typical of tangentially-fired boilers. The tilt of the nozzles can also be adjusted automatically to maintain reheat steam temperatures or can be adjusted manually to 15 degrees up or down. Manual damper controls are located at each corner

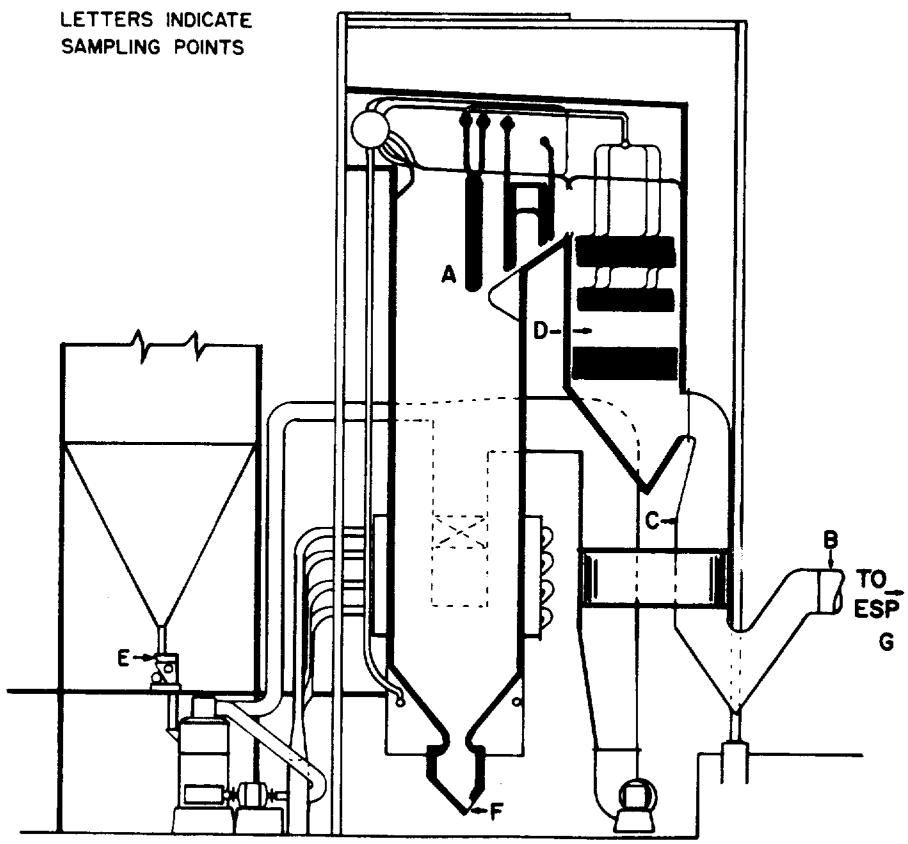


Fig. 1—Hoot Lake Boiler No. 2, Otter Tail Power Company.

of the boiler for adjusting the air flow to each inlet duct. In normal operation, only three mills out of the four, denoted as Mills A, B, C, and D, are in operation, and the pulverized lignite and primary air are injected through the three corresponding burner nozzles. The selection of the three mills has been basically random and has been varied several times each day to minimize coal retention in the bunkers.

The main objective of the test program was to determine the effect of changes in combustion conditions on ash fouling rates in a tangentially-fired boiler utilizing a North Dakota lignite and operated at conditions of low excess air and of rich fuel/air mixtures with over-fire air. For ash fouling rate measurement, two methods which have been successfully demonstrated on previous field tests [2,3] were utilized. The first method involved the use of a 10-foot, air-cooled ash-fouling probe and a high-velocity thermocouple probe to measure the furnace temperature at the test location. A sketch of the fouling probe is shown in Fig. 3. Ash fouling deposits build up on the probe and are collected and weighed at timed intervals. The

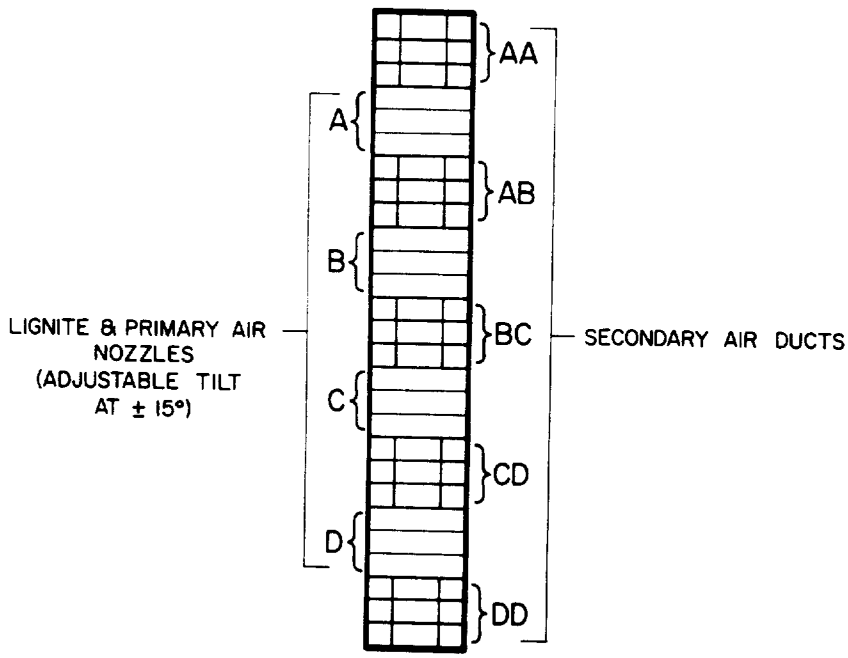


Fig. 2—Burner arrangement for Hoot Lake Unit No. 2

second method involves the use of an experienced power plant operator to observe and record the furnace condition during each test. The operator identifies areas where slagging and ash deposit buildup is occurring and evaluates the severity.

Since the operation of the tangentially-fired boiler at conditions of low excess air and at conditions of rich fuel/air mixture with overfire air are suggested methods for reducing the NO_x emissions from a lignite-fired power plant,[4,5] the secondary objective of the test program was to determine the NO_x levels at these conditions to verify the reduction and to compare with normal operation. In addition, other flue gas measurements including CO, CO_2, O_2, and SO_x were obtained. An instrumentation trailer was utilized to make these measurements on a continuous basis.

The scheduled test measurements are summarized in *Table I*, which also gives test frequencies and locations in reference to Fig. 1. In addition to the ash probe deposits and flue gas monitoring, samples were taken of the lignite, the fly ash from the electrostatic precipitator, and bottom ash to verify that changes in ash deposit rate or NO_x level were not due to changes in the characteristics of the lignite. These samples were collected and returned to GFERC for analysis. The plant operating conditions were also monitored and recorded.

The planned test conditions included operation at constant load and constant excess air during each test. To obtain the optimum test conditions for a good indication of fouling potential, operation at 95 percent of rated power load or higher (48 to 53 MW) was desirable. In addition, the lignite composition was

TABLE I
SCHEDULED TEST MEASUREMENTS, LOCATION AND SAMPLING FREQUENCY

	Sampling Location*	Sampling Frequency
1. Ash Fouling Rates (using air-cooled test probes):	A	2 to 5 probe deposit tests per run
a. Test location: Ahead of the secondary superheater.		
b. Sampling duration: Periods ranging from 15 minutes to 1 hour (during cessation of soot blowing).		
c. Measurements, data to be taken:		
(1) Temperature of flue gas (HVT probe)		
(2) Deposit weight and length		
(3) Sampling time		
(4) Temperature of test probe		
(5) Photographs of deposits		
(6) Collection and identification of deposits for analysis		
(7) Boiler operating data from control room		
(8) Operator evaluation of boiler fouling condition based on visual observation		
2. Coal Samples:		
a. Collect a riffled composite sample of all feeders for each ash probe test	E	2 to 5 per run at same time as probe sample
3. Dust Loading and Ash Samples:		
a. Determine dust loading, record test data	B	1 per run
b. Aspirate, collect, and identify enough fly ash for fly ash analyses	B	1 per run
c. Determine the flue gas volumetric flow rate	B	1 per run
d. Collect and identify representative samples of fly ash from the ESP	G	Daily
e. Collect and identify samples of furnace bottom slag	F	Daily
4. NO_x and SO_x Flue Gas Concentrations:		
a. Monitor and record NO_x on a continuous basis during test days; obtain wet sample by approved EPA methods	C	Continuous plus 2 EPA tests/day.
b. Monitor and record SO_x on a continuous basis during test days; obtain wet sample by approved EPA methods	C	Continuous plus 2 EPA tests/day.
c. Monitor any gas conditions (CO_2, CO, O_2, moisture) which are not recorded and available from the control room	D	Continuous

*See Figure 1.

held as constant as possible for the two weeks of the test program and for most of the preceding week. Lignite was provided by the mine with a sodium level of 4.5 to 5 percent Na_2O in the ash, since this level of sodium has been shown to be borderline for high fouling.[2] During ash deposit measurements, soot blowing was terminated at any locations which might affect the ash deposition on the probe.

SUMMARY OF TEST RESULTS

Test Conditions and Results

Power plant operating conditions for each test are summarized in *Table II*, and the test results at these operating conditions are summarized in *Table III*. The test program was started on August 22, with the first full run on August 23. The first test condition was maintained for about 1½ days in order to verify

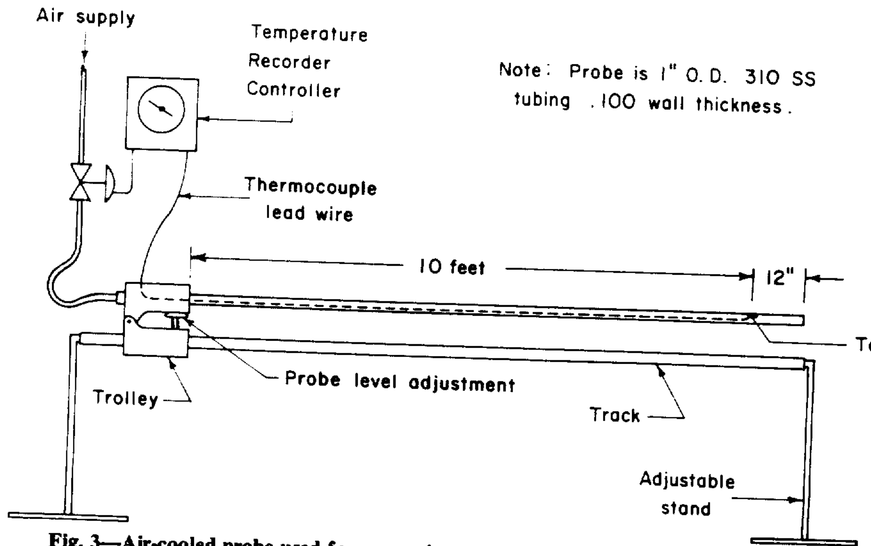


Fig. 3—Air-cooled probe used for measuring ash deposition rate in full-scale boilers.

steady-state conditions. After several runs it was found that the NO_x level stabilized within 30 minutes, and the ash fouling conditions stabilized within one hour after test conditions were changed. As a result, many more test runs were completed than originally planned. A total of 28 test runs was completed in the two weeks, with the ash fouling runs normally taking 3 to 4 hours and the shorter NO_x optimization runs taking 20 to 60 minutes. Periodically, a similar test condition was repeated to assure that test conditions did not vary significantly during the two weeks. For example, Test Runs 6 and 10, 11 and 19, 12 and 20, 14 and 27, and 13, 21, and 28 (before changing the excess air) are all comparable.

The boiler has an automatic tilt control for the burners to change the level of the flame vortex in the boiler to control superheat temperature. Since this parameter could influence both ash fouling and NO_x formation, the tilt mechanism was manually controlled to allow for evaluation of this parameter. For most tests the burner tilt was manually set at 0 degrees.

The first series of three tests was run at normal and decreased excess air to evaluate the effects of excess air. The oxygen level in the stack gas was reduced from the normal 4.6 percent in Run 1, down to 3.0 percent for Run 3. At the conditions of 3.0 percent oxygen, severe slagging and running slag were observed at the lower levels in the boiler and the run was terminated. Later, on the last test run of the program (Run 28), the excess air was again reduced to reach the 3.0 percent oxygen level, but with the lower three mills and burners operating instead of all four. Some indication of the start of slag dripping was observed at the third floor level, but was not severe at the termination of the test run.

The tests with overfire air were conducted by operating the bottom three burners with low air and the top burner with higher air flow and no fuel. The

TABLE II. - Summary of Operating Conditions for Hoot Lake Overfire And Low Excess Air Ash Fouling Test Program

Run	Date	Plant load (MW)	Mills and Loads amps A	B	C	D	Damper Positions (pct open) AA	A	AB	B	BC	C	CD	D	DD	Burner tilt (degrees)	O_2 (pct)
48 MW Runs:																	
1	8/23/77	48.0 ± 0.0	52.0	52.0	52.0	52.0	40	100	40	100	40	100	40	100	40	Auto (+12)	4.6 ± 0.5
2	8/24/77	47.5 ± 0.5	55.0	53.3	53.0	54.5	40	100	40	100	40	100	40	100	40	Auto (+10)	3.3 ± 0.6
3	8/24/77	47.5 ± 0.5	55.0	53.5	53.3	53.5	40	100	40	100	40	100	40	100	40	Auto (+10)	3.0 ± 0.2
6	8/26/77	47.5 ± 0.5	51.5	50.5	64.0	63.0	100	100	100	50	50	50	50	50	50	0	4.4 ± 0.3
7	8/26/77	48.0 ± 0.0	50.0	49.3	65.0	64.3	40	100	40	100	40	100	40	100	40	0	4.3 ± 0.6
8	8/27/77	48.0 ± 0.0	52.3	50.5	62.5	61.5	100	100	100	50	50	50	50	50	50	0	4.1 ± 0.3
9	8/27/77	48.0 ± 0.0	50.3	48.5	62.5	58.8	100	100	100	50	50	50	50	50	50	-15	4.1 ± 0.2
10	8/28/77	48.0 ± 0.0	48.4	47.2	61.2	62.2	100	100	100	50	50	50	50	50	50	+15	4.1 ± 0.3
13	8/29/77	48.5 ± 0.5	0	59.5	60.0	59.0	0	0	40	100	40	100	40	100	40	0	4.4 ± 0.1
14	8/29/77	47.5 ± 0.5	0	59.0	58.5	58.5	100	100	100	50	50	50	50	50	50	0	4.4 ± 0.3
15	8/30/77	48.0 ± 0.0	0	61.5	61.0	60.0	100	100	100	50	50	50	50	50	50	+15	4.3 ± 0.2
16	8/30/77	48.0 ± 0.0	0	60.3	61.0	61.0	100	100	100	50	50	50	50	50	50	-15	4.2 ± 0.2

17	8/30/77	48.0 ± 0.0	0	59.0	61.0	61.7	40	0	40	100	40	100	40	100	40	+15	4.6 ± 0.2
18	8/30/77	48.0 ± 0.0	63.0	60.0	62.5	0	40	100	40	100	40	100	40	0	40	+15	4.5 ± 0.0
27	9/01/77	48.0	0	61.3	61.0	60.0	100	100	100	50	50	50	50	50	50	0	4.4 ± 0.1
28	9/01/77	48.0	0	61.0	61.0	61.0	40	0	40	100	40	100	40	100	40	0	4.4 - 3.0 ± 0.1
<u>NO_x optimization runs</u>:																	
21	9/01/77	48.0	0	62	62	62	40	0	40	100	40	100	40	100	40	0	4.4 ± 0.4
22	9/01/77	48.0	0	62	62	62	100	100	100	50	50	50	50	50	50	0	4.5
23	9/01/77	48.0	0	62	62	61	100	100	100	100	20	100	20	100	40	0	4.6
24	9/01/77	48.0	0	62	62	61	100	100	100	50	40	30	40	20	40	0	4.4
25	9/01/77	48.0	0	62	62	61	100	100	100	50	40	10	40	10	40	0	4.5
26	9/01/77	48.0	0	62	61	60	100	100	100	50	50	50	50	50	50	0	4.4 overfire fans off
<u>44 MW Runs</u>:																	
4	8/25/77	44.3 ± 0.7	61.6	60.6	66.4	0	40	100	40	100	40	100	40	100	40	Auto (-15)	4.6 ± 0.1
5	8/25/77	45.0 ± 0.0	0	63.7	67.0	64.0	100	100	100	60	40	60	40	60	40	Auto (+10)	4.7 ± 0.5
11	8/28/77	44.0 ± 0.0	0	61.5	60.0	60.0	100	100	100	50	50	50	50	50	50	0	4.5 ± 0.4
12	8/29/77	44.0 ± 0.0	0	57.5	57.5	56.5	0	0	40	100	40	100	40	100	40	0	4.2 ± 0.1
19	8/31/77	44.8 ± 0.8	0	62.0	60.0	61.3	100	100	100	50	50	50	50	50	50	0	4.5 ± 0.3
20	8/31/77	44.3 ± 0.3	0	58.5	58.3	59.3	40	0	40	100	40	100	40	100	40	0	4.6 ± 0.3

TABLE III. - Summary of test results for the Hoot Lake overfire and low excess air ash fouling test program

Run	O_2 (pct)	NO_x ppm[a]	Probe ash deposit (gm/in-min x 10^2) 12" L	72" L	HVT temp. (°F)	Coal: Na_2O (pct of ash)	Coal: Ash (pct as fired)	SO_x (ppm)[c]
48 MW Runs:								
1	4.6 ± 0.5	421.5 ± 24	11.5 ± 3.4	5.9 ± 2.9	2204 ± 34	5.1 ± 0.3	9.6 ± 0.4	982 ± 13
2	3.3 ± 0.5	398.6 ± 30	14.8 ± 0.1	7.9 ± 0.5	2075	5.0 ± 0.1	10.1 ± 0.4	1100 ± 48
3	3.0 ± 0.2	385.6 ± 15	14.6 ± 1.3	6.3 ± 0.7	2050	5.0 ± 0.3	10.2 ± 0.9	1154 ± 95
6	4.4 ± 0.3	306.6 ± 10	13.8 ± 0.3	--	1750 ± 30	4.8 ± 0.4	9.6 ± 0.2	1030 ± 50
7	4.3 ± 0.6	363.3 ± 22	12.7 ± 1.4	5.7 (1)	2175 ± 25	4.6 ± 0.5	10.5 ± 0.8	1036 ± 64
8	4.1 ± 0.3	344.0 ± 25	10.9 ± 1.5	--	1975 ± 25	4.7 ± 0.4	10.3 ± 0.5	1121 ± 54
9	4.1 ± 0.2	353.8 ± 17	10.5 ± 0.6	--	1693 ± 60	4.6 ± 0.7	10.0 ± 0.9	1069 ± 15
10	4.1 ± 0.3	298.6 ± 19	11.4 ± 0.5	--	1800 ± 25	4.8 ± 0.1	8.5 ± 0.1	1117 ± 71
13	4.4 ± 0.1	358.0 ± 7	9.9 ± 0.4	4.5 ± 0.2	1820 ± 20	4.9 ± 0.4	8.4 ± 0.4	1013 ± 12
14	4.4 ± 0.3	240.0 ± 10	8.4 ± 0.5	4.0 ± 0.3	1805 ± 5	4.5 ± 0.1	8.2 ± 0.0	1025 ± 44
15	4.3 ± 0.2	278.0 ± 8	7.7 ± 1.1	2.8 ± 0.1	1744 ± 18	5.1 ± 0.4	8.5 ± 0.7	1041 ± 39
16	4.2 ± 0.2	242 ± 17	7.8 ± 0.7	--	1742 ± 16	4.9 ± 0.5	9.0 ± 0.3	1053 ± 56
17	4.6 ± 0.2	360 ± 10	6.3 ± 0.5	3.7 ± 0.6	1738 ± 8	4.6 ± 0.1	9.3 ± 0.3	1020 ± 23
18	4.5 ± 0.0	398 ± 5	11.4 ± 0.2	8.0 ± 0.0	1820 ± 30	4.5 ± 0.2	8.9 ± 0.1	958 ± 8
27	4.4 ± 0.1	274 ± 9	9.4 ± 0.4	7.3 (1)	1730 ± 10	4.1 ± 0.2	7.9 ± 0.1	978 ± 45
28	4.4[b] 3.0 ± 0.1	355[b] 320 ± 1.1	6.1 ± 1.1	3.3 ± 0.4	1715	3.7 ± 0.3	7.8 ± 0.7	1119 ± 12

27	4.4 ± 0.1	274 ± 9	9.4 ± 0.4	7.3 (1)	1730 ± 10	4.1 ± 0.2	7.9 ± 0.1	978 ± 45
28	4.4b/ 3.0 ± 0.1	355b/ 320 ± 1.1	6.1 ± 1.1	3.3 ± 0.4	1715	3.7 ± 0.3	7.8 ± 0.7	1119 ± 12

NO_x optimization runs:								
21	4.4 ± 0.4	352 ± 13	--	--	--	--	--	1077 ± 15
22	4.5	255	--	--	--	--	--	1000
23	4.6	270	--	--	--	--	--	1000
24	4.4	238	--	--	--	--	--	998
25	4.5	237	--	--	--	--	--	1000
26	Fans off d/	255	--	--	--	--	--	990
44 MW runs:								
4	4.6 ± 0.1	363.9 ± 24	11.3 ± 1.7	5.3 ± 1.4	1830	4.9 ± 0.5	9.7 ± 0.9	924 ± 24
5	4.7 ± 0.5	253.5 ± 32	7.9 ± 0.6	3.1 ± 0.3	1812	4.9 ± 0.3	9.8 ± 0.4	927 ± 50
11	4.5 ± 0.4	226.0 ± 4	6.3 ± 0.2	3.0 ± 0.2	1755 ± 45	4.3 ± 0.3	9.01 ± 0.2	1049 ± 34
12	4.2 ± 0.1	350.0 ± 10	6.6 ± 0.4	2.5 ± 0.5	1722 ± 13	4.8 ± 0.2	8.3 ± 0.3	1040 ± 6
19	4.5 ± 0.3	275.0 ± 30	9.2 ± 1.5	5.1 ± 1.0	1750 ± 30	4.7 ± 0.3	9.0 ± 0.6	1003 ± 26
20	4.6 ± 0.3	365.0 ± 15	7.7 ± 0.5	4.0 ± 0.2	1706 ± 47	5.3 ± 0.4	8.1 ± 0.6	984 ± 31

a/ The New Source Performance Standard of 0.6 lb/MM Btu for NO_x is equivalent to 506 ppm at 4.6 pct O_2, dry basis.
b/ Conditions at 4.4% O_2 immediately prior to reduction to 3.0%.
c/ The New Source Performance Standard of 1.2 lb/MM Btu for SO_x is equivalent to 550 ppm at 4.6 pct O_2, dry basis.
d/ Two small overfire air fans previously installed by Otter Tail and usually operated.

TABLE IV
LIGNITE PROPERTIES* DURING TEST

	As Received	Moisture Free
PROXIMATE ANALYSIS, %		
Moisture	33.0±0.8	—
Volatile matter	27.3±0.6	40.7±0.9
Fixed carbon	30.1±0.6	44.9±0.9
Ash	9.7±0.9	14.5±1.3
ULTIMATE ANALSIS, %		
Hydrogen	6.5±0.1	4.2±0.1
Carbon	41.2±0.5	61.5±0.7
Nitrogen	0.56±0.02	0.84±0.03
Sulfur	0.93±0.07	1.39±0.10
Oxygen	41.1±0.6	17.6±0.6
Ash	9.7±0.9	14.5±1.3
HEATING VALUE,		
Btu/lb	6,945±80	10,365±120
ASH TEMPERATURES, F		
Initial deformation		2015±48
Softening		2048±49
Fluid		2080±52

*Values shown are means and standard deviations for 22 tests. The analyses were performed by the United States Bureau of Mines at Pittsburgh.

air flow was controlled manually by setting the damper positions at each corner of the boiler. The relative percentage of opening of the dampers is summarized in *Table II*. The letter "A" designates the top burner, as indicated previously in Fig. 2. Test runs with relatively high overfire air include Runs 14, 15, 16, 20, 22, 23, 24, 25, and 26 at 48 MW and Runs 5, 11, and 19 at 44 MW. The series of runs, Runs 21 through 26, was conducted to evaluate the potentials for further reduction in NO_x at more extreme fuel rich and overfire air conditions. The results as summarized in *Table III* indicate a reduction in NO_x with overfire conditions. The implications of these results and the ash fouling potential are discussed further in the next section.

Coal and Coal Ash Analysis

In order for the results of the individual test runs to be comparable for ash fouling and for NO_x levels, the lignite properties were held fairly constant throughout the two weeks. The sodium level (Na_2O in the coal ash) and the ash level in the lignite are especially critical for ash fouling, and the fuel-bound nitrogen level could be critical for the NO_x formations. The sodium and ash levels for each test run are included in *Table III*. The lignite delivered for the test program by the Knife River Coal Mining Co. was very close to the requested 4½ to 5 percent sodium level and remained fairly constant for the two weeks. The mean properties for the lignite for the total two weeks are summarized in *Table IV*, and the ash properties are summarized in *Table V*. The standard deviations indicate that the critical properties were all held within 10 percent throughout the test program. The ash content was at 9.7 ± 0.9 percent, with the sodium at 4.7 ± 0.5 percent. The nitrogen in the lignite was 0.56 ± 0.02 percent.

Additional Results

Additional results for the test program include elemental analysis of the electrostatic precipitator (ESP) ash, bottom ash, and dust loading ash samples, and the analysis of the probe ash deposit samples. Photographs of the probe ash deposits were also taken after each test. As an indication of trends, the mean test values for the ash analysis results for the ESP fly ash and probe ash deposit samples are presented in *Table VI*. Except for the SO_3 in the ash, all of the oxides remained within 10 percent of the mean value for the whole two weeks. The results in *Table VI* can be compared with the coal ash results in *Table V* as an indication of which oxide levels tend to be enriched (increase) or to be depleted (decrease) from the fuel to the

TABLE V
COAL ASH ANALYSIS SUMMARY

Compound	Percent of Ash* Mean	Standard Deviation	Mean (Without SO_3)
Silica, SiO_2	32.2	±3.8	38.9
Aluminum oxide, Al_2O_3	11.6	±0.7	14.0
Ferric oxide, Fe_2O_3	10.8	±1.5	13.0
Titanium oxide, TiO_2	0.5	±0.05	0.6
Phosphorus pentoxide, P_2O_5	0.4	±0.08	0.5
Calcium oxide, CaO	15.1	±1.5	18.2
Magnesium oxide, MgO	4.8	±0.44	5.8
Sodium oxide, Na_2O	4.7	±0.46	5.7
Potassium oxide, K_2O	0.9	±0.14	1.1
Sulfur trioxide, SO_3	17.2	±2.0	—
TOTAL	98.3		97.8

*Mean and Standard Deviation of ash analysis results for all coal samples taken during the test program from August 23 until December 2. Ash analysis by X-ray fluorescence analysis.

fly ash and deposits. For these comparisons, the SO_3-free analysis, as presented in the last column of *Table V*, should be used.

DISCUSSION OF RESULTS

General Results and Problems

The test results have been summarized in *Tables II* and *III*. The first two test runs indicated that steady-state levels of NO_x and ash deposit rate were possible within two hours. The test program was developed to cover a matrix of test conditions including boiler load, combinations of burners, burner tilt angle, excess air, and primary and secondary air distribution. In addition, a series of tests was included to determine the optimum air distribution to obtain the lowest possible NO_x level. All of the variable conditions used in the test program matrix have been summarized in *Tables II* and *III*.

In the following discussion of results, the ash fouling potential is based on the

TABLE VI
FLY ASH AND PROBE DEPOSIT COMPOSITION*

Compound	ESP, % of Ash	Ash Fouling Probe Deposit: White, % of Deposit	Ash Fouling Probe Deposit: Sinter, % of Deposit
Silica, SiO_2	33.3±2.1	27.1±2.3	38.0±3.3
Aluminum oxide, Al_2O_3	13.6±0.4	12.7±0.8	12.7±0.9
Ferric oxide, Fe_2O_3	9.5±0.7	15.2±1.1	13.7±0.7
Titanium oxide, TiO_2	0.53±0.05	0.61±0.05	0.55±0.05
Phosphorus pentoxide, P_2O_5	0.58±0.1	0.73±0.11	0.51±0.08
Calcium oxide, CaO	19.9±0.3	25.0±1.7	19.1±2.1
Magnesium oxide, MgO	6.0±0.5	7.3±0.7	5.7±0.6
Sodium oxide, Na_2O	7.1±0.2	3.5±0.5	4.0±0.7
Potassium oxide, K_2O	1.05±0.06	0.72±0.13	0.91±0.13
Sulfur trioxide, SO_3	5.3±1.0	3.1±0.5	2.0±0.4
TOTAL	96.9	96.0	97.2

*Mean and Standard Deviation for all samples from August 23 through December 1. Ash analysis by X-ray fluorescence analysis.

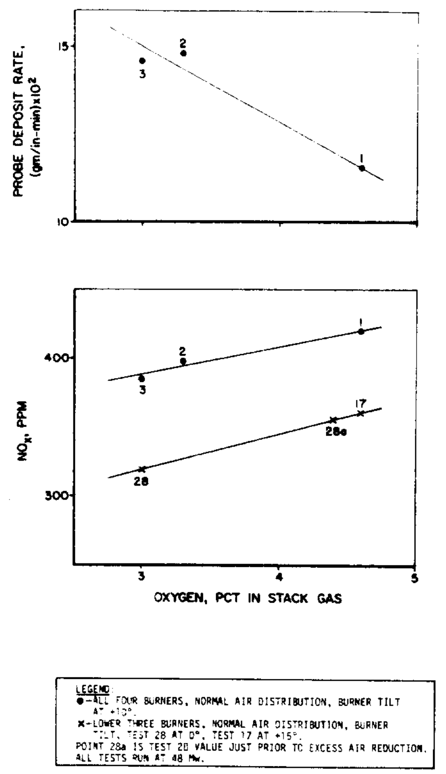


Fig. 4—Ash deposit rate and NO_x concentration versus excess air (stack O_2) (numbers refer to test runs in Tables II and III).

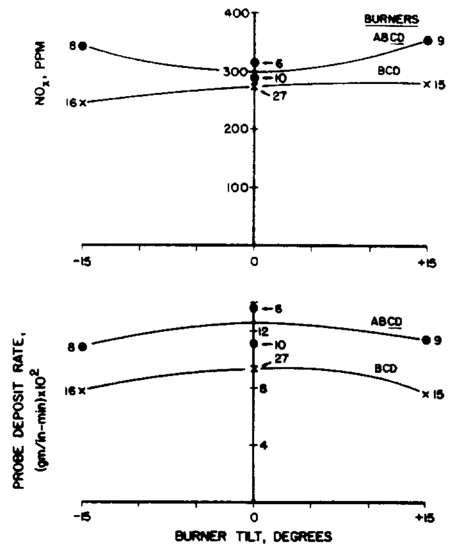


Fig. 5—Effect of burner tilt on NO_x and probe deposit rate, 48 MW with overfire (numbers refer to test runs in Tables II and III).

ash deposit rate on a 12-inch length near the tip of the ash fouling test probe. This 12-inch length is located at the thermocouple to assure that the desired 1000 F temperature of the probe wall is maintained. Since many of the previous tests at Hoot Lake and other power plants were made using a 72-in. length, the deposit rate for both, 12 and 72 inches, is included in *Table III*. Statistical correlation of the data indicates that the per inch deposit rate on the 72-inch length is about 0.52 times the deposit rate on the 12-inch length.

The NO_x level in the flue gas is reported in *Table III* in dry ppm as measured with a Thermo Electron chemiluminescence NO_x analyzer. The analyzer was used to monitor two separate sample lines to the GFERC instrument trailer. Wet tests were also made regularly by the approved EPA method to verify the results.

Excess Air Results

In previous tests at Grand Forks using a 75-lb/h ash fouling test furnace, an increase in ash deposit rate was noticed in some tests at low excess air. Testing to measure this potential was needed to evaluate the consequences of reducing NO_x emissions by decreasing the excess air. Because of this need, the excess air effects were tested in the initial three test runs of the test program. The excess air was again reduced on the last day of testing to confirm the previous tests.

The effects of excess air on the probe deposit rate and NO_x emissions are presented in Fig. 4. The results indicate that the NO_x emissions are only reduced by 7 to 10 percent by reducing the flue gas oxygen level from 4.6 percent to 3.0 percent. On the other hand, the probe deposit rate is increased by as much as 28 percent in Tests No. 1 through 3, which were run on four burners. Tests run on three burners over a similar change in excess air (Runs 17 and 28) did not confirm this trend, owing to coincidental changes in ash and sodium levels, but the visual observations of the boiler did indicate increased slagging and fouling at the low excess air conditions for Test Run 28. Visual observations indicated severe slag flow on the furnace walls during Test 3 when the test was terminated. This condition persisted for about one day after the test run.

These results indicate that little reduction in NO_x emissions is obtained by reducing the O_2 level, but much potential for increased ash fouling may exist. The formation of significant quantities of running slag in a dry bottom boiler can cause severe bottom ash handling problems, as well as affect boiler operation.

Burner Tilt

The Hoot Lake Unit 2 is equipped with an automatic tilt control on the burners to move the combustion zone within the boiler to maintain a desired steam temperature. Since the burner tilt and resultant relocation of the combustion zone might influence the ash fouling and NO_x emission levels, a series of test runs was run at 0, +15, and −15 degrees tilt by manually setting the tilt. The results from two series of these tests are presented in Fig. 5. These test runs were all made with the primary and secondary air dampers set for minimum NO_x generation.

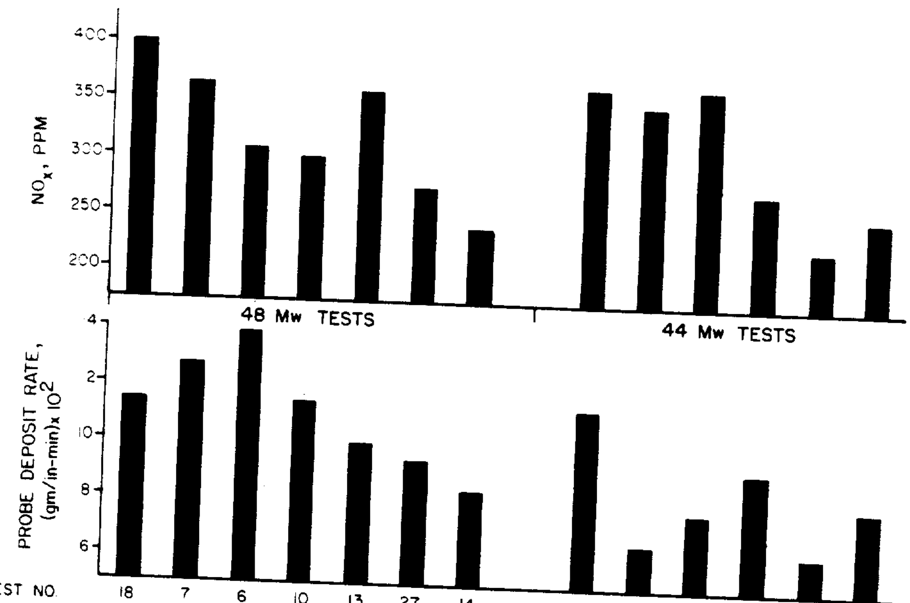
The results indicate that the probe deposit rate may decrease 14 to 18 percent for a +15 degree or −15 degree tilt compared with no tilt. The NO_x emission results are less conclusive: (1) an increase of 16 percent for ± 15 degree tilt for the four-burner tests (AB$\overline{\text{CD}}$); (2) an increase of 1 percent for $\overline{+15}$ degree, and a decrease of 11 percent for −15 degree tilt for the three burner tests (BCD). These results indicate that the burner tilt does have some effect on both ash fouling and NO_x emissions. However, the offset in ash fouling and NO_x emission levels for the two different burner combinations (AB$\overline{\text{CD}}$ versus BCD) remained in the same order, regardless of tilt. Since tilt could possibly influence the test results, most test runs for overfire air were run at 0 degree tilt. A negative tilt would tend to intensify an overfire air effect, while a positive tilt could nullify it.

Overfire Conditions and Selective Burner Operation

One of the most effective methods of reducing NO_x emissions is the use of overfire air with a fuel-rich mixture at the burners.[4-6] Since the Hoot Lake Unit 2 does not include provisions for overfire air, these conditions were developed by selective operation of the lower burners with manual setting of the primary and secondary air dampers.

In order to study the effects of overfire air or reduced excess air on fouling rate, a series of burner/mill/damper combinations was studied to represent a logical sequence from minimal to optimum NO_x reduction. The combination at which the plant normally operates was chosen as a baseline test condition.

Tables II and *III* present the overfire air combinations studied. Optimum overfire conditions were attained by operating the three bottom burners (Fig. 2, B,C,D) with their upper three upper dampers 100 percent open and the remaining dampers 50 percent open. This combination results in a fuel-rich mixture



TEST NO.	18	7	6	10	13	27	14	4	12	20	19	11	5
Mw	48.0	48.0	47.5	48.0	48.5	48.0	47.5	44.3	44.0	44.3	44.8	44.0	45.0
BURNERS	TOP 3	4 1/	4 1/	4 1/	BOT 3	BOT 3	BOT 3	TOP 3	BOT 3	BOT 3	BOT 3	BOT 3	BOT 3
DAMPERS	N-3	N-1	OF	OF	N-2	OF	OF	N-1	N-2	N-3	OF	OF	OF
TILT	+15°	0	0	0	0	0	0	-15°	0	0	0	0	+10°
O_2	4.5	4.3	4.4	4.1	4.4	4.4	4.4	4.6	4.2	4.6	4.5	4.5	4.7
A F ASH	8.9	10.5	9.6	8.5	8.4	7.9	8.2	9.7	8.3	8.1	9.0	9.0	9.8
Na_2O, % OF COAL ASH	4.5	4.6	4.8	4.8	4.9	4.1	4.5	4.9	4.8	5.3	4.7	4.3	4.9

1/ BOTTOM 2 MILLS AT MAXIMUM CAPACITY. TOP 2 MILLS AT REDUCED CAPACITY.

KEY

DAMPER SETTING, % OPEN

DAMPER	N-1	N-2	N-3	OF
AA	40	0	SAME	100
A	100	0	AS N-1	100
AB	40	40	BUT	100
B	100	100	DAMPER	50
BC	40	40	CLOSED	50
C	100	100	AT	50
CD	40	40	UNUSED	50
D	100	100	BURNER	50
DD	40	40		50

(DESIGNATION: N-1, N-2, N-3, OF)

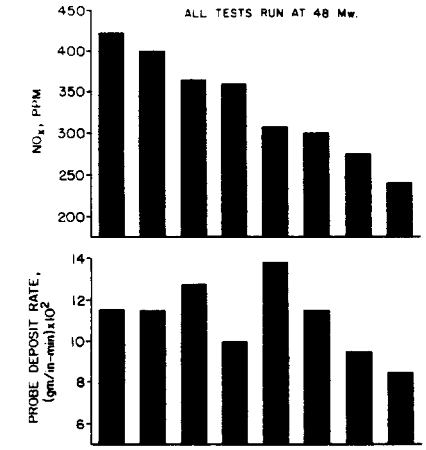
Fig. 6—Effects of burner selection and overfire condition on probe deposit rate and NO_x emissions.

at each burner and a higher flow of air over each.

The results of the best combinations of burners for three-burner and four-burner operation with and without overfire air are presented in Fig. 6. For uniformity in comparison of results, the selected test runs are mostly at 0 degree burner tilt and are separated into two groups at 44- and 48-MW plant load. The test results as presented in Fig. 6 tend to indicate two trends: (1) The NO_x emission levels are consistently lower for the test runs with overfire air than for the runs without overfire air; and (2) the probe deposit rate is less for operation with the three bottom burners, compared with the operation with four burners. From these test runs, the probe deposit rate does not appear to be a function of the air distribution but is more a function of burner position at constant load.

Further comparison of the probe deposit rate and NO_x emissions for various burner selections and overfire conditions are presented in Fig. 7. As conditions are improved by using a fuel-rich mixture at the lower burners and overfire air, the NO_x emissions are decreased consistently from a high at 422 ppm with four mills and normal air distribution to a low of 240 ppm with three lower burners and overfire air. This is a 43 percent reduction in NO_x emissions.

Comparisons of the probe deposit rates in Fig. 7 again indicate that the deposit rate is more a function of the burner position than of the overfire condition (as was the case in Fig. 6). The probe deposit rates with four burners (ABCD) with and without overfire air are similar, and the rates with the three bottom burners (BCD) with and without overfire are similar, but the rates for four burners are about 37 percent higher than for the three-burner condition.



TEST NO.	1	18	7	13	6	10	27	14
BURNERS	4	TOP 3	4[1]	BOT 3	4[1]	4[1]	BOT 3	BOT 3
DAMPERS[2]	N-1	N-3	N-1	N-2	OF	OF	OF	OF
TILT	+12°	+15°	0	0	0	0	0	0
O_2	4.6	4.5	4.3	4.4	4.4	4.1	4.4	4.4
A F ASH	9.6	8.9	10.5	8.4	9.6	8.5	7.9	8.2
Na_2O, % OF COAL ASH	5.1	4.5	4.6	4.9	4.8	4.8	4.1	4.5

[1] BOTTOM 2 MILLS AT MAXIMUM CAPACITY, TOP 2 MILLS AT REDUCED CAPACITY.

[2] FOR DAMPER DESIGNATIONS, SEE KEY IN FIGURE 6.

Fig. 7—Effects of burner selection and overfire conditions on probe deposit rate and NO_x emissions at high load.

NO_x Optimization Runs

Tests 22 through 26 (shown in *Tables II* and *III*) were run to further optimize NO_x emissions. Since the best results up to this time had been obtained by using the bottom three burners with the dampers positioned for overfire air, including air to the top burner (as in Runs 11 and 14), the tests to reduce the NO_x level further centered on additional dampening of the lower vents to increase the fuel-rich burner and overfire air conditions. This further dampening resulted in only marginal reduction in the NO_x levels from 255 ppm to 237 ppm for a change in the damper position from 50 percent to 10 percent open for the bottom two burners (Tests 22 and 25).

NO_x Levels and Fuel Nitrogen

an additional consideration, the highest NO_x emission level obtained during this test program was 422 ppm, which corresponds to 0.5 lb/10^6 Btu. This emission level is below the current limit of 0.6 lb/10^6 Btu for pulverized-coal firing.

The fuel-bound nitrogen was measured at 0.56 percent in the lignite as received. The corresponding emission if all fuel nitrogen were converted to NO_x is 1090 ppm. Actual emissions were 21 to 39 percent of this potential fuel-related value.

SO_x Levels

The SO_x levels for each test run have also been measured and included in *Table III*. The sulfur content in the lignite was 0.93 ± 0.07 percent for the total test program (see *Table IV*) which converts to about 1200 ppm for 100 percent emission as SO_2. Comparison for the measured SO_x emissions (*Table III*) indicates that 75 to 90 percent of the coal sulfur is emitted as SO_x.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

1. The reduction in overall excess air to the boiler reduced the NO_x level by a small amount but increased the potential for ash fouling significantly. Aside from the probe tests, severe running slag on furnace walls and tube fouling were observed in the boiler during tests at low excess air. Potential problems with increased slag formation make this technique undesirable, especially for dry bottom boilers.
2. The NO_x level was reduced without modification of the boiler by using the lower three burners and was reduced further by changing the damper positions from the normal to an overfire air condition. A total reduction of about 36 percent from 400 ppm to 255 ppm was achieved.
3. The burner selection appears to influence the ash fouling potential as measured by the probe deposit rate. The desposit rate is lowest for operation with the three bottom burners.
4. The change in damper positions from normal to overfire air conditions does not appear to increase the ash fouling potential as measured by the probe deposit rate.
5. Changes in the burner tilt angle can modify the NO_x level and ash fouling potential but do not change the relative advantages of burner selection and damper position.
6. The test results on probe deposit rates do not correlate well with the flue gas temperatures obtained by HVT, based on the strong relationship between fouling rate and temperature observed in previous test programs.[2] Since the probe weights are corroborated by observations made on the boiler, some of the temperature measurements may be in error.

Recommendations

Since the conclusions are based on one test program at one older tangentially-fired boiler, the recommendation is made to follow up with additional tests at other tangentially-fired power plants using similar marginally high-fouling lignite as a test fuel. Of particular interest would be low excess air and overfire air testing of a cyclone boiler. If modifications to the existing Hoot Lake unit are made to inject some secondary air as overfire air, then further testing to evaluate these modifications is also recommended. Other possible tests could include new improved burner concepts.

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