United States
Environmental Protection
Agency

Industrial Environmental Research
Laboratory
Research Triangle Park NC 27711

Research and Development

EPA-600/S7-81-111 Dec. 1981

EPA

Project Summary

Emissions and Efficiency Performance of Industrial Coal-Stoker-Fired Boilers

P. L. Langsjoen, J. O. Burlingame, and J. E. Gabrielson

The report gives results of field measurements of 18 coal stoker-fired boilers including spreader stokers, mass-fired overfeed stokers, and mass-fired underfeed stokers. The test variables included stoker design, heat release rate, excess air, coal analysis and sizing, overfire air, and flyash reinjection. Measurements included O_2, CO_2, CO, NO, NO_2, SO_2, SO_3, gaseous hydrocarbons, uncontrolled and controlled particulate mass loading, particle size distribution of the flyash, combustible content of ash, sulfur retention in the ash, and boiler efficiency. Particulate loading is shown to be largely dependent on stoker type and degree of flyash reinjection. It increases with heat release rate, but can be controlled with proper use of overfire air in many cases. NO_x increases with excess air and grate heat release rate. These relationships are defined in the report. Overfire air, as it exists in current boiler designs, does not affect NO_x. The report also addresses other relationships between operating variables and measured emissions and efficiency. A separate data supplement is available.

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

In late 1977, the American Boiler Manufacturers Association (ABMA) was awarded a contract to update specifications and design parameters for coal-burning boiler and stoker equipment. The project was jointly funded by the U.S. Department of Energy and the U.S. Environmental Protection Agency (EPA), with the purpose of increasing coal usage in an environmentally acceptable manner.

The Need

The need for such a program is clear. In recent years the vast majority of industrial boiler installations have been packaged or shop-assembled gas- and oil-fired units. These boilers could be purchased and installed at substantially lower costs than conventional coal-burning boiler-stoker equipment. Because of the declining demand for coal stokers, little or no work has been done in recent years to improve specification data or product information made available to consulting engineers and purchasers of coal burning boiler-stoker equipment.

Furthermore, the market for coal suitable to be fired in industrial boilers is being held back by critical uncertainties in the environmental and energy areas, causing potential customers of coal-fired industrial boilers to shelve plans for capital expansion and conversion.

The current implementation of more rigid air pollution regulations has made it difficult for many coal burning installations to comply with required stack emission limits.

It is highly desirable to remove these uncertainties and thereby encourage industrial users to order and install coal-stoker-fired boilers. This would lead to significantly increased coal usage and decreased dependence on scarce and imported fuels.

The Objectives

Objectives of this program are:

1. To advance stoker boiler technology through comprehensive testing of various stoker boiler designs, thereby facilitating the design and fabrication of stoker boilers which are economically and environmentally satisfactory alternatives to gas- and oil-fired units.
2. To contribute to the design and application of pollution control equipment by generating a large data base of boiler outlet dust loading data and particle size distribution data
3. To provide guidelines for boiler operators concerning techniques for clean and efficient stoker boiler operation.
4. To facilitate preparation of intelligent and reasonable national emission standards for coal-stoker-fired boilers by the EPA.
5. To provide assistance in planning for coal supply contracts both through an increased knowledge of the effects of coal properties on emissions, and through the development of reasonable emission regulations.
6. To promote the increased utilization of coal-fired-stoker boilers by U.S. industry by ensuring compatibility of emissions from these units with applicable environmental requirements.

The Project Organization

The ABMA formed a Stoker Technical Committee (STC) composed of personnel from member companies to oversee the project. The STC, in turn, subcontracted the field testing and report work to KVB, Inc., a combustion consulting firm in Minneapolis, MN. The original scope of work included the testing of six spreader stokers. Testing on the first unit began August 9, 1977.

As the project progressed successfully, additional funding was obtained and the scope of work was increased to include five mass-fired overfeed stokers. These units were also tested by KVB, Inc.

A separate subcontract was let to Pennsylvania State University to test seven small stoker boilers including two overfeed stokers and five underfeed stokers located in central steam heating plants. The purpose of this subcontract was to determine particulate mass emission rates and particle size distribution for small stokers. On November 12, 1979, all testing was completed. In total, 400 tests on 18 coal-stoker-fired boilers were conducted.

Related Reports and Data

A Project Summary cannot discuss all the ramifications of the project and the data collected. The reader is directed to the final report (which this summarizes), the various site reports, and "A Guide to Clean and Efficient Operation of Coal-Stoker-Fired Boilers," EPA-600/8-81-016, May 1981, for additional information.

Summary and Conclusions

This report is the culmination of an extensive testing effort on 18 coal-stoker-fired boilers. The effort includes 400 tests on 36 boiler/coal combinations over a 2-year period. The boilers, identified by letter designators, fall into three major stoker classifications: spreader stokers (Sites A, B, C, E, F, G), mass-fired overfeed stokers (Sites D, H, I, J, K, L2, L4), and underfeed stokers (Sites L1, L3, L5, L6, L7). Each classification is presented separately in this report. The units are described in Table 1 along with the number of coals fired and tests conducted.

The major objective of this test program was to update stoker specification data by measuring boiler emissions and efficiency on a variety of boiler-stoker designs and under a variety of operating conditions. The operating variables included heat release rate, excess air, overfire air, flyash reinjection, and coal properties. The measurements included both uncontrolled and controlled particulate loading, nitrogen oxides (NO_x—NO, NO_2), sulfur oxides (SO_x—SO_2, SO_3), oxygen (O_2), carbon dioxide (CO_2), carbon monoxide (CO), unburned hydrocarbon (UHC), combustibles in the flyash and bottom ash, particle size distribution, and boiler efficiency. The tests were conducted under steady load conditions.

In stoker firing of coal, there are so many variables that even with the extensive amount of testing conducted during this program it was not possible to analyze them all. The interactions between these variables are difficult to assess.

Not all of the parameters were determined on each site nor under the full range of operating variables. For example, the CO analyzer was out-of-service during testing at Sites G, I, and J. The UHC analyzer was only operable during testing at four sites, and boiler nameplate rating was not achieved on three of the units due to retrofit equipment on two units and start-up problems on a third. In addition, the testing at Sites L1 through L7 was conducted under a separate contract and included a more limited number of test measurements under a single operating condition on each unit.

This report is organized in two separate formats so as to be a convenient reference to the widest possible audience. The first section is organized by the measured parameter first and the operating variable second. Thus, for example, all observations on particulate loading are grouped together.

The second format follows the format of the final report text. It is organized by operating variable so that, for example, the effects of overfire air on all emissions are grouped together.

The range of data encountered at full load is summarized in Table 2.

Summary of Findings Organized by Measured Parameter

Particulate Loading

Type of Stoker—Spreader stokers with flyash reinjection from their mechanical dust collectors had by far the highest uncontrolled particulate loadings, 13-36 lb/10^6 Btu. Spreader stokers without reinjection from their dust collectors were next with emis-

Table 1. Unit Description and Data Base

Site	*Stoker Type*	*Design Capacity lb/hr*	*Number Coals Tested*	*Number Test Conditions*
A	*Spreader*	*300,000*	*3*	*68*
B	*Spreader*	*200,000*	*4*	*42*
C	*Spreader*	*182,500*	*3*	*76*
D	*Vibrating Grate*	*90,000*	*3*	*31*
E	*Spreader*	*180,000*	*3*	*25*
F	*Spreader*	*80,000*	*2*	*38*
G	*Spreader*	*75,000*	*3*	*35*
H	*Traveling Grate*	*45,000*	*1*	*24*
I	*Traveling Grate*	*70,000*	*2*	*23*
J	*Chain Grate*	*70,000*	*2*	*13*
K	*Traveling Grate*	*50,000*	*3*	*18*
L1	*Multiple Retort*	*26,000 **	*1*	*1*
L2	*Vibrating Grate*	*30,000*	*1*	*1*
L3	*Single Retort*	*23,300*	*1*	*1*
L4	*Traveling Grate*	*27,000*	*1*	*1*
L5	*Multiple Retort*	*28,460*	*1*	*1*
L6	*Multiple Retort*	*20,000*	*1*	*1*
L7	*Multiple Retort*	*50,000*	*1*	*1*

**The site L1-L7 report expresses steaming capacity in terms of peak, or maximum, rating. This report expresses the Site L1-L7 steaming capacity in terms of maximum continuous ratings so as to be consistent throughout.*

sions of 2.1-8.8 lb/10^6 Btu. As shown in Figure 1, without flyash reinjection from the mechanical collector, the uncontrolled particulate data were 2.1-8.8 lb/10^6 Btu. Test Site C was operated both with and without flyash reinjection from the mechanical collector and had very different particulate loadings under the two conditions. As a result of operating without reinjection, uncontrolled particulate loading was reduced by 70-80 percent and controlled particulate loading by 40-50 percent. This shows that a portion of the reinjected flyash is reentrained in the gas stream and results in increased particulate loadings. Three boilers had some degree of flyash reinjection from the boiler hopper, and at Site F from the economizer hopper. The amount of flyash reinjected depends on duct geometry and whether or not the boiler is equipped with baffles. In most cases, the actual rate of reinjection was not known. These are followed by mass-fired overfeed stokers with 0.57-2.2 lb/10^6 Btu and underfeed stokers with 25-0.71 lb/10^6 Btu. Figure 2 shows uncontrolled particulate loadings of 0.57-2.2 lb/10^6 Btu on the five extensively tested mass-fired overfeed stokers. Averages for these same five stokers were 0.78-1.4 lb/10^6 Btu. Sites L2 and L4 had lower particulate loadings of 0.56 and 0.50 lb/10^6 Btu, respectively, but these were obtained at lower loads of 85 and 78 percent of design capacity, respectively. The Site L2 and L4 particulate data is not out of line when compared with data obtained at the same grate heat release from the other stokers.

Heat Release Rate—It cannot be said that units with higher design heat release rates have higher particulate loadings, but for a given unit the uncontrolled particulate loading always increased as heat release rate, or load, increased. The rate of increase varied form site to site, and at some sites it appeared to accelerate as full load was approached. On spreader stokers with flyash reinjection from mechanical dust collectors, the last 10 percent increase in heat release rate resulted in a 9-20 percent increase in particulate loading. On spreaders without dust collector reinjection, the increase was 8-12 percent. On mass-fired overfeed stokers, particulate loading increased 3-20 percent as heat release rate was increased from 90 to 100 percent of design.

Excess Air—No relationship was established between particulate loading and excess air. This does not foreclose the existence of such a relationship, but rather indicates that such a relationship could not be deciphered from the data due to data scatter and uncontrolled variables.

Overfire Air—Uncontrolled particulate loading was reduced by 20-50 percent on four of six spreader stokers and three of five mass-fired overfeed stokers when overfire air pressures were increased. Two sites showed the opposite trend and two sites were unaffected by changes in overfire air pressure.

Coal Ash—Coal ash could be related to particulate loading at only four of the ten test sites at which multiple coals were fired. On three of the spreader stokers, particulate loading increased by 0.24-0.38 lb/10^6 Btu for each 1 percent increase in coal ash. Stated another way, if the coal ash is doubled at these sites, the particulate loading will increase by 15-30 percent. Thus, the relationship between coal ash and particulate loading was not 1:1 on these three units.

On one of the traveling grate stokers, a 4-percent ash-washed coal and a 10-percent ash unwashed coal from the same mine were tested. The 250 percent increase in coal ash resulted in a 300 percent increase in particulate loading. In this case, the dramatic increase in particulate loading can be attributed to the type of ash, a clay like material in the surface of the coal, and to a corresponding increase in coal fines on the unwashed coal.

Coal Fines—Because of the movement of air through the grate and the upward movement of combustion gases through the furnace, the smallest coal and ash particles are carried out of the furnace by the gases rather than staying on the grate. This is called particle entrainment and is a problem from both a pollution and an efficiency standpoint. The likelihood of a particle being entrained is a function of its size and density, and the velocities in the furnace. The test data from this program showed a mathematical correlation between coal fines and particulate load-

Table 2. *Range of Data Encountered at High Load**

	*Spreader Stokers With Reinjection from D.C.***	*Spreader Stokers W/O Reinjection from D.C.*	*Mass-Fired Overfeed Stokers*	*Mass-Fired Underfeed Stokers*
Uncontrolled Particulate, lb/10^6 Btu	12.7 - 36.4	2.1 - 8.8	0.57 - 2.2	0.25 - 0.71
Controlled Particulate, lb/10^6 Btu	0.60 - 3.5	0.17 - 3.8	0.11 - 0.75	0.46 - 0.58
Mechanical Collector Efficiency, %	94.9 - 98.0	40.6 - 96.0	10.9 - 92.7	26.6 - 42.9
Excess Air, %	18 - 113	19 - 82	26 - 97	33 - 186
Nitric Oxide, lb/10^6 Btu as NO_2	0.30 - 0.60	0.36 - 0.61	0.21 - 0.50	No Data
Carbon Monoxide, ppm dry @ 3% O_2	22 - 1600	33 - 702	39 - 2300	<1000
Unburned Hydrocarbons, ppm wet @ 3% O_2	No Data	0 - 41	5 - 112	No Data
Combustibles in Flyash, %	7.1 - 65.6	26.6 - 83.5	21.8 - 56.0	20.2 - 20.5
Combustibles in Bottom Ash, %	0.0 - 34.4	0.3 - 27.2	7.1 - 69.1	8.1 - 25.0
Flyash Combustibles Heat Loss, %	0.54 - 5.5	0.51 - 9.2	0.16 - 1.1	0.07 - 0.21
Bottom Ash Combustibles Heat Loss, %	0.00 - 3.0	0.04 - 3.4	0.42 - 9.4	1.2 - 3.9
Boiler Efficiency, %	75.79 - 83.43	73.00 - 83.07	69.75 - 84.10	64.13 - 76.81

* *Underfeed stokers were tested at loads 55 to 100% of capacity. Data from the other stokers were obtained within the upper 10% of the obtainable load range.*

** *Does not include tests in which reinjection from the dust collector was reduced. For example, a NO level of 0.68 lb/10^6 Btu as NO_2 measured during one reduced reinjection test is not included in this table. A particulate loading of 9.6 lb/10^6 Btu is excluded for the same reason.*

ing on five stokers. Particulate loading increased by 0.10-0.55 lb/10^6 Btu whenever the percent of coal passing a 16 mesh screen increased by 1 percent. No correlation was found in studies of six other stokers.

Flyash Reinjection—Flyash from the dust collector was reinjected to the furnace of three of the six spreader stokers. In each case, uncontrolled particulate loading was increased as a result of reentrainment of a portion of the reinjected ash. At one site, reinjection was completely eliminated for test purposes. As a result, uncontrolled particulate loading was reduced by 70-80 percent and controlled particulate loading was reduced by 40-50 percent. Reducing the degree of flyash reinjection reduced the percentage of larger particles in the flyash. This in turn reduced the mechanical dust collector efficiency.

Emission Factors—EPA report AP-42, Compilation of Air Pollutant Emission Factors, Third Edition, contains factors used for predicting emissions from stoker boilers. The data from this program compares as follows:

	Uncontrolled Particulates lb/ton (A = % Ash in Coal)	
	AP-42	This Program
Spreaders with Reinjection	20A	29A-50A
Spreaders without Reinjection	13A	14A-17A
Overfeed Stokers	5A	1.1A-3 8A
Underfeed Stokers	5A	0.6A-1.7A

Particle Size Distribution—Particle size distribution of the flyash was determined by a variety of methods including cascade impactor, Bahco classifier, SASS cyclones, and sieve analysis. Results varied from one method of measurement to another, but clearly showed that spreader stokers emit a higher percentage of coarse, more easily collected particles than mass-fired overfeed and underfeed stokers.

Nitric Oxides (NO_x)

Type of Stoker—**As a class, spreader stokers emitted higher concentrations of** NO than did mass-fired overfeed stokers. Under full load, spreader stokers emitted 0.30-0.61 lb/10^6 Btu NO corrected to NO_2. Figure 3 shows NO data, measured at the boiler outlet using a chemiluminescent analyzer, of 0.30-0.68 lb/10^6 Btu, calculated as NO_2 when measured at full load. NO levels were found to be a function of excess air, heat release rate, and combustion temperature. Where NO_x is measured,

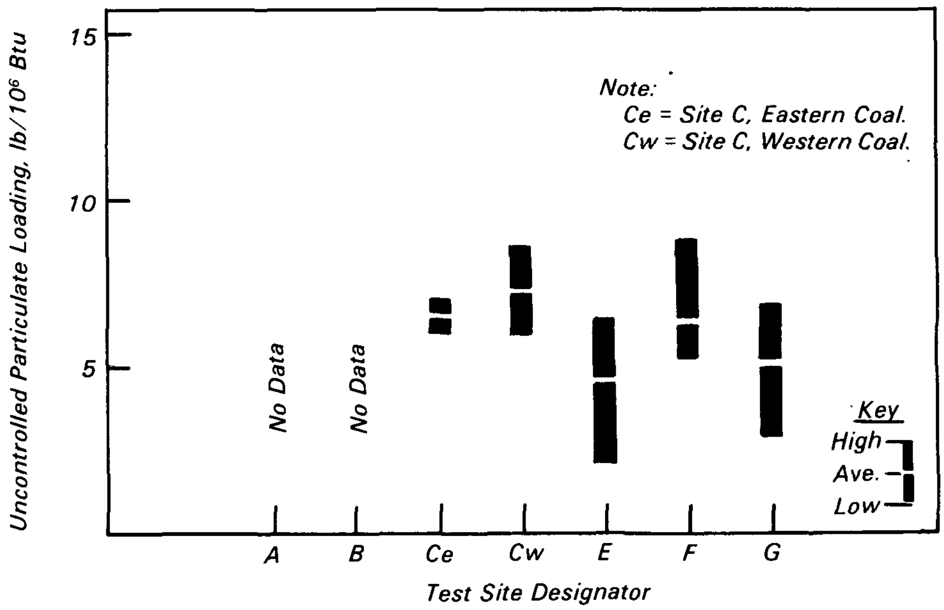

Figure 1. *Uncontrolled particulate loadings of four spreader stokers fired at full load without flyash reinjection from the mechanical collector.*

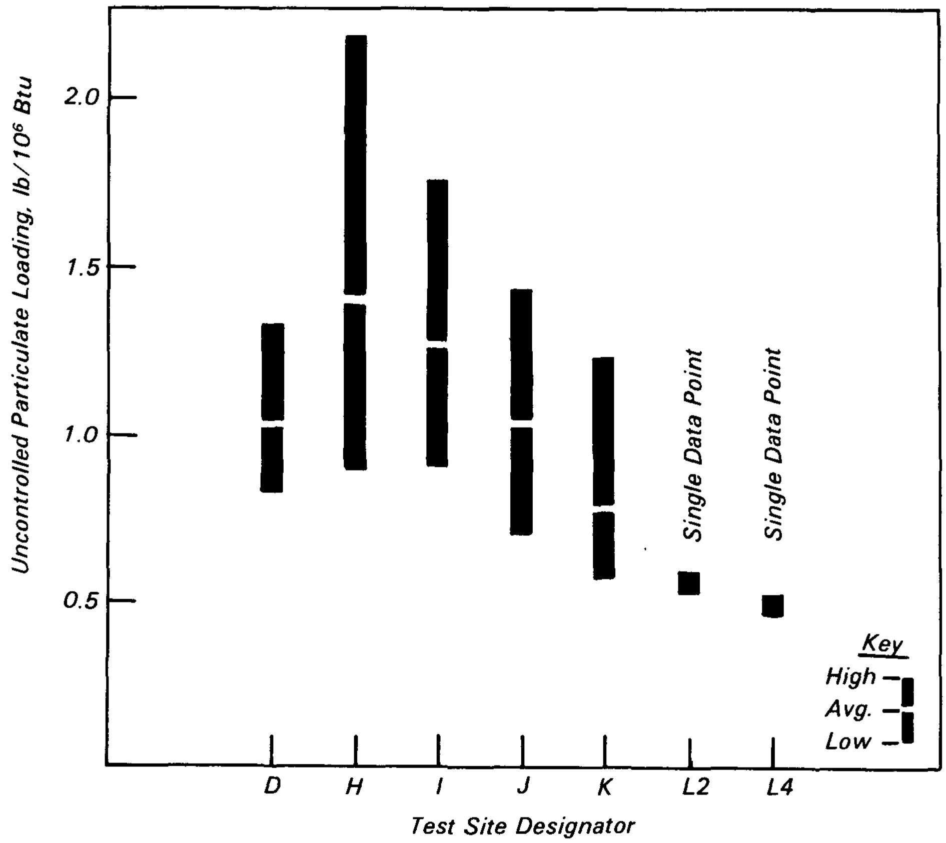

Figure 2. *Uncontrolled particulate loadings of seven mass-fired overfeed stokers fired at or near full load.*

NO_2 did not exceed 4 percent of the total NO_x and was most often negligible. Mass-fired overfeed stokers emitted 0.21-0.50 lb/10^6 Btu NO. However, overfeed stokers operated at higher excess air levels than did the spreader stokers. When compared at the same excess air levels, the difference in NO levels is even greater. As shown in Figure 4, NO emissions were 0.21-0.50 lb/10^6 Btu computed as NO_2. Site averages were 0.27-0.41 lb/10^6 Btu. Some of the variations between sites are the result of different excess air operating levels. For example, Site H was operated at an average excess air of 70 percent compared to 51 percent for Site I. As a result, Site H NO emissions were higher.

Heat Release Rate—For spreader stokers, an increase in heat release rate equivalent to 10 percent of capacity resulted in an average increase in NO emissions of 0.025 lb/10^6 Btu as NO_2 at constant excess air. For mass-fired overfeed stokers, the relationship was 0-0.026 lb/10^6 Btu per 10 percent increase in capacity at constant excess air. In all cases, NO emissions were invarient with load at normal firing conditions because the effects of decreasing excess air effectively canceled the effects of increasing load. Although NO increased with heat release rate on each given unit, it was not true that units with higher design heat release rates emitted higher concentrations of NO.

Excess Air—On four spreader stokers without air preheat and one with air preheat, NO increased by 0.021-0.036 lb/10^6 Btu for each increase of 10 percent excess air. The sixth spreader stoker used air preheat and its NO increased by 0.067 lb/10^6 Btu per increase of 10 percent excess air. On five-mass fired overfeed stokers, NO increased by 0.016-0.027 lb/10^6 Btu.

Overfire Air—NO emissions were not influenced by changes in overfire air pressure when considered at constant excess air.

Fuel Nitrogen—Variations in fuel nitrogen of 0.75-1.50 percent by weight had no measurable effect on NO emissions. This may simply reflect difficulties in sorting out the other variables.

Flyash Reinjection—Flyash reinjection from the mechanical dust collector had no measurable effect on NO emissions.

Emission Factors—EPA report AP-42, Compilation of Air Pollutant Emission

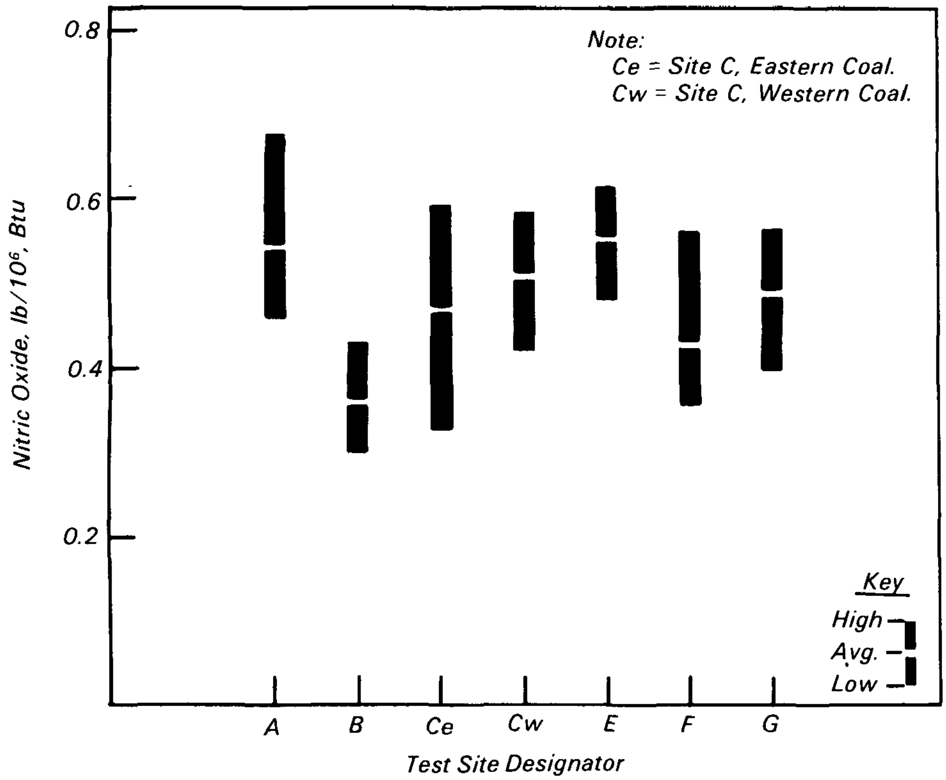

Figure 3. *Nitric oxide emissions of six spreader stokers fired at full load.*

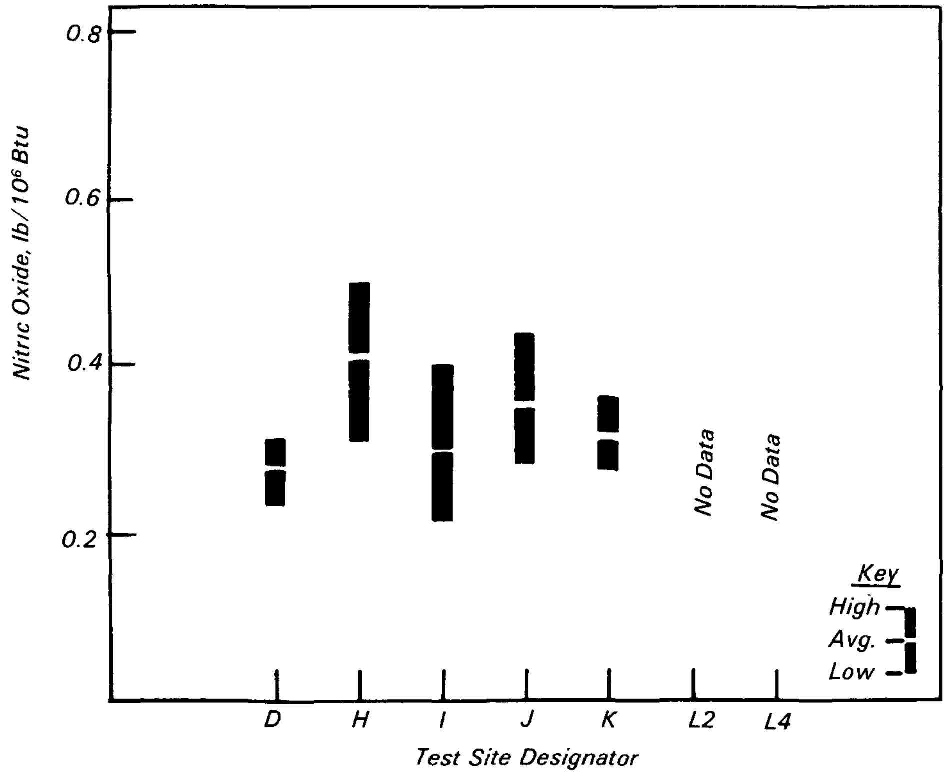

Figure 4. *Nitric oxide emissions of five mass-fired overfeed stokers fired at or near full load.*

Factors, Third Edition, contains factors used for predicting emissions from stoker boilers. The data from this program compares as follows:

	Nitrogen Oxides, lb/ton	
	AP-42	This Program
Spreader Stokers	15	9.4-14.2
Overfeed Stokers	None	7.1- 9.4

Sulfur Oxides (SO_x)

Type of Stoker—The spreader stokers retained an average 4.4 percent of the fuel sulfur in the ash, while the mass-fired overfeed stokers retained an average 2.1 percent. The remainder was emitted as SO_2 and SO_3, with SO_3 comprising less than 2 percent of the total. Operating parameters such as excess air, overfire air, and load had no effect on the emissions of SO_x or the retention of sulfur in the ash.

Fuel Sulfur—Although good sulfur balances were difficult to obtain, the data indicates that fuel sulfur conversion efficiencies of 95-98 percent are reasonable assumptions.

Carbon Monoxide (CO)

Type of Stoker—Spreader stokers emitted lower concentrations of CO than traveling grate stokers while firing Eastern bituminous coals. Emissions from three of the spreader stokers were 50-250 ppm at full load. A fourth was 200-600 ppm. By comparison, two traveling grate stokers emitted 50-700 ppm CO at full load, and a vibrating grate stoker emitted 50-2000+ ppm CO. The comparison is limited to these seven stokers. CO emissions were not measured on three other stokers due to instrument failure, and a fourth fired only Western coals. At Test Sites L1 through L7, the CO concentration was measured with an Orsat analyzer with a minimum detection limit of 0.1 percent or 1000 ppm. Significantly, the CO emissions were below this detection limit on the Site L stokers.

Heat Release Rate—CO emissions were highest at high heat release rates under low excess air conditions, and at low heat release rates under high excess air conditions. At full load, CO emissions could be controlled with proper application of combustion air.

Excess Air—CO was more prevalent as excess air dropped below about 30-40 percent on spreader stokers and about 60 percent on mass-fired overfeed stokers. CO increased gradually as excess air increased about 60 percent on spreader stokers and 100 percent on mass-fired stokers.

Overfire Air—CO emissions were reduced by the increased use of overfire air.

Coal Rank—CO emissions were greatest while firing Western sub-bituminous coals. On one spreader stoker where both an Eastern and a Western coal were fired, the full-load Western coal emissions were 163-702 ppm and averaged 342 ppm. By comparison, the full-load Eastern coal emissions were 33-263 ppm and averaged 71 ppm.

Flyash Reinjection—Flyash reinjection from the mechanical dust collector had no measurable effect on CO emissions.

Unburned Hydrocarbon (UHC)

Type of Stoker—Based on limited data, the spreader stokers emitted lower UHC emissions than the mass-fired overfeed stokers. Full-load emissions from the spreader stokers were 0-15 ppm for Site F and 35-41 ppm for Site G. By comparison, the mass-fired overfeed stokers emitted 5-112 ppm for Site H and 80 ppm for a single point on Site J.

Heat Release Rate—UHCs tended to decrease as heat release rate increased on three of four stokers where they were measured. On the fourth stoker, the opposite trend was observed.

Excess Air—UHC emissions showed little or no correlation with excess air on spreader stokers. On mass-fired overfeed stokers, UHCs increased in almost direct proportion to the excess air.

Overfire Air—UHCs were reduced 82 percent by increasing the overfire air pressure on one traveling grate stoker. No correlation was found on one spreader stoker. The other two units where UHC emissions were measured had insufficient data to make a correlation.

Coal Properties—The site firing the lower volatile coal had the lowest UHC emissions. The 29 percent volatile coal yielded 19-41 ppm UHCs, while the 41 percent volatile coal yielded 163-702 ppm UHCs. Volatiles are expressed here on a dry mineral-matter-free basis.

Carbon Monoxide—UHCs increased with increasing CO emissions on one traveling grate stoker. No correlation was found on one spreader stoker.

Excess Air

Type of Stoker—At full load, most spreader stokers were capable of operating at 30 percent excess air (5 percent O_2). By comparison, the mass-fired overfeed stokers generally required 50 percent excess air (7 percent O_2).

Size of Stoker—With one exception, the excess air operating level was inversely proportional to the size of the stoker. The larger the stoker, the lower the excess air requirement.

Heat Release Rate—The excess air requirement drops as heat release rate increases on stoker boilers. The excess air requirement levels off as 30 percent excess air is approached.

Coal Properties—Coal properties were not found to alter excess air requirements on these stoker boilers.

Combustibles in Bottom Ash

Type of Stoker—Combustible levels were lower in the bottom ash of spreader stokers than they were for mass-fired overfeed stokers or underfeed stokers. The average for each of six spreader stokers fired at full load was 0 to 14 percent. By comparison, mass-fired overfeed stokers were 16-26 percent, with one unit averaging 43 percent, and underfeed stokers were 19-25 percent, with one unit averaging 8 percent.

Heat Release Rate—Heat release rate had very little effect on combustibles in the bottom ash.

Excess Air—No correlation was found between excess air and combustibles in the bottom ash.

Coal Properties—Small differences in bottom ash combustible levels were observed which appeared to be related to coal properties at some sites. However, the particular coal properties causing these differences were not identified.

Ash Balance—It was found that 65-85 percent of the coal ash remained on the grate in spreader stokers, compared to 80-90 percent for mass-fired overfeed stokers. To compute combustible heat losses, 75 and 85 percent are good estimates for spreaders and mass-fired overfeed stokers, respectively.

Combustibles in the Flyash

Type of Stoker—Combustible levels in the flyash were higher in the spreader stokers than in either the mass-fired overfeed stokers or the underfeed stokers. Except at Test Site C, the spreader stoker data were 47-84 percent and averaged 60 percent. On the other hand, the mass-fired overfeed stoker data were 22-56 percent and averaged 28 percent. Flyash samples taken from the dust collector hoppers of two underfeed stokers revealed 20.2 and 20.5 percent combustibles.

Heat Release Rate—Combustibles in the flyash tended to increase slightly as heat release rate increased on spreader stokers. On mass-fired overfeed stokers, no significant trend was observed.

Excess Air—No correlation was found between combustibles in the flyash and excess air level on either spreader stokers or mass-fired overfeed stokers.

Overfire Air—Increasing overfire air pressure effectively reduced the combustible content of the flyash by an average 40 percent in 74 percent of the overfire air tests. This resulted in an average efficiency gain of 1.70 percent of heat input for spreader stokers and 0.27 percent of heat input for the mass-fired overfeed stokers. However, 26 percent of the tests gave the opposite result

Coal Properties—At Test Site C, the combustibles in the flyash were 2 to 4 times higher while firing an Eastern bituminous coal than while firing a Western sub-bituminous coal. This was the only site where flyash combustibles could be directly related to coal properties. The property of the coal responsible for the difference was not identified.

Flyash Reinjection—Combustibles in the flyash at the boiler outlet increased by 23-63 percent when the rate of flyash reinjection was reduced. At the dust collector outlet, similar increases were observed.

Particle Size—The largest flyash particles contain the largest combustible fractions. Flyash samples from two spreader stokers and two mass-fired overfeed stokers were analyzed.

Boiler Efficiency

Type of Stoker—Boiler efficiencies were determined by the ASME Abbreviated Efficiency Test (PTC-4.1). At or near full load, the measured boiler efficiencies were 73.0-83.4 percent for six spreader stokers. As shown in Figure 5, boiler efficiency was determined by the heat loss method using the ASME Abbreviated Efficiency Test (PTC 4.1). At full load, boiler efficiencies were 73.0-83.4 percent. The lowest efficiency belongs to Site G, the only site which did not have either an air heater or an economizer. Design efficiencies of these units were: A-83.68, B-84.16, Cw-81.40, E-80.41, F-83.10, and G-77.04 percent. Results of 69.8-84.1 percent were obtained for seven mass-fired overfeed stokers. As shown in Figure 6, increased boiler efficiencies for these units were 69.8-84.1 percent. Sites D, J and K, equipped with economizers, had the highest average efficiencies: 83.8, 81.8, and 78.4 percent, respectively. Sites H and I, which did not have economizers, averaged 75.4 and 73.9 percent boiler efficiencies, respectively. Boiler efficiencies were determined by the ASME heat loss method (PTC 4.1). Results of 64.1 to 76.8 percent were measured for five mass-fired underfeed stokers.

Heat Release Rate—In most cases, boiler efficiencies were relatively constant with changing heat release rates. At a few sites, efficiency dropped as heat release rate dropped because increasing dry gas heat losses predominated.

Excess Air—Boiler efficiency decreased as excess air increased on all of the extensively tested stokers. Dry gas heat losses dominated this trend, overshadowing any effects due to combustible heat losses. For each 10 percent excess air decrease, boiler efficiency increased by 0.33-1.0 percent.

Overfire Air—Boiler efficiency improved by an average 1 percent when overfire air was increased on spreader stokers as a result of reduced carbon carryover. However, on mass-fired overfeed stokers, efficiency was reduced by an average 2.75 percent when overfire air was increased due to increased dry gas losses and increased bottom ash combustible heat losses.

Coal Properties—Coal properties affected boiler efficiencies on two occasions. At Test Site C, the high moisture Western coal produced efficiencies which were 3-4 percent lower than similar tests on low moisture Eastern coals. At Test Site K, the unwashed coal produced lower boiler efficiencies than either of the others because this coal led to a greater combustible heat loss.

Flyash Reinjection—Some but not all of the carbon in the reinjected flyash

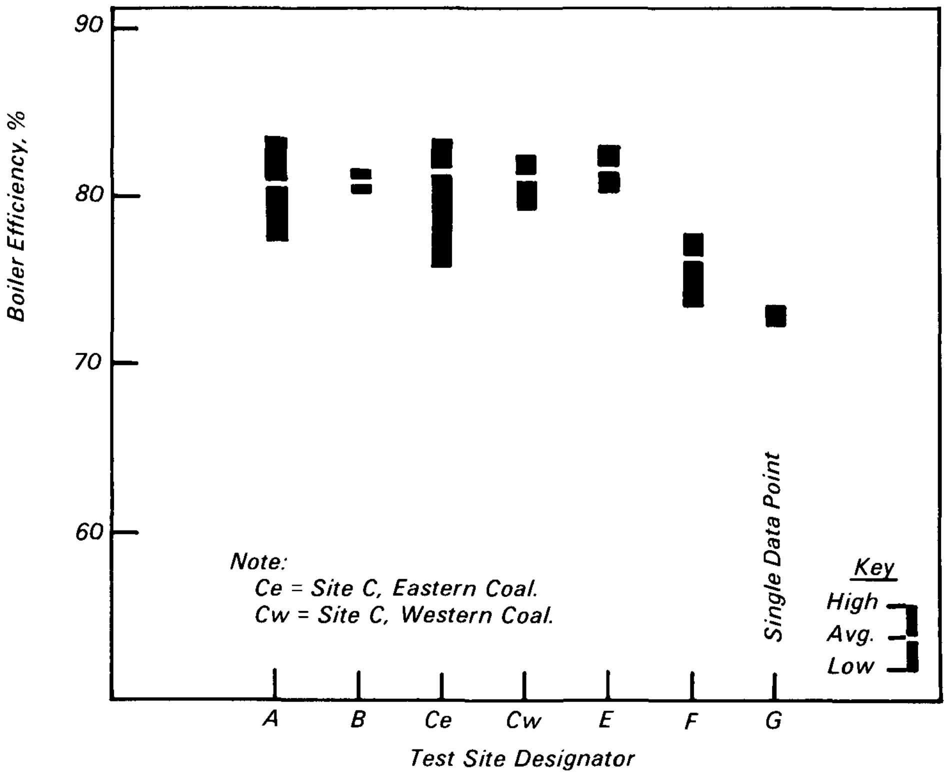

Figure 5. *Boiler efficiency of six spreader stokers fired at full load.*

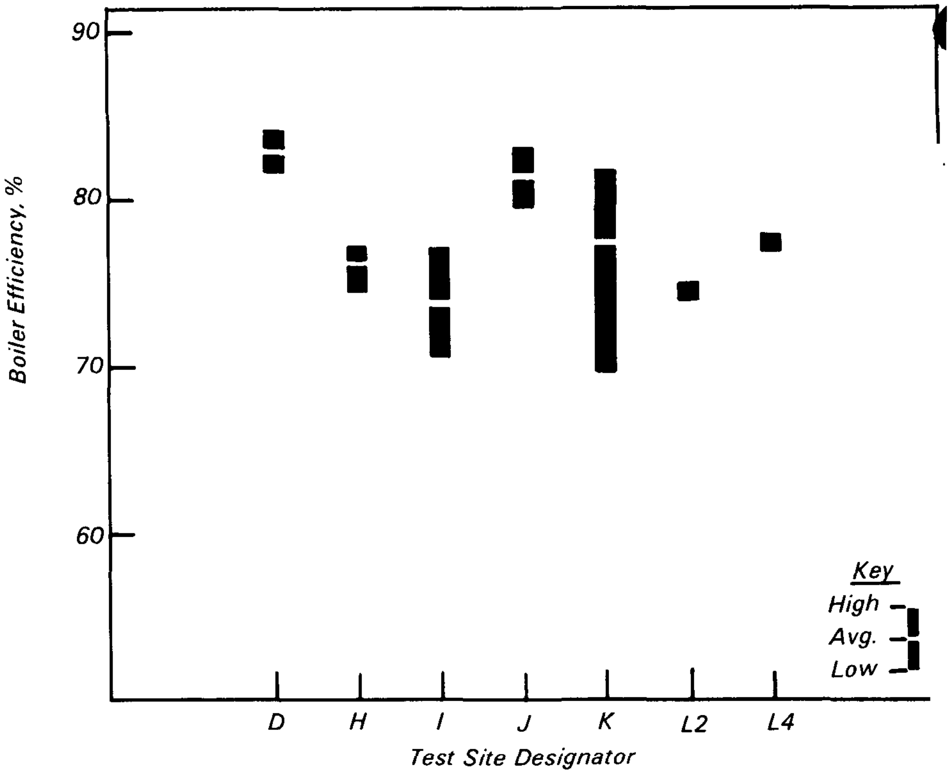

Figure 6. *Boiler efficiency of seven mass-fired overfeed stokers fired at or near full load.*

was recovered at Sites A, B, and C. There was insufficient data to calculate carbon recovery rates with any accuracy.

Summary of Findings Organized by Test Variable

Differences Between Stoker Types

Excess Air—At full load, most spreader stokers were capable of operating at 30 percent excess air (5 percent O_2). By comparison, the mass-fired overfeed stokers generally required 50 percent excess air (7 percent O_2).

With one exception, the excess air operating level was inversely proportional to the size of the stoker. The larger the stoker, the lower the excess air requirement.

Particulate Loading—Spreader stokers with flyash reinjection from their mechanical dust collectors had by far the highest uncontrolled particulate loadings: 13-36 lb/10^6 Btu. Spreader stokers without reinjection from their dust collectors were next with emissions of 2.1-8.8 lb/10^6 Btu, followed by mass-fired overfeed stokers with 0.57-2.2 lb/10^6 Btu and underfeed stokers with 0.25-0.71 lb/10^6 Btu.

Combustibles in the Flyash—Combustible levels in the flyash were higher in the spreader stokers than in either the mass-fired overfeed stokers or the underfeed stokers. Except at Test Site C, the spreader stoker data were 47-84 percent and averaged 60 percent. On the other hand, the mass-fired overfeed stoker data were 22-56 percent and averaged 28 percent. Flyash samples from the dust collector hoppers of two underfeed stokers revealed 20.2 and 20.5 percent combustibles.

Combustibles in the Bottom Ash—Combustible levels were lower in the bottom ash of spreader stokers than for mass-fired overfeed stokers or underfeed stokers. The average for each of six spreader stokers fired at full load was 0-14 percent. By comparison, mass-fired overfeed stokers were 16-26 percent with one unit averaging 43 percent, and underfeed stokers were 19-25 percent with one unit averaging 8 percent.

Sulfur Oxides (SO_x)—The spreader stokers retained an average 4.4 percent of the fuel sulfur in the ash, while the mass-fired overfeed stokers retained an average 2.1 percent. The remainder was emitted as SO_2 and SO_3, with SO_3 comprising less than 2 percent of the total. Operating parameters such as excess air, overfire air, and load had no effect on the emissions of SO_x or the retention of sulfur in the ash.

Nitric Oxides (NO_x)—As a class, spreader stokers emitted higher concentrations of NO than did mass-fired overfeed stokers. Under full load, spreader stokers emitted 0.30-0.61 lb/10^6 Btu NO corrected to NO_2 while mass-fired overfeed stokers emitted 0.21-0.50 lb/10^6 Btu NO. In addition, overfeed stokers operated at higher excess air levels than did spreader stokers. When compared at the same excess air levels, the difference in NO levels is even greater.

Carbon Monoxide (CO)—Spreader stokers emitted lower concentrations of CO than traveling grate stokers while firing Eastern bituminous coals. Emissions from three of the spreader stokers were 50-250 ppm at full load. A fourth was 200-600 ppm. By comparison, two traveling grate stokers emitted 50-700 ppm CO at full load, and a vibrating grate stoker emitted 50-2000+ ppm CO. The comparison is limited to these seven stokers. CO emissions were not measured on three other stokers due to instrument failure, and a fourth fired only Western coals. At Test Sites L1 through L7, the CO concentration was measured with an Orsat analyzer with a minimum detection limit of 1 percent or 1000 ppm. Significantly, the CO emissions were below this detection limit on the Site L stokers.

Unburned Hydrocarbon (UHC)—Based on limited data, the spreader stokers emitted lower UHC emissions than the mass-fired overfeed stokers. Full-load emissions from the spreader stoker were 0-15 ppm for Site F and 35-41 ppm for Site G. By comparison, the mass-fired overfeed stokers emitted 5-112 ppm for Site H and 80 ppm for a single point on Site J.

Boiler Efficiency—Boiler efficiencies were determined by the ASME Abbreviated Efficiency Test (PTC 4.1). At or near full load, the measured boiler efficiencies were 73.0-83.4 percent for six spreader stokers, 69.8-84.1 percent for seven mass-fired overfeed stokers, and 64.1-76.8 for five mass-fired underfeed stokers.

Response to Heat Release Rate

Excess Air—The excess air requirement drops as heat release rate increases on stoker boilers. The excess air requirement levels off as 30 percent excess air is approached.

Particulate Loading—It cannot be said that units with higher design heat release rates have higher particulate loading, but for a given unit the uncontrolled particulate loading always increased as heat release rate, or load, increased. The rate of increase varied from site to site; at some sites it appeared to accelerate as full load was approached. On spreader stokers with flyash reinjection from mechanical dust collectors, the last 10 percent increase in heat release rate resulted in a 9-20 percent increase in particulate loading. On spreaders without dust collector reinjection, the increase was 8-12 percent. On mass-fired overfeed stokers, particulate loading increased from 3 to 20 percent as heat release rate was increased from 90 to 100 percent of design.

Combustibles in the Flyash—Combustibles in the flyash tended to increase slightly as heat release rate increased on spreader stokers. On mass-fired overfeed stokers, no significant trend was observed.

Combustibles in the Bottom Ash—Heat release rate had very little effect on combustibles in the bottom ash.

Nitric Oxides (NO_x)—For spreader stokers, an increase in heat release rate equivalent to 10 percent of capacity resulted in an average increase in NO emissions of 0.025 lb/10^6 Btu as NO_2 at constant excess air. For mass-fired overfeed stokers, the relationship was 0-0.026 lb/10^6 Btu per 10 percent increase in capacity at constant excess air. In all cases, NO emissions were invarient with load at normal firing conditions because the effects of decreasing excess air effectively canceled the effects of increasing load. Although NO increased with heat release rate on each given unit, it was not true that units with higher design heat release rates emitted higher concentrations of NO.

Carbon Monoxide (CO)—CO emissions were highest at high heat release rates under low excess air conditions, and at low heat release rates under high excess air conditions. At full load, CO emissions could be controlled with proper application of combustion air.

Unburned Hydrocarbon (UHC)—UHCs tended to decrease as heat release rate increased on three of four stokers where UHCs were measured. On the fourth stoker, the opposite trend was observed.

Boiler Efficiency—In most cases, boiler efficiencies were relatively constant with changing heat release rates. At a few sites, efficiency dropped as heat release rate dropped because increasing dry gas heat losses predominated.

Response to Excess Air

Particulate Loading—No relationship was established between particulate loading and excess air. This does not foreclose the existence of such a relationship, but rather indicates that such a relationship could not be deciphered from the data due to data scatter and uncontrolled variables.

Combustibles in the Flyash—No correlation was found between combustibles in the flyash and excess air level on either spreader stokers or mass-fired overfeed stokers.

Combustibles in the Bottom Ash—No correlation was found between excess air and combustibles in the bottom ash.

Nitric Oxide (NO_x)—On four spreader stokers without air preheat and one with air preheat, NO increased by 0.021-0.036 $lb/10^6$ Btu for each increase of 10 percent excess air. The sixth spreader stoker used air preheat and its NO increased by 0.067 $lb/10^6$ Btu per increase of 10 percent excess air. On five mass-fired overfeed stokers, NO increased by 0.016-0.027 $lb/10^6$ Btu.

Carbon Monoxide (*CO*)—CO was more prevalent as excess air dropped below about 30-40 percent on spreader stokers and about 60 percent on mass-fired overfeed stokers. CO increased gradually as excess air increased above about 60 percent on spreader stokers and 100 percent on mass-fired overfeed stokers.

Unburned Hydrocarbon (*UHC*)—UHC emissions showed little or no correlation with excess air on spreader stokers. On mass-fired overfeed stokers, UHCs increased in almost direct proportion to the excess air.

Boiler Efficiency—Boiler efficiency decreased as excess air increased on all of the extensively tested stokers. Dry gas heat losses dominated this trend, overshadowing any effects due to combustible heat losses. For each 10 percent excess air decrease, boiler efficiency increased by 0.33-1.0 percent.

Response to Coal Composition and Sizing

Excess Air—Coal properties were not found to alter excess air requirements on these stoker boilers.

Particulate Loading—Because of the movement of air through the grate and the upward movement of combustion gases through the furnace, the smallest coal and ash particles are carried out of the furnace by the gases rather than staying on the grate. This is called particle entrainment and is a problem from both a pollution and an efficiency standpoint. The likelihood of a particle being entrained is a function of its size and density, and the velocities in the furnace. The test data from this program showed a mathematical correlation between coal fines and particulate loading on five stokers. Particulate loading increased by 0.10-0.55 $lb/10^6$ Btu whenever the amount of coal passing a 16 mesh screen increased by 1 percent. No correlation was found in studies of six other stokers.

Coal ash could be related to particulate loading at only four of the ten test sites at which multiple coals were fired. On three of the spreader stokers particulate loading increased by 0.24-0.38 $lb/10^6$ Btu for each 1 percent increase in coal ash. Stated another way, if the coal ash is doubled at these sites, the particulate loading will increase by 15-30 percent. Thus, the relationship between coal ash and particulate loading was not 1:1 on these three units.

On one of the traveling grate stokers, a 4-percent ash-washed coal and a 10 percent ash-unwashed coal from the same mine were tested. The 250 percent increase in coal ash resulted in a 300-percent increase in particulate loading. In this case, the dramatic increase in particulate loading can be attributed to the type of ash, a clay like material in the surface of the coal, and to a corresponding increase in coal fines on the unwashed coal.

Combustibles in the Flyash—At Test Site C, the combustibles in the flyash were 2 to 4 times higher while firing an Eastern bituminous coal than while firing a Western sub-bituminous coal. This was the only site where flyash combustibles could be directly related to coal properties. The property of the coal responsible for the difference was not identified.

Combustibles in the Bottom Ash—It was found that 65-85 percent of the coal ash remained on the grate in spreader stokers as compared to 80-90 percent for mass-fired overfeed stokers. To compute combustible heat losses, 75 and 85 percent are good estimates for spreaders and mass-fired overfeed stokers, respectively.

Small differences in bottom ash combustible levels were observed which appeared to be related to coal properties at some sites. However, the coal properties causing these differences were not identified.

Sulfur Oxides (SO_x)—Although good sulfur balances were difficult to obtain, the data indicates that fuel sulfur conversion efficiencies of 95-98 percent are reasonable assumptions.

Nitric Oxides (NO_x)—Variations in fuel nitrogen from 0.75 to 1.50 percent by weight had no measurable effect on NO emissions. This may simply reflect difficulties in sorting out the other variables.

Carbon Monoxide (*CO*)—CO emissions were greatest while firing Western sub-bituminous coals. On one spreader stoker where both an Eastern and a Western coal were fired, the full-load Western coal emissions were 163-702 ppm and averaged 342 ppm. By comparison, the full-load Eastern coal emissions were 33-263 ppm and averaged 71 ppm.

Unburned Hydrocarbon (*UHC*)—The site firing the lower volatile coal had the lowest UHC emissions. The 29-percent volatile coal yielded 19-41 ppm UHCs, while the 41-percent volatile coal yielded 163-602 ppm UHCs. Volatiles are expressed here on a dry mineral-matter-free basis.

Boiler Efficiency—Coal properties affected boiler efficiencies on two occasions. At Test Site C, the high moisture Western coal produced efficiencies 3-4 percent lower than similar tests on low moisture Eastern coals. At Test Site K, the unwashed coal produced lower boiler efficiencies than either of the others because it led to a greater combustible heat loss.

Response to Overfire Air

Particulate Loading—Uncontrolled particulate loading was reduced by 20-50 percent on four of six spreader stokers and three of five mass-fired overfeed stokers when overfire air pressures were increased. Two sites showed the opposite trend and two sites were unaffected by changes in overfire air pressure.

Combustibles in the Flyash—Increasing overfire air pressure effectively reduced the combustible content of the flyash by an average 40 percent in 74 percent of the overfire air tests. This resulted in an average efficiency gain of 1.70 percent of heat input for spreader stokers and 0.27 percent of heat input for the mass-fired overfeed stokers. However, 26 percent of the tests gave the opposite result.

Nitric Oxides (NO_x)—NO emissions were not influenced by changes in overfire air pressure when considered at constant excess air.

Carbon Monoxide (CO)—CO emissions were reduced by the increased use of overfire air.

Unburned Hydrocarbon (UHC)—UHCs were reduced 82 percent by increasing the overfire air pressure on one traveling grate stoker. No correlation was found on one spreader stoker. The other two units where UHC emissions were measured had insufficient data to make a correlation.

Boiler Efficiency—Boiler efficiency improved by an average 1 percent when overfire air was increased on spreader stokers as a result of reduced carbon carryover. However, on mass-fired overfeed stokers, efficiency was reduced by an average 2.75 percent when overfire air was increased due to increased dry gas losses and increased bottom ash combustible heat losses.

Response to Flyash Reinjection

Particulate Loading—Flyash from the dust collector was reinjected to the furnace of three of the six spreader stokers. In each case, uncontrolled particulate loading was increased as a result of reentrainment of a portion of the reinjected ash. At one site, reinjection was completely eliminated for test purposes. As a result, uncontrolled particulate loading was reduced by 70-80 percent and controlled particulate loading was reduced by 40-50 percent. Reducing the degree of flyash reinjection reduced the percentage of larger particles in the flyash. This in turn reduced the mechanical dust collector efficiency.

Combustibles in the Flyash—Combustibles in the flyash at the boiler outlet increased by 23-63 percent when the rate of flyash reinjection was reduced. At the dust collector outlet, similar increases were observed.

Nitric Oxides (NO_x)—Flyash reinjection from the mechanical dust collector had no measurable effect on NO emissions.

Carbon Monoxide (CO)—Flyash reinjection from the mechanical dust collector had no measurable effect on CO emissions.

Boiler Efficiency—Some but not all of the carbon in the reinjected flyash was recovered at Sites A, B, and C. There was insufficient data to calculate carbon recovery rates with any accuracy.

Particle Size Distribution

Particle Loading—Particle size distribution of the flyash was determined by a variety of methods including cascade impactor, Bahco classifier, SASS cyclones, and sieve analysis. Results varied from one method of measurement to another, but clearly showed that spreader stokers emit a higher percentage of coarse, more easily collected particles than mass-fired overfeed and underfeed stokers.

Combustibles in the Flyash—The largest flyash particles contain the largest combustible fractions. Flyash samples from two spreader stokers and two mass-fired stokers were analyzed.

P. L. Langsjoen, J. O. Burlingame, and J. E. Gabrielson are with KVB, Inc., 6176 Olson Memorial Highway, Minneapolis, MN 55422.
***Robert E. Hall** is the EPA Project Officer (see below).*

The complete report is in two parts, entitled "Emissions and Efficiency Performance of Industrial Coal-Stoker-Fired Boilers," (Order No. PB 82-115 312; Cost: $25.50, subject to change)
Data Supplement (Order No. PB 82-115 320; Cost: $34.50, subject to change)
will be available only from:
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
Telephone: 703-476-4650
The EPA Project Officer can be contacted at:
Industrial Environmental Research Laboratory
U.S. Environmental Protection Agency
Research Triangle Park, NC 27711

Cincinnati OH 45268

Environmental
Protection
Agency
EPA-335

ss
vate Use, $300

PS 0000329
U S ENVIR PROTECTION AGENCY
REGION 5 LIBRARY
230 S DEARBORN STREET
CHICAGO IL 60604