



Project Summary

Development of Criteria for Extension of Applicability of Low Emission, High Efficiency Coal Burners: Second Annual Report

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This report describes the second year's effort under EPA Contract 68-02-2667, which concerns the development of criteria for the evaluation and applicability of low-emission, high-efficiency coal burners. The report describes progress in three major areas: (1) bench scale studies, (2) distributed mixing burner development, and (3) comparison with commercial practice. The bench scale studies concern the impact of fuel characteristics on fuel NO formation during the combustion of pulverized coal. Although fuel NO emissions generally increase with increasing fuel nitrogen content, coals with the same rank and similar nitrogen contents may produce markedly different fuel nitrogen levels. Preliminary results indicate that a simple procedure, evaluating reactive volatile nitrogen, can be used to assess the impact of coal type on fuel NO formation. Data relating to the development of the distributed mixing burner have been reviewed, and data have been obtained with both single and multiple burners. No operability problems were encountered with different fuel types, but NO emissions were fuel dependent. Several commercial burners have been tested satisfactorily in the test facility. One gave severe flame impingement. Carbon monoxide emissions were generally higher and nitrogen oxide (NO_x) emissions were slightly lower than commercial practice.

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

NO_x formation in pulverized coal flames can be reduced by using the burner to control the rate of fuel/air mixing to minimize fuel nitrogen conversion. This report describes the second year's progress on EPA Contract 68-02-2667. The program is aimed to:

- Expand the fuel capability of low NO_x burners to include the major types of solid fossil fuels projected for use by the utility industry.
- Explore additional burner concepts and configurations that show potential for improving the emission and thermal performance of pulverized coal burners.
- Determine the effects of multiple burner configurations that are encountered in utility boilers.
- Provide for direct comparison between the experimental burners being developed here and the current state-of-the-art for commercially available coal burners.
- Arrange for coordination of the technology development program with boiler manufacturers and users.
- Provide testing in support of planned application of the burner technology.

Figure 1 shows the relationship of the

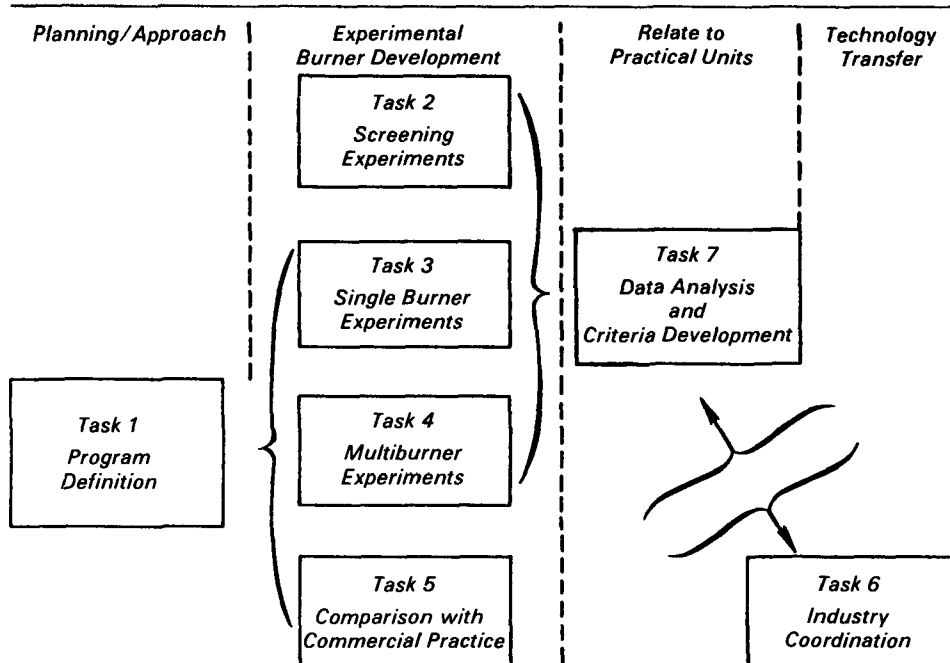


Figure 1. Overall program logic.

various tasks that are planned to meet these objectives. In this, the second year of the program, efforts were expended on the following tasks:

- Bench scale fuel screening studies to assess the impact of fuel properties on fuel NO formation (Task 2).
- Tests with the distributed mixing burner and different fuel types (Tasks 3 and 4).
- Tests with commercial burners to allow a comparison with commercial practice.

Bench Scale Studies

In the first year's effort, a bench scale reactor was constructed with a design input firing rate ranging from 50 to 150 x 10³ Btu/hr.* This facility, to be used for fuel screening studies and concept development, had several versatile features including:

- The ability to burn the fuel with nitrogen-free oxidant mixtures composed of O₂, CO₂, and Ar, to define fuel NO production.
- Complete control over fuel input rate and fuel size distribution.
- A modular combustion chamber to permit probe access and variable heat extraction rates.

Table 1 lists the 25 coals tested to date in this furnace and their properties. Initially, the impact of fuel properties on NO formation under excess air is discussed; then data obtained to date on the evaluation of advanced concepts for NO_x control will be presented.

The Influence of Coal Properties on Fuel NO Formation

Pulverized coal was burned under premixed and diffusion flame conditions in nitrogen-free atmospheres to evaluate fuel nitrogen conversion. Figure 2 summarizes the data obtained with the coals tested to date under premixed and axial diffusion conditions. Fuel NO emissions are shown in pounds of NO₂ per 10⁶ Btu as a function of percentage nitrogen in the coal on a dry ash-free basis for overall 5 percent excess oxygen in the combustion products. The data presented illustrate two major points:

1. Fuel NO emissions tend to increase with increasing fuel nitrogen content. This is most pronounced for premixed conditions. However, for any given nitrogen content there is a considerable spread in fuel NO emissions, indicating that some property other than total fuel nitrogen content influences fuel NO formation.
2. Fuel nitrogen conversion decreases with decreasing fuel/air mixing

rates. Since oxygen availability controls fuel NO formation, this is expected.

Some anomalous behavior was observed associated with fuel/air mixing effects and fuel nitrogen formation. Some coals show a very strong dependence of fuel nitrogen formation on fuel/air mixing characteristics. However, this is not always the case; even for coals of the same rank, the influence of fuel/air mixing appears to be also coal-dependent. Two fuels tested to date show very different characteristics. The anthracite shows almost no impact of fuel/air mixing rate. Since anthracite is very low in volatile content, it can be assumed that most of the fuel NO formed is produced from solid nitrogen, and that the impact of fuel/air mixing characteristics is minimized. Alternatively, the Australian lignite showed a decrease in fuel NO from 950 to 675 to 175 ppm as the combustion conditions changed from premixed to radial diffusion to axial diffusion.

It can be argued that the fraction of the coal fuel nitrogen that is volatile (i.e., emitted with the volatile fractions during thermal decomposition) has a major impact on the formation of fuel NO. Therefore, two simple experiments were carried out to determine if volatile fuel nitrogen (determined by either the ASTM volatile matter procedure or an inert pyrolysis experiment developed under EPA sponsorship) can be used to predict fuel NO formation in pulverized coal flames. The char residue from an ASTM volatile test was analyzed for nitrogen content to determine the fraction of the nitrogen that had been liberated with the coal volatiles. The results suggest that this method of assessing volatile nitrogen evolution is not even capable of ranking fuels, and is certainly not suitable as a predictive tool. Under EPA sponsorship, a pyrolysis reactor was developed to investigate the conversion of fuel nitrogen to HCN under both inert and oxidative pyrolysis conditions. Gas-phase kinetics experiments suggest that HCN is a reasonable model for volatile fuel nitrogen compounds; therefore, the amount of fuel nitrogen that is converted to HCN could indicate the potential for a particular coal to produce fuel NO. The pyrolysis experiment was operated as a two-stage system. The fuel was placed in an initial reactor whose temperature could be varied, and the pyrolysis compounds were swept into a secondary reactor (maintained at 1373 K) with an inert Ar flow. Experiments have demonstrated

*To convert nonmetric units to their metric equivalents, please use the conversion factors at the back of this Summary.

Table 1. Fuel Analysis

Fuel Symbol	□	◊	□	○	◇	△	▽	○	○	△	○	⊙	□
Fuel Source	Hazleton PA	Upper Cliff AL	Rosa AL	Black Creek AL	W.KY	WV	Elkay WV	Gauley Eagle WV	Price UT(I)	Price UT(II)	Utah (Coal)	Utah (Char)	Cadiz OH
Proximate Analysis (% as received)													
Moisture	5.13	3.00	8.02	2.25	5.43	7.57	0.60	3.72	6.39	7.41	4.20	2.70	4.29
Ash	5.74	9.49	6.79	4.45	7.53	12.05	11.61	26.89	7.40	8.83	9.62	16.83	18.05
Volatile Matter	4.39	20.44	21.81	28.28	37.79	29.12	33.35	26.65	38.89	38.84	42.97	10.29	34.87
Fixed Carbon	84.74	67.07	63.38	65.02	49.25	51.26	54.44	42.74	47.32	44.92	43.21	70.18	42.79
Ultimate Analysis (% Dry)													
C	88.45	79.32	81.23	82.12	71.58	74.68	73.96	59.43	73.52	72.24	69.36	75.39	62.08
H	2.14	4.47	4.73	5.21	5.43	4.96	4.93	4.11	5.52	5.75	5.32	1.28	4.44
N	0.79	1.47	1.54	1.79	1.55	1.38	1.39	1.35	1.44	1.55	1.50	1.22	1.07
S	0.47	1.30	1.04	0.76	3.21	0.86	2.47	0.84	0.61	0.76	1.04	1.12	7.40
Ash	6.05	9.78	7.38	4.56	7.96	13.04	11.69	27.94	7.89	9.54	10.05	17.30	18.86
O	2.10	3.66	4.08	5.56	10.27	5.08	5.56	6.33	11.29	10.16	12.73	3.69	6.15
Heating Value (Btu/lb. Wet)	13,124	13,254	13,394	14,284	12,082	12,228	13,115	10,110	12,340	11,877	11,718	11,185	11,038
CLASSIFICATION (ASTM D388)	Anthracite	Medium Volatile Bituminous	Medium Volatile Bituminous	Medium Volatile Bituminous	High Volatile A Bitu- minous	High Volatile A Bitu- minous	High Volatile A Bitu- minous	High Volatile A Bitu- minous	High Volatile B Bitu- minous	High Volatile B Bitu- minous	High Volatile B Bitu- minous	—	High Volatile B Bitu- minous
Fuel Symbol	▽	◊	○	▽	○	▽	▽	◇	◇	□	△	▽	●
Fuel Source	Farmington NM	Four Corners NM	Fruitland NM	Colstrip MT	Hardin MT	Hardin MT	Shell TX	Scranton ND	Beulah ND	Beulah ND	Savage MT	Morwell Australia	Saar Germany
Proximate Analysis (% as received)													
Moisture	7.76	5.24	11.02	21.27	22.70	20.49	25.23	34.96	33.10	34.63	36.36	9.07	2.16
Ash	17.96	24.06	20.72	9.58	11.26	8.62	10.28	7.50	7.12	4.97	4.61	3.38	8.04
Volatile Matter	34.95	35.94	31.66	30.82	31.26	33.24	35.31	28.85	28.65	27.02	28.48	48.79	36.23
Fixed Carbon	39.33	34.76	36.60	38.33	34.88	37.65	29.18	28.69	31.13	33.38	30.55	38.76	53.57
Ultimate Analysis (% Dry)													
C	63.06	55.99	58.71	67.52	65.54	67.88	60.99	64.61	65.29	66.15	64.99	66.25	76.13
H	4.65	4.71	4.21	4.36	4.15	4.65	4.49	4.17	3.96	4.20	4.04	5.01	5.25
N	1.40	1.23	1.30	1.38	0.95	0.99	1.13	0.83	0.99	0.96	1.00	0.65	1.37
S	0.81	1.03	0.93	0.63	0.79	1.07	1.02	1.52	1.14	0.37	0.42	0.28	0.83
Ash	19.47	25.39	23.29	12.17	14.57	10.84	13.74	11.53	10.64	7.60	7.25	3.72	8.21
O	10.61	11.65	11.56	13.94	14.00	14.57	18.63	17.34	17.98	20.72	22.30	24.09	8.21
Heating Value (Btu/lb. Wet)	10,391	9,425	9,344	9,169	8,603	9,229	8,131	6,446	7,245	7,245	6,995	10,051 (wet)	13,657 (dry)
CLASSIFICATION (ASTM D380)	High Volatile C Bituminous	High Volatile C Bituminous	High Volatile C Bituminous	Sub- bituminous B	Sub- bituminous B	Sub- bituminous B	Sub- bituminous C	Lignite A	Lignite A	Lignite A	Lignite A	—	—

almost quantitative conversion of nitrogen in pyridine to HCN at 1373 K. Thus, in this experiment, the fraction of fuel nitrogen capable of conversion to HCN could be assessed as a function of first-stage pyrolysis temperature. The results shown in Figure 3 compare the fraction of fuel nitrogen converted to NO for the three combustion conditions as a function of the fraction of the fuel nitrogen converted to HCN under pyrolysis conditions at 1373 K. It can be seen that the pyrolysis data agree qualitatively with the experimental results obtained in the premixed and radial diffusion flames. The Savage lignite (△) gives the highest percentage conversion of fuel nitrogen to NO under combustion conditions, and also has the highest fraction of volatile nitrogen yield in the inert pyrolysis study.

Optimization of Staged Combustion Conditions

It is generally recognized that staged combustion offers the most cost-effective control technique for minimizing fuel NO formation. The basis for staged combustion as an NO_x control technique involves the competition between two reaction paths: one forms N₂, and the other NO from the fuel-nitrogen species. The path producing N₂ is favored under fuel-rich conditions. Thermodynamic limitations indicate that the total fixed nitrogen species (NO, NH₃, HCN) are minimum at about 65 percent of the theoretical air requirements for complete combustion for most hydrocarbon fuels, and that this minimum concentration is of the order of 10 ppm under combustion conditions.

Thus, it could be concluded that if all the nitrogen species were in the gas phase then this thermodynamic limitation would represent the minimum NO achievable under staged combustion conditions, since it is reasonable to assume total conversion of these small TFN concentrations during second-stage burnout. Gas-phase kinetics would also indicate that the approach to thermodynamic equilibrium is accelerated at high temperatures, even though the minimum TFN concentration would tend to increase. Staged combustion also has an impact on the formation of thermal NO because the heat release process is extended in time allowing enthalpy loss, thus reducing peak temperatures.

The primary control options in a staged system are:

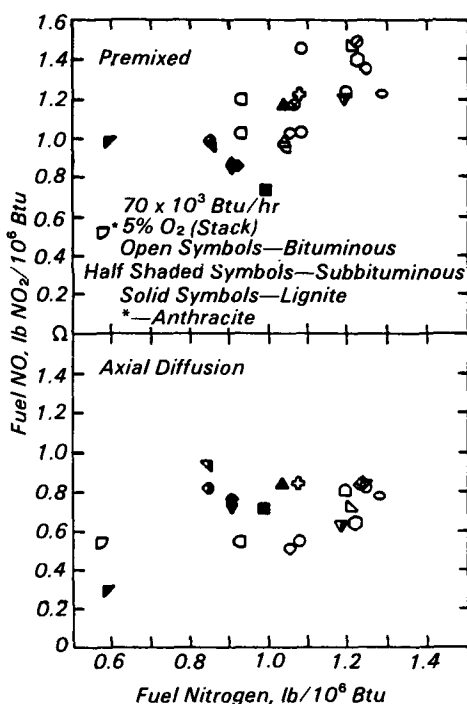


Figure 2. Fuel NO emissions as a function of fuel nitrogen content and mixing conditions.

- How long and at what temperature must the fuel products remain under fuel-rich conditions?
- What is the optimum stoichiometry or distribution of stoichiometries in fuel-rich zone?

Two series of experiments have been carried out: one involved three-stage combustion; and the other, heat extraction from the primary and/or secondary zone to assess the various options.

Experiments were carried out in which the fuel-rich stage was divided into two sections: the first fuel-rich stage stoichiometry was maintained constant (as was the overall excess air level), and the stoichiometry of the second fuel-rich stage was varied. Exhaust NO emissions were reduced by about 15 percent when operating under three-stage conditions compared to two-stage operation. In another experiment the bench scale reactor was modified to allow removable space cooling coils to be added to the fuel-rich first stage, or the second stage of a two-stage combustion system. Maximum emissions were obtained without cooling, and minimum emissions were obtained when heat was extracted from the primary section. This is surprising since a reduction in temperature of the first stage would be expected to increase the concentration of total fixed nitrogen at

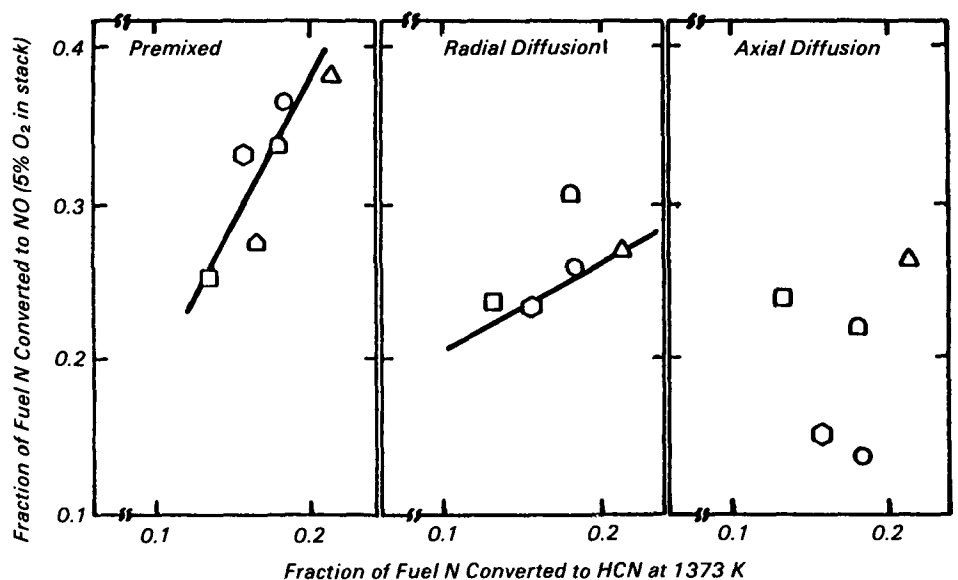


Figure 3. Fuel nitrogen conversion can be correlated by HCN produced during pyrolysis for well mixed combustion conditions.

the exit of the first stage, thus increasing (not decreasing) final emissions.

Commercial Burner Testing

Since a primary goal of the program is to demonstrate the distributed mixing burner (DMB) technology in field operating boilers, some assurance is required that the DMB, which has been demonstrated only in the large watertube simulator (LWS) research furnace, will also perform in the field as predicted. Also, the basis for the prototype design is the LWS furnace, not a steam raising system. Although indirect, the approach taken was to evaluate commercial burner operation in the LWS and compare it against field experience. This approach provides some assurance that, if the burner operates satisfactorily in the LWS, it will also operate satisfactorily in the field.

The burners selected for testing under this program are:

- Babcock and Wilcox dual-register burner.
- Peabody Engineering Corporation standard pulverized-coal burner with low-NO_x modification.
- Steinmuller low-NO_x burner (similar to burners currently used at the Weiher plant in West Germany).

All the burners were designed for a nominal firing rate of 50×10^6 Btu/hr, and the installation in the LWS was similar to that in the field. To date, the B&W and Peabody burners have been tested with the baseline Utah bituminous

coal. The Steinmuller burner will soon be tested with a bituminous coal from Germany (similar to coal used in the field) and baseline Utah coal. In support of the industrial demonstration program (EPA Contract 68-02-3127), an 80×10^6 Btu/hr, Foster Wheeler intervine burner (pre-NSPS) was also evaluated; results are included in this report for completeness. All of the burners gave stable flames and performed satisfactorily. However, the Babcock and Wilcox dual-register burner produced a flame that was too long for the LWS firing depth and gave severe flame impingement on the back wall. Thus, it is very difficult to compare field and LWS experience because impingement prevented complete heat release of the input coal. Several general conclusions can be drawn from the studies with commercial burners:

- The flames observed in the LWS were judged, by experienced engineers, to be very similar to those observed in the field.
- CO levels were consistently higher than measured in the field.
- NO levels were slightly lower than measured in field operating units.

Conclusions

- **Bench Scale Studies.** These studies concerned the development of a data base on the effect of coal type on NO formation and the definition of optimum conditions for minimum NO formation under idealized fuel/

air contacting. Although fuel NO emissions increased with increasing coal nitrogen content, coals with the same rank and similar fuel nitrogen content produce markedly different fuel NO levels. Preliminary results suggest that a simple procedure (that evaluated reactive volatile nitrogen) could be used to assess the impact of coal type on NO production. Studies on the optimization of the conditions in the fuel-rich stage of a staged system indicate that minimum gas-phase nitrogen species (HCN + NH₃ + NO) does not necessarily give minimum emissions after burnout.

- **Distributed Mixing Burner Development.** Data relating to the development of the distributed mixing burner have been reviewed and summarized. Single and multiple burner data have been obtained for two different fuels. The distributed mixing concept can be operated with different fuels, and it appears that emission levels are sensitive to fuel type. However, no attempt was made to reoptimize the burner for different fuels.
- **Comparison with Commercial Practice.** Several commercial burners have been tested in the research facility. All the burners performed satisfactorily and produced stable flames. However, one burner gave a flame length that caused severe flame impingement on the rear wall of the test furnace. Since severe impingement cannot be tolerated in the field, comparison with commercial practice is invalid. Carbon monoxide emissions produced with the commercial burners were slightly higher than those usually found in field operating units, and NO_x emissions were slightly lower.

Conversion Factors

Readers more familiar with metric units may use the following factors to convert the nonmetric units used in this Summary:

Nonmetric	Times	Equals Metric
Btu/hr	2.93	W _t
Btu/lb	2.33	J/g
lb/10 ⁶ Btu	430	ng/J

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The complete report, entitled "Development of Criteria for Extension of Applicability of Low Emission, High Efficiency Coal Burners: Second Annual Report," (Order No. PB 84-163 898; Cost: \$19.00, subject to change) will be available only from:

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