DOE/PC/92151--T1-Rev.A

DE93 012473

TECHNICAL PROGRESS REPORT - SECOND QUARTER

Date:	10 February 1993, Revision A
Contract Title:	Industrial Pulverized Coal Low NO_x Burner: Phase I
Contract Number:	DE-AC22-92PC92151
Contract Period:	1 April 1992 to 31 March 1993
Contractor Name:	Arthur D. Little, Inc. 20 Acorn Park Cambridge, MA 02140

1.0 Introduction

The objective of Phase I of the "Industrial Pulverized Coal Low NO_x Burner" Program is to develop a novel low NO_x, pulverized coal burner, which offers near-term commercialization potential, uses preheated combustion air of up to 1000°F, and which can be applied to high-temperature industrial heating furnaces, chemical process furnaces, fired heaters, and boilers. The program team is led by Arthur D. Little, Inc., and includes the Massachusetts Institute of Technology (MIT) and Hauck Manufacturing Company.

First Quarter Summary. During the first quarter of the program (April 1992 to June 1992), the program team developed the overall program management plan; began a market survey to identify coals suitable for modeling the low NO_x burner design and performance, as well as for use in the Phase II burner tests; and defined the preliminary burner design specifications, sized the prototype burner, and produced the first concept schematic.

Second Quarter Summary. This report is for the second quarter of the program (July 1992 to September 1992). During this period the program team:

- Completed the study of industrial coal usage and sources;
- Attended a PETC conference in Pittsburgh, PA, and gave a poster-type presentation on the burner;
- Refined the preliminary burner design and confirmed it as the basis for computer modeling; and
- Started definition of the modeling work scope, including the development of fuel and process specifications, design criteria, and modeling approaches.

2.0 Coal Selection

2.1 *Task Objectives*

The objective of the coal selection task was to choose a set of coal characteristics for use in the development of the burner design and in the combustion/NO_x formation modeling work. The task also identified potential coal seams and coal grinding facilities from which ground coal samples could be obtained for future burner test activities. The task activities were to:

- Develop a set of coal selection criteria for burner design/modeling activities;
- Identify US industries currently burning coal, determine their locations, business applications, and coals used;
- Identify a set of US coals that meets the selection criteria; and
- Identify facilities capable of grinding coal in 2 to 10 ton batches for future low NO_x burner testing.

2.2 Approach

To achieve the objectives of the coal selection task, data were gathered and analyzed from the coal industry, coal and boiler/furnace trade associations, boiler/furnace operators, the Department of Energy (DOE), and technical literature on pulverized coal combustion/NO_x formation. Coal selection criteria were developed based on program needs, DOE/PETC requirements, and US industrial coal use patterns. Specifically, the approach used was to:

- Review industrial coal-use databases to determine the US Geographic distribution of industrial, coal-fired boilers/furnaces and the distribution of US coal use by industrial application;
- Conduct interviews with representatives of industrial trade associations, coal companies, and industrial coal users to understand important issues for coal selection and use in industry;
- Review DOE PETC requirements/interests for coal selection (e.g., compatibility of coal selection with parallel DOE-sponsored combustion modeling activities, and consistency of coal selection among other burner development contractors);
- Review literature on fundamental coal pyrolysis/char combustion/NO_x formation studies to assess the availability of kinetic information for targeted US coals; and
- Review of US coal seams to identify coals that meet the selection criteria developed in the previous tasks.

2.3 Contacts/Sources

A variety of sources were contacted to gather the required information. These sources included trade associations, coal companies, coal database services, industrial coal users, grinding facilities, and a DOE PETC representative. The sources are listed in Table 1.

Table 1: Sources Contacted for Coal Selection Information

Group	Source	Location
Trade Associations	• CIBO (Council of Industrial Boiler Operators)	Burke, VA
	• Portland Cement Association	Skokie, IL
	• National Coal Association	Washington, DC
Coal Sales	• AMAX Coal Sales	Sullivan, IN
	• Consolidated Coal	Library, PA
Coal Database Services	• Keystone Coal Manual	Chicago, IL
	• Resource Data International	Boulder, CO
	• Energy Information Agency	Washington, DC
Industrial Coal Users	• Kaiser Cement	Cupertino, CA
	• PMC, Inc. (Chemicals)	Cincinnati, OH
	• Emory Chemicals	Cincinnati, OH
	• Archer Daniels Midland (Food Processing)	Decatur, IL
	• Campbell Soup	Napolean, OH
Grinding Facilities	• ABB/Combustion Engineering	Windsor, CN
	• Resource Engineering, Inc.	Waltham, MA (Mill in PA)
	• Microfuels, Corp.	Ely, IO
DOE PETC	• Clifford Smith, Program Manager	Pittsburgh, PA

2.4 Results

2.4.1 Coal Selection Criteria

Four criteria were considered in the selection of coal properties for the combustion modeling and burner design tasks. These criteria are listed in order of importance to the program:

- Coal properties should be typical of coals used in common US industrial applications;

- Coal(s) selected should be characterized in sufficient detail (in the literature) that their combustion characteristics can be modeled with existing pyrolysis/char combustion correlations;

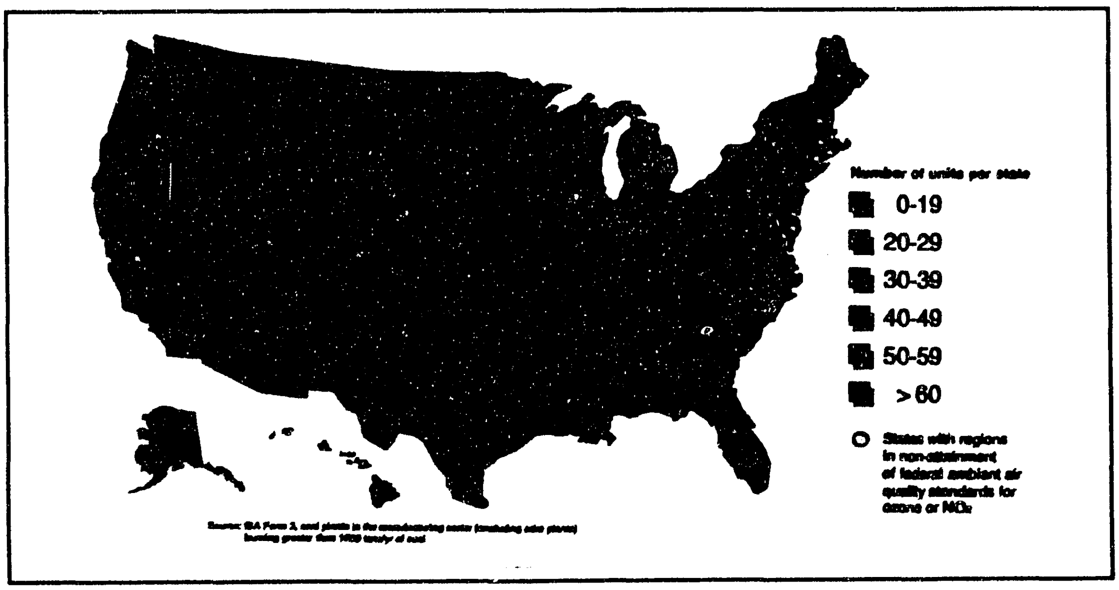
- Coal properties should be consistent with those of coals available for purchase in small quantities for (future) combustion tests at the MIT Combustion Research Facility; and

- Coal(s) should be representative of the type used in recent or ongoing burner development work (sponsored by DOE or industry) so that the results of these programs are comparable.

2.4.2 U.S. Industrial Coal Use

Figure 1 shows the distribution of US industrial coal-fired boilers/furnaces. These coal-fired combustors include all boiler types, such as stoker fired boilers, pulverized coal boilers, and fluidized bed boilers. They also include furnaces such as cement kilns. This map shows that the states with the highest industrial coal-use are Ohio and Pennsylvania. In Ohio there are a total of 91 industrial combustors (other than coke plants) that operate on coal. In Pennsylvania there are 60 industrial facilities burning coal. Other states with high industrial coal usage include Michigan (59 facilities), Illinois (37 facilities), Tennessee (31 facilities), and Kentucky (34 facilities). All these states have regions of non-attainment of National Ambient Air Quality Standards (NAAQS) for ozone or NO_2, indicating that expansion of coal use in these states may be limited by NO_x emissions from existing and/or new facilities.

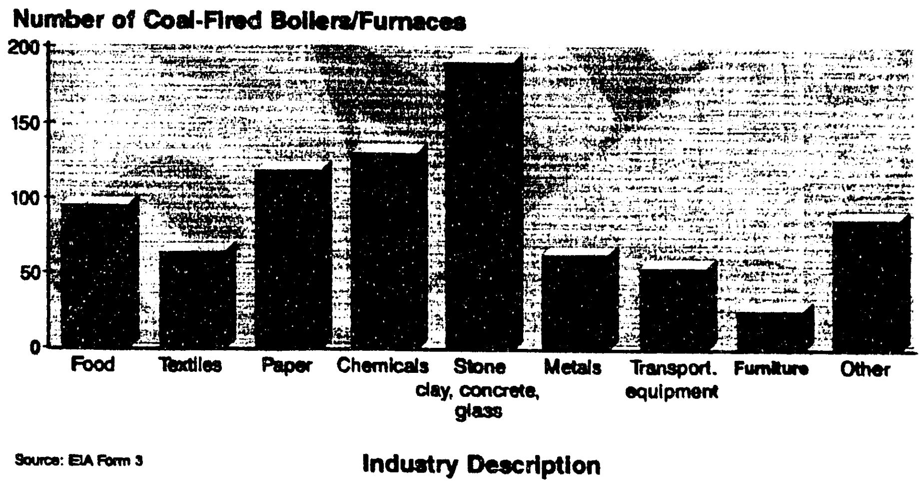
Figure 1: Distribution of US Industrial, Coal-Fired Boilers/Furnaces



The data in the map in Figure 1 comes from the Energy Information Agency Form EIA 3, a mailing list of manufacturing facilities (excluding coke plants) burning more than 1,000 tons/year of coal (see Appendix A). These data provide insight to areas of coal use in general and areas of potential expansion of coal use in the future. These numbers do not correspond directly to potential markets for the low NO_x burner under development because some of the boiler/furnace geometries are incompatible with retrofit pulverized coal-fired burners (e.g., fluidized bed boilers or some stoker boilers).

Figure 2 shows that the largest percentage of coal-fired facilities in US industry is in the combined industrial sector of stone, clay, concrete, and glass manufacture/processing. This usage is dominated by the cement industry, which uses coal to fire kilns in Portland cement plants. Other industries operating significant numbers of coal plants include: chemicals, paper, food, and textiles. The data for this analysis were also derived from the EIA Form 3.

Figure 2: Distribution of Coal-Fired Boilers and Furnaces by Industry

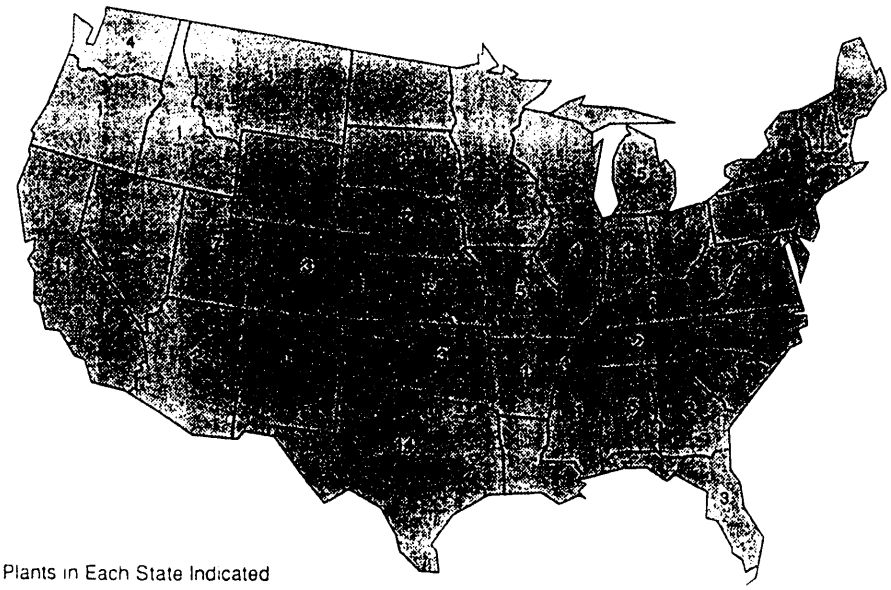


The distribution of Portland cement plants in the US is shown in Figure 3. This figure shows large numbers of coal-fired cement plants in Pennsylvania, Texas, Utah, and California. All of these states have regions in non-attainment of NAAQS for ozone or NO_2. Most California coal-fired cement kilns operate on Utah bituminous coal.

2.4.3 Interviews with Coal Sales and Coal Use Industries/Associations

Interviews with coal sales and coal use representatives indicated that coal selection in US industry is based on delivered coal price. The price of the coal is determined by both the coal cost (FOB mine) and the coal transportation cost. Therefore, coal users tend to use local coals to minimize transportation costs. In some cases, coal selection

Figure 3: Distribution of Coal-Fired Portland Cement Manufacturing Plants



Number of Plants in Each State Indicated

is limited by access to rail lines between mine and user site, thereby limiting a boiler operator's choice in coals. Industrial coals are typically bituminous. Coal ash and sulfur contents vary widely by application. Generally, however, the coal ash content is approximately 8 to 12%; the sulfur content can vary from 0.8 to 4.5%. The nitrogen content of bituminous coal ranges from 1.2 to 1.8%.

In the cement industry, coal properties vary widely by site. Kilns can take high or low sulfur coals depending on the necessary chemical balance for the cement manufacture. Generally, higher volatile content (>20%) are desired for kiln applications. Kilns typically run on highly preheated combustion air (from recuperated heat), with secondary air temperatures up to 2000°F. The cement plants contacted indicated a need for NO_x controls on existing and future facilities.

The analysis of US industrial coal use indicated that there is no "typical" industrial coal. However, it did show that coal use is driven by price and that local coals are frequently selected for cost effectiveness. Therefore, coals from Pennsylvania and Ohio were candidate coals for selection for the NO_x burner development program because these states have the most coal-fired industrial facilities in the US. It is likely that many coal-fired industries in Michigan (another state with high numbers of coal-fired industrial boilers/furnaces) would use coal from these states as well. Alternatively, bituminous coals from Utah, representing the coal used in the cement industries in California and Utah, may provide a useful alternative coal.

The discussions and interviews with members of the coal burning industry, relative to using coal, revealed a number of concerns. These concerns are summarized in Table 2.

Table 2: Concerns of Coal Burning Industry Relative to Using Coal

Type of Coal User	Use Description	Concern
Boiler, Cement, and Glass Melting Industrial Processes	• Employ large, often single burners • High forward velocity is used to maximize coal particle residence in flame • Long flames • Use of stokers is predominant	• Incomplete burn-out (soot) • Char impingement on furnace walls and heat exchange surfaces (erosion) • Char entrapment in ash (loss of heating value) • Blockage of flue gas passages • Disposal of ash • Auxiliary fuel (gas or oil) often required for more complete combustion • Small coal-fired burners are not commercially available • Permitting is difficult to obtain (burner performance varies widely with coal type and quality; non-attainment frequently experienced) • High NO_x emissions
Brick Tunnel Kiln	• Utilize multiple small burners • Burner performance characteristics must be similar to gas or oil • Stokers not applicable (expensive, dirty, high maintenance)	
Small Industrial Boilers	• Utilize small burners with gas/oil combustion characteristics	

In reviewing these coal burning industry concerns, it is apparent that the low NO_x pulverized coal burner design directly addresses a number of the concerns cited in Table 2:

- The low NO_x coal burner can be scaled down to approximately 3.0 MMBTU/h firing rate;

- It is expected to develop a flame envelope similar to an equivalent oil fired burner;

- It employs pneumatic coal transport to each burner. Stokers cannot be used;

- Pre-volatilization in flue gas lift line will ensure more complete carbon burn-out (Kobayashi has determined that devolatilization has a profound influence on combustion of pulverized coal. The rate of evolution of volatiles, and the volatile yield influence ignition and flame stability);

- Anticipated forward flame velocity will be 100-200 actual fps. Therefore, the burner flame may not be long enough for cement kilns. However, it will be highly useful for glass melting, tunnel kiln, and boiler applications;

- Lower brick erosion can be expected due to lesser velocity of char impingement;

- Better defined burning characteristics will improve permitting process; and

- Low NO_x emission may bring the process into compliance with regulatory emission limits.

2.4.4 Review of Coals Well Characterized by Fundamental Combustion/Pyrolysis Experiments

A brief literature review of coal pyrolysis and char combustion work was conducted to determine what coals have been used in fundamental experimental studies of coal combustion/NO_x formation. This information is important for coal selection because the coal chosen needs to be characterized sufficiently well to enable modeling the coal pyrolysis, NO_x formation, and char combustion mechanisms in the low NO_x burner. Table 3 summarizes the papers reviewed and the coals included in these studies.

Table 3: Summary of Literature Reviewed

Paper Topic	Authors	Coals Studied or Referenced
Coal Pyrolysis	Kobayashi, Howard, and Sarofim	• Montana Lignite-A (Savage Mine) • Pittsburgh #8 hvA-bituminous (Ireland Mine)
	Ubhayakar, Stickler, Von Rosenberg, and Gannon	• Pittsburgh Seam Bituminous
	Suuberg, Peters, and Howard	• Montana Lignite-A (Savage Mine) • Pittsburgh #8 hvA-bituminous (Ireland Mine)
	Anthony, Howard, Hottel and Meissner	• Montana Lignite-A (Savage Mine) • Pittsburgh #8 hvA-bituminous (Ireland Mine)
Char Combustion	Hurt and Hardesty (Sandia)	• PETC Suite of Coals – Lower Kittaning, lvb – Pocahontas #3 lvb – Pittsburgh #8 hvb – Illinois #6 Utah hvb – Dietz subbit – Lower Wilcox Lignite
	Lester, Seeker, and Merklin	• Pittsburgh Seam Bituminous Illinois #6
	Laurendeau	• Various (review paper)
	Smith	• New Zealand bituminous
NO_x Formation • Nitrogen Devolatilization and Oxidation	Pohl and Sarofim	• Montana Lignite-A (Savage Mine) • Pittsburgh #8 hvA-bituminous (Ireland Mine)
• NO_x destruction during fuel rich combustion	Glass and Wendt	• Utah Bituminous
• Thermal and fuel NO_x	Pershing and Wendt	• Colorado Pittsburgh #8 Western Kentucky Montana subbit
	Wendt, Pershing, Lee, and Glass	• Western Kentucky Coal

The coals of interest repeatedly referenced in these papers include Pittsburgh Seam coals, specifically #8. This coal is a medium-to-high volatile bituminous coal with ash content of 8 to 10%, moisture of 2 to 5%, and sulfur content of 1.5 to 3.5%.

There are some studies that include work with Utah bituminous coals, which are also of interest to this program because of its use in the cement industry in California and Utah.

2.4.5 Preliminary Recommendations for Coal Selection

On the basis of the above review, the coals that adequately meet the requirements of the project include:

- Pittsburgh Seam bituminous
- Pittsburgh #8
- Utah Bituminous Coals (Castlegate, Sunnyside)

All of these coals are well characterized, available for purchase in small quantities, and are representative of coals used by US industry. The Pittsburgh #8 Seam is mined both in Pennsylvania and Ohio. In fact, almost 20% of total Ohio coal production is from the Pittsburgh #8 Seam. Pittsburgh Seam coal also provides about 25% of the total Pennsylvania coal production. It is produced almost entirely from very large underground mines.

After review by the program team of the three options, Pittsburgh #8 bituminous coal was selected. Its physical properties are as follows:

• Size	30 microns (mean partical dia)
• Volatile content	35 wt-%
• Fuel-bound N	1.4 wt-%
• Heating value	13,000 Btu/#
• Ash content	< 5 wt-%
• Moisture	< 3 wt-%
• Swelling index	Low
• Availability	Several sources

3.0 Poster Session Presentation at PETC Contractor's Review Meeting

A poster was presented at the PETC Contractor's Review meeting on 29 July 1992 in Pittsburgh, Pennsylvania. The poster presentation summarized the program objectives, approach, team, low NO_x burner concept, and results of the preliminary market analysis conducted at the start of the program. A plan for modeling the performance of the low NO_x burner was also presented.

4.0 Preliminary Design/Process

A mid-range burner size was selected for the modeling study. Although a variable area jet-pump nozzle would benefit the low-end of the turndown, a fixed nozzie was chosen for this design phase. The parameters are as follows:7

• Maximum firing rate	5.0 million Btu/hr
• Turndown	TBD
• Exit velocity	> 50 afps
• Secondary air jet velocity	150 to 250 afps

For the combustion process, it was determined that flue gas recirculation (FGR) and air staging would be incorporated in the NO_x control strategy. Benefits from pre-volatizing coal particles in the flue gas duct (in-line) will be assessed. The process specifications are as follows:

• FGR	20 to 40 wt-%
• FGR temperature range	1,500 to 2,000
• Air staging	20 to 60%
• Air preheat	800°F
• Residence time	50 to 200 ms
• Lift line velocity	> 20 afps
• O_2 in combustions product	< 5%

5.0 Modeling

It was determined that three models may be required to map out the low NOx performance in fuel-rich Zone 1 of the PC burner:

- Model-1 will be a one-dimensional heat transfer and devolatilization model. It will describe the lift line process and facilitate (hand) computation of the residence time required for heating and devolatilizing of coal particles in the presence of hot recirculating flue gas. A determination will also be made of the fraction of volatile nitrogen (N) liberated from coal.

- Model-2, a jet entrainment model, will focus on the jet pump region, and help compute the entrainment of flue gas, volatiles, and char by the turbulent air jet. The model will also examine the mixing process, and predict the kinetics of the ensuing reactions. The stickiness and agglomeration of coal particles will be addressed, and methods for avoiding build-up of coal/ash will be suggested.

- Model-3, the NO_x model, will look at the conversion of FBN to N_2, at flame temperatures, specie concentrations, and the kinetics of reactions. NO_x concentrations will be predicted for a fully mixed precess. Stoichiometry of the fuel-rich zone will be selected for minimum NO_x production.

Another model will be used to characterize the mixing of the primary char and Zone-1 combustibles with the secondary air. That model will combine the results from chemical kinetic modeling of the fuel-rich zone with the results from a computational fluid dynamic *(Fluent)* model to determine the residence time for complete oxidation of unburned char in the fuel-lean NO_x Zone-2.

6.0 Plans for the Next Reporting Period

In the third quarter of the program (October 1992 - December 1992), the following activities are planned:

- Complete lift-line design of the burner on the pyrolsys analysis of the model;

- Define the mixing and burning zones of the burner based on its kinetic model; and

- Establish NO_x predictions for the rich burning zone of the burner.

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