DEVELOPMENT AND TESTING OF A NOVEL COAL PREHEATING TECHNOLOGY FOR NO_x REDUCTION FROM PULVERIZED COAL-FIRED BOILERS

Joseph Rabovitser
Bruce Bryan
Richard Knight
Sergei Nester
Stan Wohadlo
Gas Technology Institute
1700 South Mount Prospect Road
Des Plaines, Il 60018-1804

Anatoly G. Tumanovsky
Eugene N. Tolchinsky
Edward H. Verbovetsky
Ministry of Fuel And Power of Russia
ALL-RUSSIAN THERMAL ENGINEERING INSTITUTE
14/23, Avtozavodskaya Str.
MOSCOW, 109280, RUSSIA

Robert Lisauskas
Roderick Beittel
Terrence Ake
Babcock Borsig Power, Inc.
45 McKeon Road
Worcester, MA 01610

ABSTRACT

The Gas Technology Institute's (GTI's) METHANE de-NOX® for PC Boilers is a NO_x reduction process being developed under a Cooperative Agreement with the U.S. DOE to provide a cost effective, combustion-based alternative to SCR. The technology combines GTI's proven METHANE de-NOX reburn technology with a pulverized coal-preheating approach developed for utility PC boilers by the All-Russian Thermal Engineering Institute (VTI). Development targets include NO_x reduction to below 0.15 lb/million Btu, reduced CO_2 emissions, and 55% electricity cost reduction compared to SCR. GTI and VTI are joined in the project by Babcock Borsig Power (BBP), providing commercial PC burner design expertise and testing facilities for 3- and 100-million Btu/h preheat burner prototypes in their Coal Burner Test Facility (CBTF). The paper presents results of VTI's laboratory and scale up (60 MW_{th}) PC Preheat burner field tests with Russian coals, results of GTI's firing tests and CFD modeling of a natural gas-fired PC preheat combustor along with the status of design and installation of a 3-million Btu/h pilot unit at the CBTF for firing tests with U.S. utility coals.

INTRODUCTION

Over half of the electric power generated in the U.S. is produced by coal combustion, and more than 80% of these units utilize PC combustion technology. Conventional measures for NO_x reduction in PC combustion processes rely on combustion and post-combustion modifications. In general, combustion modification technologies try to reduce the formation of NO_x precursors while destroying already-formed NO_x. This approach usually involves combustion staging and slow mixing to redistribute combustion and create a fuel-rich environment. These measures reduce oxygen levels in the NO_x formation zone and burn the fuel at lower peak flame temperatures. A variety of NO_x reduction technologies are in use today, including Low-NO_x Burners (LNB's), flue gas recirculation (FGR), air staging, and natural gas or other fuel reburning. Selective Non-Catalytic Reduction (SNCR) and Selective Catalytic Reduction (SCR) are post-combustion techniques. NO_x reduction effectiveness from these technologies varies from 30 to 60% and up to 90-93% for SCR.

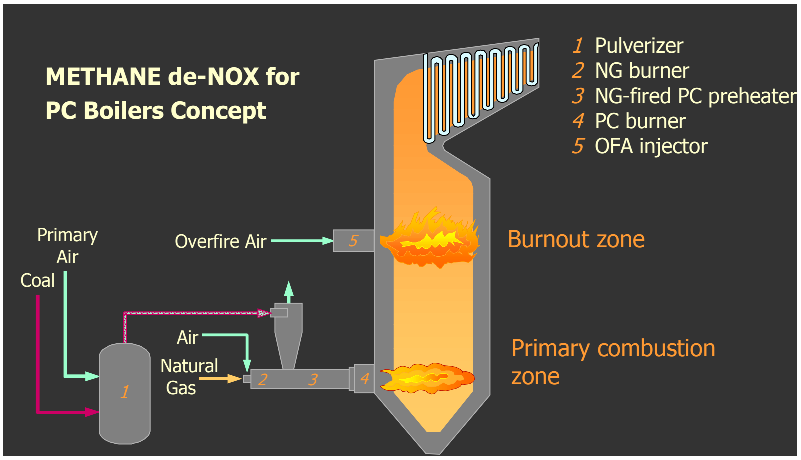
Typically, older wall-fired PC burner units produce NO_x emissions in the range of 0.8 - 1.6 lb/million Btu. Low-NO_x burner systems, using combinations of fuel staging within the burner and air staging by introduction of overfire air in the boiler, can drop the NO_x emissions by 50-60%. This approach alone is not sufficient to meet the desired 0.15 lb/million Btu NO_x standard with a range of coals and boiler loads. Furthermore, the heavy reliance on overfire air can lead to increased slagging and corrosion in the furnace, particularly with higher-sulfur coals, when LNB's are operated at substoichiometric conditions to reduce fuel-derived NO_x in the flame. Therefore, it is desirable to minimize the need for overfire air by maximizing NO_x reduction in the burner.

CONCEPT DESCRIPTION

The proposed combustion concept aims to greatly improve this situation by incorporating a novel modification to conventional *or* low-NO_x PC burners using *gas-fired coal preheating* to destroy NO_x precursors and prevent NO_x formation. A concentrated PC stream enters the burner where flue gas from natural gas combustion is used to heat the PC up to about 1500°F prior to coal combustion. Secondary fuel consumption for preheating is estimated to be 3 to 5% of the boiler heat input. This thermal pretreatment releases coal volatiles, including fuel-bound nitrogen compounds into oxygen-deficient atmosphere, which converts the coal-derived nitrogen compounds to molecular N_2 rather than NO.

The PC preheat combustion system under development for use with U.S. coals combines the VTI reheat burner with elements of GTI's METHANE de-NOX technology for NO_x reduction. METHANE de-NOX has been commercially demonstrated on coal, MSW, and biomass-fired stoker boilers in the U.S. and Japan. The advanced PC preheat system combines several NO_x reduction strategies into an integrated, low-NO_x PC combustion system, incorporating a novel PC burner design using natural gas-fired coal preheating and combustion staging in the coal burner. The schematic of the conceptual combustion system is shown in Figure 1. This integrated system can achieve very low NO_x levels–down to 0.15 lb/million Btu–without the complications, limitations, and expense of SCR technology.

Figure 1: Simplified Diagram of the PC Preheat NOx Reduction Concept for PC Boilers



This design improvement permits the boiler operator much more flexibility in burner operation, particularly with LNB's, to obtain the optimal balance of conditions necessary to achieve minimum NO_x along with acceptable carbon burnout. When combined with the third component, overfire air, this combustion control system can achieve NO_x reduction down to 0.15 lb/million Btu over a wide range of load swings without downstream amine-based NO_x reduction technology. In this system, natural gas is carefully introduced at selected points in the combustion process to lower NO_x emissions in three ways:

- Releasing and reducing NO_x precursors before they have a chance to react with oxygen to form NO or NO_2;
- Limiting NO_x formation in the PC flame via combustion staging in the burner;
- reducing NO_x formation in the coal combustion products by use of low excess air, followed with overfire air to complete burnout at lower temperature [1, 2, 3].

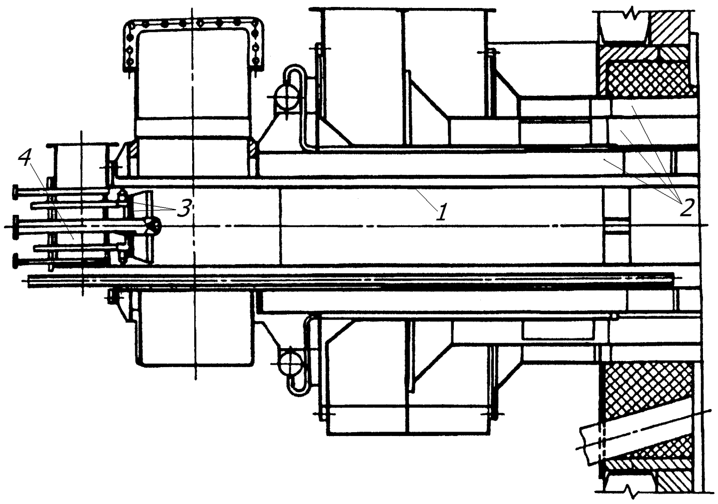
VTI'S BENCH SCALE AND FIELD TEST RESULTS

Pulverized coal preheating has been investigated by VTI with Russian utility coals[4, 5]. The technology consists of a burner modification that preheats PC to elevated temperatures (up to 1500°F) prior to combustion. This approach releases coal volatiles, including fuel-bound nitrogen compounds, into a reducing environment. Preferential conversion of coal-derived nitrogen compounds to molecular N_2 occurs, making the nitrogen unavailable for NO_x formation in the early stages of the combustion process. Other coal volatiles including H_2, CO, and hydrocarbons remain in the fuel stream, thus promoting easy ignition of the coal as it enters the combustion zone.

In one version of this burner, shown in Figure 2, natural gas is first combusted with air, and the hot flue gases are then mixed with the highly concentrated PC/primary air stream inside the burner. Because primary air has been reduced to the minimum level required to maintain entrainment, the coal devolatilization products provide an enhanced reducing atmosphere, which allows the reduction of NO_x precursors to occur.

This approach adds another degree of freedom to NO_x control strategies with either conventional or low-NO_x burners. In comparison to existing low-NO_x burner designs using substoichiometric coal combustion in the primary flame to provide a fuel-rich condition, the PC Preheat approach exposes the coal to very little oxygen during the release of volatile nitrogen components. By providing the heat for devolatilization from natural gas combustion, which produces far less NO_x than coal combustion due to low flame temperature and the absence of fuel-bound nitrogen, all coal combustion is delayed until most of the devolatilization and consequent release of fuel-bound nitrogen has taken place in an oxygen-deficient atmosphere. The quantity of natural gas fuel required for PC preheating is estimated to be 3 to 5% of the total burner heat input.

Figure 2: Diagram of Natural Gas Preheated PC Burner
(1 = PC preheater; 2 = secondary and tertiary combustion air;
3 = natural gas burner; 4 = PC/primary air mixture injector)

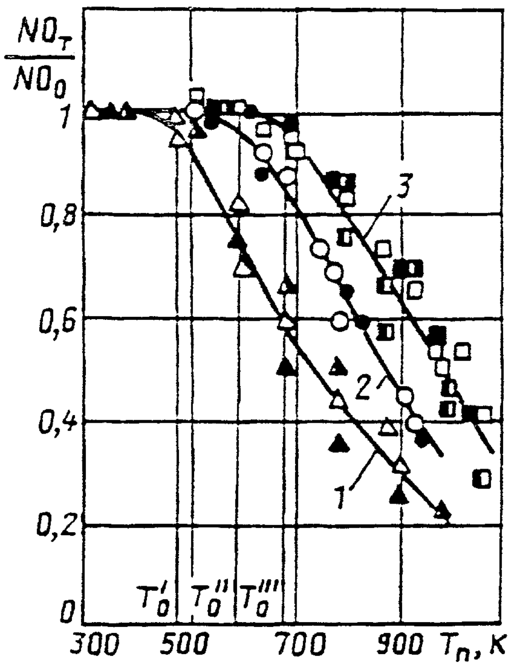


Basic combustion research, lab-scale testing, and field testing using the natural gas preheated PC burner were done at VTI in Moscow. Previous work at VTI in 1980-83 established the effects of coal thermal pretreatment in considerable detail. Five Russian coals were investigated with preheat temperatures up to 1508°F. Following promising laboratory studies, coal preheating for fuel NO_x reduction was scaled up and field-tested in a number of facilities:

- 1982-83 – a single burner was tested at a 3.8-million Btu/h (1.12 MW_{th}) demonstration facility;
- 1983-84 – a single 205-million Btu/h (60 MW_{th}) prototype burner was installed and tested through 1991at a 300-MW double boiler;
- 1994 – all 12 burners of the opposed-fired furnace were installed with preheating at a 420 t/h wet-bottom furnace;
- 1997-1999 – one burner at Kashira TPS 300-MW facility was equipped with an upgraded burner design

Figure 3 shows test data reported by VTI from their laboratory-scale combustion test rig. NO_x reduction performance versus preheat temperature of three different coals with varying levels of volatile matter content are shown: Coal #1 VM = 45%; SR = 1.16, 0.97, 1.18; Coal #2 VM = 25%; SR = 1.02, 1.19; Coal #3 VM = 13%; SR = 0.92, 1.09, 1.25 (VM = volatile matter; SR = air-to-fuel stoichiometric ratio). The burner coal feed consisted of PC and air mixed at a 1:1 (by mass) coal/air ratio. Time of combustion in the test rig ranged from 1 to 2 seconds, and combustion air was introduced to adjust stoichiometric ratio. As PC preheat reached coal devolatilization temperatures ($T_o^{\prime}$, $T_o^{\prime\prime}$, and $T_o^{\prime\prime\prime}$), NO_x levels started to decrease, and significant NO_x reduction was achieved at elevated PC temperatures, depending on the coal type. For instance, with coal #1, NO_x reduction reached 80% at PC preheat temperature of about 1000K (1340°F). Lower-volatile coals required higher preheat temperatures to reach equivalent levels of NO_x reduction.

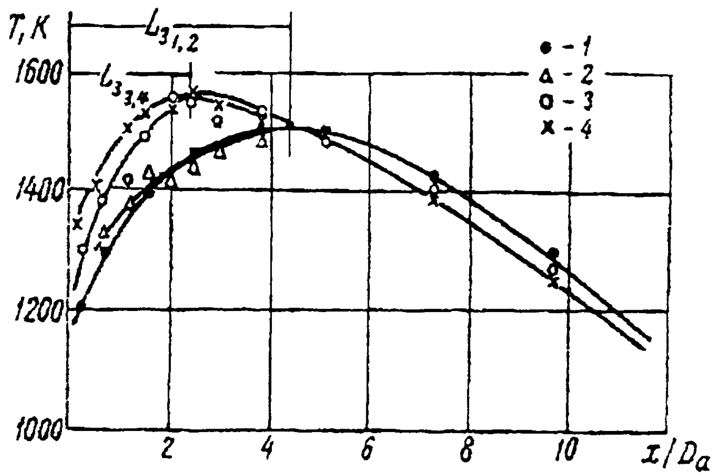
Figure 3. Fractional NOx Reduction versus PC Preheat Temperature



VTI's scale-up and field demonstrations of preheated PC burners have confirmed the effectiveness of NO_x reduction from coal preheating with Russian utility coals. With the 1.12-MW_{th} demonstration burner operating at a preheat temperature of 1085°F, NO_x was reduced by 60%, from 51.8 to 21.2 lb/10^6 ft^3. Because of the design constraints of the 1.12-MW_{th} unit, the preheat temperature was limited to about 1090°F, which prevented burner testing at elevated temperatures necessary to achieve 80% NO_x reduction. It was also established that the coal preheat considerably improved the coal ignition conditions. The temperatures in the near-axial zone of the backflow streams, at the flame close to the burner, and in the flame core increased, and the distance from the burner mouth to the maximum temperature zone was found to decrease by almost 50%. Figure 4 shows these data for four different coal preheat temperatures. NO_x emissions were significantly reduced *despite* the fact that maximum flame temperature increased by more than 100°F.

This is important, as it shows that the destruction of NO_x precursors through preheating is far in excess of any increase in NO_x formation from higher temperature, and that coal preheating may thus be able to confer operational benefits (improved flame stability and increased carbon burnout) at the same time as reducing NO_x formation. VTI has reported that preheating also intensifies flame ignition, and consequently, a wider turndown of the burner/boiler load range is anticipated without the need to use a backup fuel.

Figure 4. Preheated Coal Combustion Flame Temperature at Various Preheat Temperatures.
Preheat temperature: ● = 184°F; △ = 526°F; ○ = 796°F; ▲ = 895°F; × = 1084°F



Testing of the 60-$MWth_h$ burner at the Mosenergo Cogeneration Plant #22 focused on studying the operating conditions of the burner components. The maximum temperature of the fire tube wall was about 1770°F at its outlet, and the coal-air mixture temperature distribution over the fire tube section was found to be uniform. A blade swirler was also installed at the combustor outlet, causing the active burning zone temperature to rise. Tests at this facility in 1991 showed a 42% NO_x reduction, from 74.9 to 43.7 lb/10^6 ft^3 with a coal preheat temperature of 1112°F. Preheating was limited to this temperature because of a pulsation problem with the microflame gas burners employed.

1994 testing at the Izhevsk Cogeneration Plant #2, with all 12 burners of the 420-t/h boiler outfitted with coal preheating to 1202°F, showed a NO_x reduction of 56-67%. This result was obtained with natural gas usage amounting to 2.5-3.0% of the total heat release. At the same time, the flame temperature increased by 180-250°F, which contributed to stable flame and reliable liquid slag removal. VTI has also reported that the use of overfire air in conjunction with coal preheating in field operation has reduced NO_x by an additional 50-60%.

DEVELOPMENT OF PC PREHEAT TECHNOLOGY FOR U.S. UTILITY COALS

A development project sponsored by the U.S. DOE's National Energy Technology Laboratory (NETL), GRI, and GTI's Sustaining Membership Program (SMP), the PC Preheat concept is being developed and tested for commercial application with U.S. utility coals and U.S. PC firing methods.

Initial effort focused on comparison of Russian and U.S. utility coal properties and PC firing practices in order to evaluate the potential for, and guide the development of, applications of the PC preheat technology in the U.S utility market.

Coal Properties Study

Six U.S. coals were selected for initial screening, and four of these were chosen by the project team for comprehensive analysis. In addition, three Russian coals that had been studied extensively by VTI during development of the preheat burner technology were also evaluated using the same laboratory methods. The U.S. coals were selected to cover a wide range of physical and chemical properties and to present a suitable representation of coals widely used in U.S. PC boilers for power generation. The selection was made with the participation of two major U.S. electric utilities that have expressed interest in field demonstration of this technology. One Western coal and two Eastern U.S. coals, and one Illinois coal were chosen, and their major properties are shown in Table 1, followed by properties of the three Russian coals for comparison.

Most U.S. coals that are used in power generation have fairly high volatile matter content, which is required by the power plant fuel specifications. The selected U.S. coals are typical, and the NO_x reduction (see Table 2) is expected to be similar to that of Russian coals with similar volatile content. For example, at 1400°F preheat temperature, the NO_t/NO_0 ratio for U.S. Southern Appalachian bituminous coal (1261-02) is 0.255 (74.5% NO_x reduction) compared to 0.248 (75.2% NO_x reduction) for the Russian bituminous coal (1251-03) with similar volatile matter. Except for the Russian brown coal (1251-02), the nitrogen contents of the coals at equivalent heating value are also similar, so the NO_x reduction on a lb/million Btu basis is expected be similar. The validity of these predictions will be tested in pilot and commercial prototype tests in the current project.

Table 1. Analyzed Properties of Four U.S. and Three Russian Coals

COAL ORIGIN	US—Western	US—Central Appalachian	US—South Appalachian	US—Illinois Basin	Russia—lean coal	Russia—brown coal	Russia—bituminous
COAL ID #	1183-01	1261-01	1261-02	1261-03	1251-01	1251-02	1251-03
ASTM RANK	SubbitA	HVbitB	MVbit	HVbitC	Semianthr	SubbitB	HVbitC
PROXIMATE, % as rec'd							
Moisture	10.68	2.10	1.40	10.41	2.75	10.46	1.63
Ash	6.09	9.58	16.29	8.80	21.81	5.80	43.80
VM	37.54	32.13	26.82	34.52	11.58	41.64	18.21
Fixed carbon	45.69	56.19	55.49	46.27	63.86	42.10	36.36
ULTIMATE, % dry							
C	70.77	75.70	70.78	71.15	68.82	64.75	43.50
H	5.28	5.05	4.57	5.14	2.69	4.47	2.93
S	0.80	0.73	1.64	4.64	0.31	0.29	0.59
N	1.24	1.38	1.29	1.42	1.40	0.76	0.76
O (by diff)	15.09	7.35	5.20	7.83	4.35	23.25	7.69
Ash	6.82	9.79	16.52	9.82	22.43	6.48	44.53
HHV, Btu/lb dry	12,610	13,530	12,590	12,980	11,360	10,730	7,330
HHV, Btu/lb wet	11,263	13,246	12,414	11,629	11,048	9,608	7,211
Sulfur by type, % dry							
Sulfide	NA	< 0.01	< 0.01	0.02	< 0.01	< 0.01	< 0.01
Sulfate	NA	0.03	0.23	0.21	0.03	0.06	0.11

COAL ORIGIN	US—Western	US—Central Appalachian	US—South Appalachian	US—Illinois Basin	Russia—lean coal	Russia—brown coal	Russia—bituminous
Pyritic	NA	0.15	0.56	1.92	0.14	0.07	0.29
Organic	NA	0.55	0.85	2.49	0.14	0.16	0.19
Total	0.80	0.73	1.64	4.64	0.31	0.29	0.59
FSI	0.0	4.5	7.0	4.5	0.0	0.0	0.0
Particle density, lb/ft^3	78.7	81.9	84.8	74.9	NA	NA	NA
Ash fusion temp, °F							
Reducing							
Initial	2085	2360	2670	2165	2375	2280	2700
Softening (H=W)	2100	2410	2695	2180	2440	2345	2700
Hemispherical	2120	2460	2700	2210	2510	2360	2700
Fluidity	2140	2515	2700	2250	2590	2380	2700
Oxidizing							
Initial	2200	2515	2700	2405	2585	2370	2700
Softening (H=W)	2215	2540	2700	2435	2615	2395	2700
Hemispherical	2240	2575	2700	2470	2640	2415	2700
Fluidity	2265	2605	2700	2510	2675	2450	2700
Ash composition, %							
Na_2O	3.07	0.49	0.27	0.50	0.53	0.44	0.22
MgO	5.06	1.64	0.68	0.73	0.80	3.66	0.22
Al_2O_3	13.65	24.00	23.44	17.65	19.09	8.24	29.11
SiO_2	29.95	52.41	61.82	40.64	60.96	19.96	61.82
P_2O_5	< 0.20	0.11	< 0.11	< 0.11	0.32	< 0.18	0.34
SO_3	12.17	4.44	0.46	2.50	1.01	7.54	0.05
K_2O	1.25	3.61	2.22	2.11	2.57	0.59	0.86
CaO	19.17	3.44	0.49	2.08	1.75	33.02	0.31
TiO_2	0.65	1.20	1.82	0.82	0.87	0.42	1.25
ZnO	0.61	0.00	0.00	0.00	0.00	0.00	0.00
BaO	0.31	0.00	0.00	0.00	0.00	0.00	0.00
Fe_2O_3	9.27	6.66	7.21	27.60	9.50	16.59	4.85
Unidentified	4.85	1.99	1.60	5.37	2.61	9.54	0.99

Table 2. Predicted NO_x Reduction for U.S. and Russian Coals

COAL ORIGIN	US—Western	US—Central Appalachian	US—Southern Appalachian	US—Illinois Basin	Russia—lean coal	Russia—brown coal	Russia—bituminous
COAL ID #.	1183-01	1261-01	1261-02	1261-03	1251-01	1251-02	1251-03
ASTM Rank	SubbitA	HVbitB	MVbit	HVbitC	Semianthr	SubbitB	HVbitC
VM, %maf	45.10	36.38	32.58	42.73	15.35	49.73	33.37
N content, lb/Million Btu	0.98	1.02	1.03	1.09	1.23	0.71	1.04
Preheat Temp, ° F	----------------------------- Predicted NO_t/NO_0 ratio -----------------------------						
800	0.587	0.674	0.713	0.610	0.920	0.543	0.705
900	0.508	0.591	0.628	0.531	0.813	0.466	0.621
1000	0.433	0.513	0.548	0.454	0.720	0.392	0.541
1100	0.360	0.437	0.471	0.381	0.635	0.320	0.464
1200	0.289	0.364	0.397	0.309	0.554	0.250	0.390
1300	0.220	0.293	0.325	0.240	0.477	0.182	0.318
1400	0.152	0.224	0.255	0.172	0.403	0.115	0.248
1500	0.086	0.156	0.187	0.105	0.331	0.049	0.180

To obtain more detailed information, the pyrolysis behavior of each coal was further investigated by means of a pyrolysis-gas chromatograph (Py-GC) method. The device used for this evaluation was a CDS Pyroprobe. In this apparatus, a 1-mg coal sample in a quartz tube was preheated to 550°F under helium to remove moisture and adsorbed gases, then heated rapidly to the desired pyrolysis temperature by capacitive discharge through a platinum coil surrounding the sample. The heating rate and final temperature are programmable. For these analyses, a heating rate of 10,000 °F/s was selected to represent the preheating section of the burner, and final temperatures of 1200°, 1400°, and 1600°F were studied. The Py-GC method yields a "pyrogram" which shows the distribution of volatile components as measured by a flame ionization detector (FID). The chromatograms were integrated in six ranges: C_1-C_4, C_5-C_6, C_6-C_{12}, C_{12}-C_{18}, C_{18}-C_{24}, and C_{24}-C_{40}. The method is unable to measure hydrocarbons above C_{40}, but GTI's experience with coal pyrolysis has shown that this fraction is typically less than about 2% of total volatiles. Results for the four U.S. coals and three Russian coals are shown in Table 3.

Table 3. Pyrolysis-GC Data for Four U.S. and Three Russian Coals

COAL ORIGIN	US—Western	US—Central Appala-chian	US—South Appala-chian	US—Illinois Basin	Russia—lean coal	Russia—brown coal	Russia—bituminous
COAL ID #	1183-01	1261-01	1261-02	1261-03	1251-01	1251-02	1251-03
ASTM RANK	SubbitA	HVbitB	MVbit	HVbitC	Semianthr	SubbitB	HVbitC
ASTM VM, %maf coal	45.1	36.4	32.6	42.7	15.3	49.7	33.4
Pyrolysis at 1200°F	% by weight of MAF coal						
C_1-C_4	8.7	7.0	5.7	8.0	1.9	3.3	5.9
C_5-C_6	2.2	4.5	3.5	3.5	0.5	1.9	1.5
C_6-C_{12}	11.3	10.1	5.6	10.5	0.9	6.4	4.9

COAL ORIGIN	US—Western	US—Central Appala-chian	US—South Appala-chian	US—Illinois Basin	Russia—lean coal	Russia—brown coal	Russia—bituminous
C_{12}-C_{18}	13.1	7.5	3.9	12.3	0.8	6.7	3.7
C_{18}-C_{24}	11.3	6.3	3.3	6.9	0.7	4.7	2.7
C_{24}-C_{40}	9.1	7.9	5.0	14.5	1.7	5.0	4.4
Total	55.6	43.4	27.0	55.7	6.5	28.1	23.1
Pyrolysis at 1400°F							
C_1-C_4	10.8	7.1	8.9	7.9	3.0	7.5	9.2
C_5-C_6	2.6	3.2	2.7	3.2	0.9	2.4	1.6
C_6-C_{12}	11.7	10.5	6.8	11.8	1.1	7.5	4.9
C_{12}-C_{18}	10.6	8.6	4.7	12.5	0.5	5.7	2.4
C_{18}-C_{24}	9.1	7.8	4.3	6.4	0.3	3.6	1.6
C_{24}-C_{40}	7.6	10.3	6.4	11.9	0.9	3.6	2.6
Total	52.4	47.6	33.8	53.7	6.8	30.3	22.4
Pyrolysis at 1600°F							
C_1-C_4	9.7	9.1	7.7	9.7	5.8	9.0	11.9
C_5-C_6	3.5	3.6	2.2	3.0	0.5	1.8	1.5
C_6-C_{12}	13.5	10.4	7.0	12.6	1.2	8.2	4.9
C_{12}-C_{18}	10.5	6.9	5.5	13.2	0.6	6.3	2.4
C_{18}-C_{24}	8.7	5.9	5.3	7.1	0.4	3.9	1.6
C_{24}-C_{40}	6.2	7.4	8.1	13.5	1.6	7.3	2.7
Total	52.0	43.3	35.8	59.0	10.2	36.5	25.1

These data show that there are very significant differences in devolatilization behavior between the four selected U.S. coals and the Russian coals. Based on the fraction of the coal organic matter, the release of volatile hydrocarbons was found to be greater for U.S. coals than for Russian coals, with the exception of the highest-volatile Russian coal 1251-02 which is comparable to the lowest-volatile U.S. coal 1261-02. These data are being further interpreted and utilized for burner design as the project progresses.

Another important consideration for burner design is the agglomerating or caking properties of bituminous U.S. coals with mild to strong agglomerating tendency. This property is not normally important for PC combustion, but it will be important in the preheating burner, which functions similarly to an entrained coal pyrolysis reactor. None of the Russian coals had significant caking tendency. The pilot test burner will incorporate design features into the burner that will facilitate operation with agglomerating coals. Key design issues include:

- Ejection of coal particles from the PC delivery tube prior to development of mesophase (sticky phase) at approximately 660-750°F
- Rapid dispersion and mixing of the coal particles into the preheating medium (gas burner combustion products)
- Heat transfer to the coal particles sufficient to destroy the agglomerating property prior to wall contact

The natural gas burner is designed with these issues fully addressed, based on extensive published studies of pyrolysis of caking coals and direct GTI experience with coal pyrolysis. CFD modeling was utilized to model the gas velocity profiles, temperature and pressure distributions, particle trajectories, heat transfer, and mass transfer properties in the burner under design operating conditions.

Based on these data, the design case (US—Illinois Basin Coal 1261-03, preheat temperature 1400°F) is projected to result in a NO_x reduction of 82.8%, compared to uncontrolled PC combustion. Combustion air staging (LNB design) and application of METHANE de-NOX reburning is projected to reduce NO_x by an additional 50%, resulting in an overall NO_x reduction of 91.4%. Based on current PC boiler NO_x emissions of 0.8-1.6 lb/million Btu, the projected flue gas emissions will be 0.07-0.14 lb/million Btu.

Modeling Results

The PCP gas combustor was designed using three-dimensional CFD modeling. A parametric modeling study of the PCP combustor performance was done by varying geometry of the combustion chamber, injection arrangements for the gas/air mixture and PC/air mixture, and the composition of selected pulverized coals shown in Table 1. FLUENT CFD software from Fluent, Inc., was used for these studies. The different configurations then were compared based on the required operating parameters, which include temperature level and temperature uniformity inside the combustion chamber, uniformity of mixing patterns of the combusted gas and solids, uniformity of trajectory patterns of the injected particles inside the combustor, and sufficient residence time for the particles' moisture release and devolatilization. One of the main requirements for the design was to avoid interaction of injected solids and gas/air mixture before ignition of natural gas flame, so the flame would not be extinguished by the cold particles. Another important requirement was to minimize the interaction of the solids inside the combustion chamber and the chamber walls by optimizing the flow pattern and trajectories of the particles.

Geometry and Mesh

Figure 5 shows the outline of the combustion chamber as well as the inlet ports for one of the computed cases. Meshes with approximately 70,000 cells have been generated (Figure 6) for the modeled cases. The computational domain is filled with an unstructured tetrahedral and hexahedral mesh. A refined mesh has been employed around the inlet ports to allow the cell size to grow from the areas with the high strain rates to the rest of the domain. With this approach it was possible to resolve recirculation pattern of gas flow and possible recirculation patterns of the solid particles. The mesh was further refined during the calculations in the areas with high rates of devolatilization of solids.

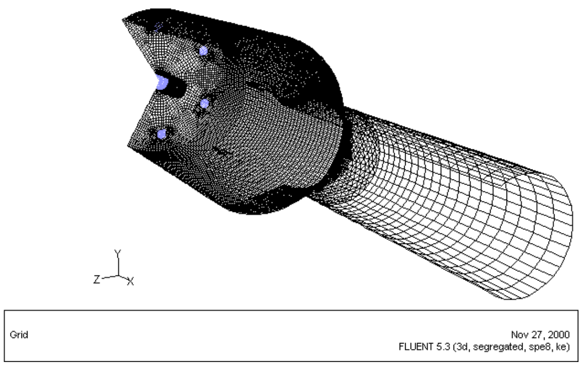


Figure 5. PCP burner, computational domain

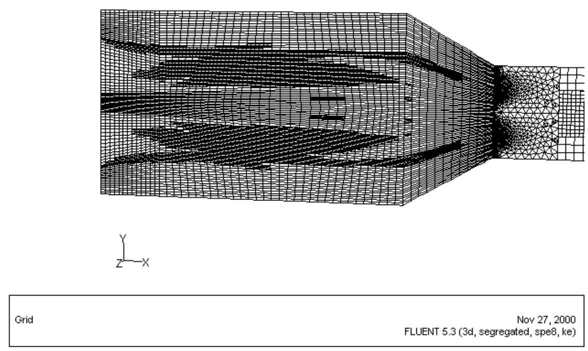


Figure 6. 3D computational mesh, Combustion chamber, Symmetry plane through the NG/Air injection nozzles center line.

Boundary Conditions

Total mass flow of all injected agents in the combustion chamber is given in Table 4 and was kept unchanged for all modeled cases for better comparison. Coal properties for the model were calculated based on chemical analysis of the selected coals performed in GTI's Chemical Lab (see Table 1).

Particles are set-up with 9 different particle sizes. Diameters between 30 μm and 150 μm have been used. The size distribution has been applied based on typical coal size distribution analysis for PC burners. [6] The boundary conditions (injection velocities) for the computed case were set up based on chemical composition and size distribution of coal and design requirements set in Table 4. Constant temperature boundary conditions were considered for combustion chamber walls. In order to preserve a consistent basis for comparison, boundary conditions were kept unchanged for all computed cases.

Burner heat input was also kept unchanged for all computed cases. Approximately 10 % of the total 3-million Btu/h heat input is delivered by natural gas and 90% by pulverized coal.

Physical Models

The CFD simulation of any solid fuel combustor (e.g. pulverized coal furnace) involves modeling of turbulent fluid flow, particle flow, heat transfer including radiation, homogenous and heterogeneous combustion reactions, and heat and mass transfer between solids and gas. In addition, numerous boundary conditions are required to describe entering flows, thermal conditions at the wall, and fuel properties. A number of models were used for simulating the PCP gas combustor. Flow, heat transfer, and species transport models were enabled. The standard k-ε model was deployed for turbulence modeling. The Discrete Ordinates radiation model has been used for radiative heat transfer. The particle tracking includes laws for inert heating, drying (wet combustion model), devolatilization, and char burnout. Radiation interaction between particles and the furnace environment was also enabled. Chemical reactions were modeled using the Eddy-Break-Up model. The reaction mechanism was based on a 4-step mechanism with carbon monoxide and hydrogen as intermediate combustion species. The stoichiometric coefficients were determined from the fuel analysis for each fuel (coal, volatiles, and methane) separately.

The CFD design approach is illustrated in Figure 7 to Figure 10 showing trajectories of 30 µm PC particles colored by particle mass for four different burner designs

Figure 7. Design is not optimal, Stream #1, 30 µm, colored by the particle mass, 90% devolatilization

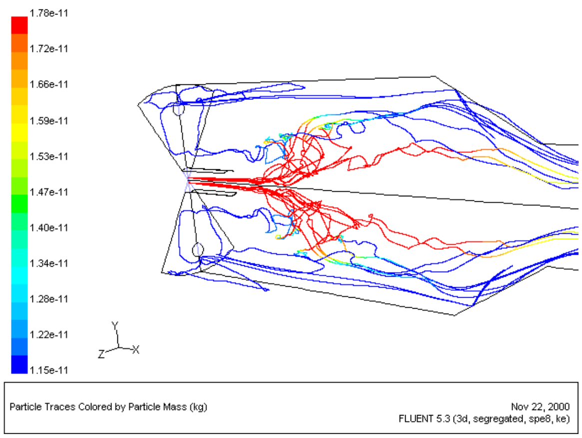


Figure 8. Design is not optimal, Stream #1, 30 µm, colored by the particle mass, 70% devolatilization

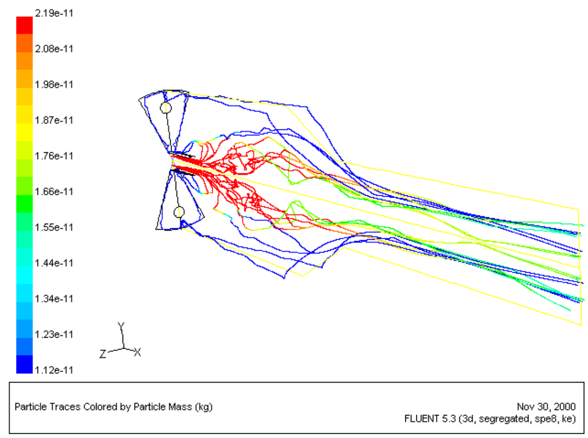


Figure 9. Design is not optimal, Stream #1, 30 µm, colored by the particle mass, 62% devolatilization

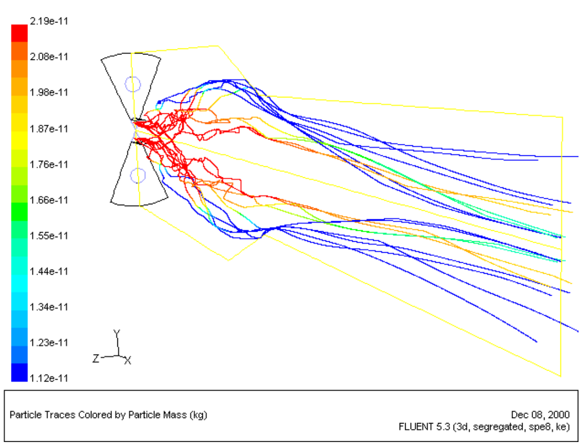
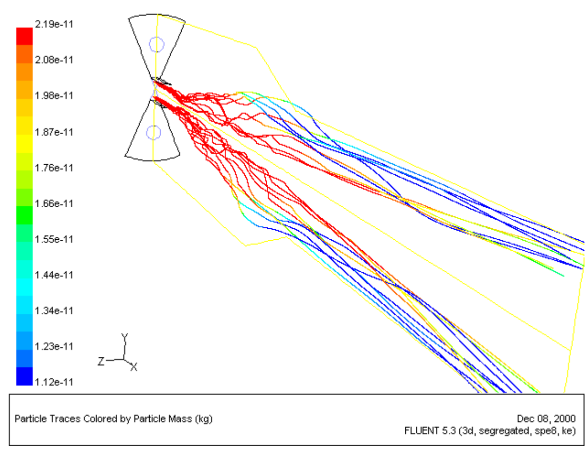


Figure 10. Optimized geometry, Stream #1, 30 µm, colored by the particle mass, 90% devolatilization



In Figure 7 and Figure 8 particles are entrained by the recirculation flow to the area of gas/air inlets and into the natural gas flame ignition area. Mixing of the cold particles and the gas/air mixture prior to ignition can extinguish the flame and lead to unstable operation of the PCP combustor. Particle trajectories also exhibit intensive interaction of the solids with the combustion chamber walls, which can lead to deposition of solids on the walls. The case shown in Figure 9 presents a more uniform flow pattern for the particles, but the degree of devolatilization inside of the combustion chamber is rather low. Finally, the optimized design is shown in Figure 10. Here the trajectories of the pulverized coal particles do not interact with the walls, and devolatilization inside the combustion chamber is sufficiently high.

Figure 11 through Figure 13 present more insight on the flame and flow inside the combustion chamber for optimized design. Flow path lines (see Figure 11) show no strong recirculation pattern, which could bring cold coal particles to the gas/air inlets. Coal devolatilization for the optimized case is shown in Figure 12 and Figure 13. The pattern of devolatilization is uniform, and the walls are shielded from solids by combustion products.

Figure 11. Flow path lines, nozzle centerline

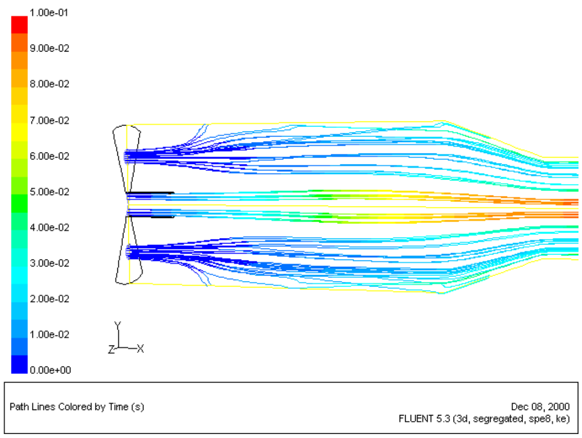


Figure 12. Mole fraction of volatiles along nozzle centerline

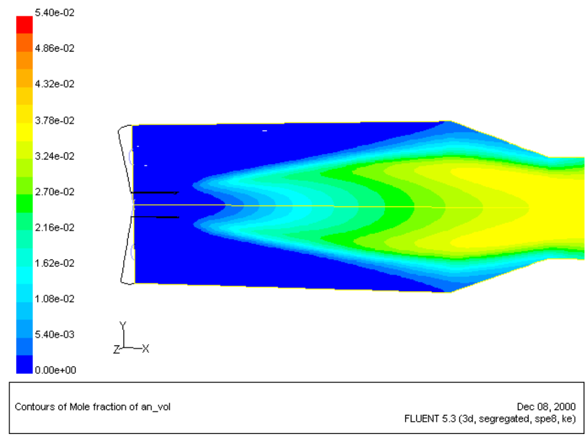
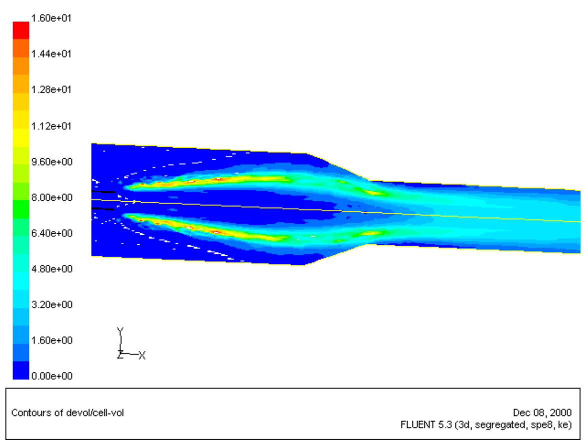


Figure 13. Rate of devolatilization along nozzle centerline

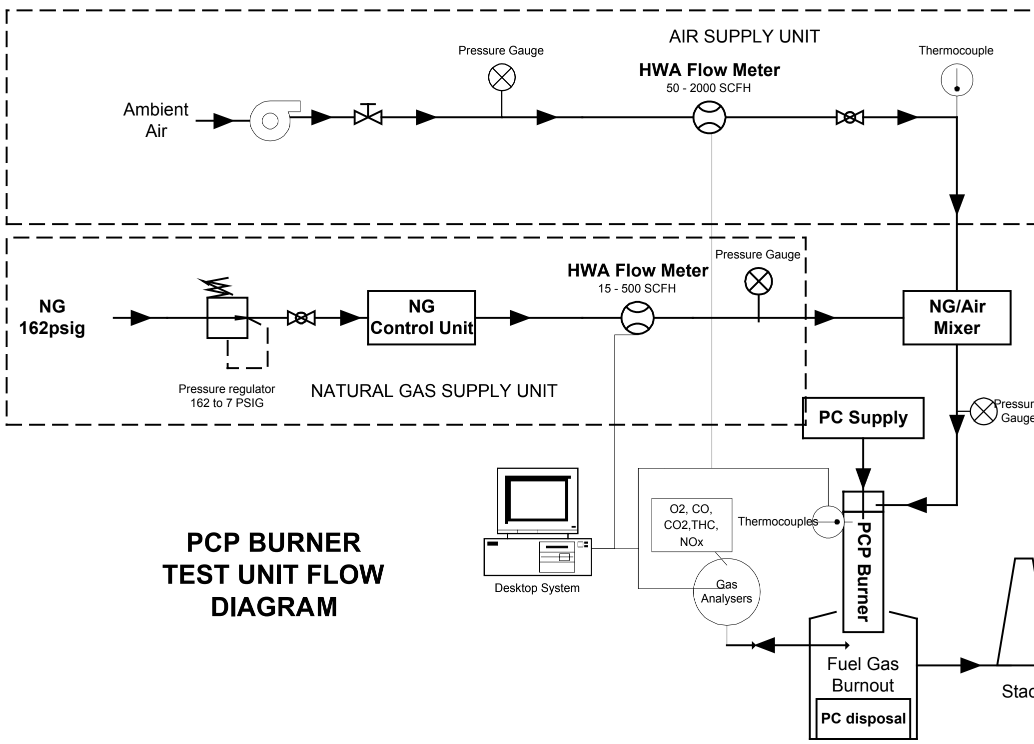


The best CFD case was chosen for manufacturing and testing. Test results shown below are in good agreement with modeling results.

Pilot Scale PC Preheat Gas Combustor Testing

A pilot scale PC preheat (PCP) gas combustor has been built and operated at GTI's Emerging Energy Technology Campus (EETC) lab. A schematic of the PCP gas combustor test rig is shown in Figure 14.

Figure 14. PC Preheat Unit, flow diagram



The pilot PC Preheat combustor was designed using three-dimensional CFD modeling. The design basis for the combustor is shown in Table 4:

Table 4. Design basis for the pilot scale PC Preheat combustor

Firing Rate	250,000 Btu/h
Flow rate, PC	230 lb/h
Flow rate, PC transport air	11 lb/h
Operating Combustor Pressure	atmospheric
Operating Combustion Temperature	2000 degrees F
PC preheat temperature	1400 degrees F

In the pilot test rig, natural gas is supplied to a pipe train at 162 psig and regulated down to 2 psig for testing. A fuel control module is equipped with safety shutoff valves, flow control valve, and hot wire anemometer-flowmeter calibrated for methane. A fuel/air mixer is located before the burner inlet. Combustion air is supplied by a blower. Air flow is controlled manually from the flow control panel and air flow is measured by a second flowmeter. The concentrations of CO, CO_2, O_2, THC and NO/NO_x in the PCP unit exhaust are continuously monitored by on-line gas analyzers: a Rosemount Analytical Model 880A infrared CO analyzer, a Rosemount Analytical Model 880A infrared CO_2 analyzer, a Rosemount Model 400 flame ionization total hydrocarbons (THC) analyzer, a Rosemount Analytical Model 755R paramagnetic O_2 analyzer, and a ThermoElectron Model 14A chemiluminescence NO_x analyzer.

Pilot testing was conducted to confirm gas combustor performance and stability with #16 silica sand prior to installation of the combustor in BBP's research facility in Worcester, MA for integrated testing with pulverized coal. The size distribution and specific heat of the sand particles used in GTI's testing was similar to size distribution of the selected coals (see Table 5).

Table 5. Screen analysis for silica sand # 16 used for PCP unit testing

U.S. Sieve	120	140	170	200	230	270	325	Total
Percent retained	5.1	22.7	26.5	24.4	13.4	5.9	2.0	100

Sand was supplied into a specially designed (PC/Air) mixer by an Acrison Model BDF-1.5 volumetric feeder. In the PC/Air mixer, solids are mixed with air in controlled proportions (see Table 4) and then introduced into the PCP burner. Solids are injected into the PCP burner at ambient temperature. The mass flow rate of solids exceeds the mass flow rates of natural gas and air. Therefore, one of the main test goals was to explore stability of natural gas combustion in the PCP unit and find operation regimes where the flame is not extinguished by the injected cold particles. Flame stability testing was performed by varying the amount of injected solids from 20% to 160% of designed load (see Table 4). The natural gas flame remained stable through the whole load range.

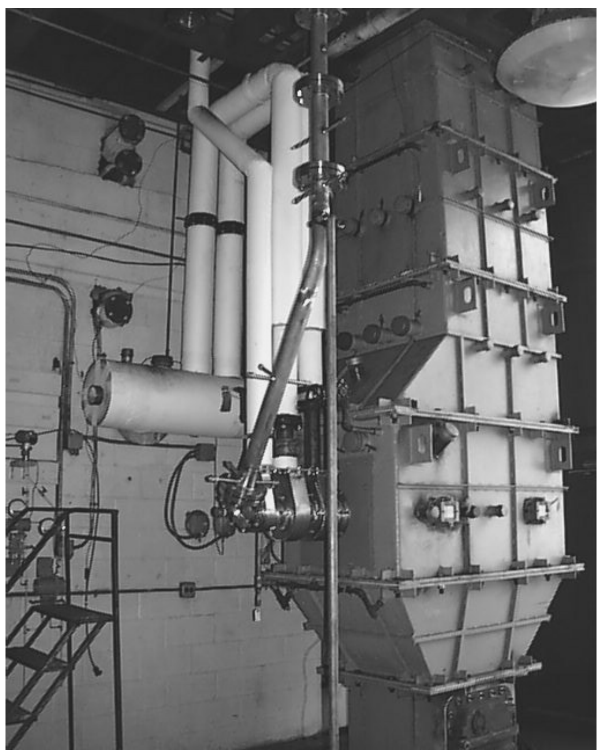
The burner wall temperature was monitored by thermocouples installed on both the outer walls of the combustion chamber and the inside of the combustion chamber. Temperature of the gas/air mixture was monitored also in the gas/air plenum upstream of the nozzles. Temperature measurements showed uniform temperature distribution on the burner walls, and no hot spots were detected during the testing. The temperature of the gas/air mixture injected into the combustion chamber was 100 °F.

The tests demonstrated stable, pulsation-free operation of the PCP unit, uniform temperature distribution inside the burner, and stability of combustion at solids loads of 20% to 160% of design load value.

Pilot Scale PC Preheat Test Rig at BBP

The 3-million Btu/h preheat burner prototype with the PCP combustor is being installed at Babcock Borsig Power in their Pilot Scale Combustion Facility (PSCF) in Worcester, MA. A photograph of the test unit is shown in Figure 15. The firing tests are planned for Fall, 2001.

Figure 15. Photograph of the 3-million-Btu/h test unit



BBP will perform pilot-scale firing tests with both direct and indirect PC feeding systems. Pilot testing will be followed by design, construction, and testing of a 100-million Btu/h commercial prototype PC preheat system in the 29 MW_{th} Coal Burner Test Facility (CBTF), also at Babcock Borsig Power's R&D Center. A CFD model of the CBTF furnace will be developed and validated during the commercial prototype testing. The preheater model developed during pilot testing will be used to guide the scale up of the PC preheater burner. When validated through

CBTF testing, the combined preheater and furnace models will form a valuable design tool for future commercial installations.

SUMMARY

Gas Technology Institute's (GTI's) METHANE de-NOX for PC Boilers is being developed to provide a cost-effective, combustion-based alternative to SCR to achieve 0.15 lb/million Btu NO_x emissions from pulverized coal-fired boilers. The technology employs a coal-preheating approach for NO_x reduction from PC utility boilers which was suggested by the All Russian Thermal Engineering Institute (VTI). The PC preheat technology comprises a burner modification that uses 3 to 5% of the total burner heat input to preheat pulverized coal to elevated temperatures (up to 1500°F) prior to coal combustion. This thermal pretreatment releases coal volatiles, including fuel-bound nitrogen compounds, into a reducing environment, which converts the coal-derived nitrogen compounds to molecular N_2 rather than NO_x.

GTI's advanced PC preheat combustion system under development for use with U.S. coals combines the VTI preheat approach with elements of GTI's successful METHANE de-NOX technology for NO_x reduction. METHANE de-NOX has been commercially demonstrated on coal, MSW, and biomass-fired stoker boilers in the U.S. and Japan. The advanced PC preheat system combines several NO_x reduction strategies into an integrated, low-NO_x PC combustion system, incorporating a novel PC burner design using natural gas-fired coal preheating and combustion staging in the coal burner. This integrated system can achieve very low NO_x levels–down to 0.15 lb/million Btu–without the complications, limitations and expense of SCR technology. The benefits of the technology are:

- NO_x reduction to below 0.15 lb per million BTUs with natural gas requirements as low as 3-5% of total heat input
- Up to 55% less expensive than state-of-the-art SCR on a levelized cost of electricity basis
- CO_2 emissions reductions (up to 5% of coal replaced by natural gas)
- Operational benefits including improved boiler turndown ratio, reduced carbon losses, increased boiler efficiency, and stable combustion with low heating value coals

In a development project sponsored by the U. S. Department of Energy's National Energy Technology Laboratory (NETL), GRI, and GTI's Sustaining Membership Program (SMP), a 3-million Btu/h pilot-scale PC preheat system is being designed and installed for development testing at Babcock Borsig Power's Research and Development Center in Worcester, MA. CFD modeling was used extensively in the pilot preheater design. Data from the pilot testing will be used to validate the preheater model. Pilot testing will be conducted with up to four U.S. coals and will include firing tests with both direct and indirect PC feeding systems. Pilot testing will be followed by design, construction and testing of a 100-million Btu/h commercial prototype PC preheat system in the 29 MWth Coal Burner Test Facility (CBTF), also at the Babcock Borsig Power's R&D Center. A CFD model of the CBTF furnace will be developed and validated

during the commercial prototype testing. The preheater model developed during pilot testing will be used to guide the scaleup of the PC preheater burner. When validated through CBTF testing, the combined preheater and furnace models will form a valuable design tool for future commercial installations.

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