METHANE de-NOX® for Utility PC Boilers

Final Report

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DISCLAIMER

ABSTRACT

The overall project objective is the development and validation of an innovative combustion system, based on a novel coal preheating concept prior to combustion, that can reduce NO_x emissions to 0.15 lb/million Btu or less on utility pulverized coal (PC) boilers. This NO_x reduction should be achieved without loss of boiler efficiency or operating stability, and at more than 25% lower levelized cost than state-of-the-art SCR technology. A further objective is to ready technology for full-scale commercial deployment to meet the market demand for NO_x reduction technologies.

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. A variety of combustion-based NO_x reduction technologies are in use today, including low-NO_x burners (LNBs), 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 ranges 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 reduce 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 furnaces, particularly with higher-sulfur coals, when LNBs are operated at sub-stoichiometric 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.

The proposed combustion concept aims to greatly reduce NO_x emissions 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.

Design, installation, shakedown, and testing on Powder River Basin (PRB) coal at a 3-million Btu/h pilot system at RPI's (Riley Power, Inc.) pilot-scale combustion facility (PSCF) in Worcester, MA demonstrated that the PC PREHEAT process has a significant effect on final NO_x formation in the coal burner. Modifications to both the pilot system gas-fired combustor and the PC burner led to NO_x reduction with PRB coal to levels below 0.15 lb/million Btu with CO in the range of 35-112 ppmv without any furnace air staging.

Pilot testing with caking coal resulted in deposition and plugging by caked material inside the gas combustor. A series of modifications to the combustor configuration and operation have been developed and tested. One of these approaches, using a stainless steel liner directly cooled with air, was successful in sustaining operation with caking coal up to full firing rate of 150 lb/hr (3-million Btu/h). Pilot results indicate bituminous coal NO_x reduction with preheating may be higher than for PRB coal.

The installation of the large-scale prototype coal preheater for PRB testing in the CBTF and shakedown testing with natural gas and PRB coal were completed. Scale-up testing with PRB coal at 17 MWt shows results similar to pilot-scale NO_x reduction. Large-scale testing was cut short due to the inability of the coal mill to meet the 85-MMBtu/h design firing rate. The project was redirected toward design, installation and testing of the 85-million Btu/h preheater for bituminous coal. Based on extensive pilot-scale testing and CFD modeling, a design utilizing staged, annular protective air films to control temperature and prevent deposition on the preheater walls was developed, and complete set of drawings for manufacturing a bituminous coal commercial prototype burner was released.

The advanced PC preheating combustion system developed in this project for direct-fired PC boilers combines the modified VTI (All-Russian Thermal Energy Institute, Moscow) preheat burner approach with elements of GTI's successful METHANE de-NOX technology for NO_x reduction in stoker boilers. The new PC preheating system combines several NO_x reduction strategies into an integrated system, including a novel PC burner design using natural gas-fired coal preheating, and internal and external combustion staging in the primary and secondary combustion zones.

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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 (LNBs), 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 LNBs are operated at sub-stoichiometric 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.

EXECUTIVE SUMMARY

In 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 developed and tested for commercial application with U.S. utility coals and PC firing methods. GTI has teamed with VTI and Riley Power Inc. (RPI) for the project.

The overall objective of the project was the development and validation of the PC PREHEAT concept to reduce NO_x emissions to 0.15 lb/million Btu or less on U.S. utility PC boilers. This NO_x reduction should be achieved without loss of boiler efficiency or operating stability, and at more than 25% lower levelized cost than state-of-the-art SCR technology. A further objective is to make the technology ready for full-scale commercial deployment in order to meet market demand for NO_x reduction technologies resulting from the EPA's NO_x SIP call.

Initial project efforts 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. Based on the results of these studies, a 3-million Btu/h pilot-scale PC PREHEAT system was designed, fabricated, and installed at RPI's Pilot-Scale Combustion Facility (PSCF) in Worcester, MA. Computational Fluid Dynamics (CFD) modeling was used extensively in the pilot system design for both the gas combustor and PC burner. Pilot testing was conducted with two U.S. coals and data from this testing was used to validate the initial PREHEAT system model.

Pilot scale development and testing effort led to NO_x reduction with PRB coal to levels below 0.15 lb/million Btu with CO in the range of 35-112 ppmv without any furnace air staging.

Pilot testing with caking coal resulted in deposition and plugging by caked material inside of the pilot gas combustor. A series of modifications to the combustor configuration and operation have been developed and tested. One of these approaches using a stainless steel liner directly cooled with air was successful in sustaining operation with caking coal up to full firing rate of 150 lb/hr or 3 million Btu/h. Pilot results indicated that bituminous coal NO_x reduction with preheating may be higher when compared to NO_x reduction for PRB coal.

Pilot testing was followed by design, construction and testing of a 100-million Btu/h commercial prototype PC PREHEAT system in RPI's 29 MWth Coal Burner Test Facility (CBTF). A CFD model of the CBTF furnace was developed and validated during the commercial prototype testing. The pilot-validated preheat system model was used to guide the scale up of the system. When validated through CBTF testing, the combined preheat and furnace models forms a valuable design tool for future commercial installations. The installation of the large-scale prototype coal preheater for PRB testing in the CBTF and shakedown testing with natural gas and PRB coal were completed. Scale-up testing with PRB at 17 MWt shows similar to pilot scale NO_x reduction. Large-scale testing was cut short due to the inability of the coal mill to meet the 85-MMBtu/h design firing rate. The project was redirected toward design, installation and testing of the 85-million Btu/h preheater for bituminous coal. Based on extensive pilot-scale testing and CFD modeling, design utilizing staged, annular protective air

films to control temperature and prevent deposition on the preheater walls was developed, and complete set of drawings for manufacturing bituminous coal commercial prototype was released.

EXPERIMENTAL

Concept Description

The proposed combustion concept aims to greatly reduce NO_x emissions 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.

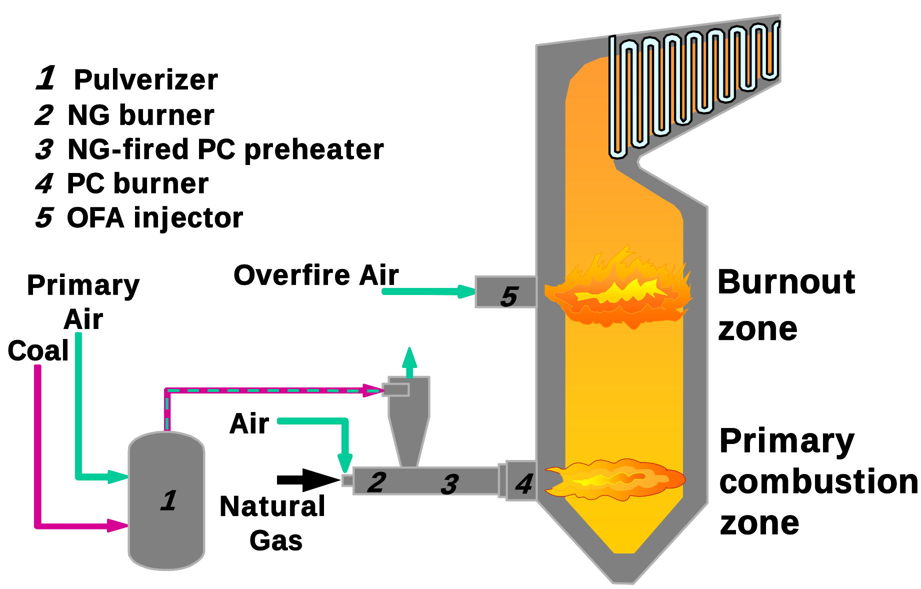


Figure 1: Simplified diagram of the PC PREHEAT NO_x reduction concept for PC boilers

This design improvement permits the boiler operator much more flexibility in burner operation, particularly with LNBs, 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 - 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 sub-stoichiometric 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.

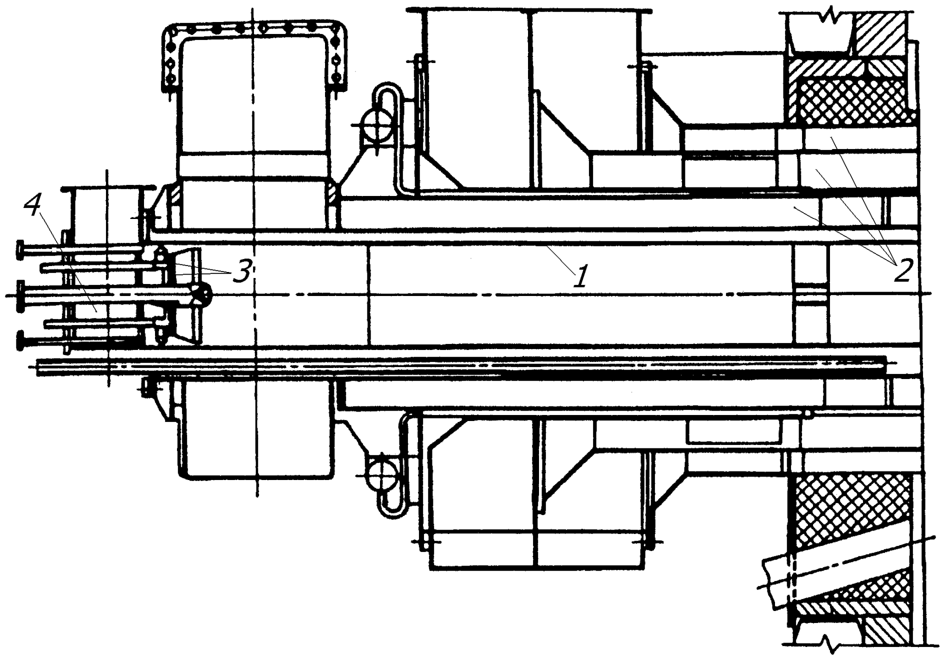


Figure 2: Diagram of natural gas preheated PC burner (1 = PC preheater; 2 = secondary and tertiary combustion air; 3 = natural gas burner; 4 = PC/primary air mixture injector)

Basic combustion research, lab-scale testing, and field testing using the natural gas preheated PC burner were done at VTI in Moscow, Russia. 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 MWth) demonstration facility;
- 1983-84 – a single 205-million Btu/h (60 MWth) prototype burner was installed and tested through 1991 at 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', T_o'', and T_o'''), 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.

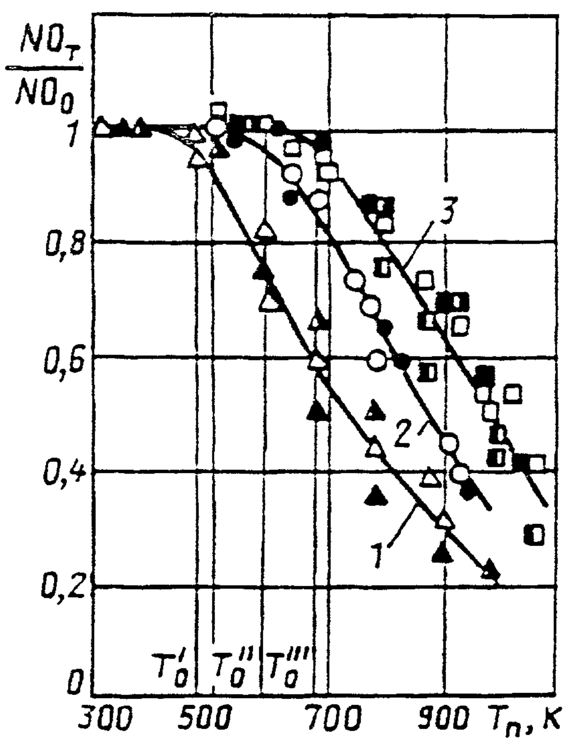


Figure 3. Fractional NO_x reduction versus PC PREHEAT temperature

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.

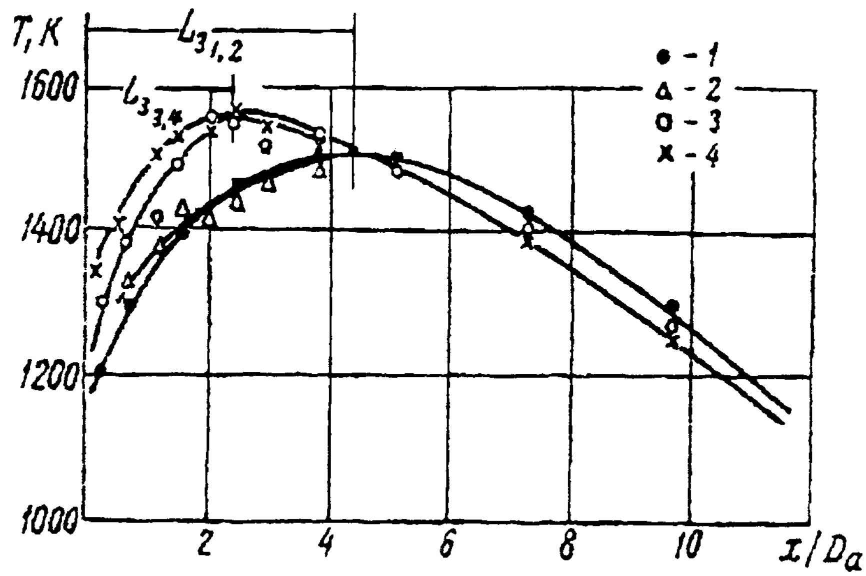


Figure 4. Preheated coal combustion flame temperature at various preheat temperatures. Preheat temperature: ● = 184°F; △ = 526°F; ○ = 796°F; σ = 895°F; × = 1084°F

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

In 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 was developed and tested for commercial application with U.S. utility coals and PC firing methods. GTI has teamed with VTI and Riley Power Inc. (RPI) for the project.

The overall objective of the project is the development and validation of the PC PREHEAT concept to reduce NO_x emissions to 0.15 lb/million Btu or less on U.S. utility PC boilers. This NO_x reduction should be achieved without loss of boiler efficiency or operating stability, and at more than 25% lower levelized cost than state-of-the-art SCR technology. A further objective is to make the technology ready for full-scale commercial deployment in order to meet market demand for NO_x reduction technologies resulting from the EPA's NO_x SIP call.

Initial project efforts 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. Based on the results of these studies, a 3-million Btu/h pilot-scale PC PREHEAT system was designed, fabricated, and installed at RPI's Pilot-Scale Combustion Facility (PSCF) in Worcester, MA. [6 - 10] Computational Fluid Dynamics (CFD) modeling was used extensively in the pilot system design for both the gas combustor and PC burner. Pilot testing was conducted with two U.S. coals and data from this testing was used to validate the initial PREHEAT system model. Pilot testing was followed by design, construction and testing of a 100-million Btu/h commercial prototype PC PREHEAT system in RPI's 29 MWth Coal Burner Test Facility (CBTF). A CFD model of the CBTF furnace was developed and validated during the commercial prototype testing. The pilot-validated PREHEAT system model was used to guide the scale up of the system. When validated through CBTF testing, the combined PREHEAT and furnace models forms a valuable design tool for future commercial installations.

Transfer of VTI Technical Information

GTI reviewed the test data provided by VTI, covering the pilot-scale 1.1 MW_t testing as well as commercial scale burner demonstrations up to 60 MW_t. The development and demonstration testing has been conducted with 20 different Russian coals, including coal ranks from subbituminous to anthracite. A summary of the characteristics for three Russian utility coals representative of the range of coals tested is presented in Table 1. Also shown in the table are the compositional ranges for the representative U.S. utility coals selected for the U.S. burner design basis.

Table 1. Comparison of Russian and U.S. utility coal compositions

	Selected Russian Utility Coals Tested by VTI			U.S. Utility Coals
Composition	Berezovo Subbit. B	Ekibastuz Subbit. C	Kuznetsk Semi Anthracite	Bituminous & Subbituminous
VM, wt % AR	40.27	23.68	9.28	22.9 – 42.0
C, wt%(dry)	66.03	53.13	71.6	74.0 – 86.5
H "	4.09	3.06	2.8	4.9 – 5.7
O "	21.49	8.31	3.12	6.0 – 19.4
N "	0.88	1.13	1.68	1.3 – 1.8
S "	0.5	0.86	0.8	0.5 – 2.8
Ash, wt% (dry)	7.00	33.5	20.0	6.0 – 13.9
HHV, Btu/lb	10820	9055	11859	11417-14288

From Table 1 it can be seen that, in general, the composition of U.S. coals falls within the range of compositions successfully demonstrated with Russian coals. The typical U.S. utility coal tends to be somewhat higher quality than the Russian coals, with lower ash content and higher volatile matter and heating value. The lower ash content of U.S. coals may simplify the preheat burner design and materials selection, although the increased sulfur content must be carefully evaluated with respect to materials selection. The most important (and favorable) compositional difference is the significantly higher level of volatile matter in most U.S. utility coals, the impact of which is discussed below.

The major findings of the VTI's investigation of NO_x formation in pulverized coal (PC) combustion were:

- Most (80-90%) of the NO_x formed during PC combustion is fuel-bound NO_x - thermal NO_x formation is negligible
- Most of the fuel-bound nitrogen contributing to NO_x formation is contained in the volatile matter, which is released and burned quickly as the coal particles are initially heated and partially pyrolyzed – the remaining char contributes very little to NO_x formation as it burns
- NO_x formation is strongly influenced by the concentration of oxygen in the flame region where the volatile matter is released, and the reaction of fuel-bound nitrogen with oxygen in this region is the primary mechanism for NO_x formation in PC combustion.

NO_x reduction in PC combustion is therefore favored when the nitrogen-bearing volatile matter is released into a zone of low excess oxygen content. This is the basis for the PC preheating approach to NO_x reduction. Provided the excess air in the pyrolysis zone is kept low, any factor that increases the amount of volatile matter released increases the efficiency of NO_x reduction. For a given coal, therefore, increasing the preheat temperature improves NO_x reduction efficiency by increasing the amount of volatile matter released during thermal pretreatment. For a given preheat temperature, increasing the volatile matter content of the coal increases NO_x reduction efficiency. This is the primary effect of coal type and composition on the NO_x reduction efficiency of the preheat process, and is illustrated in Figure 3, where it is clearly seen that coals with higher volatile matter require lower preheating temperatures to achieve a given level of NO_x reduction. The implications of this for use of the preheat approach with U.S. coals are therefore quite favorable. In general, lower preheating temperatures are required. This results in reduced auxiliary fuel requirements and smaller, more compact preheater designs that can be more easily retrofitted on existing PC boilers.

Lists of technical information and patents submitted by VTI to GTI are presented below in Table 2 and Table 3.

Table 2. List of submitted technical information

No	Item Description
1.	Verbovetsky E. Kh. "Investigation of the NO_x Reduction Method by Thermal Pulverized Coal Pretreatment. Design and Testing of the Pulverized Coal Burner." Moscow. VTI 1999.
2.	Titov S. I., Babiy V. I., Barbarash V.M. "Investigations of NO formation from fuel nitrogen in firing Kuznetsk coal dust." Teploenergetika, No. 3, 1980, pp. 64-67.
3.	Babiy V. I., Alaverdov P.I., Barbarash V.M., *et al*. The effect of coal dust pretreatment on fuel NO_x yield." Teploenergetika. 1983. #9. P. 10-13.
4.	Babiy V. I., Imankulov E. R., Alaverdov P. I., *et al*. "Investigation of the fuel nitrogen oxide formation in the furnace chamber with coal dust thermal pretreatment." In: "Problems of effective burning of energetic coals". Moscow. ENIN. 1984. P. 49-55.
5.	Imankulov E. R., Kanlybayev K. I., Babiy V. I., *et al*. "The effect of coal dust thermal pretreatment on the ignition of coal dust flame" Collected works: "Coal dust furnaces and burners (rig tests)". Moscow. ENIN. 1983. P. 31-35.
6.	Enyakin Yu. P., Kotler V. R., Babiy V. I., *et al*. "VTI works on the NO_x emission reduction by technological methods." Teploenergetika. 1991. #6. P. 33-38.
7.	Babiy V. I., Kotler V. R., Verbovetsky E. Kh. "Coal dust combustion in utility boilers." Collected works: "Developments in fuel preparation and combustion at power plants." Moscow. VTI. 1996. P. 46-57.
8.	Ed.: V. R. Kotler. "Investigation and implementation of new technologies for fossil fuel combustion to reduce atmospheric emission of toxic NO_x from thermal power stations and boiler houses (analytical survey)." Moscow. VTI. 1997. P. 409, 12-18.
9.	Babiy V. I., Kolodtsev K. I., Verbovetsky E. Kh., Serebryakova A. G. Author certification #243767 "A method of solid fuel combustion." Priority of 05. 02. 1968 Bulletin of Inventions 1969 #17.
10.	Babiy V. I., Alaverdov P. I. Patent of the Russian Federation #1114115 "A method of preparing of pulverized fuel for combustion". Priority of 04. 03. 1983 Bulletin of Inventions 1991 #12.
11.	Babiy V. I., Verbovetsky E. Kh., Artemyev Yu. P., Tumanovsky A. G. Patent application #99114725/06. "A method of reduction of nitrogen oxide formation in pulverized fuel combustion and low-NO_x burner " Priority of 07. 07. 1999.
12.	Babiy V. I., Alaverdov P. I. "The effect of coal dust thermal pretreatment on the fuel NO_x yield in firing dust of Berezovo coal (report)." Moscow. VTI. 1981. (**CONFIDENTIAL**)
13.	Babiy V. I., Alaverdov P. I. "The effect of coal dust thermal pretreatment on the fuel NO_x yield in firing dust of coals of various degree of metamorphism (report)." Moscow. VTI. 1983. (**CONFIDENTIAL**)
14.	Babiy V. I., Alaverdov P. I. "Investigation of the effect of coal dust preheating on the formation of fuel NO_x (report)." Moscow. VTI. 1982 (**CONFIDENTIAL**)
15.	16. Babiy V. I., Verbovetsky E. Kh., Tumanovsky A. G. *et al*. "The development and implementation of the thermal pretreated pulverized coal-fired burners on the Mosenergo Cogeneration plant-22 TPP-210A boiler (report)." Moscow. VTI. 1992 (**CONFIDENTIAL**)
17.	Babiy V. I., Verbovetsky E. Kh., Pelipenko A. S. "Investigation of the processes in the burner in-built device for coal dust thermal pretreatment (report)." Moscow. VTI. 1998. (**CONFIDENTIAL**)

No	Item Description
18.	Babiy V. I., Verbovetsky E. Kh., Artemyev Yu. P. *et al*. “The development of the technology of coal dust combustion to reduce as low as two times the formation of nitrogen oxides by thermal pretreatment (report).” Moscow. VTI. 1999. (**CONFIDENTIAL**)
19.	Drawings for installation of the device for coal dust thermal pretreatment in the burner of the TPP-210A boiler. (**CONFIDENTIAL**)
20.	Drawings for installation of the device for coal dust thermal pretreatment in the burner of the P-50 boiler. (**CONFIDENTIAL**)

Table 3. List of submitted patents

No	Item Description
1.	Babiy V. I., Kolodtsev K. I., Verbovetsky E. Kh., Serebryakova A. G. Author certificate #243767 “A method of solid fuel combustion.” Priority of 05. 02. 1968. Bulletin of Inventions 1969 #17.
2.	Babiy V. I., Alaverdov P. I. Patent of the Russian Federation #1114115 “A method of preparing of pulverized fuel for combustion.” Priority of 04. 03. 1983. Bulletin of Inventions 1991 #12.
3.	Babiy V. I., Verbovetsky E. Kh., Artemyev Yu, P., Tumanovsky A. G. Patent application #99114725/06. “A method of reduction of nitrogen oxide formation in pulverized fuel combustion and low-NO_x burner.” Priority of 07. 07. 1999.

The pilot-scale PC PREHEAT burner specifications and design documentation was received from VTI and an initial design was reviewed by GTI. The primary design issues identified in GTI review were as follows:

- U.S. PC boilers are typically fed directly from air swept pulverizers with coal/air mass ratios in the feed stream of about 0.5 – 1.0 lb coal / lb air. To maintain a low stoichiometric air ratio during preheating, a cyclone separator should be used to remove most of the transport air prior to entering the PC preheater.
- The separated air from the cyclone should be routed initially to one of the coal burner air channels rather than overfire air ports on the furnace. Later testing should consider both air and fuel staging, after the NO_x reduction performance of the preheat PC burner alone is characterized.
- Preheat residence time is to be varied during testing by adding or removing sectional preheater piping between the natural gas-fired preheater and the PC burner. The preheater pipe sections to be air-cooled to simulate the conditions in a full-scale burner. Differential thermal expansion of the inner and outer pipes to be accommodated with sealed bellows, as the overall thermal expansion of the preheater assembly.

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 analyses performed on these coals are summarized in Table 4:

Table 4. Analytical methods

ANALYSIS	METHOD	DESCRIPTION
Proximate analysis	ASTM D3172	Measures moisture, ash, and volatile matter by weight
Ultimate analysis	ASTM D3176	Determines major elements by weight
Calorific value	ASTM	Measures heating value
Sulfur by type	ASTM D2492	Determines forms of sulfur as pyritic, organic, sulfate, and elemental sulfur
Free swelling index	ASTM D720	Measures caking/swelling tendency
Particle density	Micrometrics 9310 mercury porosimeter	Measures density of coal particle; also measures pore size distribution excluding micropores
Ash fusion temperature (oxidizing and reducing)	ASTM D1857	Measures development of ash fluidity at combustion temperatures
Ash composition (major and minor oxides)	ASTM D2795, ASTM D3682	Determines oxide composition of ash
Pyrolysis-GC	CDS Analytical Pyroprobe 1000	Measures products of rapid pyrolysis by on-stream analysis of volatiles up to C_{40}; pyroprobe is interfaced with GC which can use FID, TCD, or NPD detector

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 5, 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 6) was 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 was tested in pilot and commercial prototype tests in this project and the test results are described in detail in the following sections of the report.

Table 5. 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
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

COAL ORIGIN	US—Western	US—Central Appalachian	US—South Appalachian	US—Illinois Basin	Russia—lean coal	Russia—brown coal	Russia—bituminous
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 6. Predicted NO_x reduction for U.S. and Russian coals

COAL ORIGIN	US—Western	US—Central Appala-chian	US—Southern 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
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_o 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_7-C_{12}, C_{13}-C_{18}, C_{19}-C_{24}, and C_{25}-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 7.

Table 7. 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_7-C_{12}	11.3	10.1	5.6	10.5	0.9	6.4	4.9
C_{13}-C_{18}	13.1	7.5	3.9	12.3	0.8	6.7	3.7
C_{19}-C_{24}	11.3	6.3	3.3	6.9	0.7	4.7	2.7
C_{25}-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_{13}-C_{18}	10.6	8.6	4.7	12.5	0.5	5.7	2.4
C_{19}-C_{24}	9.1	7.8	4.3	6.4	0.3	3.6	1.6
C_{25}-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_7-C_{12}	13.5	10.4	7.0	12.6	1.2	8.2	4.9
C_{13}-C_{18}	10.5	6.9	5.5	13.2	0.6	6.3	2.4
C_{19}-C_{24}	8.7	5.9	5.3	7.1	0.4	3.9	1.6
C_{25}-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 were further interpreted and utilized for burner design as the project progressed. These data were used to determine the natural gas-fired preheat burner heat release requirements for the pilot-scale burner assembly, and to characterize chemical and physical properties of the vapor phase pyrolysis products so that the required velocity and residence time is maintained in the preheat section ahead of the PC burner.

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 is 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 incorporates design features into the burner that 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 burner design should fully address these issues, 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. Several design approaches to control agglomerating tendency were evaluated during the pilot scale concept validation testing.

The preheat burner development in Russia included extensive laboratory and field demonstration work that was performed by VTI using 20 Russian coals ranging from brown coal to anthracite. Extensive experimental work with three of these coals led to a correlation of NO_x reduction with two process variables: preheat temperature and coal volatile matter content. The VTI correlation is based on the equation:

$$NO_t/NO_0 = 1 - 0.00535\,(t + 6.7V_{maf} - 500)^{0.8}$$

where NO_t is flue gas NO_x from combustion of coal preheated to temperature t, NO_0 is flue gas NO_x from combustion of the same coal without preheating, t is the preheat temperature in °C, and V_{maf} is weight percent volatile matter of coal on moisture- and ash-free basis. In this context, the four selected U.S. coals were evaluated for projected performance over the temperature range of 800-1500°F. The results are shown in Table 6 and in Figure 5.

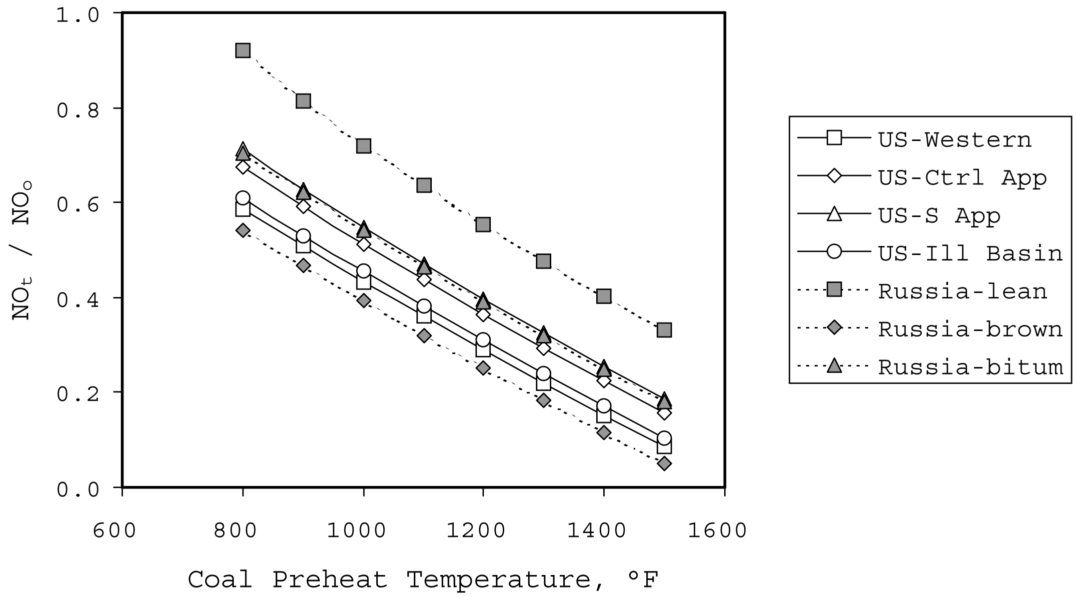


Figure 5. Plot of NO_x reduction versus preheat temperature for U.S. and Russian coals

Pilot-Scale Design

Based on the technology transfer documentation provided to GTI by VTI and review and comparison of Russian and U.S. utility coals and PC firing methods, a design coal (Table 8) was selected and the design basis (Table 9) established for the pilot-scale PC PREHEAT system.

Table 8. Design coal analysis (Harrisburg #5)

PROXIMATE, as received	Wt %
Moisture	10.85
Volatile Matter	32.09
ULTIMATE, dry	
C	75.32
H	4.95
O+Cl	8.58
N	1.68
S	1.80
ASH	7.67
HHV, Btu/lb (wet)	12,072

Table 9. Pilot scale PC PREHEAT design basis:

PC PREHEAT Burner Firing Rate, kcal/hr	756,048
Fuel	Pulverized Coal
Burner Design Basis Coal	Harrisburg #5 (VM^{daf} = 38.99%)
PC mass flow rate (2% moisture), kg/hr	103.5
Preheat Temperature of PC/Combustion products mixture, °C	710
Velocity of PC/ Combustion Products mixture at burner exit, m/s	18
Total flow rate of secondary air, nm^3/hr	838
Temperature of secondary air, °C	300
Velocity of secondary air at burner exit, m/s	25
Velocity of dusty air stream at burner exit, m/s	18
Excess air at the burner exit, %	10

Note: Vm^{daf} is volatile matter in mass percent on a dry and ash free basis

<u>Pilot-Scale PC PREHEAT System Description</u>

The flow diagram in Figure 6 and the drawing summary in Table 10 present an overview of the PC PREHEAT technology and its components, as it was applied in Riley's pilot-scale furnace test facility. System equipment and major flow streams are shown for two modes of pilot test operation: Option #1 is based on a bin storage system for delivering PC to the burner while the second mode, Option #2, is a direct-fired PC delivery system that is considered the standard scheme used in U.S. utility boiler operations.

Raw coal transported to the site is stored in an existing bin at the Riley Power test furnace facility. From storage, raw coal is sized in an existing pulverizer at Riley's site and stored in a dedicated silo. PC flow from the silo is controlled via an existing volumetric Vibra-Screw Feeder. Downstream of the feeder is an existing Rotary Airlock isolating the equipment from the test furnace. From this point on, two different PC delivery systems were considered:

Option #1

In the bin storage system, PC from the existing feeder/rotary airlock is routed into a Mixer, Item #1, where a small amount of air (~20 °C) is mixed with PC for transport purposes. From the Mixer, PC is conveyed through a Compensator device, Item #2. The Compensator makes up for the vertical growth as the Preheater sections, Items #4 & 6, heat up to 800 °C. PC now enters the Natural Gas Combustor, Item #3, where it mixes with the hot products of combustion from a natural gas burner.

Directly flanged to the Combustor is the Preheater, which is divided into two sections: 1st Preheater (Item #4) and the 2nd Preheater (Item #6). The first section, Item #4 is an air-cooled jacketed pipe constructed in 3 flanged segments. Air-cooling simulates full-scale applications and the segmented design permit changes to the PC PREHEAT residence time by removing segments from the arrangement. The 2nd Preheater, Item #6, is non-cooled. Based on achieving a PC PREHEAT temperature of 710 °C, calculations show that PC/combustion product mixture velocity in the preheater (Item #4 & 6) and residence time are well within the design criteria determined in previous testing by VTI. The preheated mixture directly enters the pilot-scale PC burner. Based on VTI's experience in operating similar pilot-scale preheat burners, orientation of the test burner fuel inlet is rotated from the vertical. The burner design incorporates multi-annular channels for injection of PC and secondary air into the test furnace. The central tube of the burner is used for probing the flame. Vanes are also provided in the secondary air channels to impart swirl.

<u>Option #2</u>

In the direct fired system, the pilot plant arrangement changes in order to prepare a fuel stream containing PC and primary air to simulate pneumatic transport conditions found in the majority of, if not all, existing U.S. utility PC burner systems. PC PREHEAT technology implementation with this type of fuel delivery scheme requires a solids separator, PC Coal Cyclone, Item #9.

In this test scheme, PC first drops by gravity from the Vibra Screw Feeder/Rotary Airlock and is directed into the Eductor Mixer, Item #8. In the mixer, PC is combined with air and pneumatically transported into the PC Coal Cyclone. At the cyclone, PC solids are separated from the air and drop from the cyclone outlet through a new Rotary Airlock, Item #12, into the inlet of Mixer, Item #1. See Option #1 to complete the system description.

The PC Coal Cyclone off gas is piped to the PC PREHEAT Burner where it can be re-introduced at the burner assembly and injected into the furnace.

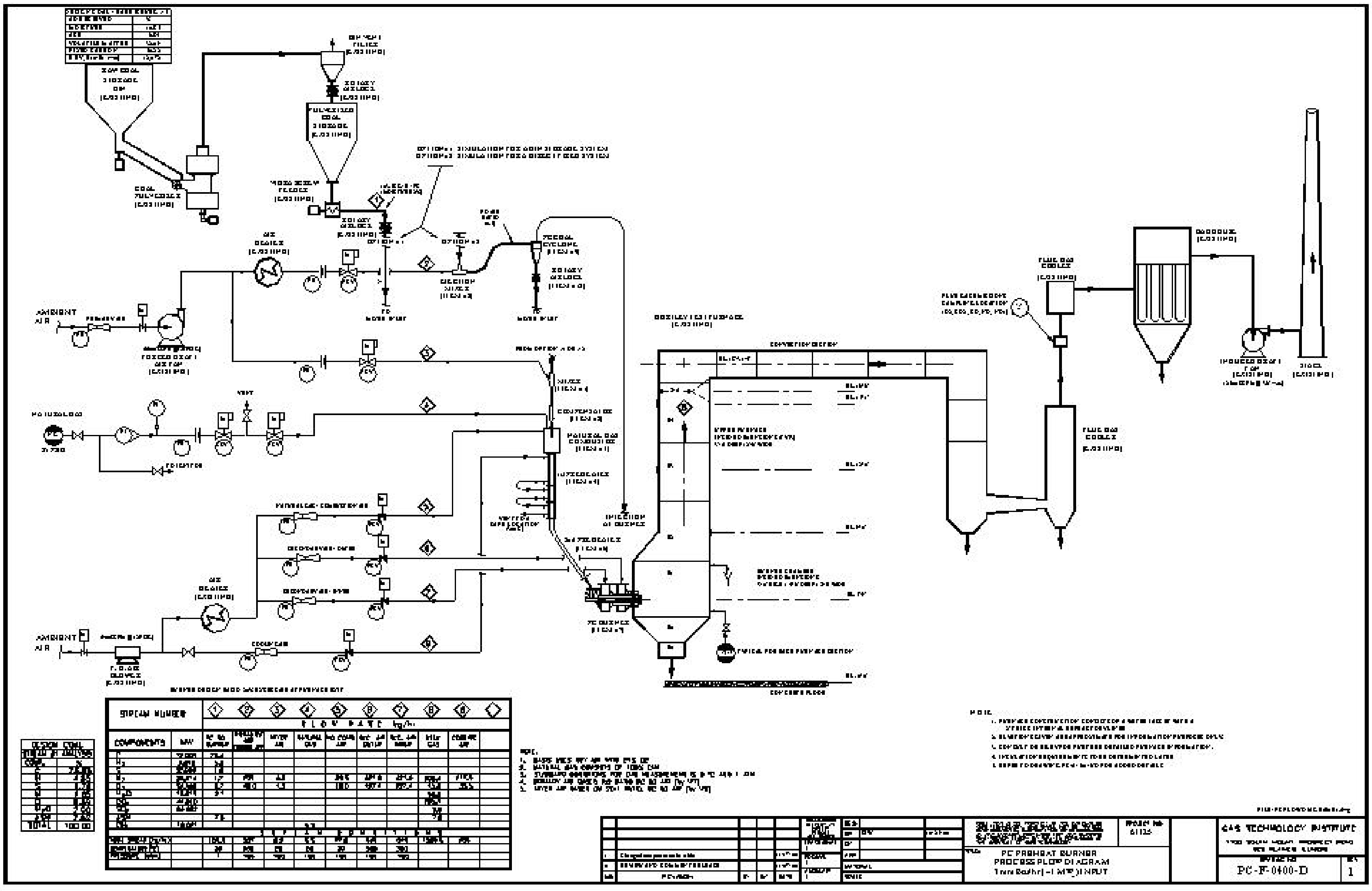


Figure 6. PC PREHEAT burner process flow diagram, GTI drawing No. PC-F-0400-D

Table 10. PC PREHEAT burner drawing summary

	SUBJECT:				Gas Technology Institute	
	PC PREHEAT BURNER DRAWING SUMMARY				COMBUSTION TECHNOLOGY GROUP	
					1700 S. Mt. Prospect Rd	
					Des Plaines, Illinois 60018	
					Date: November 29, 2000	
						Revision: 3
Drawing No.	**Drawing Title**	**Date**	**Rev.**	**Item #**	**Paper Size** (mm x mm)	**ACAD File Name**
Babcock Borsig Power						
200000-7-2	General Arrgt of Pilot Test Furnace Front & Side Elevations	01/11/85	2			none
200001-7-2	General Arrgt of Pilot Test Furnace Plan Views Elev's 0'-0", 24'-0" & 42'-0"3	01/14/85	2			none
200026-5-0	Test Furnace Burner Mount	08/24/84	0			none
Gas Technology Institute						
PC-A-0500-D (SHEET 1 OF 2)	Test Furnace Burner Mount Details	05/26/00	0		D size 34" x 22"	PCBurnerMount.dwg
PC-A-0500-D (SHEET 2 OF 2)	Test Furnace Burner Mount Details	05/26/00	0		D size 34" x 22"	PCBurnerMount.dwg
PC-A-0501-UD	PC PREHEAT Burner - Pilot Scale Assembly	11/07/00	0		Undefined	PC BURNER ASSEMBLYR0.dwg
PC-B-0300-D	DB Riley Pilot Scale Combustion Facility Diagram (3-mmBtu/hr Input)	06/01/00	0		D size 34" x 22"	DBrileyP&ID.dwg
PC-MEC-03-D (SHEET 1 OF 2)	Natural Gas Combustor	12/07/00	0		D size 34" x 22"	--
PC-MEC-03-D (SHEET 2 OF 2)	Natural Gas Combustor	12/07/00	0		D size 34" x 22"	--
PC-MEC-04-D	1st Preheater		0		D size 34" x 22"	1st PreheaterR0.dwg
PC-F-0400-D	PC PREHEAT Burner - Process Flow Daigram	11/17/00	1		D size 34" x 22"	PC FLOW DIAGRAMR1.dwg
PC-PI-1000-D	PC Coal Burner Simplified P&ID	05/26/00	0		D size 34" x 22"	PCBurnerP&ID.dwg
SK-PC-1	Preheated PC Block Diagram	none			14" x 9"	PreheatedPCBlockDiagram.dwg

	SUBJECT:				Gas Technology Institute	
	PC PREHEAT BURNER DRAWING SUMMARY				COMBUSTION TECHNOLOGY GROUP	
					1700 S. Mt. Prospect Rd	
					Des Plaines, Illinois 60018	
					Date: November 29, 2000	
						Revision: 3
Drawing No.	**Drawing Title**	**Date**	**Rev.**	**Item #**	**Paper Size** (mm x mm)	**ACAD File Name**
VTI						
1-00.10 (SHEET 1 OF 2)	Additional Devices for the Test Facility - 3 mmBtu/h (Sheet 2 of 2 Plan views)	09.00	0	-	-	Komponovka-1.jpg (Note: not an ACAD file)
1-00.10 (SHEET 2 OF 2)	Additional Devices for the Test Facility - 3 mmBtu/h (Sheet 1 of 2 Elevations views)	09.00	0	-	-	Komponovka-1.jpg (Note: not an ACAD file)
1-00.11	Location of the Test Burner	09.00	0	-	1108 x 720	Burner 1.dwg
1-00.20 (SHEET 1 OF 2)	Additional Devices (Sheet 2 of 2 Plan elevations)	09.00	0	-	-	Komponovka-2.jpg (Note: not an ACAD file)
1-00.20 (SHEET 1 OF 2)	Additional Devices for PC Coal Supply Sys (Sheet 2 of 2 Elevations views)	09.00	0	-	-	Komponovka-2.jpg (Note: not an ACAD file)
1-01	Dependence of the necessary temperature of pc preheating on desired NOx reduction	07.00	0		215 x 279	Fig 1-01.doc (NOT an ACAD file)
1-01.00	Mixer	09.00	0	1	267 x 400	Mixer1.dwg
1-02.00	Compensator	09.00	0	2	267 x 400	Compensator.dwg
1-04.00	PC Preparation Facility VOID	09.00	0		2870 x 4050	PC coal heater-faterr.dwg
1-04.00A	PC Preparation Facility	11.00	0		2870 x 4050	PC coal heater.dwg
1-04.10 (SHEET 1 OF 2)	1st PC Preparation Area (Sheet 1 of 2) VOID	09.00	0	4	574 x 820	PC coal heater.dwg
1-04.10 (SHEET 2 OF 2)	1st PC Preparation Area (Sheet 2 of 2) VOID	09.00	0	4	574 x 820	"
1-04.10A (SHEET 1 OF 2)	1st PC Preparation Area (Sheet 1 of 2)	11.00	0	4	574 x 820	PC coal heater-1A.dwg
1-04.10A (SHEET 2 OF 2)	1st PC Preparation Area (Sheet 2 of 2)	11.00	0	4	574 x 820	"
1-04.20	FGR Mixer NOT APPLICABLE	09.00	0	5	574 x 810	PC coal heater-2.dwg

	SUBJECT:				**Gas Technology Institute**	
	PC PREHEAT BURNER DRAWING SUMMARY				COMBUSTION TECHNOLOGY GROUP	
					1700 S. Mt. Prospect Rd	
					Des Plaines, Illinois 60018	
					Date: November 29, 2000	
						Revision: 3
Drawing No.	**Drawing Title**	**Date**	**Rev.**	**Item #**	**Paper Size** (mm x mm)	**ACAD File Name**
1-04.30	2nd PC Preparation Area VOID	09.00	0	6	574 x 810	PC coal heater-3.dwg
1-04.30A	2nd PC Preparation Area	11.00	0	6	574 x 810	PC coal heater-3A.dwg
1-04.40A	PC Preheat, Setting 1	11.00	0	4	574 x 810	PC coal heater-2A.dwg
1-04.50A	PC Preheat, Setting 2	11.00	0	4	574 x 810	PC coal heater-2A.dwg
1-05.00	The Test Burner NOT APPLICABLE	09.00	0	7	1540 x 1108	Burner 2.dwg
1-05.00A	Location of the Test Burner NOT APPLICABLE	11.00	0	7	1540 x 1108	Burner ve1.dwg
1-05.10	Central Tube NOT APPLICABLE	09.00	0	7	1560 x 1108	Central tube.dwg
1-05.10A	Central Tube NOT APPLICABLE	11.00	0	7	1560 x 1108	Central tube ve1.dwg
1-05.20	Pipe of PC Duct NOT APPLICABLE	09.00	0	7	1560 x 1108	Tube 1.dwg
1-05.20A	Pipe of PC Duct NOT APPLICABLE	11.00	0	7	1560 x 1108	PC coal tube ve1.dwg
1-05.21	Vane NOT APPLICABLE	09.00	0	7	180 277	Inner vane.dwg
1-05.21A	Vane NOT APPLICABLE	11.00	0	7	180 277	Secondary inner vane-A.dwg
1-05.30	Duct and Pipe of Inner Secondary Air Duct NOT APPLICABLE	09.00	0	7	1560 x 1108	Tube and duct-inner.dwg
1-05.30A	Duct and Pipe of Inner Secondary Air Duct NOT APPLICABLE	11.00	0	7	1560 x 1108	Tube and duct-inner ve1.dwg
1-05.31	Vane NOT APPLICABLE	09.00	0	7	180 x 277	Outer vane.dwg
1-05.31A	Vane NOT APPLICABLE	11.00	0	7	180 x 277	Secondary outer vane-A.dwg
1-05.40	Duct and Pipe of Peripheral Secondary Air Duct NOT APPLICABLE	09.00	0	7	1560 x 1108	Tube and duct-outer.dwg
1-05.40A	Duct and Pipe of Peripheral Secondary Air Duct NOT APPLICABLE	11.00	0	7	1560 x 1108	Tube and duct-outer ve1.dwg
1-06.00	PC Coal Tube	09.00	0	8	3900 x 5740	PC coal tube.dwg
1-07.00	Ejection Mixer	09.00	0	8	554 x 360	Mixer.dwg

	SUBJECT:				Gas Technology Institute	
	PC PREHEAT BURNER DRAWING SUMMARY				COMBUSTION TECHNOLOGY GROUP	
					1700 S. Mt. Prospect Rd	
					Des Plaines, Illinois 60018	
					Date: November 29, 2000	
						Revision: 3
Drawing No.	**Drawing Title**	**Date**	**Rev.**	**Item #**	**Paper Size** (mm x mm)	**ACAD File Name**
1-08.00	PC Coal Cyclone	09.00	0	9	3900 x 5740	PC coal cyclone.dwg
1-09.00	Distributor	09.00	0	10	390 x 574	Divisor.dwg
1-10.00	Nozzle	09.00	0	11	180 x 277	Nozzle.dwg
1-11.00	Location of the Test Burner	11.00	0	7	1540 x 1108	Burner ve2.dwg
1-11.10	Central Tube	11.00	0	7	1540 x 1108	Central tube ve2.dwg
1-11.20	Pipe of PC Duct	11.00	0	7	1540 x 1108	PC coal tube ve2.dwg
1-11.21	Vane	11.00	0	7	180 x 277	Drying agent duct vane.dwg
1-11.30	Duct and Pipe of Inner Secondary Air Duct	11.00	0	7	1540 x 1108	Tube and duct-inner ve2.dwg
1-11.31	Vane	11.00	0	7	180 x 277	Secondary air outer vane.dwg
1-11.40	Duct and Pipe of Peripheral Secondary Air Duct	11.00	0	7	1540 x 1108	Tube and duct-outer ve2.dwg
1-11.50	Duct and Pipe of Drying Agent	11.00	0	7	1540 x 1108	Drying agent tube ve2.dwg
1-11.51	Vane	11.00	0	7	180 x 277	Secondary air inner vane.dwg
1-12.00	Scheme of the mixer	11.00	0	7	390 x 277	Mixer2.dwg

Pilot System Thermal Insulation Requirements

Insulation is required for personnel safety and control of heat losses around the following equipment.

- Natural Gas Combustor, Item #3
- 1st Preheater, Item #4
- 2nd Preheater, Item #6
- PC Burner, Item #7
- PC Coal Cyclone, Item #9
- Piping and Ducts to be determined

Pilot System Piping Requirements

- Solid/Air transport piping shall utilize long radius elbows, not less than 5 pipe diameters.
- Solid transfer piping shall contain no sudden restriction or obstructions. Flange and/or fitting internal diameters shall be aligned and surfaces smooth.

Pilot System Instrumentation Requirements

An instrumentation summary is given below.

- Thermocouple for measurement of gas temperature at the Natural Gas Combustor – 1700 °C type R
- Thermocouple for measurement of PC temperature in preheater; 2 – up to 1700 °C (type R) and 8 - up to 900 °C (type N)
- Thermocouple for measurement of Preheater wall temperature, 6 – up to 1100 °C
- Thermocouple for measurement of PC temperature at test burner inlet, 1 – up to 800 °C
- Thermocouple for measurement of cooling air, 3 – up to 400 °C
- Thermocouple for measurement at test burner of: secondary air and PC Coal Cyclone gas outlet,
- Gas sample probes, gas species to be determined.
- At Natural Gas Combustor Outlet
- At 1st and 2nd Preheater – select 4 elevations
- PC solid sample probes
- At 1st and 2nd Preheater – select 4 elevations
- At test furnace - select 2 locations
- Pressure measurements
- Measure supply pressure of all system streams
- Measure pressure at burner inlet for PC, secondary air and cyclone outlet gases
- Measure delta-P across PC Coal Cyclone
- Flow measurements
- Measure PC flow to burner
- Measure natural gas flow to Combustor
- Measure air flow to the following
- Natural Gas Combustor, Combustion Air
- Mixer Transport Air
- PC Burner Secondary Air – Inner Air

- PC Secondary Air – Outer Air
- 1st Preheater Cooling Air
- Ejection Mixer Transport Air

RESULTS AND DISCUSSION

PC PREHEAT Pilot Scale Combustor Development

Natural gas-fired preheat combustor was designed extensively using CFD modeling, fabricated and tested in GTI's combustion laboratory for proof-of-performance prior to shipping to Riley for installation in the pilot-scale test system.

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 5. 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 7 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 8) 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.

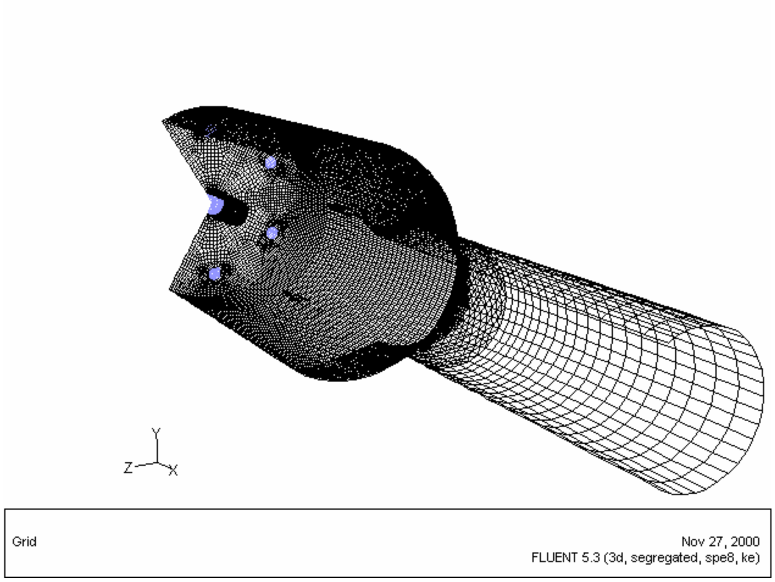


Figure 7. PCP burner, computational domain

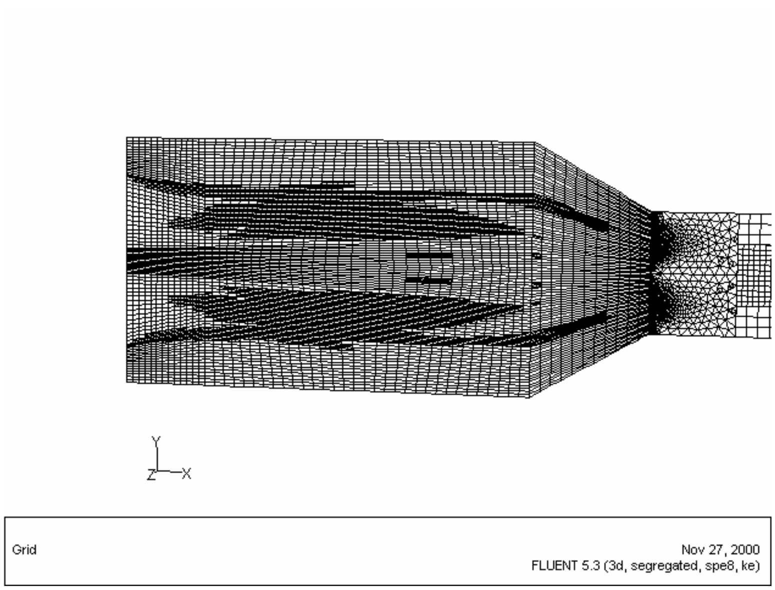


Figure 8. 3D computational mesh, Combustion chamber, Symmetry plane through the NG/Air injection nozzles centerline.

Boundary Conditions

Total mass flow of all injected agents in the combustion chamber is given in Table 11 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 5).

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. [11] 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 11. 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 9 to Figure 12 showing trajectories of 30 μm PC particles colored by particle mass for four different burner designs

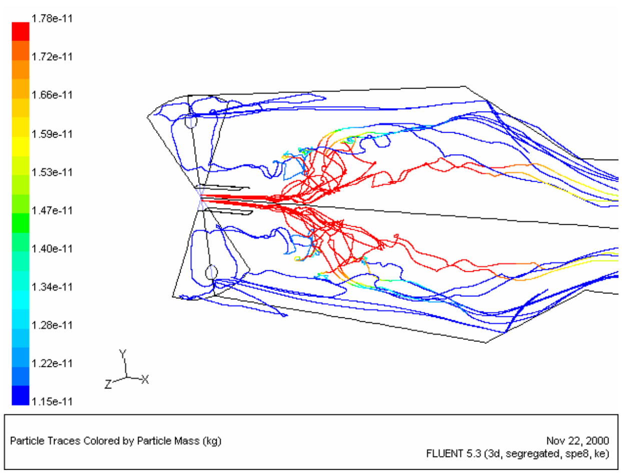


Figure 9. Design is not optimal, Stream #1, 30 μm, colored by the particle mass, 90% devolatilization

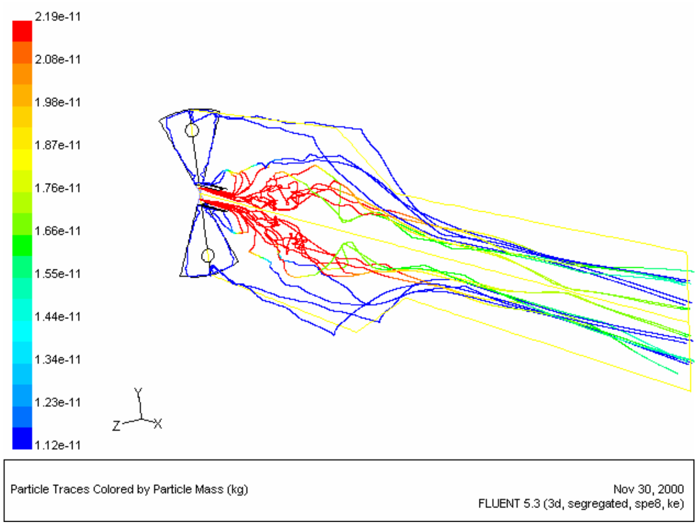


Figure 10. Design is not optimal, Stream #1, 30 μm, colored by the particle mass, 70% devolatilization

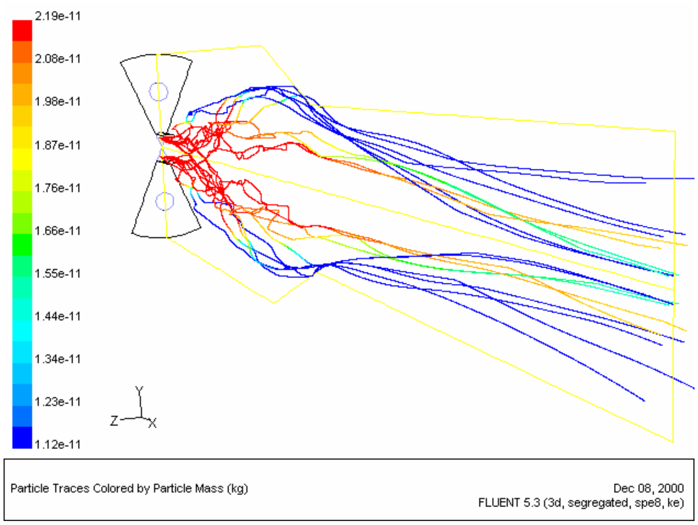


Figure 11. Design is not optimal, Stream #1, 30 μm, colored by the particle mass, 62% devolatilization

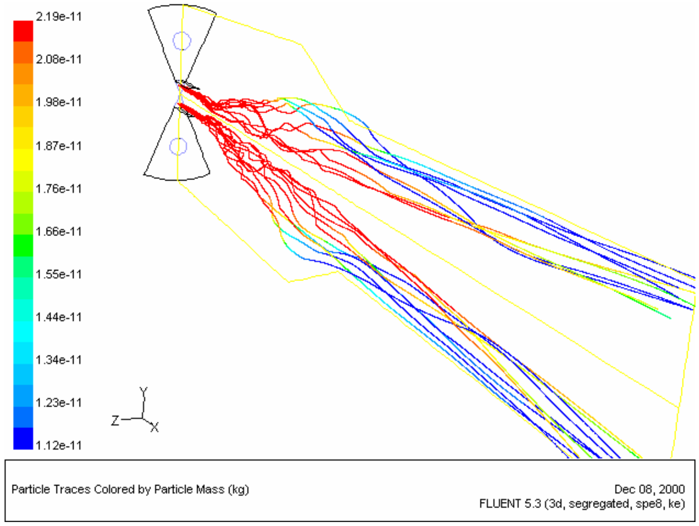


Figure 12. Optimized geometry, Stream #1, 30 μm, colored by the particle mass, 90% devolatilization

In Figure 9 and Figure 10 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 11 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 12. Here the trajectories of the pulverized coal particles do not interact with the walls, and devolatilization inside the combustion chamber is sufficiently high.

Figure 13 through Figure 15 present more insight on the flame and flow inside the combustion chamber for optimized design. Flow path lines (see Figure 13) 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 14 and Figure 15. The pattern of devolatilization is uniform, and the walls are shielded from solids by combustion products.

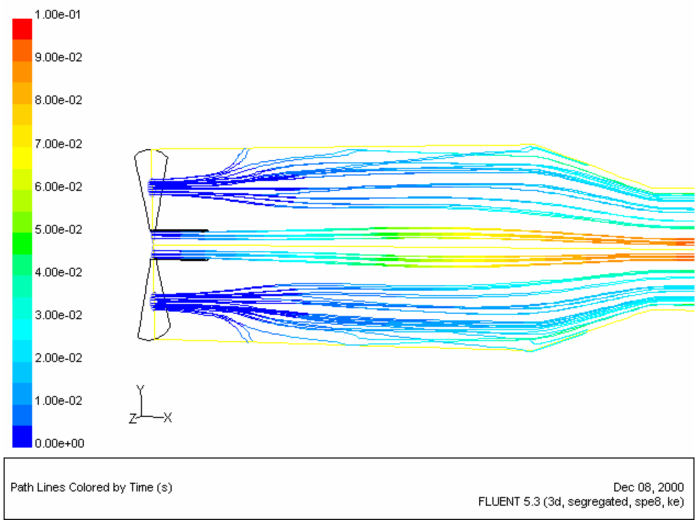


Figure 13. Flow path lines, nozzle centerline

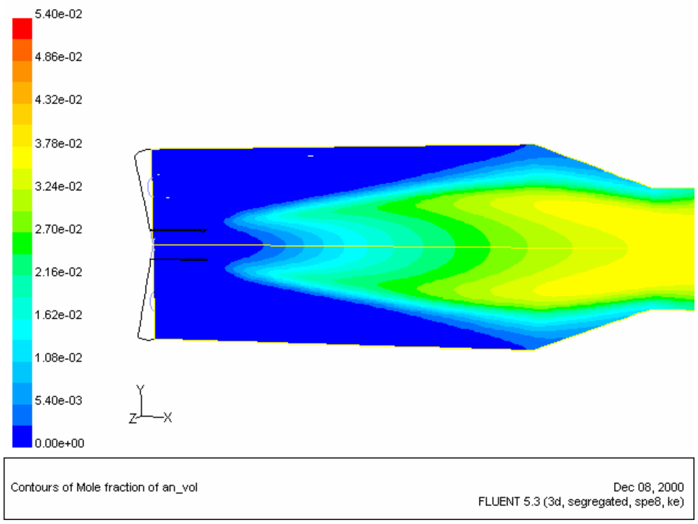


Figure 14. Mole fraction of volatiles along nozzle centerline

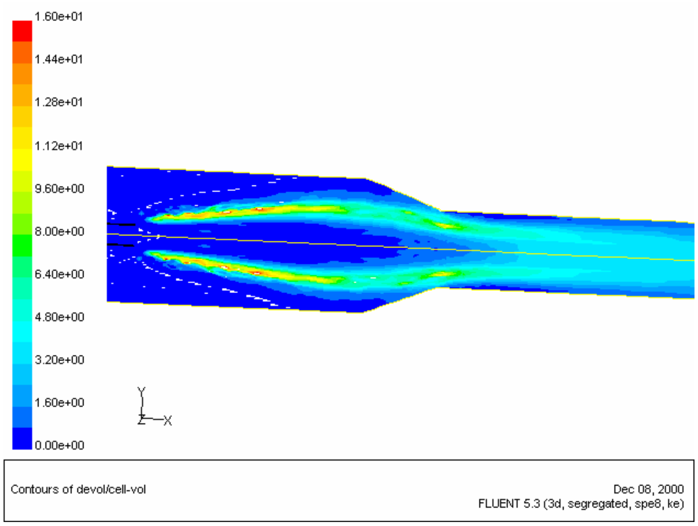


Figure 15. Rate of devolatilization along nozzle centerline

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 Pre-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 16. Proof of performance testing at GTI included:

- Startup testing to insure the combustor reputably achieves stable operation in the 2000°F range within 5-10 minute of light off.
- Confirmation of stable combustor operation at near-stoichiometric combustion air flow
- Testing with inert solids feed to the combustor to simulate operation with pulverized coal
- Tests with silica to simulate heating of coal particles in the combustor (similar density and heat capacity)
- Tests with mixture of silica and $CaCO_3$ to simulate additional devolatilization heat load due to coal pyrolysis

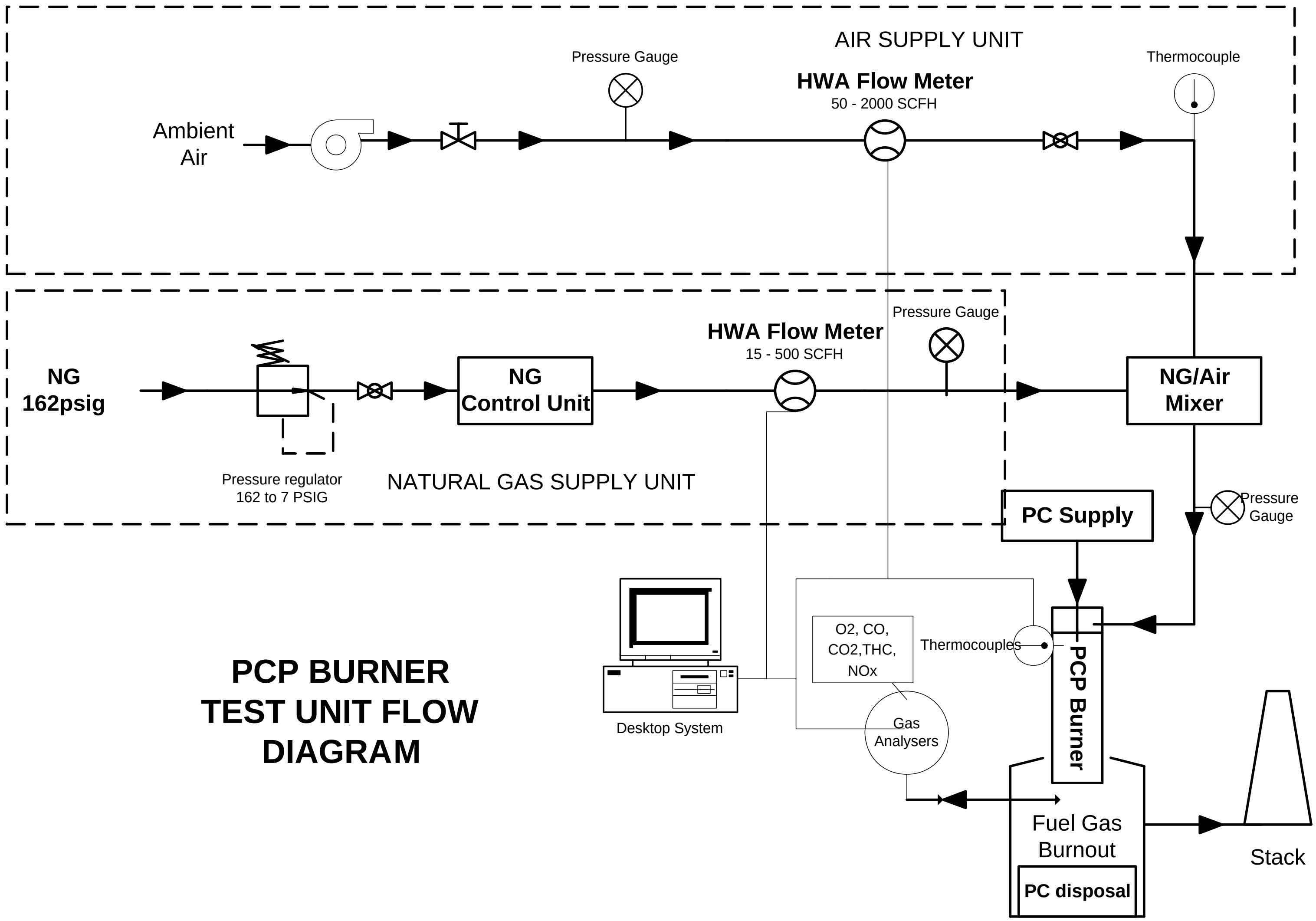


Figure 16. PC PREHEAT burner system combustor test arrangement in GTI's combustion laboratory

The pilot PC PREHEAT combustor was designed using three-dimensional CFD modeling. The design basis for the combustor is shown in Table 11:

Table 11. 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

Installation of the PC PREHEAT burner in GTI's combustion laboratory is shown in Figures 2 and 3 below. Proof-of-performance testing of the pilot-scale natural gas-fired PCP combustor in GTI's combustion laboratory was successfully completed prior to prior to installation of the combustor in Riley's research facility in Worcester, MA for integrated testing with pulverized coal.

Figure 17. PC PREHEAT combustor unit - view from the top of the sectional furnace

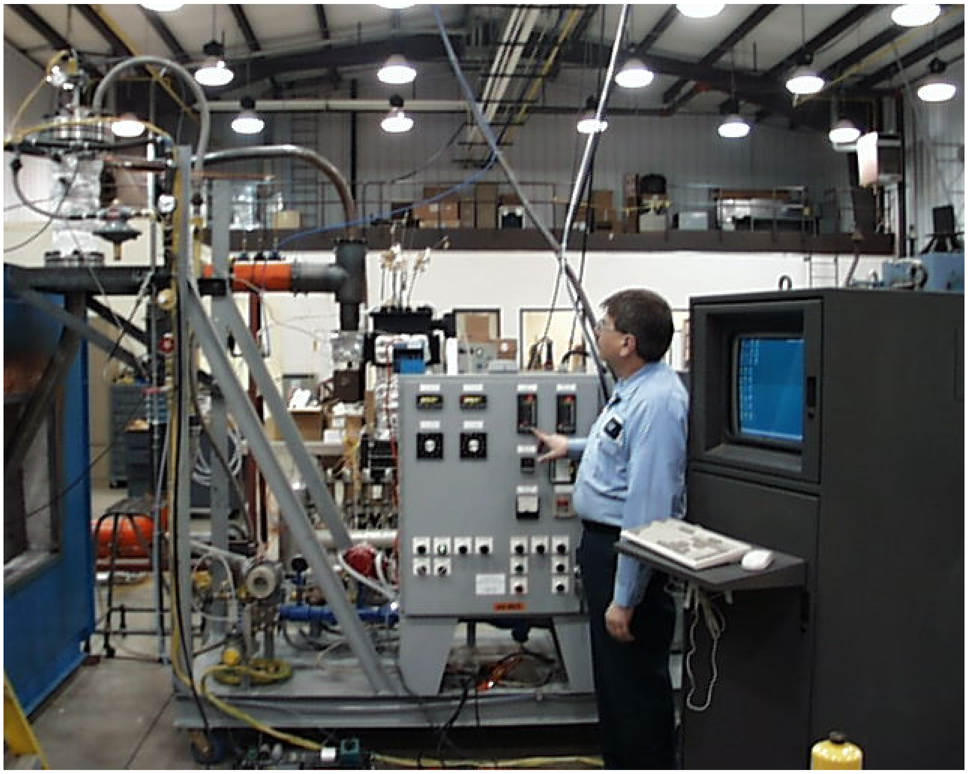


Figure 18. PC PREHEAT combustor, sectional furnace, gas and air supply skid, and controls

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 Riley's research facility in Worcester, MA for integrated testing with pulverized coal. The size distribution and specific heat of the sand particle used in GTI's testing was similar to size distribution of the selected coals (see Table 12)

Table 12. Screen analysis for silica sand # 16 used for PC PREHEAT 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 at ambient temperature were mixed with a small amount of air in controlled proportions and then introduced into the PCP combustor. 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 combustor and find operation regimes where the flame was not extinguished by the injected cold particles. Flame stability testing was performed by varying the amount of injected solids from 20% to 160% of design solids loading. 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. The 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 about 100 °F.

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

Pilot Test Unit Installation at RPI

Fabrication of the pilot scale PC PREHEAT test unit components was completed in July 2001. All fabricated components have been delivered to Riley's Pilot Scale Combustion Facility (PSCF) and installed on the refurbished 3-million Btu/h test furnace. See Figures Figure 19 through Figure 24. A P&ID for the pilot unit is shown in Figure 26.

Figure 19. Variable length preheating chamber permits testing with various preheating residence times

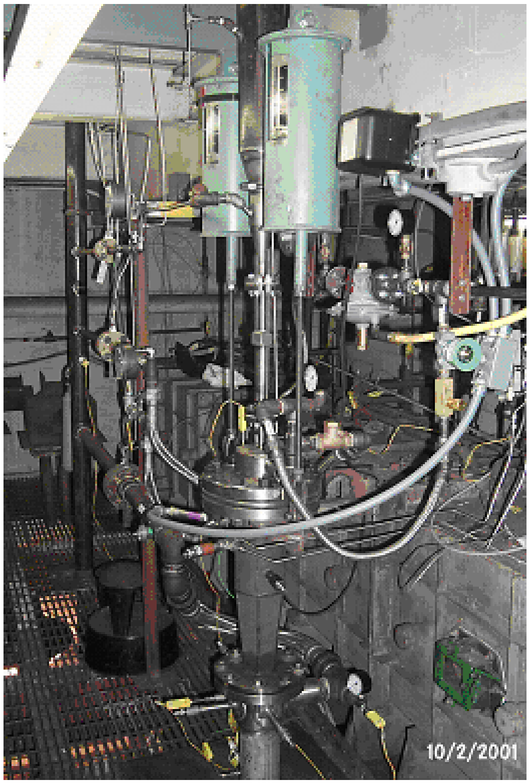


Figure 20. Gas-fired PCP combustor installed at the PSCF with natural gas and air piping and controls

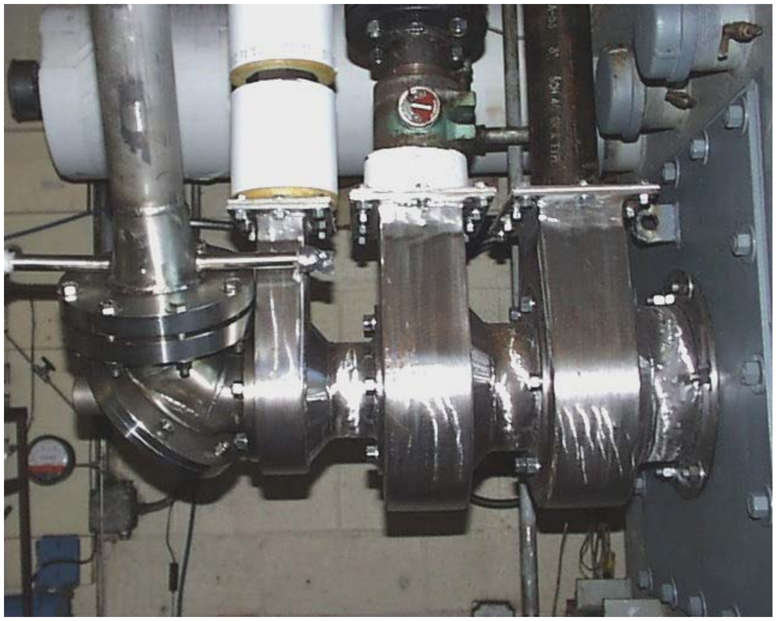


Figure 21. Air-staged PC burner combusts preheated char and pyrolysis products produced in the PCP combustor

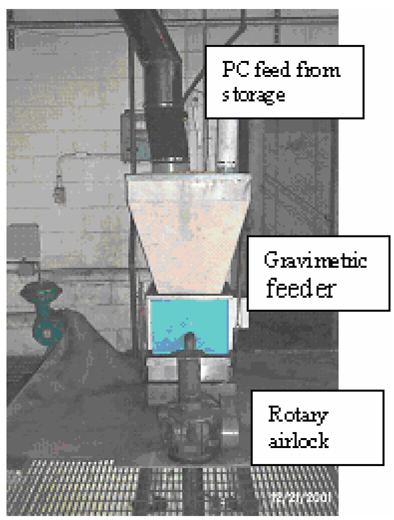


Figure 22. PC Feeder above PREHEAT combustion chamber

The PC PREHEAT pilot system regulates pulverized coal flow with a gravimetric feeder, which drops the coal through a rotary airlock into the natural gas-fired PREHEAT combustor. The combustor produces hot combustion gases, which combine with the pulverized coal to produce a mixture of coal char and pyrolysis products at the desired test temperature. Two PREHEAT pipe sections after the combustor provide additional residence time for the coal at the preheated conditions. The hot char and pyrolysis products then enter the PC burner, which is designed for operation over a broad range of flow distributions between primary, secondary and tertiary burner combustion air streams.

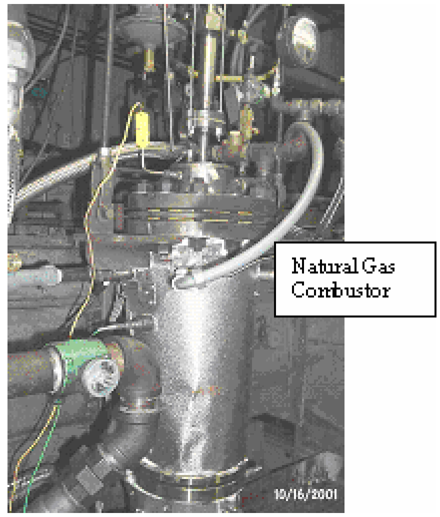


Figure 23. Gas-fired PREHEAT combustion chamber

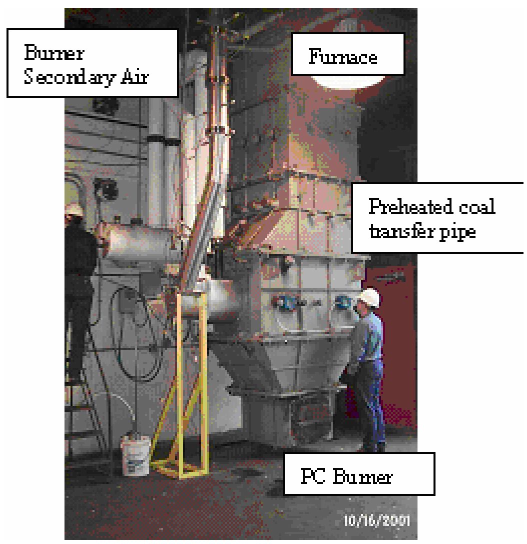


Figure 24. 3-million Btu/h PC burner and test furnace

During testing, real time operating data are collected at 1-second intervals and recorded by the personal computer-based data acquisition system (DAS). The concentrations of CO, CO_2, O_2, THC and NO/NO_x in the PC PREHEAT unit exhaust and the furnace exit are continuously monitored by on-line gas analyzers, including 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.

The PREHEAT gas combustor wall temperature is monitored by thermocouples installed on both the outer walls and inside of the combustion chamber. Temperature of the gas/air mixture is monitored in the gas/air plenum entering the combustor nozzles. Temperature are monitored downstream of the combustor by thermocouples installed in the PREHEAT pipe sections between the combustor and the PC burner.

The pilot-scale combustion facility control room is illustrated in Figure 25. This room houses the facilities gas analyzers, central control panel, and the data acquisition system (DAS). The central control panel operates the facilities major equipment such as the FD and ID fans. Flue gas samples are cooled, dried, and filtered in the field before the analyzers and the data acquisition system (DAS) is based on a personal computer platform.

Figure 25. PSCF control room

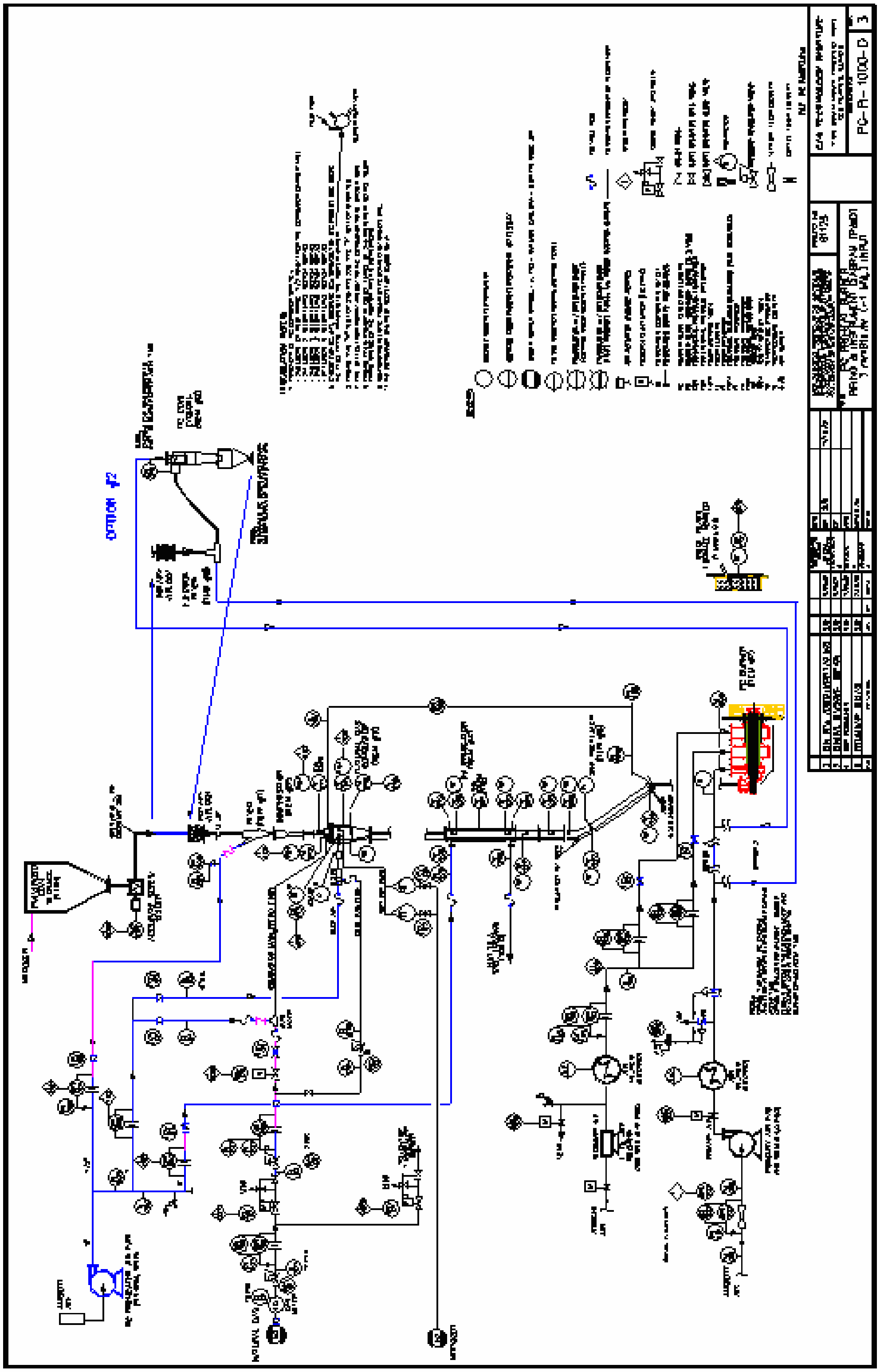


Figure 26. P&ID for the pilot-scale PC PREHEAT Burner Test System installed at the PSCF in Worcester, MA

PRB Pilot-Scale Development and Testing

The first coal tested in the pilot unit was a Powder River Basin (PRB) coal out of the Rochelle/North Antelope mine in Wyoming. This coal was obtained from the Hennepin Power Station in northern Illinois (Figure 27). The non-caking PRB coal was selected for initial testing to facilitate NO_x reduction proof-of-concept testing by avoiding plugging anticipated when firing caking coals in relatively small diameter pilot equipment with high heat losses.

Figure 27. Hennepin Power Station

Upon receipt, the as-received PRB coal was placed in a 20-ton storage silo, delivered to the Riley Research Center in super sacks (Figure 28) and pulverized as needed on-site.

Figure 28. Five tons of PRB coal delivered to the Riley Research Center

Before introduction of coal, a functional check of the PCP pilot unit was conducted that confirmed proper and safe operation of the different test system components. A functional test of the Natural Gas Combustor (Combustor) light off discovered a problem with the Combustor's pilot flame operation. This problem was resolved and a reliable light-off procedure was established. Overall, the check out was completed without many troubles and in a timely manner.

The PCP pilot unit start-up procedure requires heat up of the test furnace and PC PREHEAT system prior to introduction of coal. Heat from natural gas combustion in the PCP Combustor raises temperatures in the preheat sections while furnace components are heated via insertion of a 1-MMBtu/hr gas-fired ignitor placed in the test furnace chamber. Spring hangars and a compensator element in the PCP pilot system worked well handling the system thermal growth of about 2 inches. PC flow starts after elevated temperatures are obtained in the PCP pilot system and furnace. Initial tests of the PCP pilot unit demonstrated stable PC flow rates up to 250 lb/hr. At PC flow rates above 150 lb/hr, the furnace gas ignitor is shut down and retracted from the chamber leaving the coal flame. A picture of the coal flame (with furnace igniter retracted) produced from the original pilot PC Burner design is shown in Figure 29.

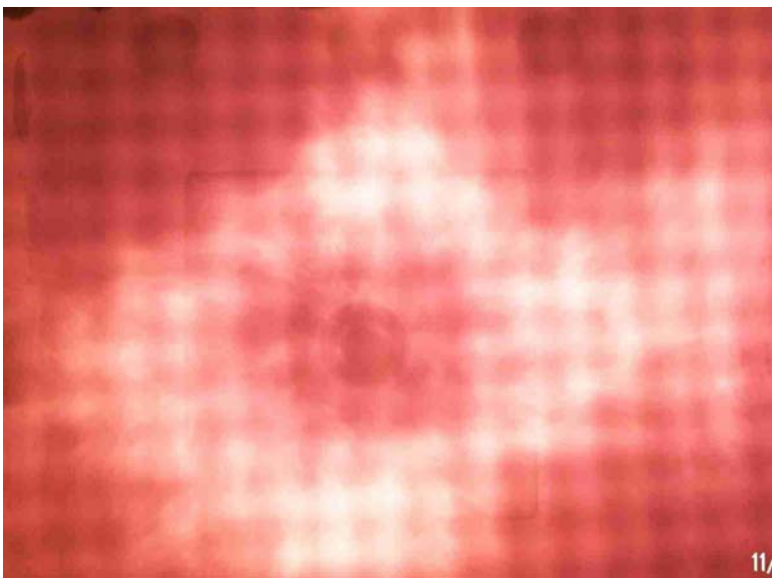


Figure 29. Short, intense flame produced by the original pilot PC burner design

The initial test objective was to confirm the NO_x reduction effectiveness of the PC PREHEAT system as implemented in the pilot unit. With a high-volatile coal such as PRB, VTI experience indicated that a preheat temperature of 1300 °F would be required. Early pilot tests were unable to achieve this preheat temperature, however. High-pressure drops were observed in the gas combustor air and natural gas piping, causing a reduction in flow capacity. This problem was fixed by changing the piping on both the air and gas supply systems. This allowed the pilot-scale system to achieve preheat temperatures in the range of 1100° to 1400 °F in accordance with VTI guidelines.

Extensive testing was conducted with the original PC PREHEAT pilot system. During the initial testing period, approximately 5,000 pounds of the PRB coal was processed. Test data covering over 50 different operating periods were collected for analysis. After initial problems with providing stable coal feed to the PREHEAT gas combustor were resolved, the pilot unit operated well. In addition to GTI and RPI personnel, two staff members from VTI traveled from Moscow and actively participated in testing from end of November through mid December 2001.

Analysis of the initial test data confirmed that the PC PREHEAT system has a significant effect on final NO_x formation in the coal burner and that the mechanism by which this is effected is not directly controlled by the final equilibrium preheat temperature, but rather by the residence time of the coal in the high temperature region within the gas-fired PREHEAT combustor.

Modifications to the pilot system gas-fired combustor were determined to be necessary in order to test the full potential of the process for NO_x reduction.

Pilot results from three test runs with PRB coal are given in Figure 30. Operating parameters for these three tests such as furnace exit oxygen, coal flow, combustor firing rate, combustor stoichiometry and preheat exit temperature were very similar. The main difference between these tests was the small amount of conveying gas flow used to transport coal to the PREHEAT combustor, which, at constant gas combustor firing conditions, can be varied to control the residence time of the coal in the high temperature portion of the gas combustor. In the plot shown below, the PRB40 transport gas flow was roughly double that of tests PRB41 and PRB42, which had significantly higher NO_x reduction due to increased residence time of coal in the high temperature zone of the gas combustor.

Mixer gas sweeps PC dropping from the rotary feeder through a ½" pipe section into the Natural Gas Combustor main chamber. Increasing the mixer gas flow increases the velocity in this pipe, which propels the coal particle towards the chamber exit changing internal circulation patterns and shortening PC residence time in the Combustor. Residence times given below are approximations predicted from GTI's CFD model of the pilot scale unit. A 45% reduction in NO_x was found as a result of decreasing mixer gas flow, which increased coal residence time in the Combustor zone from 21 ms to 42 ms.

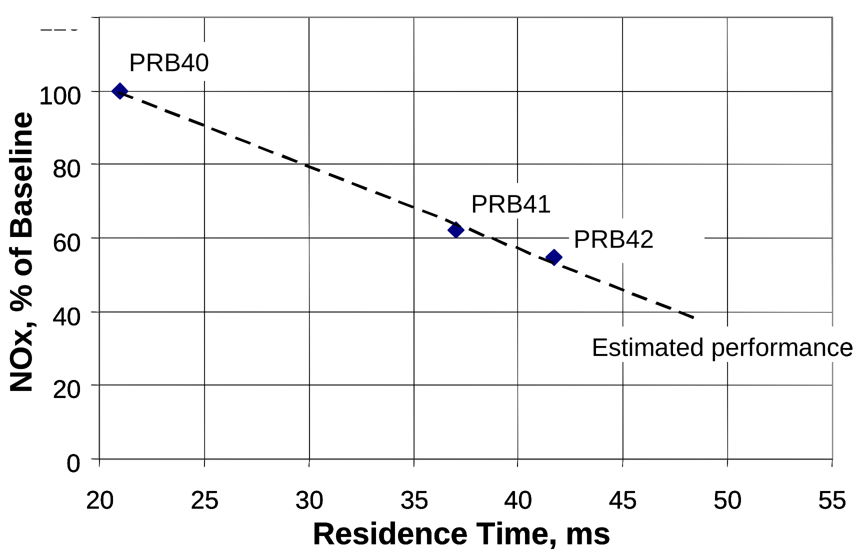


Figure 30. NO_x reduction vs. coal residence time in combustor

A second significant determination from this initial testing was that the PC burner design utilized was not optimally constructed for low-NO_x combustion of the preheated char and pyrolysis products generated in the PREHEAT combustor. The burner produced a short, hot, intense flame (Figure 29) rather than the longer, cooler staged-combustion flame necessary to achieve low NO_x emissions. It was determined that to function properly with preheated coal, the burner design must consider the high proportion of gaseous fuel components present and the fact that the char is already heated to about 1200°F before entering the burner, requiring a more distributed flame with internal staging as in, for example, GTI's gas-fired forced internal recirculation (FIR) low-NO_x burner designs.

Gas Combustor Modifications

A CFD modeling study for a modified PC PREHEAT gas combustor was performed using flow conditions from the pilot-scale tests with a computational mesh generated for the modified combustor. Combustor modifications are required to increase the residence time of the pulverized coal in the high temperature region of the combustor. In addition to increasing the length of the combustion chamber, a set of secondary gas inlets was added partway down the chamber from the coal inlet to reheat the pyrolysis products after initial devolatilization (See Figure 31 and Figure 32). The effect of this modification can be seen in Figure 3, where a secondary flame front is seen to develop at the secondary gas inlet. The model indicates that the average residence time of coal particles in the high temperature chamber is increased from 0.11 seconds to 0.2 seconds.

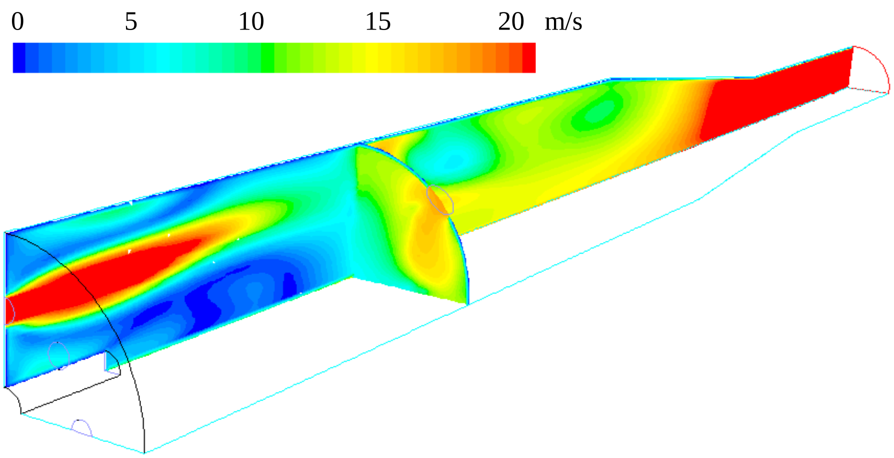


Figure 31. Velocity contours for the simulation of quarter of the system

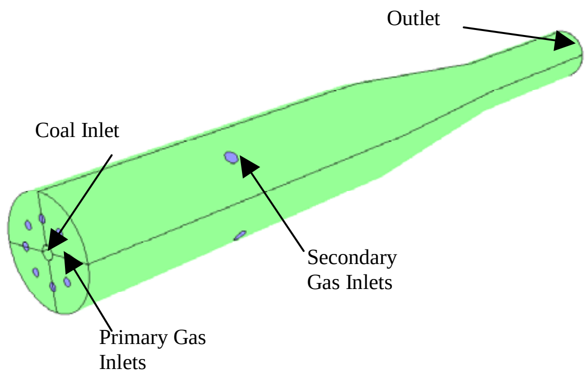


Figure 32. Modified gas-fired combustor design for the PC PREHEAT pilot-scale test

Completed modifications to the pilot-scale combustor are shown in Figure 34. In the new gas combustor, the average residence time of coal particles in the high temperature chamber is approximately double that of the original design.

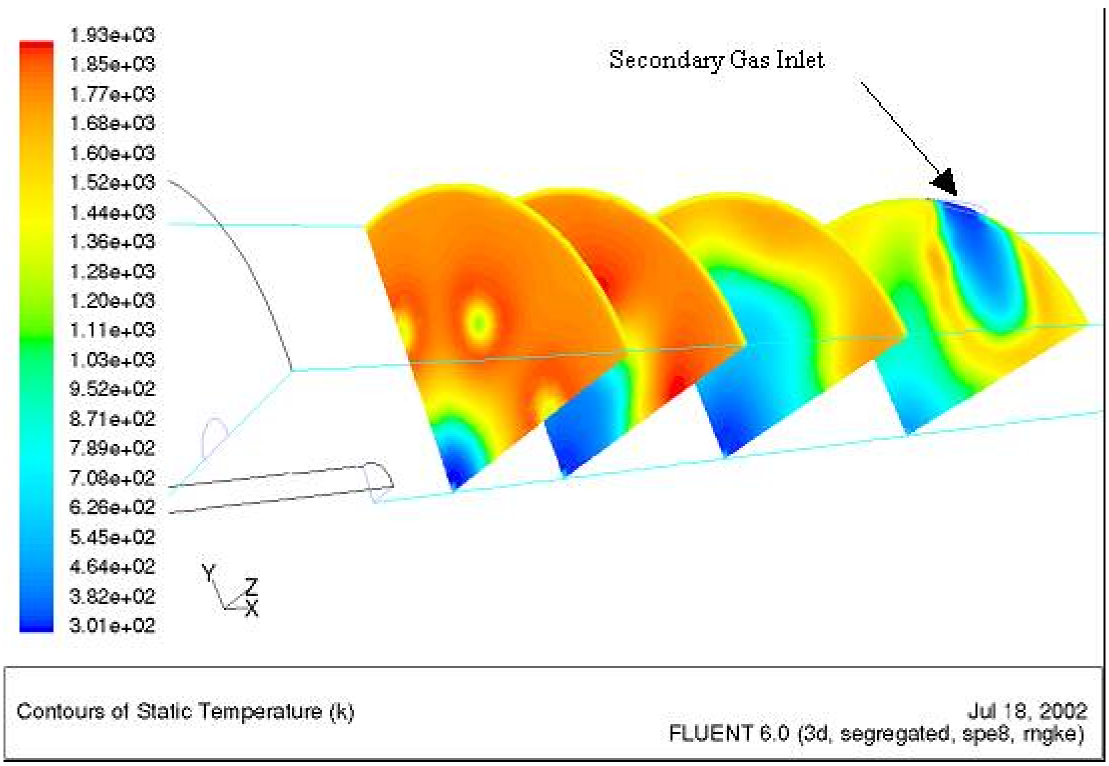


Figure 33. Temperature contours for the modified gas combustor

Figure 34. Modified gas-fired combustor for pilot scale testing

Coal Burner Modifications

Evaluation of data from pilot-scale testing with the unmodified gas combustor clearly indicated that in addition to changes in the gas combustor design, the pulverized coal (PC) burner would also require modification from the original pilot-scale design in order to perform as a low-NO_x burner in the PC PREHEAT system. The original PC burner, shown in Figure 4, would have been an appropriate low-NO_x design for unheated pulverized coal applications. With preheated coal, however, the hot char and pyrolysis gas mixture entering the burner combusts much more rapidly than unheated coal, producing a very short, intense flame as shown in Figure 29.

Figure 35. Original PC burner used for pilot-scale PC PREHEAT testing

It was apparent that the PC burner design must be modified to significantly improve air staging to allow low-NO_x combustion of the highly reactive preheated coal products. CFD modeling was also used to develop a modified PC burner around design concepts normally employed in GTI's natural gas-fired low-NO_x burners.

Computational meshes were developed for both the original and modified burner designs in order to compare their flame characteristics and optimize the modified design for preheated coal. Modeling of velocity vectors in the original PC burner design is presented in Figure 36, which shows the original three tangential air inlets with swirl. The predicted flame shape agrees very well with that observed with the original burner (Figure 29). The flame is very short, with a very limited fuel-rich zone indicative of a poorly staged flame.

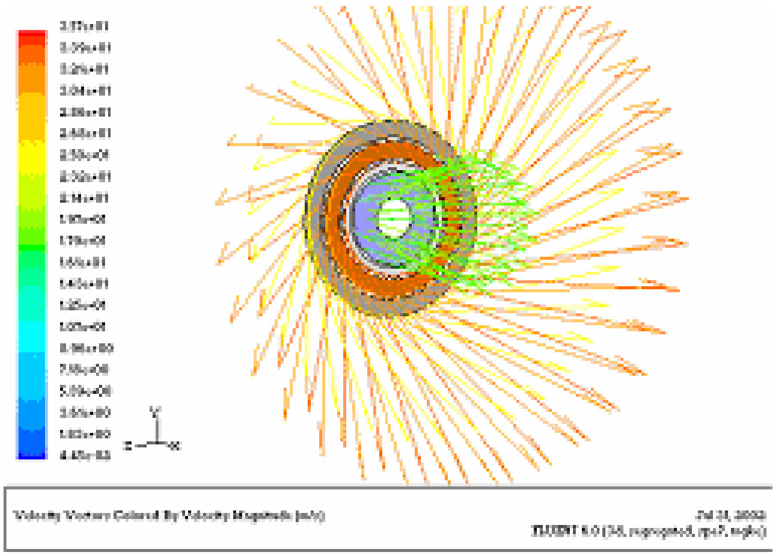


Figure 36. Velocity vectors for the original PC burner design

Figure 37 and Figure 38 compare the reducing regions produced in the original and modified pilot PC burners, respectively. In the modified burner, a much longer "reducing zone" is produced, allowing NO_x precursors to be destroyed and more heat to be removed from the flame before final burnout. This comparison indicates that the modified burner design approach is much more suitable for the highly reactive preheated fuel produced by the PC PREHEAT process. Another comparison of the original and modified burner design is shown in Figure 39 and Figure 40, which look at fuel particle path lines from the burner in the pilot furnace. Again, a short, intense mixing region is shown immediately in front of the burner with the original design and very little recirculation of particles predicted in the upper and lower furnace. Figure 38, however, shows a significantly longer mixing profile with much more recirculation of particles in both the lower and upper furnace. The result is a longer, more staged flame and a significantly more reducing atmosphere in the lower furnace, both of which contribute to much lower NO_x production.

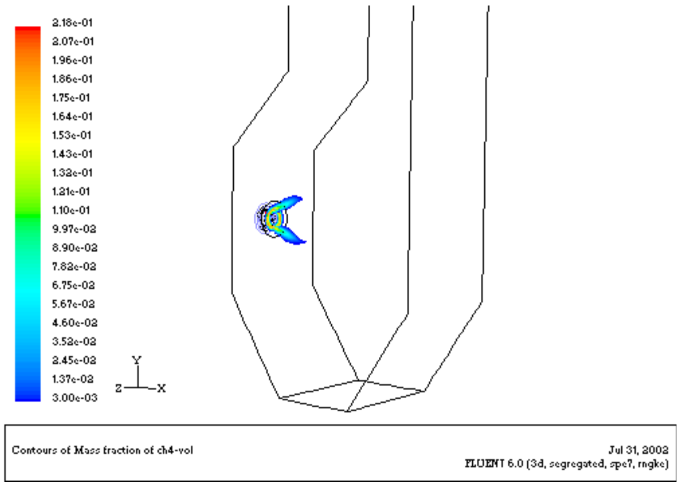


Figure 37. Vertical cross section of volatile matter in the original PC burner flame

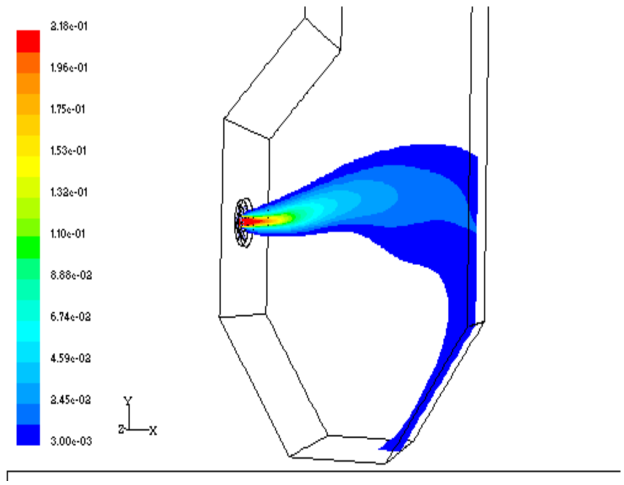


Figure 38. Vertical cross-section of volatile matter in the modified PC burner flame, indicating increased flame length

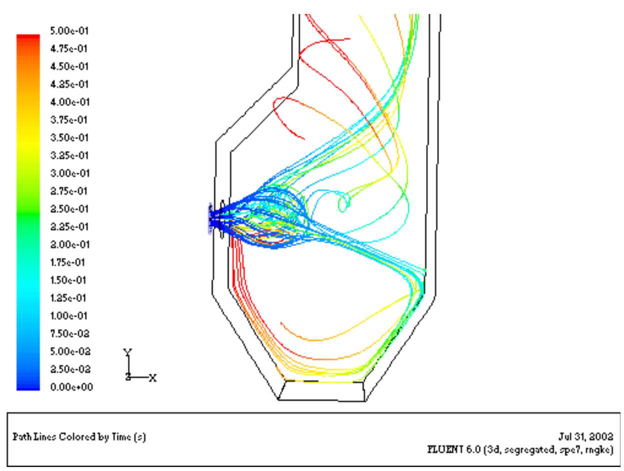


Figure 39. Fuel particle path lines with the original PC burner design

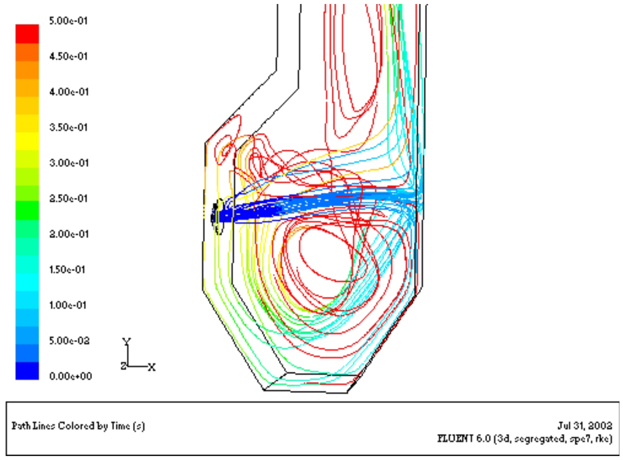


Figure 40. Fuel particle path lines with the modified PC burner design

The sequence of steps to complete the pilot testing was as follows:

- Extend the existing gas-fired preheat combustor chamber to double the design residence time and add a tangential gas combustion stage about half way down the extended chamber to maintain elevated preheat temperature throughout the chamber.
- Conduct testing with PRB coal to confirm proper operation of the modified combustor and characterize NO_x reduction.
- Modify the existing PC burner to provide a distributed, internally-staged flame
- Complete testing with remaining PRB coal to characterize NO_x reduction for the modified preheat combustor and burner system.
- Conduct PCP pilot tests with the Central Appalachia coal.

Modified Combustor Testing

The pilot test system was reactivated with the modified PREHEAT gas combustor and a series of shakedown tests was completed for gas-only operation. A series of twelve PRB coal-fired tests were then completed using the modified gas combustor and the original PC Burner design. Significant improvement in the previously attained NO_x emissions was achieved with the modified gas combustor. NO_x at the furnace exit was reduced to as low as 150 ppm with only 36 ppm CO (all gas data is reported on a dry basis, corrected to 3% O_2).

Testing further indicated that increased residence time for coal the high temperature region of the enlarged combustion chamber was primarily responsible for the improvement in NO_x performance. Operation of the second combustion stage to bring additional heat to this zone was not necessary and indeed, could be detrimental to NO_x reduction. The dependence on residence time was further demonstrated by varying the amount of air entering with the coal into the chamber. Increasing this air increased coal velocity and reduced residence time in the preheat chamber. In all cases, reduced residence time resulted in increased NO_x levels at the furnace exit.

Modified Burner Testing

Observation of the PC burner flame during these tests confirmed that modification of the coal burner was still necessary to achieve the full NO_x reduction potential of the PC PREHEAT approach. For this reason, redesign of the PC burner was continued in collaboration with RPI design engineers. The design approach considered both NO_x performance and fabrication cost and complexity. Two modified PC burner designs were developed using different approaches for burner air distribution-air channels and air nozzles. The modified PC burners also incorporated a new coal injector design. This design was based on RPI's Combustion Controlled Venturi (CCV™) burner coal nozzle technology[7].

Air Channel Burner Testing

The modified PC burner included a low swirl coal spreader and a flame stabilizer ring. These design modifications together with changes to the secondary and tertiary air channel design helped to produce an attached fuel-rich flame core. Fabrication and testing of the air channel version of the modified PC burner was then completed and a total of 38 firing tests were conducted with the modified system using PRB coal. Summary data from these tests are given in Table 13.

Table 13. PC PREHEAT pilot operating data collected in October-December 2002 with PRB coal, reduced data (115 ppm NO_x at 3% exit O_2 corresponds to 0.15 lb NOx/MMBtu)

tests	Test date	Test time	Comments	NOx @ 3% O2	CO @ 3%O2	Furnace exit O2	Preheat firing rate	Coal flow	Total air flow
Units	MM/DD	HH:MM	-	ppm	vppm	% vol.	Mbtu/hr	lb/hr	lb/hr
tests, Oct, 2002	**10/29**	**Modified coal burner, PRB**							
200PRB3-1	10/29	17:27	low comb-r temp	**101**	**66**	**1.4**	0.41	198	1844
200PRB3-2	10/30	11:09	low comb-r gas	**67**	**93**	**1.1**	0.29	198	1751
200PRB3-3	10/30	11:22	low comb-r-gas	**64.5**	**60**	**1.2**	0.28	198	1751
200PRB3-4	10/30	12:13	comb-r gas 320	**64**	**112**	**0.8**	0.32	198	1762
200PRB3-5	10/30	12:35	higher comb-r air	**86**	**43**	**1.1**	0.33	198	1805
200PRB3-6	10/30	12:49	1100 deg F preheat	**75**	**46**	**1.2**	0.32	198	1823
200PRB3-7	10/30	13:08	1200 deg F preheat	**83**	**35**	**2.1**	0.32	198	1863
200PRB3-8	10/30	13:40	lower burner air	**137**	**67**	**1.3**	0.32	198	1776
200PRB3-9	10/30	14:12	1250 deg F preheat	**140**	**40**	**1.2**	0.36	198	1800
tests, Oct-Nov, 2002		**New PRB coal, Modified burner, residue of CA coal in the system, unsteady**							
200PRB4-1-1-1	11/13	16:23	a1, t1	**119**	**150**	**0.7**	0.29	198	1823
200PRB4-1-1-2	11/13	10:59	a1, t2	**116**	**370**	**0.9**	0.31	198	1709
200PRB4-1-1-3	11/15	11:59	a1, t3	**114**	**340**	**0.6**	0.28	198	1731
Tests Nov,25-26,2002		**PRB coal, Modified coal burner, some residue of CA coal in the system**							
200PRB4-1-4	11/25	16:30	a2,t1	**158**	**144**	**1.0**	0.31	198	1791
200PRB4-1-5	11/25	17:32	a2, t2	**174**	**50**	**1.4**	0.37	198	1814
200PRB4-1-6	11/25	17:48	a2, t3	**152**	**85**	**0.9**	0.36	198	1806
200PRB4-1-7	11/25	18:26	a3, t1	**163**	**111**	**1.2**	0.39	198	1836
200PRB4-3-1	11/26	13:02	150 lbh coal	**135**	**135**	**1.3**	0.22	159	1527
200PRB4-3-2	11/26	13:31	198 lbh coal	**79**	**872**	**0.4**	0.22	198	1615
200PRB4-1-8	11/26	14:03	a3, t2	**77**	**869**	**0.3**	0.22	198	1610
200PRB4-1-9	11/26	16:52	a3, t3	**169**	**73**	**1.2**	0.22	198	1751
200PRB4-1-10	11/26	17:40	a4	**117**	**324**	**0.5**	0.30	198	1759
200PRB4-1-11	11/26	19:22	osa	**97**	**221**	**1.5**	0.31	198	2141
Tests Dec,3,4,2002		**PRB coal, Modified coal burner, no spreader in coal burner**							
200PRB4-1-12	12/3	12:18	a1	**156**	**64**	**1.4**	0.20	198	1720
200PRB4-1-13	12/3	13:37	a2	**161**	**86**	**1.6**	0.26	198	1798
200PRB4-1-14	12/3	14:36	a3	**131**	**135**	**1.0**	0.30	198	1805
200PRB4-1-15	12/3	15:38	a4	**128**	**413**	**1.1**	0.36	198	1896
200PRB4-1-16	12/3	16:37	a5	**125**	**162**	**0.9**	0.39	198	1888
200PRB4-1-17	12/4	9:58	Ign air 18	**161**	**78**	**1.7**	0.25	198	1814
200PRB4-1-18	12/4	10:34	Ign air 5	**135**	**238**	**1.0**	0.25	198	1757
200PRB4-1-19	12/4	11:13	isa/osa	**111**	**385**	**0.6**	0.25	198	1733
200PRB4-1-20	12/4	11:41	a1	**93**	**656**	**0.5**	0.21	198	1715
200PRB4-1-21	12/4	12:12	EXIT O2 .4	**73**	**872**	**0.4**	0.22	198	1638
200PRB4-1-22	12/4	13:14	osa/isa	**172**	**79**	**1.1**	0.22	198	1846
200PRB4-1-23	12/4	13:36	osa/isa	**137**	**80**	**2.0**	0.23	198	2070
200PRB4-1-24	12/4	13:53	a2, isa/osa	**116**	**106**	**1.9**	0.23	198	2081
200PRB4-1-25	12/4	14:22	a5, isa/osa	**112**	**66**	**2.2**	0.26	198	2062
200PRB4-1-26	12/4	14:39	a4, isa/osa	**112**	**73**	**2.1**	0.26	198	2073
200PRB4-1-27	12/4	14:53	a3, isa/osa	**107**	**76**	**1.9**	0.29	198	2090

During these tests, NO_x reduction was improved to levels below 100 vppm at 2% stack O_2 and CO ranging from 35-112 vppm without any furnace air staging. The coal flame from the modified PC burner was observed to be extremely stable and uniform and filled the combustion chamber. Figure 41 shows another view toward the burner along the centerline of the flame before the burner modifications. Figure 42 shows the same view with the modified PC burner. Figure 43 shows a side view of the modified burner flame. As predicted in the modeling studies reported earlier, the longer, less intense flame produced by the modified burner significantly reduced NO_x production.

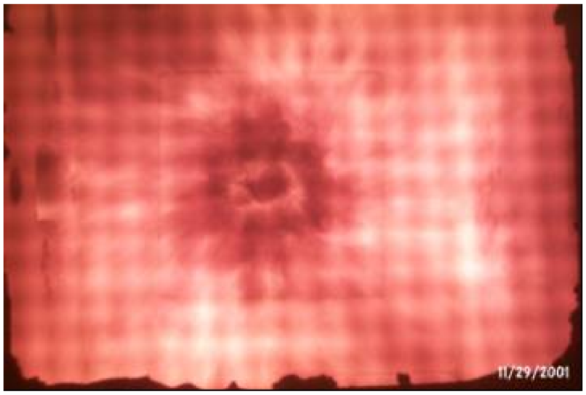


Figure 41. Intense, high NO_x flame before burner modification, rear furnace window view

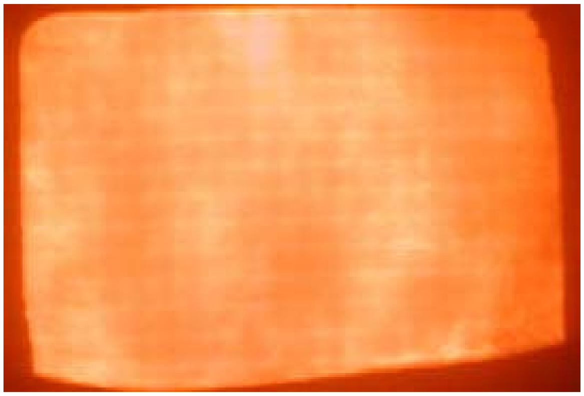


Figure 42. More uniform, low-NO_x flame with modified burner, rear furnace window view

Figure 43. Modified burner, flame roots are more uniform

The balance of the original inventory of PRB coal was consumed during the first nine tests, and it was therefore decided to conduct several tests with bituminous Central Appalachian coal to evaluate operation of the PC PREHEAT system with caking coal. As anticipated, operation of the pilot unit with caking bituminous coal resulted in incidences of plugging in the system, the severity of which depended on the gas combustor operating conditions. Sufficient testing was completed to allow preliminary analysis of the plug formation and operating parameters used, which indicated several approaches to eliminate plugging in future tests, including further changes to the PREHEAT chamber geometry and operating conditions.

It was decided to complete parametric testing of both of the modified burner designs with PRB coal prior to any additional tests with bituminous coals. Accordingly, additional PRB coal was obtained and PRB testing continued in order to fully characterize the PC PREHEAT system operation with respect to the gas combustor and PC burner operating variables. Testing included varying air to the gas combustor, varying the gas combustor firing rate and varying air distribution to the PC burner. Test results presented in Figure 44 show NO_x emissions versus furnace-exit O_2 for optimized air channel burner operating conditions relative to the project goal of 0.15 lb NO_x per MMBtu. This data was used in development of the design for a 100 MM Btu/h prototype PC PREHEAT burner for testing in the next phase of the project.

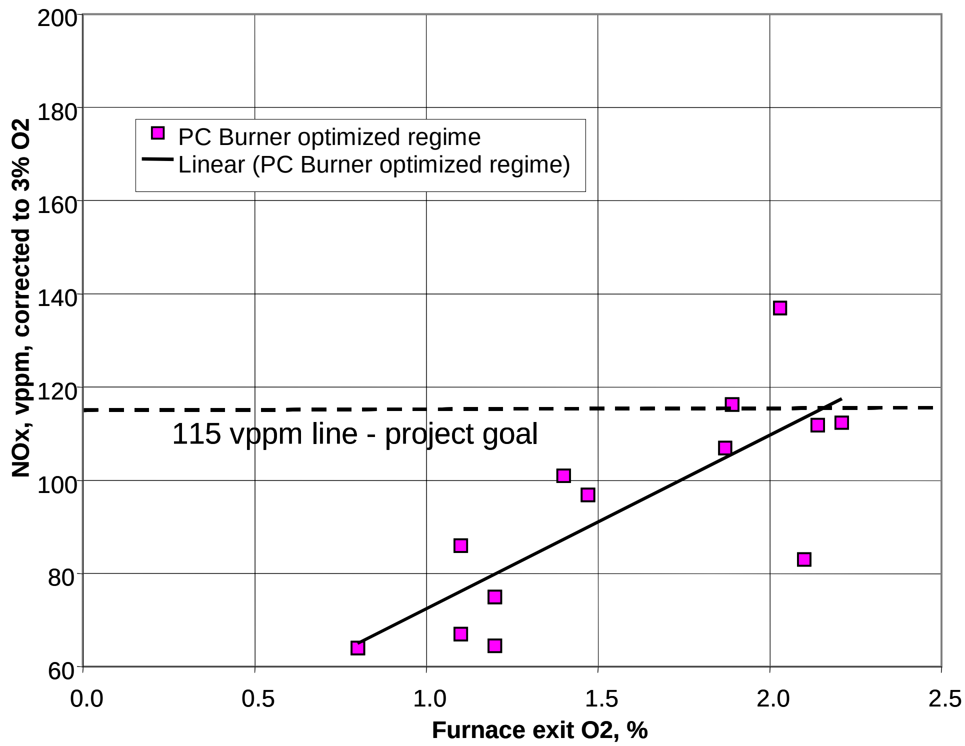


Figure 44. Optimized PC burner operation during Oct- Dec. 2002 testing.

Additional PRB coal was obtained and PRB testing continued in order to fully characterize the PC PREHEAT system operation with respect to the gas combustor operating variables as well as the PC burner operating variables. This was necessary to facilitate development of a conceptual design for the 100 MM Btu/h prototype PC PREHEAT burner.

An expanded parametric test plan (see Table 2) was developed and reviewed with RILEY for the additional PRB testing. The test plan addressed four objectives:

- Minimize gas usage
- Evaluate NO_x vs. excess air and air distribution in the new coal burner
- Evaluate NO_x vs. load
- Long term (4-8 hour) performance test

Table 14. Test matrix for modified PC burner testing

Test tasks:	**1**	**minimize natural gas**					**200prb41-x-xx**						
	2	**excess air and air distribution betw. burner channels**					**200prb43-xx**						
	3	**different test loads**					**xxprb42-xx**						
	4	**Long term (4-8 hr) performance run**					**200prb44-xx**						
	5	**Optional: PC burner modifications**					**200prb45-xx**						
Baseline case:		**200PRB3-3**											
Task	**1**	**minimize natural gas**				**Task**	**2**	**excess air and air distribution betw. burner channels**					
Test variables:			min	max	comment	Test variables:		min	max	comm.			
	1	combustor air, lb/hr	a1	a5			air 1	0	ta2	drying agent air			
	2	combustor wall temp-re	t1	t3	varied by adjusting NG		air 2	0	ta2	inner secondary air			
	3	mixer air, scfm	ma1	ma5			air 3	0	ta2	outer secondary air			
PC burner:						tot. burner air, lb		ta1	ta2				
	1	Drying Ag. Air, lb/h	da1			Coal feed, lb/h		198					
	2	Inner Sec. Air. Lb/h	isa1			comb-r set up		from task 1					
	3	Outer Sec. Air, lb/h	osa1										
	4	Coal, lb/h	198										
Test matrix for task 1													
		Test #	Comb-r Air, lb/h	peak wall temp-re, deg.F			Test #	air1, lb/h	air2, lb/h	air2, lb/h	total PC burner air, lb/h		
one stage firing		200PRB41-1-1	**a1**	t1	Optional		200PRE	ta2	0	0	ta2		
SubTask 1-1		200PRB41-1-2	a1	t2			200PRE	0	ta2	0	ta2		
		200PRB41-1-3	a1	t3	Optional		200PRE	0	0	ta2	ta2		
		200PRB41-1-4	**a2**	t1			200PRE	da1	(ta2-da1)/2	(ta2-da1)/	ta2		
		200PRB41-1-5	a2	t2			200PRE	250	(ta2-da1)/2	(ta2-da1)/	ta2		
		200PRB41-1-6	a2	t3			200PRE	450	(ta2-da1)/2	(ta2-da1)/	ta2		
		200PRB41-1-7	**a3**	t1			200PRE	350	(ta2-da1)/2	(ta2-da1)/	ta2		
		200PRB41-1-8	a3	t2			200PRE	350	(ta2-da1)/2	(ta2-da1)/	ta2	(ta2-da1)/2	
		200PRB41-1-9	a3	t3			200PRE	tbd	tbd	tbd	ta3	exit O2	
		200PRB41-1-10	**a4**	t1	Optional		200PRE	tbd	tbd	tbd	ta4	exit O2	
		200PRB41-1-11	a4	t2			200PRE	tbd	tbd	tbd	ta5	exit O2	
		200PRB41-1-12	a4	t3	Optional								
		200PRB41-1-13	a5	t1	Optional								
		200PRB41-1-14	a5	t2									
		200PRB41-1-15	a5	t3	Optional								
		200PRB41-1-16	tbd	tbd			**Task**	**3**	**different test loads**				
		200PRB41-1-17	tbd	tbd			Test variables:		min	max	comm.		
		200PRB41-1-18	tbd	tbd			1	coal fee	150	240			
two stage comb-r firing		Optional	comb-r air 1st Stage, lb/h	comb-r air 2 Stage, lb/h	peak wall temp-re, deg.F		Combustor settings are selected from task 1						
tot. comb-r air is defined from 1 stage firing							Burner air is adjusted proportionally to the load						
SubTask 1-2		200PRB41-2-1	ca1	tbd	t1			Test#	Coal feed, lb/h				
		200PRB41-2-2	ca1		t2			150PRB	150				
		200PRB41-2-3	ca1		t3			234PRB	234				
Lean Comb-r firing		Optional	Comb-r Air, lb/h	peak wall temp-re, deg.F									
SubTask 1-3		200PRB41-3-1	120	1800									
		200PRB41-3-2	120	1950									
		200PRB41-3-3	120	<2100		**Task**	**4**	**Long term (4-8 hr) performance run**					
		200PRB41-3-4	150	1800			Test #						
		200PRB41-3-5	150	1950			200PRB44-1		settings are TBD based on tasks 1-3				
		200PRB41-3-6	150	<2100									

A new 20-ton shipment of PRB coal was received for this testing from Hennepin Power Station in Illinois in December 2002. Testing with the air channel burner was therefore started with benchmark tests to determine whether performance with the new coal was comparable to that with the previous batch of PRB coal. Baseline testing was then performed to characterize performance of the PC Burner without coal preheating. Finally, parametric testing was performed to evaluate the effect of various preheat combustor and PC burner operating variables, including gas firing rate in the preheat combustor, combustor temperature, coal firing rate, furnace exit O_2, burner air flow and internal air distribution, and use of a low-swirl spreader in the burner coal nozzle.

A series of benchmark pilot tests were conducted with operating conditions similar to tests with the same system using the previous batch of PRB coal. A comparison of NO_x vs. furnace exit O_2 with the old and new coals is shown in Figure 45, which indicates very little performance difference between the two. All emissions results are given on a dry basis, corrected to 3 % O_2.

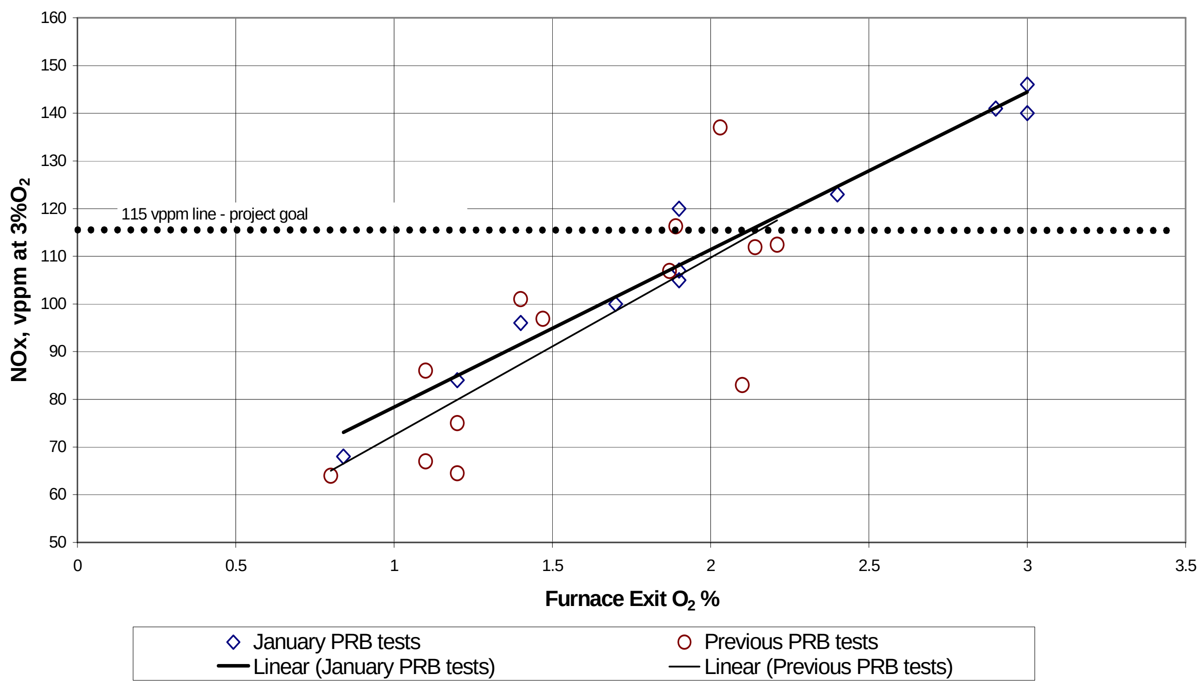


Figure 45. Benchmarking tests comparing pilot-scale preheating system performance with current and previous batches of PRB coal

A series of tests with PC preheating were conducted at furnace exit O_2 concentrations from 0.8% to 3.0 % by varying airflow to the outermost channel of the PC burner. The results of these tests without a coal spreader in the central coal tube are shown as the lower curve in Figure 2 relative to the project goal of 115 vppm. The upper curve in Figure 46 shows that addition of the coal spreader significantly increased NO_x production.

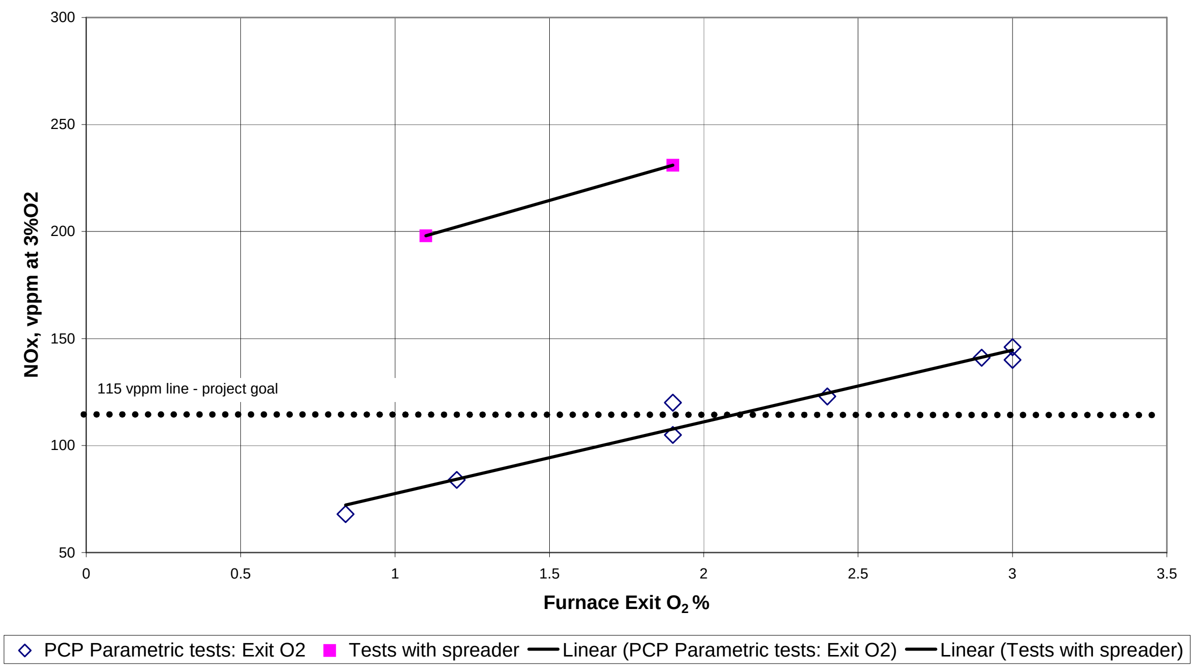


Figure 46. NO_x vs. exit O_2 curve for preheated PRB coal without coal spreader (lower curve) and with coal spreader (upper curve).

A series of baseline tests were conducted with the gas-fired coal preheater combustor shut off in order to assess the contribution of the combustor to NO_x reduction relative to that of the PC burner alone. Seven of the tests without the gas combustor used a PC burner configuration without a low-swirl spreader installed in central coal tube and one test was conducted with the spreader. Furnace exit NO_x readings with and without preheating in the gas combustor are shown Figure 47. Note that addition of the spreader again increased NO_x for the one point tested.

Two tests were conducted at a reduced coal-firing rate of 160 lb/h compared to the normal firing rate of 200 lb/h. The NO_x results for these tests are shown in Figure 48 4 vs. exit O_2 along with the same curve for operation at a 200-lb/h coal feed rate. The 20 % reduction in coal firing rate reduced NO_x at the furnace exit by about 20 % at 2.0 % exit O_2.

The modified PC burner has 3 concentric air channels surrounding a central coal tube. A series of tests was conducted to determine the effect of varying the air distribution between these channels on NO_x formation. Air flow to the innermost air channel (drying agent air) was adjusted to 3 different levels and, over the range tested, showed little effect on NO_x production compared to the base air distribution (Figure 49). Increasing air distribution separately to the secondary and tertiary air channels, however, showed significant increases in NO_x formation.

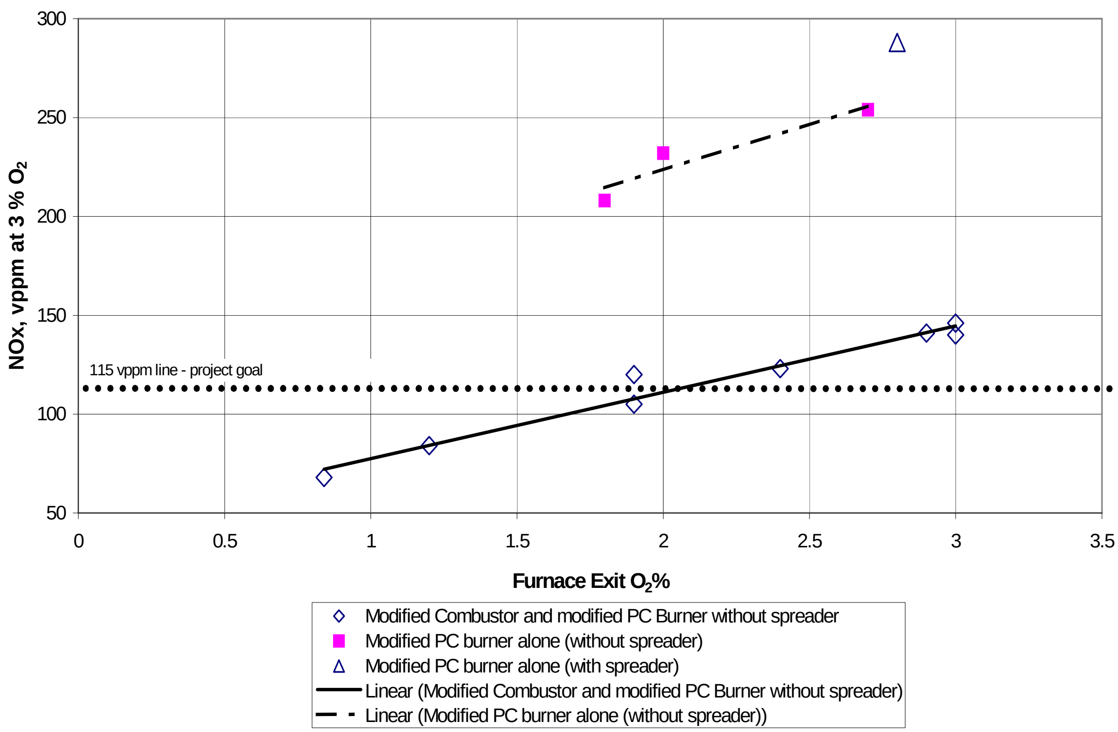


Figure 47. Baseline comparison of pilot-scale system performance on PRB coal with and without gas firing in the preheat combustor.

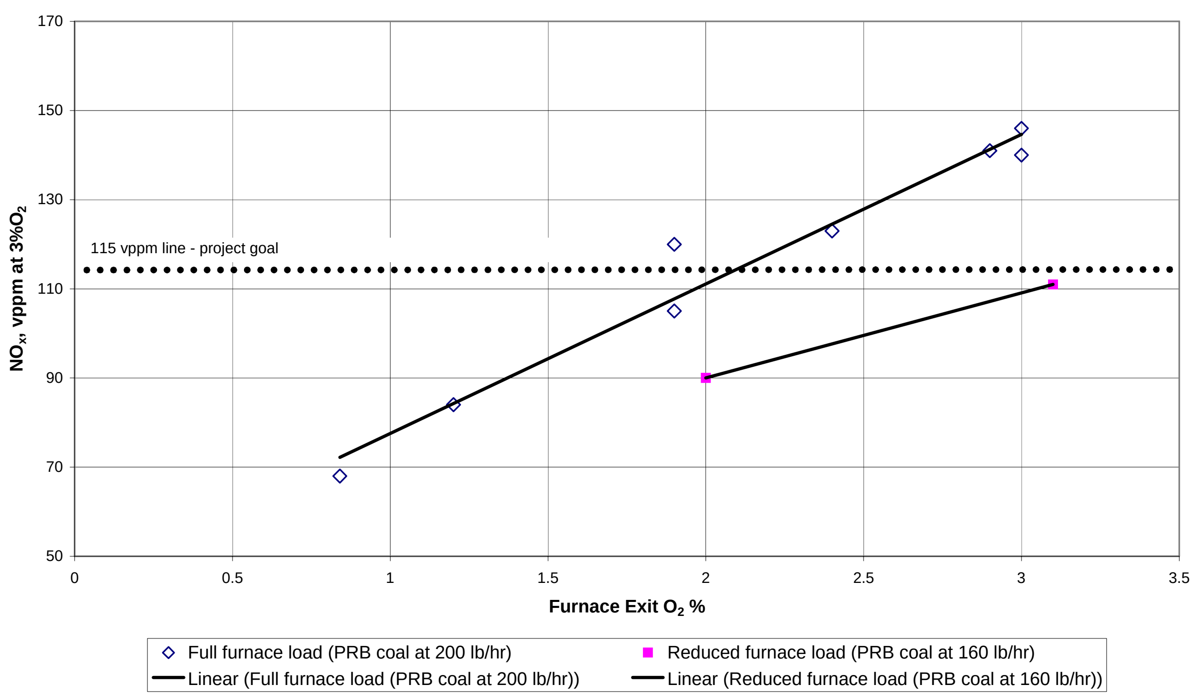


Figure 48. Effect of reduced coal firing rate on NO_x at the furnace exit.

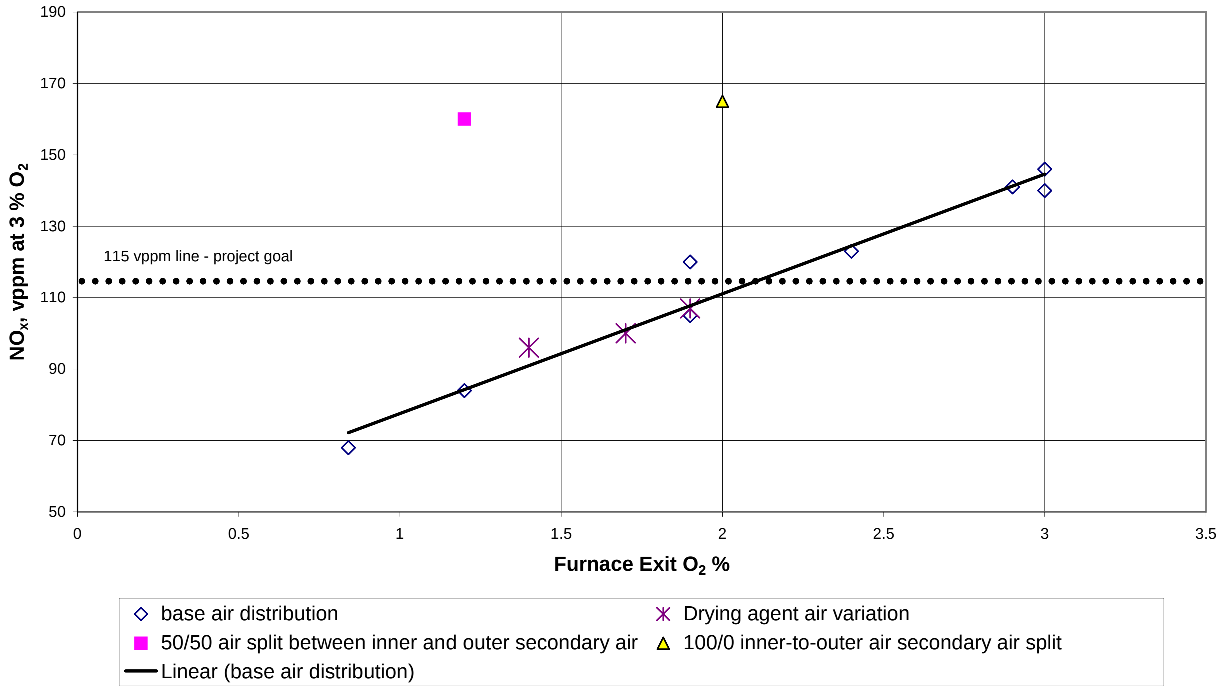


Figure 49. Effect of PC burner combustion air distribution on NO_x at the furnace exit

A series of tests was also conducted to determine the effect of reduced gas usage in the preheater combustor on NO_x formation. Gas usage was reduced to about 7 % of total thermal input from the 10-12% used for the base tests. NO_x formation at the reduced gas usage was essentially the same as for the base gas usage as shown in Figure 50. It is expected that when the process is scaled up to the 100 million Btu/h level that gas usage will be further reduced to the range of 3 to 5% of thermal input. The pilot unit includes a relatively long transfer pipe between the gas combustor and PC burner to allow variation of the residence time of preheated coal and pyrolysis products at the equilibrium preheat temperature before they enter the burner. It is expected that this transfer pipe, and the relatively high heat losses from it, will be eliminated in the scaled up design. The larger surface to volume ratio of the pilot-scale equipment also contributes to higher heat losses, and this ratio will be reduced in the larger burner.

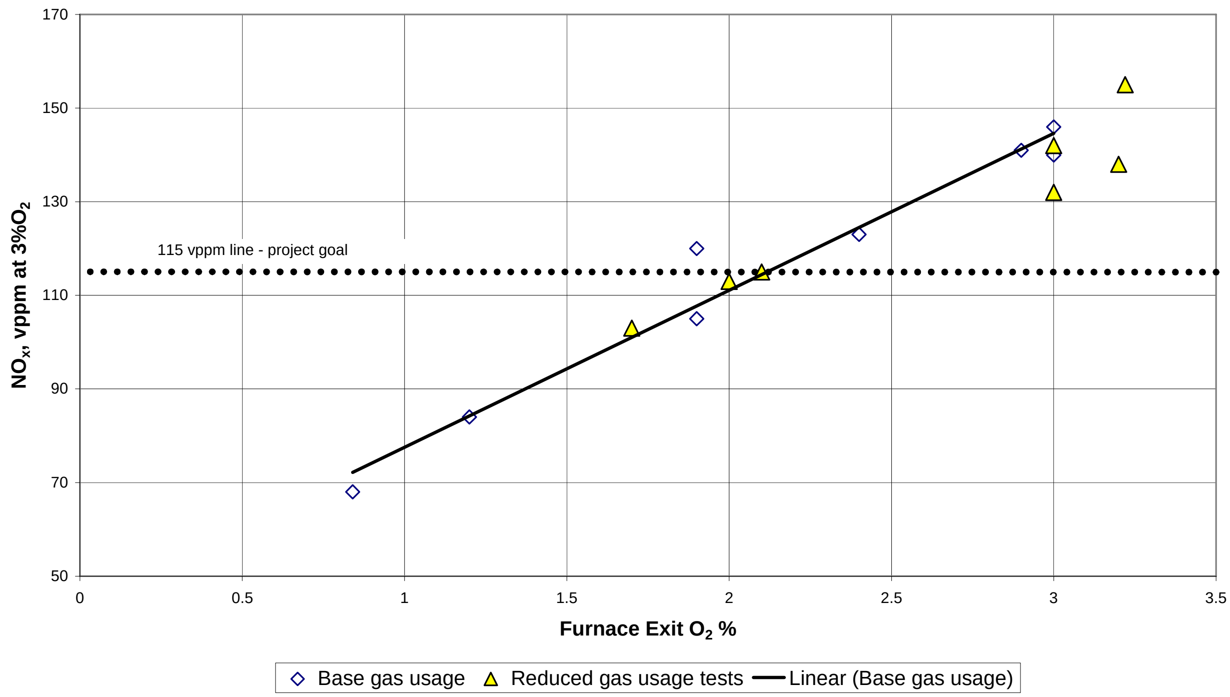


Figure 50. Effect of reduced gas usage in the preheat combustor on NO_x at the furnace exit

The pilot-scale PC PREHEAT system has achieved the initial target for NO_x reduction to below 0.15-lb/MMBtu (115 ppmv) with PRB coal. NO_x reduction was demonstrated at levels below 100 ppmv with CO in the range of 35-112 ppmv without any furnace air staging and furnace exit oxygen levels of 2%. NO_x levels between 110 and 115 ppmv were achieved with natural gas usage equivalent to about 7% of the total thermal input. It is expected that when the process is scaled up to the 100 million Btu/h level that gas usage will be further reduced to the range of 3 to 5% of thermal input. Operation with furnace air staging can be expected to reduce NO_x emissions further.

While the pilot-scale results for PRB coal are important, the most important potential market for the PC PREHEAT technology is expected to be in the Eastern portion of the U.S. where PRB coal is generally not economic to use. This region includes the 22 states and the District of Columbia that are subject to the NO_x SIP call limit of 0.15 lb NOx/MMBtu. The Eastern U.S. will be subject to an even more stringent limit of 0.11 lb NOx/MMBtu when the NO_x provisions of the Clear Skies Initiative are fully implemented. For the PC PREHEAT technology development to be relevant in the Eastern U.S., it is necessary to develop and demonstrate the technology with Eastern caking coals. For this reason, upon completion of the PRB testing with the air nozzle version of the PC Burner, the most successful version of the PC Burner was to be selected for additional pilot-scale testing with Central Appalachian caking coal. This testing focused specifically on identifying the system configuration and operational changes necessary for successful operation with caking coal, for incorporation into the design and operation of the 100-MMBtu/h test unit for caking coals.

Air Nozzle Burner Testing

An air nozzle version of the PC burner was also tested. The secondary air channels were closed and 6 air nozzle installed in its place. Initial testing of this burner design revealed problems with pressure pulsations, flame stability, and flame attachment at the burner face. A number of modifications were made to the burner during testing conducted in April to eliminate these problems. Changes to the air nozzle diameter eliminated the pressure pulsations. Other changes to the burner and burner operating conditions tested included:

- Length of the coal nozzle
- Addition of various flame holders at the end of the coal nozzle
- Addition of several different coal swirlers in the coal nozzle
- Adjustment of relative velocity of primary, secondary and tertiary air streams

The best NO_x result measured during this testing was 110 vppm corrected to 3% O_2, with 120 vppm CO. In general, problems of flame stability continued throughout the testing and were not satisfactorily resolved by the various modifications to the burner and its operating conditions. It was therefore decided to return the burner to its previous air channel configuration for the balance of the pilot testing.

Bituminous Coal Pilot-Scale Development and Testing

GTI continued pilot testing in June 2003 with air channel version of the coal burner. The goal of the testing was to evaluate several new approaches to operation with caking coal to eliminate deposition and plugging in the gas combustor chamber. The technical approach used was to intensify heat transfer between coal and natural gas flame through combustor design and operating changes such that all of the char and devolatilization products would pass through the sticky mesophase before reaching the diameter reduction at the exit of the combustor.

Four baseline tests with PRB coal were conducted using the previously tested gas combustor design. During those tests, radial profiles of temperature in the combustor were measured at two locations, 7 and 17 inches from the combustor front wall. The temperature profile at 17 inches for this combustor configuration is shown in Figure 51. In general, temperatures in the devolatilization product stream near the centerline of the combustor were found to be near or below the minimum temperature (about 900 ºF) expected to be necessary to avoid sticking with caking coal.

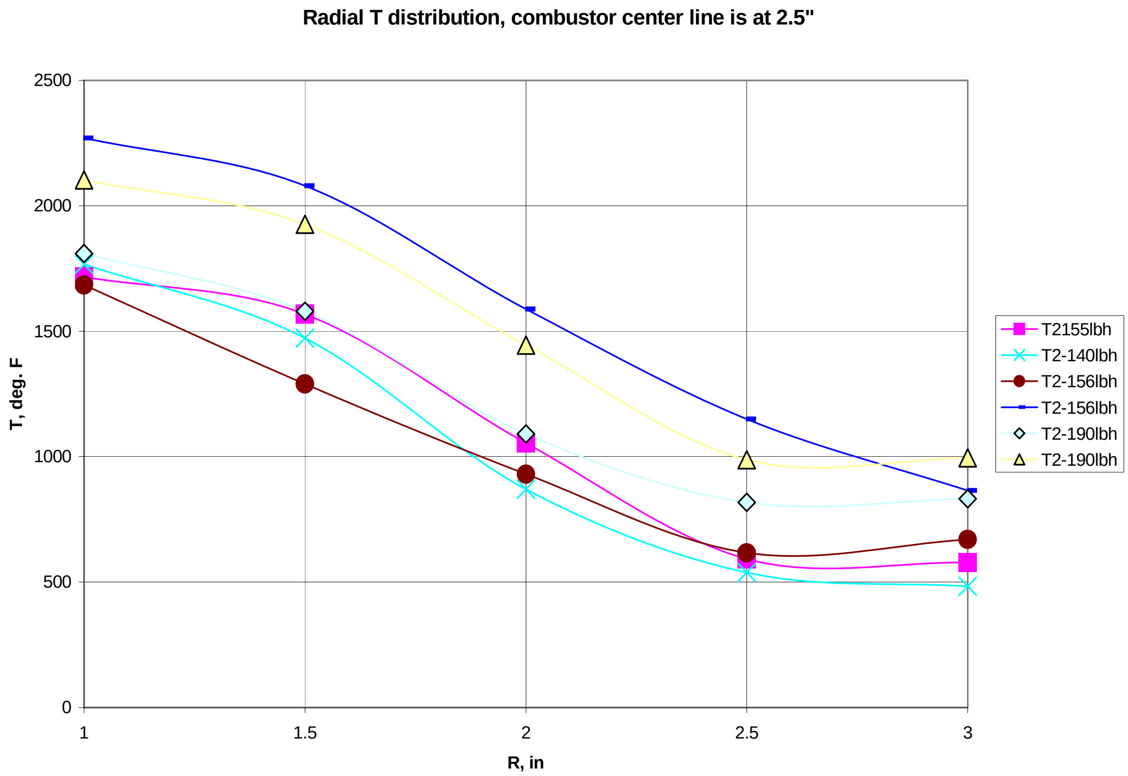


Figure 51. Radial temperature distribution at 17 inches from combustor front wall shows relatively low devolatilization product temperatures for the baseline combustor design

Two modifications of the coal injection nozzle were then tested with PRB coal to determine their effect on heat transfer between the coal stream and the natural gas flame. The modifications included increasing the diameter of the coal injection nozzle, adding perforations through the nozzle walls and adding a small cross-section bluff body at the bottom. The resulting temperature profile at the same location 17 inches from the combustor front wall is shown in Figure 52. Comparison of the temperature profiles in Figure 52 (modified coal nozzles) to the profiles in Figure 51 (straight nozzle) shows that both modifications provide faster heat transfer from the natural gas flame to the coal stream than coal injection through the straight nozzle. Temperatures are significantly higher and more uniform at the 17-inch point, which is 3 inches from the combustor exit.

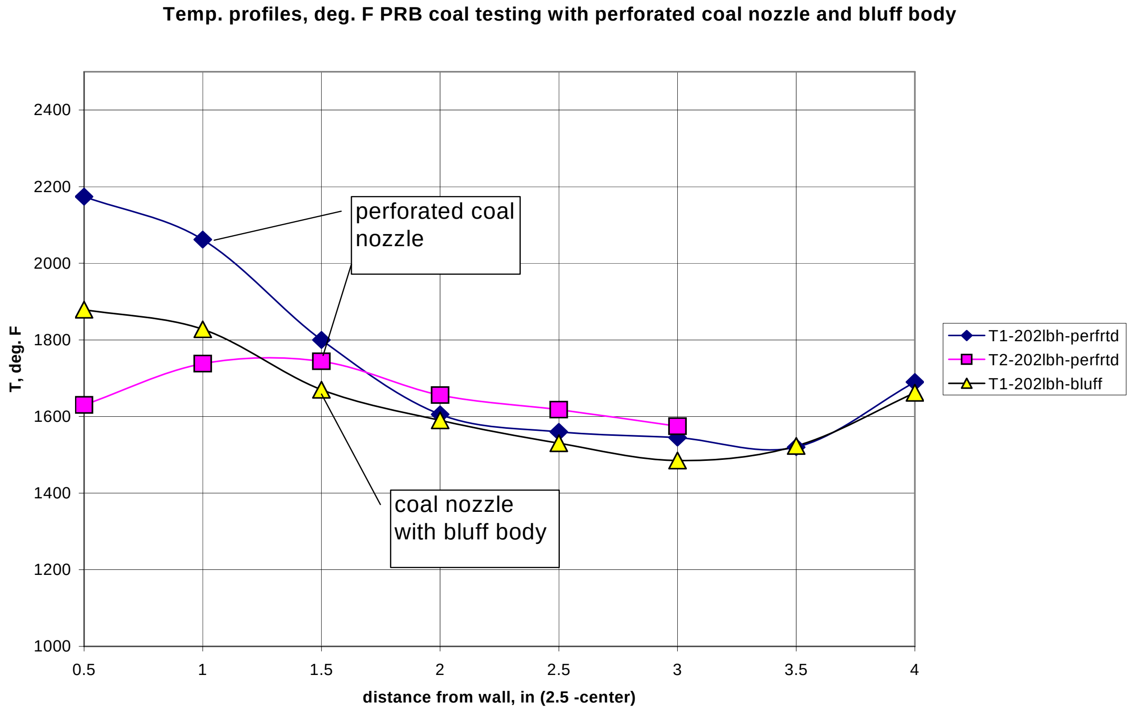


Figure 52. Modifications to gas combustor coal nozzle significantly increase heat transfer to coal devolatilization products

Based on the favorable results with PRB coal, four versions of the modified coal injection nozzles were tested with caking bituminous Central Appalachian (CA) coal. Continuous operation was achieved with a perforated coal nozzle at a CA coal-feeding rate of 50 lb/h (30% of full firing rate). However, plugging of the combustor with caked material occurred when the rate was increased above this level. Several different preheat regimes were tested, including high, medium, and low temperature preheat regimes, and preheat with both lean and rich natural gas flames. Inspection of the preheater after plugging showed that accumulation occurs wherever there was direct wall impingement by preheated coal particles. The coal nozzle modifications tested greatly improved mixing and heat transfer between the coal and combustion gases, but did so at the expense of increased coal particle impingement on the walls of the combustor in the immediate vicinity of the coal nozzle. This approach to nozzle design appears promising for non-caking coals like PRB, since it can significantly shorten the required combustor length by improving mixing and heat transfer. For caking coals, however, a different approach is necessary.

Based on these results, development of further pilot combustor modifications was started, including reducing the combustor diameter to increase velocity and eliminate the diameter reduction at the combustor outlet, and increasing the combustor length to maintain coal residence time. Also, RPI's initial guidance on the 100-MMBtu commercial burner design based on typical-installation layout considerations is that the preheat combustor should be oriented horizontally on the axial centerline of the coal burner. Accordingly, it was decided that the pilot gas combustor would be relocated to this orientation during the current changes so that the pilot results will be directly applicable to the preferred 100-MMBtu design.

Pilot Scale Unit Modifications

The pilot experience, together with commercial design guidance from RPI that favors a horizontal orientation for the combustor, has redirected the development of both the pilot and commercial units toward a horizontal combustor design with no diameter change between the combustor and burner. The velocity of the devolatilization products in the combustor and burner is increased over previous pilot testing to minimize separation and impingement of coal on inner surfaces prior to reaching the burner face. The velocities utilized are consistent with standard design criteria developed by RPI for their commercial CCV burners. The pilot unit was operated in parallel with the 100-MMBtu commercial prototype design in order to be able to test various design alternatives as they are developed. While it was expected that some plugging may always occur in the pilot unit due to its relatively small size, it still provides valuable insight on both caking and emissions performance in a much more economical and timely manner than testing a large number of design alternatives at the 100-MMBtu scale.

In the original pilot system configuration, the combustor centerline was vertical and two PREHEAT pipe sections after the combustor provided additional residence time for the coal at the preheated conditions prior to entering the PC burner. The PREHEAT combustor was relocated to a horizontal configuration with the combustor exit coupled directly to the PC burner inlet, eliminating the two PREHEAT pipe sections.

In the modified pilot unit, the velocity of the devolatilization products in the combustor and burner is increased over previous pilot testing to minimize separation and impingement of coal on inner surfaces prior to reaching the burner face. The higher velocities are more consistent with standard design criteria developed by RPI for their commercial CCV burners. The P&ID for the modified pilot system with the horizontal PREHEAT combustor is shown in Figure 1. The higher combustor velocities were achieved by inserting a liner in the combustor to reduce its internal diameter. The liner also facilitates testing of various designs and operating approaches to eliminate plugging of the combustor with caking coals. Various liner materials, including metal and ceramic, and liner cooling methods are developed and tested to determine their effect on wall deposition and plugging.

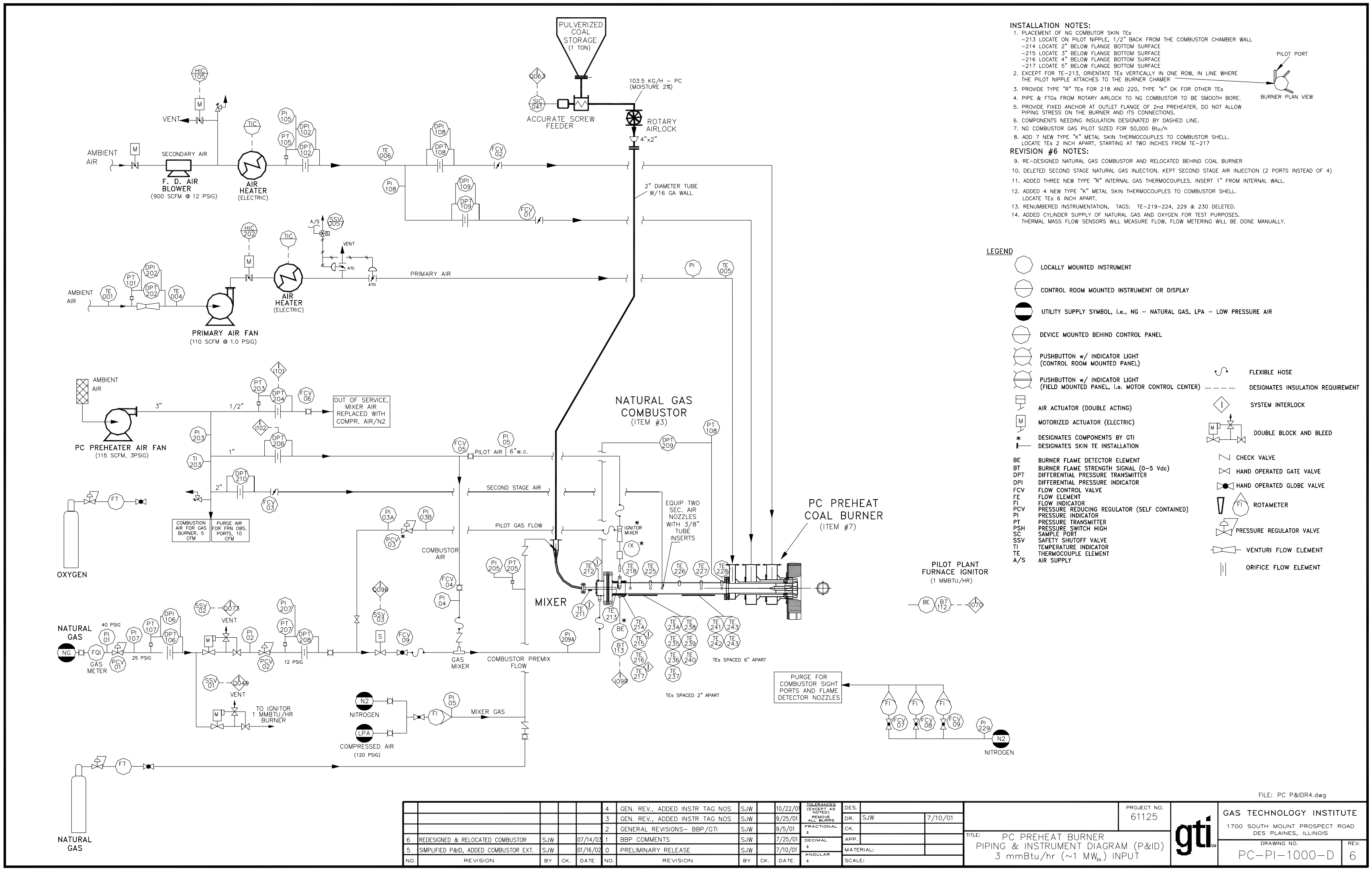


Figure 53. Process and Instrument Diagram for the modified pilot unit

During testing, real time operating data are collected at 1-second intervals and recorded by the personal computer-based data acquisition system (DAS). The concentrations of CO, CO_2, O_2, THC and NO/NO_x in the PC PREHEAT unit exhaust and the furnace exit are continuously monitored by on-line gas analyzers, including 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.

The PREHEAT gas combustor temperatures are monitored by thermocouples installed on both the outer walls and inside of the combustion chamber. Temperature of the gas/air mixture is monitored in the gas/air plenum entering the combustor nozzles.

CFD Analysis of Modified Geometry

3-D CFD modeling was conducted for the horizontal PC PREHEAT pilot combustor arrangement at two gas/air nozzle inlet velocities, 102 ft/s and 148 ft/s, to evaluate the impact of the new configuration on combustor volatile matter release and temperature, density and velocity profiles. The objective of this evaluation was to determine a suitable length for the modified combustor to allow sufficient residence time for devolatilization.

Comparisons of gas phase temperature and density at various distances from the gas inlet nozzles along the combustor centerline for the two gas inlet velocities are shown in Figure 54 and Figure 55. It can be seen from these figures that for both inlet gas velocities, the temperature and gas phase density are essentially stabilized at about 40-inches from the combustor inlet, indicating that devolatilization is complete at this point. Based on this, the horizontal PREHEAT pilot combustor length was set at 40-inches.

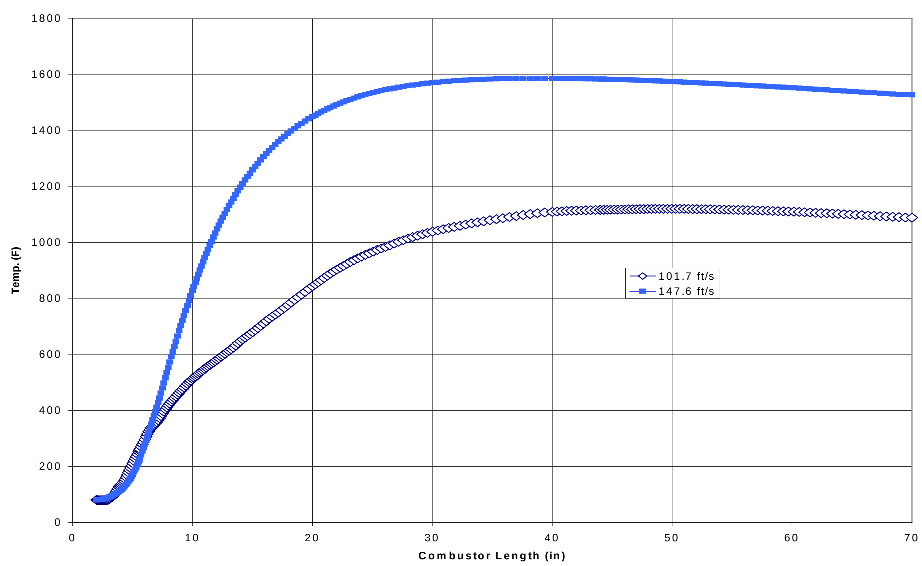


Figure 54. Temperature at the combustor centerline for two inlet gas velocities

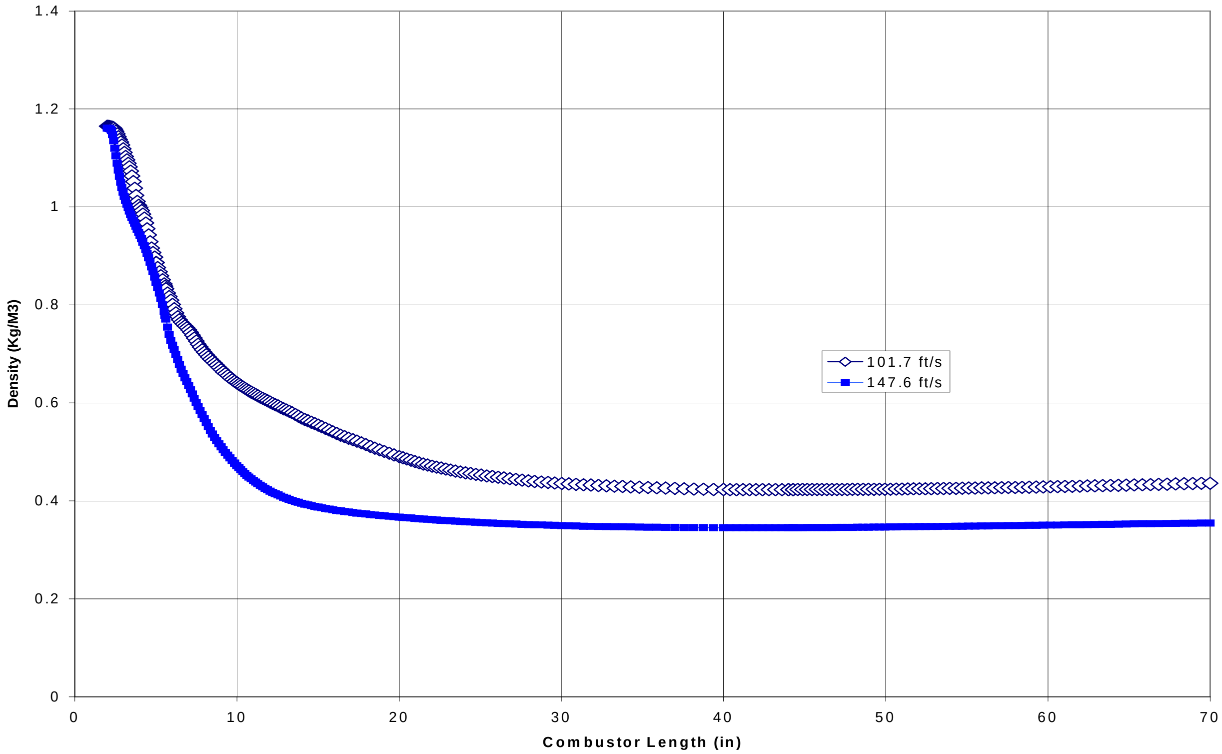


Figure 55. Gas phase density at the combustor centerline for two inlet gas velocities

Design work was completed to relocate the pilot gas combustor to a horizontal orientation along the centerline of coal burner so that the pilot results with caking coal is directly applicable to the preferred 100-MMBtu design. Other pilot design changes to accommodate caking coal include lengthening the combustor and reducing its diameter to match the coal burner. This eliminates the diameter reduction at the combustor outlet that has been a source of plugging with caking coal, while slightly increasing the residence time for char and devolatilization product within the combustor. Design documents were prepared and forwarded to RPI for fabrication and installation.

Design drawings, including the PC burner modifications, the horizontal PREHEAT combustor details, and the overall system arrangements were developed for relocating the 3-MMBtu/h preheat combustor to a horizontal orientation. The general arrangement drawing for the modified pilot system is shown in Figure 3. Reorientation of the combustor to horizontal placement required changes in the unit's thermal expansion provisions. The thermal expansion compensator for vertical growth in the system was eliminated and a movable support was developed for the combustor to accommodate horizontal thermal expansion of the combustor. This horizontal movement is now taken as bending in the long vertical coal pipe.

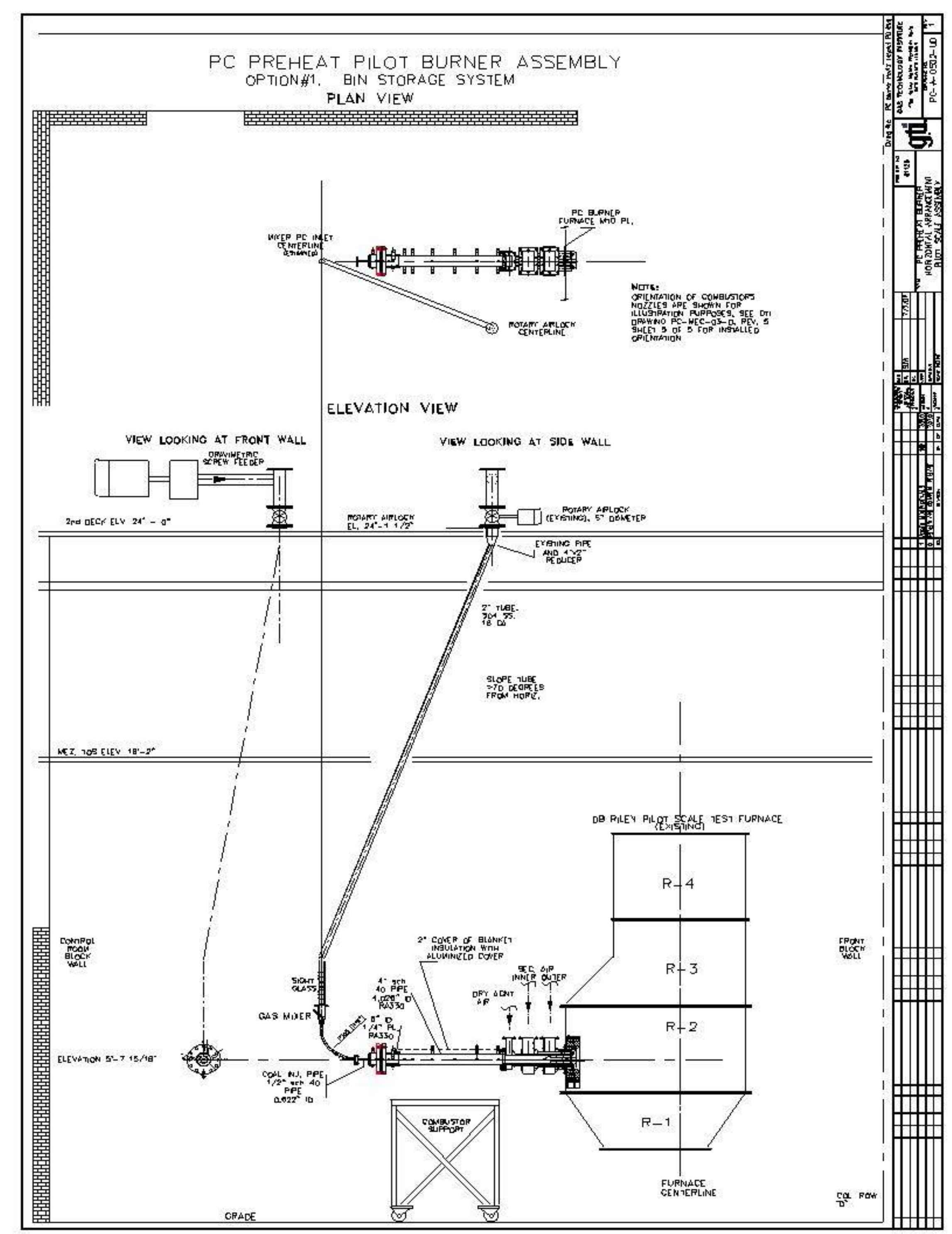


Figure 56. General arrangement for the horizontal PREHEAT combustor and associated components.

Pilot-Scale Equipment Fabrication and Installation

All installation work was completed to relocate the pilot gas combustor to a horizontal orientation along the centerline of coal burner. The relocated PREHEAT combustor and associated piping and instrumentation are shown in Figure 57. Other pilot design changes to accommodate caking coal included a reduction in the combustor diameter to match the coal burner and an increase in the combustor length. This increased the combustor velocity and eliminated the diameter reduction at the combustor outlet that has been a source of plugging with caking coal, while slightly increasing the residence time for char and devolatilization products within the combustor. All combustor natural gas and air piping and controls were relocated to grade level near the combustor for convenience in operating the unit. The 2-in diameter coal feed pipe was lengthened to accommodate the new combustor location and the coal gas mixer was relocated just above the combustor. The transition from the vertical coal feed pipe to the horizontal combustor coal inlet was accomplished using a long-radius bend after the mixer.

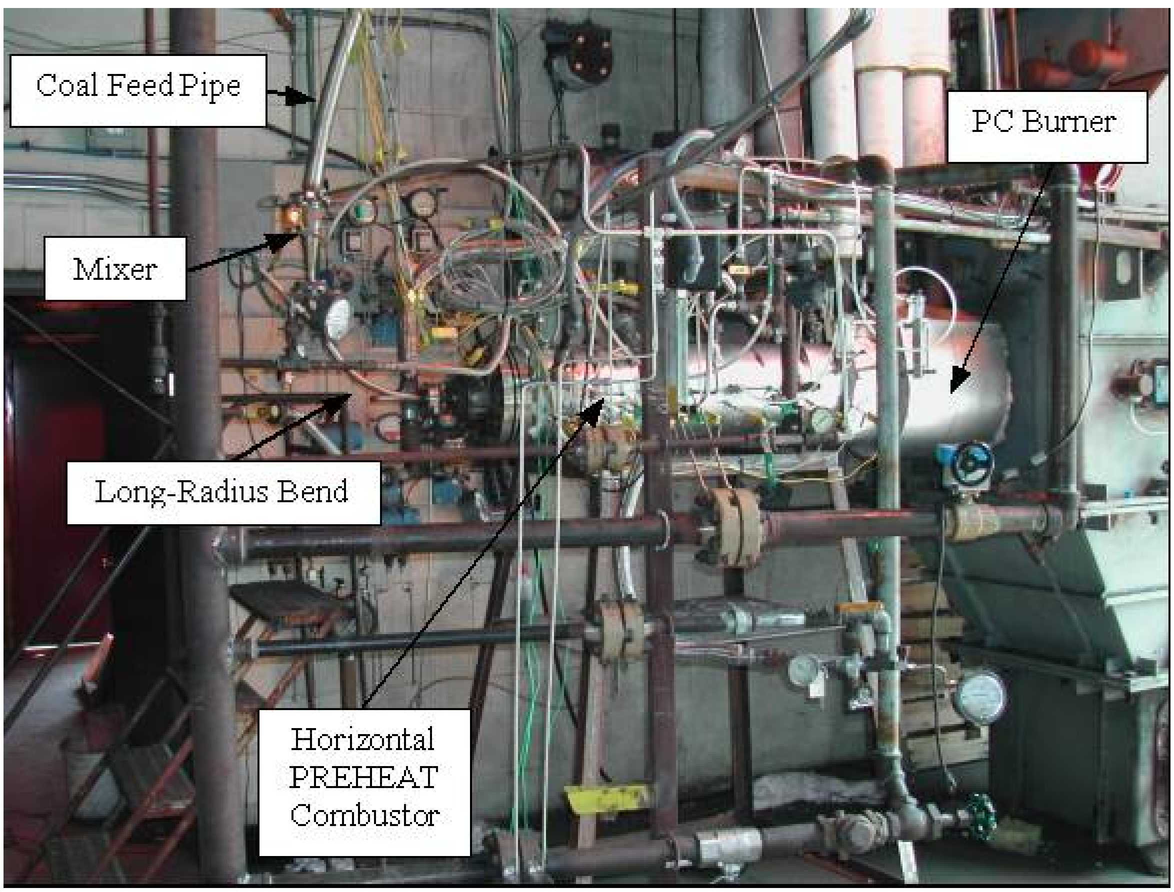


Figure 57. Horizontal Pilot PREHEAT combustor installation

Pilot-Scale Testing

Pilot system checkout, instrument calibration, and preliminary natural gas test firing were conducted in August 2003. All instruments were checked for proper installation and documented, including placement of skin and internal thermocouples. All pressure transducers were calibrated and thermocouples checked for correct input type to the data acquisition system (DAS). The modified DAS screens were checked for proper configuration and to insure that screen readings matched field readings. Dimensions of the modified combustor and burner were checked and confirmed. Purge lines to the inspection ports and flame sensors were installed and tested. A vibrator was installed on the extended coal feed line ahead of the combustor. Air and gas lines were pressure tested for leaks. The combustor pilot and main flames were tested for pulse-free operation and strong visible flames. The pilot and main flame were shutdown and restarted several times to insure consistent operation. The system was then fired to an internal temperature of 1800ºF to check for any thermal expansion problems.

A series of quick scoping tests were conducted CA coal to determine the most favorable operating approaches to avoid plugging and coal particle agglomeration in the modified horizontal combustor. The first 2 tests were conducted with PRB coal, which confirmed that the combustion and emissions performance of the horizontal combustor was similar to that achieved with the vertical combustor. Tests were then conducted with Central Appalachian caking coal to evaluate the effect of various operating regimes on caking in the combustor. Three different combustor internal diameters (ID) were tested by using various inserts in the combustor housing. Settling out of the coal is a concern in the horizontal combustor as opposed to the vertical combustor where it was not an issue. Tests were therefore conducted at 3 velocities in the horizontal combustor ranging from 53 ft/s to 96 ft/s at each combustor ID, significantly higher than the 30-40 ft/s tested with the vertical combustor orientation. While continuous operation had been achieved with caking coal only up to 50 lb/h with the vertical unit, continuous operation at 126 lb/h was achieved with the modified horizontal unit at the higher velocities. Some deposition of caked material was still observed on the combustor walls, however, and agglomerated char particles were observed exiting the burner into the furnace. This will have a negative impact on LOI. It was noted in these tests, however, that caking on the wall of the combustor occurred only in a discreet range of distance from the combustor inlet, with no deposition at all either before or after this region.

Due to the scoping nature of these tests, operating conditions were selected to evaluate impact on caking rather than combustion or emissions performance and steady-state operating periods were therefore not defined. All operational data including flue gas analyses were recorded as usual to aid in the evaluation. While not measured under steady-state operating conditions, NO_x results with bituminous coal were promising none-the-less, with readings in the range of 150 ppmv at 4% O_2 in the exit gas. NO_x results for test conducted with a 3-in ID ceramic insert in the combustor are shown as a function of furnace exit oxygen in Figure 58. Further pilot testing is planned to minimize particle agglomeration and increase operation with caking coal to the full 150-lb/h design value.

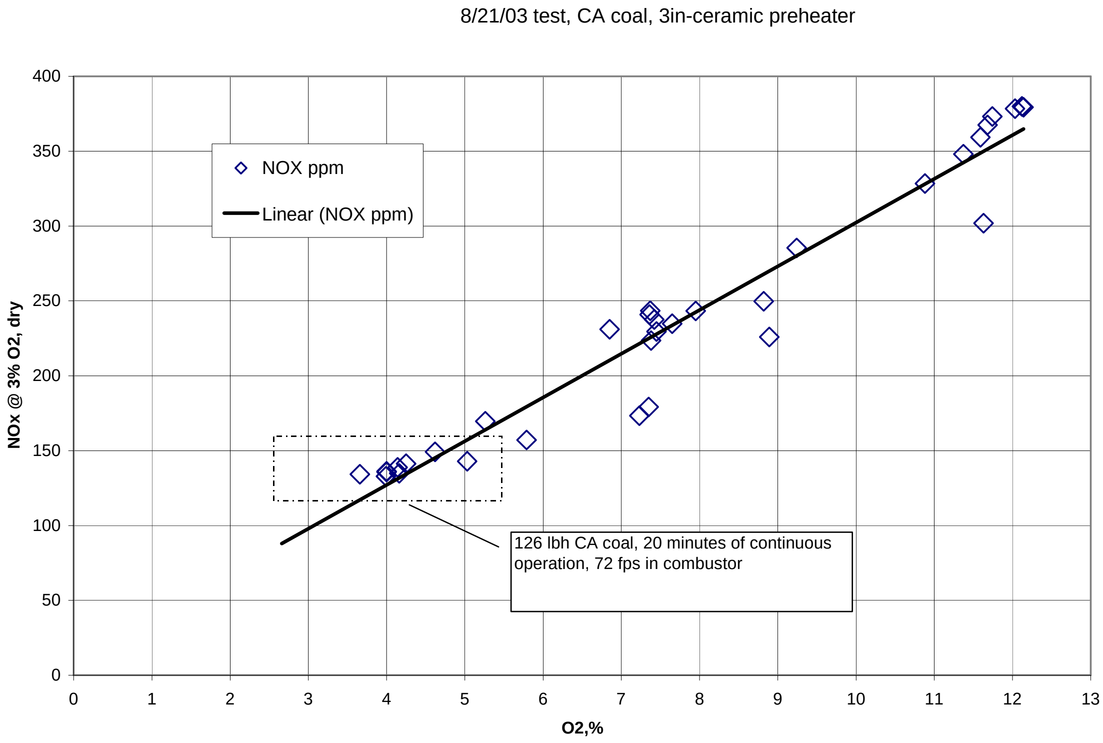


Figure 58. NO_x results as a function of furnace exit oxygen for test conducted with a 3-in ID ceramic insert in the combustor

Based on the results of the scoping tests, a number of strategies were developed to improve operation of the 3-MMBtu/h pilot system with caking coal. The objective for these strategies is to achieve continuous operation of the pilot system at its design coal feed rate of 156 lb/h, without plugging or agglomeration of the pulverized coal. The following modifications to the pilot system were defined for operation with Central Appalachian caking coal:

- Modification of the mixer air/N2 injection pipe to avoid the potential for “clumping” of the pulverized coal prior to entering the Preheat combustor.
- Introduction of natural gas in the mixer instead of air or N2 to preheat the coal (and pass through the sticky phase) more rapidly in the combustor.
- Lengthening the coal pipe inside the combustor to slow the preheating and to shorten the residence time of preheated coal in the combustor.
- Installation of a Venturi insert at the end of the coal pipe to force the combustion gases and coal/char together in the center of the pipe for improved mixing/heating and to keep solids away from the combustor walls.
- Modification of combustion air distribution in the gas combustor.

Drawings of the required components and modifications were forwarded to RPI for fabrication in preparation for additional pilot testing. Fabrication and installation of the required components and modifications for testing these strategies were completed by RPI at the beginning of October 2003.

As a result of this testing, all but the last approach have been abandoned as potential concepts for a workable caking coal design. Modification of the mixer/N_2 injection pipe and introduction of natural gas into the mixer ahead of the combustor did not reduce caking in the combustor. Lengthening of the coal pipe to effectively shorten the combustor and increase indirect heating of the coal resulted in plugging in the coal pipe, even when the coal pipe was insulated to reduce heat transfer. Installation of the Venturi was also unsuccessful at reducing plugging in the combustor. Finally, several brief tests with combustion air distributed further along the combustion chamber liner showed promise. Tests at 50-lb/h coal feed with air distributed in a 12-inch test section of the combustor resulted in no caking in the combustor and no evidence of agglomerated particles passing through the coal burner. When the coal feed rate was increased to 110 lb/h, small agglomerated particles were observed passing through the burner. However, continuous operation was maintained up to 126 lb/h. The combustor eventually plugged when the firing rate was raised to 156 lb/h. However, the plugging was found to have occurred ahead of and after the test section of the combustor. The test section itself was completely clean.

Based on these results, the 3-MMBtu/h pilot combustor needed to be further modified and tested with the new air distribution method applied over various portions of the combustor length.

While not measured under steady-state operating conditions, NO_x results from these caking coal tests were promising. Figure 59 shows a plot of NO_x vs. the oxygen concentration at the furnace exit for selected pilot tests in which the coal firing rate was able to be increased enough to allow the furnace's 1-MMBtu/h gas-fired ignitor to be shut off. These data points cover a broad range of operating conditions in the pilot unit. Taken together, they show the expected trend of declining NO_x emissions as the furnace excess air is reduced. It should be noted that NO_x readings approach 100 ppmv at about 6% O_2 in the furnace exit gas. This is considerably lower than the NO_x results at this oxygen level with PRB coal, which did not approach 100 ppmv until exit O_2 was around 2 %. This indicates a potential for NO_x emissions below 100 ppmv with caking coal and furnace exit oxygen in the 2-4% range, provided a satisfactory method is found to eliminate plugging in the gas-fired combustor.

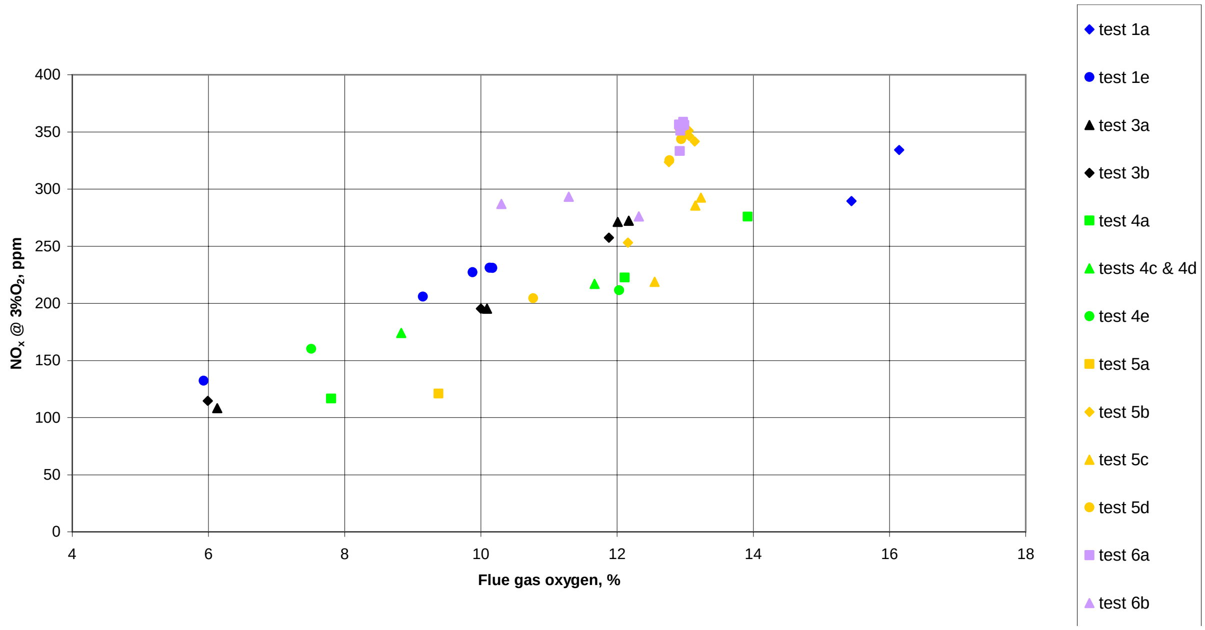


Figure 59. NO_x vs. O_2 Results for 3-MMBtu/h tests with Central Appalachian caking coal

A total of 22 pilot tests were conducted during January- February 2004 over a broad range of operating conditions with caking coal. The objective for these tests was to achieve continuous operation of the pilot system at its design coal feed rate of 156 lb/h, without plugging or agglomeration of the pulverized coal.

Process variables affecting coal deposition on the preheater combustor walls have been found to include velocity in the preheater, the mixing pattern of the coal particles with products of natural gas combustion, combustion air distribution in the preheater and the surface temperature of the combustor walls. Previous pilot-scale testing demonstrated that plugging is initiated by agglomeration of coal particles on the preheater inner walls and no contribution of volumetric agglomeration was detected in all tested regimes. This indicates that adequate local protection of the combustor walls against deposition of coal volatiles should resolve the issue. Technical approaches under development and testing included (i) creation of a thin oxidizing film over the preheater inner wall, (ii) use of less adherent inner wall material, and (iii) use of indirect cooling of the preheater inner wall. Two liner designs were developed and tested based on the oxidizing film or “air-bleed” approach. Two additional liner designs, including one stainless steel and one ceramic liner, were developed and tested based on the indirect air-cooled approach.

Both configurations of the “air-bleed” liners were tested in a total of 32 pilot tests. In the first configuration, an air injection approach utilized air injection holes through the inner liner similar to the ones used in gas turbine combustors for wall cooling. In second tested design, co-flow air jet injection was applied in either one or two locations along the length of the tube for wall protection. Both designs demonstrated the ability to prevent agglomeration on the preheater walls at partial load. Several tests were conducted using nitrogen in place of air through the bleed holes that resulted in much more plugging than with air. This indicates that oxidation of volatile matter near the walls may be the main mechanism by which deposition is avoided with the air-bleed approach.

The air-bleed approach resulted in higher combustor temperatures, on the order of 1700ºF at the combustor exit, due to heat generated by combustion of a portion of the volatile matter at the walls. Gas samples collected directly from the combustor indicated that all oxygen introduced to the combustor was being consumed, with oxygen readings of 0% and CO readings of about 5%. Char samples collected from combustor showed about 95% devolatilization, much higher than previously tested configurations. The higher temperatures and more complete devolatilization did not appear to significantly improve NO_x reduction, however, and may require more durable and expensive heat resistant alloys for the combustor. On the other hand, the air bleed method does reduce deposition on the walls and also offers a way to generate more of the heat for devolatilization from combustion of the coal devolatilization products, reducing the amount of natural gas required. It appears therefore that limited use of the air bleed approach in conjunction with other methods such as indirect cooling of the combustor liner may offer the most benefit in terms of both avoiding deposition and reducing natural gas usage.

Coal feed rates of 50 – 100 lb/h were tested with deposition generally encountered above about 70 lb/h. The main difficulty in creating reliable inner wall protection for the pilot scale unit is its small size with only 1.5-inches between inner wall and centerline of the preheater combustor. The oxidizing film with an estimated thickness of between 0.25 and 0.5 inches occupies more than 50% of total combustor volume, which imposes limitations on the preheating process at this small scale. Careful inspection of the combustor also revealed that after over a hundred test firings, the combustor shell has sagged somewhat into an oval shape and the coal feed pipe is no longer properly aligned with the longitudinal axis of the combustor. The coal feed pipe was found to be pointing at an area of the combustor wall near the exit where deposition frequently occurs. The current pilot combustor is therefore nearing the end of its useful life.

Due to the scoping nature of the pilot-scale caking coal tests to date, operating conditions were selected to evaluate impact on caking rather than optimized combustion or emissions performance and steady-state operating periods were therefore not defined. All operational data including flue gas analyses were recorded as usual, however, to aid in the evaluation. While not measured under steady-state operating conditions, NO_x results with caking coal have been promising none-the-less, with readings in the range of 130 ppmv with 4% O_2 at the boiler exit. NO_x results for test conducted with PRB coal were around 180-200 ppmv at this exit oxygen level, indicating the potential for better NO_x reduction with caking coal than PRB.

The two modified "air-bleed" liners and two indirect air-cooled liners were fabricated and installed in the 3-MMBtu/h pilot combustor. The air-bleed liners were fabricated from stainless steel with 1/8-in diameter holes at regular intervals along the length of the liner as shown in Figure 60. A version with 54 holes and another with 79 holes were fabricated and tested. The two indirect air-cooled liners are shown in Figure 61 (stainless steel) and Figure 62 (Silicon carbide).

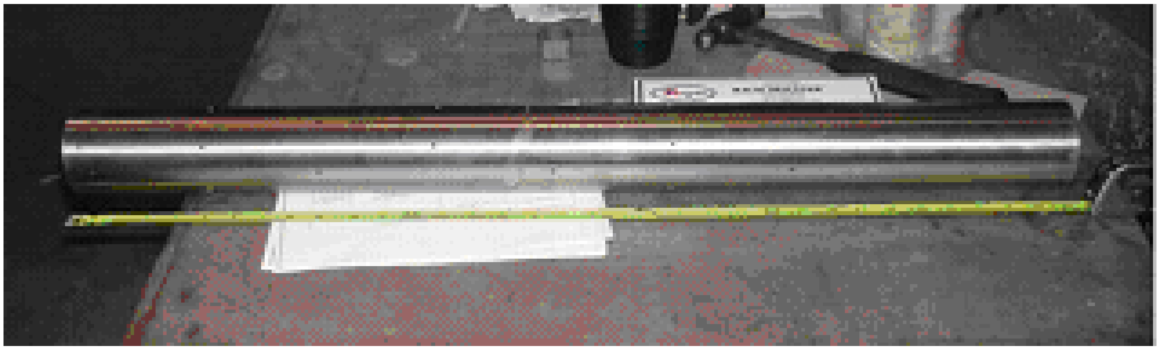


Figure 60. Air-bleed stainless steel liner with 54 1/8-in diameter holes prior to attachment of transition pieces

Figure 61. Stainless steel indirect air-cooled liner with spiral fins and transition pieces

Figure 62. Silicon carbide indirect air-cooled liner with transition pieces

Additional 32 tests in the pilot unit were conducted to evaluate indirect cooling of the liner and the use of ceramic liner materials as ways to further reduce deposition were planned, and the remaining development work for caking coals to be conducted in the 100-MMBtu/h unit. The plugging issue is expected to be less of a problem for the 100-million Btu/hr unit because of its much larger preheater combustor diameter and smaller surface to volume ratio. The air-bleed configurations tested used air injection holes perpendicular to the liner's longitudinal axis with the number, size and air flow though the air-bleed holes varied to determine the effect on combustor plugging. The indirect cooling configurations tested included a stainless steel liner with spiral fins in the annular space between the liner and the combustor wall to increase turbulence and heat transfer surface, and a silicon carbide liner without fins. Continuous pilot operation was maintained for up to 30 minutes at a coal feed rate of 50 lb/h with the 79-hole air-bleed liner. The best result achieved was for the stainless steel indirect air-cooled liner with 20 minutes of continuous operation at 126 lb/h of coal followed by an additional 20 minutes at 150 lb/h. The SiC indirect air-cooled liner achieved 5-10 minutes of continuous operation at 126 – 150 lb/h of coal feed.

Operating conditions for these tests were selected to evaluate impact on caking rather than optimized combustion or emissions performance and steady-state operating periods were therefore not defined. All operational data including flue gas analyses were recorded as usual, however, to aid in the evaluation. While not measured under steady-state operating conditions, NO_x results in the range of 150 ppmv were measured with 3.5 – 5.5% O_2 at the boiler exit. NO_x results for test conducted with PRB coal were around 180-200 ppmv at this exit oxygen level, indicating the potential for equal or better NO_x reduction with caking coal than with PRB.

100-MMBtu/hr Demo Test Unit Installation at RPI

The CBTF comprises a large horizontally fired dry bottom furnace capable of testing full-scale burner systems with firing capacities up to 100-MMBtu/h. The furnace is fully integrated with coal storage, grinding and feeding, emissions control, and continuous flue gas sampling and analytical subsystems.

A process flow diagram for the 100-MMBtu/h unit is shown in Figure 63. Coal is pulverized and dried in a DB Riley Model 350 Atrita pulverizer, which is fed from a 40-ton bunker by a weigh-belt feeder and rotary valve. The mill's air supply system includes a Venturi air flow meter, fan, and natural gas direct-fired heater to supply a measured amount of hot air to the pulverizer to dry and transport the coal. The CBTF is capable of firing in both the direct fire mode and from an intermediate storage bin (indirect fire). All testing was conducted in the direct fire mode to simulate the most common firing method in the U.S. market. Drying and transport air is separated from coal stream immediately ahead of the preheater combustor inlet. The separated air is directed to one of the three air channels in the coal burner. Secondary air is preheated to 600 ºF by a separate fan and heater and routed to the coal burner. Air can be routed to the burner through an integral windbox plenum or through separate external ducts. Flow to each burner air channel can be regulated independently. Ports are also available at several locations for furnace air staging.

Flue gas composition was monitored continuously. A multiple-probe sampling grid consisting of sintered Hasteloy filters is mounted in the CBTF exit duct, just upstream of the flue gas scrubber. The in-duct filters remove the majority of particulate, and the flue gas is drawn through stainless steel tubing, ice-bath conditioners, and a final filter by individual sample pumps. A rotameter at the outlet of each pump is used to admit equal flow of clean, dry sample from each grid probe to a manifold. The proper flow of sample for each continuous analyzer is supplied from the manifold.

Continuous monitors are used to measure O_2, CO_2, CO, NO/NO_x, and SO_2. In addition to the gas sampling grid, a separate water-cooled probe is used to withdraw particulate samples at the CBTF outlet for determination of carbon burnout. A high velocity thermocouple probe monitors furnace outlet temperature.

The CBTF is fully instrumented to allow continuous measurement and recording or all relevant flow, pressure, and temperature readings to allow complete material and energy balances to be developed for each testing period.

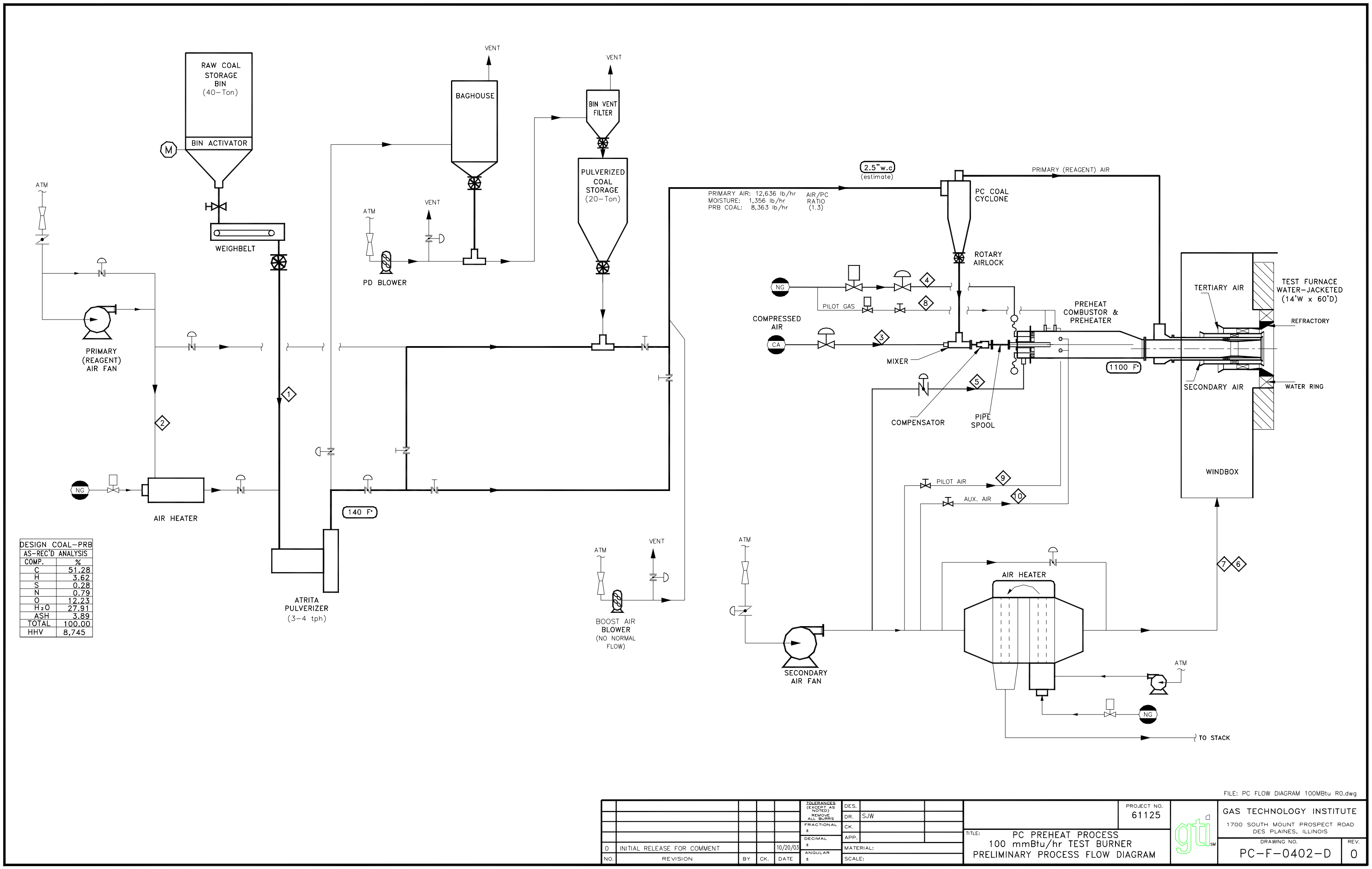


Figure 63. Process and Instrument Diagram for 100-MMBtu/h test unit

CFD Modeling of the 100-MMBtu/hr Unit

Modeling was conducted in support of the 100-MMBtu/h design. The approach used was to have RPI perform 2-D axisymmetric aerodynamic CFD simulations without combustion to fix the major parameters of the burner design while GTI conducted 3-D simulations with combustion for the PREHEAT combustor. The output of the combustor simulations are then used as input to the burner simulation to simulate and evaluate the overall system.

For the initial 2-D modeling, GTI provided typical properties of the pyrolysis products entering the burner as fuel based on 3-MMBtu/h pilot testing experience. The degree of devolatilization of the feed coal within the combustor was set at 70% for the simulation. Due to limitations in the CBTF coal mill capacity with PRB coal, the maximum firing case for the burner was determined to be 85 MM Btu/h.

The design basis coal analyses for Central Appalachian and PRB coals were set. The basic burner configuration approach for the 100 MM Btu/h design was also set, including primary, secondary and tertiary air streams, the tertiary to secondary air ratio, the use of swirl in the air streams, the use of a Venturi and toothed ring in the coal tube, velocities in the coal tube (including turndown operation), the range of possible burner quarl and air diverter angles, and a fixed excess air concentration of 15%.

In order to maintain a low oxygen concentration in the PREHEAT combustor, the primary air stream is separated from the pulverized coal using an existing cyclone in the CBTF just upstream of the combustor inlet. This air is then routed to a third air channel between the burner coal tube and the secondary air channel. This primary air arrangement was incorporated into the burner design and modeling.

Using the above burner design criteria, RPI prepared burner design and record sheets for the 100-MMBtu/h Coal Burner for both Central Appalachian and PRB coal based on their CCV DAZ (CCV Dual Air Zone) design approach. It was determined that in order to maintain the coal tube velocity within recommended ranges, two different coal tube diameters are required for these coals. The initial 2-D aerodynamics CFD simulations for PRB and Central Appalachian (CA) coal were performed using typical combustion product flows and temperatures based on RPI’s modeling and testing results with about 10 different coals. A circular tunnel furnace with a diameter of 17 feet was used in the simulation, matching the CBTF furnace cross-section area. Some of the initial CFD results are shown as contour plots of axial velocity (ft/s) for PRB coal (Figure 64) and CA coal (Figure 65). In these plots, negative axial velocity regions are shown as white areas indicating the extent of internal recirculation zones. Both the PRB and CA coal burners were found to produce similar near burner aerodynamics, creating an internal recirculation zone (IRZ) with an axial length comparable to the burner discharge diameter. The near burner aerodynamics indicated an attached tubular flame.

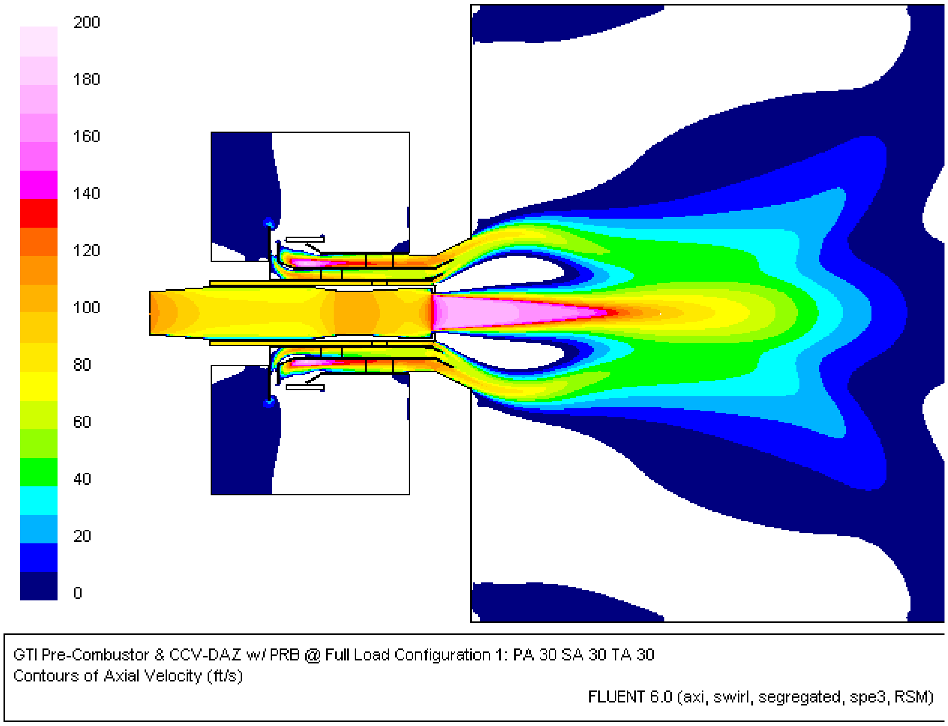


Figure 64. CFD results on near burner aerodynamics with PRB coal firing, axial velocity contour

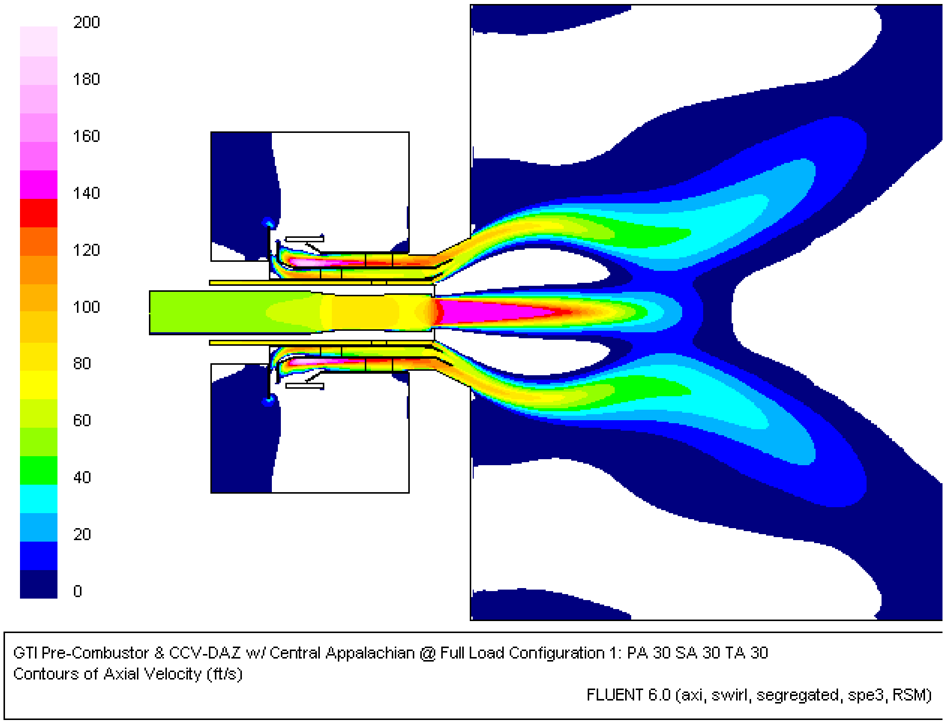


Figure 65. CFD results on near burner aerodynamics with ca coal firing, axial velocity contour

RPI's CCV® DAZ burner [12]typically produces two distinct internal recirculation zones close to the burner discharge with an axial length on the order of two burner throat diameters. Figures 6 and 7, however, indicate a single, relatively weak recirculation zone with the initial burner design. The CFD simulations were therefore continued in order to a achieve near burner flow field similar to that which CCV burner experience indicated would result in low NO_x emissions. Various burner operational and geometry changes were investigated including:

- Flame stabilizer flow area
- Tertiary swirl vane angle
- Secondary Air (SA) / Tertiary Air (TA) flow rate ratio
- Burner quarl, SA and TA flow diverter angles

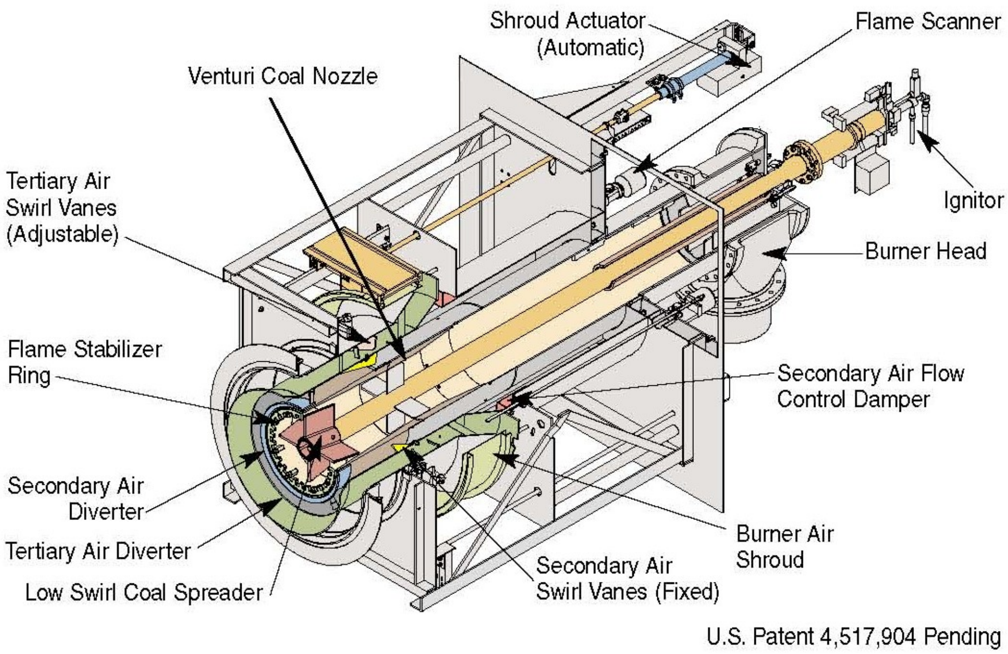


Figure 66. Low NOX Dual Air Zone CCV® burner

The CFD simulation results for the optimized burner design is shown in Figure 67 and Figure 68 as plots of Stream Function (lbm/s) for PRB and CA coals, respectively. This burner arrangement produces an acceptable CCV-like near burner flow field with two distinct internal recirculation zones close to the burner discharge. This arrangement was therefore accepted as the design basis for detailed design and drafting effort for the 100-MMBtu/h burner. Detailed hardware specifications were then developed to guide the designers in drawing development and fabrication for both the PRB and CA versions of the burner. It was further decided that the test burner should include adjustable swirl vanes in all three air channels to facilitate burner testing and optimization.

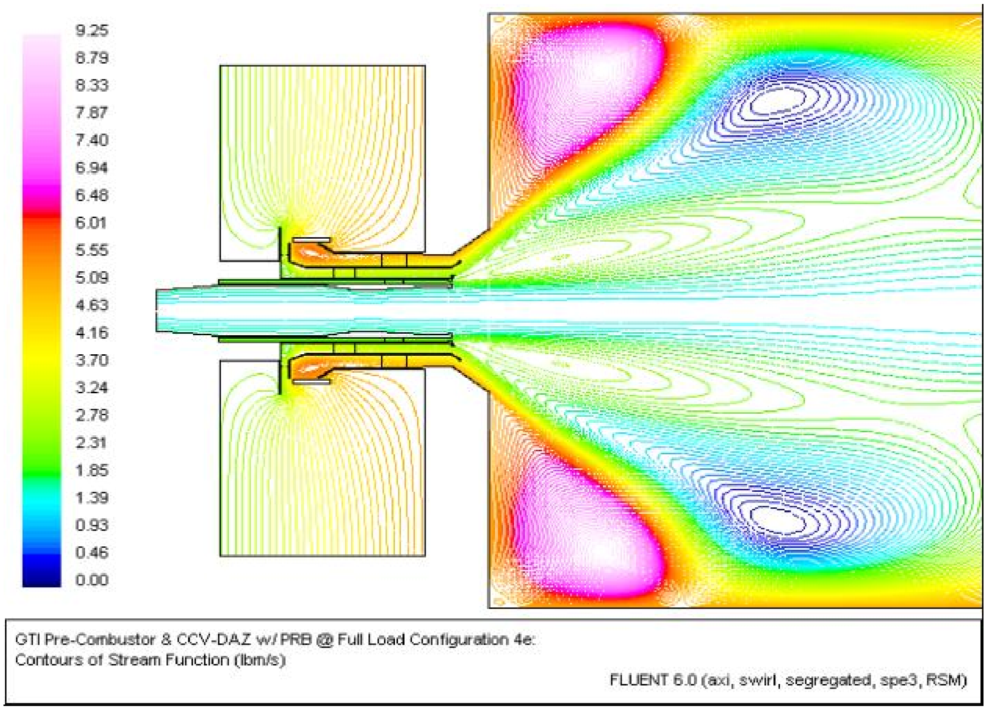


Figure 67. CFD results on near burner aerodynamics with PRB coal firing, stream function (lbm/s)

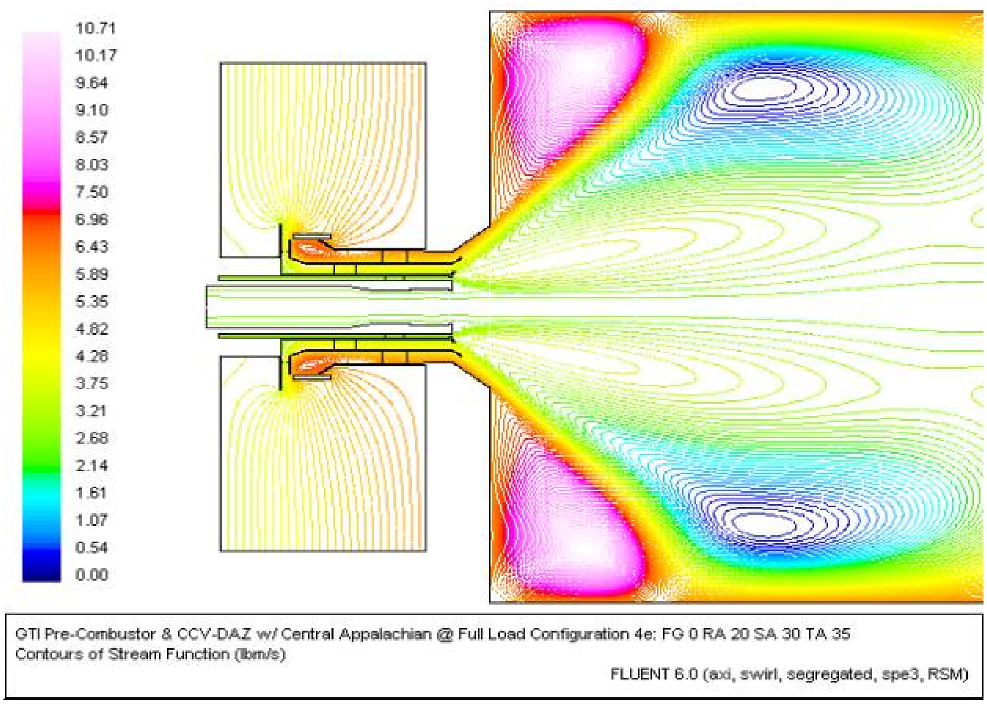


Figure 68. CFD results on near burner aerodynamics with CA coal firing, stream function (lbm/s)

With the burner design basis established, CFD modeling (3-D with combustion) with PRB coal was conducted in support of the 100-MMBtu/h design. Modeling studies focused on the size and position of the natural gas/air nozzles with respect to the central coal pipe. Design variables evaluated included coal feed pipe size and location, and the number, size and radial location of the gas nozzles relative to the coal pipe. In addition, two preheat combustor diameters were modeled. The effect on temperature, velocity magnitude, and volatile matter release along the combustor centerline was evaluated. A comparison of the mass flow of volatile matter along the combustor centerline for the various configurations evaluated is shown in Figure 69. The results indicate that the larger diameter combustor (Approach 6) is preferred. In addition to releasing more volatile matter at a shorter distance from the combustor inlet (shorter combustor required), the larger diameter increases the coal residence time in the hot zone of the combustor by 2.5 times. Based on these results, design and fabrication drawings for the PRB version of the PC PREHEAT were developed.

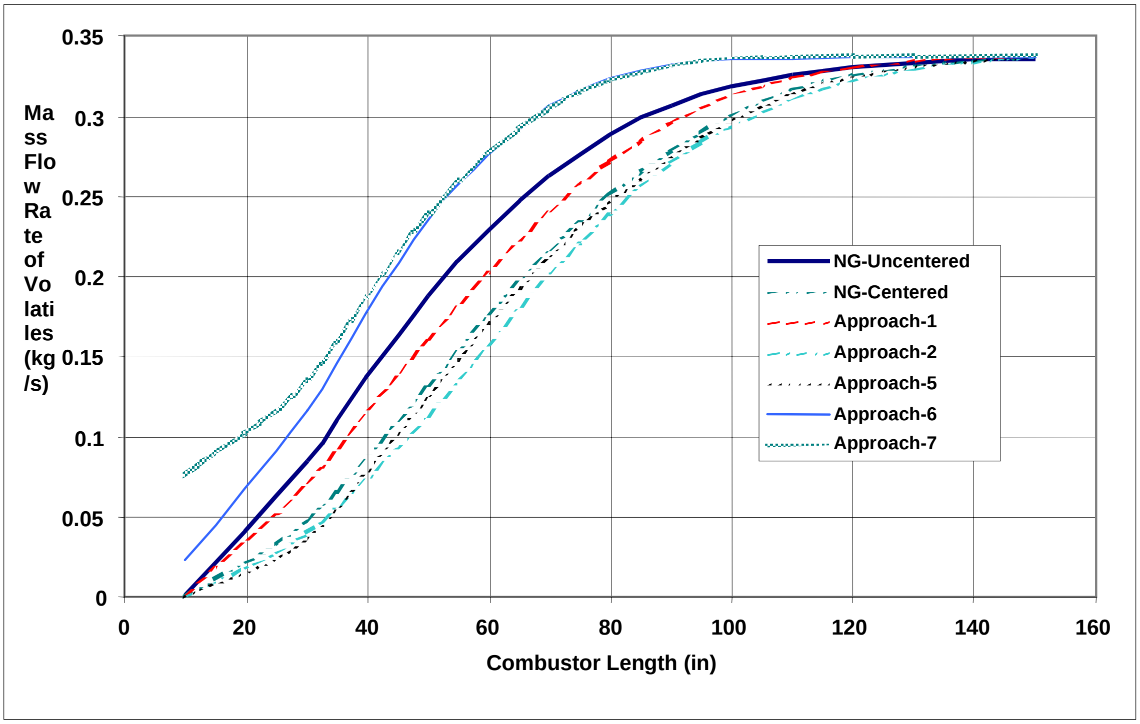


Figure 69. Distribution of the mass flow rate of volatiles along the preheater centerline for the 100-MMBtu/h PRB coal case

PRB Coal Prototype Design and Construction

Development of the commercial prototype burner design was conducted by GTI with collaboration from RPI and VTI. Based on the 100-MMBtu/h unit CFD modeling work discussed above, hardware specification details for the test burner configurations for both PRB and Central Appalachian coals were developed by RPI specific to the CBTF. The specifications include all burner critical dimensions, quarl and diverter angles, and internals including swirl vane locations and angles. All swirl vanes in the test burner are specified as adjustable.

A layout for the 100-MMBtu/h unit was developed, reviewed, and modified to straighten the coal transport pipe inlet to the cyclone. General arrangements were defined for the combustor, thermal expansion compensator, gas mixer, and a spool piece to compensate for the difference in combustor lengths between the PRB and CA coal PREHEAT combustors. Temperature ranges for the burner fuel and air channels were established to facilitate selection of their materials of construction. Design details and process flows were established for 4 tertiary air ports around the burner throat for possible future testing with air ports rather than a channel. Modifications to the PC burner ignitor support tube were developed to minimize interference with airflow and spin. The spark rod and gas gun centerlines were positioned relative to the burner centerline. A design for the surrounding support structure was developed to facilitate removal and replacement of both the burner and PREHEAT combustor.

A full time draftsman was assigned to the project by RPI for development of the 100-MMBtu systems. A scheduler was also assigned and a draft schedule developed.

The design for the 100-MMBtu/h unit for PRB testing in the CBTF was completed and fabrication started in November 2003 (see Figure 70 through Figure 73). As a result of weather- and equipment fabrication-related delays, testing with PRB coal was rescheduled to start in 2004. This pushed project completion beyond the 3/30/04 end date, and revised project schedule and estimated cost had to be developed.

Figure 70. CCV burner during PREHEAT modifications

Figure 71. PREHEAT combustor shell during fabrication

Figure 72. Cyclone support tower set on the CBTF burner deck

Figure 73. The cyclone and inlet pipe support installed on the burner deck

Fabrication and installation of the 100-MMBtu/h PRB combustor components, including the combustor, mixer, compensator and spool piece was completed in March 2004. The assembled 100-MMBtu/h PRB combustor components, including the combustor, mixer, compensator, and spool piece were lifted into the structure (See Figure 74 and Figure 75).

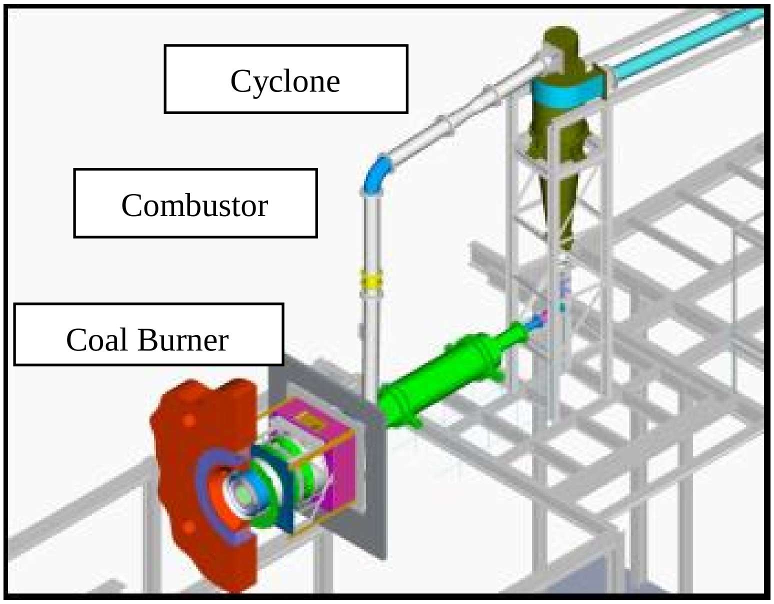


Figure 74. The CPTU consists of a preheater combustor close -coupled to a modified CCV burner from RPI

Figure 75. Installation of the CPTU

A draft Test Matrix and Sequence of Operation were prepared for the 100-MMBtu/h unit. Dynegy's Hennepin Power Station supplied PRB coal to be for the 100-MMBtu/h testing.

PRB Coal Commercial Prototype Testing

Commissioning and shakedown testing of the large-scale prototype unit firing natural gas in the preheat combustor was completed in June 2004. The objectives for this testing were:

- Develop and test a startup procedure for the combustor firing natural gas
- Confirm mechanical integrity of the combustor including adequacy of thermal expansion provisions
- Confirm functionality of all instruments and controls
- Confirm combustor operation over the full design firing range
- Confirm ability to produce accurate heat and mass balances around the combustor/furnace
- Develop a final punch list for necessary repairs and changes prior to testing with PRB coal

The completed coal preheater gas combustor for PRB coal is shown in Figure 76 as installed on the burner deck of the Coal Burner Test Facility. The PRB combustor is designed to preheat 85 MMBtu/h of PRB coal with 8 MMBtu/h of natural gas. Prior to testing with natural gas and coal, three cold flow tests were conducted in the unit at various combustor air flows to evaluate flow measurement accuracy and system pressure drops. During these tests, the main furnace ignitor was fired at about 12 MMBtu/h to confirm proper ignitor operation. This ignitor is used to preheat the water-cooled furnace into which the preheater combustor and coal burner will be firing and to ignite the coal burner flame during PC burner tests. Following the cold testing, the 1-MMBtu/h preheater combustor ignitor was lit and test fired for about 30 minutes to confirm proper operation.

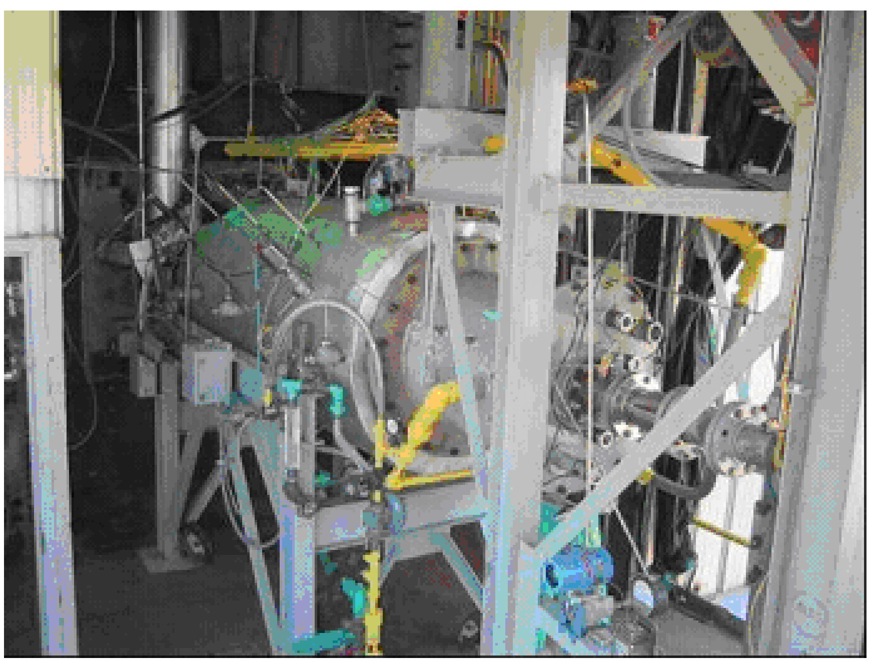


Figure 76. Large-scale prototype coal preheating combustor installed in the CBTF at RPI's R&D Center

Following corrections to the auxiliary air flow measurement instruments, the combustor ignitor was fired at 0.8 MMBtu/h for about 1 hour to a combustor temperature of 500ºF to cure the combustor refractory. The main flame of the preheat combustor was then lit for the first time and fired for about 1 hour under lean conditions at about 3.3 MMBtu/h and a stoichiometric ratio (SR) of about 1.4. The combustor was then switched to sub-stoichiometric firing at its full gas firing rate (without coal) of about 12.5 MMBtu/h. The combustor ignitor was then shut off and the main flame maintained at an SR of 0.43 while a full set of combustor and furnace data was collected to confirm proper operation of the units instrumentation and data acquisition system.

Based on observations during the initial gas-fired testing, modifications were made to the combustor auxiliary air nozzles in order to anchor the combustor flame closer to the gas burner face. After resolving several flame sensor issues, the main combustor flame was lit in lean mode at about 3.2 MMBtu/h and an SR of 1.6 and was eventually switched to rich mode at 12.5 MMBtu/h and 0.40 SR to check the effects of the auxiliary air modifications, which proved to have the desired effect of moving the flame nearer to the burner face.

At the conclusion of the gas-fired shakedown tests, a punch list was developed for repairs, adjustments, and modifications to be completed prior to commissioning and testing with PRB coal. Several issues related to the supports for the combustor gas/air plenum and improvements to thermal expansion compensation for the combustor body were identified along with additional minor changes to instruments and controls.

All items on the punch list were satisfactorily resolved and commissioning with PRB coal was started during the fourth week in June 2004. The objectives for shakedown activities were:

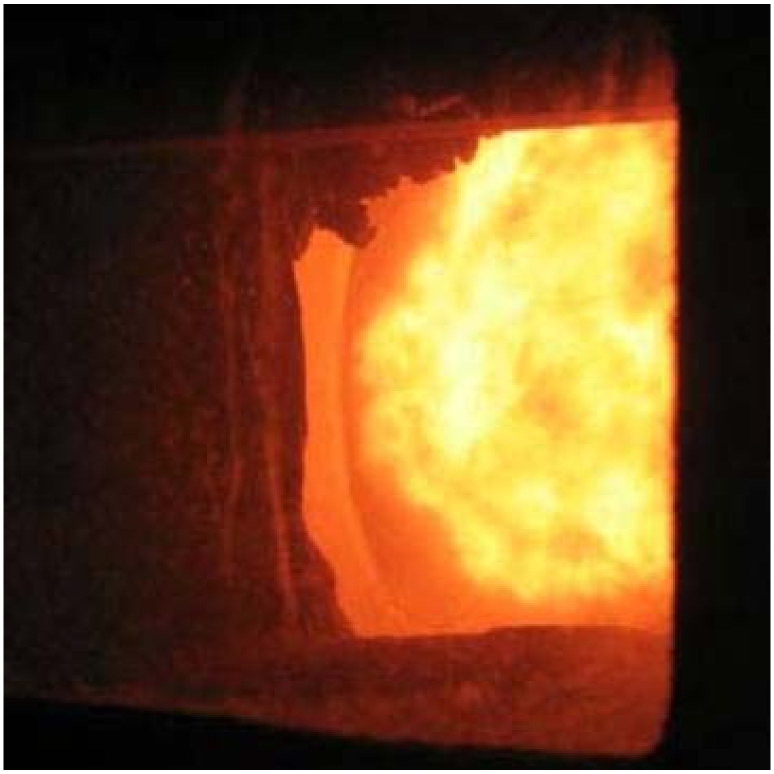
- Repeat cold flow tests with mixer, combustor and auxiliary air flows
- Repeat gas firing test for the preheat combustor over the full design firing range to confirm instrument readings
- Test fire the unit with 2000 lb/h PRB coal feed after preheating with gas in rich (sub-stoichiometric) mode to 2000ºF
- Confirm steady, non-pulsing coal feed and proper operation of the coal cyclone, rotary air lock feed and cyclone exhaust air transport to the inner (reagent) air channel to the coal burner
- Confirm coal system, combustor and burner operation at 4000, 6000 and 8000 lb/h (design) PRB coal feed rates
- Complete a series of quick parametric tests with the preheat combustor firing conditions to determine effect on combustor operating stability and the coal burner flame
- Conduct a series of quick parametric tests altering the swirl angle of the inner (drying agent) air channel in the coal burner

A brief cold flow test was conducted with auxiliary combustor air to characterize rotameter settings vs. nozzle pressures and data system flow readings. The combustor was then started on gas and operated for a brief period until an electrical problem in the furnace air heater caused the furnace ignitor to trip. The problem was determined to be a dead short in one of the control wires between the field panel and the control room. This ultimately required a full day to remove and relocate the conduit run and all of the associated control wiring.

Cold flow tests were then conducted to check the maximum air flow through the coal mixer, main combustor air and combustor auxiliary air flow loops. The combustor was started on natural gas and operated at two different sets of gas and air settings in order to verify flow readings by comparing calculated and measured O_2 concentration at the furnace exit.

The combustor was then heated to 2000ºF in gas-rich (sub-stoichiometric) mode prior to introducing PRB coal to the combustor for the first time. The unit tripped after a brief period of coal feed at 1000 lb/h due to a logic error in the safety interlock system. This was corrected and the coal restarted at 1000 lb/h. Shakedown operation continued on coal with several intermittent shutdowns to repair leaks in the coal feed and reagent air lines until the unit was stable and firing 2000 lb/h of PRB coal. This was gradually increased to 6000 lb/h. Figure 77 shows the flame at the coal burner face when (1) firing the furnace igniter and reducing gases (CO and H2) produced from the combustor firing in gas-rich mode, and (2) firing coal at 6000 lb/h without the furnace ignitor.

(1)



(2)

Figure 77. Flame at the coal burner face with the combustor in sub-stoichiometric firing with gas only (1) and with gas plus 6000 lb/h PRB coal feed (2)

The coal mill reached its high amp limit at about 6400 lb/h so the balance of the shakedown was conducted at about 6000 lb/h. A full set of operating data was taken at 6000 lb/h and 1400ºF preheat temperature. A series of brief parametric tests was then conducted over a range of combustor, mixer and auxiliary air flows to determine operating limits and the effect on combustor and burner operating stability. Additional operating data was collected at four different settings for the swirl vanes in the inner air channel of the burner around the coal channel. This is where the drying agent air that is separated from the coal stream by the cyclone is utilized after it is exhausted from the cyclone. The swirl vane angle was varied from 20º to 35º in these tests. System operation was maintained at 6000-lb/h coal feed for about 3.5 hours after which testing was voluntarily terminated. Over 20,000 lb of PRB coal was fired during this shakedown operating period.

The best NO_x reading observed at the furnace exit during the initial shakedown testing was about 260 ppm (corrected to 3% O_2) with an actual exit O_2 above 6%. This was a promising initial result considering the high exit O_2, which resulted from the coal feed being limited to 75% of its design value. For reference, the initial NO_x readings from the pilot unit were about 600 ppm, and were eventually reduced to below 100 ppm once the combustor and burner operation were optimized. The furnace exit O_2 varied in a range from about 6.5% to 9% during the various shakedown conditions tested, and CO in all cases was below 10 ppmv.

A turnaround period of about 2 weeks was expected to resolve the various mechanical, operational and control issues identified during shakedown operations. The coal mill settings had to be evaluated before the next coal tests to bring the mill back to its previously proven capacity of 8000-9000 lb/h with PRB coal at 28% moisture. The combustor support system was further evaluated to see if additional spring hangers were required at the furnace windbox end of the combustor. The use of a toothed vs. smooth ring at the burner face as a flame holder was also re-evaluated. A smooth ring is currently used. The flow range of the mixer air loop had to be increased by about 150% by changing the orifice plate and/or re-ranging the flow transmitter. Additional inspection and cleaning of the burner, combustor and connecting process, instrument impulse and sample lines had to be completed. Provisions for sampling coal from the concentrated coal line below the cyclone and from the drying agent air exhaust line after the cyclone had to be completed. Provisions for videotaping the coal flame in the furnace had also to be completed. Data from the shakedown testing were reconciled and evaluated and used to prepare the coal test matrix for the balance of the PRB coal test campaign.

Initial shakedown tests in the large-scale unit with PRB coal at 75% of the design coal rate have confirmed the operability of the scaled-up design, including smooth, non-pulsing coal flow through the cyclone separator to the preheating combustor, and smooth non-pulsing flow of the separated reagent air from the cyclone into the inner air channel of the coal burner.

The "hot wall" design of the prototype combustor also appears to be serviceable for the planned test work. This design approach is the same used for the pilot unit in order to allow a multitude of penetrations into the combustor for auxiliary air ports, temperature and pressure sensors, and observation ports. Adequate allowance was made for thermal expansion of the unit, but addition spring hanger supports should be added to better carry the weight of the combustor in the hot position.

The coal burner operation during the initial shakedown was fairly good, although flame shape and attachment were issues at some operation conditions. Relatively high pressure drops across all three air channels indicate that the various swirl vanes and internal windbox dampers may not be properly adjusted, and these were inspected. It is expected that a toothed ring should be added to the coal channel to improve flame attachment.

The coal mill was unable to deliver the design coal feed rate to the unit. Both the preheat combustor and burner are sized for about 33% more coal flow than was available from the mill in shakedown testing. It appears that the backpressure on the mill from the coal cyclone and reagent air ducting and channel may be partially responsible for the reduced coal rate.

In the initial shakedown tests, stable operation of the coal system, combustor, and burner were achieved for the first time with coal feed rates up to 6000 lb/h (about 50 MMBtu/h). However, attempts to increase the firing rate to the design level of 85 MMBtu/h were prevented by a high-amp condition in the coal mill. Reduced gas velocities in the preheater due to reduced firing rates resulted in some accumulation of coal in the bottom of the preheater chamber.

Inspection of the combustor following the shakedown showed no remaining accumulation of coal on the bottom of the combustor, indicating that all accumulation was burned out during the shutdown procedure. Evaluation of the combustor supports after coal testing resulted in the installation of two additional spring hangers at the ends of the combustor to better carry the weight of the combustor during hot operation, when it lifts off its support stand. A toothed ring was also designed and fabricated in accordance with RPI standards and installed at the burner face on the central coal tube to improve coal flame attachment.

Various instrument repairs and calibration checks identified during the shakedown coal testing were completed and two additional thermocouples were installed in the bottom (5 o'clock position) of the combustor to monitor coal accumulation.

An internal inspection of the burner windbox was conducted to determine the cause of high-pressure drops measured across the secondary and tertiary air channels during the coal testing. These pressure drops were on the order of 9-10 in. wc. vs. the expected 3-4 in. wc. It was determined that the high pressure drops were the result of improper settings of the secondary air vanes and the tertiary air shroud that control air flow from the windbox to the air channels. It was also found that the swirl vanes for the secondary air were set to 0° (no swirl) and they were therefore adjusted to the correct setting of 30°.

The pressure drop across the reagent air channel was also on the order of 10 in. wc, which, together with the 8-10 in wc drop across the cyclone resulted in a backpressure of over 20 in. wc on the coal mill. This restricted air flow through the mill and was one of the causes for reduced mill capacity during the shakedown tests. Tests were conducted with the auxiliary air blower downstream of the mill shut off, which resulted in increased primary air flow through the mill. It was also noted that the reagent air enters the reagent air channel tangentially in a direction opposite to the reagent air channel swirl vanes, and this is increased the pressure drop in the reagent air line by several in. wc.

Evaluation of previous mill performance data indicated that the reduction in auxiliary air and increase in primary air should result in increased mill capacity. Investigation of the feasibility and cost of reactivating an existing bin-firing system to supplement coal feed from the mill determined that the system was difficult to operate and had significant safety issues relative to storage of highly reactive pulverized PRB coal in the intermediate storage bin.

Additional testing was conducted at the R&D center in Worcester, MA in order to determine whether the coal mill capacity with PRB coal could be increased to 85 MMBtu/h. The objective of the tests was to increase the coal output from the mill from 6000 lb/h (wet) previously achieved to 9700 lb/h (wet) required to meet the preheater system design basis. After evaluating the previous results and comparing them to historical mill data, it was that the mill had not been operated at the correct air to coal ratio. Strategies for increasing coal output included reducing the introduction of auxiliary air to the coal line after the mill and reducing backpressure on the mill by reducing the pressure drop through the cyclone and reagent air piping.

A total of 6 test periods were conducted to improve mill performance. During these tests it was necessary to fire the preheat combustor and burner as there was nowhere else to discharge the coal. This amounted to costly full-scale testing of the system even though the objective was only to verify and improve the mill performance. The results were that coal throughput was increased to about 7550 lb/h (wet) at an air/coal ration of 1.35. Coal fineness met the mill spec of 70% passing 200-mesh but coal drying was less than expected at 18 to 22% vs. 12-15% expected. This mill performance was not close enough to the required performance to warrant further testing with PRB. The high cost of operating the entire system precluded operation of the preheat system for mill testing and optimization. A decision was therefore made to stop the work with PRB and proceed with preheater design, installation, and testing with bituminous coal, which would meet the required 85-MMBtu/h capacity at the reduced coal throughput due to the higher heating value of bituminous coal. Efforts to increase the coal mill throughput to the design capacity of the PRB preheating system fell significantly short of the required 85-million Btu/h. The time and cost required modify the PRB preheater or upgrade the mill was judged unacceptable by the project team. The project was therefore redirected toward design, installation and testing of the 85-million Btu/h preheater for bituminous coal.

Bituminous Coal Commercial Prototype Development

CFD Modeling

Fourteen 2-D modeling cases were conducted for the modified preheater for bituminous coal. The preheater concept modeled was based on an expanding preheater chamber where the diameter of the chamber is increased in steps along its length and annular cooling/protective air is introduced at each step. This design approach was developed based on favorable results in the pilot testing when protective air was introduced through annular ports next to the inner wall of the preheater chamber to cool the wall and oxidize sticky volatile matter that approached the wall. In this design, the preheater chamber is positioned inside the burner in place of the burner coal tube. This results in only the cyclone and combustor plenum having to be mounted in front of the PC burner, greatly reducing the space required for the system. Several versions of this design were modeled and a version with three steps for annular air introduction provided the best compromise between protection of the wall and design complexity.

It was found that when the hot combustion products from the natural gas burner nozzles around the outside of the coal feed pipe were used, the tendency for coal particles to migrate to the preheater wall was minimized, but the extent of coal heating and devolatilization was limited by poor heat transfer between the hot gas and coal streams. For this reason, a small gas burner was added inside the coal feed pipe to increase coal heating. Coal flows around this burner through the annular space between the burner pipe the coal pipe. Heat transfer to the coal stream is greatly improved by this approach with a corresponding improvement in the degree of devolatilization of the coal at the preheater exit. Adjusting the firing rates of the coal pipe and annular gas burners is used to achieve the maximum degree of devolatilization consistent with minimizing the migration of coal particles and sticky devolatilization products to the preheater walls. The firing balance between these burners can also be varied to improve startup and turndown capabilities of the system. A process diagram for the new preheater configuration is shown in Figure 1. The yellow arrows in Figure 78 represent the velocity vectors for the annular gas burners and red arrows for the coal pipe gas burner. The arrow colors correspond to the magnitude of the velocity for each stream.

Figure 79 shows the static temperature profiles inside the preheater resulting from this dual-firing configuration together with the corresponding wall temperatures along the preheater's length. The effectiveness of annular air introduction on reducing the preheater wall temperature is also clearly shown in Figure 2.

Figure 80 shows the concentration (mole fraction) profiles of devolatilization products released from coal in the preheater. Red areas in Figure 3 indicate the highest concentration of devolatilization products corresponding to overall devolatilization of 70 percent at the preheater exit.

Figure 81 shows predicted particle tracks in the preheater colored by particle residence time in the preheater. Note that impingement of particles is minimal in this case, with the exception of a small particle recirculation zone at the entrance to the preheater chamber. It is expected that this zone can be minimized by further adjustment of the annular burner firing rate and the position of the coal pipe relative to the preheater chamber inlet.

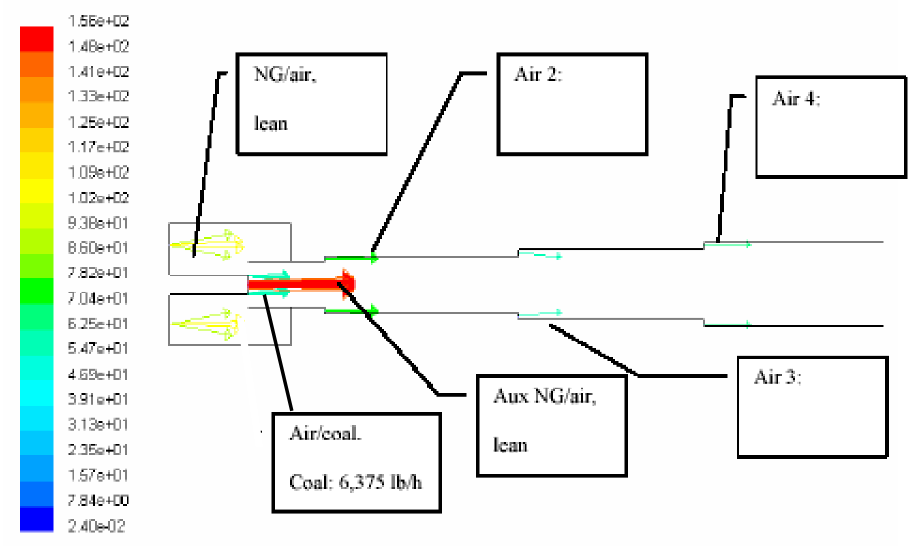


Figure 78. Process schematic for the bituminous coal preheater

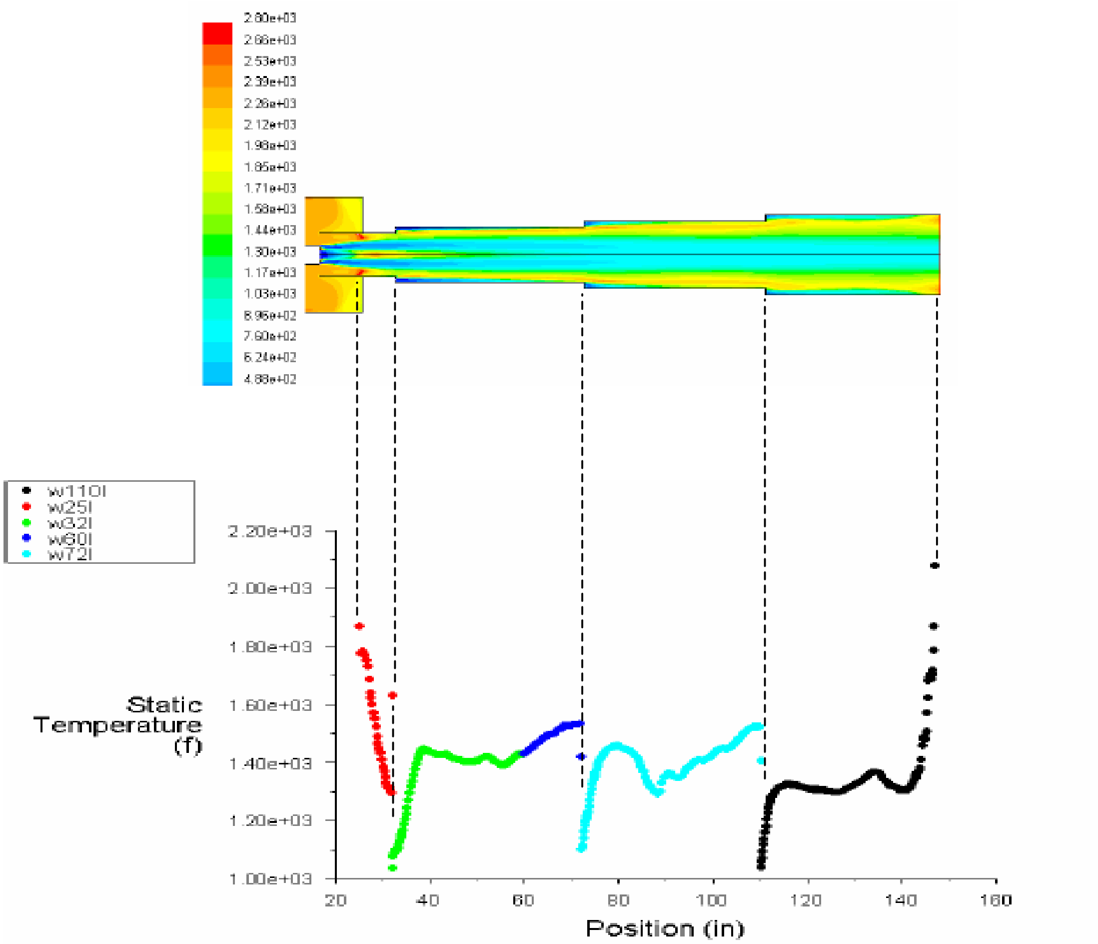


Figure 79. Preheater static temperature contours (top) and corresponding wall temperatures (bottom)

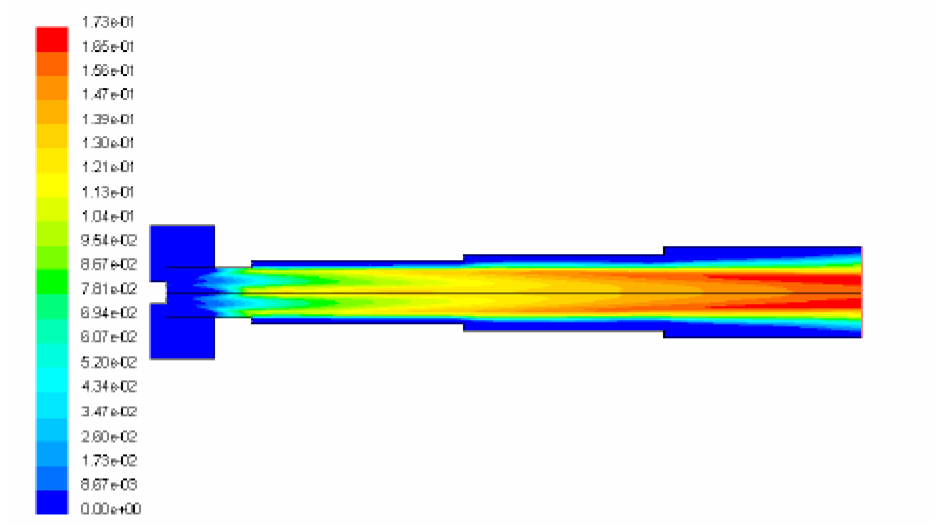


Figure 80. Contours of devolatilization products resulting from the dual-firing system

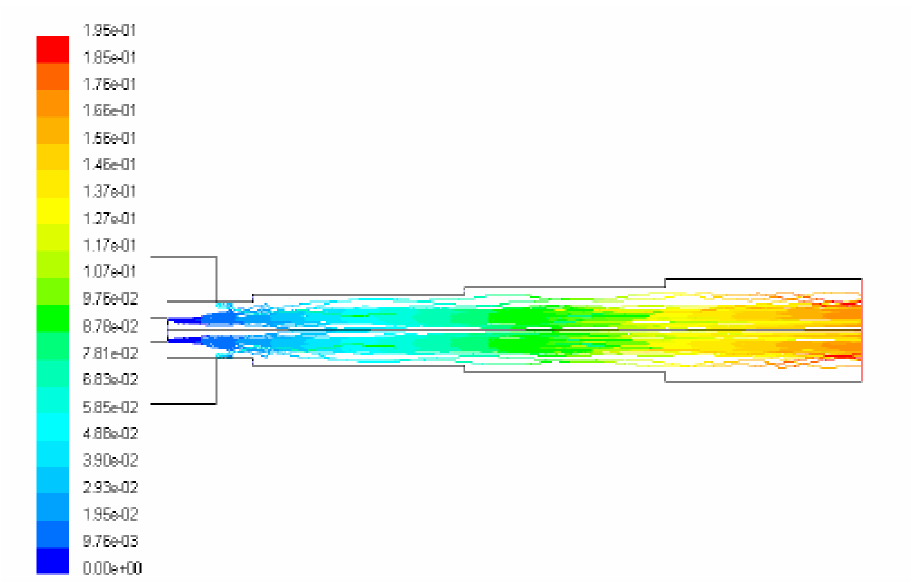


Figure 81. Particle tracks colored by particle residence time in the preheater

Commercial Prototype Engineering Design

The following bituminous coal specification was developed for 85-MMBtu/h preheater testing and a supplier was identified.

Table 15. Bituminous coal characteristics:

HHV=13,000 Btu/lb
HGI=43-45
Moisture=6-8%
Size=2"
Ash=8%
Sulfur=1%

Calculations were performed using the design standards for the RPI R&D Center's 350s Atrita pulverizer with the above coal specification. In any pulverizer, the quality of the product (fineness) is dependent on the coal and air throughput. An Air/Coal (A/C) ratio of 1.36 is the original value used in the early standards for this machine. The following table illustrates the relationship between the mill A/C ratio and the fineness and throughput of the machine.

Table 16. Relationship between mill A/C ratio and the fineness and throughput of the machine

HHV BTU/lb	%<200 Mesh	Air/Coal Ratio	Capacity MMBtu/hr
13,000	70	1.50	81
13,000	70	1.36	85
13,000	65	1.36	94

The design basis for the bituminous coal preheater was therefore selected as 85 MMBtu/h with a minimum coal HHV of 13000 Btu/lb and an A/C ratio of 1.36 requiring 6500 lb/h of coal from the mill. Previous testing with PRB coal having a similar HGI of 45 achieved over 7500 lb/h of coal through the mill with an A/C ratio of 1.35.

A process flow diagram (PFD) was developed for the bituminous preheater system specifying the normal and maximum flows for all coal, gas, and airflows together with the corresponding stream conditions.

Based on the above design basis information, a design drawing for the bituminous coal preheater was prepared and released.

CONCLUSION

The coal preheating combustion system for conventional or low-NO_x PC burners uses gas-fired coal preheating to destroy NO_x precursors and prevent NO_x formation. In this process, a concentrated pulverized coal stream enters the preheating chamber where flue gas from natural gas combustion is used to rapidly heat the coal up to about 1500°F prior to complete coal combustion in the PC burner. Secondary fuel consumption for preheating in commercial-scale burners is estimated to be 3 to 5% of the boiler heat input. This thermal pretreatment releases coal volatiles, including fuel-bound nitrogen compounds into an oxygen-deficient atmosphere that converts the coal-derived nitrogen compounds to molecular N_2 rather than NO. This allows the system to achieve very low NO_x levels–down to 0.15 lb/million Btu or below–without the need for post-combustion flue gas cleanup technology.

The coal preheating system will provide more flexibility in burner operation, particularly with LNB's, to achieve minimum NO_x production while maintaining acceptable carbon burnout. In an integrated system with overfire air, the fully staged combustion process lowers NOx emissions in three ways:

- Natural gas-fired coal preheating releases and reduces NOx precursors before they have a chance to react with oxygen to form NO or NO_2;
- NO_x formation is limited in the PC flame via combustion staging in the burner;
- NO_x formation in the coal combustion products in the furnace is reduced by use of low excess air, followed with overfire air to complete burnout at lower temperature.

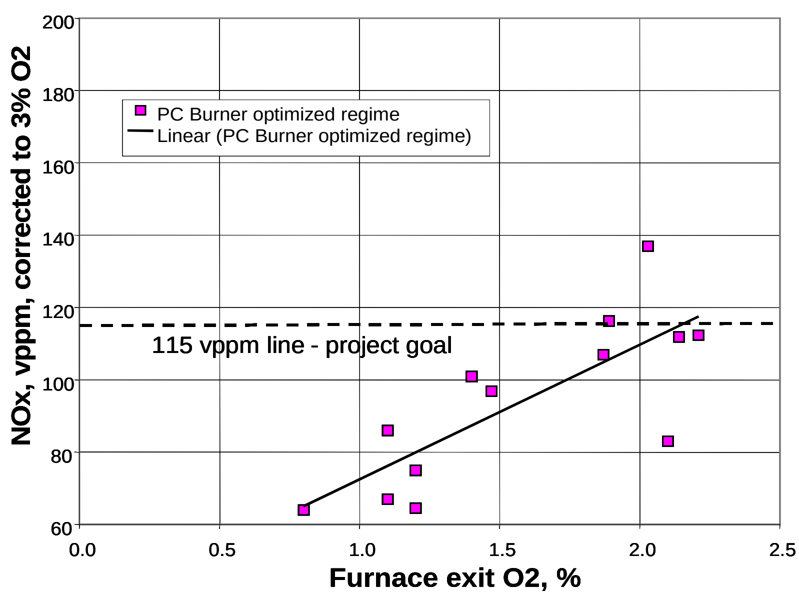


Figure 82. NO_x VS. Furnace exit O_2 for pilot scale tests with PRB coal

Design, installation, shakedown and initial PRB coal testing of a 3-million Btu/h pilot system at RPI's Pilot-Scale Combustion Facility (PSCF) in Worcester, MA has demonstrated that the PC Preheat process has a significant effect on final NO_x formation in the coal burner. The performed tests have revealed two major PC PREHEAT process stages responsible for PC burner NO_x reduction. In the first stage, coal volatile matter including fuel nitrogen is released into the natural gas flame, and fuel nitrogen participates in reburn reactions in the reducing atmosphere of the natural gas flame in the PC preheater. The second stage of NO_x reduction is the inner core of the PC burner flame, where produced hot mixture of coal char and fuel gas is combusted in oxygen deficient atmosphere. This second stage NO_x reduction mechanism is similar to that utilized in low-NO_x burners, however has an operating advantage compared to traditional low-NO_x burners technology due to higher inner core flame temperature (up to 200 °F), and better ignition properties of the preheated fuel, which allows deeper air staging in a low-NO_x burner. Based on these findings, process variables responsible for NO_x reduction include coal residence time in the preheater and coal burner air distribution. Modifications to both the pilot system gas-fired combustor and the PC burner to optimize theses process variables led to NO_x reduction with PRB coal to levels below 100 ppmv (0.13 lb/.mmBtu) with CO in the range of 35-112 ppmv without any furnace air staging (all emissions are @3%O_2). NO_x measurement results from this testing are summarized in Figure 83. Pilot testing with PRB coal is complete[[13]].

Pilot-scale work with high volatile bituminous coal is also complete. Firing tests with high volatile bituminous Central Appalachian coal were conducted to evaluate operation of coal preheating with bituminous coal. As anticipated, operation of the pilot unit with caking bituminous coal resulted in incidences of plugging by caked material inside of the gas-fired preheater, the severity of which depended on the gas combustor operating conditions. Twelve modifications to the combustor configuration and operation were developed and tested during 2003. Four modification of the coal nozzle in the Preheater were tested to define effect of mixing on caking properties. Both vertical and horizontal orientations of the preheater combustor were tested with the horizontal orientation finally selected. Three different combustor internal diameters (ID) were tested by using various inserts in the combustor housing. Settling out of the coal is a concern in the horizontal combustor as opposed to the vertical combustor where it was not an issue. Tests were therefore conducted at 3 velocities in the horizontal combustor ranging from 53 ft/s to 96 ft/s at each combustor ID, significantly higher than the 30-40 ft/s tested with the vertical combustor orientation. While continuous operation had been achieved with caking coal only up to 50 lb/h with the vertical unit, continuous operation at 150 lb/h was achieved with the modified horizontal unit at the higher velocities. Some deposition of caked material was still observed on the combustor walls, however. In all, more than eighty-two scoping tests have been performed with bituminous coal. Sufficient testing was completed to allow preliminary analysis of the plug formation, which indicated several approaches to eliminate plugging. In order to further reduce deposition, two configurations with injection of protective air along the combustor wall were tested. In the first configuration, an air injection approach utilized air injection holes through the inner liner similar to the ones used in gas turbine combustors for wall cooling. In second tested design, co-flow air jet injection was applied for wall protection. Both designs have demonstrated the ability to completely prevent agglomeration on the preheater walls at partial load.

Process variables affecting coal deposition on the preheater combustor walls include velocity in the preheater, the mixing pattern of the coal particles with products of natural gas combustion, and combustion air distribution in the preheater. The performed tests demonstrated that plugging is initiated by agglomeration of coal particles on the preheater inner walls, while no contribution of volumetric agglomeration was detected in all tested regimes. This finding indicates that local protection of the reactor walls against deposition of coal particles should resolve the issue. Viable technical approaches to prevent plugging include (i) creation of thin oxidizing film over the Preheater inner wall, and (ii) use of less adherent inner wall material. The main difficulty in creating reliable inner wall protection for the pilot scale unit is its small size with only 1.5-inches between inner wall and centerline of the preheater combustor. The oxidizing film with an estimated thickness of between 0.25 and 0.5 inches will occupy more than 50% of total reactor volume, which imposes limitations on the preheating process at this small scale. The plugging issue is expected to be less of a problem for the 100-million Btu/hr unit because of its much larger preheater combustor diameter.

Due to the scoping nature of these tests, operating conditions were selected to evaluate impact on caking rather than optimized combustion or emissions performance and steady-state operating periods were therefore not defined. All operational data including flue gas analyses were recorded as usual to aid in the evaluation. While not measured under steady-state operating conditions, NOx results were promising none-the-less, with readings in the range of 150 ppmv at 4% O_2 in the exit gas. NO_x results for test conducted with a 3-in ID ceramic insert in the combustor are shown as a function of furnace exit oxygen in Figure 84. For reference, NO_x data obtained for PRB coal at similar firing conditions are presented and it can be seen that projected performance with bituminous coal will actually be better than with PRB.

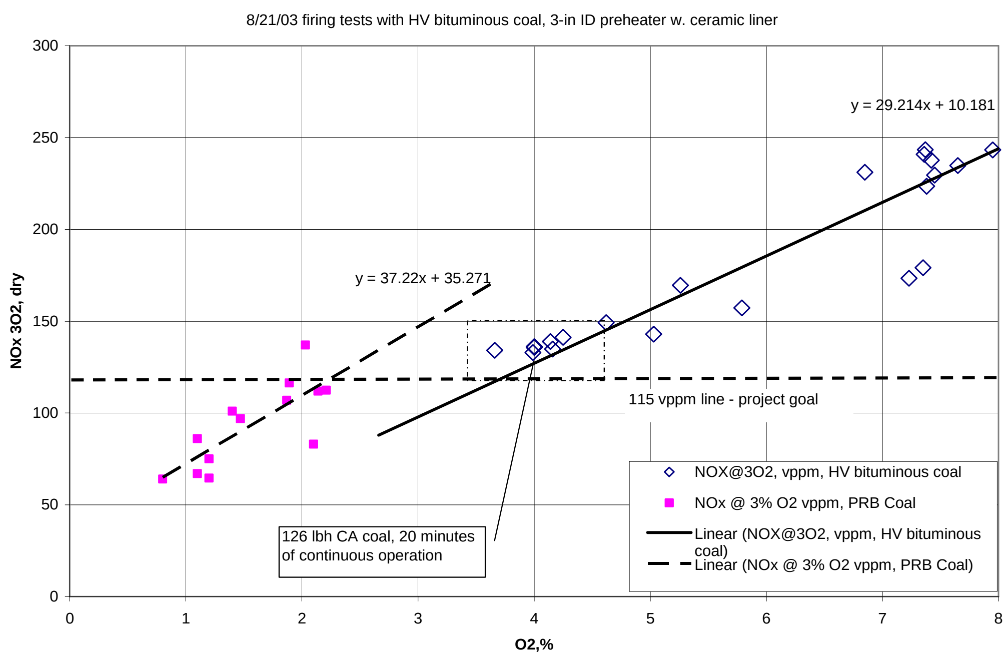


Figure 83. NO_x emissions for pilot tests with HV bituminous coal

The installation of the large-scale prototype coal preheater for PRB testing in the CBTF and shakedown testing with natural gas and PRB coal was completed. Scale-up testing with PRB at 17 MWt shows similar to pilot testing NO_x reduction. Large-scale testing was cut short due to the inability of the coal mill to meet the 85-MMBtu/h design firing rate. The project was redirected toward design, installation and testing of the 85-million Btu/h preheater for bituminous coal. Based on extensive pilot-scale testing and CFD modeling, design utilizing staged, annular protective air films to control temperature and prevent deposition on the preheater walls was developed, and complete set of drawings for manufacturing bituminous coal commercial prototype was released.

LIST OF ACRONYMS AND ABBREVIATIONS

CBTF	Coal Burner Test Facility
CFD	Computational Fluid Dynamics
FGR	Flue gas recirculation
GC	Gas Chromatograph
GTI	Gas Technology Institute
LNB	Low-NOx burners
NETL	National Energy Technology Laboratory
OFA	Overfire air
PC	Pulverized coal
PRB	Powder River Basin
PSCF	Pilot-Scale Combustion Facility
RPI	Riley Power, Inc.
SCR	Selective catalytic reduction
SMP	Sustaining Membership Program
SNCR	Selective non-catalytic reduction
VTI	All-Russia Thermal Engineering Institute

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