A NOVEL INTEGRATED OXY-COMBUSTION FLUE GAS PURICATION TECHNOLOGY - A NEAR-ZERO EMISSIONS OPTION

SER Contract No. WY49283WRI

FINAL EXECUTIVE SUMMARY REPORT

Coal-based power generation will continue to play a major role for decades. However, coal use faces challenges through ever evolving regulatory actions with regard to gaseous emissions, such as CO_2. Currently, coal-fired power plants account for over 40% of electricity generation in the country. About 40% of the total coal-based generation is fueled by subbituminous coal, such as the coal being produced from Wyoming's Powder River Basin (PRB) and being transported nationwide. PRB coal is used throughout the U.S and abroad for electrical power production. However, the climate change issue threatens both the existing PRB coal-fired power industry as well as future expansion of clean energy from PRB coal. In order to achieve cleaner use of coal, oxygen-enhanced combustion (oxy-combustion) appears to be a leading option for retrofitting the existing fleet of coal-fired subcritical plants.

In oxy-combustion, the coal is combusted in a mixture of oxygen and recycled flue gas, containing predominantly carbon dioxide (CO_2). In air-fired coal plants, the coal is combusted in air, containing essentially nitrogen (N_2) and oxygen (O_2). The result of oxy-combustion is a flue gas that contains a high concentration of CO_2 that can be used in such applications as enhanced oil recovery (EOR) or sequestered (stored) in sound geological formations.

The conversion of existing air-fired power plants to oxy-fired plants involves the addition of equipment and attendant modifications to allow for the recycle part of the CO_2-rich flue gas for the combustion of the coal with O_2. Key process subsystems of an oxy-combustion system include (1) an air separation subsystem, (2) an oxy-pulverized coal combustor, (3) conventional flue gas cleaning, and (4) a flue gas CO_2 purification and/or scavenging subsystem for producing a pipeline compatible CO_2 stream.

Commercial deployment of oxy-combustion for PRB-coal fired retrofit applications has been hampered by a number of issues. WRI's proposed WRITECoal™ Oxy-Combustion integrated process addresses these issues through the integration of the WRITECoal™ upgrading process, advanced oxy-burner design, and novel purification/scavenging and/or CO_2 re-use subsystems that are especially suited for PRB coal-fired power plants.

Both DOE and the industry recognize the fact that oxy-combustion in general is a leading technology for retrofitting coal-fired plants with a carbon enriched stream that can be purified and compressed for pipeline transport and storage. The recent switch in the FutureGen program to oxy-fuel illustrates DOE's confidence in oxy-combustion in reducing the impact of parasitic power and capital and O&M costs associated with amine based processes on the cost of electricity (COE) (Figure ES-1).

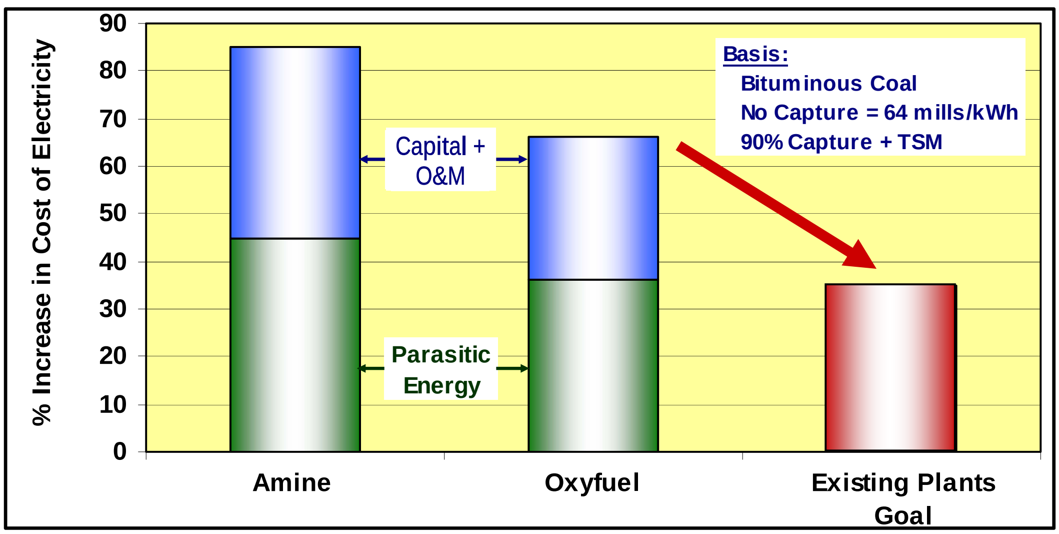

Figure ES-1 Parasitic power and capital + O&M Impact on COE for CCS retrofit option (Source: U.S. DOE NETL, 2009, Annual NETL CO_2 Capture Technology for Existing Plants R&D Meeting)

WRITECoal™ Oxy-combustion Process

The WRITECoal™ Oxy-combustion concept is based in part on WRI's patented process wherein WRI's coal upgrading process (WRITECoal™) is integrated into an existing air-fired power generation plant and retrofitted to an oxy-combustion plant wherein energy conversion efficiency is increased.

Importantly, emissions, including volatile species such as mercury, arsenic and selenium, are reduced by thermally evolving them from the coal prior to combustion; water is liberated during upgrading with potential to offset raw water consumption and CO_2 is captured and used or sequestered and parasitic power is recovered through the application of a small natural gas combined cycle gas turbine. A generalized schematic of the WRITECoal™ oxy-combustion system without the NGCC is presented in Figure ES-2 as retrofitted into an existing subcritical plant and the deployment can be staged.

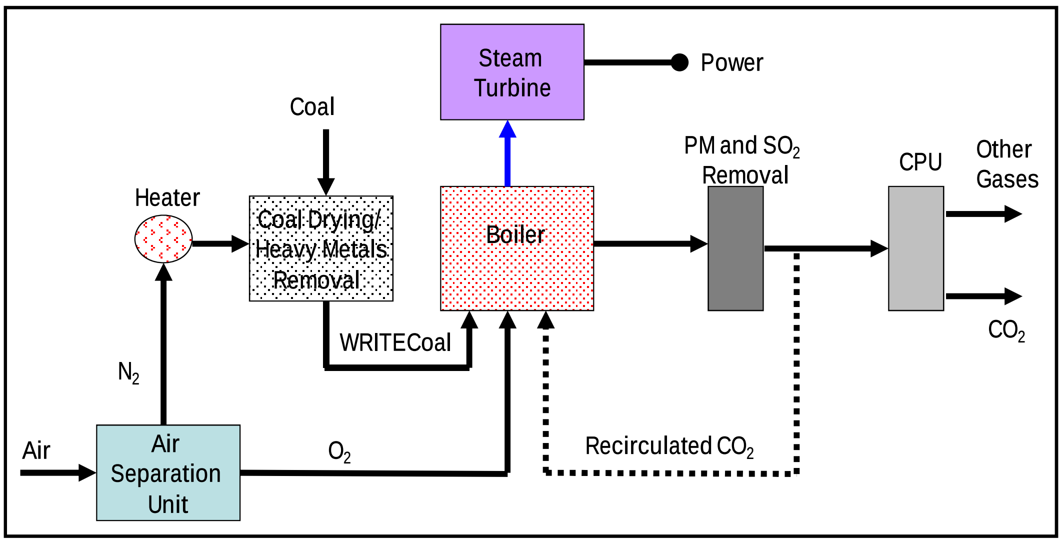

Figure ES-2 Schematic of the WRITECoal™-Based Oxy-Combustion Plant
Note – Figure does not show proposed NGCC.

Goals and Objectives

The project goal was to maintain the current power market for Wyoming's subbituminous Powder River Basin (PRB) coals by retrofitting to oxy-combustion via WRI's WRITECoal™ oxy-fired combustion process. More specifically, the objective of the project was to demonstrate at a 1 MWth-scale WRI's novel WRITECoal™ oxy-combustion process (patent-pending) integrated with an existing pc-fired pilot plant. Process optimization, system engineering and cost reduction analysis were used in addition to 1 MWth pilot-scale testing to validate the integrated process and to assess the economics of the retrofit of PRB coal-fired plants to oxy-combustion. As such, it was intended to determine if the WRITECoal™ process could reduce compression capital and parasitic power loads, and optimize oxy-combustion for 80-90% carbon capture, while reducing the increase in COE by less than that of other CO_2 capture processes.

Teaming Arrangements

Western Research Institute (WRI) teamed with Southern Research Institute (SRI), Foster Wheeler Development Corporation (FW), Etaa Energy, Inc. (EEI), and URS Energy and Construction (URS E&C) to address the potential of retrofitting Wyoming PRB coal via WRI's WRITECoal™ combustion process. WRI and EEI conducted testing and modeling of the performance of WRITECoal™ upgraded coals in the WRITECoal™ oxy-combustion retrofit process. WRI also teamed with EEI and URS E&C in performing an economic study of the commercial-scale application of the integrated WRITECoal™ oxy-combustion process. Co-sponsors included the State of Wyoming Clean Coal Technology Program through the University of Wyoming's School of Energy Resources (SER), the U.S. Department of Energy National Energy Technology Laboratory (DOE), Peabody Energy and Southern Company.

Key Test Results

A summary of the key results of the study is as follows:

WRITECoal™ 1-2 MWth-scale Testing A WRITECoal™-treated PRB coal was produced at WRI's Advanced Technology Center. The WRITECoal™ fuel is a low-moisture (<1.5%), low-sulfur, (<0.6%), high heating value (11,000+ Btu/lb) fuel. It also has low-mercury and other volatile trace metals, such as arsenic and selenium (e.g., <0.03 ppmd mercury) and maintains a high volatile matter content and a high O_2 content compared to bituminous coal, a beneficial feature in the integration of the process with gasification/IGCC systems. The condensate from the WRITECoal™ treatment of PRB coal is amenable for use in the plant.

The WRITECoal™ mobile process development unit (PDU) contains an electric heater, dryer, heavy metals release section, flue gas cooling heat exchanger and electrical and control systems. In this unit, the coal flow rate can be controlled by adjusting the weir at the discharge end of the vibrating fluidized bed. The drying gas is electrically heated and the temperature is controlled between 200 and

300 °F for drying and 500 and 600 °F for releasing the heavy metals. After the heat processing, the coal is discharged to a cooler below the drying/heating bed. The unit can process 700-800 lb/hr raw coal and over 40 tons of PRB coal was processed for the tests (Figure ES-3).

Figure ES-3   Mobile WRITECoal™ 1-2 MW$_{th}$-Scale Pilot Plant at WRI to be integrated with the Oxy-Combustion System at SRI. Blue item is condenser/heat exchanger.

Oxy-burner Design and Testing   Foster Wheeler (FW), under contract with WRI, designed and fabricated an oxy-burner with a heat input rating of 1 MWth (3.4 MMBtu/hr) for the project testing. The burner was installed and run through a series of commissioning trials and was modified to provide a more flexible unit. Testing was also conducted with Maxon's Revision 2 burner.

The FW burner uses a swirl to achieve the substantial anchoring of the flame required (Figure ES-4). A photograph of the F/W burner tip after testing in the SRI oxy-combustor is shown below (Figure ES-5). The performance of the FW burner was acceptable even without pilot assist. Based on the test results, a commercial oxy-burner was designed and cost estimate made.

Oxy-Combustion Testing at SRI   Testing of the WRITECoal™ products was accomplished in Southern Research Institute's 1 MWth pilot combustor. A schematic of the SRI oxy-combustion research facility is shown in Figure ES-6. The test furnace has a capacity of 3.4 MMBtu/hr heat input and can fire natural gas and/or pulverized coal. The time-temperature profile in the flue gas path simulates a utility size pc-fired utility unit. The test furnace is a vertical, up-fired, 28-foot tall cylinder, with an inner diameter of 3.5 feet. This allows gas velocities of 10 to 15 feet per second and residence times of 1.3 to 2.5 seconds. The design furnace exit gas temperature is approximately 1,800 °F. The body of the furnace is made up of seven 4-foot tall sections, each being a water-cooled jacket with 4 inches of cast refractory lining the fireside.

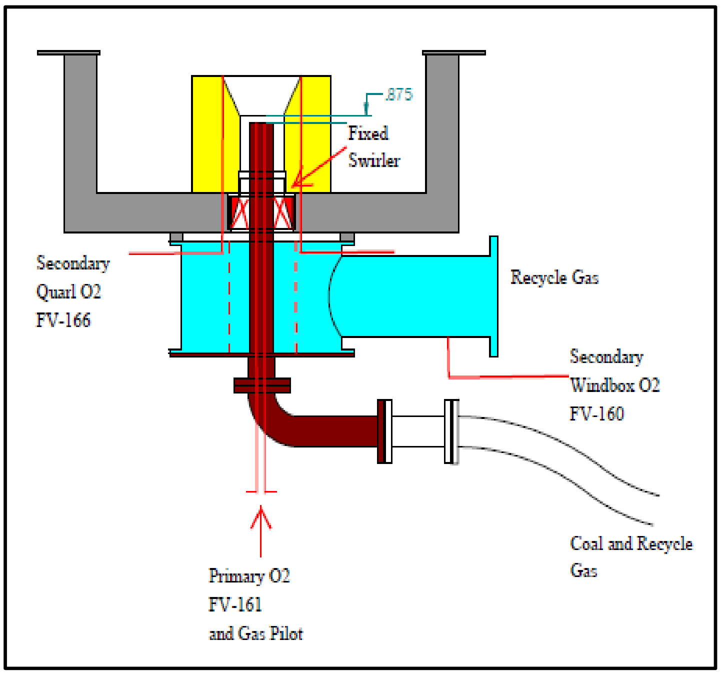

Figure ES-4 Photograph of the F/W Oxy-Burner Tip after Testing at SRI (above)

Figure ES-5 Schematic of the F/W Burner (left)

Refractory lining is used to limit the heat extraction and to ensure the proper simulation of the radiation environment found inside the full-scale furnaces. There is much more gas/wall contact in pilot-scale furnaces, and the flame would be quenched if the entire interior were lined with conventional waterwalls (Gale, 2012).

The testing of the WRITECoal™ fuels included the evaluation of the O_2 concentration in the input streams to the burner, and the impact of the following operational parameters on the plant performance: over firing and air ingress, furnace exit gas temperatures, the reduction of NOx emissions, and the CO_2 content of the flue gas. The increase in O_2 content in the recycle is designed as a means of reducing the volume of recycle that needs to be handled. The impact is a reduced capital and power demand (blowers) needed with increased O_2 content when retrofitting an existing PRB coal-fired subcritical plant.

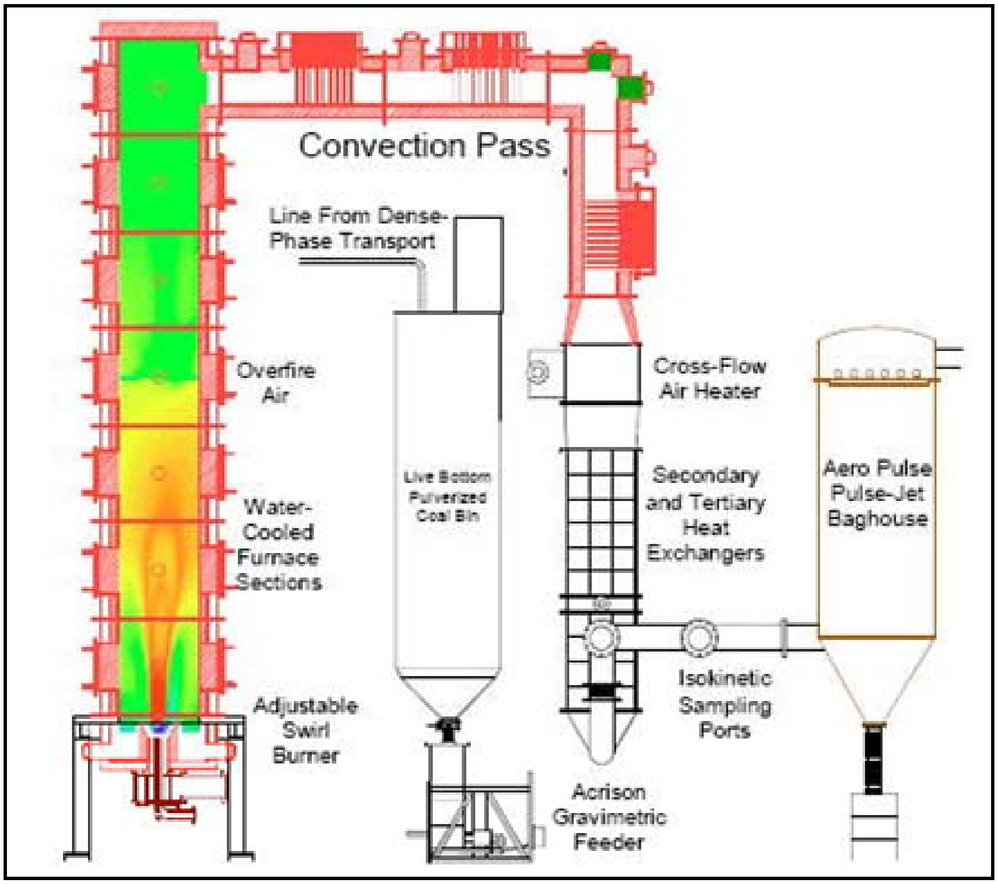

Figure ES-6 Schematic of the SRI Combustion Test Facility

Key findings from of the testing include:

- The impact of oxy-combustion on the Furnace Exit Gas Temperature (FEGT), an important criterion from a materials durability issue, increased by only ~100 ^{o}F increase with the use of WRITECoal™ treated PRB coal, compared to the raw PRB coal and a recycle gas O_2 content of 21%. At 27-28% recycle O_2 content, the increase in FEGT has remained the same, but the quantity of recycle gas was reduced by 30%, thereby reducing the capital and operating costs associated with system retrofitting.

- The impact of the recycle O_2 content on NOx reduction is shown in Figure ES-7. The data shows a substantial reduction of about 30% for the same excess O_2 level. The impact of operating conditions on the CO_2 concentration in the flue gas at the furnace exit showed that with potential air leakage, CO_2 concentrations exceeding 85% are achievable.

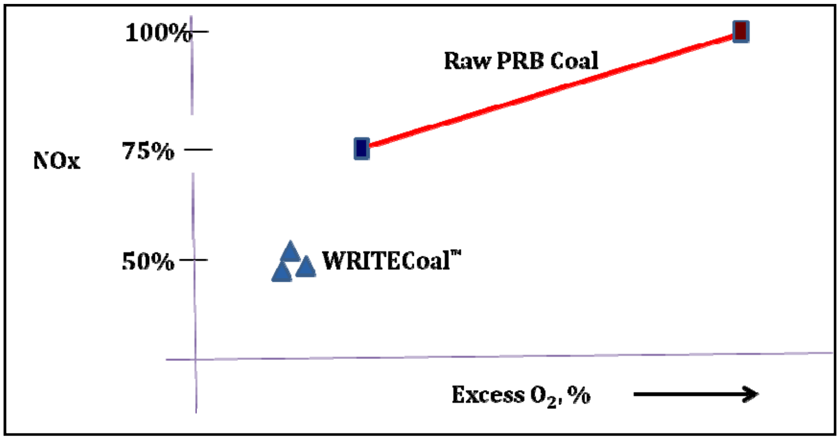

Figure ES-7 Impact of Furnace Excess O_2 on NOx Emissions

Another major objective of the testing was to ascertain the impact of real flue gas on the recovered water from the WRITECoal™ Condensing Heat Exchanger (CHX). Tests were conducted where the condenser heat exchanger (CHX) recovered about <u>70%</u> of the water from the flue gas of a composition compatible for use in the plant for cooling for example (Table ES-1).

Modeling of the WRITECoal™ Oxy-combustion System Both ASPEN Plus® and Computational Fluid Dynamics (CFD) modeling of the WRITECoal™ oxy-combustion system were performed. In addition, a 3-D CFD simulation of the furnace was performed using proprietary programs with Foster Wheeler to determine the details of the furnace fuel combustion performance including heat flux distribution, required burner tilt, maximum superheater metal temperature, and pendant superheater absorption (Table ES-2). Furnace performance similar to air-fired combustion is achievable (also see Figure ES-8).

Modeling of the overall retrofitted power plant scenarios were conducted with ASPEN Plus™. The fully integrated ASPEN Plus® model incorporated the base case (590 MWe gross tangentialfired unit) with Air Separation Unit (ASU) and supplemental parasitic power module (e.g., NGCC) and conventional CO_2 Processing Unit (CPU) for an oxy-fired system and an air-fired Econamine CO_2 capture retrofitted subcritical units.

Table ES-1 Composition of WRITECoal™ Recovered Water

Constituent	Flue Gas	WRITE-Coal™	Constituent	Flue Gas	WRITE-Coal™
Lab pH, SU	6-7	6-7	**Cations, mg/L**		
TDS, mg/L	61	48	- Calcium, diss.	6	8
TSS, mg/L	194	1170	- Iron	3.83	8.41
Anions, mg/L			- Lithium	<0.1	<0.1
- Chloride	<1	<1	- Magnesium	1	2
- Alkalinity as $CaCO_3$, diss.	26	94	- Potassium	<0.2	<0.2
- Bicarbonate Alkalinity	32	114	- Silicon	0.5	0.7
- Ammonia Nitrogen as N	5.9	26.8	- Sodium	1	2
- Nitrate & Nitrate as N	0.9	0.5	**Trace Metals, mg/L**		
- Phosphorus	<0.2	<0.2	- Arsenic	<0.001	<0.001
- Sulfates	<1	<1	- Mercury	<0.001	<0.001
- Cyanide	<0.005	<0.005	- Selenium	0.001	0.002

Table ES-2 Power Plant Flow Streams

	Base	WRITECoal™ Air-Fired	WRITECoal™ Oxy-Fired
Feed			
Air, Mlb/hr	5039	5262	0
O_2, Mlb/hr	0	0	1085
Coal, Mlb/hr	633	661	669
Recycle FG, Mlb/hr	0	839	4952
Furnace			
FEGT,ºF	**2228**	**2282**	**2205**
Fluegas, Mlb/hr	5638	6481	6481
Fluegas, MlMcf/hr/hr	379	434	353
Q in, MMBtu/hr	5525	5770	5840
Q Loss, MMBtu/hr	98	98	98
Boiler Efficiency, %	**84.8**	**88.4**	**90.2**
Q HRA, MMBtu/hr	2553	2930	3043
Q Furnace, MMBtu/hr	2228	2062	1983
Q Total	4781	4992	5026

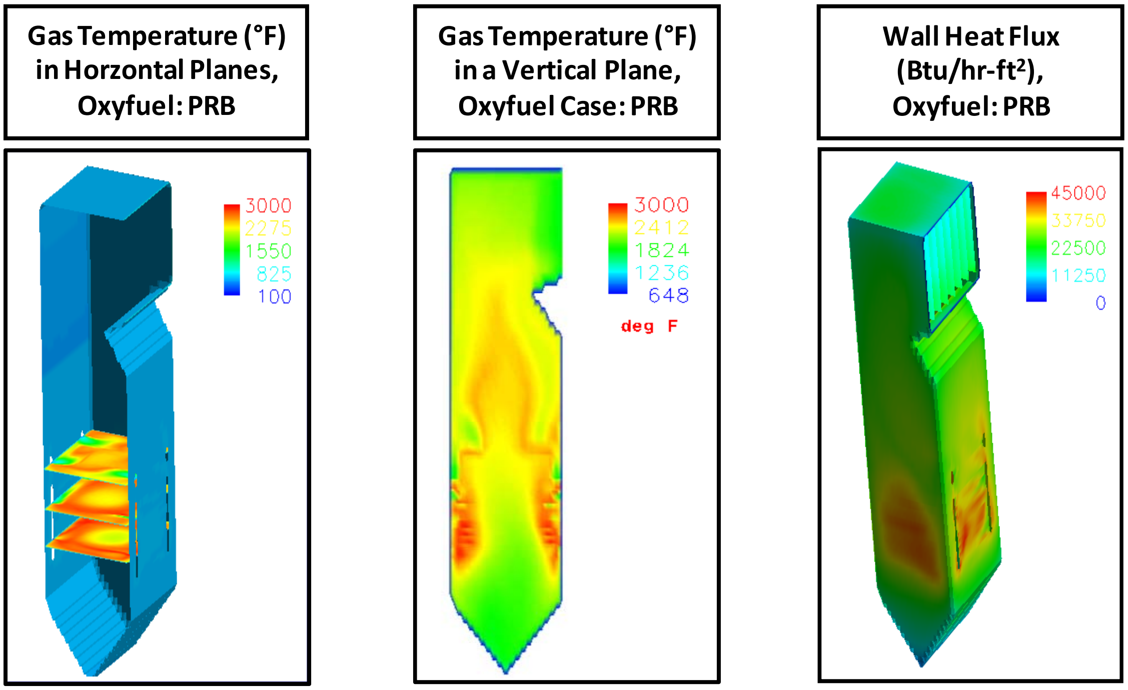

Figure ES-8 Impact of Oxy-fired Combustion on Furnace Gas Temperatures and Wall Heat Flux

ASPEN Plus® modeling evaluated the following cases. Process configuration and performance characteristics are presented in Table ES-3.

- Raw PRB Coal Oxy-fired Unit (Case 1);
- WRITECoal™ Treated PRB Coal Oxy-fired Unit (Case 2);
- Case 2 with Natural Gas Combined Cycle (NGCC) to Offset the Parasitic Power (Case 4);
- Raw PRB Coal Air-fired Unit with Econamine System for CO_2 Capture (Case 5);
- WRITECoal™ Treated PRB Coal Air-fired Unit with Econamine (Case 6); and
- Case 6 with NGCC to Offset the Parasitic Power (Case 7).

Part of the basis of the overall analysis of the as-received coal cases is to purchase power so that the generated electricity plus purchased electricity is equal to the corresponding WRITECoal™ treated cases as follows:

- Case 1 purchases 42MW so that the net output + purchased power are equal to the net output of the WRITECoal™ Case 2.

- Case 3 purchases 191MW so that the net output + purchased power are equal to the net output of WRITECoal™ (Case 4). Case 3 is Case 1 with greater amount of purchased power.
- Case 5 purchases 30MW so that the net output + purchased power are equal to the net output of WRITECoal™ Case 6.

Using the raw coal scenario as the base, the addition of the WRITECoal™ oxy-combustion process increases efficiency by 1.09% and raises the net power to 443MWe. The large parasitic (auxiliary) power (Table ES-3) associated with air separation unit operation and compression power requirements results in the derating of a 590MWe gross plant to 401 MWe net. When NGCC is added to offset the parasitic power, the efficiency is increased by 4.9% with a net power of 592MWe. The purchase power in Case 1 is to offset the increase in power output with addition of the WRITECoal™ process. Alternatively, most of the parasitic power can be offset through the purchase of power. The impact of the NGCC and purchased power were considered in the economic analysis.

For comparison, the retrofit of a 590MWe subcritical pulverized coal (pc) with Econamine carbon capture results in a net power of 351MWe, due to 111MWe of auxiliary power and a derate due to the need for steam for the amine process, thereby lowering steam turbine power output. The efficiency increase, with the addition of the WRITECoal™ process to the amine retrofit case, amounts to a 0.6% gain. The amine data were taken from the scenario presented by NETL in their recent report with WRITECoal™ addition options. These two scenarios (oxy-firing and amine-based post combustion capture) represent the most near-term options for retrofitting existing plants to carbon capture.

An interesting finding is that the WRITECoal™ when deployed with the Econamine process and using NGCC (Case 7) to offset parasitic power increases efficiency by 5.4%, confirming the benefits of the application of WRI's WRITECoal™ process in post-combustion CO_2 capture applications.

Table ES-3 Economics Design Basis for PRB Oxy-fired Cases and Air-Fired Amine Cases

	PRB Oxy-Fired with CO_2 Capture				PRB Air-Fired with Econamine CO_2 Capture		
	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7
Coal Drying Process	No	W-Coal	W-Coal	W-Coal	No	W-Coal	W-Coal
Coal Moisture Fired, %	28.35	0.0	0.0	0.0	28.35	0.0	0.0
Coal Flow, klb/hr	634.5	671.0	634.5	671.0	634.5	671.0	671.0
Heat Input (Coal), MMBtu/hr	5,580	5,901	5,580	5,901	5,584	5,905	5,906
Heat Input (NG), MMBtu/hr	0	0	0	978	0	0	1107
Firing Technology	Oxy	Oxy	Oxy	Oxy	Air	Air	Air
Air Separation Process	Yes	Yes	Yes	Yes	No	No	No
Sulfur Removal via SDA	Yes	Yes	Yes	Yes	Yes	Yes	Yes
CO_2 Capture, %	90	90	90	82*	90	90	81
Plant Capacity Factor	85	85	85	85	85	85	85
Gross Power-Coal, MWe	590.0	641.5	590.0	641.5	461.1	501.6	501.6
Gross Power-NG, MWe	-	-	-	149.3	-	-	178.1
Purchase Power, MWe	41.9		191.2		30.1		
Aux Power , MWe	189.0	198.6	189.0	198.6	110.5	120.9	121.0
Net Plant Rating, MWe	401.0	442.9	401.0	592.0	350.6	380.7	559.0
Net Plant Heat Rate, Btu/kWh	13,920	13,330	13,920	11,620	15,920	15,500	12,740
Efficiency, %	24.5	25.6	24.5	29.4	21.4	22.0	26.8
Efficiency Gain	0.0	1.1	0.0	4.9	0.0	0.6	5.4

*NGCC flue gas CO_2 not capture. W-Coal=WRITECoal™

The Econamine CO_2 removal process has a larger impact on the net plant heat rate of the air-fired cases than the compression and purification system used to capture CO_2 in the oxy-combustion cases. Although both plants have the same coal burn rate, the net plant heat rate of air-fired Case 5 is 15,920 Btu/kWh compared to 13,920 Btu/kWh for oxy-combustion Case 1.

Economics/Costing An independent economic analysis of the WRITECoal™ oxy-combustion technology by URS and Etaa Energy, Inc. in conjunction with WRI and Etaa Energy, Inc. was conducted. The facility is located at a retrofit site in Wyoming with an elevation of 6,700 feet and a nominal plant output of 590 MW net. Capital costs, operating costs, and levelized cost of electricity (LCOE) shown in Table ES-4 in January 2012 dollars were estimated with all cost estimates having an accuracy of -25%/+30%[1].

Table ES-4 Preliminary Economic Summary for PRB Oxy-fired Cases and Air-Fired Amine Cases

	PRB Oxy-Fired with CO_2 Capture				PRB Air-Fired with Econamine CO_2 Capture		
Costs Jan. 2012 $	**Case 1 Base Raw**	**Case 2 Treated**	**Case 3 W-Coal w/ Purchase Power**	**Case 4 W-Coal w/ NGCC**	**Case 5 Raw**	**Case 6 W-Coal PC**	**Case 7 W-Coal w/NGCC**
TCR (1), 1000$ $/kW	1,110,000 2,800	1,220,000 2,800	1,110,000 2,800	1,420,000 2,400	1,000,000 2,900	1,120,000 2,900	1,360,000 2,400
TPC(2), 1000$ $/kW	990,000 2,500	1,100,000 2,500	990,000 2,500	1,270,000 2,100	890,000 2,500	1,010,000 2,700	1,220,000 2,200
Fixed O&M, 1000$	24,800	28,700	24,800	32,200	20,300	22,600	28,400
Var. O&M, 1000$(4)	69,700	56,700	125,300	86,530	70,800	60,120	93,860
Total O&M, 1000$	94,500	85,400	150,100	118,800	91,100	82,700	123,200
PWRR. 1000	1,870,000	1,840,000	2,560,000	2,360,000	1,720,000	1,740,000	2,380,000
LCOE, cents/kWh	**6.8**	**6.0**	**9.3**	**5.8**	**7.1**	**6.6**	**6.2**

TCR – Total Capital Requirements; TPC – Total Plant Costs; PRWW – Present Worth Revenue Requirement ; Natural Gas ($3.70/MBtu) and Purchased Power (5 cents/kWh)

The WRITECoal™ with NGCC improves the economics of the oxy-fired retrofit cases based on the COE. Key findings are as follows:

Compared to as-received coal (Case 1), the higher capital cost of WRITECoal™ Case 2 is more than offset by a 4% improvement in plant efficiency and the fact that Case 2 has no purchased power cost. The levelized cost of WRITECoal™ Case 2 is 11% lower than the levelized COE of as-received coal (Case 1).

[1] Capital cost estimates conform to the requirements and characteristics of an AACE International Class 5 estimate as outlined in AACE Recommended Practice 18R-97.

Compared to the as-received coal (Case 3), the higher capital cost of WRITECoal™ Case 4 is more than offset by 17% improvement in plant efficiency and the fact that Case 4 has no purchased power cost. The levelized cost of NGCC + WRITECoal™ Case 4 is 38% lower than the levelized COE of the as-received coal (Case 3).

Compared to the as-received coal (Case 5), the higher capital cost of WRITECoal™ Case 6 is more than offset by 3% improvement in plant efficiency and the fact that Case 6 has no purchased power cost. The levelized cost of WRITECoal™ Case 6 is 7% lower than the levelized COE of the as-received coal (Case 5).

Compared with Case 5, the higher capital cost of the WRITECoal™ Case 7 is more than offset by 20% improvement in plant efficiency and the fact that Case 7 has not purchased power. The levelized cost for of NGCC + WRITECoal Case 7 is 13% lower than the levelized COE of Raw coal Case 5.

Sensitivity analyses of the impact of natural gas prices and the price of purchased power were conducted. Key results were as follows:

- For Case 1, an increase in purchased power price from 5 to 7 cents/kWh increases the levelized COE from 6.8 to 7.1 cents/kWh.
- For Case 3, an increase in purchased power price from 5 to 7 cents/kWh increases the levelized COE from 9.3 to 10.5 cents/kWh.
- For Case 4, an increase in natural gas price from \$3.70/MMBtu to \$5.55/MMBtu (increase of 50%) increases the levelized COE from 5.8 to 6.2 cents/kWh.
- For Case 4, an increase in natural gas price from \$3.70/MMBtu to \$7.40/MMBtu (increase of 100%) increases the levelized COE from 5.8 to 6.6 cents/kWh.

Conclusions and Recommendations

In summary, the deployment of the WRITECoal™ process can improve both oxy-fired and air-fired systems heat rate and COE. The WRITECoal™ oxy-combustion process has higher efficiency, lower net heat rates and lower cost of electricity compared to oxy-combustion without WRITECoal™ and compared with air-fired units with Econamine CO_2 capture.

Results from 1 MWth oxy-combustor testing showed that the integrated operation with the WRITECoal™ 1-2 MWth-scale mobile unit was seamless. Efficient recovery of clean water for plant use was demonstrated. Modeling showed a net efficiency gain of 4.9% for WRITECoal™ integration and 82% carbon capture compared to oxy-combustion without WRITECoal™. An independent Class 5 economic analysis indicates a LCOE of 5.8 cents/kWh. Based on the data from this study, the WRITECoal™ oxy-combustion process will also improve performance and lower COE for Greenfield plants employing supercritical and ultra-supercritical steam conditions. The process has a wide range of applications in the power and even the chemicals and fuels industry. As such, it is recommended that further scale-up of the WRITECoal™ process be undertaken that would ultimately lead to a larger scale (e.g., 5-10MWth) demonstration to resolve possible scale-up issues.
