WRI'S PRE-GASIFICATION TREATMENT OF PRB COALS FOR IMPROVED ADVANCED CLEAN COAL GASIFIER DESIGN

SER Contract No. WY49975WRI
Dr. Al Bland
Western Research Institute

FINAL EXECUTIVE SUMMARY REPORT

WRI'S PRE-GASIFICATION TREATMENT OF PRB COALS FOR IMPROVED ADVANCED CLEAN COAL GASIFIER DESIGN

SER Contract No. WY49975WRI

FINAL EXECUTIVE SUMMARY REPORT

Project Overview

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 about 46% 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 the Wyoming's Powder River Basin (PRB) and being distributed throughout the U.S. The climate change issue threatens both the existing PRB coal-fired power industry as well as future expansion of clean energy from PRB coal. However, for cleaner use of coal, Integrated Gasification Combined Cycle (IGCC) appears to be a leading option for new coal-based plants.

In the coal gasification process, the coal is first converted into synthetic fuel gas. The conversion is accomplished by providing sub-stoichiometric quantity of oxidant in the form of air or oxygen and operating the gasifier under atmospheric or pressurized hot conditions. The syngas usually has a lower heating value in excess of 100 Btu/scf. Syngas is cleaned and combusted at desired excess air levels to provide the necessary thermal energy to run a gas turbine with the effluent turbine exhaust gas generating steam to run steam turbines. Thus an IGCC plant integrates both gas turbine and steam turbine power generation. IGCC plants with CO_2 capture can convert energy at higher efficiency and reduced CO_2 emissions.

The use of Wyoming coal with its low heating value is at an efficiency disadvantage with eastern bituminous coals due to the high moisture content of the coal. The efficiency is even further degraded when PRB coal is to be used in IGCC at high elevations.

WRITECoal™ IGCC Process

The WRITECoal™ IGCC concept is based in part on WRI's patented process wherein WRI's coal upgrading process (WRITECoal™) is integrated into a gasification/IGCC power generation plant wherein energy conversion efficiency is increased, emissions, including volatile species such as mercury, arsenic and selenium, are reduced by thermally evolving them from the coal prior to gasification and water is liberated during upgrading with potential to offset raw water consumption and CO_2 is recycled as an oxidant and coal feed assist gas, thereby lowering O_2 consumption.

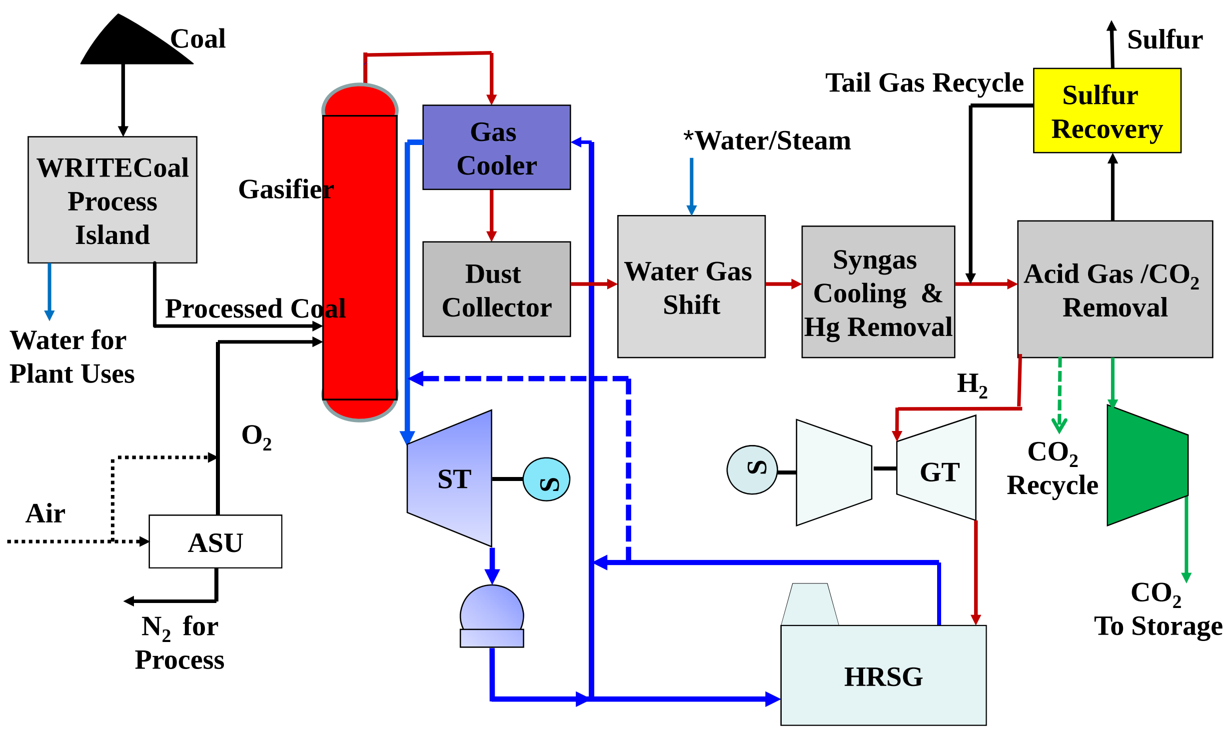

Figure ES-1. Schematic of a Typical WRITECoal™ Gasification/IGCC Integration Goals and Objectives

WRITECoal™ IGCC technology can provide fuel flexibility especially for Wyoming subbituminous coals gasified at high altitude, and produce syngas of quality applicable to various uses, such as power generation and chemicals manufacture. Figure ES-1 shows a conceptual schematic of the WRITECoal™ gasification/IGCC process with moisture removal and use in the plant and CO_2 re-use in coal feed and fluidization. The net result of these features is a reduction in gasifier capital from a reduction in size and parasitic load from the Air Separation Unit (ASU) and increased power output from the integrated system per unit of coal feed.

The project goal is to enhance the competitiveness of Wyoming's subbituminous coals when employed in IGCC, especially at high altitude. More specifically, the objectives are: (1) assess the technical and economic viability of the WRITECoal™ process on coal properties and gasification reactivity, water reuse, and mercury removal, (2) assess the benefits and issues of integrating WRI's process with the gasification process to achieve an increase in IGCC plant efficiency when employing upgraded PRB coals, and (3) acquire the general engineering data needed to demonstrate the WRI technology at a pilot-scale.

Teaming Arrangements

Western Research Institute (WRI) teamed with Gas Technology Institute (GTI), Etaa Energy Inc. (EEI), and URS Energy and Construction (URS E&C) to address the potential of upgrading of Wyoming PRB coal via WRI's WRITECoal™ gasification process in order to enhance efficiency, reduce freshwater consumption, and reduce volatile trace species from the syngas product or emissions from the IGCC. WRI and GTI conducted testing and modeling of the performance of WRITECoal™ upgraded coals in the UGAS® gasification system. WRI also teamed with EEI and URS E&C in performing an economic study of the commercial-scale application of the integrated WRI process-gasification/IGCC process. Co-sponsors include the State of Wyoming Clean Coal Technology Program and the U.S. Department of Energy National Energy Technology Laboratory.

Process Description

The following description illustrates the main subsystems of the integrated WRITECoal™ gasifier/IGCC system. There are three integrated process technology islands – the WRITECoal™ process island, the gasifier island and the power island. The source of heat for the WRITECoal™ process island is the high temperature (≈1700-2000 °F) syngas out of the gasifier and/or flue gas in the downstream of the waste heat boiler. Other than the recycle of CO_2 to the gasifier, no major retrofits are required.

WRI's WRITECoal™ Coal Upgrading Process The WRITECoal™ process is a WRI patented two-step thermal coal upgrading and emissions (mercury) control process that removes water in the first stage and captures it for plant use, followed by the volatilization and capture of volatile metals species such as mercury prior to combustion or gasification at the plant site. Waste heat from the plant is used in part of the process. In this process, raw coal is heated to a temperature not exceeding 300 °F wherein the free water and most of the more tightly bound water is evaporated and removed from the zone by the heated inert sweep gas. Evolution of mercury and other volatile metals (e.g., arsenic and selenium) does not occur in this zone thus allowing for water recovery without treatment for metal species removal. The coal is then heated to a temperature of 500-600 °F, wherein 75-80% of the mercury in PRB coal, for example, is volatilized and removed by an inert sweep gas. High temperature (500-600 °F) sorbents, capable of capturing volatile metals, such as mercury and arsenic, have been developed to avoid the thermal energy efficiency loss resulting from cooling the sweep gas to 275 °F to enable conventional activated carbon sorbents to effectively capture the volatile metals. The sweep gas stream, containing the evolved volatile metals such as mercury, pass into the volatile metals removal equipment and are captured via a high load capacity fixed sorbent bed from the relatively clean sweep gas.

<u>GTI UGAS® Gasifier</u> The GTI gasification process (Figure ES-2), for example, is based on a single-stage fluidized bed for production of low-to-medium heating value synthesis gas or 'syngas' from a variety of feed stocks including coal, biomass and wastes.

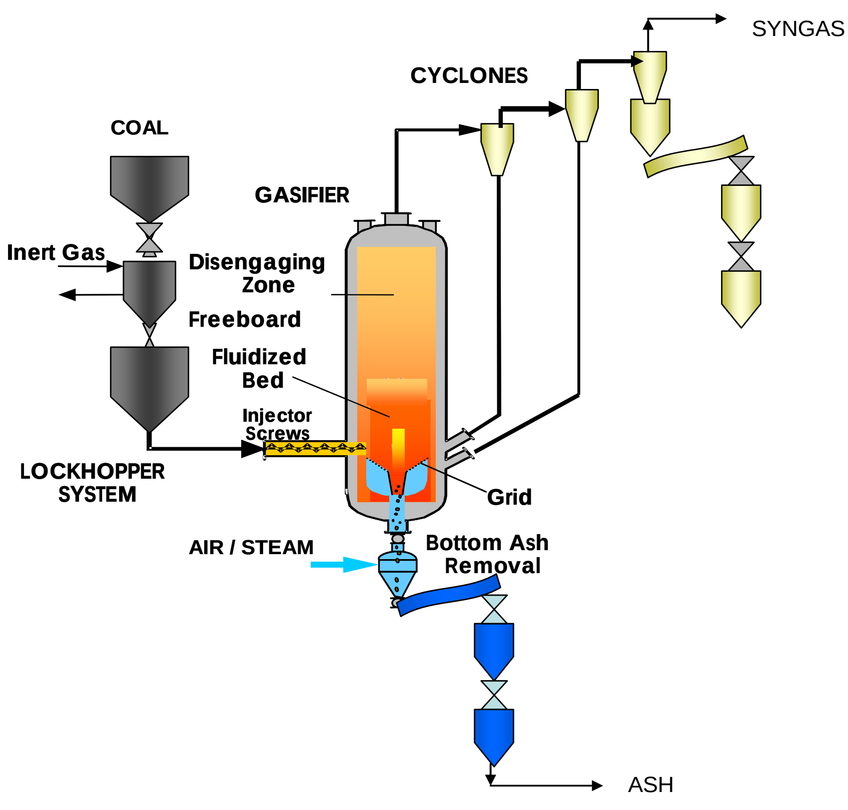

Figure ES-2 Schematic of the GTI U-GAS® Gasifier

The U-GAS® technology was developed for gasification of all ranks of coal. In the GTI UGAS® process, fuel is dried to the extent required for handling purposes and conveyed into the gasifier from a lockhopper system. Within the fluidized bed, the fuel reacts with steam and air or oxygen at a temperature of 1550 °F to 2000 °F (843 °C to 1093 °C). The temperature for gasification depends on the type of fuel used and is controlled to maintain high carbon conversion and non-slagging conditions for the ash. The GTI process accomplishes four important functions in a single-stage fluidized bed gasifier. It decakes, devolatilizes, and gasifies fuel, and, if necessary, agglomerates and separates ash from the reacting char. The operating pressure of the gasifier depends on the end use for the syngas and may vary from 40 to 435 psia (3 to 30 bar) or more. After cleaning, the product gas can be used as industrial fuel gas for process heating, synthesis gas for production of ammonia, hydrogen or liquids, and for power generation via IGCC or fuel cells.

Cold gas efficiencies of over 80% can be achieved. Fines elutriated from the fluidized bed are typically separated from the product syngas by up to three stages of external cyclone separators, one or two of which may return the fines to the fluidized bed for increased carbon conversion. The product syngas is essentially free of tars and oils due to the temperature and residence time of the gases in the fluidized bed, simplified downstream heat recovery and gas cleaning operations.

Testing Methodology

The project used facilities at WRI's Advanced Technology Center as well as testing facilities at Gas Technology Institute.

<u>WRITECoal™ Facilities</u> The batch operation bench-scale and continuous operation WRITECoal™ pilot-scale facilities were used in order to determine the characteristics of volatile

species release and capture and the quality of the evolved water for use in a gasifier/IGCC application. The treated coals were thoroughly tested for chemical and physical properties and handling characteristics. The pilot unit contains each of the components of the commercial installation, with the exception of an electrical heater which is used for process heat instead of the use of waste and process heat from the power plant. The pilot unit is instrumented for temperature and pressure measurements across the drying and volatile species removal steps (Figure ES-3). The pilot-scale facility was operated at a fixed residence time and at a temperature determined from prior trials.

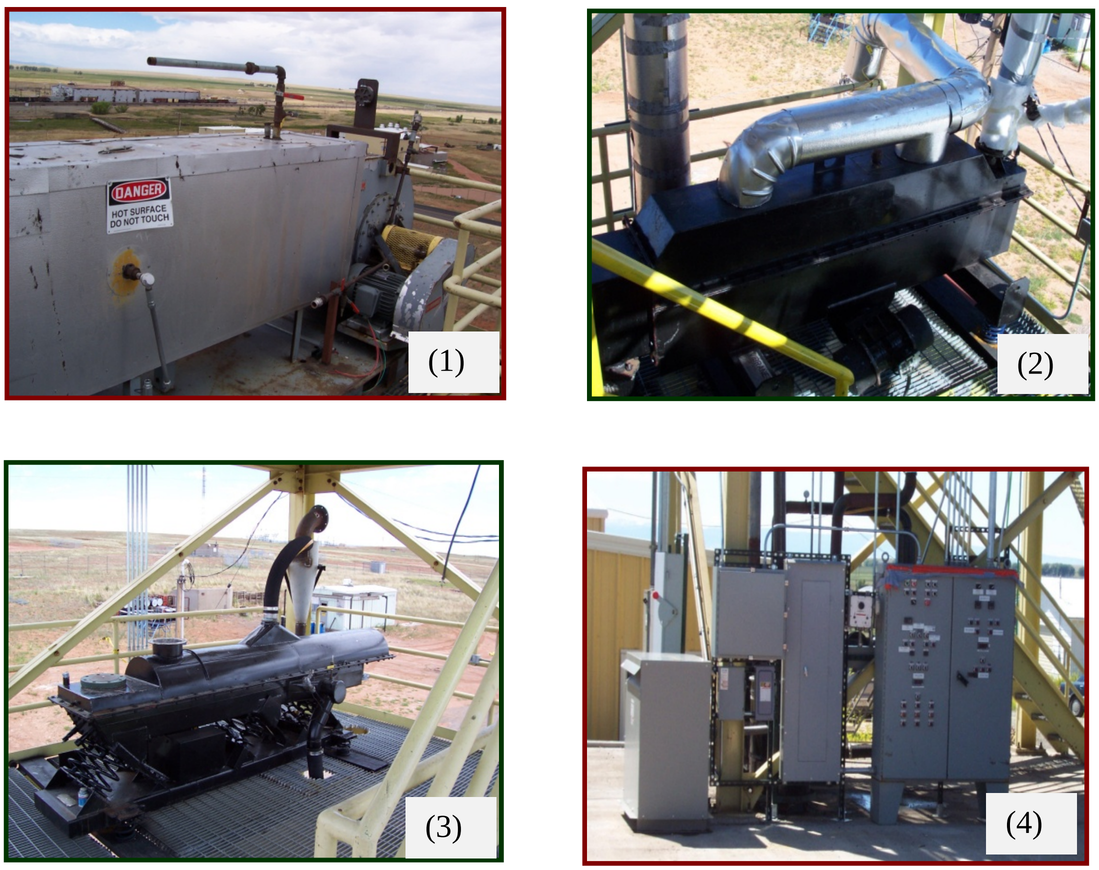

Figure ES-3 Photographs of Components of the Pilot-Scale Unit. (1) Electrical Heater; (2) Vibratory Fluid Bed Dryer; (3) Product Cooler; and (4) Motor Control Center

<u>Coal Gasification Facilities.</u> Both High Temperature Thermogravimetric Analysis (HPTGA) and bench-scale fluidized bed gasifier were used to assess the reactivity of the coal and to

determine the syngas composition. Reactivity and syngas composition impacts IGCC efficiency and the costs of the WRITECoal™ gasification/IGCC process.

HPTGA Methodology. A high-pressure thermogravimetric analyzer (HPTGA) was used to determine the relative coal reactivity of the raw and treated coals. A photograph of one of GTI's state-of-the-art HPTGA units is presented in Figure ES-4. Coal reactivity at a given temperature is an indicator of the minimum reactor residence time requirements and the carbon conversion that could be expected in a gasifier. This HPTGA unit is capable of operation up to 2000 °F (1093 °C) and 1100 psia (69 bar). The coal was first devolatilized and then char burnout tests were conducted. The char reacts slowly, while the devolatilization of the coal takes place in a much shorter duration. HPTGA was used to determine the carbon conversion defined as that percentage of carbon that is left over after devolatilization is complete to syngas.

Bench-scale Gasifier GTI's bench-scale gasification unit in Des Plaines, Illinois (Figure ES-5) was used to evaluate the gasification performance of the raw and WRITECoal™ treated coal. The gasification reactor consists of a bottom reaction zone and a top solids-disengaging zone (freeboard). The reaction zone is electrically heated by a three-zoned furnace while the disengaging zone is insulated without an external heater. Temperature, oxidant feed and other operating parameters are controlled and the syngas produced is analyzed with a micro gas chromatograph.

Test Results

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

WRITECoal™ Process Testing A WRITECoal™-treated PRB coal has been produced at WRI's Advanced Technology Center. The WRITECoal™ fuel is a low-moisture (<1.5%), low-sulfur

Figure ES-4. Photograph of the HPTGA Apparatus at GTI Used for Testing.

Figure ES-5. Photograph of the Bench-scale U-GAS® Gasifier Used in the Testing.

(<0.6%), high heating value (11,000+ Btu/lb), and low-mercury and other volatile trace metals, such as arsenic and selenium (e.g., <0.03 ppmd mercury) that 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 of sufficient quality for use in the plant.

Coal Reactivity Testing HPTGA testing determined the relative reactivity of the run-of-mine PRB and WRITECoal™ PRB coals. The coals were devolatilized and HPTGA tests using gas mixtures: 50%N_2/50%Steam and 30%H_2/12% CO/ 8% CO_2/50%Steam at two different temperatures: 1700 °F and 1800 °F and 300 psig were conducted. A summary of the results of the HPTGA testing under syngas/steam gas conditions is presented in Table ES-1. The results demonstrate a reduction (40%) in residence time of the char conversion reaction and a high carbon conversion (>99%).

Table ES-1. Summary of Key Gasification Results at 1,800 °F and 300 psig

Coal Type	Gasification Conditions	Carbon Conversion, %			Char Residence Time, min.
		Devolatilization	Char Reaction	Total	
Raw PRB	Syngas/Steam	56.5	99.0	99.6	42
WRITECoal™	Syngas/Steam	73.2	99.0	99.7	25
Raw PRB-AM	Syngas/Steam	64.8	100	100	35

AM – Ash Modified
Syngas/Steam – 30% H_2; 12% Co; 8% CO_2; 50% H_2O

HPTGA tests conducted on the raw and WRITECoal™ treated coal doped with alkali metal under a gas mixture of 50% N_2/50% Steam and 50% Syngas/50% Steam at 1700 °F and 1800 °F and 300 psig showed an increase in carbon conversion with both the raw and WRITECoal™ treated coals.

HPTGA tests using raw and WRITECoal™ treated coal and syngas with different compositions were conducted to ascertain possible carbon deposition. The syngas compositions were determined using a proprietary Fortran-based model of the fluidized bed gasifier, while carbon deposition probability was determined using an Excel-based program. Effects of water and oxygen addition to syngas were investigated and the results for carbon-deposition free syngas compositions determined. Also, testing with different levels of carbon dioxide recycle as an oxidant indicated that CO_2 could serve as a partial oxidant in the gasification. This has significant impacts on the economic and efficiency improvements for the WRITECoal™ IGCC technology including the level of oxygen demand.

<u>Gasification Modeling</u> The syngas compositions for the raw and WRITECoal™ fuels indicated that the WRITECoal™ syngas has a high CO + H_2 content of 81 vol. % compared to 40 vol. % for the raw PRB coal case (Table ES-2).

Table ES-2. Comparison of Various Gasifier Syngas Compositions
(EPRI, 2006, Nexant, 2004, and WRI)

	Shell (3)	**WRITECoal™ Shell (3)**	**GTI U-GAS®**	**WRITECoal™ U-GAS®**
Coal	**Subbituminous**	**Subbituminous**	**Subbituminous**	**Subbituminous**
	Syngas Composition (vol. %)			
CO_2 Recycle(1)	-	8.7%	-	10%
H_2	26.8	27.3	22.7	12.5
CO	59.9	58.7	16.9	69.9
CO_2	2.7	3.0	20.6	5.1
H_2O	4.1	8.4	34.3	1.4
CH_4		0.8	4.3	8.7
Other	6.7	1.8	1.2	2.4
CGE (2)	83.8	91.2	79.2	88.2

(1) Recycle is CO_2 recycle, based on wt.% of coal feed
(2) CGE – Cold Gas Efficiency
(3) Steam from quench in recycle gas to gasifier
Bechtel, Global Energy and Nexant, Gasification Plant Cost and Performance Optimization, Final report, NETL Contract No. DE-AC26-99FT40342, Sep. 2003

The WRITECoal™ syngas also has a low CO_2 content of 6.3 vol. % compared to 20.6 vol. % for the raw PRB Fluidized Bed gasification case, thereby highlighting the efficient use of the oxygen supplied to the gasifier. The WRITECoal™ syngas has a higher heating value of 356 Btu/scf compared to 173 Btu/scf for the raw PRB coal case. The WRITECoal™ syngas appears to be an excellent feedstock for chemicals manufacturing or use with fuel cells. The lower CO_2 reflects a lower heat input requirement for the gasifier and therefore results in a more efficient use of O_2. This is reflected in a cold gas efficiency gain of >5% to levels exceeding 88%.

Bench-scale Gasifier Testing Bench-scale tests were completed that confirmed the results of the HPTGA laboratory-scale testing. In order to verify the HPTGA and modeling results, bench-scale gasifier tests were conducted in GTI's U-GAS facilities in Des Plaines, Illinois using raw and WRITECoal™ PRB coals from the WRI pilot-scale facilities. The bench-scale unit operated well and the coals did not show signs of "stickiness" or agglomeration. The tests were all terminated voluntarily after performing for planned duration. Addition of carbon dioxide during gasification showed an immediate increase in product carbon monoxide indicating the possible direct reaction of carbon with carbon dioxide to form two moles of carbon monoxide. It is significant that it was possible to add carbon dioxide as an oxidant to the gasification process related to efficiency and cost.

IGCC System Modeling The WRITECoal™ IGCC technology modeling by WRI and EEI has shown a major increase in the net IGCC plant efficiency of about 4.3% compared to other power options with CO_2 capture (Table ES-3). Calculations based on the ASPEN Plus® runs with the WRITECoal™ gasification/IGCC process showed a two percentage point plant efficiency advantage over other IGCC plant designs with a partial drying process (NETL Case 3, in Grol, 2010). The data generated from the bench-scale and modeling effort assisted in defining the issues with the WRITECoal™ gasification/IGCC process for future scale-up efforts.

Economics/Costing An independent economic analysis of the WRITECoal™ gasification/IGCC technology by URS and Etaa Energy in conjunction with WRI was conducted. This assessment was based on an IGCC plant utilizing a 2x1 combined cycle configuration with advanced F class combustion turbines fired with syngas. The facility is located at a greenfield site in Wyoming with an elevation of 6,700 feet and a nominal plant output of 400 MW net. Capital costs, operating costs, and levelized cost of electricity (LCOE) in January 2011 dollars were estimated for the following two cases: All cost estimates have an accuracy of -25%/+30%[1].

Table ES-3. Power Plant Performance with WRITECoal™ Gasification/IGCC

Parameter	Base Case	NETL Case 3 (1)	WRITECoal™
	Raw PRB	Partially Dried PRB Coal	Completely Dried
Moisture Content Main Fuel, %	28.35	6.00	0.00
CO_2 Recycle to Gasifier	No	No	Yes
Mercury Removal	IGCC	IGCC	WRITECoal™
Gas Turbine Power, kWe	364,000	385,700	384,800
Steam Turbine Power, kWe	225,800	200,000	223,100
TOTAL POWER, kWe	589,800	585,700	607,900
Net Power, kWe	371,100	386,800	411,100
Efficiency Increase, %	**0.00**	**2.26**	**4.33**

(1) **Grol, E., "Assessment of Power Plants that meet Proposed Greenhouse Gas Emission,** "DOE/NETL-401/110509, 2009 revised 2010.

Three scenarios (Cases) were evaluated for capital costs, O&M costs and levelized cost of electricity (LCOE).

- Raw Coal (Case 1) – Raw PRB coal at 28.3% moisture is fed to gasifier following the process components and design specifications from Crol, (2010)
- NETL (Case 3) – Raw PRB dried to 6% moisture prior to gasification, following the process components and design specifications from Grol (2010).

[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.

- WRITECoal™ (Case 8) – Raw PRB dried to 0% moisture prior to gasification. The IGCC plant is basically the same as the NETL case except that the WRITECoal™ process replaces the WTA coal drying process. In addition, the WRITECoal™ process removes 75% of the mercury from the coal prior to gasification. This case also differs from Case 3 in the use of heat from the IGCC plant by the WRITECoal™ process to achieve complete PRB drying and CO_2 is recycled to the gasifier to increase syngas yield and efficiency.

The WRITECoal™ case is estimated to generate about 6% additional net MW over the NETL-Case 3. Based on the ASPEN Plus® diagrams and flow rates, URS E&C analyses show that the Total Capital Requirement for the WRITECoal™ case is \$5,500/kW compared to \$5,900/kW for the NETL case and \$6,400/kW for Raw Coal (Case 1).

Table ES-4 Summary-Level Comparison of Performance and Cost of IGCC Cases

		Raw Coal (Case 1)	NETL Case 3 (Grol, 2010)	WRITECoal™ Case 8
Carrying Costs **Capital Cost**	mills/kWh	**115.00**	**104.49**	**97.58**
Fixed O&M Costs				
Operating Labor	mills/kWh	1.80	1.73	1.62
Maintenance Labor & Materials	mills/kWh	34.15	30.55	27.51
Periodic Replacement Items	mills/kWh	0.40	0.33	0.28
SUBTOTAL, FIXED O&M	**mills/kWh**	**36.35**	**32.61**	**30.58**
Variable O&M Costs				
Fuel	mills/kWh	19.62	17.96	16.70
All Other Consumable Costs	mills/kWh	1.08	0.96	0.92
SUBTOTAL, VARIABLE O&M	**mills/kWh**	**20.70**	**18.93**	**17.62**
Total Levelized Cost	**cents/kWh**	**17.2**	**15.6**	**14.6**

The WRITECoal™ Case 8 capital costs are about 6.8% less than the NETL (Case 3) 6% moisture case, and 14.1% less than the raw coal (28% moisture) Case 1. The lower \$/kW capital cost of the WRITECoal™ case is mainly due to its plant output and efficiency advantage. Case 1 raw PRB coal fed gasification is impacted by a large gasifier and ASU, two of the most costly capital items and the ASU is a major source of parasitic power load. Oxygen feed to the gasifier(s) for Case 1 is 26% more than for the WRITECoal™ Case 8, and the air feed to the ASU system for Case 1 is 36% more than air for the WRITECoal™ Case 8. As indicated in Table ES-4, the estimated LCOE for the WRITECoal™ case 8 is 14.6 cents/kWh, while the for the NETL case 3 it is 15.6 cents/kWh and 17.2 cents/kWh for the raw coal gasification scenario (Case 1). This is a 15.1% decrease in LCOE for the WRITECoal™ Case 8 compared to Case 1 and 6.4% decrease compared to Case 3 (NETL Shell case with WTA drying to 6%).

Conclusions and Recommendations

In summary, WRITECoal™ gasification/IGCC HPTGA and bench-scale gasifier testing and modeling have shown improved gasifier cold gas efficiency and IGCC efficiency, unique syngas compositions and ability to use recovered water/steam for plant use. Modeling has shown a net efficiency gain of 4.3% for IGCC with WRITECoal™ integration and 90% carbon capture compared to IGCC cycles without WRITECoal™. The WRITECoal™ IGCC process has shown the potential to be deployed with nearly all of the commercially available gasification systems. The impact on efficiency and ultimately the COE varies with gasifier and IGCC subsystem integration. A comparison of the WRITECoal™ IGCC system with a commercial gasifier that partially dries the PRB coal to 6% the shows its positive cost impact of lowering the capital and operating costs and thus lowering the COE. Sensitivity studies show the WRITECoal™ gasification IGCC provides lower LCOE than either off-site independent processers delivering a 6% moisture coal to the gasifier owner for an incremental increase in coal price or on-site processes that partially dry to 6% moisture.

It is recommended that further scale-up of the WRITECoal™ IGCC process be undertaken that will ultimately lead to designing (Phase III) an adiabatic pilot-scale demonstration such as in the Flex Fuel Test Facility (FFTF) at a rate of up to 20 ton/day in order to gather information needed for a commercial design. Along those lines, WRI has been awarded a 1-2 MWth demonstration of the WRITECoal™ process with funding from the State of Wyoming Clean Coal Technology program through the UW School of Energy Resources and the Lignite Research Council through the North Dakota Industrial Commission with additional financial support from utilities and commercial entities.