FINAL REPORT
WRITECOAL™ GASIFICATION PROCESS FOR LOW-RANK COALS FOR IMPROVED INTEGRATED GASIFICATION COMBINED CYCLE WITH CARBON CAPTURE: PHASE II-PILOT-SCALE DEMONSTRATION

EXECUTIVE SUMMARY

Western Research Institute (WRI) with funding from the State of Wyoming Clean Coal Technology Program and the North Dakota Industrial Commission contracted with Gas Technology Institute (GTI), Energy and Environmental Research, University of North Dakota (EERC) URS Energy and Construction (URS E&C) and Etaa Energy Inc. (EEI) to conduct testing of WRI's coal upgrading/gasification technology (WRITECoal™ gasification) for subbituminous and lignite coals.

WRITECoal™/Gasification Technology: WRI's proprietary patent-pending WRITECoal™ upgrading/gasification process is a promising technology for conversion of upgraded low-ranked, high-moisture fuels to syngas via various proprietary process including operational modifications to existing gasification technologies. There seems to be a synergy between fuel-upgrading technologies such as WRI's WRITECoal™/gasification process and hydrogen and CO_2 removal technologies. The WRITECoal™ improves the efficiency of the plant and reduces the overall CO_2 footprint (lb of CO2 emitted/MWh). It can integrate with downstream systems such as efficient and cost-effective membranes for the separation of hydrogen and CO_2 as a potential novel competing technology for the coproduction of power, hydrogen, and/or fuels and chemicals.

Objectives: The project goal is to demonstrate at a 1-2MWth pilot-scale the Western Research Institute's (WRI's) WRITECoal™ gasification process for IGCC with CO_2 capture, fuel cell applications, and chemicals production, to identify engineering and scale-up issues and to estimate the cost of WRITECoal™ gasification process. Key project objectives of the program are:

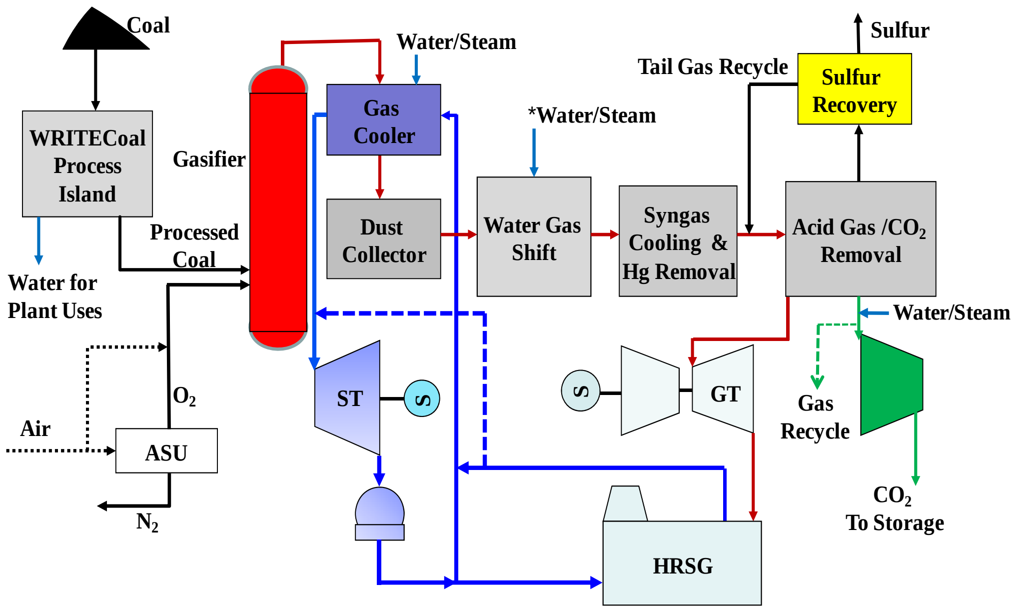

Figure ES-1 Schematic of a Typical WRITECoal™ Gasification/IGCC Integration

- Develop efficient energy conversion processes for high-moisture coals. This is achieved by completely separating the gasification and water-gas shift reactions.
- Demonstrate the co-benefits of the WRITECoal™ gasification process with downstream IGCC system modifications and gasifier operation changes.
- Provide technology pathway for co-generation of chemicals (along with power) using high-moisture fuels thereby making the technology application fuel neutral (i.e. applicable to all coal ranks).

WRI has teamed with Gas Technology Institute (GTI) Energy and Environmental Research Center (EERC), URS-Energy and Construction (URS E&C), and Etaa Energy, Inc. (EEI) with support from the State of Wyoming, the North Dakota Industrial Commission (NDIC), DOE's National Center for Hydrogen Technology (through EERC), and industry partners of Montana-Dakota Utilities and Basin Electric Power Cooperative. The team is addressing the potential of upgrading of Wyoming PRB coal and North Dakota lignite via WRI's WRITECoal™ Integrated Gasification Combined Cycle (IGCC) process in order to enhance efficiency, reduce freshwater consumption, and reduce hazardous air pollutants, such as CO_2, SOx, NOx and mercury at 1-2 MWth and sub-pilot-scale at WRI, GTI and EERC. The ultimate intent of this Phase II effort is to develop the conceptual engineering data and Class 5 costing information needed to design a larger demonstration in support of the commercial deployment of the technology at plants using western coal.

WRITECoal™ Fuel Processing: 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 across the drying and volatile species removal steps. Photographs of the 1-2 MWth WRITECoal pilot plant is presented in Figure ES-.1. The pilot-scale facility was operated at a fixed residence time and at a temperature determined from prior trials

Figure ES-2 Mobile WRITECoal™ 1-2 MW_{th}-Scale Pilot Plant at WRI's Advanced Technology Center.

In summary, he WRITECoal™ process upgrades the ~8,900 Btu/lb raw as received PRB coal to ~ 12,100 Btu/lb product on a dry basis. This represents an increase in the heat rate of about 36%. The

WRITECoal™ process also reduces the mercury by 75% and other metals to a lesser extent. As such, the WRITECoal™ produces a PRB coal with a low ash (~7%), low sulfur (~0.4% - 0.5%), low moisture (<1%), a relatively high O_2 content (15.03%), low nitrogen (`1.1%), and hydrogen contents (~4.5%). The oxygen content of the WRITECoal™ product is approximately 6 wt% higher (in absolute terms) than that for bituminous coals.

The WRITECoal™ process upgraded the raw North Dakota lignite from 7,245 Btu/lb to 10,800 Btu/lb, on a dry basis representing an increase in heat value of about 49%. As such, the WRITECoal™ process produces a lignite coal with a moderate ash (12.68%), medium sulfur (1.27%), low moisture (<1.5%), relatively high O_2 content (14.95%), low nitrogen (~1.1%), and moderate hydrogen (3.71%) contents. The oxygen content of the lignite-based WRITECoal™ product is approximately 6% higher (in absolute terms) than that for bituminous coals.

Table ES-1 Proximate and Ultimate Analyses of Raw and WRITECoal™ Treated Lignite and PRB Coal

Coal Analysis / Parameter, Dry Basis		Raw ND Lignite	WRITECoal Lignite	Raw PRB Coal	WRITECoal PRB Coal
Proximate Analysis, wt.%d	Moisture	38.0	0	28.30	0
	Ash	7.19	12.68	4.70	7.36
	Volatile Matter	26.68	39.29	32.85	41.25
	Fixed Carbon	28.13	48.03	34.14	51.39
Ultimate Analysis, wt.%d	Carbon	40.21	66.29	51.00	71.81
	Hydrogen	2.63	3.71	3.53	4.45
	Nitrogen	0.51	1.08	0.74	1.13
	Sulfur	0.74	1.27	0.36	0.58
	Oxygen	10.70	14.95	11.36	14.67
HHV	Btu/lb	6,700	10,873	8,636	12,133

* Suspect data. Note that this data is reported on an "as received" or process basis and also on a dry basis in order to see difference in the composition (losses) as a result of WRITECoal™ processing.

Mercury content of the raw coal ranged from 0.166 ppmd for the subbituminous coal to 0.060 ppmd for the North Dakota lignite. The WRITECoal™ process reduces the mercury content to 0.040 ppmd for the PRB coal and to 0.030 ppmd for the North Dakota lignite. Chlorine, another important parameter, was less that 50 ppmd in most western coals. The PRB subbituminous coal collected for this study contained ~ 11ppmd, while the North Dakota lignite contained ~23 ppmd chlorine.

Water Harvesting Testing - A slipstream of the dryer gas is diverted through a water-cooled condensing/heat exchanger (CHX). The coolant flows inside the tube, with the condensate collected at the bottom of the shell side of the heat exchanger. The condenser/heat exchanger is designed the same as for commercial installation, using the same materials of construction. Water quality testing focuses on the water produced from the WRI pilot unit and the need for cleanup, if any, for use in different areas of the gasification/IGCC system. The effluent gas stream with increased moisture fraction in the dryer gas is cleaned of the fine coal dust using a cyclone.

The composition of the recovered water was determined from the WRITECoal™ when processing both the North Dakota lignite and the PRB coals. The water derived from the harvesting tests showed very low concentration of total dissolved solids (36mg/L for both the lignite and PRB -derived waters), total anions (0.410 meq/L to 0.920 meq/L), cations (0.438 meq/L to 1.09 meq/L) for the lignite recovered and the PRB coal recovered waters, respectively.

U-GAS® WRITECoal Gasification/IGCC: WRITECoal™ gasification testing at GTI consisted of (1) High Pressure Thermogravimetric Analyzer (HPTGA) and (2) subpilot-scale U-GAS® gasifier. The U-GAS® gasifier performance was also modeled with proprietary software.

HPTGA Testing - Thermogravimetric Analysis tests were completed for raw and treated coal samples using gas mixtures of 50%N_2/50%Steam, 100% CO_2 and 30%H_2/12%CO/8%CO_2/50%Steam at 1700 and 1800 °F and 300 psig. Based on TGA test results and chemical analyses of the samples, it was determined that raw and treated lignite samples are more reactive than Kentucky # 9 (Base Case) coal. Carbon conversions for the samples were 100 % after the combined devolatilization and subsequent TGA tests. The TGA tests provide initial information on reactivity, and preferred operating temperatures that can be used in modeling to size the fluidized-bed gasification reactors.

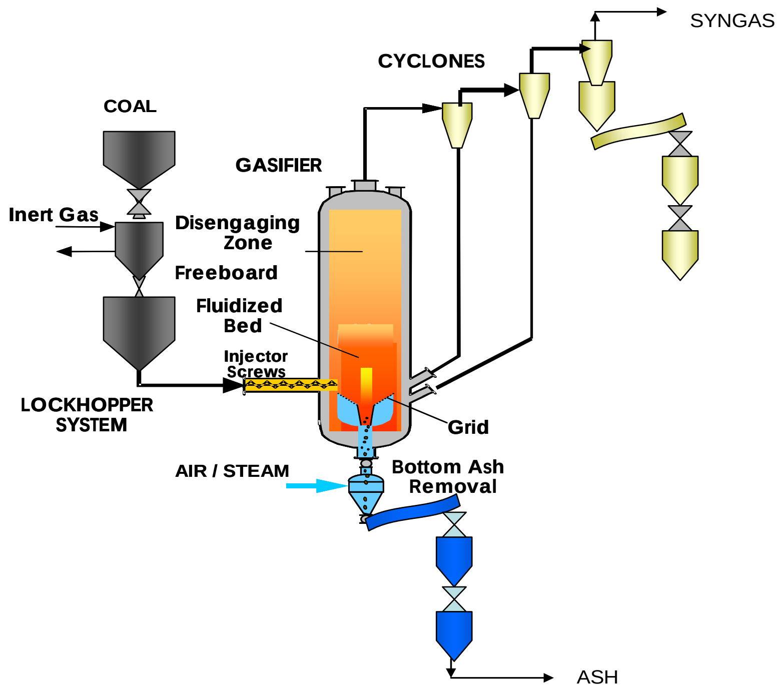

Figure ES-3 Schematic of GTI UGAS® Gasifier

U-GAS Gasifier Modeling - GTI, using their proprietary program, modeled the syngas composition and the potential for carbon deposition for each of the subpilot-scale test runs. The modeling showed a high concentration of CO and H_2 and low CO_2 in the syngas for the WRITECoal™-treated lignite compared to the raw lignite.

In all the subpilot-scale test cases, gasifier process conditions are close to the lines where carbon deposition may occur. Coke formation also depends on kinetics as well as equilibrium. Increased carbon dioxide addition, decreases the probability of coking. All the subpilot-scale test cases showed coking probability at exit gas (250 °F) conditions, but the kinetics are so slow that carbon deposition is not expected to be a problem there. GTI uses a rapid gas quench between gasifier and gas exit conditions at both pilot plant and commercial scale to minimize any tendency to form coke.

Subpilot-scale Testing - Based on TGA analysis and modeling results, conditions for the subpilot-scale U-GAS® gasifier tests were chosen. The subpilot-scale unit tests were conducted using raw and treated coals. The bench-scale unit operated well and the coals that were tested did not show signs of "stickiness" or agglomeration. The addition of carbon dioxide during gasification leads to an increase in product carbon monoxide and an increase in hydrogen. Increase of carbon monoxide can be explained by carbon reaction with carbon dioxide where two moles of carbon monoxide are formed. Alternatively, the CO_2 can react with the methane to produce CO and H_2. As a result of this reaction, water-gas shift equilibrium reaction will shift to produce more products (CO_2 and H_2) and hydrogen content will be increased. Overall, the WRITECoal™ upgrading/gasification technology was shown to produce a syngas significantly lower in CO_2 content and significantly higher in CO content without CO_2. The lower CO_2 reflects the lower gasifier energy required with dried fuels.

Table ES-2 Syngas Composition from the U-GAS® Pilot-scale Tests

Syngas Composition	WRITECoal™ Process Treated Subbituminous Coal, mol %
Hydrogen (H_2)	7.26
Carbon Monoxide (CO)	90.10
Carbon Dioxide (CO_2)	2.59
Methane (CH_4)	0.06

TRIG™ WRITECoal™ Gasification/IGCC: Raw and upgraded fuels were prepared by WRI using WRI's proprietary patent pending process at WRI and shipped to EERC and tested in EERC's TRDU (Figure ES-4). Each fuel was demonstrated to gasify well with minimal operational issues. The biggest system upset for the tests was the loss of the main air compressor for a couple of hours that was caused by cold ambient January air temperatures. Fuel feeding for the test run progressed with minimal issues, and no differences were noted in the feeding of the fuels. The treated fuels were shown to have a significant reduction in moisture, certain volatile metals and lower levels of silica were also observed in the treated coals. No ash agglomeration issues were observed in any of the tests.

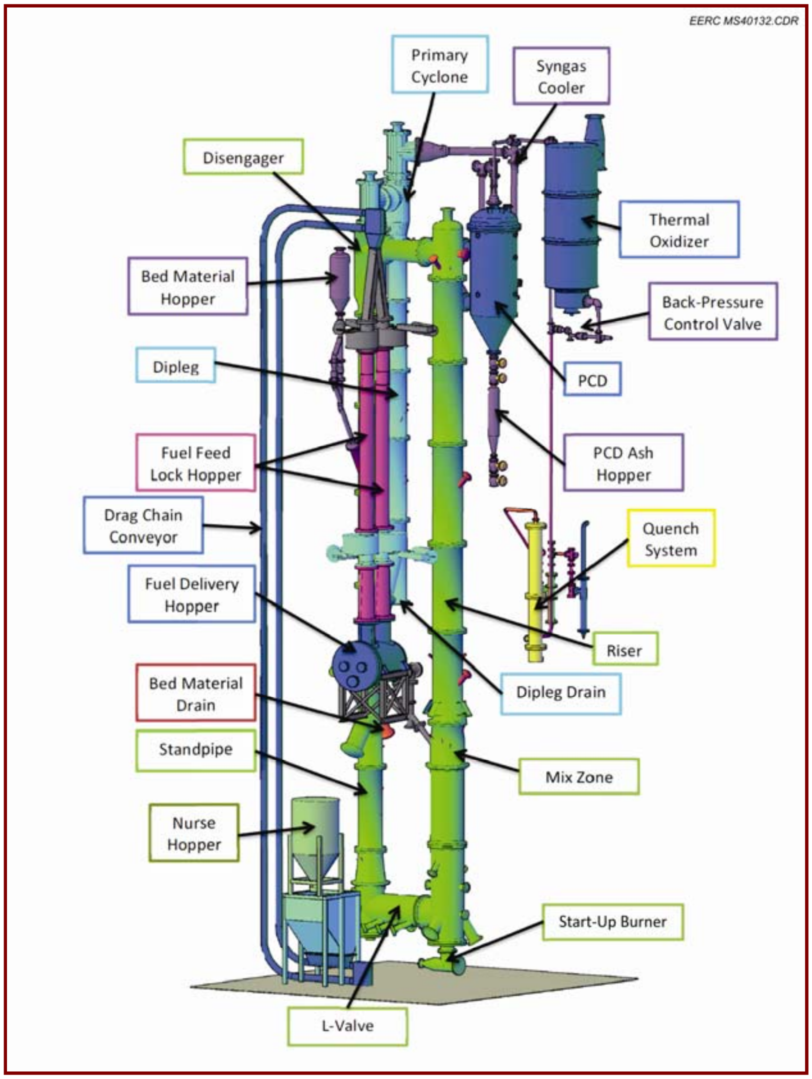

Figure ES-4 Schematic of the TRDU Gasifier at EERC.

The most dramatic transition observed throughout the testing was the change in CO and CO_2 concentrations as the gasifier was switched from raw to upgraded fuels (ES-5). For both the PRB and lignite fuels, CO levels significantly increased, and CO_2 levels significantly decreased when the dried fuel was brought online. This change resulted in a syngas with increased heating value. This transition was also observed when switching from the upgraded PRB to the raw lignite. Proprietary gas injection at selected location(s) in the gasifier resulted in higher CO fractions and syngas quality.

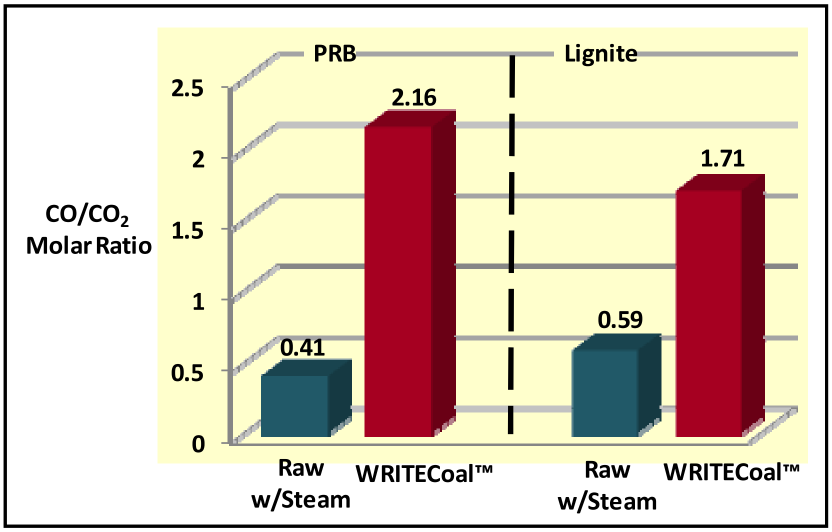

Figure ES-5. Comparison of the CO/H_2 and CO/CO_2 Ratio for Raw and WRITECoal™ Fuels

Syngas samples produced from the gasifier were analyzed for organic content as related to tar generation. Lower levels of organics were observed on the WRITECoal™ upgraded fuel as compared to the raw fuel runs. Significantly higher concentration of organic material was produced during the steam–oxygen gasification tests (Figure ES-6).

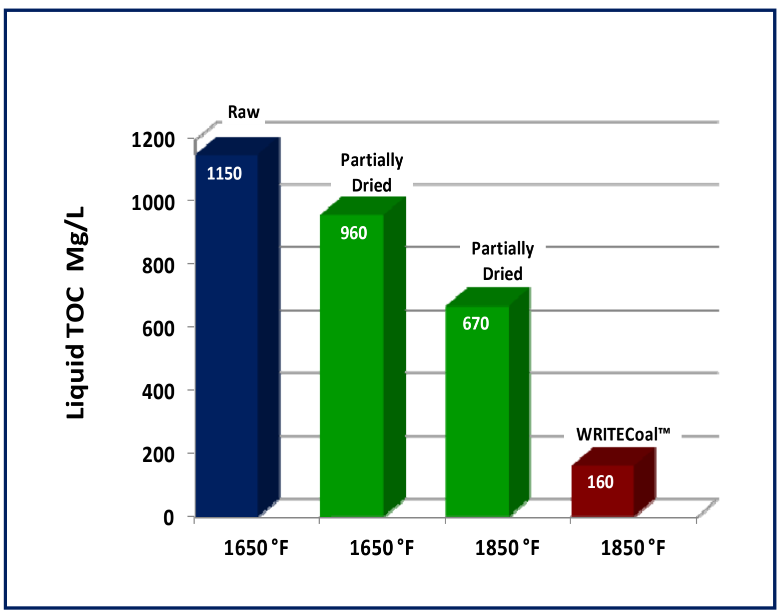

Figure ES-6 Impact of Temperature and WRITECoal™ Drying on Tar Formation

Warm-Gas Cleanup   The warm-gas cleanup equipment, sorbents, and catalysts used were shown to be capable of removing sulfur down to less than 2 ppm and the shift catalyst was able to reduce CO levels to below 1%. Water and tars were condensed out of the syngas prior to compression for the membrane exposure. Warm-gas cleanup techniques have been shown to be needed to provide a low H_2S and other impurities in the syngas fed to the hydrogen membranes. While the majority of the impurities were removed in a gas cleanup process, concentrations of less than 1 ppmv may be required for long-term viability. Success of hydrogen separation membranes will require long-term exposure to coal-derived syngas to understand the impact of the impurities.

Hydrogen Separation   EERC with funding from the DOE National Center for Hydrogen Technology® (NCHT®) Program has exposed two membranes to WRITECoal™ gasification-derived syngas produced in the pilot-scale TRDU. A slipstream of the syngas produced from the WRITECoal™ upgrading/gasification process was used to demonstrate warm-gas cleanup and hydrogen membrane separation technology. Two membranes were exposed to coal-derived syngas, and the impact of coal-derived impurities was evaluated.

Both the hydrogen separation membranes were shown to be able to produce greater than 2 lb/day of hydrogen (DOE milestone standard). Membrane 1 appeared to experience some performance degradation which may have been caused by coking. The coking could be attributed to a system upset and lack of steam available for the water–gas shift reaction. The membrane was exposed to oxygen at high temperature at the supplier’s laboratory to burn out the contaminant, and the membrane performance returned to expected levels. Membrane 2 developed a significant leak during the testing. Both membranes were shown to be capable of producing hydrogen from coal-derived syngas during the entire test period.

Modeling: IGCC modeling was conducted by WRI and Etaa Energy using the TRIG™ and U-GAS® gasifiers, with and without the WRITECoal™ gasification modifications. A standard line of syngas cleanup and CO_2 processing and compression followed the protocol from the U.S. DOE effort. Three scenarios were used, including (1) Raw coal – no drying, (2)partial coal drying as commercially deployed and, (3) drying to <1% for WRITECoal™ plus CO_2 recycle for U-GAS® and TRIG™ gasifier/IGCC scenarios. The WRITECoal™ modifications resulted in a 2-5% increase in efficiency.

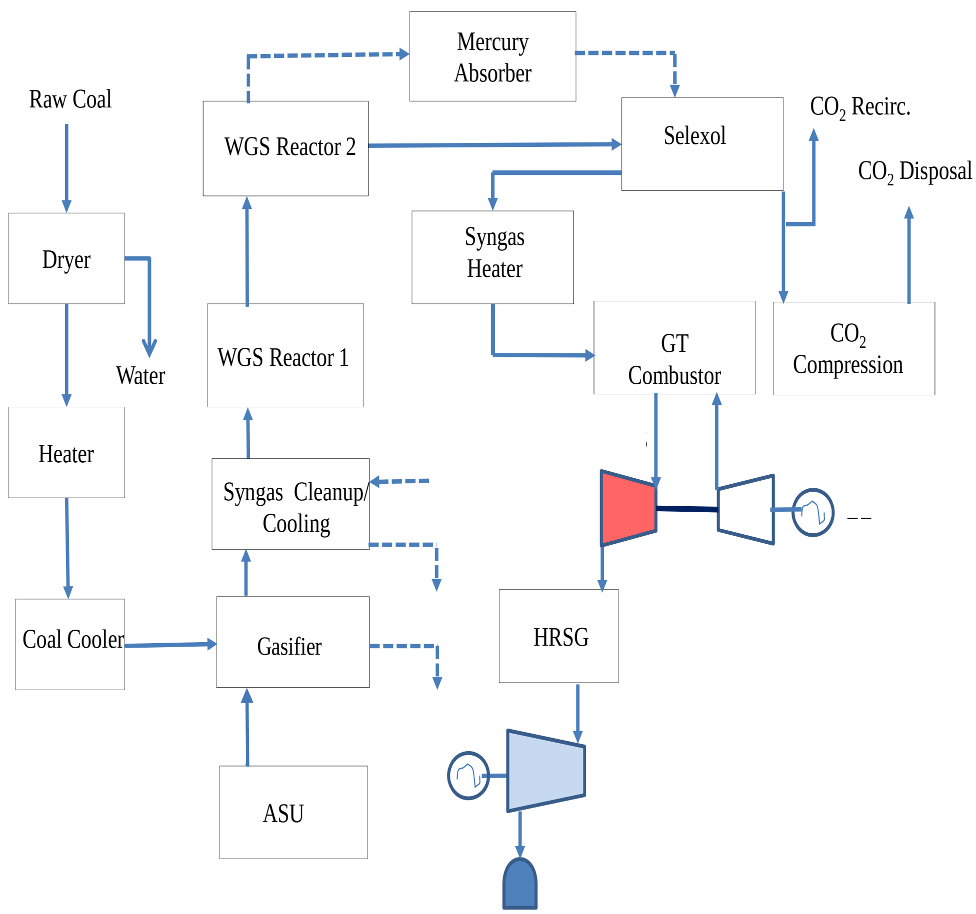

Figure ES-7 Schematic of the IGCC Scenarios Evaluated.

Modeling of the WRITECoal™ TRIG™ IGCC technology by WRI and EEI has shown a major increase in the net IGCC plant efficiency increase of about 6.2% for lignite fired IGCC with WRITECoal™

gasification and 79% CO_2 capture, while PRB –fired TRIG™ IGCC with WRITECoal™ increased efficiency by 4.8%. Calculations based on the ASPEN Plus® runs with the WRITECoal™ gasification/IGCC process showed a 1.2 percentage point plant efficiency advantage for lignite TRIG™ IGCC plant designs with a partial drying process (18% moisture) compared to PRB coal-fired TRIG™ IGCC.

Table ES-3. IGCC Performance with WRITECoal™ U-GAS® and TRIG™Gasification/IGCC

TRIG™	**Raw Lignite**	**Partial Dry Lignite**	**W-Coal Lignite**	**Raw PRB**	**Partial Dry PRB**	**W-Coal PRB**
Moisture Content,%	38	18	<1	28	18	<1
CO_2 Recycle	No	No	Yes/20%	No	No	Yes/20%
Gross Power, kWe	686.3	638.3	625.9	645.8	610.1	639.4
Aux Power, kWe	209.9	192.1	150.0	177.5	167.5	137.0
Net Power, kWe	476.4	446.2	475.9	468.3	442.6	502.4
Efficiency Increase	**Base**	**1.2**	**6.2**	**Base**	**0.0**	**4.8**
U-GAS®	**Raw Lignite**	**Partial Dry Lignite**	**W-Coal**	**Raw PRB**	**Partial Dry PRB**	**W-Coal**
Moisture Content, %	38	20	<1	28	20	<1
CO_2 Recycle	Yes/10%	Yes/10%	Yes/20%	Yes/10%	Yes/10%	Yes/20%
Gross Power, kWe	606.3	590.8	597.3	605.6	590.4	610.8
Net Power, kWe	180.1	179.7	161.3	175.6	165.3	158.3
Net Power, kWe	426.2	417.1	436.0	430.0	425.1	452.5
Efficiency Increase,%	**Base**	**1.4**	**4.4**	**Base**	**0.1**	**3.2**

U-GAS uses 10% CO2 for feed assistance; W-Coal=WRITECoal

WRITECoal™ U-GAS IGCC technology has shown a major increase in the net IGCC plant efficiency increase of about 4.4% for lignite fired IGCC with WRITECoal™ gasification and 79% CO_2 capture, while PRB coal–fired U-GAS® IGCC with WRITECoal™ increased efficiency by 3.2%. Calculations based on the ASPEN Plus® runs with the WRITECoal™ gasification/IGCC process showed that the efficiency advantage for lignite and PRB coal-fired U-GAS® IGCC plant designs with a partial drying process (18 or 20% moisture) were similar.

In each case the WRITECoal™ deployment improves the efficiency of the IGCC cycle in the range of 3.2 to 6.2%. The U-GAS™® IGCC also showed a lower efficiency than the TRIG™ gasifier/IGCC. The WRITECoal™-TRIG™ IGCC was 4.8% higher than the U-GAS® IGCC. This is partly due to the lower gasifier pressure for the U-GAS® gasifier and as such the TRIG™ IGCC provides a higher efficiency than the U-GAS®.

Table ES-4. Summary of the IGCC Efficiencies When Deploying WRITECoal™ Gasification/IGCC with the TRIG and U-GAS Gasifiers and with Lignite and PRB Coals.

Process - Fuel	Plant Efficiency with Raw Coal	Plant Efficiency with WRITECoal™ Drying	Improvement Resulting from WRITECoal™ Drying,
TRIG™ - Lignite	27.2%	33.4%	6.2
TRIG™ - PRB	29.8%	34.2%	4.8
U-GAS® - Lignite	24.2%	28.6%	4.4
U-GAS® - PRB	26.3%	29.5%	3.2

The efficiency gain occurs for both lignite and PRB fuel. The efficiency benefit of WRITECoal™ drying is the largest in lignite gasification cases since lignite has the highest as-received moisture content. The efficiency gain is larger in TRIG™ cases than in U-GAS® cases. U-GAS® gasification technology has a 10-14% higher heat rate (lower efficiency) than TRIG™ technology, which reduces the relative improvement from the WRITECoal™ treatment process.

Costs and Economics: The economic analysis examined the capital costs, O&M costs and levelized cost of electricity (LCOE) for a series of options for PRB coal- and lignite-fired with and without the WRITECoal™ gasification upgrading and gasification modifications integrated with the TRIG® and U-GAS™ gasifier/IGCC with CO_2 capture of 75-79% for the TRIG deployment and 75% for the UGAS™ deployment due to the relatively high CH_4 content of low temperature gasifiers. Pilot-scale gasifier testing (this study) showed a lowering of the methane (CH_4) content in the syngas with increased CO_2 recycle. For comparison, the economic analysis of an oxy-combustion supercritical IGCC and an air-fired supercritical PC with amine CO_2 separation are provided.

Adding the WRITECoal™ process to an IGCC plant reduces the size of equipment such as the gasifiers and air separation unit. It therefore decreases the capital costs, and at the same time increases efficiency. The combined effects decrease the levelized costs. The WRITECoal™ treatment process results in efficiency gains that are higher for IGCC plants than for air-fired PC plants or oxy-fired PC plants. This results in a lower levelized cost for an IGCC with WRITECoal™ (Table ES-5).

Table ES-5. Total Capital Requirement (TCR) and Levelized Cost of Electricity (LCOE) with WRITECoal™ TRIG® Gasification/IGCC (2012$)

TRIG™	Case 1 Raw Lignite	Case 2 18% H_2O Lignite	Case 3 W-Coal Lignite	Case 4 Raw PRB	Case 5 18% H_20 PRB	Case 6 W-Coal PRB
TCR, 1000S $/kW	2,159,000 4,500	1,964,400 4,000	1,829,000 3,800	1,903,000 4,100	1,838,000 4,200	1,782,000 3,500
Carrying Capital Costs, mills/kWh	45.91	44.57	38.94	41.17	42.10	35.92
Fixed O&M Costs, mills/kWh						
Operating Labor	1.40	1.50	1.40	1.43	1.51	1.33
Maintenance Labor & Mtls	21.61	21.06	18.00	19.14	19.74	16.38
Periodic Replace items	15.07	14.47	12.48	12.93	13.53	11.94
Subtotal Fixed O&M	38.15	37.08	31.89	33.49	34.76	29.65
Variable O&M Costs, mills/kWh						
Fuel	17.87	17.13	14.54	16.32	16.33	14.22
All Other Consumables	1.87	1.77	1.51	1.24	1.21	1.08
Subtotal Variable O&M	19.74	18.89	16.04	17.56	17.55	15.29
Total LCOE, cents/kWh	**10.4**	**10.1**	**8.7**	**9.2**	**9.4**	**8.1**

W-Coal = WRITECoal™

TRIG™ IGCC Results: On a dollar per kW basis, the net effect is 17% reduction in Total Capital Requirement (TCR) from 4,500 $/kW to 3,800 $/kW. For the Wyoming PRB coal, the benefits are slightly smaller, since as-received moisture content of PRB is lower than that of lignite. The TCR for WRITECoal™ IGCC with PRB coal is 15% less than as received Case .

U-GAS™ IGCC Results: The benefit of the WRITECoal™ process on IGCC shows the benefits are somewhat less because the UGAS® process is less efficient than the TRIG™ process. The TCR of WRITECoal™/U-GAS® IGCC with lignite is 11% less than the TCR of the as received Case without the WRITECoal™ process. The TCR of PRB Case with WRITECoal™ is 6% less than the as-received Case without WRITECoal™. Partial drying with the WRITECoal™ process (to 20% or 18% H_2O) does not result in cost benefits in proportion with the decrease in moisture content due to the fact that the change in heat rate is minimal and about half of the savings in the costs of coal handling, gasification, and air separation are offset by the cost of the WRITECoal™ process.

Table ES-6. Total Capital Requirement (TCR) and Levelized Cost of Electricity (LCOE) with WRITECoal™ U-GAS® Gasification/IGCC (2012$)

U-GAS®	Case 7 Raw Lignite	Case 8 20% H_2O Lignite	Case 9 W-Coal Lignite	Case 10 Raw PRB	Case 11 20% H_2O PRB	Case 12 W-Coal PRB
TCR, 1000$ $/kW	2,341,000 4,900	2,266,000 4,900	2,132,000 4,400	2,125,000 4,400	2,094,000 4,400	2,063,000 4,100
Carrying Capital Costs, mills/kWh	55.65	56.06	49.54	50.07	49.91	46.17
Fixed O&M Costs						
Operating Labor	1.57	1.60	1.53	1.55	1.57	1.48
Maintenance Labor & Mtls	31.34	30.25	26.54	26.97	26.78	24.15
Periodic Replace Items	22.34	25.00	22.53	19.67	18.66	23.95
Subtotal Fixed O&M	56.25	56.85	50.61	48.19	47.01	49.57
Variable O&M Costs						
Fuel	19.78	19.01	17.02	18.51	18.40	16.48
All Other Consumables	2.02	1.94	1.76	1.41	1.36	1.25
Subtotal Variable O&M	21.80	20.95	18.78	19.92	19.76	17.73
Total LCOE	**13.3**	**13.3**	**11.9**	**11.48**	**11.7**	**11.4**

W-Coal = WRITECoal™

The impact of elevation on the levelized costs indicates, as expected, a lowering of the LCOE at lower elevations and an increase in LCOE at higher elevations.

Recommendations and Conclusions: The present program was quite promising in its findings. The costs of IGCC, using both the U-GAS® and the TRIG™ gasifiers indicate that they both perform quite well and produce a high CO/CO_2 syngas. In fact, by using the WRITECoal™ fuels and water-gas-shift (WGS), one is able to design the target CO/H_2 ratio needed for synfuels.