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COMMERCIALIZATION OF AN ATMOSPHERIC IRON-BASED CDCL PROCESS FOR POWER PRODUCTION. PHASE I: TECHNOECONOMIC ANALYSIS

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Luis Velazquez-Vargas

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The Babcock & Wilcox Power Generation Group, Inc

180 South Van Buren Avenue

Barberton, OH 44203-0622

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ABSTRACT

Coal Direct Chemical Looping (CDCL) is an advanced oxy-combustion technology that has potential to enable substantial reductions in the cost and energy penalty associated with carbon dioxide (CO_2) capture from coal-fired power plants. Through collaborative efforts, the Babcock & Wilcox Power Generation Group (B&W) and The Ohio State University (OSU) developed a conceptual design for a 550 MWe (net) supercritical CDCL power plant with greater than 90% CO_2 capture and compression. Process simulations were completed to enable an initial assessment of its technical performance. A cost estimate was developed following DOE's guidelines as outlined in NETL's report "*Quality Guidelines for Energy System Studies: Cost Estimation Methodology for NETL Assessments of Power Plant Performance", (2011/1455).* The cost of electricity for the CDCL plant without CO_2 Transportation and Storage cost resulted in $ $102.67 per MWh, which corresponds to a 26.8 % increase in cost of electricity (COE) when compared to an air-fired pulverized-coal supercritical power plant. The cost of electricity is strongly depending on the total plant cost and cost of the oxygen carrier particles. The CDCL process could capture further potential savings by increasing the performance of the particles and reducing the plant size. During the techno-economic analysis, the team identified technology and engineering gaps that need to be closed to bring the technology to commercialization. The technology gaps were focused in five critical areas: (i) moving bed reducer reactor, (ii) fluidized bed combustor, (iii) particle riser, (iv) oxygen-carrier particle properties, and (v) process operation. The key technology gaps are related to particle performance, particle manufacturing cost, and the operation of the reducer reactor. These technology gaps are to be addressed during Phase II of project. The project team is proposing additional lab testing to be completed on the particle and a 3MWth pilot facility be built to evaluate the reducer reactor performance among other aspects of the technology.

A Phase II proposal was prepared and submitted to DOE. The project team proposed a three year program in Phase II. Year 1 includes lab testing and particle development work aimed at improving the chemical and mechanical properties of the oxygen carrier particle. In parallel, B&W will design the $3MW_t$ pilot plant. Any improvements to the particle performance discovered in year 1 that would impact the design of the pilot will be incorporated into the final design. Year 2 will focus on procurement of materials and equipment, and construction of the pilot plant. Year 3 will include, commissioning, start-up, and testing in the pilot.

Phase I work was successfully completed and a design and operating philosophy for a 550 MWe commercial scale coal-direct chemical looping power plant was developed. Based on the results of the techno-economic evaluation, B&W projects that the CDCL process can achieve 96.5% CO_2 capture with a 26.8% increase in the cost of electricity exceeding DOE's goal of 90% capture at a less than 35% increase in COE.

Key words: Advanced Oxy Combustion, Coal Direct Chemical Looping, CDCL, CO_2 Capture, Power Generation.

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ACRONYMS AND ABBREVIATIONS

AACE	American Association of Cost Engineering
AFUDC	Accumulated --Funds Used During Construction
AR	As Received
ASU	Air Separation Unit
BEC	Bare Erected Cost
B&W	The Babcock & Wilcox Power Generation Group, Inc.
CDCL	Coal-Direct Chemical Looping
CP	Capacity Factor
CPU	Compression and Purification Unit
DC	Direct Current
DOE	Department of Energy
EPA	United States Environmental Protection Agency
EPC	Engineering, Procurment and Construction
EPRI-TAG	Electrical Power Research Institute – Technical Assessment Guide
FD	Forced-Draft
FEED	Front End Engineering Design
FGD	Flue Gas Desulfurization
FOA	Funding Opportunity Announcement
HAP	Hazardous Air Pollutants
HHV	Higher Heating Value
IBC	International Building Code
ID	Induced-Draft
IGCC	Integrated Gasification Combined Cycle
IOU	Investor-Owned Utility
IRROE	Internal Rate of Return of Electricity
ISO	International Organization for Standardization
LCOE	Levelized Cost of Electricity
LHV	Lower Heating Value
MeO	Metal Oxide
NEC	National Electric Code
NEMA MG	National Electrical Manufacturers Association - Motors and Generators
NETL	National Energy Technology Laboratory
NFPA	National Fire Protection Association
NGCC	Natural Gas Combined Cycle
O&M	Operating and Maintenance
OSU	The Ohio State University
PRB	Powder River Basin
RCRA	Resource Conservation and Recovery Act
SCR	Selective Catalytic Reduction
TASC	Total As Spent Capital Cost
TPC	Total Plant Cost
TOC	Total Overnight Cost
TS&M	Transport, Storage and Monitoring
UPS	Uninterrupted Power Supply

WGS Water Gas Shift

EXECUTIVE SUMMARY

I. GOAL AND OBJECTIVES

The goal of the project was to investigate the commercial viability of the Coal Direct Chemical Looping (CDCL) Technology. The project consists of two phases. Phase I is a techno-economic evaluation of a conceptual 550 MWe (net) commercial plant. The specific objectives of Phase I were as follows: 1) conduct minimal laboratory work to support the design in commercial scale, 2) develop a 550 MWe supercritical commercial plant design, 3) perform a techno-economic evaluation of the commercial design, 4) identify technology gaps and an approach to address such gaps, and 5) develop a pilot scale facility design and budget estimate to address the technology gaps.

The work from Phase I was submitted to DOE for a Phase II continuation. After a downselect technology evaluation, DOE will select the projects that are allowed to continue into Phase II. Phase II consists of laboratory and pilot tests designed to solve the technology gaps identified during Phase I of the project. At the end of Phase I, specific performance targets were set for CDCL in order to be commercially viable. In the first year of Phase II, the CDCL technology would be evaluated according to these targets. If CDCL successfully achieve these targets, the project will move into a pilot plant demonstration. The objective of the pilot facility is to confirm and provide the necessary data to scale up the technology to a demonstration- or commercial-scale process.

II. APPARATUS AND TESTING METHODS

A conceptual design for a 550 MW_e supercritical power plant was designed and costed at a level to perform an economic analysis with a tolerance of -15%/+30%. The conceptual plant was based on an actual PC supercritical plant using the coal direct chemical looping technology in place of the PC boiler and related auxiliary equipment. Where practical, conventional equipment was used to minimize the first-of-a-kind technology involved.

Common design inputs for site characteristics and ambient conditions follow NETL's "*Quality Guidelines for Energy System Studies: Process Modeling Design Parameters*" (DOE/NETL-321/042613). The plant site is assumed to be in a Midwest United States location consisting of approximately 300 usable acres. The feedstock is assumed Illinois No. 6 coal.

The chemical looping components were designed and sized based on OSU developed technology and B&W's experience in designing solids handling equipment and fluidized bed reactors for power plants. Limited laboratory testing was performed to obtain critical information on design parameters to support the commercial design. These experiments included TGA tests on particle oxidation, particle reduction kinetics, and char gasification. OSU's 25 kW_t-scale CDCL Process data was used for solids circulation rates, attrition rates, coal conversion, particle conversion, zone seals, solids mixing and distribution, system control and conditioning strategy, fines removal methods, system hydrodynamics, and additional data as necessary.

Heat and material balances were developed using in-house excel spreadsheet and ASPEN Plus® simulations. Modeling assumptions were taken from NETL's *Quality Guidelines for Energy System Studies: Process Modeling Design Parameters* (DOE/NETL-341/042613). Results from the heat and mass balances were used to determine parasitic loads and overall system performance and efficiency. Parasitic losses from ASPEN were cross checked with other values obtained from vendors, references, or from B&W's database. ASPEN results were also used to determine air emissions, size process equipment, and generate an equipment list.

The economic analysis performed for the 550-MWe CDCL commercial plant is in accordance with NETL's *Quality Guidelines for Energy Systems Studies: Cost Estimation Methodology for NETL Assessments of Power Plant Performance (DOE/NETL-2011/1455)*. Capital cost estimates were developed based on a combination of adjusted vendor-furnished cost data and B&W's cost estimating database for first-of-a-kind equipment. The capital cost includes all equipment, materials, labor, indirect construction costs, engineering, contingencies and overnight costs. Cost values for production, operation, and maintenance are determined on a first-year basis to form a part of the economic analysis. The CDCL plant follows a high-risk, investor-owned-utility finance structure with a 5 year capital expenditure period. The system variable costs were estimated in accordance with *Updated COSTS (June 2011 Basis) for Selected Bituminous Baseline Cases (DOE/NETL-341/082312).*

III. TASK 1. PROJECT MANAGEMENT AND PLANNING

During this task, all the necessary activities were performed to ensure the coordination and planning of the project with DOE/NETL and other project participants. Work under this task also ensured that all technical information was supplied to DOE through the delivery of reports and a comprehensive final report. Reports and other deliverables were provided in accordance with Attachments A-F of FOA: DE-FOA-0000636, Section D, and the Federal Assistance Reporting Checklist requirements. The following reports were prepared and submitted:

1. Technology Engineering Design Basis Report (10/31/12)
2. Updated Project Management Plan (10/30/12)
3. Quarterly Progress and Financial Reports (1/30/13, 4/30/13), which include
    a. Documentation of experimental results and feasibility study,
    b. Technology benefits and shortcomings,
    c. Recommendations for future R&D to address shortcomings, and
    d. Scale-up strategy to move the technology toward commercialization
4. Technology Engineering Design Interim Report (3/31/13)
5. Phase I Topical Report – Draft Final Report (6/28/13)
6. Final Phase I Technology Engineering Design and Economic Analysis Report (6/28/13)
7. Final Phase I Technology Gap Analysis Report (6/28/13)
8. Final Phase II Application (6/28/13)

A project kick-off meeting was held in accordance with the Project Management Plan at the NETL in Pittsburgh, PA. A project advisory committee was formed and two meetings were held with B&W representatives, utility users and NETL/DOE (DOE attended the first meeting). The Project Advisory Committee provided guidance to ensure that project activities were aligned with commercial needs.

Closing documents and activities will be performed within this task which include preparing a Final Report, Final Invention and Patent Report, Final Property Report, and Final Report.

IV. TASK 2. COMMERCIAL PLANT DESIGN AND ECONOMIC ANALYSIS

The objective of this task is to provide an overall evaluation of the CDCL technology for power generation and its economic feasibility. A 550 MWe supercritical CDCL commercial plant was designed and evaluated against existing technologies. The results of this evaluation helped determine the commercial viability of such a plant and identify technology or commercial gaps.

Subtask 2.1 – Develop Design Basis. The design basis for the commercial CDCL plant was developed by following Section 3.2.1 “Design Basis” of Attachment A of this solicitation. In this task, the team collected information and data regarding the oxygen carrier particle performance and intrinsic process performance. Specifically, OSU and B&W gathered performance data from the work done under DOE project (DE-NT0005289) which includes reaction kinetics (oxidation and reduction), particle reactivity, oxygen carrying capacity, deactivation rates and thermal capacity. Additionally, the project team collected intrinsic process information from the 25 kW_t-scale CDCL unit for solids circulation rates, attrition rates, coal conversion, particle conversion, gas sealing, solids mixing and distribution, system control and conditioning strategy, fine removal methods, system hydrodynamics, and additional data when necessary.

B&W has used its extensive experience with commercial fluidized boilers to generate the extrinsic process information, which is dependent on scale, for the design of the equipment and processes for the CDCL system. Other process performance data was extrapolated from systems that are similar in scale and operating conditions and applied to the CDCL commercial plant design. Some necessary information to develop the design basis was not available and is identified as a technology gap. The project team assumed values which will have to be confirmed through experimentation and/or pilot scale testing in Phase II. The results of Subtask 2.1 were reported in the Technology Engineering Design Basis Report.

Subtask 2.2 – Develop Conceptual Plant Design. The proposed CDCL process consists of (i) oxygen-carrier particles circulation loop with coal feed system, (ii) steam generation system, (iii) power generation system, (iv) environmental equipment, and (v) auxiliary equipment. Figure 1 shows a simplified block diagram of the CDCL process and systems.

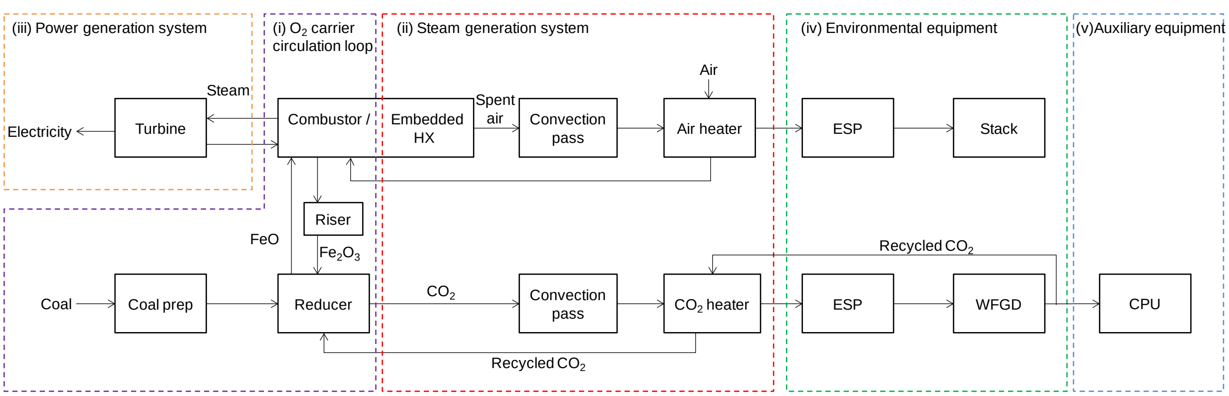

Figure 1 Simplified Block Flow Diagram of the CDCL Process

The Oxygen Carrier Circulation Loop was designed based on OSU’s advanced moving bed technology. Most of the engineering effort in this task was focused on the design of the novel technology components and integration of the novel components with the commercial components of the plant. Heat and material balances for the overall reference plant were developed using in-house excel spreadsheets and ASPEN® simulations.

Based on the parameters defined in the design basis, sizing of major equipment components and general arrangement drawings were prepared. In addition, individual component drawings, process flow diagrams, process and Instrumentation diagrams (P&IDs), general arrangement drawings, overall plant lay out and 3-D models of the commercial plant were generated. These drawings provided a complete view of the commercial plant. This information was used to estimate the plant cost to proposal level for B&W to perform an economic evaluation of the technology. These drawings were submitted to DOE as part of this application as separate reports. The preliminary plant control philosophies were determined. The plant electric design includes design of power distribution to equipment and the controls and instrumentation specifications. The result of this subtask was reported in Technology Engineering Design Interim Report.

Subtask 2.3 –Techno-Economic Analysis. Based on the commercial plant design, the team developed a capital cost estimate, first-year cost of electricity estimate and levelized economics of the 550 MW supercritical CDCL power plant with CO_2 removal.

The Phase I cost estimate is an AACE Class 4 estimate as defined by the NETL report, "Quality Guidelines for Energy System Studies: Cost Estimation Methodology for NETL Assessments of Power Plant Performance." The estimate is consistent with the DOE requirements and standardized DOE cost basis.

When appropriated, the team used pre-existing DOE's balance of plant cost guidelines for estimating purposes. For example, the team used the Coal & Sorbent Handling, Coal & Sorbent Prep and Feed, and others costs for common components to allow for a more accurate comparison between the DOE baseline case and the CDCL case.

Table 1 shows a summary of the economic analysis performed using the DOE guideline costing assumptions. The DOE program objectives are a less than 35% increase in cost of electricity while removing 90% of the CO_2 from coal combustion. The CDCL process economics show a 26.8% increase in cost of electricity while removing 96.5 % of the CO_2 emissions. Based on the preliminary economics, the CDCL process meets both of the DOE CO_2 removal objectives. In addition, as part of this program, B&W will evaluate fabrication and construction techniques to reduce the erection cost of the equipment.

Table 1 Summary of Process Economic Study

	Base Case 11	CDCL Case Study
Total Plant Cost, $ in millions	1,089	1,380
Fixed O&M Cost, Annual Cost in millions	38.8	48.8
Variable O&M Cost, Annual Cost in millions	31.7	27.7
Fuel, Annual Cost in millions	104.59	114.81
First Year Cost of Electricity, COE, without TS&M, $/MWh	**80.95**	**102.67**

TASK 3. TECHNOLOGY GAP ANALYSIS

In this task, the team identified mechanical and technology deficiencies (gaps) that directly impact the commercial CDCL process design. These technology gaps were identified and, when possible, quantified to determine the impact they will have on the successful scale up of the CDCL technology. It was determined that some technology gaps were best addressed though additional lab scale testing and others though large pilot scale plant design testing in Phase II. The technology gap report includes mechanical and process uncertainties which could affect the cost of the CDCL unit. The technology gaps are: (i) moving bed reducer reactor, (ii) fluidized bed combustor, (iii) particle riser, (iv) oxygen-carrier particles properties, and (v) process operation.

1. Moving bed reducer reactor:

In the reducer reactor, coal reacts with Fe_2O_3 to form a CO_2-rich gaseous stream while reducing the Fe_2O_3 the oxygen-carrier particles to a mixture of FeO and Fe. Figure 2 shows a conceptual drawing of the reducer reactor. In the reducer, coal is injected near a mid-point elevation in a constricted zone where particles are mildly fluidized. This allows mixing of the coal and iron particles while the coal simultaneously volatilizes. The coal-char and oxygen particle mixture flows down from the constricted zone to the lower zone of the reducer in a moving packed-bed flow reactor. The coal char in the lower half of the fuel reactor is gasified with CO_2 producing two molecules of CO per each molecule of carbon.

$$C + CO_2 \leftrightarrow 2CO$$

The CO then reacts with the oxygen-carrier particles reducing the Fe_2O_3 to a mixture of FeO and Fe and producing more CO_2. This chain reaction type mechanism ensures that all the char is consumed while the oxygen-carrier particles are reduced.

The coal volatiles and unconverted gasification products such as CO and H_2 travel to the top-zone of the reducer reactor. The top zone acts as a polishing bed where the oxidized oxygen-carrier particles ensure that all the volatiles, carbon monoxide, and hydrogen molecules are converted to CO_2 and H_2O.

Recycled CO_2 gas is injected at the bottom of the reducer, as an enhancer gas. The injection of this gas serves two purposes: to provide a gasification media to fully convert the char in the reducer, and to prevent coal and ash from entering the combustor by creating a high gas velocity area which lifts the char and ash particles upward creating a zone seal. The CO_2 enhancer gas and the char gasification products (CO, CO_2, H_2O, and H_2) flow upwards countercurrent to the flow of particles. Hence, the ash particles exit with the CO_2 stream at the top the reducer reactor.

The contaminants in coal i.e., sulfur, Hg, As, Se along with other HAPs elements are expected to exit with the CO_2 gas. Although, experimental data from Phase II is required to verify this assumption, thermodynamic data and equilibrium ASPEN simulations show that Hg, As and Se do not absorb on the oxygen carrier particles at the reducer operating conditions. Hence, these elements are expected to exit with the CO_2 stream from the reducer.

Two features of the moving bed reactor which provide additional benefits are (1) The moving bed reactor allows for a higher utilization of the oxygen in the iron oxide particle and (2) a more-compact reactor size is possible because of the lack of freeboard region as compared to a fluidized bed. These factors lower the capital cost of the system.

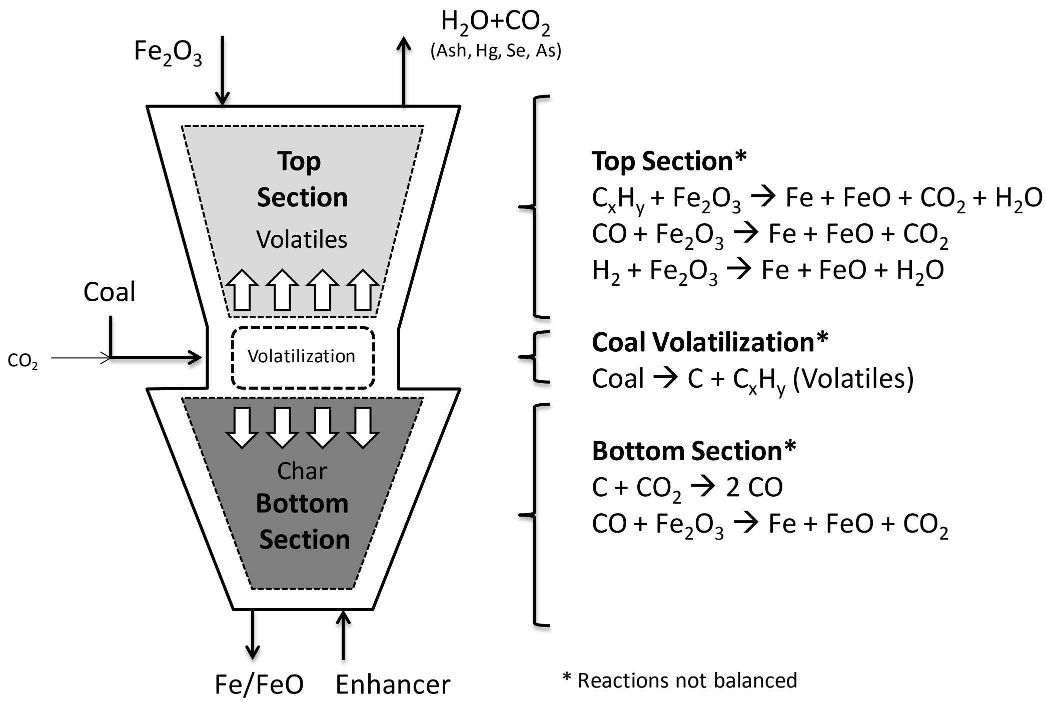

Figure 2 Reducer Conceptual Design

1.1 Coal injection and distribution: Coal injection in the reducer reactor has been identified as a technology gap. Coal injection is currently performed using a constriction near the middle of the reducer. Oxygen carrier particles and coal quickly mix together in a fluidized bed annular region in the middle zone of the reducer reactor. The mixture of oxygen carrier particles and coal moves downwards into the bottom section of the reducer. The distribution of coal in The Ohio State University design is governed by the radial movement of coal towards the center of the moving bed. Scaling up the reducer to a commercial size potentially inhibits uniform distribution of coal due to the residence time and axial distance required for mixing. The non-uniform coal distribution could cause agglomeration, increase in residence time of oxygen-carrier particles in the reducer, and interfere with the heat management in the reducer. Cold and hot model studies of the coal distribution will be performed in Phase II to determine the hydrodynamics of the commercial unit.

As shown in Figure 3, an alternate approach is to engineer a coal injection and volatilization zone in the commercial scale reducer. In this concept, a small coal feeding zone is constructed in the middle of the reducer. Coal is fed into the small cavity formed within the reactor wall. In this cavity, the reactor inside wall will be designed to permit the CO_2 and volatile gases to pass through. The gas flowing through the cavity will create a fluidized bed of coal and particles at the outer ring of the feeding zone. The mixture of coal and particles will then move towards the bottom section of the bed while the gas will move towards the top bed. This design aims to facilitate coal mixing and prevent agglomeration of coal.

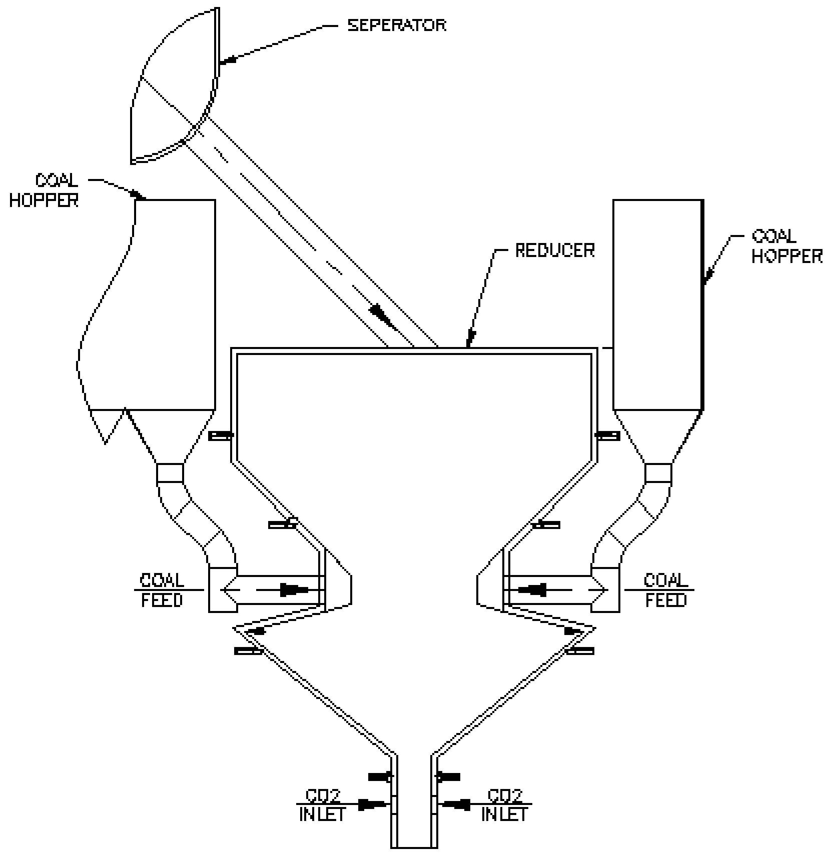

Figure 3 Schematic of the Coal-Injection Section in the Reducer

1.2 Char residence time in the reducer: The gasification reaction of char with CO_2 occurs while the char moves downward in the reducer. As the gasification reaction progresses the char particle size is reduced in the moving bed of oxygen-carrier particles. As the char particle size is reduced, the char reaches a point where it gets entrained and moves upward in the reducer. The countercurrent flow of the char particle allows the char particle to move to a region where the oxygen carrier particles are both hotter and more fully oxidized. These two factors allow the gasification-oxidation reactions to proceed to completion producing a pure stream of CO_2. Note that due to the behavior of char in the bed, the residence time of char is different from the residence time of the oxygen-carrier particles. The total residence time of char is the combination of the residence times of char while it is moving cocurrent with the oxygen particle and the residence time that char takes while it moves countercurrent to the moving bed. Evaluation of the char residence time allows for an optimization of the oxygen carrier and char particles residence time, hence, optimizing the reducer size.

The char residence time will be evaluated in more detail during Phase II. An experiment to determine the residence time of char while it is moving countercurrent to the oxygen carrier particle will be performed. The effect of char particle size and upward gas flow rate on the residence time of char travelling countercurrent to the moving bed will be studied in cold flow model tests designed using cold-to-hot scaling factors.

1.3 Enhancer gas: The amount of CO_2 enhancer gas depends on the reducer reactor design, coal particles hydrodynamic behavior, and the char gasification and particle oxidation rates. Gas and particle flow simulations will be performed to understand flow patterns within the reactor vessel and decide on an optimal reducer reactor design and the amount of CO_2 required.

1.4 Coal preparation and particle size: Prior to the injection of coal into the reducer, coal is crushed or pulverized to the desired particle size. The coal particle size depends on various factors such as coal type, coal volatilization rate, char gasification rate, and the oxygen-carrier particle size (due to the minimum fluidization velocity). The amount of CO_2 carrier gas will vary depending on the coal particle size. The fewer the pounds of CO_2 used per pound of coal, the higher the CO concentration in the upper half of the reducer reactor will be. CO_2 carrier gas decreases the rate of oxygen-carrier particles reduction. Hence, there is a motivation to introduce larger coal particle size and reduce the amount of CO_2 carrier gas used to inject coal into the reducer. The method of coal preparation depends on the coal particle size. The approach taken is to design the system to take crushed coal which will reduce the amount of CO_2 carrier gas. To further reduce CO_2 requirements, optimization of the solid fraction in the pneumatic coal-feeding line will be studied in the pilot plant. To determine optimal coal size, coal volatilization and char gasification studies will be performed as a function of particle size.

1.5 Fate of alkaline metals: Alkali metals of the coal ash could be a critical issue for the CDCL technology. The alkali may coat the oxygen-carrier particles, causing agglomeration and or oxygen-carrier deactivation. The rate of particle agglomeration or deactivation may be dependent on the type of coal, temperature, oxygen-carrier chemical composition, and speciation of Na and K in the ash and coal volatiles. The severity of particle agglomeration or deactivation caused by alkaline elements will be tested in Phase II in a laboratory-scale fluidized bed reactor. The test aims to determine the exposure limit of oxygen-carrier particles to the alkaline elements. The effects of coal type, temperature, oxygen-carrier composition have to be evaluated. In the event that any of these parameters become a limitation on the current process, the effects of these parameters on the commercial viability of the process will be addressed.

1.6 Fate of sulfur, mercury and fuel nitrogen: The fate of sulfur, mercury and fuel nitrogen in coal is critical to the design of off-gas stream treatment(s). The sulfur contained in the coal may be oxidized and released with the CO_2-gas from the reducer reactor. However, sulfur may also react with the iron oxide forming FeS. In this event, sulfur may be transferred to the combustor reactor where may be released with the spent air. Furthermore, if particles are not fully regenerated, sulfur may deactivate the oxygen-carrier particles impacting their recyclability, life expectancy or oxygen-carrier capacity.

Due to the high temperature of the reducer reactor, mercury is expected to exit with the CO_2 gas and not adsorb on the oxygen-carrier particles surface. Mercury in the gas phase could be present in two oxidation states, as elemental or ionic mercury. The mercury oxidation state is important on selecting the optimal mercury capture method. Mercury measurements in Phase II will be used to determine the fate and speciation of Mercury in the CDCL process.

In traditional combustion processes, fuel nitrogen is usually more reactive and prone towards formation of NO_x. The amount of NO_x in the off-gas from the reducer needs to be quantified. Given the controlled temperature profiled of the reducer, the amount of NO_x is expected to be low. Due to the controlled temperature environment inside the combustor, NO_x formation in the combustor is expected to be negligible. However, these assumptions need to be further demonstrated in Phase II.

The fate of sulfur, mercury and fuel nitrogen will be measured and quantified during operation of the Phase-II pilot facility.

2. Fluidized bed combustor:

The reduced oxygen-carrier particles are regenerated in the fluidized bed combustor reactor. The oxygen-carrier particle oxidation (particle regeneration) air reaction releases large amounts of heat. This heat is extracted from the combustor to produce steam for power production.

The Ohio State University has a good understanding of the particle oxidation reaction based on the particle regeneration reactions in the 25 kW_t unit. However, the particle regeneration process with imbedded heat extraction needs to be studied. B&W has an experience with heat extraction in fluidized beds and the design and operation of heat transfer surface is well understood. However, due to the slower oxidation kinetics of the oxygen-carrier particles compared to coal or gas combustion, heat extraction in a fluidized bed is considered a technology gap.
A concern is not being able to extract sufficient heat from the bed which will cause particles to exceed design oxygen-carrier particle temperature and cause deactivation or degradation. On the other hand, extracting heat too fast from the bed could cause the particles to be below the design operating temperature and shut down the reaction. For these reasons, heat extraction in the combustor reactor has been identified as technical issues which need to be studied during Phase II. The fluidized bed combustor technology gaps include:

2.1 Embedded heat exchanger: Oxidation of oxygen-carrier particles generates a significant amount of heat. If all of the heat of reaction remains in the fluid bed combustor, the oxygen carrier particle might exceed its design temperature (1100 to 1200 ºC) .Recovering the heat of reaction using excess fluidizing air requires substantial amount of air due to its low heat capacity. The amount of excess air required can be reduced by adding heat exchange surface area. The heat exchanger extracts heat from the bed to maintain the desired oxygen-carrier particle temperature. Extracting heat from the bed reduces the air requirements and makes the process more efficient. Design of the imbedded heat exchanger in the fluidized bed at high temperatures requires knowledge of materials of construction, heat transfer coefficients, and fluidized bed operation experience; B&W has ample experience in this area. B&W expertise on embedded heat exchange surface will be used to design the combustor in Phase II. The pilot facility will be used to study the heat transfer coefficient in the combustor as a function of gas velocity, tube geometry and arrangement. Furthermore, the combustor will be designed to allow temperature mapping across the bed with a high-temperature probe. Phase II data and calculations will help to match the rate of heat generated and the heat extracted in the combustor reactor.

2.2 Heat distribution in the combustor: Non-uniform heat distribution in the fluidized bed combustor could create hot spots especially close to the air inlet where oxygen concentration is the highest. Hot spots in the combustor could increase the particle temperature above the maximum temperature causing oxygen-carrier particles to deteriorate. Particle maldistribution could also cause cold spots close to the heat-exchanging surface. Cold spots close to the heat exchanger could inhibit the oxidation reaction and decrease heat transfer efficiency. Particle and gas hydrodynamics in the combustor reactor will be evaluated in the pilot facility. Temperature gradients will be monitored using high-temperature probes at various locations in the bed. Various factors that enhance particle and gas mixing inside the combustor will be investigated. Factors such as gas flow rate and gas injection points will be studied.

3. Particle riser:
The riser transports the hot particles from the combustor reactor to the reducer reactor. The riser uses air as the transport media. The amount and source of air needs to be identified. Exhausted air from the combustor may be recycled to the riser. This would reduce the heat demand and increase the overall process efficiency. The amount of air depends largely on the transport properties of the oxygen carrier particles. The amount of air should be as low as possible to prevent energy losses but large enough to transport the solids without reaching a choking condition in the riser.

4. Oxygen-carrier particle properties:

The oxygen-carrier particles are at the core of the CDCL technology. Two main technology gaps were identified with regards on particle optimization.

4.1 Verification of the maximum operating temperature: The maximum oxygen-carrier operating temperature is an important parameter that affects several design aspects of the process. The CDCL system benefits from a high reducer operating temperature. An increase in operating temperature of the oxygen-carrier allows for an increase in the reducer and combustor operating temperatures. Higher system temperatures will increase the volatile and char reaction rates, increase the particle reduction and oxidation reaction rates, increase the bed temperature for steam generation, reduce the air consumption and lower the particle circulation rates. Overall, this will result in an increase in the CDCL system efficiency, smaller vessel size, and less particle inventory. Increasing the system operating temperature, however, may cause particle agglomeration, sintering or deactivation of the oxygen-carrier particles. The maximum operating temperature of the oxygen-carrier particle will be verified in the pilot facility during Phase II. Pilot unit will be designed to operate at different temperature ranges and loadings.

4.2 Optimization of particle properties: We can classify the oxygen-carrier particle properties as physical and chemical properties. The physical properties of the particles will be optimized by changing the manufacturing process. The chemical properties, although influenced by the physical properties of the particles, will be optimized by changing the chemical composition of the particles. The project team plans to vary the chemical composition of the particle to determine how the chemical properties affect the physical properties. This will optimize the oxygen carrier formulation.

5. Operation technology gaps:

Several technology gaps related to the operation of the CDCL unit were also identified. These issues will be incorporated into the plant operating schedule. The project team will also evaluate the need for additional equipment to operate the CDCL system reliably. We will also evaluate the ability of the system to eliminate unneeded equipment, lowering the capital cost. The identification and solution of these issues will result in a better economical projection of the capital and operating cost of the plant.

5.1 Startup procedure: Startup of the CDCL process requires an external energy source to heat up the oxygen-carrier particles to the minimum operating temperature that allows oxidation and reduction reactions to take place. Since conventional PC boilers utilize start-up burners which are natural gas or oil fired, a natural gas burner is the most likely option to provide heat during process startup. The location and operation of burners will be studied in the Phase II to optimize the process.

5.2 Operation procedure: The control loop of the CDCL will be designed to minimize the lag time and allow stable operation. B&W's experience from the design and operation of the syngas chemical looping unit will facilitate the design of the CDCL control loop.

5.3 Turn down and Long Term Outage methodology: Design effort will be spent to identify the most efficient way to retain the heat in the oxygen-carrier particles during the turn down and maintenance outages of the CDCL plant. The oxygen-carrier particles will be stored in the insulated reducer which is suitable for storage and maintaining the particles at high temperature. The design of the reducer will address these issues during Phase II. For short term process trips, we don't believe that will be a technical issue since the heat will be retained in the reducer and combustor for short periods of time.

5.4 Autothermal operation: Phase II pilot plant operation should demonstrate autothermal operation of the CDCL plant. To achieve a low volume to surface ratio in the pilot plant, the size of the demonstration plant needs to be increased. The heat released during particle oxidation should be sufficient to maintain the endothermic reaction between coal and iron oxide particles at a temperature near 850 ºC and to generate steam during the oxidation of Fe/FeO in the combustor. Phase II will quantify heat sources and sinks across the CDCL system.

5.5 Hazardous operation analysis: Safe operation of the CDCL plant is essential. Possible hazardous scenarios need to be identified to locate essential instrumentation and inherently safe control systems. These types of analysis will be performed during Phase II to address the pilot plant operation, which in turns will be instrumental to identify any hazardous operation of the commercial unit.

V. TASK 4. SUPPORT TESTING AND ANALYSIS

Minimal laboratory testing has been performed to support the commercial plant design and techno-economic analysis. All testing was performed at OSU, since OSU has an extensive range of testing equipment, including a 2.5 kWth bench-scale moving bed reactor and a 25 kWth-scale CDCL system. Laboratory testing has been used to evaluate the performance of the oxygen carrier particles and the reactor system. Experimental data was used to scale up the CDCL system and to support the techno-economic analysis. Due to the first-of-the-kind nature of the CDCL system, there is not enough experimental data that supports the design of a commercial CDCL system. Although testing was kept to the minimum, the team faces the need for additional testing in three areas: 1) Coal/Char conversion, 2) Coal distribution in the reducer reactor, 3) Particle attrition, particle performance, and oxygen-carrier particle cost.

1. Coal/Char Conversion. OSU performed experiments to evaluate the rate of coal conversion in the reducer reactor. This information was necessary to properly size the reactor and determine the particle residence time in the reducer reactor to achieve >97% coal utilization. This task is important since the reactor dimensions are a critical factor in the overall cost of the plant.

Char gasification kinetics were studied using a Setaram SETSYS Evolution Thermogravimetric Analyzer (TGA) at the Ohio State University. The tests involved studying the effect of temperature, char particle size and presence of oxygen carriers on the rate of char gasification under CO_2 conditions. Figure 4 shows TGA experiment results of char and char/oxygen-carrier particles mixture gasification with CO_2 at 950 ºC. The results show that an increase in char particle size from 74 μm to 500 μm increased the residence time of char by 2.5 fold. However, further investigation indicates that increasing char particle size larger than 500 μm did not result in an increase in the residence time. This result benefits the design of the reducer and char preparation system, as a series of crushers can be used instead of pulverizers to achieve this range of char particle size. The catalytic effect of the oxygen-carrier in the gasification reaction was also studied with TGA. Results show that char gasification in the presence of the oxygen-carrier reduces the residence time as much as 75 %. This catalytic effect of the oxygen-carrier particles will be further investigated and could result in significant reduction in the reducer size and overall commercial plant cost estimate. The kinetic parameters for the char gasification reactions were calculated based on the data obtained from the temperature effect tests. The activation energy calculated was 214 kJ/mol and the pre-exponential factor was $9.9 \times 10^8\ s^{-1}$. Activation energy values reported in literature for char gasification in CO_2 environments, are in the range of 80-240 kJ/mol for lignite coal, 100-260 kJ/mol for Pittsburg#8 and 180-360 kJ/mol for sub-bituminous coal.

The char gasification kinetic study provides necessary information for the moving bed reducer reactor design including minimal char residence time and operating temperature. The test results also show that crushed size coal could be used in the coal direct chemical looping process.

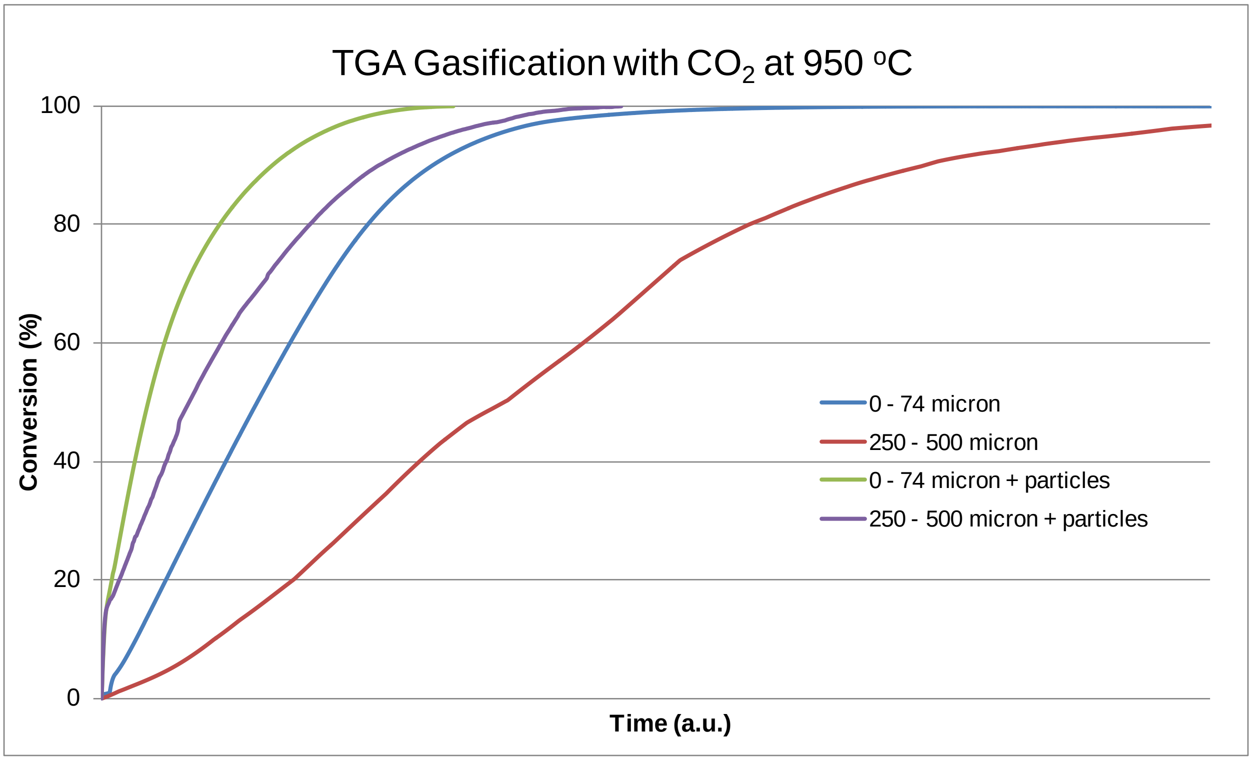

Figure 4 Char Conversion during Gasification with CO_2 in TGA at 950 ºC

2. Coal distribution. Coal distribution is a significant area of study for the team. The mechanics of coal distribution in the reducer reactor dictates the optimal design and operation of the reducer reactor. Due to the complex nature of coal and the unique reducer design, testing of coal distribution is essential to validate the reducer design. OSU performed preliminary tests to address this knowledge gap. The distribution of coal in the reducer was evaluated using a coal feed distribution cold flow model. The tests helped determine the distribution of coal when injected into a moving bed of oxygen-carrier particles under various upward gas flow rates. Results of these experiments show that coal is effectively distributed from the feed point along the reducer wall into the center of the moving bed. There are various factors that affect coal or char distribution which are concentration gradients, gas upward flow rates, particle size and temperature. The result of these preliminary experiments provided the basis for the reducer design. However, further understanding of the coal and char distribution mechanics in the reducer reactor is necessary to scale up the reducer design to a commercial or demonstration plant.

3. Particle attrition, performance and cost. The work in this task focused on determining the cost of the oxygen carrier particles. When estimating the manufacturing cost, two issues were considered. One is the ability to recycle the attrited particles and the second issue was the size of the central composite particle manufacturing plant. Regarding this issue, if we build a plant that is initially too large for the market, then the capital recovery would drive the particle cost upward. On the other hand, if we build too small of a plant, we are not taking advantage on the economies of scale and the cost per particle will be high. Taking these issues in consideration, an optimal manufacturing plant scale was proposed and the particle manufacturing cost was obtained. In addition to its manufacturing cost, the particle cost is directly related to its performance and attrition rate. The lower its attrition rate and the better performance the lower the hourly addition rate of the particles that needs to be introduced into the system and the better economics of the process. Particle attrition rates were taken from OSU tests on the 25 kW_t sub-pilot unit. Preliminary tests also showed that attrited particles have the same reactivity as fresh particles. The

ability to use recycled particles will significantly lower the cost of the oxygen carrier particles. Experiments in Phase II need to better quantify the particle attrition rate and verify the performance of the recycled particles.

VI. TASK 5. PILOT SCALE FACILITY DESIGN

To close many of the technology gaps requires a pilot plant of sufficient size to reduce or eliminate scale effects. The team is proposing to build a 3 MW_t pilot plant facility that will generate data for the design of a commercial CDCL unit. This unit will be operated in an auto-thermal condition or mode, which means that the system will generate sufficient heat and minimize the heat loss through the walls to sustain its own operation. The pilot unit will answer the main technical barriers that prevent the technology from moving to a commercial or demonstration scale. These technical issues include coal distribution, particle performance, and system performance.

5.1 Develop Functional Specifications

In this task the functional specification of the pilot plant facility will be developed based on the information obtained from the technology gap analysis. During the pilot plant design, the heat and material balance, P&ID drawings, general arrangement drawings, component mechanical and control specifications will be developed.

The specifications for the pilot facility are divided into two sections: 1) the primary loop and 2) the auxiliary equipment. The primary loop consists of the Reducer, Combustor and the Riser. The auxiliary equipment includes all other equipment, such as heat exchangers, coolers, filters, lock-hoppers required to operate the pilot unit. The environmental units i.e., scrubbers and bag house for the 3 MW_t pilot facility, will be integrated with existing facilities in the B&W Research Center in Barberton, OH. Figure 5 shows a 3D drawing of the proposed pilot plant facility.

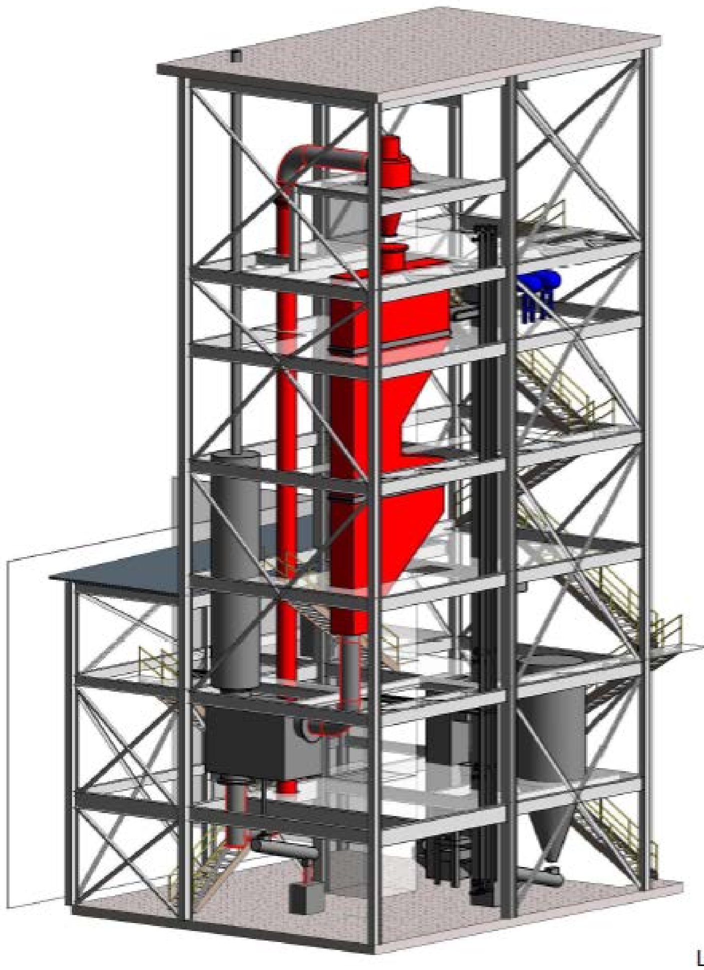

Figure 5. 3D Diagram of the Proposed Pilot Plant Facility to be Built in Barberton, OH.

The pilot facility is designed to use Illinois #6 coal which is consistent with the DOE commercial design requirements. In addition, the facility will be able to utilize a wide range of coal types such as Ohio bituminous coal, Powder River Basin coal and lignite. The facility is rated at 10.25 MBtu/hr (3.0 MW_t) based on Illinois 6 bituminous coal. The nominal coal feed rate is 880 lbs/hr (400 kg/hr). This pilot facility is assumed to have a 12-year life. The CDCL pilot facility will be installed at the Babcock & Wilcox Research Center in Barberton, Ohio. A new steel structure and foundation will be constructed which will house the pilot facility. The location of the structure is outside the existing building steel and in close proximity to the existing Small Boiler Simulator and includes all the environmental control equipment.

The operating pressure of the facility is nominally atmospheric pressure. The maximum system pressure will be 250 "H_2O at the outlet of the air supply system. This pressure will allow us to compensate for pressure drop and upstream pressure fluctuations within the system. The chemical looping facility will operate at a maximum reaction temperature of 2102 ºF (1150 ºC). The reactors will be refractory lined to keep the surface or shell temperature at or below 185 ºF (85 ^{o}C).

The pilot plant test program will address issues identified in the Phase I Technology Gaps Report. The following development needs based on the technology gap report will be evaluated in the pilot plant.

Moving Bed Reducer Reactor

Coal injection and distribution

- The coal injection concepts will be tested in a coal cold flow model prior to the pilot testing. The coal feeding mechanism into the reducer will be evaluated with various coal particle sizes. The pilot facility will be able to utilize both crushed and pulverized coal. The feeding zone of the pilot reducer is designed to accommodate further modification.
- Coal distribution in the reducer is one of the most critical issues in the CDCL process. The distribution of coal in The Ohio State University's design is governed by the radial movement of coal into the center of the moving bed. Scaling up the reducer size in commercial design potentially inhibits uniform distribution of coal due to the residence time and axial distance required for mixing. The pilot reducer width is uniquely designed to test the limitation of radial movement of coal.

Char residence time

- The coal devolatilization process needs to be studied to determine the rate of volatilization and composition of the volatilized products. The coal devolatilization rate will affect the design of the coal feeding zone that must be able to accommodate the volatilization process.
- An experiment to determine the residence time of char during the entrainment upward through the moving bed of oxygen-carrier particles will be performed.

Enhancer gas

- The pilot facility will have the ability to test CO_2, steam, or a mixture of steam and CO_2 as an enhancer gas.

Fate of alkaline metals:

- The test facility will aid in the study of several aspects of the technology gaps related to alkaline metals. These include: (i) determine the maximum concentration allowable of alkaline in oxygen carrier particles, (ii) fate of the alkaline metals, and, if required, (iii) method of alkaline treatment on the alkaline-contaminated particles.

Fate of sulfur, mercury and fuel nitrogen:

- The test facility will be used to determine the fate of sulfur. Sulfur contained in the coal may be oxidized and released with the CO_2-gas from the reducer reactor. However, sulfur may also react with the iron oxide forming FeS. In this event, sulfur may be transferred to the combustor reactor where may be released with the spent air. In limited testing using PRB coal in the 25 kW_t unit, the SO_2 released in the reducer contained all of the coal sulfur. This issue will be verified with a gas analyzer installed in the pilot facility.

Fluidized Bed Combustor

Embedded heat exchanger

- The embedded heat exchanger in the combustor will be tested in the pilot plant. The pilot facility will be used to study the heat transfer coefficient in the combustor as a function of gas velocity, tube geometry and arrangement. Furthermore, the combustor will be designed to allow mapping temperature across the bed with a high-temperature probe. Tube erosion also will be investigated.

Riser

- Circulation of large amount of solids at high temperature requires a hard face refractory scheme. Refractory scheme of two layers, one layer of a softer refractory with low heat conductivity with an inner layer of a refractory with high attrition resistance will be demonstrated.
- Fines separation efficiency as function of attrition will be extrapolated to large scale.
- Air flow requirements to transport the solids from the combustor back to the reducer reactor will be determined.

Operation

Operating Procedure Development.

- Various operation and safety procedures will be developed during the design and testing of the pilot facility. The following procedures will be developed: Start up procedure, Operation procedure, and Turndown methodology.

Autothermal Operation.

- The thermal input has been chosen to enable demonstration of auto thermal operation. The surface-to-volume ratio at this scale is sufficiently small to minimize heat loss to allow sustained operation without support fuel. A natural gas burner will be installed on the system for start-up.

Hazardous Operation Review

A hazardous operating analysis will be performed during the design phase of the pilot facility. All recommendations and issues raised during the analysis will be addressed before the issuance of released for construction drawing are finalized

5.2 Develop Budgetary Cost.

Based on the functional specification developed in Subtask 5.1, a budgetary cost estimate was developed for the large scale pilot facility and submitted with the Phase II funding application. The cost estimate include engineering, procurement of equipment, fabrication, and any modifications needed to the existing facility in order to install the unit at the B&W Research Center in Barberton, OH.

The B&W team is proposing a $15.6 million dollar program. B&W will commit $2.85 million and the Ohio State University will commit $0.32 million. The team will provide 20.3 % cost share. DOE will provide 79.7 % cost share. The cost details are presented in Project Narrative of this proposal.

Table 2 Schedule of the pilot plant design, construction, and testing

Phase II:	BP1												BP2												BP3											
	2013			2014												2015												2016								
	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9
Task 3. Pilot Facility Detailed Design																																				
3.1 Updated Design of the Pilot Facility			x	x	x	x	x																													
3.2 Detail Heat and Material Balances					x	x	x	x																												
3.3 Performance Analysis							x	x																												
3.4 Detail P&ID Drawings								x	x																											
3.5 Equipment Selection and General Arrangement Drawings									x	x	x	x																								
3.6 Mechanical, Electrical & Piping Design										x	x	x																								
3.7 Detail Fabrication Drawings											x	x	x	x																						
3.8 Cost Estimate for Construction and Operation of Pilot Facility												x	x	x																						
Pilot Cost Estimate Go/no Go Decision Point														x																						
3.9 Vendor, Fabricator, and contractor Selection														x	x																					
Task 4. Pilot Facility Construction																																				
4.1 Equipment/Materials Procurement and Reactor Fabrication															x	x	x	x	x	x	x	x	x													
4.2 Foundation and Steel Construction																x	x	x	x	x																
4.3 Equipment Installation																				x	x	x														
Task 5. Building and Utilities																																				
5.1 General Conditions														x	x	x	x	x	x	x	x	x	x	x												
5.2 Site Construction														x	x	x	x	x	x	x	x	x	x	x												
5.3 Concrete														x	x	x	x	x	x	x	x	x	x	x												
5.4 Masonry														x	x	x	x	x	x	x	x	x	x	x												
5.5 Metals														x	x	x	x	x	x	x	x	x	x	x												
5.6 Wood & Plastic														x	x	x	x	x	x	x	x	x	x	x												
5.7 Building Envelope														x	x	x	x	x	x	x	x	x	x	x												
5.8 Doors & Windows														x	x	x	x	x	x	x	x	x	x	x												
5.9 Finishes														x	x	x	x	x	x	x	x	x	x	x												
5.10 Specialties														x	x	x	x	x	x	x	x	x	x	x												
5.11 Equipment														x	x	x	x	x	x	x	x	x	x	x												
5.12 Furnishings														x	x	x	x	x	x	x	x	x	x	x												
5.13 Special Construction														x	x	x	x	x	x	x	x	x	x	x												
5.14 Conveying Systems														x	x	x	x	x	x	x	x	x	x	x												
5.15 Mechanical														x	x	x	x	x	x	x	x	x	x	x												
5.16 Electrical														x	x	x	x	x	x	x	x	x	x	x												
5.17 Piping														x	x	x	x	x	x	x	x	x	x	x												
Task 6. Pilot Facility Commissioning and Testing																																				
6.1 Commissioning of Components and Systems																					x	x	x	x	x											
6.2 Pilot Plant Testing																									x	x	x	x	x							
6.3 Data Reduction																													x	x	x					
6.4 Particle Performance																									x	x	x	x	x	x	x	x	x			

VII. TASK 6. FINAL REPORT

The topical and draft of the final report have been prepared. The topical report, submitted with this executive summary, is based on the Final Report formatting requirements. The report summarizes the results and findings of the tasks listed above.

VIII. SUMMARY, CONCLUSIONS, RECOMMENDATION AND ISSUES FOR FURTHER STUDY

The results of the Phase I activities indicate that the 550MW$_e$ commercial scale CDCL power plant can meet and exceed the DOE goal for 90% capture at a less than 35% increase in cost of electricity. B&W projects the COE for a CDCL power generation plant to increase by 26.8% while removing 96.5% of the CO_2. The economics for the CDCL technology is very favorable in comparison to first generation IGCC, oxy-PC, or amine based post combustion CO_2 capture systems. While a significant number of technology gaps were identified by the project team in Phase I, no fatal flaws for the technology were identified. Given the knowledge that OSU has accumulated regarding oxygen-carrier particle development and B&W's experience with commercial scale moving and fluid bed combustor designs the project team is confident and willing to take the next steps in development of the CDCL technology. If the technology gaps identified in Phase I can be successfully closed through further particle development by OSU and testing by B&W in the 3 MW$_t$ pilot plant, the technology should be ready to move to a large scale demonstration project by 2017. Given success at demonstration scale the technology could be ready for commercial deployment before 2025.

Given the technology gaps identified in Phase I, it is imperative that further particle development and testing at larger scale is done to close the gaps and give the CDCL technology the opportunity to move closer to commercialization. While the technology looks promising at this stage, enough uncertainty exists that the CDCL technology will not move forward with any speed without continued financial support from the DOE. The project team recommends that further particle development be continued and that a 3 MW_t pilot plant be built to demonstrate the key performance parameters of the Coal Direct Chemical Looping Process. The team believes the 3MW_t plant is large enough to effectively demonstrate the operating parameters necessary for moving the technology to large scale but small enough to be built at a reasonable cost. B&W believes that a 3 MW_t pilot plant is sufficient to permit autothermal operation and evaluate coal distribution, heat transfer effects in the fluid bed combustor, and oxygen carrier and char residence times. These are the key parameters that must be characterized at this demonstration scale.

The Technology Gaps Report outlines the areas of the CDCL technology that require further study. While several areas of uncertainty are identified, the chemical and mechanical performance of the oxygen carrier particle is the parameter that has the biggest impact on the overall performance and cost of the CDCL Power Plant. Any improvement to the kinetics of the particle has a direct positive impact on reducing the size and capital cost of the plant. Given the volume of particles required in the system any improvement to the mechanical performance of the particle i.e. increased attrition resistance or increased reactivity results in less particle replacement and lower operating cost. For example, if the oxygen carrier particle residence time is decreased by 40% (60 min to 40 min in the reducer), then the COE decreases from 26.8% to 24.7%. This is a significant decrease in capital cost. Additionally, if the oxygen carrier particle manufacturing cost decreases from $1199.50/ ton to $693/ton, the COE decreases from 26.8% to 24.4%. Combining the effect of decreasing the reducer size and lowering the oxygen particle manufacturing costs will reduce the increase in COE from 26.8% to 22.4%.

While the particle design is important it is still necessary to prove the ability to feed and evenly distribute the coal with the particles, separate the particles from the coal ash, transport the particles to the combustor, regenerate the particles, control emissions and successfully extract heat from the process to produce steam and electricity, hence the need for the pilot facility.

The project team believes that the recommended actions can eliminate the technical uncertainties and improve the CDCL process economics.

1.0 PLANT DESCRIPTION

Coal Direct Chemical Looping (CDCL) is an advanced oxy-combustion process. The CDCL process utilizes an Fe_2O_3-based oxygen carrier to supply the oxygen for coal combustion. The CDCL has lower cost and higher efficiencies when compared to first generation oxy-combustion processes that utilize Air Separation Units (ASU) to supply oxygen to the process. The elimination of the need for an ASU benefits both capital and operating costs of the CDCL. The proposed CDCL process consists of (i) oxygen-carrier particles circulation loop with coal feeding, (ii) steam generation system, (iii) power generation system, (iv) environmental equipment, and (v) auxiliary equipment. Figure 6 shows a simplified block diagram of the CDCL process and systems.

The oxygen-carrier particles circulation loop involves two main reactions: reduction of oxygen-carrier particles with coal in the reducer and oxidation with air in the combustor. Coal is first delivered and mildly dried using waste air. Coal is then crushed to a 500 micron range size using a series of crushers. Coal pulverizers are not necessary to reach the particle size required by the process which eliminates capital cost and creates operating savings compared to a PC plant. Coal is then introduced into the reducers using dense-phase pneumatic system with CO_2 recycle gas as sweep gas.

In the reducer reactors, coal is injected at a mid-point elevation in a constriction zone where coal particles are mildly fluidized. This allows mixing of the coal and particles while coal devolatilizes. The coal-char and particle mixture flows down to the lower zone of the reducer reactor in a moving packed-bed flow pattern. The coal char in the bottom section is gasified, producing CO and CO_2. In the bottom section of the reducer, CO_2 reacts with coal char forming CO. The CO in turn reacts with the oxygen-carrier particles reducing the Fe_2O_3 to Fe/FeO and producing more CO_2. This chain reaction mechanism ensures that all the char is consumed while the oxygen-carrier particles are reduced. The key assumption made for the reducer design is that char residence time is longer than that of oxygen-carrier particles because of the difference in the particle sizes; as a result coal can be fully consumed in the reducer. This assumption was supported by cold- and hot flow model experiments performed by OSU during Phase I. The residence time of the oxygen-carrier particles in the commercial plant is designed to be 80 min in the reducer, which includes 20 minutes for coal volatile conversion and 60 minutes for coal char gasification and conversion.

The coal volatiles and unconverted gases travel to the top-zone of the reducer reactor. In this zone, the fresh oxygen-carrier particle ensures that all the volatiles and carbon monoxide is converted to CO_2 and H_2O. The contaminants in coal i.e., sulfur and Hg along with the entrained ash particles leaves the reducer reactor with the CO_2 stream towards the reducer convection pass.

The CO_2 enhancer gas injected at the bottom of the reducer reactor serves two purposes. The first one is to provide for the gasification media to fully convert the coal in the reducer. The second purpose is to prevent coal and ash from flowing to the combustor by creating a high gas velocity section which lifts the coal and ash particles upward, creating a zone seal. The CO_2 enhancer and char gasification products (CO, CO_2, H_2O, and H_2), flow upstream countercurrently to the particle flow. The ash particles due to their small size eventually are discharged at the outlet of the reducer reactor.

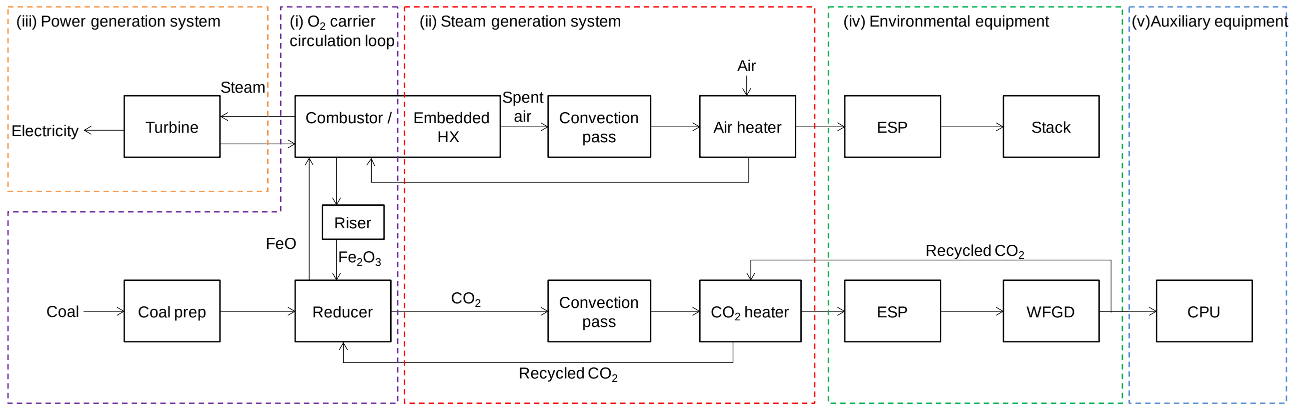

Figure 6. Block flow diagram of CDCL system

After the particles are reduced and the coal fully consumed, the reduced oxygen-carrier particles are sent to the combustor system where they are regenerated with air. The oxidation reaction of the oxygen-carrier particles liberates heat that is used to produce steam through an in-bed heat exchanger system. Each combustor reactor consists of two chambers. The separation into small chamber reduces the overall pressure drop across the. The level of solids is maintained to about 10 feet to prevent large pressure drops via L-valves systems at the inlet and outlet of the combustor. The residence time of the particles is given by the time the particles take to transverse the combustor reactor. The oxygen carrier residence time of 10 min is used in the combustor ensures all particles are fully regenerated before they are sent to the riser.

The air used to fluidize the particles in the combustor is a mixture of the exhaust hot air from the riser reactor and process air from the compressor. Recovering and utilizing the exhaust air from the riser enhances the thermal integration of the plant. The combustor air is then sent to the combustor convection pass to generate steam for power generation.

Regenerated oxygen carrier particles from the combustor reactor are sent to the riser to be transported with air back to the reducer reactor. The solid fraction in the riser is assumed to be 0.14 % to achieve dilute phase transport. Currently, in the commercial 550-MWe plant design, there are two riser systems. Each riser receives particles from two combustor systems. After the riser, particles are sent to particles separators, which separate the hot air from the particles and distributes particles to the reducers. The solid fraction in the riser is high to reduce the air requirements but low enough to prevent a choking condition.

The Steam Generation System (SGS) transfer thermal energy from hot flue gas to water to generate steam. The steam drives a steam turbine generator within the Power Generation System (PGS) to produce electricity.

The steam generator for the CDCL plant is a once-through, supercritical, Rankine cycle power plant configuration. The SGS components are split between three plant subsystems; the combustor outlet flue, the reducer outlet flue, and in-bed and boiler surface in the combustor. The combustor outlet flue contains clean, oxygen depleted air. The steam generating surface within this flue is made up of superheat and economizer surface. The CO_2 flue gas stream off of the reducer contains reheat and additional economizer surface. This flue gas stream contains particulate and is considered dirty.

The steam generating surface in these two flue gas streams account for approximately fifty percent of the thermal duty of the steam generator. The other fifty percent is located within the combustor in the form of in-bed heat exchangers (IBHX) in the bubbling fluidized bed, and in the combustor stack division walls and boiler walls. The IBHX surface is split between evaporating surface, final superheat and final reheat. Both flue gas streams contain Ljungstrom type preheaters to recover heat from the flue gas.

For a supercritical steam system, feedwater is preheated using high pressure feedwater heaters. The water then enters the bottom header of the economizer and passes upward through the economizer tube bank. From the outlet headers, water flows to the IBHX evaporator surface via external downcomers. Water then flows upward through the evaporator tube banks and discharges into the evaporator outlet headers. From the outlet headers, water flows to the combustor wall inlet headers and the combustor division wall inlet headers via external downcomers. Water then flows upward through the combustor walls and the combustor division wall (which makes up the floor and roof of each fluidized bed compartment). From the combustor walls, water flows to the steam water separator. During low load operation (operation below the Benson point), the water is recirculated to the economizer inlet with a boiler circulation pump. Operation above the Benson point is considered once-through.

Steam flows from the separator to the convection pass enclosure walls, primary superheater, and through the first stage of water attemperation. From the primary superheater, the steam flows through a second stage of water attemperation and then to the intermediate superheater. The steam then flows to the final superheater which raises the temperature in order to meet the design steam throttle temperature of the steam-turbine.

The Power Generation System (PGS) is designed with a reheat cycle. Therefore, the steam that exits the high pressure turbine is sent back to the SGS where it passes through the primary reheater surface, then through crossover piping with inter-stage attemperation. The crossover piping then feeds the final reheater banks to be heated back to the temperature of 1126 °F (608 °C).

2.0 COMPONENT DESCRIPTIONS

Major components in the CDCL system are categorized into 5 subsystems:

1. Oxygen-carrier particle circulation loop,
2. Steam generation system
3. Power generation
4. Environmental equipment
5. Auxiliary Equipment

Table 3 Major component list of oxygen carrier particles circulation loop

Component	Basis for Design			Operating Condition				Assumed Performance Characteristics	Calculated Performance Characteristics	Contaminant Removed (% Removed)	Assumptions Regarding Anticipated Application Issues	Technology Readiness
				Inlet		Outlet						
	Self-Defined	Vendor Data/Commercial	Vendor Data/Future design	Temperature (F)	Pressure (psig)	Temperature (F)	Pressure (psig)					
O2 carrier particles circulation loop												
Reducer	X			2012	17.5	1562	0	Char conversion	95%	100% ash removal	**Technology gaps report*	New concept with small pilot plant data
Combustor			X	1562	7.96	2012	0.5	Iron conversion	100%		**Technology gaps report*	New concept with small pilot plant data
Riser			X	2012	0.5	2012	0.5	Solid fraction	0.14%		**Technology gaps report*	New concept with small pilot plant data
Particle separator hopper			X	2012	0.5	2012	0.2					Commercial process
L-Valves		X		1562		1562						Commercial process
Oxygen carrier make-up storage silo		X		59	0	59	0					Commercial process
Oxygen carrier make-up conveyors		X		59	0	59	0					Commercial process
Coal Handling		X		59	0	59	0					Commercial process
Coal crushers and feeder		X		59	0	59	0	Coal particle size	500 micron			Commercial process

Table 4. Major component list of steam generation system

Component	Basis for Design			Operating Condition				Assumed Performance Characteristics	Calculated Performance Characteristics	Contaminant Removed (% Removed)	Assumptions Regarding Anticipated Application Issues	Technology Readiness
				Inlet		Outlet						
	Self-Defined	Vendor Data/Commercial	Vendor Data/Future design	Temperature (F)	Pressure (psig)	Temperature (F)	Pressure (psig)					
Steam generation system												
RH HX (CO2)		X		688	826	1114	794	Efficiency	100%			Commercial process
ECON1 HX (CO2)		X						Efficiency	100%			Commercial process
SSH HX (air)		X		576	4374	1114	3789	Efficiency	100%			Commercial process
PRI HX (air)		X						Efficiency	100%			Commercial process
ECON2 HX (air)		X						Efficiency	100%			Commercial process

Table 5. Major component list of environmental equipment

Component	Basis for Design			Operating Condition				Assumed Performance Characteristics	Calculated Performance Characteristics	Contaminant Removed (% Removed)	Assumptions Regarding Anticipated Application Issues	Technology Readiness
				Inlet		Outlet						
	Self-Defined	Vendor Data/Commercial	Vendor Data/Future design	Temperature (F)	Pressure (psig)	Temperature (F)	Pressure (psig)					
Environmental equipment												
Bag house		X						Solid separation				Commercial process
Exhaust Stack		X										Commercial process
Wet FGD scrubber		X		300	-0.9	300	-1.1					Commercial process
ESP		X		300	-0.7	300	-0.9	Solid separation				Commercial process

Table 6. Major component list of power generation system

Component	Basis for Design			Operating Condition				Assumed Performance Characteristics	Calculated Performance Characteristics	Contaminant Removed (% Removed)	Assumptions Regarding Anticipated Application Issues	Technology Readiness
				Inlet		Outlet						
	Self-Defined	Vendor Data/Commercial	Vendor Data/Future design	Temperature (F)	Pressure (psig)	Temperature (F)	Pressure (psig)					
Power generation system												
Turbine Plant Auxiliaries and Steam Piping		X						Efficiency				Commercial process

Table 7 Major component list of auxiliary equipment

Component	Basis for Design			Operating Condition				Assumed Performance Characteristics	Calculated Performance Characteristics	Contaminant Removed (% Removed)	Assumptions Regarding Anticipated Application Issues	Technology Readiness
				Inlet		Outlet						
	Self-Defined	Vendor Data/Commercial	Vendor Data/Future design	Temperature (F)	Pressure (psig)	Temperature (F)	Pressure (psig)					
Auxillary equipment												
CO2 heater		X		494	7.7	1832	17.5	Efficiency	100%			Commercial process
CO2 reheater		X						Efficiency	100%			Commercial process
CO2 recycle compressor		X		300	-0.9	494	17.7	Efficiency	100%			Commercial process
CO2 compression and drying		X		90								Commercial process
Air heater		X		152	7.96	466	7.96	Efficiency				Commercial process
Air blower		X		59	0	152	7.96	Efficiency	100%			Commercial process
Steam condenser		X		319	0.2	69	0					Commercial process
ID fan (air)		X		337	-0.6	358	0.5					Commercial process

3.0 SPARING PHILOSOPHY

The plant is configured with four trains each consisting of two reducer reactors and one particle combustor. There are no spares for the primary loop (Reducer, Combustor, Riser and Separator) components. The four particle trains are laid out as mirror images of one another and should lend themselves to lower installation cost using modularized construction methods.

Spare equipment selection was based on the same philosophy as a conventional PC unit. Air heaters, fans, blowers and compressors are all specified as two 50% capacity units. Coal crushers are also two 50% trains and empty into eight hour storage bins. Based on conventional technology this should result in a capacity factor of 85% and 95% or greater availability.

4.0 BLOCK FLOW DIAGRAMS AND STREAM TABLES

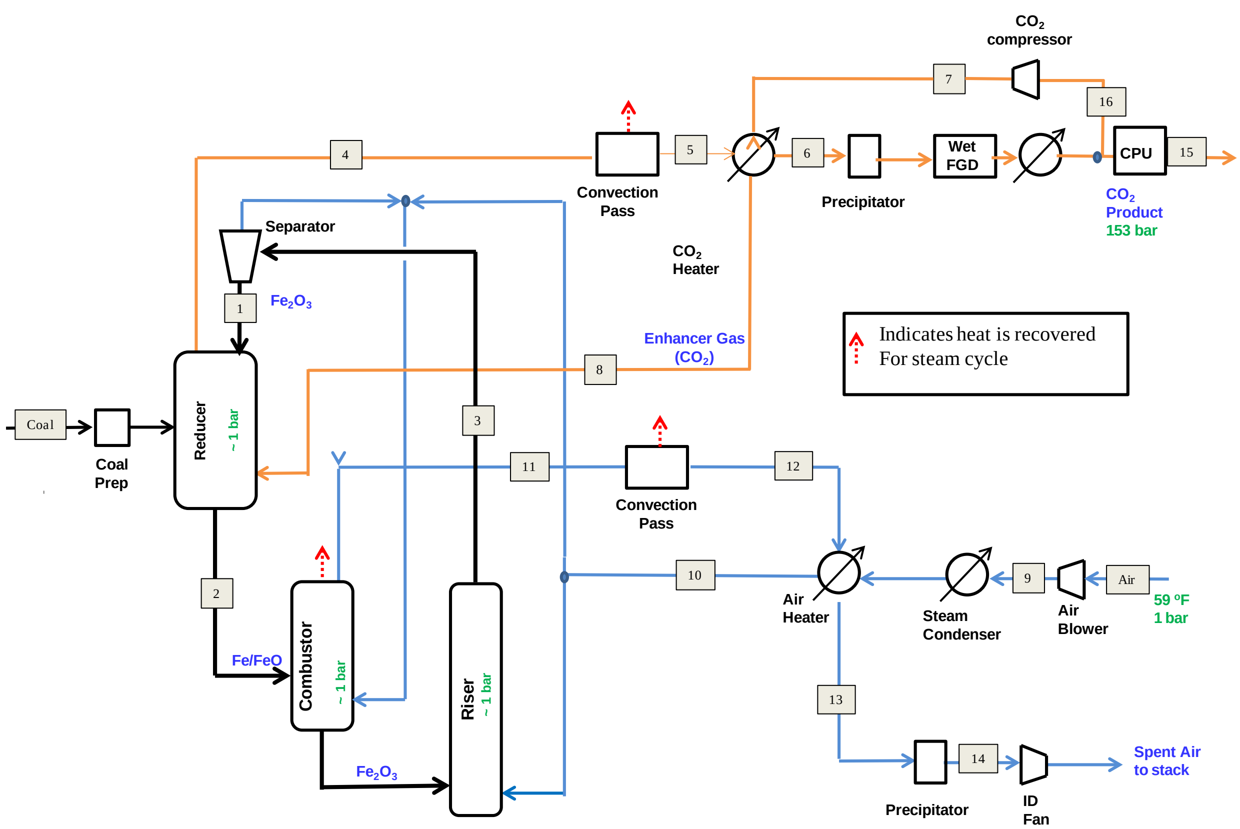

Figure 7 Simplified Process Flow Diagram

Table 8 Stream table

Stream number	1	2	3	4	5	6	7	8	9	10
Temperature (ºF)	2011.68	1579.564	2012	1990.609	1862.243	300	515.8933	1832	143.47	458.0693
Pressure (psig)	0	0	0.54205	0	-0.18064	-0.68642	17.71023	17.52959	7.1735	7.1735
Vapor Fraction	0	0	1	1	1	1	1	1	1	1
Mass Flow (lb/hr)	20161500	19283400	4462050	1440570	1440570	1440490	159090	159090	5340110	5340110
Enthalpy (MMBtu/hr)	-84090	-79990	-82050	-5085.2	-5154.2	-5892	-640.47	-571.56	-114.97	296.514
CO	0	0	0.00113	0.781374	0.781374	0.78136	0.086295	0.086295	0	0
CO_2	0	0	471.590	26052.3	26052.3	26052.2	2877.25	2877.25	55.518	55.5188
CH_4	0	0	5.35E-30	5.75E-21	5.75E-21	5.75E-21	6.35E-22	6.35E-22	0	0
COS	0	0	0	4.23E-10	4.23E-10	4.22E-10	4.67E-11	4.67E-11	0	0
CHN	0	0	3.88E-19	4.85E-15	4.85E-15	4.85E-15	5.35E-16	5.35E-16	0	0
H_2	0	0	0.00202	0.198268	0.198268	0.198212	0.021891	0.021891	0	0
H_2O	0	0	1832.12	14468.49	14468.49	14464.49	1597.481	1597.481	1832.12	1832.123
N_2	0	0	143059	226.836	226.836	226.8345	25.05196	25.05196	143091	143091
NO	0	0	63.8273	0.11419	0.11419	0.11417	0.012609	0.012609	0	0
NO_2	0	0	0.26897	4.03E-05	4.03E-05	4.03E-05	4.45E-06	4.45E-06	0	0
NH_3	0	0	2.11E-11	2.98E-09	2.98E-09	2.98E-09	3.29E-10	3.29E-10	0	0
HNO_3	0	0	1.32E-07	3.07E-11	3.07E-11	3.06E-11	3.38E-12	3.38E-12	0	0
O_2	0	0	10337.3	0	0	0	0	0	38382.0	38382.04
AR	0	0	1702.57	0	0	0	0	0	1702.57	1702.579
S	0	0	0	8.17E-10	8.17E-10	8.16E-10	9.02E-11	9.02E-11	0	0
O_2S	0	0	0	396.6939	396.6939	396.5846	43.79943	43.79943	0	0
O_3S	0	0	0	0.629075	0.629075	0.628868	0.069453	0.069453	0	0
H_2S	0	0	0	3.33E-09	3.33E-09	3.33E-09	3.68E-10	3.68E-10	0	0
Cl_2	0	0	0	0.00013	0.00013	0.00013	1.44E-05	1.44E-05	0	0
HCl	0	0	0	41.59339	41.59339	41.59311	4.593609	4.593609	0	0
C	0	416.073	0	416.0591	416.0591	416.0591	0	0	0	0
Fe	0	0	0	0	0	0	0	0	0	0
$Fe_{0.947}O$	0	130016	0	0	0	0	0	0	0	0
Fe_3O_4	0	1042.29	0	0	0	0	0	0	0	0
Fe_2O_3	63126.1	0	63126.1	0	0	0	0	0	0	0
$Fe_{0.877}S$	0	0	0	0	0	0	0	0	0	0
$FeCL_2$	0	0	0	0	0	0	0	0	0	0
$FeCL_3$	0	0	0	0	0	0	0	0	0	0
$FeCO_3$	0	0	0	0	0	0	0	0	0	0
SiC	0	0	0	0	0	0	0	0	0	0
SiO_2	0	0	0	0	0	0	0	0	0	0
Al_2O_3	98868.3	98868.3	98868.3	0	0	0	0	0	0	0
COAL	0	0	0	0	0	0	0	0	0	0
ASH	0	21938.0	21938.0	21938.01	21938.01	21938.01	0	0	0	0

Table 9 Stream table (cont.)

Stream number	11	12	13	14	15	16	AIR	COAL	TO STACK
Temperature (ºF)	2012.001	700	337	336.9972	189.472	59	59	59	358.1099
Pressure (psig)	0.180778	-0.325	-0.325	-0.54177	2000.304	0	0	0	0.478233
Vapor Fraction	1	1	1	1	1	0.821199	1	0	1
Mass Flow (lb/hr)	4462050	4462050	4462050	4462050	1026220	120094	5340110	452330	4462050
Enthalpy (MMBtu/hr)	2021.89	404.626	-6.8553	18.1364	-3955.1	-315.57	-223.96	-411.52	41.5603
CO	0.001131	0.001131	0.001131	0.001131	0.695065	0	0	0	0.001131
CO_2	471.5908	471.5908	471.5908	471.5908	23174.75	0	55.51886	0	471.5908
CH_4	5.35E-30	5.35E-30	5.35E-30	5.35E-30	0	0	0	0	5.35E-30
COS	0	0	0	0	0	0	0	0	0
CHN	3.88E-19	3.88E-19	3.88E-19	3.88E-19	0	0	0	0	3.88E-19
H_2	0.00202	0.00202	0.00202	0.00202	0.176321	10097.25	0	0	0.00202
H_2O	1832.121	1832.121	1832.121	1832.121	34.6058	2792.024	1832.123	0	1832.121
N_2	143059	143059	143059	143059	201.7825	201.8359	143091	0	143059
NO	63.82732	63.82732	63.82732	63.82732	0.101561	0	0	0	63.82732
NO_2	0.26897	0.26897	0.26897	0.26897	3.30E-05	0	0	0	0.26897
NH_3	2.11E-11	2.11E-11	2.11E-11	2.11E-11	0	0	0	0	2.11E-11
HNO_3	1.32E-07	1.32E-07	1.32E-07	1.32E-07	0	0	0	0	1.32E-07
O_2	10337.33	10337.33	10337.33	10337.33	0	972.546	38382.04	0	10337.33
AR	1702.579	1702.579	1702.579	1702.579	0	0	1702.579	0	1702.579
S	0	0	0	0	0	354.0661	0	0	0
O_2S	0	0	0	0	0	0	0	0	0
O_3S	0	0	0	0	0	0	0	0	0
H_2S	0	0	0	0	0	0	0	0	0
Cl_2	0	0	0	0	0	18.5001	0	0	0
HCl	0	0	0	0	0	0	0	0	0
C	0	0	0	0	0	24008.02	0	0	0
Fe	0	0	0	0	0	0	0	0	0
$Fe_{0.947}O$	0	0	0	0	0	0	0	0	0
Fe_3O_4	0	0	0	0	0	0	0	0	0
Fe_2O_3	12.62521	12.62521	12.62521	0	0	0	0	0	0
$Fe_{0.877}S$	0	0	0	0	0	0	0	0	0
$FeCL_2$	0	0	0	0	0	0	0	0	0
$FeCL_3$	0	0	0	0	0	0	0	0	0
$FeCO_3$	0	0	0	0	0	0	0	0	0
SiC	0	0	0	0	0	0	0	0	0
SiO_2	0	0	0	0	0	0	0	0	0
Al_2O_3	19.77366	19.77366	19.77366	0	0	0	0	0	0
COAL	0	0	0	0	0	0	0	452330	0
ASH	21938.01	21938.01	21938.01	0	0	43876.01	0	0	0

5.0 ENERGY AND MASS BALANCES

Table 10 Overall energy balance table

	HHV	Sensible+Latent	Power	Total
	Heat In (kW)			
Coal	1546655			
Total	1546655			1546655
	Heat Out (kW)			
Stack Gas		96696		
Blowdowns		2050		
Motor Losses		12005		
Ambient Losses		15825		
Cooling Tower Duty		782243		
Net Power		87501		
Total			550335	1546655
Energy Imbalance				0

*Process losses are assumed to match the heat-input to the plant. Process losses include losses from gas-cooling, low-grade heat-HRSG, TURBINES, etc.

6.0 THERMODYNAMIC PERFORMANCE

Heat and material balances were developed using in-house excel spreadsheets and ASPEN Plus® simulations. Modeling assumptions for the air pollution control systems, and balance of plant (e.g., coal handling and feed systems, ash handling system, cooling water system, CO_2 compressor, fans, pumps, etc.) were taken from NETL's *Quality Guidelines for Energy System Studies: Process Modeling Design Parameters* (DOE/NETL-341/042613).

The plant is configured with four trains each consisting of two reducer reactors and one particle combustor. The steam cycle was modeled after B&W's commercial steam generator systems modified to match the needs of the CDCL plant. Results from the heat and mass balances were used to determine parasitic loads, system performance and plant efficiency. Parasitic losses from the ASPEN model were cross checked with information from vendors and from B&W's power plant database. The ASPEN model was also used to determine air emissions, size process equipment, and generate equipment lists.

The CDCL plant is designed to produce a net output of 550,335 kWe at a net plant efficiency of 35.56 % (HHV basis). The net-plant heat rate is 9588 (BTU/kWh HHV) and the overall carbon-capture efficiency is 96.5 %. An overall performance for the plant shown in Table 11 which includes the detailed break-up of auxiliary loads and power requirements for the respective unit-operations. The compression and purification unit accounts for approximately 40% of the total auxiliary load. The air compressor accounts for around 36.5 % of the auxiliary load. The cooling water system, including cooling water pumps, ground water pumps and cooling tower fans account for approximately 7% of the total auxiliary load. All other individual auxiliaries are below 4% the total load.

Table 11 Plant Performance Summary

POWER SUMMARY (GROSS POWER AT GENERATOR TERMINALS, (kW_e)	
Steam Turbine Power	730000
Turbine cycle generator losses	-73000
Total Power (kWe)	**657000**
Auxiliary Load Summary, kW_e	
Coal Handling & Conveying	486
Limestone Handling & Reagent Preparation	983
Coal Pulverizer	1390
Ash Handling	585
Induced Draft Fans	3400
CO_2 Compressor	4142
Air Compressor/Blower	38975
Bag-house	24
FGD Pumps & Agitators	1006
Compression & Purification Unit	42835
Misc. BOP[2,3]	2000
Steam Turbine Auxiliaries	400
Condensate Pumps	906
Circulating Water Pumps	4730
Ground Water Pumps	543
Cooling Tower Fans	2440
Transformer Loss	1820
Total Auxiliaries (kW_e)	**106665**
Net Power (kW_e)	**550335**
Net Plant Efficiency, % (HHV)	35.6
Net Plant Heat Rate (Btu/kWh HHV)	9588
Condenser Cooling Duty (MBTU/h)	**2465**
Consumables	
As-Received Coal Feed, lb/h	452330
Thermal Input, kW_{th}[1]	1546655
WFGD Limestone Sorbent Feed, lb/h (Ca/S)=1.05	45581
Raw Water Withdrawal, gpm	6023
Oxygen Carrier Makeup, lb/hr	3489

7.0 CAPITAL COSTS

The economic analysis follows NETL's *Quality Guidelines for Energy Systems Studies: Cost Estimation Methodology for NETL Assessments of Power Plant Performance*. The cost for the CDCL plant was developed at the Total Plant Cost (TPC) level, which includes equipment, materials, indirect labor costs, engineering and contingencies. The total plant cost is approximately $2508 per net kW. A detailed capital cost breakdown is presented in Table 12 and indicates the individual costs assigned to each account identified in Table 13.

Table 12 Total Plant Cost and Estimate Basis in Thousands of dollars.

Account Number	Title	Cost ($x1000)	$/kW
1	Coal & Sorbent Handling	$ 45,930	$ 83
2	Coal & Sorbent Prep and Feed	$ 21,772	$ 40
3	Feedwater & Misc. BOP Systems	$ 95,364	$ 173
4	CDCL Equipment	$ 554,053	$ 1,007
5	Flue Gas Cleanup	$ 154,402	$ 281
5B	CO_2 Removal & Compression	$ 87,535	$ 159
6	Combustion Turbine/Accessories	$ -	$ -
7	HR, Ducting & Stack	$ 44,799	$ 81
8	Steam Turbine Generator	$ 146,288	$ 266
9	Cooling Water System	$ 44,951	$ 82
10	Ash/Spent Sorbent Handling System	$ 15,256	$ 28
11	Accessory Electric Plant	$ 61,392	$ 112
12	Instrumentation & Controls	$ 25,903	$ 47
13	Improvements to Site	$ 16,394	$ 30
14	Buildings & Structures	$ 66,362	$ 121
	Total Plant Cost	$1,380,401	$2,508

The CDCL Equipment (advanced technology), includes the reducers, combustors, risers, distributors, coal injection, particle makeup, steam generating surface in the combustor and heat transfer surface at the exit of the combustor, air and CO_2 heaters, burners, and CO_2 compressor. Conventional technology costs (steam turbine-generator and other non-CDCL technology related BOP equipment) were estimated based on NETL's Report, Updated Cost (June 2011 Basis) for Selected Bituminous Baseline Cases, DOE/NETL-341/082312. Capacity and scale-up factors were used to adjust the cost of the conventional equipment from DOE's base case to match the CDCL plant. The total plant cost includes a 20% process contingency and 15% project contingency applied to the CDCL equipment cost following AACE guidelines.

The TPC was adjusted to account for start-up costs, working capital, inventory capital, land, financing costs and other owner's costs. The Total Overnight Cost (TOC) is $1.725 billion dollars. Total As-Spent Cost (TASC) is $1.967 billion dollars, which follows a high-risk Investor Owned Utility (IOU) finance structure with a 5 year capital expenditure period.

Table 13: CDCL Power Plant Capital Cost Details

Project: **Atmospheric Iron Based Coal Direct Chemical Looping** — Report Date 2013-June-28

TOTAL PLANT COST SUMMARY

Client: USDOE/NETL

Plant Size: 550,335 MW,net — **Estimate Type:** — Cost Base (Jun) 2011

Account	Units	Equipment Capital Cost	Material Cost	Labor (Erection)	Bare Erected Cost	Eng CM & HO Fee	Process Contingency	Project Contingency	TOTAL COST	Cost in $/kW
1.0 COAL & SORBENT HANDLING										
1.1 Coal Receive & Unload	k$	$ 4,088		$ 1,842	$ 5,930	$ 514		$ 967	$ 7,411	$ 13
1.2 Coal Stackout & Reclaim	k$	$ 5,283		$ 1,181	$ 6,464	$ 548		$ 1,052	$ 8,064	$ 15
1.3 Coal Conveyors & Yard Breaker	k$	$ 4,912		$ 1,168	$ 6,080	$ 516		$ 989	$ 7,586	$ 14
1.4 Other Coal Handling	k$	$ 1,285		$ 270	$ 1,555	$ 132		$ 253	$ 1,940	$ 4
1.5 Sorbent Receive & Unload	k$	$ 164		$ 49	$ 213	$ 18		$ 35	$ 266	$ 0
1.6 Sorbent Stackout & Reclaim	k$	$ 2,641		$ 477	$ 3,118	$ 263		$ 507	$ 3,888	$ 7
1.7 Sorbent Conveyors	k$	$ 942	$ 205	$ 228	$ 1,375	$ 115		$ 223	$ 1,713	$ 3
1.8 Other Sorbent Handling	k$	$ 569	$ 134	$ 294	$ 997	$ 85		$ 162	$ 1,244	$ 2
1.9 Coal & Sorbent Hnd. Foundations	k$	$ -	$ 4,738	$ 6,247	$ 10,985	$ 1,030		$ 1,802	$ 13,818	$ 25
SUBTOTAL	**k$**	**$ 19,884**	**$ 5,077**	**$ 11,756**	**$ 36,717**	**$ 3,222**	**$ -**	**$ 5,991**	**$ 45,930**	**$ 83**
2.0 COAL & SORBENT PREP & FEED										
2.1 Coal Crushing & Drying	k$	$ 2,341		$ 450	$ 2,791	$ 236		$ 454	$ 3,481	$ 6
2.2 Coal Conveyor to Storage	k$	$ 5,995		$ 1,291	$ 7,286	$ 617		$ 1,185	$ 9,089	$ 17
2.3 Coal Injection System	k$	$ -		$ -	$ -	$ -		$ -	$ -	$ -
2.4 Misc. Coal Prep Equipment	k$	$ -		$ -	$ -	$ -		$ -	$ -	$ -
2.5 Sorbent Prep Equipment	k$	$ 4,486	$ 194	$ 919	$ 5,599	$ 472		$ 911	$ 6,982	$ 13
2.6 Sorbent Storage & Feed	k$	$ 540		$ 204	$ 744	$ 64		$ 121	$ 929	$ 2
2.7 Sorbent Injection System	k$	$ -		$ -	$ -	$ -		$ -	$ -	$ -
2.8 Booster Air Supply System	k$	$ -		$ -	$ -	$ -		$ -	$ -	$ -
2.9 Coal & sorbent Feed Foundation	k$	$ -	$ 547	$ 480	$ 1,027	$ 96		$ 168	$ 1,291	$ 2
SUBTOTAL	**k$**	**$ 13,362**	**$ 741**	**$ 3,344**	**$ 17,447**	**$ 1,485**	**$ -**	**$ 2,840**	**$ 21,772**	**$ 40**
3.0 FEEDWATER & MISC BOP SYSTEMS										
3.1 Feedwater System	k$	$ 22,338		$ 7,202	$ 29,540	$ 2,523		$ 4,809	$ 36,872	$ 67
3.2 Water Makeup & Pretreating	k$	$ 5,434		$ 1,719	$ 7,153	$ 654		$ 1,561	$ 9,368	$ 17
3.3 Other Feedwater Subsystems	k$	$ 7,027		$ 2,885	$ 9,912	$ 852		$ 1,615	$ 12,379	$ 22
3.4 Service Water Systems	k$	$ 1,088		$ 569	$ 1,657	$ 149		$ 361	$ 2,167	$ 4
3.5 Other Boiler Plant Systems	k$	$ 8,511		$ 8,046	$ 16,557	$ 1,507		$ 2,710	$ 20,773	$ 38
3.6 FO Supply Sys & Nat Gas	k$	$ 327		$ 382	$ 709	$ 63		$ 116	$ 888	$ 2
3.7 Waste Treatment Equipment	k$	$ 3,565		$ 2,064	$ 5,629	$ 542		$ 1,234	$ 7,405	$ 13
3.9 Misc. Power Plant Equipment	k$	$ 3,203		$ 991	$ 4,194	$ 399		$ 919	$ 5,511	$ 10
SUBTOTAL	**k$**	**$ 51,493**	**$ -**	**$ 23,858**	**$ 75,351**	**$ 6,689**	**$ -**	**$ 13,325**	**$ 95,364**	**$ 173**
4.0 CDCL EQUIPMENT										
4.1 CDCL Process Equipment		$ 235,789		$ 132,042	$ 367,831	$ 33,657	$ 80,298	$ 72,268	$ 554,053	$ 1,007
SUBTOTAL		**$ 235,789**	**$ -**	**$ 132,042**	**$ 367,831**	**$ 33,657**	**$ 80,298**	**$ 72,268**	**$ 554,053**	**$ 1,007**
5.0 FLUE GAS CLEANUP										
5.1 Absorber Vessels & Accessories	k$	$ 66,871		$ 14,297	$ 81,168	$ 7,535		$ 8,870	$ 97,573	$ 177
5.2 Other FGD	k$	$ 3,490		$ 3,927	$ 7,417	$ 703		$ 812	$ 8,932	$ 16
5.3 Baghouse & Accessories	k$	$ 18,833		$ 11,870	$ 30,703	$ 2,885		$ 3,359	$ 36,947	$ 67
5.4 Other Particulate Removal Materials	k$	$ 1,274		$ 1,354	$ 2,628	$ 249		$ 288	$ 3,165	$ 6
5.5 Gypsum Dewatering System	k$	$ 5,543		$ 935	$ 6,478	$ 600		$ 708	$ 7,786	$ 14
5.6 Mercury Removal System	k$				$ -	$ -		$ -	$ -	$ -
SUBTOTAL	**k$**	**$ 96,011**	**$ -**	**$ 32,383**	**$ 128,394**	**$ 11,972**	**$ -**	**$ 14,037**	**$ 154,402**	**$ 281**
5.0B CO2 REMOVAL & COMPRESSION										
5B.1 CO2 Cooler in WFGD	k$	$ -		$ -	$ -	$ -		$ -	$ -	
5B.2 Compression & Drying	k$	$ 48,646		$ 18,072	$ 66,718	$ 6,228		$ 14,589	$ 87,535	$ 159
SUBTOTAL	**k$**	**$ 48,646**	**$ -**	**$ 18,072**	**$ 66,718**	**$ 6,228**	**$ -**	**$ 14,589**	**$ 87,535**	**$ 159**

Project		Atmospheric Iron Based Coal Direct Chemical Looping	Report Date	2013-June-28
		TOTAL PLANT COST SUMMARY		
Client		USDOE/NETL		
Plant Size	550,335 MW,net	**Estimate Type:**	Cost Base (Jun)	2011

			Equipment	Material	Labor	Bare Erected	Eng CM	Process	Project	TOTAL	Cost
6.0 COMBUSTION TURBINE/ACCESSORIES											
	6.1 Combustion Turbine Generator	k$				$ -				$ -	$ -
	6.2 Combustion Turbine Accessories	k$				$ -				$ -	$ -
	6.3 Compressed Air Piping	k$				$ -				$ -	$ -
	6.9 Combustion Turbine Foundations	k$				$ -				$ -	$ -
	SUBTOTAL	k$	**$ -**	**$ -**	**$ -**	**$ -**	**$ -**	**$ -**	**$ -**	**$ -**	**$ -**
7.0 HR, DUCTING & STACK											
	7.1 Flue Gas Recycle Heat Exchanger	k$	$ -		$ -	$ -	$ -		$ -	$ -	$ -
	7.2 SCR System	k$				$ -	$ -		$ -	$ -	$ -
	7.3 Ductwork	k$	$ 10,572		$ 6,673	$ 17,245	$ 1,457		$ 2,805	$ 21,508	$ 39
	7.4 Stack	k$	$ 10,513		$ 6,110	$ 16,623	$ 1,560		$ 1,818	$ 20,001	$ 36
	7.9 Duct & Stack Foundations	k$		$ 1,146	$ 1,361	$ 2,507	$ 235		$ 548	$ 3,290	$ 6
	SUBTOTAL	**k$**	**$ 21,085**	**$ 1,146**	**$ 14,144**	**$ 36,375**	**$ 3,252**	**$ -**	**$ 5,172**	**$ 44,799**	**$ 81**
8.0 STEAM TURBINE GENERATOR											
	8.1 Steam TG & Accessories	k$	$ 66,640		$ 8,221	$ 74,861	$ 6,572		$ 8,143	$ 89,576	$ 163
	8.2 Turbine Plant Auxiliaries	k$	$ 418		$ 890	$ 1,308	$ 125		$ 143	$ 1,576	$ 3
	8.3 Condenser & Auxiliaries	k$	$ 8,091		$ 2,740	$ 10,831	$ 1,010		$ 1,184	$ 13,025	$ 24
	8.4 Steam Piping	k$	$ 21,119		$ 9,383	$ 30,502	$ 2,338		$ 4,926	$ 37,766	$ 69
	8.9 TG Foundations	k$		$ 1,248	$ 2,060	$ 3,308	$ 312		$ 724	$ 4,344	$ 8
	SUBTOTAL	**k$**	**$ 96,268**	**$ 1,248**	**$ 23,294**	**$ 120,810**	**$ 10,357**	**$ -**	**$ 15,121**	**$ 146,288**	**$ 266**
9.0 COOLING WATER SYSTEM											
	9.1 Cooling Towers	k$	$ 10,951		$ 3,387	$ 14,338	$ 1,336		$ 1,567	$ 17,241	$ 31
	9.2 Circulating Water Pumps	k$	$ 2,187		$ 138	$ 2,325	$ 198		$ 252	$ 2,775	$ 5
	9.3 Circ. Water System Auxiliaries	k$	$ 601		$ 80	$ 681	$ 63		$ 74	$ 819	$ 1
	9.4 Circ. Water Piping	k$		$ 5,062	$ 4,584	$ 9,646	$ 854		$ 1,575	$ 12,075	$ 22
	9.5 Mack-up Water System	k$	$ 545		$ 701	$ 1,246	$ 115		$ 204	$ 1,565	$ 3
	9.6 Component Cooling Water Sys	k$	$ 490		$ 376	$ 866	$ 79		$ 142	$ 1,087	$ 2
	9.9 Circ. Water System Foundations	k$		$ 2,687	$ 4,463	$ 7,150	$ 674		$ 1,565	$ 9,389	$ 17
	SUBTOTAL	**k$**	**$ 14,774**	**$ 7,749**	**$ 13,729**	**$ 36,252**	**$ 3,319**	**$ -**	**$ 5,380**	**$ 44,951**	**$ 82**
10.0 ASH/SPENT SORBENT HANDLING SYS											
	10.1 Ash Coolers	k$				$ -	$ -		$ -	$ -	$ -
	10.2 Cyclone Ash Letdown	k$				$ -	$ -		$ -	$ -	$ -
	10.3 HGCU Ash Letdown	k$				$ -	$ -		$ -	$ -	$ -
	10.4 High Temperature Ash Piping	k$				$ -	$ -		$ -	$ -	$ -
	10.5 Other Ash Recovery Equipment	k$				$ -	$ -		$ -	$ -	$ -
	10.6 Ash Storage Silos	k$	$ 711		$ 2,176	$ 2,887	$ 277		$ 316	$ 3,480	$ 6
	10.7 Ash Transport & Feed Equipment	k$	$ 4,725		$ 4,684	$ 9,409	$ 867		$ 1,028	$ 11,304	$ 21
	10.8 Misc. Ash Handling Equipment	k$				$ -	$ -		$ -	$ -	$ -
	10.9 Ash/Spent Sorbent Foundations	k$		$ 161	$ 198	$ 359	$ 34		$ 79	$ 472	$ 1
	SUBTOTAL	**k$**	**$ 5,436**	**$ 161**	**$ 7,058**	**$ 12,655**	**$ 1,178**	**$ -**	**$ 1,423**	**$ 15,256**	**$ 28**

Project			Atmospheric Iron Based Coal Direct Chemical Looping					Report Date	2013-June-28	
			TOTAL PLANT COST SUMMARY							
Client			USDOE/NETL							
Plant Size			550,335	MW,net	**Estimate Type:**		Cost Base (Jun)		2011	
		Equipment	Material	Labor	Bare Erected	Eng CM	Process	Project	TOTAL	Cost
11.0 ACCESSORY ELECTRIC PLANT										
11.1 Generator Equipment	k$	$ 1,943		$ 311	$ 2,254	$ 202		$ 184	$ 2,640	$ 5
11.2 Station Service Equipment	k$	$ 3,314		$ 1,111	$ 4,425	$ 411		$ 363	$ 5,199	$ 9
11.3 Switchgear & Motor Control	k$	$ 3,803		$ 661	$ 4,464	$ 413		$ 488	$ 5,365	$ 10
11.4 Conduit & Cable Tray	k$	$ -	$ 2,608	$ 8,426	$ 11,034	$ 1,030		$ 1,810	$ 13,874	$ 25
11.5 Wire & Cable	k$	$ -	$ 4,966	$ 8,877	$ 13,843	$ 1,112		$ 2,243	$ 17,198	$ 31
11.6 Protective Equipment	k$	$ 306		$ 1,063	$ 1,369	$ 131		$ 150	$ 1,650	$ 3
11.7 Standby Equipment	k$	$ 1,498		$ 35	$ 1,533	$ 140		$ 167	$ 1,840	$ 3
11.8 Main Power Transformers	k$	$ 9,896		$ 206	$ 10,102	$ 767		$ 1,087	$ 11,956	$ 22
11.9 Electrical Foundations	k$	$ -	$ 359	$ 913	$ 1,272	$ 120		$ 278	$ 1,670	$ 3
SUBTOTAL	**k$**	**$ 20,760**	**$ 7,933**	**$ 21,603**	**$ 50,296**	**$ 4,326**	**$ -**	**$ 6,770**	**$ 61,392**	**$ 112**
12.0 INSTRUMENTATION & CONTROLS										
12.1 PC Control Equipment	k$				$ -	$ -		$ -	$ -	$ -
12.2 Combustion Turbine Control	k$				$ -	$ -		$ -	$ -	$ -
12.3 Steam Turbine Control	k$				$ -	$ -		$ -	$ -	$ -
12.4 Other Major Componenet Control	k$				$ -	$ -		$ -	$ -	$ -
12.5 Signal Processing Equipment	k$				$ -	$ -		$ -	$ -	$ -
12.6 Control Boards, Panels & Racks	k$	$ 528		$ 323	$ 851	$ 80		$ 140	$ 1,071	$ 2
12.7 Computer & Accessories	k$	$ 5,331		$ 951	$ 6,282	$ 580		$ 686	$ 7,548	$ 14
12.8 Instrument Wiring & Tubing	k$	$ 3,214		$ 5,849	$ 9,063	$ 734		$ 1,470	$ 11,267	$ 20
12.9 Other I & C Equipment	k$	$ 1,506		$ 3,488	$ 4,994	$ 477		$ 547	$ 6,018	$ 11
SUBTOTAL	**k$**	**$ 10,579**	**$ -**	**$ 10,611**	**$ 21,190**	**$ 1,871**	**$ -**	**$ 2,842**	**$ 25,903**	**$ 47**
13.0 IMPROVEMENTS TO SITE										
13.1 Site Preparation	k$		$ 56	$ 1,195	$ 1,251	$ 122		$ 275	$ 1,648	$ 3
13.2 Site Improvements	k$		$ 1,865	$ 2,464	$ 4,329	$ 430		$ 952	$ 5,711	$ 10
13.3 Site Facilities	k$	$ 3,342		$ 3,506	$ 6,848	$ 681		$ 1,506	$ 9,035	$ 16
SUBTOTAL	**k$**	**$ 3,342**	**$ 1,921**	**$ 7,165**	**$ 12,428**	**$ 1,233**	**$ -**	**$ 2,732**	**$ 16,394**	**$ 30**

Project		Atmospheric Iron Based Coal Direct Chemical Looping	Report Date	2013-June-28
		TOTAL PLANT COST SUMMARY		
Client		USDOE/NETL		
Plant Size	550,335 MW,net	**Estimate Type:**	Cost Base (Jun)	2011

			Equipment	Material	Labor	Bare Erected	Eng CM	Process	Project	TOTAL	Cost
14.0 BUILDINGS & STRUCTURES											
	14.1 Boiler Building	k$		$ 9,922	$ 8,719	$ 18,641	$ 1,640		$ 3,042	$ 23,324	$ 42
	14.2 Turbine Building	k$		$ 14,171	$ 13,198	$ 27,369	$ 2,415		$ 4,468	$ 34,252	$ 62
	14.3 Adminstration Building	k$		$ 703	$ 742	$ 1,445	$ 128		$ 236	$ 1,809	$ 3
	14.4 Circulation Water Pumphouse	k$		$ 201	$ 160	$ 361	$ 32		$ 59	$ 452	$ 1
	14.5 Water Treatment Buildings	k$		$ 678	$ 618	$ 1,296	$ 114		$ 212	$ 1,622	$ 3
	14.6 Machine Shop	k$		$ 470	$ 315	$ 785	$ 68		$ 128	$ 981	$ 2
	14.7 Warehouse	k$		$ 318	$ 319	$ 637	$ 56		$ 104	$ 797	$ 1
	14.8 Other Building s & Structures	k$		$ 260	$ 221	$ 481	$ 42		$ 78	$ 601	$ 1
	14.9 Waste Treating Suilding & Str.	k$		$ 498	$ 1,511	$ 2,009	$ 187		$ 329	$ 2,525	$ 5
	SUBTOTAL	**k$**	**$ -**	**$ 27,221**	**$ 25,803**	**$ 53,024**	**$ 4,682**	**$ -**	**$ 8,656**	**$ 66,362**	**$ 121**
Total Plant Cost (TPC) wo/T,S&M		**k$**	**$ 401,640**	**$ 53,197**	**$ 212,820**	**$ 667,657**	**$ 59,813**	**$ -**	**$ 98,877**	**$ 1,380,401**	**$ 2,508**
	Owner's Costs										
	Preproduction Costs										
	6 Months All Labor									$ 10,581	$ 19
	1 Month Maintenance Materials									$ 1,364	$ 2
	1 Month Non-fuel Consumables									$ 2,478	$ 5
	1 Month Waste Disposal									$ 403	$ 1
	25% of 1 Month Fuel Cost at 100% CF									$ 2,831	$ 5
	2% of TPC									$ 27,608	$ 50
	Total									**$ 45,265**	**$ 82**
	Inventory Capital										
	60 Day supply of fuel and consumables at 100% CF									$ 27,229	$ 49
	0.5% of TPC (spare parts)									$ 6,902	$ 13
	Total									**$ 34,131**	**$ 62**
	Initial Cost for Catalyst and Chemicals									$ -	$ -
	Initial Cost for Oxygen Carrier									$ 20,312	$ 37
	Land									$ 900	$ 2
	Other Owner's Costs									$ 207,060	$ 376
	Financing Costs									$ 37,271	$ 68
	Total Overnight Costs (TOC)									**$ 1,725,339**	**$ 3,135**
	TASC Multipler									1.14	
	Total As-Spent Cost (TASC)									**$ 1,966,887**	**$ 3,574**

8.0 O&M COSTS

Operating costs, utilities and catalyst replacement costs are available in the literature and have been determined on a first-year basis and then applied over the plant life. Operating costs were calculated based on a projected number of operators for the plant. The operating staff for the CDCL plant includes 3 operators for the CO_2 CPU. Maintenance costs were estimated based on internal data and were individually projected for each major plant area; CDCL island, steam turbine island, steam generator components and BOP equipment. The CDCL process captures 96.5% of the CO_2, which is in excess of the 90% DOE target. O&M cost estimate results for the CDCL power plant are presented in Table 14 and Table 15.

Table 14: CDCL Power Plant Variable O&M Costs

VARIABLE O&M COSTS			Annual Cost (CDCL)	Annual Cost (Case 11)
Maintenance Materials Cost (1% of Capital)		1%	**$13,916,067**	**$10,986,170**
Consumables				
	Unit Cost	Capacity Factor	Annual Cost (CDCL)	Annual Cost (Case 11)
Water	1.67	85%	**$ 2,246,943**	**$ 2,017,015**
Chemicals				
Make up & Water Treatment Chemicals	0.27	85%	$ 1,768,357	$ 1,562,183
Limestone (WFGD)	33.48	85%	$ 5,646,611	$ 5,066,306
Ammonia	330.00	85%	$ -	$ 7,527,571
Subtotal Chemicals			**$ 7,414,968**	**$ 14,156,060**
Other				
Suplemental Fuel (MBtu)			$ -	$ -
SCR Catalyst	with equipment		$ -	$ 857,054
Emission Penalties			$ -	$ -
Oxygen Carrier Cost,	$1,200	85%	$ 15,580,903	
Subtotal Other			**$ 15,580,903**	**$ 857,054**
Waste Disposal				
Ash	25.11	85%	$ 4,081,398	$ 3,712,363
Subtotal-Waste Disposal			**$4,081,398**	**$ 3,712,363**
Total Consumables (Less Oxygen Carrier)			**$ 13,743,309**	**$ 20,742,492**
Total Variable Operating Costs			**$ 27,659,376**	**$ 31,728,662**
Fuel	2.94	85%	**$ 114,807,162**	**$ 104,591,159**

Table 15: CDCL Power Plant Fixed O&M Costs

Operating and Maintenance Labor			
Operating labor			
	Operating $/hour	Operating % of base	Labor O-H % of labor
Annual Operating Labor Cost:	$39.70	30%	25%
Operator Labor Requirements		Operators (CDCL)	Operators (Case 11)
Annual Operating Labor Cost:		17	14
Maintenance Labor Cost		11	11
Admin. & Support Labor		4	4
Total Plant O.J.'s		32	29
		Operators (CDCL)	Operators (Case 11)
Annual Operating Labor Cost		$7,685,761	$6,329,451
Maintenance Labor Cost		$9,243,366	$7,297,262
Administrative & Support Labor		$4,232,282	$3,406,678
Property Taxes & Insurance		$27,608,012	$21,795,404
Total Fixed O&M		**$48,769,421**	**$38,828,795**

9.0 ENVIRONMENTAL PERFORMANCE

The environmental performance for the CDCL system is quantified based on the fate of pollutants in the system and the corresponding strategy for handling them. The fate of sulfur, mercury, particulate matter, non-mercury HAP metal compounds like HCL and fuel nitrogen in coal is presented. This is based on detailed thermodynamics analyzed from process simulations in ASPEN Plus software and operational experience for the 25 kW_{th} sub-pilot scale unit at OSU.

Fate of Sulfur: The Illinois #6 bituminous coal contains 2.51 % sulfur on an as-received basis. The process demonstrations at OSU indicate that all the coal sulfur will react to form SO_2 in the reducer reactor. This is validated by the process simulation sulfur balance which indicates that the sulfur will be concentrated in majority as SO_2 out of the reducer outlet. The simulations also show that SO_2 is the favored product over solid FeS over the entire range design coal and Fe_2O_3 flow-rates coupled with no emissions from the combustor spent-air stream. This simplifies the sulfur control strategy to only the reducer gas-stream. The conceptual commercial plant design will include a commercially proven single WET FGD unit which reduces the sulfur concentrations to the required standards. The sulfur balance Table 16 highlights the sulfur split in the reducer for the commercial plant simulation.

Table 16 Sulfur balance

Flow, lbmol/hr	In	Out
Stream	Coal	WFGD
COS	0	3.76E-10
S	354.066	7.26E-10
SO_2	0	352.7851

SO_3	0	0.559415
H_2S	0	2.96E-09
HSO_3-	0	0
Total	354.06	354.06

Fate of fuel Nitrogen: The lower temperatures coupled with a predominantly reducing environment work against formation of thermal NO_X in the reducer reactor. The combustor does not combust nitrogen-containing fuel or produce a flame. The operating temperature is below the temperature (> 1300 ºC) considered favorable for thermal NO_x formation. This analysis is supported by the sub-pilot demonstrations at OSU indicating that majority of the fuel nitrogen is converted to N_2 as shown in Table 17. The process simulations show that the NO formation out of the combustor is insignificant.) It eliminates the need for a Selective catalytic reduction (SCR) in the preliminary design. Further experimental testing will serve to determine the NO_x formation in chemical looping reactors and validate the control strategy.

Table 17 NO_x formation analysis

Flow, lbmol/hr	In	Out
Stream	Coal	25
N (in coal)	403.6718	0
N2	0	201.7825
NO	0	0.101561
NO2	0	3.58E-05
NH3	0	2.65E-09
HNO3	0	2.73E-11

Fate of Hg, non-mercury HAP metal compounds: The mercury is expected to exit with the CO_2 gas stream in the reducer. The high temperature (> 900 ºC) of the reducer reactor prevents surface adsorption and promotes release of Hg through the CO_2 gas-outlet stream. An actual control strategy is highly dependent on the state of oxidation of Hg and further experimental testing is needed to finalize the same for a conceptual commercial plant.

The non-mercury HAP metal compounds include HCl, lead, selenium among others and have a regulatory requirement as indicated in Table 18. The thermodynamic process simulations show that all the chlorine in the coal goes as HCl out of the reducer gas outlet with no emissions out of combustor as shown in Table 18.

Table 18 Hg and non-mercury HAP metal compounds balance

Flow, lbmol/hr	In	Out	
Stream	Coal	WFGD	Spent air
HCl	0	46	0
CL2	23	0	0
Cl-	0	0	0

The other non-mercury HAP metal compounds go out of the system as ash in concentrations which are below the regulatory limits in Table 19.

Fate of filterable particulate matter: The reducer and combustor lines both have a particulate filter and precipitator to eliminate entrained particle fines and ash below the regulatory limit of 9.0 E-2 lb/MWh.

Table 19 Regulatory requirement

Pollutants	**Limits**
Filterable particulate matter	9.0E–2 lb/MWh
Sulfur dioxide (SO_2)	4.0E–1lb lb/MWh
Total non-Hg HAP metals	4.0E–1lb/GWh
Antimony (Sb)	2.0E–2 lb/GWh
Arsenic (As)	2.0E–2 lb/GWh
Beryllium (Be)	1.0E–-3 lb/GWh.
Cadmium (Cd)	2.0E–3 lb/GWh
Chromium (Cr)	4.0E–2 lb/GWh
Cobalt (Co)	4.0E–3 lb/GWh
Lead (Pb)	9.0E–3 lb/GWh
Manganese (Mn)	2.0E–2 lb/GWh
Nickel (Ni)	7.0E–2 lb/GWh
Selenium (Se)	3.0E–1 lb/GWh
Hydrogen chloride (HCl)	2.0E–2 lb/MWh
Mercury (Hg)	3.0E–3 lb/GWh

10.0 CONCLUSIONS AND RECOMMENDATIONS

The results of the Phase I activities indicate that the 550 MW_e commercial scale CDCL power plant can meet and exceed the DOE goal for 90% capture at a less than 35% increase in cost of electricity. B&W projects the COE for a CDCL power generation plant to increase by 26.8% while removing 96.5% of the CO_2. The economics for the CDCL technology is very favorable in comparison to first generation IGCC, oxy-PC, or amine based post combustion CO_2 capture systems. While a significant number of technology gaps were identified by the project team in Phase I no fatal flaws for the technology were identified. Given the knowledge that OSU has accumulated regarding oxygen-carrier particle development and B&W's experience with commercial scale moving and fluid bed combustor designs the project team is confident and willing to take the next steps in development of the CDCL technology. If the technology gaps identified in Phase I can be successfully closed through further particle development by OSU and testing by B&W in the 3 MW_t pilot plant, the technology should be ready to move to a large scale demonstration project by 2017. Given success at demonstration scale the technology could be ready for commercial deployment before 2025.

Given the technology gaps identified in Phase 1 it is imperative that further particle development and testing at larger scale is done to close the gaps and give the CDCL technology the opportunity to move closer to commercialization. While the technology looks promising at this stage, enough uncertainty exists that the CDCL technology will not move forward with any speed without continued financial support from the DOE. The project team recommends that further particle development be continued and that a 3 MW_t pilot plant be built to demonstrate the key performance parameters of the Coal Direct Chemical Looping Process. The team believes the 3MW_t plant is large enough to effectively demonstrate the operating parameters necessary for moving the technology to large scale but small enough to be built at a reasonable cost. B&W believes that a 3 MW_t pilot plant is sufficient to permit auto thermal operation and evaluate coal distribution, heat transfer effects in the fluid bed combustor, and oxygen carrier and char residence times. These are the key parameters that must be characterized at this demonstration scale.

The Technology Gaps Report outlines the areas of the CDCL technology that require further study. While several areas of uncertainty are identified, the chemical and mechanical performance of the oxygen carrier particle is the parameter that has the biggest impact on the overall performance and cost of the CDCL Power Plant. Any improvement to the kinetics of the particle has a direct positive impact on reducing the size and capital cost of the plant. Given the volume of particles required in the system, any improvement to the mechanical performance of the particle i.e. increased attrition resistance or increased reactivity results in less particle replacement and lower operating cost. For example, if the oxygen carrier particle residence time is decreased by 40% (60 min to 40 min in the reducer), then the COE decreases from 26.8% to 24.7%. This is a significant decrease in capital cost. Additionally, if the oxygen carrier particle manufacturing cost decreases from $1199.50/ ton to $693/ton, the COE decreases from 26.8% to 24.4%. Combining the effect of decreasing the reducer size and lowering the oxygen particle manufacturing costs will reduce the increase in COE from 26.8% to 22.4%.

While the particle design is important it is still necessary to prove the ability to feed and evenly distribute the coal with the particles, separate the particles from the coal ash, transport the particles to the combustor, regenerate the particles, control emissions and successfully extract heat from the process to produce steam and electricity, hence the need for the pilot facility.

The project team believes that the recommended actions can eliminate the technical uncertainties and improve the CDCL process economics.