FINAL TECHNICAL REPORT

10 MWe COAL DIRECT CHEMICAL LOOPING (CDCL) LARGE PILOT PLANT TEST – PHASE I FEASIBILITY

March 31, 2019

SUBMITTED UNDER FUNDING OPPORTUNITY ANNOUNCEMENT

DE-FOA-0001788

SUBMITTED BY

The Babcock & Wilcox Company
20 South Van Buren Avenue
Barberton, Ohio 44203

PRINCIPAL INVESTIGATOR

Luis Velazquez-Vargas
Phone: 330-860-6203
Fax: 330-860-6676
lvargas@babcock.com

SUBMITTED TO

U.S. Department of Energy
National Energy Technology Laboratory

TABLE OF CONTENTS

Introduction 4

Phase I Project Objectives 5

Overview 8

Technical and Team Status 8

MRC-1. Scientific and Technical Merit 9

A. CURRENT READINESS OF THE PROPOSED TECHNOLOGY TO BEGIN LARGE-SCALE PILOTING 9

B. READINESS OF THE PROJECT TO BEGIN FEED STUDY 22

C. ADEQUACY OF SCALE AND TIME FRAME OF THE PROPOSED LARGE CDCL PILOT 39

D. CDCL COST OF ELECTRICITY AND TECHNO-ECONOMIC ANALYSIS 42

E. PRELIMINARY COST ESTIMATION AND SCHEDULE FOR PHASE III 44

F. DETAILED COST ESTIMATE AND SCHEDULE FOR PHASE II 50

MRC-2. Applicant/Team Capabilities and Facilities 50

A. HOST SITE SELECTION AND PERMITTING 50

B. STENGTH AND PREVIOUS EXPERIENCE OF THE ORGANIZATION PERFORMING FEED STUDY 58

C. STRENGTHS AND COMPLETENESS OF THE REST PHASE II PROJECT TEAM (ASIDE FROM THE FEED ORGANIZATION) 60

D. PROJECT TEAM ORGANIZATION, ROLES, RESPONSIBILITIES, AND KEY PERSONNEL 63

E. AVAILABILITY OF PERSONNEL, FACILITIES AND EQUIPMENT TO PERFORM PROJECT TASKS 65

F. COMPLETENESS OF FINANCIAL INFORMATION AND CONSISTENCY WITH THE FUNDING REQUIREMENTS FOR PHASE II 67

G. LIKEHOOD OF THE TEAM TO SECURE COST SHARE FOR PHASE III 67

MRC-3. Technical Approach and Understanding 68

A. ADEQUACY AND FEASIBILITY OF THE APPLICANT'S APPROACH 68

B. FEASIBILITY, APPROPRIATENESS, RATIONALE, AND COMPLETENESS FOR THE PROPOSED STATEMENT OF PROJECT OBJECTIVES 71

C. ADEQUACY AND COMPLETENESS OF THE PROJECT MANAGEMENT PLAN . 72

Appendices to the Topical Report 1

APPENDIX A: Environmental Information Volume 1

APPENDIX B: Bibliography and References 2

APPENDIX C: Facilities & Other Resources 3

APPENDIX D: Equipment 9

INTRODUCTION

The Coal Direct Chemical Looping (CDCL) process, invented by the Ohio State University (OSU) and in commercial development by The Babcock and Wilcox Company (B&W), is considered a next-generation technology that is a transformative approach to power generation from coal with CO_2 capture. CDCL is an oxy-combustion process where the oxygen separation is done using an oxygen carrier, eliminating the need for an energy-intensive and expensive cryogenic air separation unit. In a comprehensive economic assessment of the commercial-scale 550 MWe CDCL process for power generation with 96.5% carbon capture (DE-FE0009761), B&W concluded the estimated increase in levelized cost of electricity (LCOE) compared to a conventional pulverized coal (PC) power plant with no carbon capture is 26.8%, while the increase in LCOE for a PC power plant with post-combustion amine-based scrubbing for 90% carbon capture is 63.7%. Compared with other oxy-combustion technologies operating with a cryogenic air separation unit, the simple yet unique design of the CDCL technology creates one of the most predictable, well-defined pathways toward commercialization, while achieving high carbon capture at low cost.

The CDCL process uses a unique counter-current gas-solid moving-bed reactor design for the reducer. In the reducer reactor, gasified coal and coal volatiles react with the iron-based oxygen carrier particles forming normal combustion products, predominantly CO_2 and H_2O, while reducing the oxidation state of the oxygen carrier from Fe_2O_3 to predominantly FeO. The reduced oxygen carrier particles are then sent to a dense-phase fluidized-bed combustor reactor where air is used to re-oxidize the oxygen carrier. The oxygen carrier oxidation reaction releases large amounts of heat, which is used for steam production. The steam produced is sent to a steam turbine for electricity generation. The CO_2 and H_2O produced in the reducer are cooled, dried, cleaned, and compressed for sequestration or industrial use. Part of the CO_2 and H_2O stream is recycled to convey the coal to the reducer reactor and to serve as enhancer gas to promote char gasification on the lower section of the reducer. **Figure 1** (left) summarizes the moving-bed reducer design. The combustor reactor, shown in **Figure 1** (right) is designed with B&W's unique and commercially proven in-bed heat exchanger (IBHX) system to maximize plant efficiency and control the operating temperature of this fluidized-bed reactor. The unique moving-bed reducer design combined with a highly reactive and attrition-resistant oxygen carrier particle allow the CDCL technology to be a highly economical and a scalable approach to coal-fired power generation with CO_2 capture.

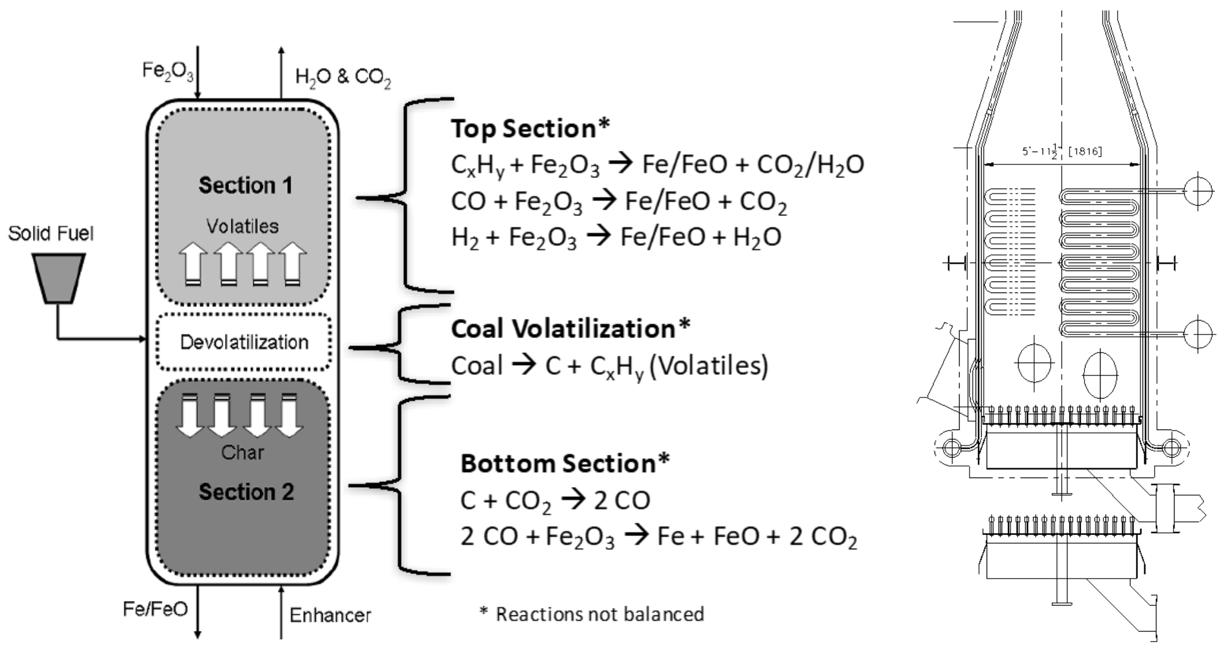


Figure 1. (Left) Conceptual Design of Moving Bed Reducer with Primary Reactions; (Right) Fluidized-bed Combustor with B&W's IBHX Design Incorporated

PHASE I PROJECT OBJECTIVES

The overall Phase I project Objective was to secure all commitments from each team member involved in the design, construction and operation of the 10 MWe CDCL large pilot plant in order to commence the Phase II Front-End Engineering Design (FEED) of the 10 MWe CDCL test facility. Work on this objective required a firm commitment from the test site host, Dover Light & Power (DL&P) and cost estimates and cost share commitments from all team members. Further, the Phase I activities also included estimating the cost of all major components of the 10 MWe large pilot facility; developing a schedule for design, construction and operation completion; and completing an Environmental Information Volume (EIV) for the DL&P host site. The specific Phase I objectives are listed below and their current status as of this report submission.

SPECIFIC PHASE I OBJECTIVES

- Select an appropriate site for construction and/or hosting of the CDCL large-scale pilot.
    - Complete – DL&P selected and committed to hosting the CDCL 10 MWe facility

- Secure commitments from the proposed host site.
    - Complete – DL&P selected and committed to hosting the CDCL 10 MWe facility

- Complete an EIV to assess National Environmental Policy Act (NEPA) study-related issues.
    - Complete – Complete with the support of DL&P and Trinity Consultants

- Secure commitments from all team members necessary for Phase II (Design). This includes a FEED contractor and a NEPA contractor.
    - Complete – Team members selected, all under contract with B&W with defined scope for Phase II. The Team includes **Dover Light & Power** (host site), **Babcock & Wilcox** (Engineering and Project Management), **Ohio State University** (Technology and Particle Supplier), **Trinity Consultants** (NEPA Contractor), **WorleyParsons** (Balance of Plant and Civil Engineering), **Electric Power Research Institute** (Techno-economic Analysis and utility perspective), and **Clear Skies Consulting** (Industrial Review Committee and Advisor).

- Update the preliminary cost and schedule for Phases II and III (Construction/Commissioning/Operation).
    - Complete – Phase II schedule includes team member roles

- Secure any needed recipient cost share commitments for Phase II.
    - Complete and provided in letter of commitment package and summarized in recipient budget justification spreadsheet

- Develop a plan for securing any needed recipient cost share for Phase III
    - Complete – DL&P providing major equipment cost share. In addition, OSU and B&W in negotiations with industrial committee partners and State of Ohio for cost share support of Phase III

SPECIFIC PHASE II OBJECTIVES

Phase II objectives are to incorporate all design information and prepare a full cost and schedule for Phase III work. The specific objectives are:

- Complete the FEED study for a 10 MWe CDCL pilot facility incorporated into the DL&P Plant, the selected host site.
- Complete a NEPA study for the selected host site.
- Complete the Permit-To-Install application for the State of Ohio Environmental Protection Agency (EPA).
- Update the Techno-Economic Analysis (TEA) for the commercial-scale CDCL system.
- Update the preliminary cost and schedule for Phase III.
- Secure commitments from all team members necessary for Phase III.
- Secure cost-share commitments from team members and industry partners for Phase III.
- Submit the final report and recipient recommendation (proposal) for Phase III.

SPECIFIC PHASE III OBJECTIVES

To mitigate risk, Phase III will first consist of the construction and testing of one 2.5 MWe first-of-a-kind CDCL module along with the full balance-of-plant components. Heat produced from the modular 10 MW_e CDCL large-pilot facility will be used to drive a subcritical steam turbine to produce electricity in order to support the City of Dover's power requirements. After the first module is tested, lessons learned from the first module will be incorporated into the design, if needed, of the remaining three 2.5 MWe modules prior to their installation at the site. Finally, all four modules will be operated together to demonstrate the generation of 10 MWe of power. The goal of Phase III is to perform multiple parametric tests of the four modules under a wide range of operating conditions to fully demonstrate boundaries of the technology on operability and performance/emissions limits. At the completion of the parametric testing, the CDCL 10 MWe will be released to the City of Dover for continued power production.

OVERVIEW

Please note that as suggested by the DOE, the applicant has addressed all of the merit review criteria (MRC) required in the proposal here in this Phase I Topical Report. The DOE suggested this approach to reduce redundancy between the Project Narrative and Topical Report.

TECHNICAL AND TEAM STATUS

As stated in the Statement of Project Objectives (SOPO) for Phase I, the following items in Table 1 were required to be addressed in the Phase I Topical Report. These items correspond to specific MRC in the Phase II proposal. For the convenience of the Phase II proposal reviewers, the MRC are presented in the Topical Report in the order that is required by the FOA.

Table 1. Cross Index of Topical Report Items and MRC for Proposal

Item Description	Corresponding MRC
Technical Status	
Pre-FEED large-scale pilot design basis	MRC-1B
Status of the technology development	MRC-1A
Choice of scale for the large pilot	MRC-1C
Detailed cost estimate and schedule for Phase II	MRC-1F
Preliminary cost estimate and schedule for Phase III	MRC-1E
Preliminary Techno-Economic Assessment (TEA)	MRC-1D
Team Status	
Host site selection	MRC-2A
Other team member status for Phases II and III	MRC-2C
Status of recipient cost share for Phases II and III	MRC-2F and MRC-2G

MRC-1. SCIENTIFIC AND TECHNICAL MERIT

A. CURRENT READINESS OF THE PROPOSED TECHNOLOGY TO BEGIN LARGE-SCALE PILOTING

The OSU CDCL program has an extensive history of continuing support from the DOE and is being developed aggressively in all possible scientific and engineering aspects to close all remaining technology gaps for it to be ready for commercialization. The major challenges in taking chemical looping combustion technologies to industrial practice are the development of a highly reactive, attrition resistant oxygen carrier that can be produced at commercial scales and a chemical looping reactor system design that can exploit the capabilities of the oxygen carrier in order to maximize fuel conversion to CO_2 and steam. OSU has developed a moving-bed chemical looping combustion reactor design to take advantage of the multiple oxidation states in an iron-based oxygen carrier and synthesized the oxygen carrier particle with the desired physical properties to maintain a moving-bed gas-solid flow pattern in the reducer and combustor reactors. The present section highlights the accomplishments of OSU oxygen carrier material development and B&W's demonstration of the moving-bed chemical looping reactor design.

OXYGEN CARRIER: A key aspect of the CDCL technology readiness is the maturity of the developed oxygen carrier. A commercially viable oxygen carrier must have high physical strength, recyclability, and reactivity characteristics that prevent excessively high oxygen carrier make-up costs due to elutriation and/or deactivation. The OSU oxygen carrier particle is iron based. Table 2 summarizes the crushing strength of the OSU's oxygen carrier particle compared to commercially available catalysts as well as iron-based oxygen carriers developed by other chemical looping research groups to date. The OSU oxygen carrier exhibits a particle crush strength that is an order magnitude stronger than traditional catalysts and over 66% greater than any other chemical looping oxygen carriers developed to date in open literature. Jet cup studies prove the OSU oxygen carrier has greater abrasion resistance than commercial FCC catalysts. These tests were conducted in a customized conical-shaped jet cup attrition measurement device. The results show that the OSU oxygen carrier achieves an attrition index of 5%, which is nearly 4 times lower than commercial FCC particles that have attrition index of 14-22% [Weeks and Abad]. Physical resistance to attrition is readily achievable in chemical looping combustion systems due to the formation of Al based skeleton structure in the oxygen carrier. However, another major cause of attrition is related to chemical stress induced on the oxygen carrier due to the cyclic change in the crystal structure occurring during the redox reactions. In addition, over multiple redox cycles, migration of the iron cations may be observed due to a lower ionic diffusion resistance for iron cations than oxygen anions during oxidation reaction, if an inappropriate support (or no support) material is used. Iron cation diffusion can result in a loss of the active material via abrasion in a fluidized bed, resulting in deactivation of the oxygen carrier over time. Chemical stress induced attrition and iron diffusion are major challenges when considering the use of naturally occurring ores or manufacturing byproducts, such as ilmenite and red mud, directly. Additionally, a correct support in the right quantity helps improve and maintain the reactivity over several redox cycles.

With the incorporation of support materials in the oxygen carrier to promote ion vacancies for reduced oxygen anion diffusion and the Al-based skeleton to stabilize the lattice structure of the oxygen carrier through each redox cycle, the OSU oxygen carrier has been experimentally proven to be able to sustain up to 3000 cyclic redox reactions at 1000 °C without any chemical and physical degradation of the particle, as illustrated in Figure 2. In comparison, most oxygen carriers reported in literature suffer some loss in either chemical or physical performance before completing even 1000 redox recycles cycles above 900°C. The 3000 redox cycles completed correspond to over 6 months of operation in a commercial CDCL plant. Recent demonstrations in two different 250 kW_t pilot-scale chemical looping units using OSU oxygen carriers of the same design have yielded excellent results regarding the reactivity and attrition resistant of the oxygen carrier. OSU's oxygen carrier has been demonstrated for >360 hours of continuous operation in the high-pressure, high-temperature Syngas Chemical Looping (SCL) reactor (DE-FE0023915) located at the National Carbon Capture Center (NCCC). No particle make-up was performed due to negligible loss in particle inventory from solid circulation, resulting in a particle attrition rate well below 0.02 wt%/hr of the total inventory per oxidation/reduction cycle. The SCL reactor hard-face refractory consisted of a dense high alumina content ceramic. The hardness of the refractory matched closely with the particle resulting in no observable refractory erosion as well. The pilot demonstration results indicate the suitability of the oxygen carrier hardness for abrasion resistance against commercial-grade refractories like the design proposed for the 10 MWe CDCL pilot plant.

Table 2. Particle Strength Comparison of Particles Commonly Used in Chemical Processes

Oxygen Carrier / Catalyst Particle	Average Strength (MPa)*
OSU Working Oxygen Carrier	120
Chemical Looping Combustion	72
Chemical Looping Steam Reforming	26
Commercial WGS Catalyst Pellet	6.8
Traditional ATR Catalyst	6.5

*Strength based on reported crush force and mean particle diameter

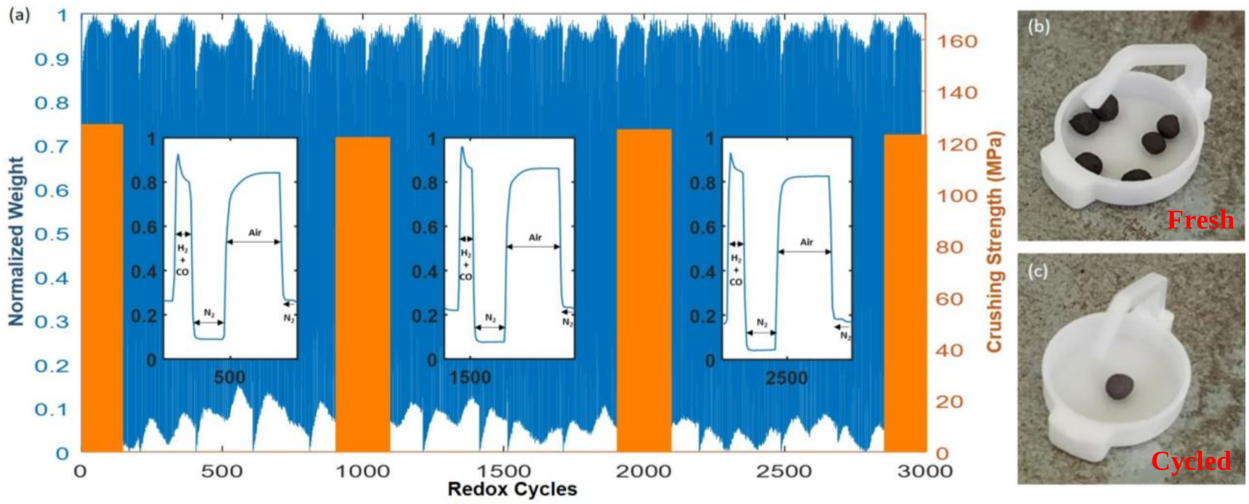


Figure 2. Long-term Cyclic Redox Test of OSU Oxygen Carrier Particles at 1000 ^{o}C. Reduction: $CO/H_2/CO_2/N_2$. Oxidation: Air.

The production method of oxygen carriers has been optimized with respect to various parameters as the cost of particle production adds to the overall economics of the technology. This optimization and economic evaluation have been done in collaboration with Johnson Matthey. Production of oxygen carrier particles includes two broad unit operations, synthesis of green particles and calcination of green particles to obtain ready-to-use oxygen carrier particles. Green particle refers to the pre-sinter compact of the metal oxide powder. Different techniques of particle manufacture have been tested to produce the green particles. These techniques have been investigated against the redox performance of the oxygen carrier, mechanical strength, and scalability of the technique. Other considerations include incorporation of ilmenite ore in place of iron and titanium to substantially reduce the raw material costs. Performance of oxygen carrier particles made using ilmenite was tested against the ones made using chemical-grade Fe_2O_3 and TiO_2. Experimental results showed similar reduction and oxidation behavior of both the compositions over several redox cycles. Post-processing of green particles involves calcining them at temperatures higher than the sintering temperature for an extended period in air. This step ensures interaction between the active metal oxide and the support, which imparts strength to the particles. The calcination step has been optimized to reduce the overall energy requirement of particle production without affecting the particle's performance. Based on these optimization steps, the overall process diagram for particle production is currently being established. Also, economic analysis and generation of cost curves for large-scale oxygen carrier production is currently being developed in collaboration with Johnson Matthey. Therefore, the OSU developed oxygen carrier is considered ready for the 10 MWe demonstration scale.

CDCL REACTOR DESIGN: Pilot test runs at the 250 kW_t SCL pilot facility at the NCCC and B&W's 250 kW_t coal direct chemical looping pilot facility demonstrate the feasibility of OSU's chemical looping technology. The SCL process incorporates the concepts of counter-current moving-bed reducer, fluidized-bed combustor, non-mechanical gas sealing and solid flow control, and the instrumentation and control architecture design at an industrially relevant scale that are directly applicable and scalable to large-scale demonstrations of the CDCL processes. The novel use of the non-mechanical L-valve was proven at the small pilot scale to provide high flexibility and control over the circulation rate of oxygen carriers at high temperature and pressure. The design knowledge and operating experience gained by the OSU and B&W project team included, but is not limited to, the following: effective communication with a multidisciplinary team; coal input and distribution in the 250 kW_t reducer; distributed control system development; and experimentally validated plant commissioning, startup, and shutdown procedures. Such knowledge and experience reduce the risk that the design, construction and operation of the CDCL 10 MWe plant will be completed on schedule, within budget, and safely.

The project team constructed and successfully commissioned a 250 kW_t CDCL pilot facility at the B&W Research Center under a DOE-sponsored project (DE-FE0009761) in 2017. Under this program many of the identified technology gaps associated with the reactor design and oxygen carrier performance were addressed through laboratory-scale testing and the 250 kW_t CDCL pilot testing in 2016-2017. Based on two operating campaigns in 2017, the project team achieved the design temperature of the pilot reactor while maintaining good control of the oxygen carrier circulation rate. Gas analysis during the initial coal injection testing showed the complete conversion of the evolved volatiles which indicates sufficient reactivity of the OSU oxygen carrier. From 2018, three test campaigns of the 250 kW_t CDCL pilot facility have been executed under a DOE-sponsored Pre-FEED 10 MWe CDCL project (DE-FE0027654). During the recent long-term operation in early 2019, the project team achieved 35 hours of continuous coal injection operation while the coal conversion could reach 95% and CO_2 purity (N_2 free) was maintained around 97%. This indicates that the design of counter current moving bed reducer reactor is sufficient to obtain high coal conversion as well as CO_2 purity. Figure 3 shows the coal conversion, CO_2 purity and the uncontrolled emissions of SO_2 and NO_x from the reducer of a representative period in the 35-hour operation window. The concentrations of SO_2 and NO_x are recorded as shown in Figure 3c to obtain uncontrolled emission data to support the design of downstream emission control system in the 10 MWe pilot unit. Including this 35-hour coal injection period, parametric study was conducted to study the influence of coal injection mass flow rate on the CDCL pilot unit. Overall, 62 hours of operation with coal injection was completed and the parametric study shows that the CDCL pilot unit can handle coal injection rates between 8 lbs/hr to 40 lbs/hr while still maintaining CO_2 purity at 95% to 99%. Additionally, from the gas analysis data collected while injecting coal, H_2S cannot be detected from the unit, indicating good sulfur conversion and uncomplicated demand on flue gas conditioning system in the CDCL process. During this long-term continuous operation with coal injection, the attrition rate of the OSU oxygen carrier was estimated to be around 0.02 wt%/hr, the lowest value that has been reported by any chemical looping developer at chemical looping conditions; and further experiments showed that the strength and reactivity of particle was maintained after the long-term operation.

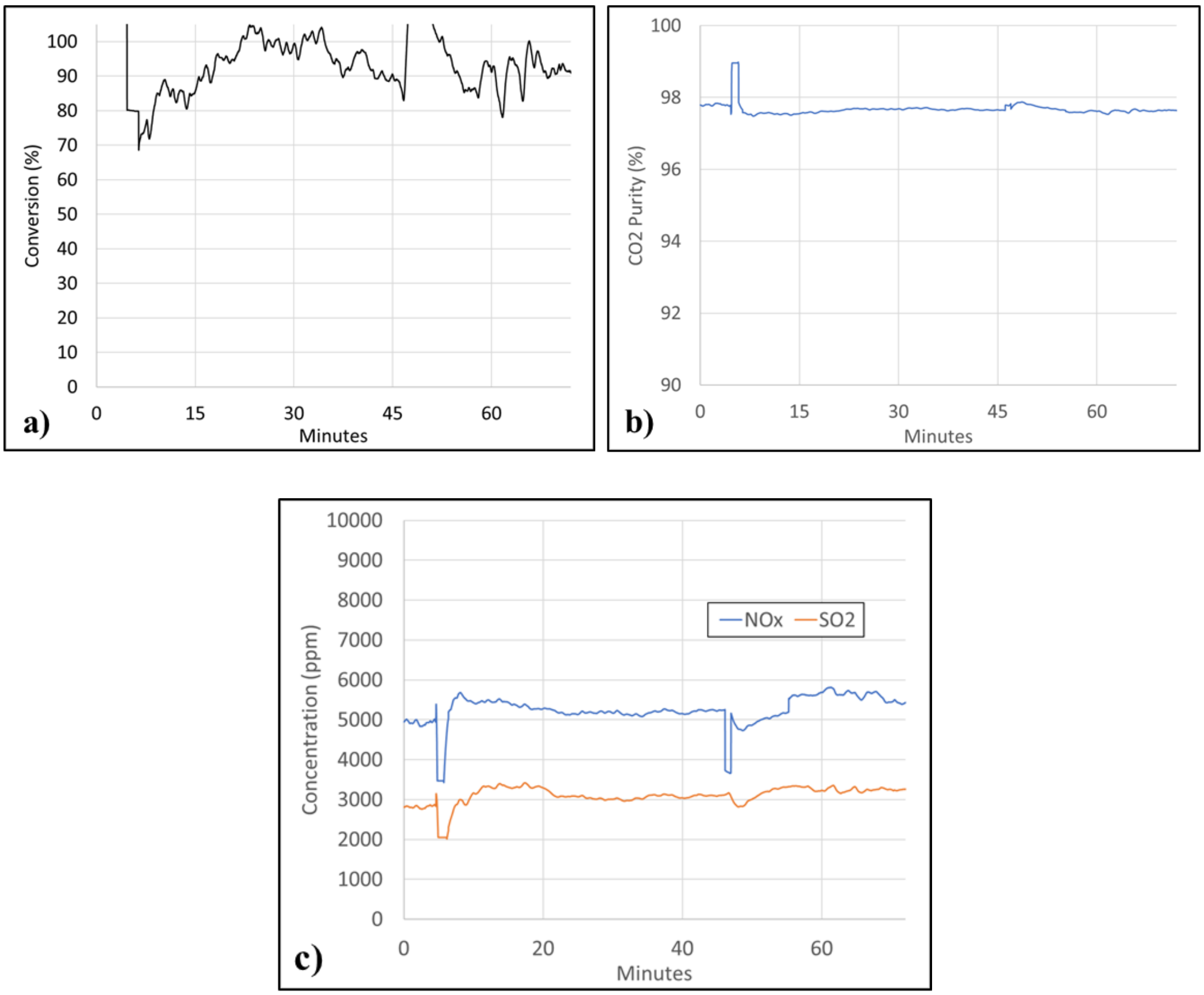


Figure 3. 250 kW_t CDCL Pilot Facility Performance: a) Coal Conversion; b) CO_2 Purity (N_2 Free); c) Uncontrolled SO_2 and NO_x Emissions from Reducer Reactor

The results from the 250 kW_t CDCL small pilot unit, including the combined effects of alkali contamination, ash separation, sustained particle reactivity, and char residence time on coal conversion, will be used in the design of the proposed large pilot plant. The remaining scale-dependent technology gaps, such as coal distribution in a large 2.5 MWe moving-bed reducer module and integration of the steam cycle with the fluidized-bed combustor, remain. However, the team has a detailed plan to resolve these gaps in the current 10 MWe Pre-FEED pilot plant project.

CDCL PROCESS OPERATION AND INTEGRATION: In addition to a successful long-term coal injection test in the 250 kW_t CDCL pilot unit under Pre-FEED study, the project team also achieved 288 hours of continuous operation with no halt of solid circulation in the CDCL pilot unit during the most recent test campaign in early 2019. Figure 4 illustrates the temperature profile in reducer and combustor reactor along the entire operation period. Reliable operability of CDCL process is shown from the temperature profile as once the designed system temperature was reached, the 250 kW_t CDCL unit maintained the operation condition until scheduled system shutdown. Additionally, the mass flow rate of solid circulation was recorded periodically as shown in Figure 5, which indicates the ability of the 250 kW_t CDCL unit to handle 1000 lbs/hr to 7000 lb/hr solid flow rate.

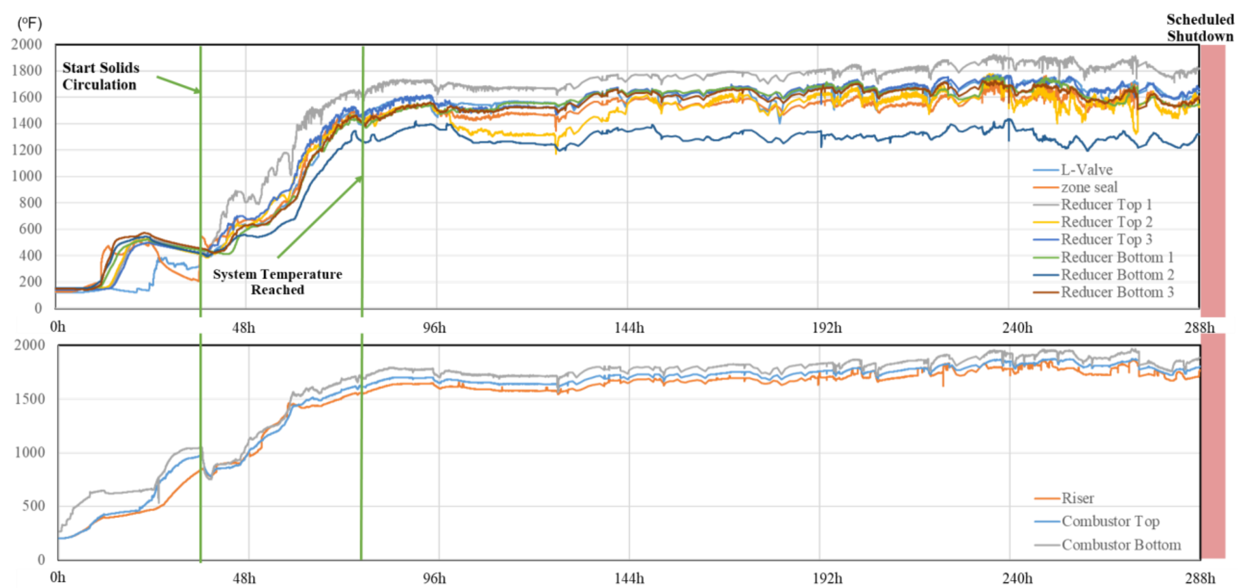


Figure 4. Temperature Profile of 250 kW_t CDCL Facility from Early 2019 Operation

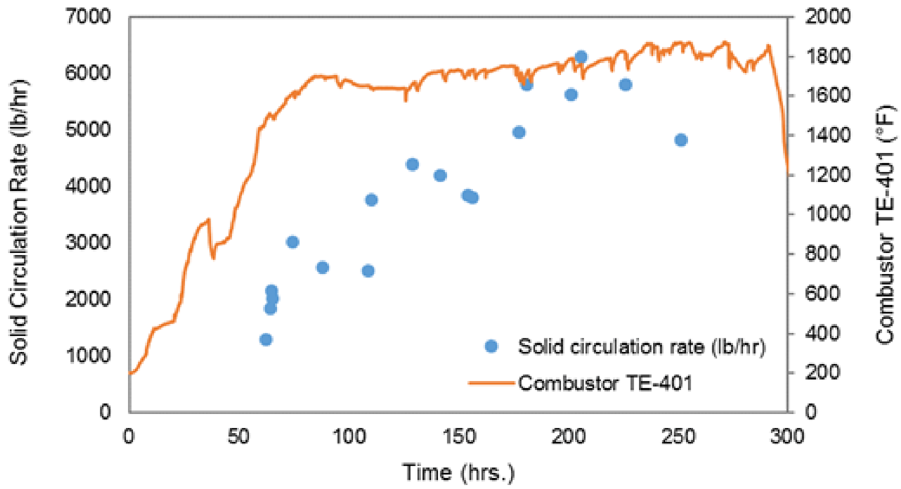


Figure 5. Solid Circulation Rate During Early 2019 Operation

From the five test campaigns on the 250 kW_t CDCL pilot unit in 2017-2019, several requirements on operation were configured and planned to be incorporated in the operation of 10 MW_e CDCL unit. While coal was gasified and oxidized by the combination of enhancer gas (steam or CO_2) and OSU oxygen carrier particle in the reducer reactor of the CDCL process, any oxidative agent with higher oxidation capability than enhancer gas and particle need to be avoided in the reducer to prevent possible local hot spot and agglomeration. So, the reducer reactor of the CDCL process was operated slightly higher than ambient pressure, different from conventional coal-fired boilers where the operation pressure is slightly lower than ambient pressure. The operation pressure requirement influences the operation of the coal feeding system and downstream gas conditioning equipment, which will be included in the design of 10 MWe CDCL unit. The project team has improved the procedure of CDCL system heat up to save start-up time and protect oxygen carrier particles. Preheated air is first introduced to heat reducer and combustor reactor, including particle. After reaching the temperature limit of air heating, the air flow rate is increased to fluidize combustor reactor and the direct fired burner is lit up after fluidization to further heat up the system. The burner stoichiometry ratio is controlled above 2, corresponding to a flame temperature below

2200 °F, to protect the particles (see Figure 6). Once the autoignition temperature of natural gas (1100 °F) was reached in the bed, natural gas was gradually switched to the injection nozzle at the bottom of the combustor to further heat up the system while minimizing the usage of the direct fired burner. Overall, the experience from the operation of the 250 kW_t CDCL unit will be incorporated in the design and operation of the 10 MWe CDCL unit.

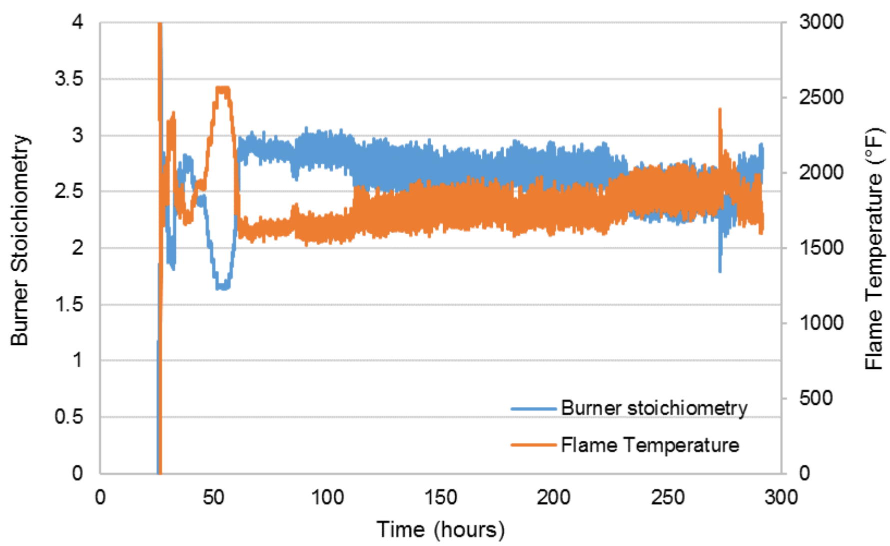


Figure 6. Start-up Burner Stoichiometry Ratio and Flame Temperature

Under another DOE-sponsored project (DE-FE0029093), thermal integration of a 10 MWe CDCL plant with a steam cycle and their dynamic interactions are being simulated to assist in the design and control development of the CDCL large pilot. A computational fluid dynamic model of the combustor is being developed to model solids distribution and heat transfer. ProTRAX, a dynamic simulation model platform, is being used to simulate the 10 MWe scale plant to evaluate operating schemes for start-up, shutdown and load following for a 4-module chemical looping plant integrated with a steam turbine.

Under a previous DOE/ODSA-funded project (DE-FE0026334/D-15-06), software and hardware technologies that could significantly enhance the control, automation, and optimization of chemical looping processes have been developed. A hybrid control architecture was developed to integrate an advanced control algorithm with industrial distributed control system (DCS) and B&W's commercial online optimization software FocalPoint. An advanced sensor based on the electrical capacitance volume tomography (ECVT) technology was developed to measure real-time solid circulation rate in chemical looping processes, which enables online optimization and diagnosis of system operation. These developments have enabled fully autonomous startup and ramp-up/ramp-down operation of the sub-pilot scale chemical looping system at OSU.

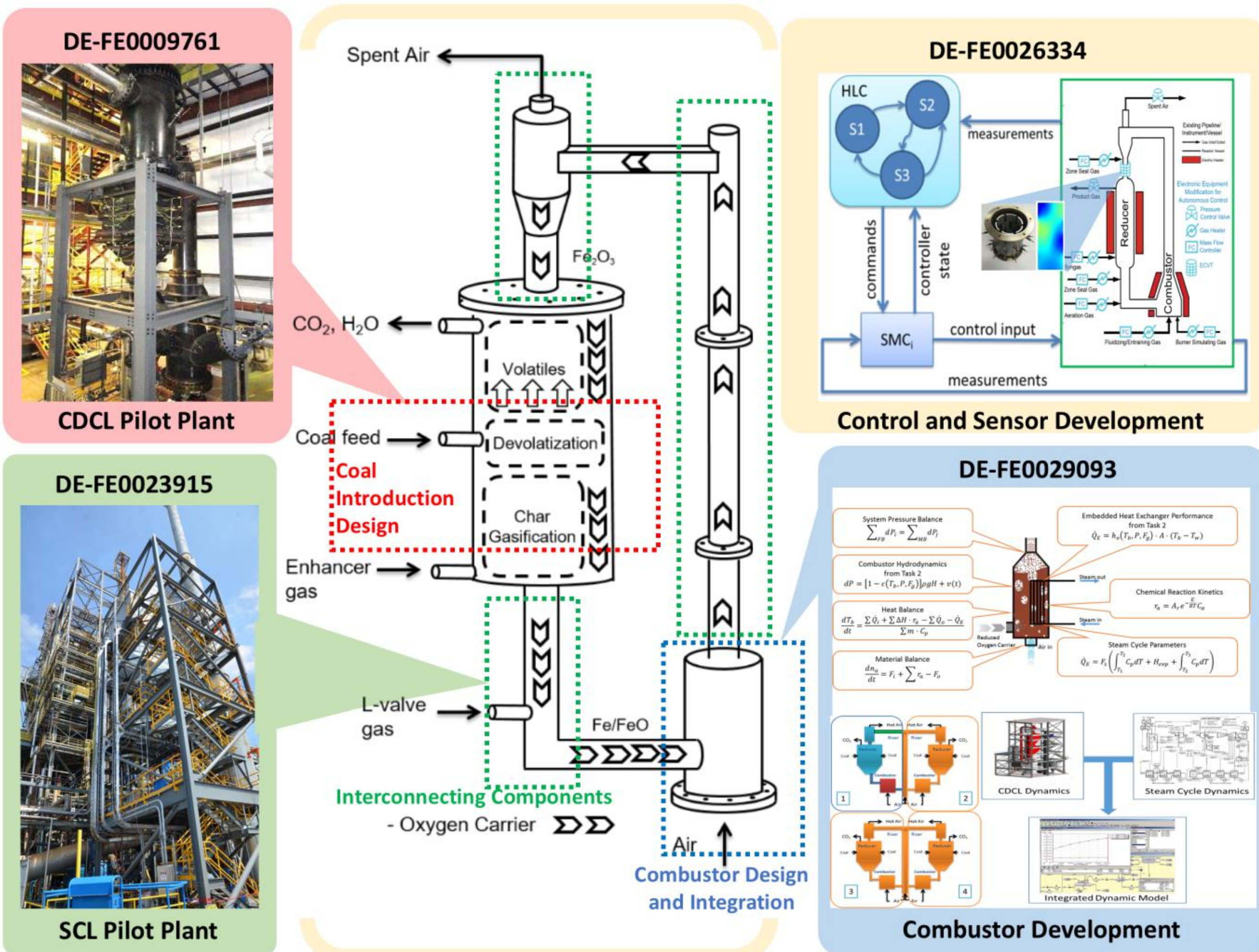


Figure 7. Connection of Past and On-Going Projects Supporting the Commercialization of CDCL Technology in Addition to the Pre-FEED Study (DE-FE0027654)

To illustrate the extent to which the CDCL process has been supported by past and current projects, Figure 7 above depicts the connection between the past and current projects in relation to the proposed large pilot demonstration of the CDCL technology.

TECHNICAL READINESS LEVEL EVALUATION: The current technology readiness level (TRL) of the CDCL system is approaching TRL-6, which requires a pilot unit that is 1-5% the size of a commercial unit with prototype components whose design and function are essentially the same as expected for full-scale deployment. The Electric Power Research Institute, Inc. (EPRI) has made this assessment based on its review of the technology and its progress. EPRI has significant experience in assessing and tracking technology TRLs across the power industry in an unbiased manner. Table 3 gives a summary of the steps that have been taken to achieve near TRL-6.

Table 3. TRL Assessment for the CDCL Technology

TRL	Description	Summary of Work Done	Comments
1	Basic principles observed and reported	Several patents have been filed starting in 2004 around CDCL and the basic elements it is composed of and early documents have been published discussing its underpinnings: • "Combustion Looping Using Composite Oxygen Carriers," T. Thomas, L.-S. Fan, et al., U.S. Patent 11,010,648, 2004. • "Hydrogen Production from Combustion Looping (Solids-Coal)," P. Gupta, L. G. Velazquez-Vargas, et al., Proceedings of the Clearwater Coal Conference, 2004. • "Systems and Methods of Converting Fuels," L.-S. Fan, P. Gupta, et al., PCT International Applications WO 2007082089, 2007.	These documents and their statements have been reviewed by EPRI and the original work has been discussed with B&W and OSU. These documents provide evidence of achieving TRL-1 and TRL-2.
2	Technology concept and/or application formulated		
3	Analytical and experimental critical function and/or	Development of the CDCL concept was largely led by OSU with the development of a flow sheet and computer model and bench-scale, proof-of-concept cold-flow models.	Documents and their statements have been reviewed by

TRL	Description	Summary of Work Done	Comments
	characteristic proof-of-concept validated	Significant oxygen carrier work was also performed. Numerous reports and papers have been published on the topic including: • "Chemical Looping Technology and Its Fossil Energy Applications," L.-S Fan and F. Li, I&EC Research, 49, 2010. • "Chemical Looping Processes for Clean Coal Conversion," S. Bayham and L-S. Fan, Eastern Coal Council, May 2013.	EPRI and the original work has been discussed with B&W and OSU. These provide evidence of achieving TRL-3.
4	Basic technology components integrated and validated in a laboratory environment	A 25 kW_t sub-scale pilot was built at OSU in the 2010 timeframe to perform testing on core components of the CDCL system. Significant testing has occurred over the last decade as the facility has achieved nearly 1000 hours of operational experience and over 200 hours of continuous operation. Numerous reports and papers have been published on the topic including this summary: "Coal Direct Chemical Looping (CDCL) Retrofit to Pulverized Coal Power Plants for In-Situ CO_2 Capture," DE-NT0005289, 2012.	EPRI has reviewed the work for this stage of the TRL having been involved in sessions detailing testing and test results and read associated technical reports. Based on this review, the technology has achieved TRL-4.
5	Basic technology components integrated and validated in a relevant environment	Both the construction and testing of the 25 kW_t and 250 kW_t CDCL pilots provide evidence that the basic components of the system (especially the reactors) have been validated in a relevant environment. Multiple reports have been published on these pilots including this summary: "Commercialization of the Iron Base Coal Direct Chemical Looping Process for Power Production with in situ Carbon Dioxide Capture," FE0009761, 2012.	EPRI has reviewed the work for this stage of the TRL. Note that TRL-5 was largely accomplished in conjunction with the advancement of TRL-6.
6	Pilot unit of ~1–5% of full scale in size with prototype components whose design and function are	A 250 kW_t CDCL unit constructed in Barberton, OH has undergone significant testing to show key characteristics of chemical looping operation over representative run times (hundreds of hours) including reactor temperatures of nearly 1000^{o}C, near complete carbon conversion, and appropriate carrier	EPRI has reviewed the work for this stage of the TRL having visited the 250 kW_t facility, been involved in

TRL	Description	Summary of Work Done	Comments
	essentially the same as expected for full-scale deployment has been deployed	flow and behavior in the system. However, the pilot is not complete. It lacks a power generation island and some of the backend environmental equipment and requires heating to operate. The power island and environmental controls are considered unnecessary for validation of the novel components of the system but require a larger-scale design. Requiring heat to operate is endemic of the scale of the 250 kW_t pilot and should not be required at larger sizes.	sessions detailing testing and test results, and read associated technical reports. Based on this review, the technology has been deemed as approaching TRL-6.

Testing the 10 MWe pilot proposed in this project integrated with a steam turbine under a representative operational environment will raise the TRL to TRL-7. Assuming success of the 10 MWe large pilot plant, the next step would be to build a single, commercial module 70 MWe demonstration plant in the 2025–2030 timeframe, which would raise the TRL for the technology to TRL-8. Most of the funds for this demonstration plant will likely need to come from a combination of the government, industry, and/or rate payers. Commercial units sized from 100-550 MWe would then follow successful operations of the 70 MWe demonstration plant, scheduled to be available after 2030.

B. READINESS OF THE PROJECT TO BEGIN FEED STUDY

Location and Environment of Proposed Plant Including Ambient Conditions

Based on the assessment of potential host sites, DL&P Municipal Plant, located in Dover, OH, serves as the ideal host site for the demonstration of the 10 MWe CDCL technology. A host site test agreement has been signed and become effective between B&W and DL&P. The environment and ambient conditions at DL&P are listed in Table 4.

Table 4. Environmental and Ambient Conditions at DL&P

Parameter	Units	Value
Elevation (City of Dover, OH)	m	268
Standard Temperature	°C	0
Standard Pressure	atm	1
Minimum Temperature	°C	-23
Maximum Temperature	°C	40.6
Nominal Barometric Pressure	kPa	97.7
Ambient Pressure[1]	kPa	101.35
Ambient Temperature[1]	°C	27
Cooling Water Temperature (Tuscarawas River)	°C	20
Ambient Humidity[1]	%	60
Reference Temperature (ASPEN)	°C	25
Reference Pressure (ASPEN)	atm	1
Density of water at sp. gr. 1.0	kg/m^3	1000
Density of air at 21 °C, 1 atm	kg/m^3	1.2
Density of air at STP 0°C, atm	kg/m^3	1.2922

1. Standard American Boiler Manufacturers Association (ABMA) atmospheric conditions.

Feedstock Analysis and Cost

The 10 MWe CDCL plant is designed based on the Ohio bituminous coal currently used by DL&P. The coal analysis, ash composition, particle size distribution and grindability are shown in Table 5.

Table 5. DL&P Design Coal Analysis

Coal	As Received (wt.%)	Dry Basis (wt.%)
Moisture	5.40	
Volatile	36.13	38.19
Fixed Carbon	48.98	51.78
Ash	9.49	10.03
Sulfur	1.38	1.46
Carbon	70.08	74.08
Hydrogen	4.77	5.04
Nitrogen	1.58	1.67
Oxygen	7.30	7.72
HHV (Btu/lb)	12563	13280
HHV (kJ/kg)	29221.538	30889.28
Ash Composition		wt.%

SiO_2	56.74
Al_2O_3	24.23
Fe_2O_3	11.50
TiO_2	1.38
P_4O_{10}	0.20
CaO	2.77
Mn_2O_3	0.64
Na_2O	0.51
K_2O	1.58
SO_3	2.27
As Received Particle Size Distribution	% Thru
50800 Microns	100.0
38100 Microns	86.5
25400 Microns	64.2
19000 Microns	49.2
12700 Microns	29.6
6350 Microns	12.0
4760 Microns	9.1
3360 Microns	6.9
2380 Microns	5.4
1190 Microns	3.8
595 Microns	2.8
297 Microns	2.0
210 Microns	1.7
149 Microns	1.4
105 Microns	1.1
74 Microns	0.8
Hardgrove Grindability Index	53

The DL&P bituminous coal costs $64.50/ton delivered to the site. Ash transportation and disposal cost are $200/ton and $11.25/ton, respectively.

Labor Costs

The DL&P plant currently employees 22 personnel at an annual cost of $1,261,500 plus approximately $550,000 overtime cost.

System Boundaries and Site Characteristics

Figure 8 shows the boundaries of the Dover plant and the future CDCL plant. DL&P is located on approximately 4 acres of land in North-Central Tuscarawas County. The land in the immediate vicinity of the Dover Plant is a mix of residential and industrial. The Tuscarawas River is located directly to the north of the plant. The nearest natural-gas transmission pipeline is located approximately 1.8 miles southeast of the Dover Plant. A 138kV transmission line runs from the Dover Plant's substations north across the Tuscarawas River. There is no rail or barge access to the plant. The 10 MWe CDCL unit will be installed in abandoned bays that previously housed boilers within the confines of the existing plant. There may be changes to on-site structures to accommodate equipment, but no additional land will be required.

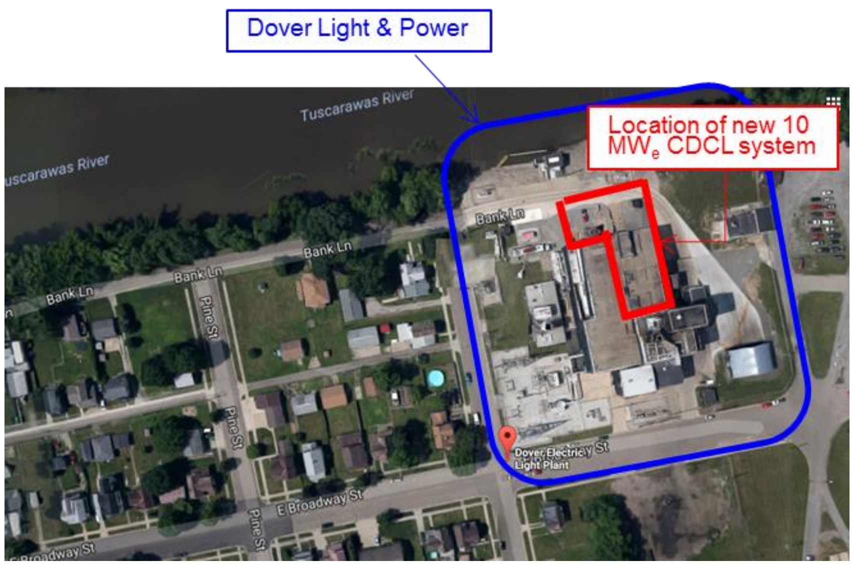


Figure 8. Dover Light & Power System Boundaries

Operating Conditions for Key Equipment and Balance of Plant

DL&P is committed to provide power for almost 1,000 commercial customers and more than 14,000 residents in the local area by the continued use of Ohio coal. Their current power capacity is 20 MWe based on a Stoker boiler. The plant is in full operation for 24/7. To further expand capacity, DL&P plans to use the CDCL 10 MWe plant and a 10 MWe natural gas package boiler to power a recently acquired 20 MWe subcritical steam turbine. The natural-gas package boiler will be purchased prior to the installation of the CDCL System. Outside of this DOE project, DL&P

will contract for the installation of the natural-gas package boiler, add-on steam turbine, and balance-of-plant equipment and upgrade control and electricity systems before the beginning of Phase III of this project. Therefore, the newly added 20 MWe steam turbine and other relevant equipment will be ready for service when Phase III begins.

Environmental Controls and Performance

DL&P uses activated carbon injection to control mercury. Since the coal used by the plant contains low sulfur (1.46 wt.% dry basis), SO_2 emissions are within the emission limit without additional capture. The Stoker boiler has staged combustion, which results in low NO_x emission as well. There is no additional removal of NO_x via selective non-catalytic or catalytic reduction technology. The plant contracts with Trinity Consultants, an environmental consulting firm, to evaluate their emissions and maintain permitting.

Process Flow Diagrams of the 10 MWe CDCL Plant

The 10 MWe CDCL plant process flow diagram developed using Aspen Plus™ is shown in Figure 9. The main systems are the CDCL reactor island, steam turbine island, coal preparation and injection system, cooling water system, CO_2 and air heater system, scrubber and particulate control system, and CO_2 compression system. The design basis of each major system is described below.

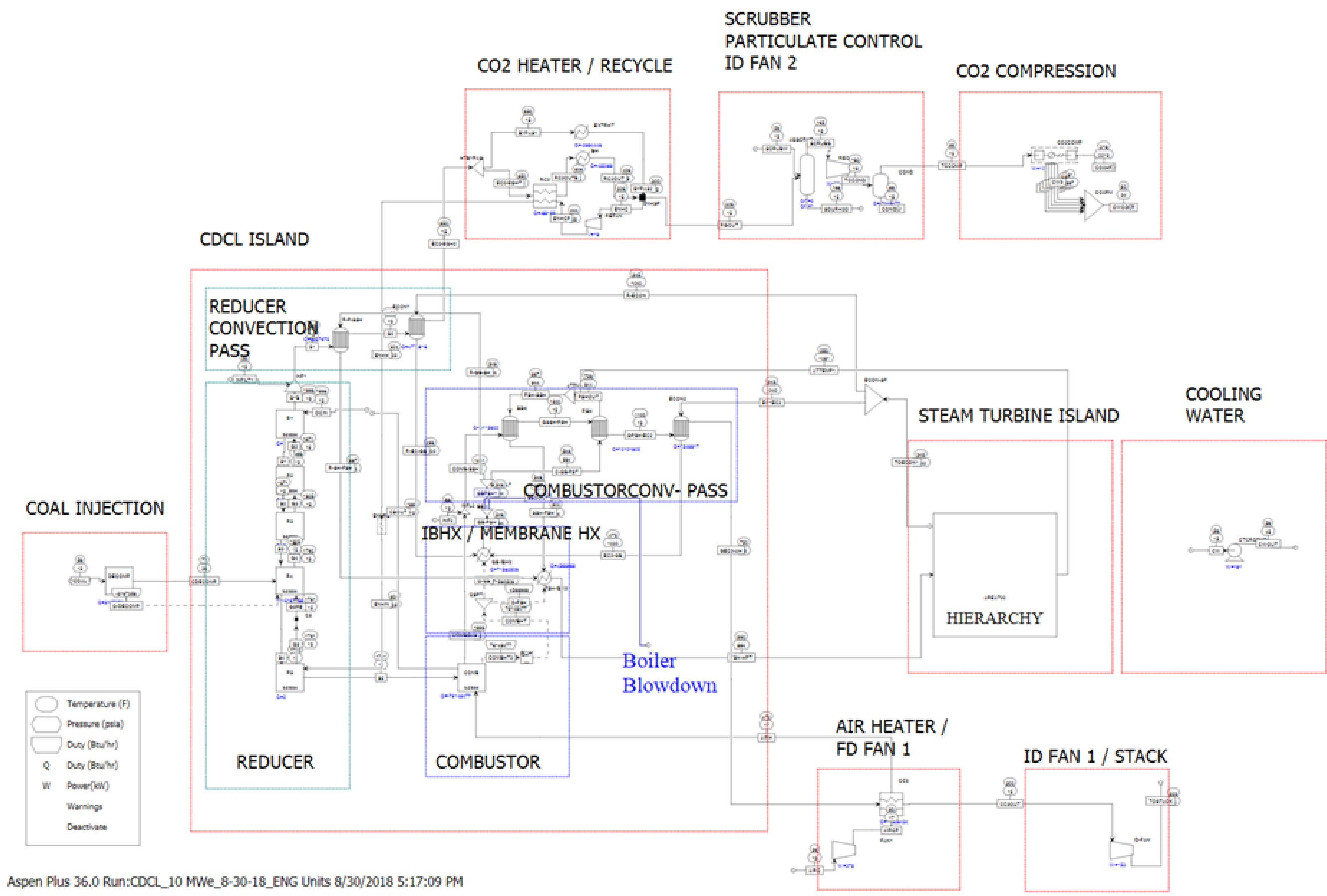


Figure 9. **10 MWe CDCL Plant Process Flow Diagram from Aspen Plus™ (combustor baghouse is not shown)**

The general arrangement drawing corresponding to the process flow diagram is shown in Figure 10.

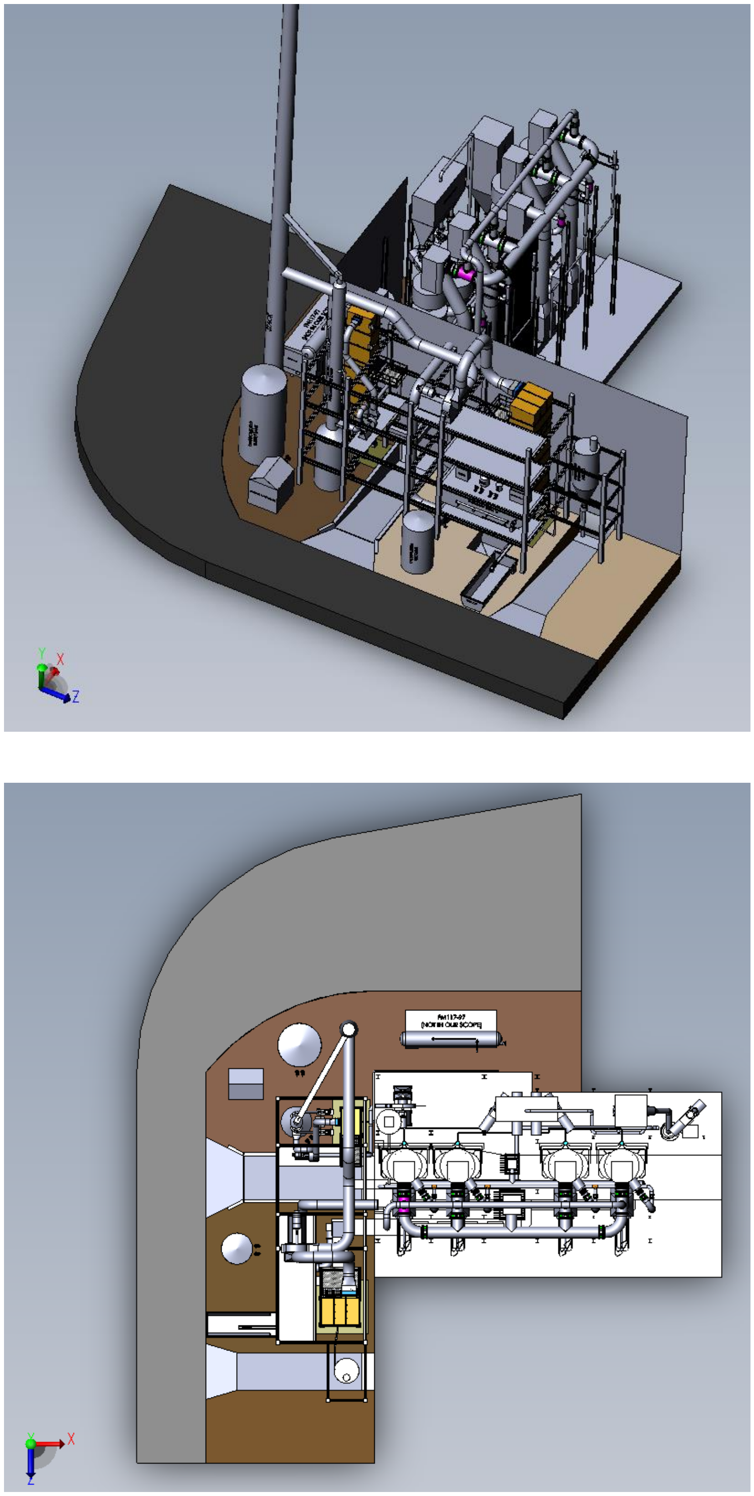


Figure 10. General Arrangement Drawing of DL&P 10 MWe CDCL Plant

CDCL Island: The CDCL island contains four (4) modules of 2.5 MWe each. The main components of each module in the primary loop are combustor, riser, disengagement zone, particle hopper and dipleg, top moving-bed (TMB) reducer, bottom moving-bed (BMB) reducer, standpipe, and L-valve. Table 6 lists the design basis of the primary loop. Figure 11 shows a preliminary design of the four modules with inlet and outlet ducts. The shell of the primary loop vessel components is fabricated from carbon steel. To reduce the reactor vessel weight and improve heat integration, the combustor and reducer will consist of water-cooled, membrane-wall construction. The four modules share one combustor convection pass and one reducer convection pass. Steam generation surfaces are placed in reactor vessels and convection passes. Feed water from feed water heater #4 is heated subsequently through the economizer and steam generator. The steam, separated by a vertical separator, is further heated by the primary superheater, secondary superheater, and final superheater. Attemperators are incorporated to adjust the steam temperature. Refer to Figure 12 for a more detailed steam cycle flow diagram.

Each module is designed to operate stand-alone or in combination with any of the other three modules. Initially, only one module will be installed at the site along with all support services and ancillary equipment required for all four modules. The one module will be operated for a sufficient period to demonstrate auto-thermal operation and achievement of the target performance parameters. Lessons learned from this operation will be incorporated into the design of the remaining three modules, if needed, before they are installed at the site. After the installation of the remaining three modules, the entire integrated system of modules will be operated to demonstrate integrated operation and achievement of target performance objectives.

Table 6. Design Basis of CDCL Primary Loop

Parameter	Units	Value
Power Output	kWe	2500
Estimated Efficiency		28%
Particle Fe_2O_3 Loading		20-50%
Particle Size	mm	1.5
Particle Density	kg/m^3	3807

Parameter	**Units**	**Value**
Particle Bulk Density	kg/m^3	2289
Estimated Particle Heat Capacity	kJ/kg/K	0.986
Angle of Free Pose		23°
Pour Angle		70°
Angle of Repose		25°
Particle to Coal Ratio		50:1 ~ 100: 1
Coal Size	µm	≤500
Operation Temperature	°C	850-1100
Operation Pressure	inH_2O (gauge)	-50 ~ +150
Vessel Shell Temperature	°C	≤121
Particle Residence Time in Combustor	min	10
Particle Residence Time in TMB Reducer	min	20
Particle Residence Time in BMB Reducer	min	40
Moving Bed Voidage		0.40
Bubbling Bed Voidage		0.60
Entrained Flow Voidage		0.99
Maximum Standpipe Solids Velocity	m/s	0.15
Disengagement Zone Cut Size	µm	600
Recommended Air Velocity in Ducts	m/s	25
Recommended Flue Gas Velocity in Ducts	m/s	15
Recommended Gas Velocity in Coal Feed Line	m/s	25
Minimum Gas Velocity in BMB		U_{mf} of coal
Maximum Gas Velocity in BMB		$U_{terminal}$ of coal
Gas Velocity in Zone Seal		$0.75U_{mf}$ of particle
Maximum Gas Velocity in Zone Seal		U_{mf} of particle
Coal Input Per Plan Area (Maximum)	$kg/hr/m^2$	82.02
Coal Input Per Plan Area (Minimum)	$kg/hr/m^2$	24.61
L-Valve H/D Ratio (Injection Point)		2
Target Combustor Outlet O_2 Concentration		3%

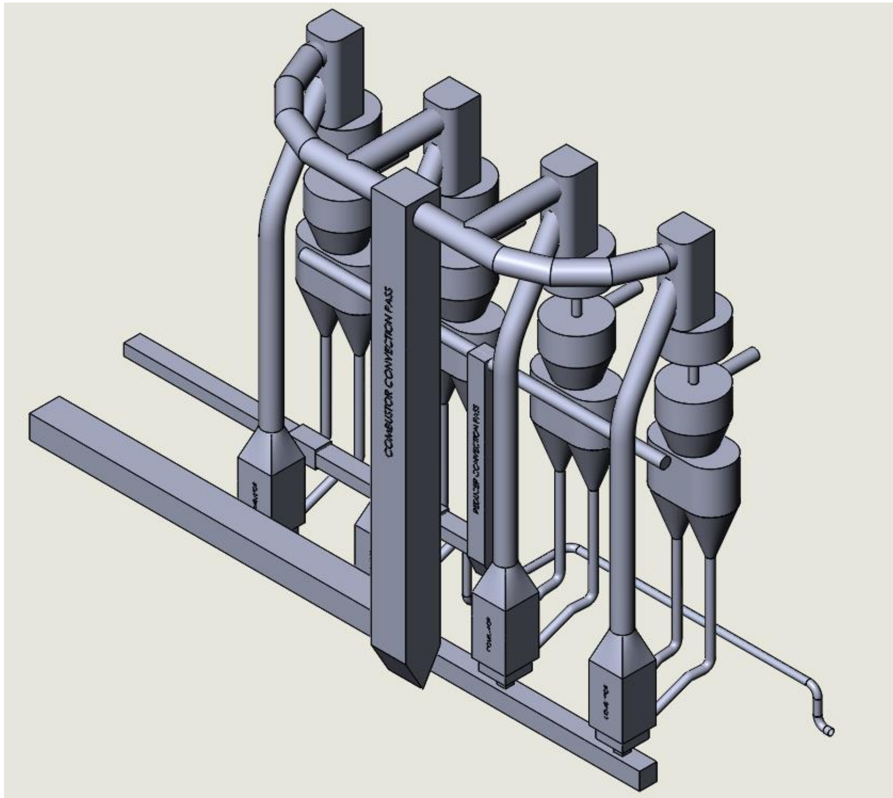


Figure 11. Preliminary Design of Four 2.5 MWe CDCL Modules with Inlet / Outlet Ducts

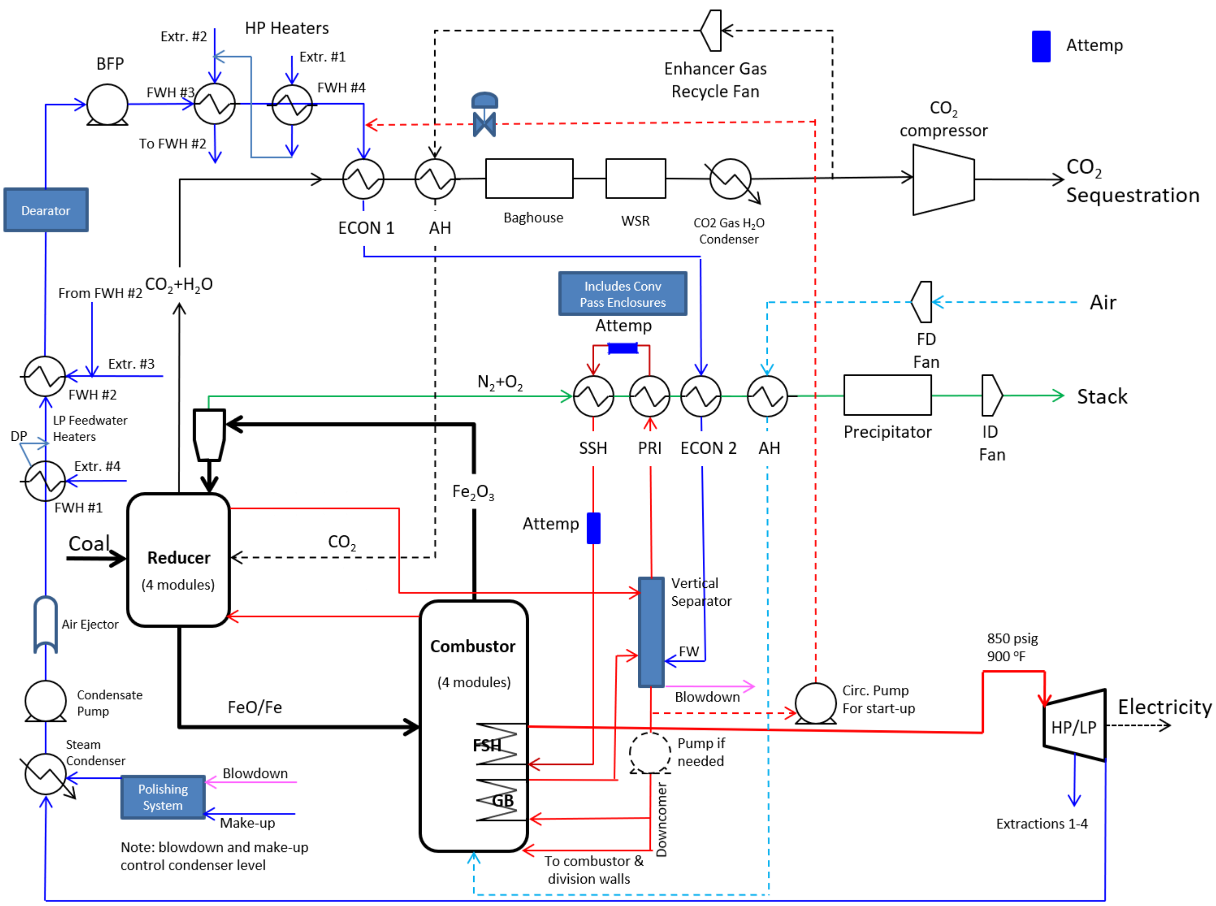


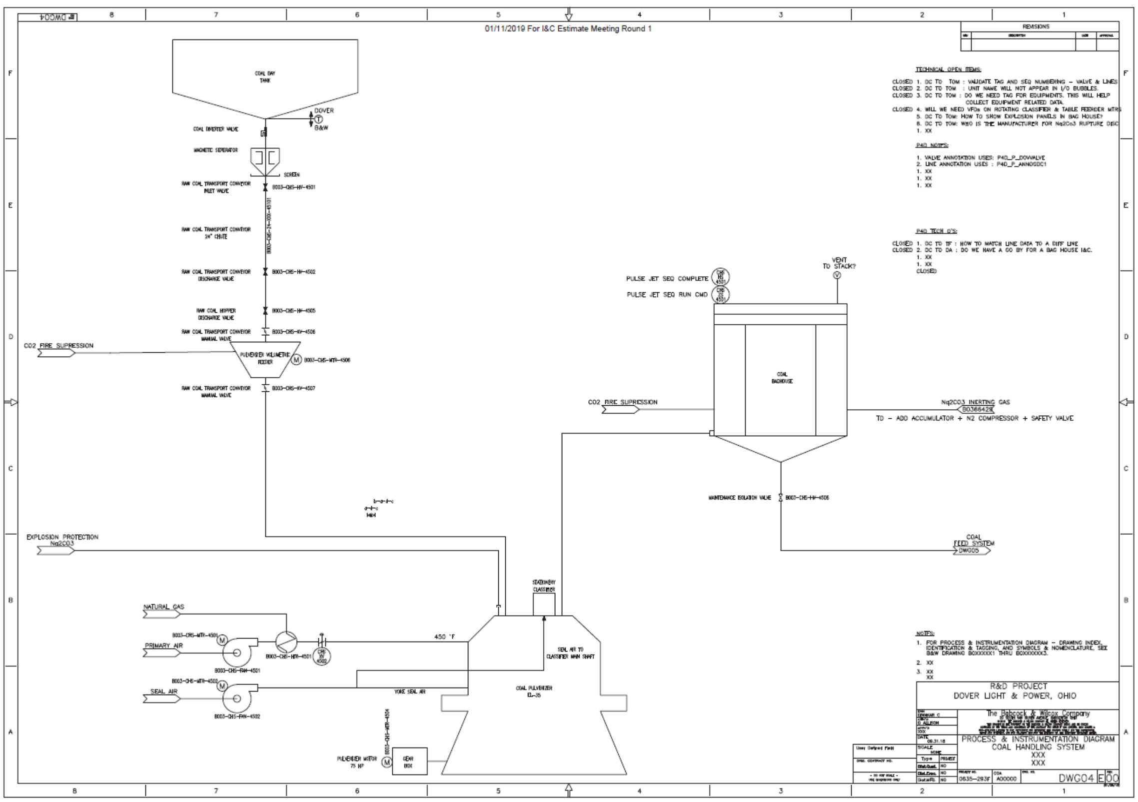
Figure 12. Steam Cycle of Dover 10 MWe CDCL Plant

Steam Turbine Island: The steam turbine recently acquired by DL&P is an impulse type and straight condensing single-flow turbine (General Electric Spec. No. LTSD-1452). The generator output is 19,743 kWe. The steam-side pressure is 864.7 psia and temperature is 900 °F as delivered to the steam header. The steam turbine has four steam extractions, supplying to four feedwater heaters (see Figure 12). The inlet terminal point to the CDCL island is the outlet of feedwater heater #4. DL&P will oversee the installation of the turbine and all associated balance of plant components to support turbine operation. Installation of the steam turbine island components will be completed before Phase III starts. B&W will supply the 10 MWe net equivalent steam flow from the four CDCL modules into the high-pressure steam header at a location designated by DL&P (CDCL outlet terminal point).

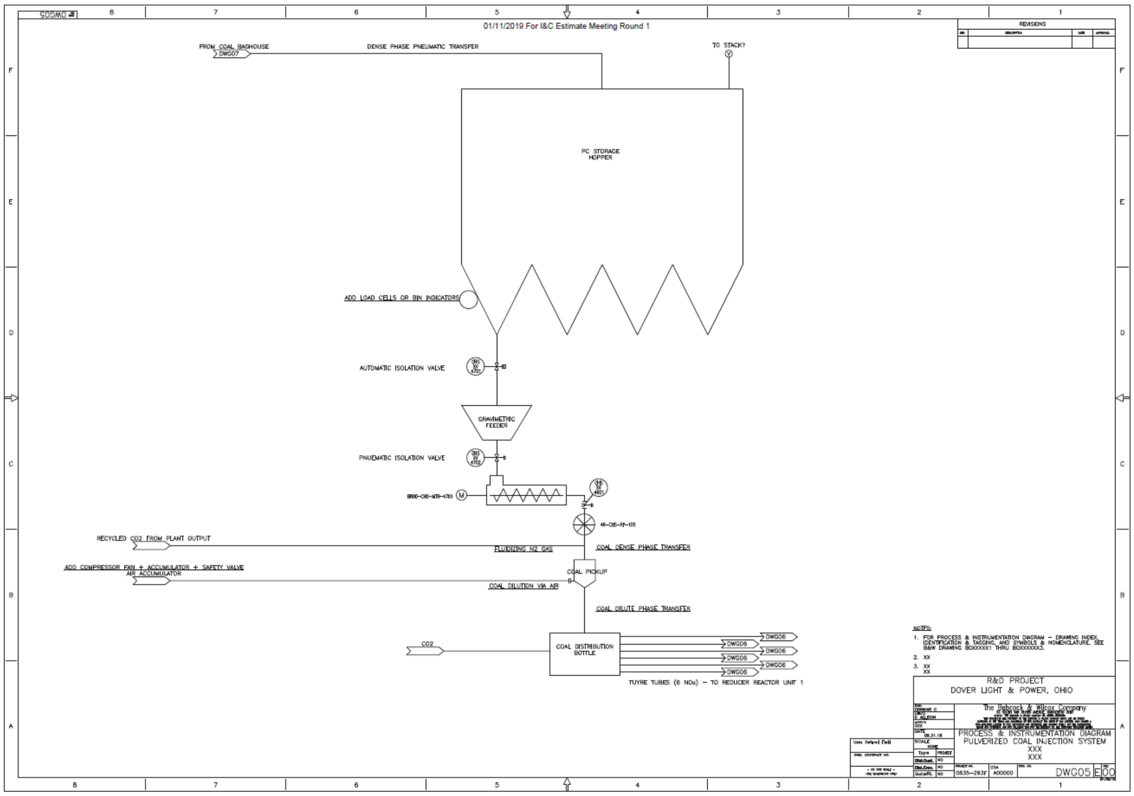
Coal Preparation and Injection System: The piping and instrumentation diagrams (P&IDs) of the coal preparation and injection system are shown in Figure 13. Currently, DL&P receives Stoker coal by truck to the site. They have ample capacity to receive and transport coal to a day tank. The coal is delivered as 2”x1/4” Stoker coal. The coal is not dried or crushed prior to loading it into the day tank. B&W plans to share the existing coal receiving equipment that services the existing Stoker boiler. A coal chute will be installed to deliver coal to a new feeder for a new pulverizer on the chemical looping system. A magnet will be installed to remove tramp iron prior to conveying the coal into a new day tank. The pulverizer uses preheated air from the air heater to dry the coal. The inlet air temperature to the pulverizer will be approximately 450 °F. A direct gas-fired trim heater will be installed to boost the air temperature prior to the air heater to the required inlet temperature of the pulverizer when only the first CDCL module is in service.

The Pulverizer will discharge to a baghouse where the PC is separated from the pulverizer air. The air is released to atmosphere. The PC is discharged from the baghouse through a rotary seal into a 40-ton PC hopper using a hopper pneumatic transport system. The PC hopper has four independent outlets, each for servicing one CDCL module. Each feed hopper is trough-shaped with 70^0 hopper walls and 90^0 vertical end walls, and a polished internal surface finish to ensure mass-flow dispensing of PC. The entire coal preparation, transfer and feed system is dust tight. The pulverizer, baghouse, PC hopper and individual PC feeders are protected with a fire suppression system and explosion protection system.

The coal injection system follows B&W’s patented Pulverized Coal Injection design. The size of the coal feed piping and nozzle will be optimized to provide plug-free operation while minimizing the carbon dioxide required to maintain the pipe velocity above the saltation velocity, thereby, avoiding drop-out of coal. The coal injection nozzle design is based on B&W’s bin-fired PC systems. Multiple feed points are identified for each module. Delivery of coal to the multiple feed points is achieved through a patented distribution bottle. The distribution bottle design has been used extensively to supply PC to blast furnaces in steel mills. Based on the successful 250 kW_t pilot-scale tests at the B&W Research Center, an initial feed point spacing and thermal input per plan area will be used to set the number of feed points on the first 2.5 MWe reducer module. Based on the lessons learned from the first module, the number of feed points will be optimized for the remaining three modules.



(a)



(b)

Figure 13. **P&IDs of (a) Coal Preparation System and (b) Coal Injection System**

Cooling Water System: Cooling water for the steam turbine cycle comes from the Tuscarawas River and is under the scope of DL&P. DL&P will install the cooling water system together with the package boiler system, which will be accomplished before the beginning of Phase III.

CO_2 and Air Heater System: Heat is extracted from the CDCL's reducer and combustor exhaust gas to preheat recycled CO_2 and combustion air, respectively. Tubular air heaters will be used to provide gas-tight sealing to ensure CO_2 purity is maintained and to provide easy cleaning. Due to the smaller scale, passive, multiple-pass heaters will be used, rather than regenerative heaters. The combustor exhaust gas will be used to preheat air. The preheated air will be split between the pulverizer and the combustor. The reducer exhaust will be used to preheat recycled CO_2, which will be used as transport gas for the coal feed, enhancer gas for the reducer, and pulse-gas for the reducer baghouse. The target air and CO_2 preheat temperature is 600 °F.

Particulate Control System: After the heat is extracted from the reducer and combustor flue gas, the cooled exhaust gases are passed through separate baghouses to remove the coal ash, unburned carbon and elutriated oxygen carrier particle fines. Pulse-jet type baghouses are located on both the combustor and reducer convection passes. Each baghouse is shared by four combustors or reducers. The solids collected in the combustor baghouse are mainly metal-oxide particles, which can be reprocessed into fresh make-up particles. The solids collected in the reducer baghouse are mainly coal ash, mixed with a small amount of metal-oxide particles. The combustor baghouse is pulsed with air, while the reducer baghouse is pulsed with recycled CO_2 to keep the CO_2-rich flue gas. A small compressor will be used to increase the pressure of the recycled CO_2 to 60-90 psig for pulsing purposes. The ash will be transported from the baghouse hoppers to the existing ash silo via the existing vacuum ash transport system. The design data of combustor and reducer baghouses are shown in Table 7 and Table 8, respectively.

Table 7. **Combustor Exhaust Gas Baghouse Design Data**

Parameter	Values
Operating Temperature, °C	149
Air/Cloth Ratio (Vol/Area)	4.98
Bag Length, m	6.096
Bag Diameter, mm	152.4
Bag Material	Nomex
Metal Oxide Circulation Rate	100:1
Metal Oxide Attrition Rate, wt%/hr	0.02
Collection Efficiency, %	99.99
Combustor Exhaust MW, g/gmole	28.183
Density at 300 °F, lb/ft^3	0.05078
Density at STP, lb/ft^3	0.07844
Air Flow (Max), kg/hr	91,254
Air Flow (Max), m^3/min at 300 °F	30,000
Coal Flow kg/hr	10,582
Metal Oxide Flow Rate kg/hr	1,090,000
Metal Oxide Attrition Flow, kg/hr	218
Number of Bags	204
Dust Loading, kg/kg	0.00239
Dust Loading, grains/lb air	16.73

Parameter	Values
Dust Loading, grains/SCF	1.3123

Table 8. Reducer Exhaust Gas Baghouse Design Data

Parameter	Values
Operating Temperature, °C	149
Air/Cloth Ratio (Vol/Area)	3.14
Length of bag, m	6.096
Diameter of bag, mm	152.4
Bag Material	PPS
Coal Ash Content, %	9.49
Molecular Weight of Gas, g/gmole	35.78
Density of Gas at 300 °F	0.06824
Density of Gas at STP	0.09997
Collection Efficiency, %	99.99
Gas Flow (Max), kg/hr	34,468
Gas Flow (Max), m^3/min	13004
Coal Flow Rate, kg/hr	10,582
Coal Ash Flow Rate, kg/hr	1004
Number of Bags	96
Dust Loading, kg/kg	0.0291
Dust Loading, grains/lb gas	203.7
Dust Loading, grains/SCF	20.36

Scrubber System: The exhaust gas from the reducer will contain sulfur dioxide, which must be removed prior to exhausting through the stack to meet EPA permitting requirements and potentially, to meet pipeline purity requirements for transport and sequestration. Therefore, a wet scrubber is placed after the reducer baghouse to remove SO_2. B&W's high-velocity wet scrubber design is used, as shown in Table 9.

Table 9. Preliminary Wet Scrubber Design Values

Parameter	Units	Value
Flue Gas Flow	lb/hr	34,478
Flue Gas Inlet Temperature	°F	295
Gas Velocity	ft/s	11
SO_2 Removal	%	99.3
Inlet Gas, SO_2	lb/hr	345
Outlet Gas, SO_2	ppm	50
Incremental CO_2 from Limestone	lb/hr	237
Limestone Consumption	lb/hr	588

Parameter	Units	Value
Stoichiometric Ratio	Mole Ca/mole SO_2 removed	1.03
Recirculating Slurry Solids	wt%	20
AR Pump Flow per Level	Gpm	230
Nozzle Pressure	Psi	15
L/G Ratio	gal/kacf	138
Limestone Grind	% passing at 325 mesh	95
Limestone Quality	% available $CaCO_3$	94
Chloride Bleed Stream	lb/hr	697
Oxidation Air Required	lb/hr	2100
Gypsum Production	lb/hr	1064
Gypsum Moisture	wt%	10
Chloride Purge (Waste Water Stream)	gpm (1.5 wt% solids) primary and secondary hydroclones in service	2

Induced Draft (ID) Fans and Stack: ID Fans will be installed on both the combustor and reducer exhaust gas paths. Variable-frequency drive ID fans will be used for lower operating cost of parasitic power. Also, it will provide greater operating flexibility in turndown, especially when operating only one module at part-load during startup.

A new stack will be installed to exhaust the CDCL gases to the atmosphere. According to Good Engineering Practice, the stack height should be 2.5 times the height of the nearest, tallest building, which will be approximately 250 ft tall.

CO_2 Purification and Compression System: The cost of CO_2 purification and compression equipment for transport for industrial use (e.g., enhanced oil recovery) or for sequestration is beyond the scope of this project and the anticipated available DOE funding. However, the project will be designed to demonstrate the ability of the technology to produce CO_2-rich gas suitable for later processing in a follow-on project. The CO_2-rich gas generated in the reducer will be emitted directly to the stack. Separate flues gas lines for the combustor and reducer exhaust will allow test personnel to measure the composition of each stream before they are combined and exhausted through the stack. In this way, the capability of producing pipeline quality CO_2 from the 10 MWe CDCL plant will be evaluated.

C. ADEQUACY OF SCALE AND TIME FRAME OF THE PROPOSED LARGE CDCL PILOT

The project team is proposing a 10 MWe pilot plant, which is a natural progression following the 250 kW_t CDCL pilot facility. The plant will be constructed as four (4) modules of 2.5 MWe each. The modular designed approach will substantially reduce the technical and financial risks associated with demonstrating this first-of-a-kind technology at the full 10 MWe scale. The modular design will address key operational aspects in the commercialization of the technology, such as evaluation of the module interaction, integration with the steam generation and plant start-up, shut down and load-following operation. B&W plans to further reduce risk by constructing and testing a single CDCL module prior to constructing the remaining three modules during Phase III of the project. It is worth pointing out that the critical dimension during scaling up for CDCL technology is coal distribution distance. As shown in Figure 14, when scaling up from 250 kW_t to 2.5 MWe, the thermal input increases by approximately 30 times. However, the coal distribution distance only increases from 3’ to 7’, corresponding to a scale up factor of 2.3. This is a practical scale-up factor for the CDCL technology in the pilot stage. Based on past circulating fluidized-bed pilot facility designs, B&W has found this scale-up also minimizes wall effects and provides chemical and thermal characteristics representative of a large commercial unit.

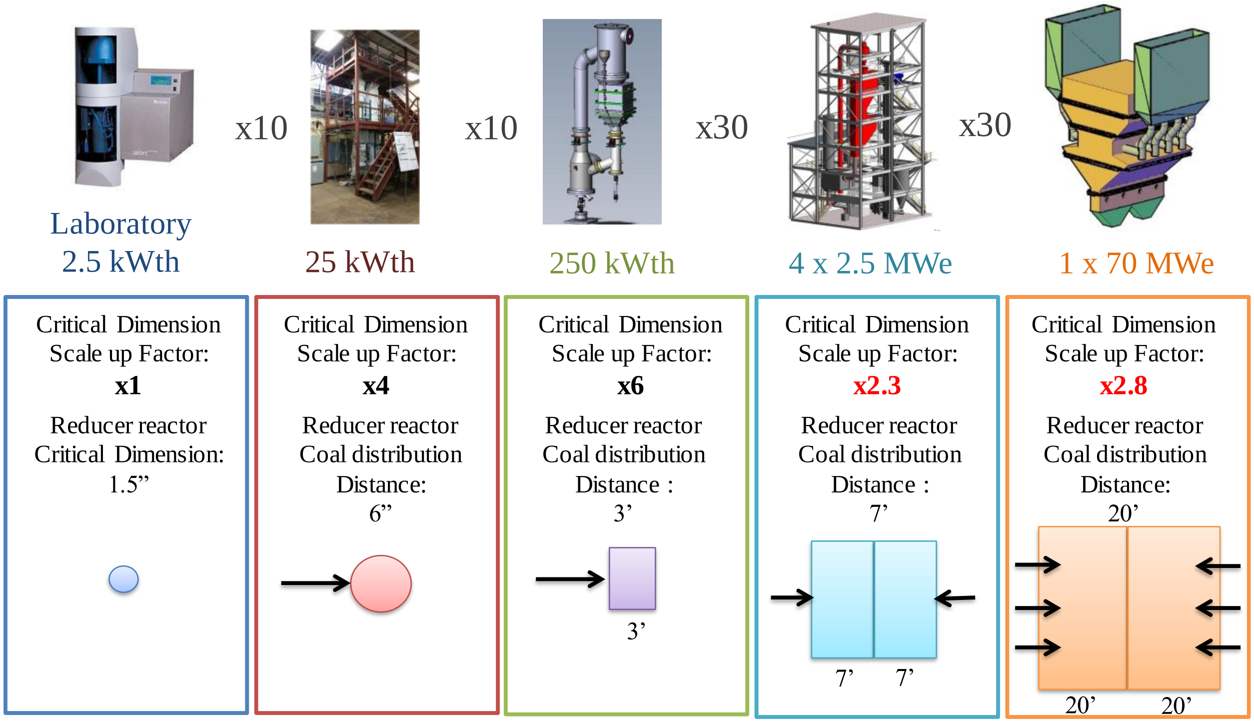


Figure 14. CDCL Technology Scale-up Plan

Critical technology gaps for the CDCL technology will be addressed during the testing of the four modules of 2.5 MWe, including coal distribution, emissions, heat integration, and auto-thermal operation. Some of these technology gaps have been validated in the 250 kW_t unit. Further investigation at a larger pilot scale in a continuous operational environment will advance the technology to be ready for commercial demonstration as the design and operation of a future 550 MWe commercial-scale CDCL plant will be very similar to the 10 MWe plant. For example, a 550 MWe commercial plant will consist of eight (8) modules of 70 MWe. With the modular design, the scale-up factor from 10 MWe to 550 MWe will be only 2.8 according to the increase of coal distribution distance, as shown in Figure 14. The relatively low scaling factor further reduces the risk at commercial scale. In addition, the input and output parameters of the 10 MWe plant resemble the final commercial application in scale. Therefore, once the technology is successfully demonstrated at the scale of 10 MWe, the technology will be ready for commercial offering.

The commercialization roadmap envisions a step-wise scale-up from a 250 kW_t to 10 MWe large pilot plant. As illustrated in Figure 15, the timeline of the CDCL technology meets DOE's schedule for initiating construction of the large pilot plant by 2020 and demonstration by 2025. Under the Pre-FEED 10 MWe CDCL project (DE-FE0027654), the functional specifications of the 10 MWe modular plant have been developed while additional tests of the 250 kW_t CDCL pilot facility were conducted to verify moving-bed reducer performance. Under the current Phase I Feasibility project (DE-FE0031582), B&W has secured firm commitments from the host site and all team members for the 10 MWe CDCL demonstration in addition to the EIV preparation. Phase II is to complete a detailed FEED of the large pilot unit, provide equipment specifications, identify vendors and develop a full construction and testing schedule and budget.

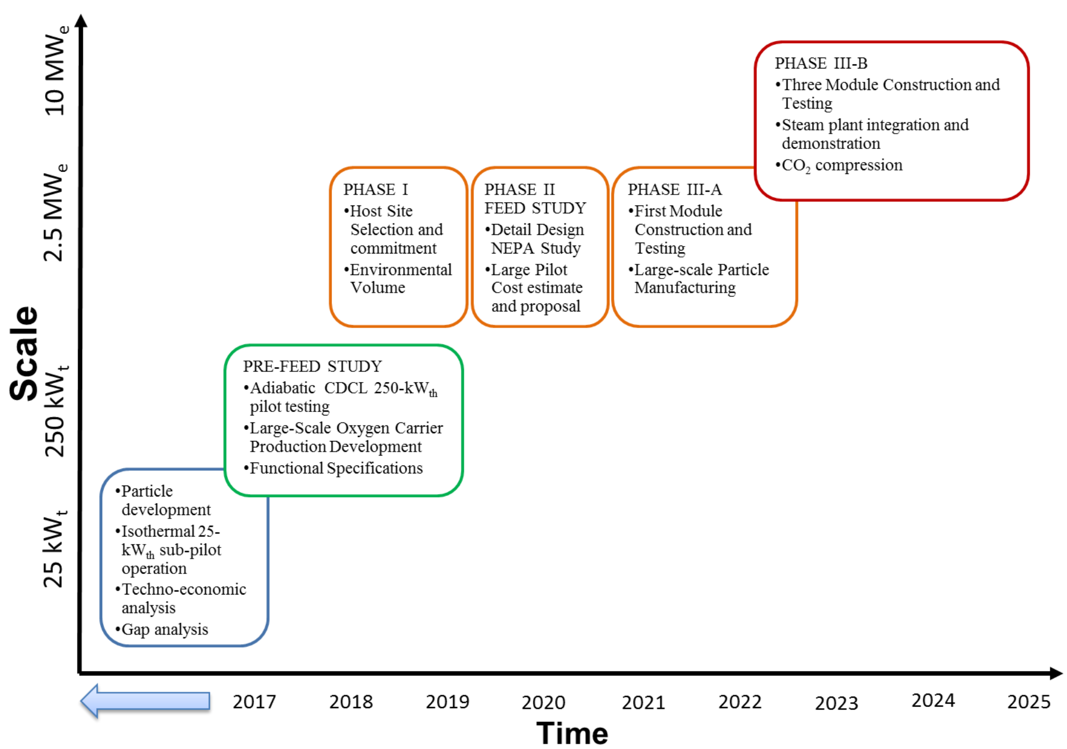


Figure 15. CDCL Technology Commercialization Timeline

D. CDCL COST OF ELECTRICITY AND TECHNO-ECONOMIC ANALYSIS

The capital cost for a 550 MWe CDCL commercial plant is close to $1,283 million, as calculated in Table 10. Fuel cost was assumed to be $1.30/MMBTU based on the U.S. Energy Information Administration. The capital cost of selective catalytic reduction (SCR) systems for a commercial plant is about $100/kWe (B&W's estimated value). For a 550 MWe plant, the cost of an SCR system is about $55 million. The adjustment of the SCR cost is applied to the total capital cost. Mercury emissions in the CDCL are expected to report to the CO_2 stream. Since mercury limits have not been specified for sequestrable CO_2, costs associated with mercury removal are eliminated from the capital cost of the CDCL plant. Since the CDCL plant uses a larger coal size than the PC plant and it is also less sensitive to coal moisture, the CDCL plant requires less coal preparation and drying equipment. A discount of 50% on the cost of coal equipment is taken on the CDCL capital equipment compared to the PC plant.

Table 10. Commercial CDCL Total Plant Costs

Account	Units	TOTAL COST
Gross electrical production	kW	657,000.00
Net electrical production	kW	550,349.00
1.0 COAL & SORBENT HANDLING	k$	$ 33,121.31
2.0 COAL & SORBENT PREP & FEED (Adjusted Coal Crushing	k$	$ 13,052.65
3.0 FEEDWATER & MISC BOP SYSTEMS	k$	$ 89,175.18
4.0 CDCL EQUIPMENT	k$	$ 525,998.81
5.0 FLUE GAS CLEANUP (NO Hg REMOVAL)	k$	$ 172,106.90
5.0B CO2 REMOVAL & COMPRESSION	k$	$ -
6.0 COMBUSTION TURBINE/ACCESSORIES	k$	$ -
7.0 HR, DUCTING & STACK	k$	$ 46,328.59
8.0 STEAM TURBINE GENERATOR	k$	$ 169,473.69
9.0 COOLING WATER SYSTEM	k$	$ 49,291.39
10.0 ASH/SPENT SORBENT HANDLING SYS	k$	$ 18,021.07
11.0 ACCESSORY ELECTRIC PLANT	k$	$ 99,570.37
12.0 INSTRUMENTATION & CONTROLS	k$	$ 32,373.59
13.0 IMPROVEMENTS TO SITE	k$	$ 18,061.88
14.0 BUILDINGS & STRUCTURES	k$	$ 71,528.93
16.0 TRANSPORTATION, STORAGE & MONITORING	k$	$ -
17.0 ADJUSTMENTS (SCR EQUIPMENT)		$ (55,000.00)
Total Plant Cost (TPC) wo/T,S&M	k$	$ 1,283,104.35
Capital Cost wo/T,S&M	$/kWn	2,331.44

Based on the cost listed in Table 10, the COE for the CDCL plant is estimated and compared with other plant configurations, as summarized in Table 11. This TEA shows that a 550 MWe supercritical CDCL plant is projected to achieve greater than 96.5% CO_2 capture with a COE of $83.32/MW-hr. The CDCL process is competitive with natural-gas combined cycle (NGCC) with CO_2 capture, where the current estimate is $83.2/MWh. Further, by combining the air pollutants in a single, concentrated gas stream, the CDCL process can lower the capital cost of the coal-fired power plant compared to a PC-fired boiler by potentially eliminating the wet flue gas desulfurization, SCR/hydrated lime injection, and carbon injection control processes for sulfur dioxide, nitrogen oxides and mercury capture, resulting in substantial capital cost savings. There has been some precedent for co-sequestering SO_2 and CO_2 if the pipeline corrosion issue can be addressed.

Table 11. Economic Analysis for Various Plants

	Dated July 6 2015 160 2011$ **Sup PC w/CO2 CAP** **Case B12B**	Dated July 6 2015 Page 192 **2011$** **NGCC** **Case B31A**	Dated July 6 2015 Page 208 **2011$** **NGCC W/CO2 CAP** **Case B31B**	Phase I 2011$ **Supercritical** **CDCL**	Phase II 2011$ **Supercritical** **CDCL**	10 Mwe Project 2011$ **Supercritical** **CDCL**
Capacity Factor	85%	85%	85%	85%	85%	85%
Net Power (kWe)	550,000.00	630,000	559,000	550,349.00	550,349.00	550,349.00
Coal Cost ($/MMBtu)	**2.937**					**1.300**
Coal Cost ($/ton) 2000 lb = ton	$68.54			$68.60	$68.60	$30.33
Natural Gas Costs, $/MMBTU	$6.13	$6.13	$6.13	$0.00	$0.00	$0.00
Net Plant Heat Rate (Btu/kWh)	10,512.22	6,624.03	7,465.37	9,524.69	9,524.69	9,933.30
Capital						
Total Plant Cost (TPC), $k	$ 1,939,143	$ 430,933	$ 827,903	$ 1,380,401	$ 1,384,130	$ 1,283,104
Total Overnight Cost (TOC), $k	$ 2,384,353	$ 527,638	$ 1,008,369	$ 1,722,059	$ 1,727,930	$ 1,591,393
Capital Factor Assumption	High Risk 5 Years	Low Risk 3 Years	High Risk 3 Years	High Risk 5 Years	High Risk 5 Years	High Risk 5 Years
Capital Factor (Page 62, Nov-2010 Report)	0.124	0.105	0.111	0.124	0.124	0.124
Fixed and Variable Costs						
Fixed Operating & Maintenance Costs, k$/year	$63,094.57	$ 15,883	$ 27,368	$48,811.96	$48,564.68	$44,025.85
Variable Operating & Maintenance Costs k$/year	$60,366.96	$ 7,800	$ 16,500	$27,645.84	$32,656.13	$31,540.73
Fuel Cost, k$/year	$126,458.92	$ 190,479	$ 190,479	$114,748.17	$114,748.17	$52,917.35
Oxygen Carrier Cost, k$/year @ $1199.50/ton				$15,580.96	$15,596.24	$15,596.24
CO2 TS&M Costs						
CO2 Removal at 85% CF (ton/year)	3,934,091.75		1,709,119.19	3,824,380.58	3,824,380.58	3,988,446.50
CO2 TS&M Costs ($/ton)	$10.00		$0.00	$10.00	$10.00	$10.00
CO2 TS&M Costs, ($k)	$39,340.92		$0.00	$38,243.81	$38,243.81	$39,884.47
CO2 Credits						
CO2 Credit $20/Ton (CO2)						
Contributions to COE, $/MWh						
Capital	$72.19	$11.81	$26.89	$52.11	$52.29	$48.15
Fixed O&M	$15.41	$3.39	$6.58	$11.91	$11.85	$10.74
Variable O&M	$14.74	$1.66	$3.96	$6.75	$7.97	$7.70
Fuel	$30.88	$40.61	$45.76	$28.00	$28.00	$12.91
Oxygen Carrier	$0.00	$0.00	$0.00	$3.80	$3.81	$3.81
COE ($/MWh)	**$133.22**	**$57.46**	**$83.19**	**$102.57**	**$103.92**	**$83.32**

E. PRELIMINARY COST ESTIMATION AND SCHEDULE FOR PHASE III

B&W completed the cost estimate and schedule for Phases II and III through the company's commercial bidding process. Developing a thorough cost estimate for a first-of-a-kind large pilot demonstration facility is a major challenge. B&W's experience with building the SCL pilot facility at the National Carbon Capture Center in Wilsonville, AL, the 250 kW_t CDCL pilot unit in Barberton, and other first-of-a-kind pilot demonstration facilities, facilitated the process to estimate the cost of the proposed CDCL large pilot facility. B&W assembled a comprehensive list of mechanical and functional specifications to capture the necessary operational features, flexibility and performance targets to help in selecting/sizing proper equipment and instrumentation. Detailed design of the facility and engineering drawings (i.e. P&IDs, general arrangement drawings, plant layouts, and 3-D models) were prepared for estimating the costs of raw materials, system components, equipment fabrication, equipment installation and permitting. Formal quotes from approved vendors and service providers were obtained and included in the overall cost estimate. For this project, B&W used its commercial estimating methodology to reduce the cost uncertainty.

The cost estimation for Phase III is a conceptual study in the Association for the AACE International Class 4 estimate. The accuracy range is -30% to +50%. Based on the preliminary design information, a budgetary estimation for Phase III was collected by B&W, as illustrated in Table 12. As more detailed engineering design data is available during Phase II, the cost estimation and breakdown for Phase III will be refined and submitted in the Phase II topical report. The BOP equipment for a 10 MWe CDCL plant that is provided by DL&P but not available at a greenfield site is cost estimated by EPRI, as shown in Table 13. The total cost for BOP at a greenfield site in Phase III is estimated to be $38,440,000, which can be eliminated by using the host site. The advantage of installing the 10 MWe unit at DL&P is substantial from the capital cost point of view.

As shown in Table 12, the cost for Phase III are high due to the large uncertainty around the design and testing of a first-of-a-kind chemical looping system. Costs for Phase III may be reduced substantially once the design of the system matures and other costs such as overall project management, environmental permitting, and testing are better defined. These costs would be better defined in Phase II after discussions with the Ohio EPA, and demonstration testing requirements are established

Table 12. Preliminary Cost Estimation for Phase III

Description	Total
Coal, Sorbent, Metal Oxide Handling	$ 5,463,174
Coal, Sorbent, Metal Oxide Preparation & Feed	$ 6,828,415
Feedwater & Miscellaneous BOP Systems	$ 2,905,962
Chemical Looping Primary Loop & Accessories	$ 22,129,062
Flue Gas Cleanup	$ 2,032,744
Combustion Turbine/Accessories (Not Applicable)	$ -
Ducts, Flues, Stack (HRSG in DOE Tab)	$ 3,287,589
Steam Trubine Generator	$ 1,193,708
Cooling Water System	$ -
Ash/Spent Sorbent/Spent Metal Oxide Handling Systems	$ 449,514
Accessory Electric Plant	$ 956,327
Instrumentation & Controls	$ 8,413,048
Improvements to Site	$ 798,776
Building & Structures	$ 6,121,968
Pilot Plant Fuctional Specifications Documents	$ 221,704
Transportation, Storage & Monitoring	$ 354,000
Engineering Project Management - Phase III	$ 3,286,924
TOTAL	**$ 64,442,915**

The cost breakdown per category for Phase III is shown below. As can be seen, most of the costs are allocated towards equipment and construction.

Category	Estimated Cost
Engineering	$ 10,307,767
Travel	$ 356,616
Equipment	$ 23,152,007
Contractual	
Sub-recipient	$ 9,812,242
Vendor	$ 3,619,866
Construction	$ 21,266,666
Total	**$ 68,515,165**

Table 13. Cost Breakdown for 10 MWe Greenfield CDCL Plant BOP (Performed by EPRI)

10 MWe Greenfield CDCL Plant Balance of Plant Total Plant Cost Details (Jun 2018 Basis)								Cost Basis Plant Size	2018 ($x1000) 10 MWe, net		
Acct No.	Item/Description	Equipment Cost	Material Cost	Labor Direct	Labor Indirect	Sales Tax	Bare Erected Cost $	Eng'g CM H.O & Fee	Contingencies Process	Contingencies Project	TOTAL PLANT COST, $1,000
1	COAL & SORBENT HANDLING										
1.1	Coal Receive & Unload	$378	$0	$170	$0	$0	$548	$55	$0	$90	$693
1.2	Coal Stack out & Reclaim	$488	$0	$109	$0	$0	$597	$60	$0	$98	$755
1.3	Coal Conveyors & Yard Crushing	$454	$0	$108	$0	$0	$561	$56	$0	$93	$710
1.4	Other Coal Handling	$119	$0	$25	$0	$0	$144	$14	$0	$24	$182
1.9	Coal & Sorbent Handling Foundations	$0	$437	$577	$0	$0	$1,014	$101	$0	$167	$1,283
	SUBTOTAL 1.	**$1,438**	**$437**	**$989**	**$0**	**$0**	**$2,864**	**$286**	**$0**	**$472**	**$3,623**
3	FEEDWATER & MISC BOP SYSTEMS										
3.1	Feedwater System	$596	$0	$192	$0	$0	$788	$79	$0	$130	$997
3.2	Water Makeup & Pretreating	$726	$0	$230	$0	$0	$956	$96	$0	$210	$1,262
3.3	Other Feedwater Systems	$187	$0	$77	$0	$0	$264	$26	$0	$44	$334
3.4	Service Water Systems	$426	$0	$223	$0	$0	$649	$65	$0	$143	$857
3.6	Natural Gas Supply	$24	$0	$28	$0	$0	$52	$5	$0	$9	$65
3.7	Waste Treatment Equipment	$229	$0	$132	$0	$0	$361	$36	$0	$79	$477
3.8	Misc Power Plant Equipment	$1,260	$0	$390	$0	$0	$1,650	$165	$0	$363	$2,178
	SUBTOTAL 3.	**$3,449**	**$0**	**$1,272**	**$0**	**$0**	**$4,721**	**$472**	**$0**	**$978**	**$6,171**
8	STEAM TURBINE GENERATOR										
8.1	Steam TG & Accessories	$4,847	$0	$529	$0	$0	$5,376	$538	$0	$591	$6,504
8.2	Turbine Plant Auxiliaries	$27	$0	$57	$0	$0	$84	$8	$0	$9	$102
8.3	Condenser & Auxiliaries	$842	$0	$294	$0	$0	$1,137	$114	$0	$125	$1,375
8.4	Steam Piping	$191	$0	$78	$0	$0	$269	$27	$0	$44	$340
8.9	TG Foundations	$0	$77	$127	$0	$0	$205	$20	$0	$45	$270
	SUBTOTAL 8.	**$5,907**	**$77**	**$1,085**	**$0**	**$0**	**$7,070**	**$707**	**$0**	**$815**	**$8,591**
9	COOLING WATER SYSTEM										
9.1	Cooling Towers	$445	$0	$138	$0	$0	$582	$58	$0	$64	$705
9.2	Circulating Water Pumps	$105	$0	$7	$0	$0	$112	$11	$0	$12	$136
9.3	Circ. Water System Auxiliaries	$26	$0	$3	$0	$0	$30	$3	$0	$3	$36
9.4	Circ. Water Piping	$0	$213	$193	$0	$0	$406	$41	$0	$67	$514
9.5	Make-up Water System	$60	$0	$77	$0	$0	$136	$14	$0	$22	$172
9.6	Component Cooling Water System	$195	$0	$150	$0	$0	$344	$34	$0	$57	$435
9.9	Circ. Water System Foundations	$0	$113	$188	$0	$0	$301	$30	$0	$66	$397
	SUBTOTAL 9.	**$831**	**$326**	**$755**	**$0**	**$0**	**$1,912**	**$191**	**$0**	**$292**	**$2,395**
10	ASH/SPENT SORBENT HANDLING SYS										
10.6	Ash Storage Silos	$129	$0	$396	$0	$0	$526	$53	$0	$58	$636
10.7	Ash Transport & Feed Equipment	$860	$0	$853	$0	$0	$1,713	$171	$0	$188	$2,073
10.9	Ash/Spent Sorbent Foundation	$0	$29	$36	$0	$0	$65	$7	$0	$14	$86
	SUBTOTAL 10.	**$990**	**$29**	**$1,285**	**$0**	**$0**	**$2,304**	**$230**	**$0**	**$261**	**$2,795**
11	ACCESSORY ELECTRIC PLANT										
	SUBTOTAL 11.	**$1,049**	**$400**	**$1,089**	**$0**	**$0**	**$2,538**	**$254**	**$0**	**$346**	**$3,138**
12A	INSTRUMENTATION & CONTROL (NO	$0	$1,227	$736	$0	$0	$1,964	$196	$0	$267	$2,427
12B	INSTRUMENTATION & CONTROL (CDCL)		TBD from B&W				TBD			TBD	
	SUBTOTAL 12.	**$0**	**$1,227**	**$736**	**$0**	**$0**	**$1,964**	**$196**	**$0**	**$267**	**$2,427**
13	IMPROVEMENTS TO SITE										
13.1	Site Preparation	$0	$20	$436	$0	$0	$456	$46	$0	$100	$602
13.2	Site Improvements	$0	$681	$899	$0	$0	$1,580	$158	$0	$348	$2,085
13.3	Site Facilities	$1,220	$0	$1,279	$0	$0	$2,499	$250	$0	$550	$3,299
	SUBTOTAL 13.	**$1,220**	**$701**	**$2,614**	**$0**	**$0**	**$4,535**	**$453**	**$0**	**$998**	**$5,986**
14	BUILDINGS & STRUCTURES										
14.1	CDCL Building		TBD from B&W				TBD			TBD	
14.2	Turbine Building	$0	$585	$545	$0	$0	$1,130	$113	$0	$186	$1,429
14.3	Administration Building	$0	$283	$299	$0	$0	$582	$58	$0	$96	$737
14.4	Circulating Water Pumphouse	$0	$27	$21	$0	$0	$48	$5	$0	$8	$60
14.5	Water Treatment Buildings	$0	$37	$34	$0	$0	$71	$7	$0	$12	$90
14.6	Machine Shop	$0	$162	$108	$0	$0	$270	$27	$0	$45	$342
14.7	Warehouse	$0	$109	$110	$0	$0	$219	$22	$0	$36	$277
14.8	Other Buildings & Structures	$0	$89	$76	$0	$0	$165	$17	$0	$27	$209
14.9	Waste Treating Building & Structures	$0	$33	$101	$0	$0	$134	$13	$0	$22	$169
	SUBTOTAL 14.	**$0**	**$1,326**	**$1,294**	**$0**	**$0**	**$2,620**	**$262**	**$0**	**$432**	**$3,314**
	CALCULATED TOTAL COST	**$14,883**	**$4,524**	**$11,120**	**$0**	**$0**	**$30,527**	**$3,053**	**$0**	**$4,860**	**$38,440**

The schedule of Phase III is shown in Figure 16. Phase III will be broken down into two parts, A and B. The first part (A), the construction of a single module of 2.5 MWe, will be carried out followed by commissioning and testing. This phase will greatly reduce project risks in the event adjustments to the design are necessary. Once the first module has been successfully commissioned, a brief update to the design will be performed. A go/no-go decision will be made before continuing into Phase III Part B. In this phase, the remaining three modules will be constructed and commissioned. Following the commissioning of each module, the four modules will be operated simultaneously, and the team will perform parametric testing under a wide range of operating conditions and coal types. A final report will be prepared summarizing the most significant results of the project.

Babcock & Wilcox

19-Mar-19 13:42

Activity Name	Original Duration	Start	Finish
Dover City Power & Light Phase 2 and 3 Schedule			
MILESTONE			
PHASE 2 START	0.0w		31-Oct-19
TASK 1 - PROJECT MANAGEMENT & PLANNING			
TASK 1 - PHASE 2			
PROJECT KICK OFF MEETING	13.0w	31-Oct-19	29-Jan-20
DOE REVIEW MEETINGS	4.0w	06-Aug-20	02-Sep-20
UPDATED PHASE 2 MANAGEMENT PLAN	13.0w	31-Oct-19	29-Jan-20
1ST IRC MEETING	4.0w	02-Apr-20	29-Apr-20
2ND IRC MEETING	4.0w	01-Oct-20	28-Oct-20
TASK 2 - FEED STUDY			
PHASE 2			
PHASE 2 - ENGINEERING			
PHASE 2 - COMMON			
PHASE 2 - STEEL (CHEMICAL LOOPING & STEAM GENERATION)			
STEEL (CHEMICAL LOOPING & STEAM GENERATION) - FOUNDATION LOADS	3.0w	05-Mar-20	25-Mar-20
STEEL (CHEMICAL LOOPING & STEAM GENERATION) - DESIGN	8.0w	26-Mar-20	20-May-20
STEEL (CHEMICAL LOOPING & STEAM GENERATION) - IFC	8.0w	21-May-20	15-Jul-20
PHASE 2 - BASIC DESIGN			
BOILER CTR	4.0w	31-Oct-19	27-Nov-19
PHASE 2 - GENERAL ARRANGEMENTS			
PRELIMINARY GENERAL ARRANGEMENT	6.0w	14-Nov-19	25-Dec-19
-0 GENERAL ARRANGEMENT	8.0w	26-Dec-19	19-Feb-20
-1 GENERAL ARRANGEMENT	8.0w	20-Feb-20	15-Apr-20
PHASE 2 - P&IDS			
-0 P&IDS	8.0w	31-Oct-19	25-Dec-19
-1 P&IDS	16.0w	26-Dec-19	15-Apr-20
-2 P&IDS	8.0w	16-Apr-20	10-Jun-20
PHASE 2 - STEAM GENERATION SYSTEM			
STEAM GENERATION - LOADS	4.0w	26-Dec-19	22-Jan-20
PHASE 2 - STEAM GENERATION SYSTEM - WALL PANELS			
WALL PANELS - PMOS	4.0w	20-Feb-20	18-Mar-20
WALL PANELS - DETAILS	4.0w	19-Mar-20	15-Apr-20
PHASE 2 - STEAM GENERATION SYSTEM - SECTIONS/GENBANK			
SECTIONS/GENBANK - PMOS	4.0w	19-Mar-20	15-Apr-20
SECTIONS/GENBANK - DETAILS	4.0w	16-Apr-20	13-May-20
PHASE 2 - STEAM GENERATION SYSTEM - SECTION/GENBANK HEADERS			
SECTIONS/GENBANK HEADERS - PMOS	4.0w	20-Feb-20	18-Mar-20
SECTIONS/GENBANK HEADERS - DETAILS	4.0w	19-Mar-20	15-Apr-20
PHASE 2 - STEAM GENERATION SYSTEM - VERTICAL STEAM SEPERATOR			
VERTICAL STEAM SEPERATOR - PMOS	4.0w	19-Mar-20	15-Apr-20
VERTICAL STEAM SEPERATOR - DETAILS	4.0w	16-Apr-20	13-May-20
PHASE 2 - COAL PREPERATION SYSTEM			
PHASE 2 - COAL PREPERATION SYSTEM - PULVERIZER (EL35)			
PULVERIZER - LOADS	2.0w	28-Nov-19	11-Dec-19
PHASE 2 - COAL PREPERATION SYSTEM - PULVERIZER PRIMARY AIR FAN			
PULVERIZER PRIMARY AIR FAN - ISSUE RFQ DATASHEET	1.0w	28-Nov-19	04-Dec-19
PULVERIZER PRIMARY AIR FAN - ISSUE VENDOR SPEC	1.0w	05-Dec-19	11-Dec-19
PULVERIZER PRIMARY AIR FAN - ISSUE RFQ	3.0w	12-Dec-19	01-Jan-20
PULVERIZER PRIMARY AIR FAN - EVALUATE QUOTE	2.0w	02-Jan-20	15-Jan-20
PULVERIZER PRIMARY AIR FAN - ISSUE PO	2.0w	16-Jan-20	29-Jan-20

Actual Work — Critical Remaining Work — Actual Level of Effort — Remaining Work — Milestone

Dover Light & Power 10 MWe Coal Direct Chemical Looping Plant

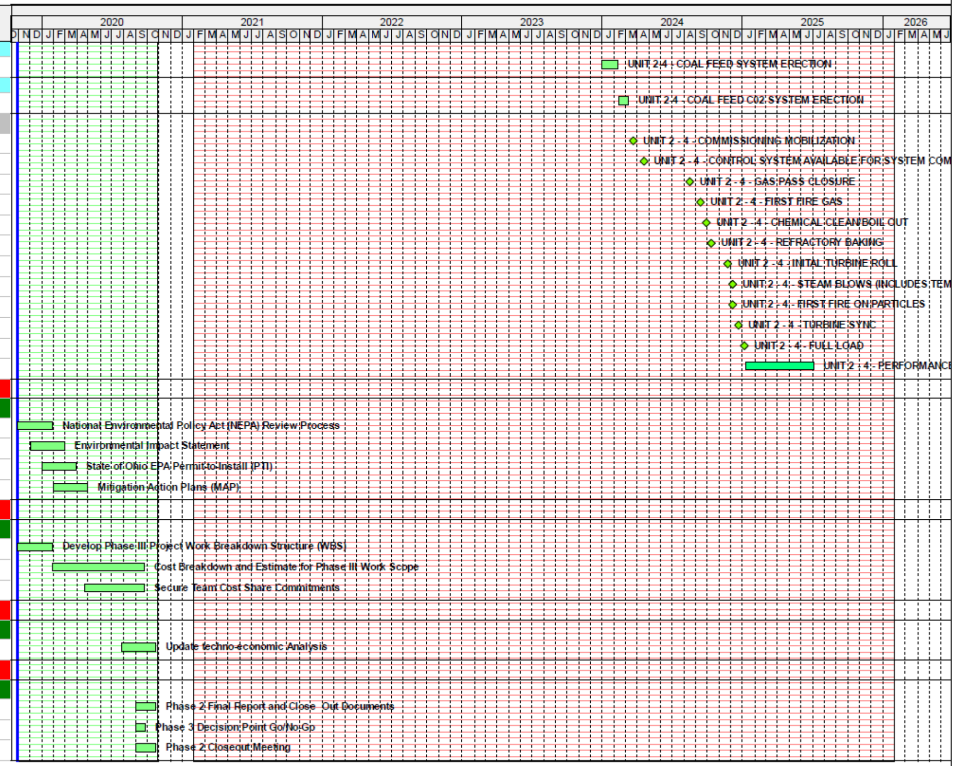
Page 1 of 9

Babcock & Wilcox			
Date	Revision	Checked	Approved

Babcock & Wilcox

19-Mar-19 13:42

Activity Name	Original Duration	Start	Finish
PHASE 3B - UNIT 2-4 - COAL FEED SYSTEM			
UNIT 2-4 - COAL FEED SYSTEM ERECTION	6.0w	01-Jan-24	09-Feb-24
PHASE 3B - UNIT 2-4 - COAL FEED C02 SYSTEM			
UNIT 2-4 - COAL FEED C02 SYSTEM ERECTION	4.0w	12-Feb-24	08-Mar-24
PHASE 3B - UNIT 2-4 - COMMISSIONING/STARTUP/TESTING			
UNIT 2 - 4 - COMMISSIONING MOBILIZATION	0.0w	20-Mar-24	
UNIT 2 - 4 - CONTROL SYSTEM AVAILABLE FOR SYSTEM COMMISSIONING	0.0w		18-Apr-24
UNIT 2 - 4 - GAS PASS CLOSURE	0.0w		15-Aug-24
UNIT 2 - 4 - FIRST FIRE GAS	0.0w		13-Sep-24
UNIT 2 - 4 - CHEMICAL CLEAN/BOIL OUT	0.0w		27-Sep-24
UNIT 2 - 4 - REFRACTORY BAKING	0.0w		11-Oct-24
UNIT 2 - 4 - INITAL TURBINE ROLL	0.0w		22-Nov-24
UNIT 2 - 4 - STEAM BLOWS (INCLUDES TEMPORY PIPING)	0.0w		06-Dec-24
UNIT 2 - 4 - FIRST FIRE ON PARTICLES	0.0w		06-Dec-24
UNIT 2 - 4 - TURBINE SYNC	0.0w		20-Dec-24
UNIT 2 - 4 - FULL LOAD	0.0w		03-Jan-25
UNIT 2 - 4 - PERFORMANCE TESTING	26.0w	06-Jan-25	04-Jul-25
TASK 3 - NEPA/PERMITTING AT HOST SITE			
TASK 3 - PHASE 2			
National Environmental Policy Act (NEPA) Review Process	13.0w	31-Oct-19	29-Jan-20
Environmental Impact Statement	13.0w	02-Dec-19	28-Feb-20
State of Ohio EPA Permit-to-Install (PTI)	13.0w	01-Jan-20	31-Mar-20
Mitigation Action Plans (MAP)	13.0w	31-Jan-20	30-Apr-20
TASK 4 - TEAM AND COST SHARE COMMITMENTS			
TASK 4 - PHASE 2			
Develop Phase III Project Work Breakdown Structure (WBS)	13.0w	31-Oct-19	29-Jan-20
Cost Breakdown and Estimate for Phase III Work Scope	34.0w	30-Jan-20	23-Sep-20
Secure Team Cost Share Commitments	22.0w	23-Apr-20	23-Sep-20
TASK 5 - UPDATE TECHNO-ECONOMIC ANALYSIS			
TASK 5 - PHASE 2			
Update techno-economic Analysis	13.0w	27-Jul-20	23-Oct-20
TASK 6 - PHASE 2 TOPICAL REPORT			
TASK 5 - PHASE 2			
Phase 2 Final Report and Close Out Documents	8.0w	31-Aug-20	23-Oct-20
Phase 3 Decision Point Go/No-Go	4.0w	31-Aug-20	25-Sep-20
Phase 2 Closeout Meeting	8.0w	31-Aug-20	23-Oct-20



Actual Work | Critical Remaining Work | Actual Level of Effort | Remaining Work | Milestone

Dover Light & Power 10 MWe Coal Direct Chemical Looping Plant

Page 9 of 9

Babcock & Wilcox			
Date	Revision	Checked	Approved

Figure 16. Timeline for Phase II and III

F. DETAILED COST ESTIMATE AND SCHEDULE FOR PHASE II

Detailed cost estimate and breakdown for each task for Phase II have been compiled and categorized to assist in estimating the total cost for performing the FEED study in Phase II, as shown in Table 14.

Table 14. Detailed Cost Estimation for Phase II

	Description	Federal	Non-Federal	Total
Task 1	Project Management and Planing	$ 235,067.55	$ 34,003.15	$ 269,070.71
Task 2	FEED Study	$ 2,026,733.64	$ 1,061,328.73	$ 3,088,062.37
Task 3	NEPA / Permitting at Host Site	$ 158,649.75	$ 14,390.00	$ 173,039.75
Task 4	Team and Cost Share Commitments	$ 137,303.83	$ 15,259.49	$ 152,563.31
Task 5	Update Techno-Economic Analysis	$ 167,637.58	$ 34,210.00	$ 201,847.58
Task 6	Phase II Topical Report and Recommendation	$ 274,607.66	$ 30,518.97	$ 305,126.63
	TOTAL	$ 3,000,000.00	$ 1,189,710.34	$ 4,189,710.34

The schedule of Phase II is shown in Figure 16. FEED study (Task 2) and NEPA/permitting (Task 3) will be conducted in parallel. The system that is going to be installed first during Phase III, such as the coal preparation and feeding system, flue gas cleanup system, and the first module of the CDCL island, will be designed and engineered in priority during Phase II. Considering that application of permit-to-install through Ohio EPA takes at least six months and the project length is only 12 months, permitting application will be initiated once NEPA study is completed, to ensure that the required permitting is obtained before construction is scheduled to begin.

MRC-2. APPLICANT/TEAM CAPABILITIES AND FACILITIES

A. HOST SITE SELECTION AND PERMITTING

DL&P, the municipal plant at Dover, OH and a steel mill in Portsmouth, OH, owned by New Steel International, Inc. (NS), have expressed strong interest in being the host site for the 10 MWe CDCL large pilot unit. These two are the potential host sites for this project – DL&P's Dover Plant is the primary site and NS' steel mill is the back-up. Since both sites are in Ohio, this helps the recipient to seek cost-share funding from the State of Ohio.

Dover Light & Power: DL&P is located only 45 minutes away from the main project recipient (B&W), which is convenient. DL&P is planning to expand its current capacity, while keeping a balance between coal and natural gas. They are committed to the continued and responsible use of Ohio coal for power production. Figure 8 shows the site location provided by DL&P. This location was originally used for two old Stoker boiler units, which were demolished. Building, steel supporting structure, platforms and utilities still exist and are available for this project. DL&P will use the CDCL 10 MWe plant and a natural-gas package boiler to power a recently acquired 20 MWe subcritical steam turbine. The steam cycle equipment will be installed before the beginning of Phase III of the 10 MWe CDCL project. Dover is willing to provide space, infrastructure, utilities, existing BOP equipment and maintenance support for the CDCL project. These will reduce the capital cost of the project by at least $38 million, according to the greenfield cost estimation from EPRI as shown in Table 13. DL&P has a history working with B&W in the retrofit of the current Stoker boiler, developing a strong relationship over the years, which will improve communication and reduce contracting time. There are a few industries near DL&P, which could provide a potential end use for captured CO_2, such as Dover Chemical, Artex Oil Company, Kraton, Chesapeake Energy, etc. This provides opportunities for utilizing CO_2 captured from the 10 MWe CDCL unit. The disadvantage of the DL&P site is that the space available for the CDCL requires some preparation work, such as clearing existing equipment in the identified floor space, raising the roof and modifications to the structural steel. Since this is a small municipal plant, the space available is limited, but based on the work performed to date the space appears to be adequate. The site preparation work will require much lower labor hours than building at a greenfield site. The cash cost-share that DL&P can provide is limited since they are a non-profit organization. However, the plant is willing to look at various ways to provide in-kind cost share by providing infrastructure, utilities, support personnel and even through expenses they would incur on the steam turbine and balance-of-plant equipment.

New Steel Portsmouth Site: NS is interested in providing a steel mill plant as the host site for the 10 MWe CDCL project for the purpose of capturing CO_2 emitted from the plant. The steel mill is in operation. The CDCL project would take a slipstream of the existing process from the steel mill. The site has ready access to coal delivery and provides existing infrastructure and sufficient space. In addition, the site can support full 24/7 operation.

Host Site Selection: The search for suitable host sites, to demonstrate CDCL technology, began in 2017. Potential sites were required to have certain high-level characteristics or “must haves” to be considered, including desire to be a host site and potential for cost share. The project team identified multiple interested sites, visited the sites and talked with representative organizations from each about the feasibility of building the 10 MWe pilot plant at their locations. Based on these initial reviews, a set of candidate host sites was selected for a more detailed assessment. The candidate host sites that were considered for the detailed assessment included:

- Dover Light and Power (DL&P) – This is a municipal plant located in Dover, OH.
- New Steel International, Inc. (NS) – This is a steel mill located in Portsmouth, OH. This site is yet to be constructed and is planned as a commercial coal-fired power and iron-making facility.

The next step was to develop a scoring matrix designed to capture key characteristics from each site in a quantifiable way so that comparisons could be made on a relative basis. A primary candidate and a backup could then be selected based on the results. The scoring matrix was divided into four major categories for which the team collected information from each site organization:

- Business and financing
- Environmental and permitting
- Operations
- Physical attributes

A weighting system was developed for every item in the scoring matrix, since some have a greater impact on the suitability of a particular host site. The weighting, labeled as "Importance" for each item, was given based on the team's assessment of its relative importance. A relative score of "High," "Medium," or "Low" was given for each item with high scores given a 9, medium a 3, and low scores a 1.

Each host site was then evaluated collectively by the team for each item getting a score from 5 (best) to 0 (worst). This score was then multiplied by the weighted importance to get a numerical value for the site for the item (for example, if the item has an importance of "High" and the site scores a 5, its score for this item is then 45). The values for every item were then summed up to give the final score for the host site, which was then non-dimensionalized into a percentage. In this way, each host site was given a quantitative score between 0 and 100% relative to each of the other potential sites. The list of items selected to assess the host sites and their relative importance is given in Table 15, along with the scores for the host sites. Note that the "must have" items are highlighted in blue in the table.

As can be seen in Table 15, we have concluded that DL&P is a better fit for the proposed pilot project. Accordingly, DL&P has been selected as the prime host site for the 10 MWe pilot project. NS steel mill plant will be the back-up site. A host site agreement has been established between

B&W and DL&P, and a cost-share commitment letter has been provided by DL&P. We have received a letter of commitment from New Steel to serve as the alternate host site.

The principal reasons why DL&P scored the highest and was selected as the primary host site for the project were:

- The DL&P is currently operating, planning to expand its capacity, and expects to continue operations through the proposed duration of the proposed pilot project.
- The site's organization has a well laid out plan for performing the project and supporting the bid.
- DL&P has sufficient existing staff to support the project test plan, including long-term operations.
- The site has sufficient space available to support the needs of the pilot plant.
- Perceived lower total cost of the site.
- DL&P is willing to provide building, space, and utilities for the project, which would reduce the project capital costs.
- No permitting issues are expected at the DL&P site.
- DL&P has expressed a strong interest in being the host site for the 10 MWe CDCL large pilot unit, in order to keep a balance between coal and natural gas.

Table 15. Host Site Comparison (performed by EPRI)

Category / Item - MUST HAVES in BLUE	**Importance**	**Dover, OH**	**Portsmouth, OH**	**Winner**
Business and Financing				
Are the organization operating the host site and the host site itself financially stable?	High	5	5	TIE
Are there perceived schedule risks for getting the site ready according to the schedule?	Medium	4	3	Dover
Does the host site organization have a track record working / contracting with DOE?	Medium	0	0	TIE
Does the organization have a successful track record with doing DOE projects?	Medium	0	0	TIE

Category / Item - MUST HAVES in BLUE	Importance	Dover, OH	Portsmouth, OH	Winner
Does the organization have a well laid out plan for performing the project and supporting the bid?	High	5	1	Dover
Does the power industry support the site?	Medium	5	3	Dover
Does the site have proximity to an international airport and accommodations?	Low	5	2	Dover
Does the site have special labor limitations or issues (e.g., union labor agreements)?	Medium	5	5	TIE
Does the site have suitable insurance to cover normal operational risks?	Low	4	3	Dover
Does the site have the support of the local and / or state governments?	Medium	5	3	Dover
Is the host willing to provide cost share?	High	5	5	TIE
Is the organization willing to and capable of contracting with other organizations?	Low	5	5	TIE
Is there a perceived risk of the host site withdrawing from the project?	High	5	4	Dover
Is there available local or state government funding for the site?	High	3	3	TIE
Is there risk associated with the cost share, e.g., is it from a source that may be hard to verify or has contingencies?	High	5	5	TIE
What is the perceived total cost of the site compared to others?	High	4	3	Dover
Physical Attributes				
Are there perceived construction risks / access issues?	Medium	5	3	Dover
Does the host site have access to coal delivery and coal handling?	Medium	5	5	TIE
Does the site have a potential need for process steam?	Medium	4	4	TIE
Would any existing buildings/structures be used or modified?	Medium	4	4	TIE
Does the site have existing infrastructure that can be used?	High	5	5	TIE
Does the site have ready access to coal?	High	5	5	TIE
Does the site have ready availability to all required utilities?	High	4	3	Dover
Does the site have sufficient plot space and are there no space restrictions?	High	4	3	Dover
Does the site have the ability to provide power to the grid?	Low	5	3	Dover
Does the site have the ability to utilize CO_2 or access to a nearby CO_2 pipeline?	Low	5	3	Dover
Environmental and Permitting				
Are there any other concerns with accessing / providing consumables?	Low	5	2	Dover
Are there any perceived HSE issues, or construction permitting concerns?	High	5	4	Dover

Category / Item - MUST HAVES in BLUE	Importance	Dover, OH	Portsmouth, OH	Winner
Are there concerns around air permitting for the site?	High	5	3	Dover
Are there concerns around water permitting for the site?	Medium	5	3	Dover
Does the site have recent NEPA study - Environmental Assessment?	Medium	0	0	TIE
Operations				
Are there any noise restrictions at the site that could limit the hours of operation and/or construction?	Low	5	2	Dover
Are there any security risks for the host site?	Low	5	4	Dover
Cost of operating the site?	High	5	2	Dover
Does the organization have a successful track record in doing pilot-scale testing?	Medium	0	0	TIE
Does the organization have experience with any of the core components of the system?	Medium	3	0	Dover
Does the site have existing staff to support the project through all phases?	High	4	1	Dover
Does the site have the ability to support full 24/7 operations?	High	5	5	Dover
Does the site location have weather-related or altitude concerns?	Medium	4	4	TIE
Does the site, its existing equipment (if any), and its staff support long-term operations?	Medium	5	2	Dover
Is the skillset needed to perform maintenance available from the site or nearby organizations?	Medium	5	4	Dover
Is there a risk of changes in future operations of host site that could impact the test plan?	Medium	5	5	TIE
	Total Score	**87.1%**	**66.1%**	

Host Site Permitting: An Environmental Information Volume (EIV) **(submitted separately)** was developed by B&W and Trinity Consultants. The NEPA study will be conducted in Phase II of this project. Detailed permitting requirements of the Dover host site can be found in EIV part D. A summary of compliance approach of environmental issues is stated below.

1) *Air permit*: The CDCL plant will use a wet scrubber to remove sulfur oxide and hydrogen chloride, inject activated carbon to control mercury and install baghouses to control particulate emissions. The environmental equipment will be designed for high efficiency, which will ensure that the emissions of SO_2, HCl, Hg and particulates are low. Emission of other pollutants, including NO_x, CO, H_2S and volatile organic compounds are

anticipated to be low and under emission limits based on 250 kW_t pilot testing results. The EIV contains a table of emissions including theoretical potential to emit, estimated emissions based on pilot data and pipeline contaminant emission criteria. The permitted emission limits will be established during Phase II with the Ohio EPA. The goal of the permitting scheme for the CDCL will be to preserve DL&P's current permitting scheme, while demonstrating the CDCL technology. Since the CDCL is first-of-a-kind technology and therefore, may not progress through the DOE down-selection process to Phase III Construction/Commissioning/Operation, or through to commercial operation at the end of the 5-year Phase III project, the existing permit of the DL&P plant should be preserved.

2) *Wastewater permit*: The Dover Plant currently has three water discharge points to the Tuscarawas River. An increase in cooling water needs is anticipated with the new CDCL unit. Additionally, if a wet scrubber is installed, there will be a new discharge point associated with the scrubber wastewater. Evaluation from Trinity Consultants and DL&P showed that wastewater treatment systems will be necessary for the new discharges to comply with applicable effluent limitations. Hence, DL&P will update the water discharge permit through Ohio EPA accordingly.

3) *Solid waste permit*: There will be no hazardous solid waste from the CDCL plant. Reducer fly ash will be sent to an approved landfill. Attrited metal oxide fines from the combustor will be sent back to the manufacturer for reprocessing. Gypsum from the wet scrubber will be sent to a wallboard manufacturer or approved landfill.

4) *Other permits*: The construction permit is effective and will be renewed from the city of Dover in Phase II. An EPA permit-to-install will be obtained during Phase II prior to the start of construction in Phase III. A permit-to-operate will be acquired in Phase III after a

compliance test is completed on the fully constructed and operating CDCL unit. The East Central Ohio Building Authority (Tuscarawas County) will issue building and occupancy permits after the project demonstrates compliance with applicable building, electrical, mechanical, plumbing and fire protection codes.

B. STENGTH AND PREVIOUS EXPERIENCE OF THE ORGANIZATION PERFORMING FEED STUDY

B&W and **OSU** together will perform the FEED study in Phase II. They have developed a close working relationship and gained much mutual experience by designing, constructing and testing two chemical looping pilot facilities in concert – the 250 kW_t SCL facility at the NCCC and the 250 kW_t CDCL facility at the B&W Research Center. Engineering design of these two similar pilot facilities has been proven to be successful based on the pilot operation. The 250 kW_t CDCL pilot facility has been operated steadily using coal up to 62 continuous hours and shows a robust response to black plant trip, specifically, safely shutting itself down without operator intervention. B&W and OSU are currently finalizing a DOE-funded Pre-FEED study of the 10 MWe CDCL plant (DE-FE0027654). Beginning with a clear definition of developmental needs, the team has itemized comprehensive mechanical and electrical functional specifications from which detailed design specifications and drawings have been developed.

B&W is a global engineering company, and supplier of power generation and environmental equipment. B&W has built several fluidized-bed pilot facilities to support the development of commercial fluidized-bed boiler products. The bubbling fluidized-bed pilot facilities that were designed, fabricated and installed at the B&W's Alliance Research Center (Alliance, OH) included a 6 ft x 6 ft steam-cooled pilot facility, 3 ft x 3 ft refractory-lined bubbling fluidized bed, and a 1 ft x 1 ft refractory-lined fluidized bed with an in-bed water-cooled surface. The circulating fluidized bed (CFB) pilot facilities included both a 9 in x 9 in. (250 kW_t) and a 2.5 MW_t pilot facility. B&W also designed and constructed the 70 MWe American Electric Power Tidd Pressurized Fluidized-Bed Demonstration Boiler as well as a number of commercial bubbling and CFB boilers. Through the process of scaling up the fluidized-bed combustor, B&W developed the knowledge to choose the appropriate scale to investigate development issues. For example, the full-height 2.5 MW_t CFB pilot facility provided representative gas emissions and carbon burnout profiles while minimizing wall effects. It produced gas emissions like B&W's commercial-scale Lauhoff Grain and Ebensburg CFBs.

With respect to PC combustion, B&W has designed and constructed 5 and 100 million BTU (10 MWe equivalent) pilot facilities at its Research Center in Alliance, OH. These facilities were equipped with flue gas desulfurization and particulate control systems. These facilities were also equipped with B&W's patented Pulverized Coal Injection systems for coal feed. In addition to accommodating low-NO_x burner tests and emissions characterization of air toxics, they hosted the world's first demonstrations of fully-integrated PC oxy-combustion at their respective scales. Therefore, B&W is well prepared for the design and construction of the proposed 10 MWe CDCL large pilot plant.

OSU is recognized as one of the world's leading developers of chemical looping technologies with significant lab, bench, sub-pilot, and small pilot-scale testing data showing the potential for commercialization of the SCL and CDCL processes. More than 3,000 hours of combined operation of the OSU chemical looping technologies at the 25 kW_t sub-pilot and continuous steady operation using coal for 62 hours at the 250 kW_t pilot. The ability of OSU to execute and realize its unique chemical looping technology beyond the laboratory while leveraging its fundamental scientific pursuit in response to the need in the power generation industry is critical for the advancement of the chemical looping technology in the U.S.

B&W's principal investigator**, Dr. Luis Velazquez-Vargas**, has been a strong driver for and expert on the CDLC technology. He has more than 15 years of experience in the moving-bed CDCL technology. **Thomas Flynn**, a technical consultant from B&W, has more than 38 years of experience in large-pilot design, construction and testing of equal or greater size, including the SCL pilot in NCCC and the most recent 250 kW_t CDCL pilot at B&W's research center. **Jeffery Vrotsos**, a senior project manager from B&W, was a project manager on many commercial contracts as well as B&W's Future Gen Oxy-Combustion Project, and hence has considerable experience with first-of-a-kind projects.

OSU's professors, **L.S. Fan** and **Andrew Tong,** are world-renowned authorities and authors of two books in the field of chemical looping. They have a strong knowledge of chemical looping process development as well as oxygen carrier synthesis.

C. STRENGTHS AND COMPLETENESS OF THE REST PHASE II PROJECT TEAM (ASIDE FROM THE FEED ORGANIZATION)

Current Team Members:

The current project team for Phases II and III that B&W has put together and the level of commitment is shown in Table 16. Other team status aside from the organization performing the FEED study (B&W and OSU) is discussed below.

Table 16. Current Project Team and Level of Commitment

Project Participants	Role of Participants	Committed Scope (Phase II)	Committed Cost Share (Phase II)
Babcock & Wilcox	Project management and technology lead. Oversee the entire project.	$2,003,994	$197,811
The Ohio State University	Technology and engineering support.	$988,000	$700,000

Project Participants	Role of Participants	Committed Scope (Phase II)	Committed Cost Share (Phase II)
Dover Light and Power	Provide host site, site information, and operation and maintenance support during Phase III	$200,000	$200,000
Clear Skies Consulting	Technology consultant and lead Industry Review Committee	$86,495	$17,299
Electric Power Research Institute	Update techno-economic analysis, TRL evaluation, and represent utility industries	$171,057	$34,210
Trinity Consultants	NEPA and permit contractor	$143,900	$14,390
WorleyParsons	Support architectural and balance of plant engineering	$285,953	$26,000
Babcock & Wilcox Construction Co. (BWCC)	Site preparation and plant construction	$50,000	

DL&P has reached a host site agreement with B&W and has been very cooperative in providing host site information for completing Phase I. They are very familiar with the site and existing equipment and have lots of experience operating power plant systems. Therefore, they have strong capability to provide support for the operation of 10 MWe unit during Phase III.

Clear Skies Consulting, **EPRI** and **JM** have been collaborating with B&W and OSU under the existing Pre-FEED project (DE-FE0027654) and Phase I of the 10 MWe CDCL project (DE-FE0031582). They are very familiar with the CDCL technology. Clear Skies has significant consulting experience in clean energy fields and has been in close contact with utility industries. EPRI is a non-profit organization that has a long history performing collaborative research with the power industry and significant experience and expertise on power plant system modeling and economic analysis. They have been involved in many carbon capture research and development projects. JM has experience in manufacturing and delivering oxygen carrier for chemical looping operations in Europe. Although JM will play a minor role in Phase II, it will have the critical role of manufacturing oxygen carrier particles in large amounts in Phase III.

Trinity Consultants is an environmental consulting firm and is currently the contractor used by DL&P for permitting the installation of the new natural-gas package boiler. The team has contacted Trinity Consultants to make them aware of the plans to install the CDCL large pilot at the same facility. Trinity Consultants is also very familiar with the DOE NEPA process. In Phases II and III, Trinity Consultants will take responsibility of the NEPA study and the plant permitting including both water and air permits.

WorleyParsons is an established engineering company, which provides project delivery and consulting services to energy sectors and process industries. They have strong expertise in engineering complex process technologies. They will play an important role in structural support and balance of plant equipment in Phases II and III.

BWCC operates as a subsidiary of B&W. It provides construction, construction management and maintenance services. They have deep experience in constructing industrial processes and equipment. They will be responsible for construction-related activities in Phases II and III.

Ntre Tech, LLC is a technology-focused company with the primary mission of developing and deploying clean energy conversion and utilization technologies. It brings strong expertise in process analysis and modeling and will be responsible for the system integration and steam cycle simulation. It will provide review of the sequence of operation including transient operation and participate in the hazard and operability (HAZOP) analysis. Ntre Tech will be working under OSU’s direction as a subcontractor.

Potential Team Members:

B&W and ClearSkies have been investigating options for utilization and sequestration of the CO_2-rich gas generated by the chemical looping process. If the CO_2 is utilized in nearby industrial processes or for enhanced oil and/or gas recovery, a $35/ton CO_2 credit would be available. If the CO_2 is sequestered, a $50/ton CO_2 credit would be available. Discussions with potential CO_2 end users near DL&P, and technology providers for CO_2 sequestration have been initiated. Artex Oil Company, Dover Chemical, and Kraton are potential users of CO_2 captured from the CDCL plant for enhanced oil and/or gas recovery. Battelle National Laboratory and the University of Utah have strong expertise in the field of CO_2 sequestration. They can help the project team investigate the possibility of sequestrating CO_2 into saline reservoirs. These team members might be added later in the project, depending on the funding availability.

According to the power industry survey conducted by EPRI, American Electric Power (AEP), Southern Company and Tri-State are interested in CDCL technology for carbon capture in power plants. B&W will communicate with them for potential collaboration through this project. Southern Company and American Electric Power have provided letters of support for the project.

D. PROJECT TEAM ORGANIZATION, ROLES, RESPONSIBILITIES, AND KEY PERSONNEL

B&W and OSU have built a strong team that works well and have successfully designed, fabricated, constructed and tested pilot-scale units. Recently, the team has concluded the design, construction and testing of the 250 kW_t CDCL pilot facility at B&W's Research Center. In Phase I of this project, the team has followed a similar organization, which functions effectively. In Phases II and III, the team will continue the same effective organization as in Phase I with minor adjustment for new team members. A breakdown structure of the project team with their respective responsibilities can be seen in Figure 17. ***All members of the team are currently under contract***

with B&W as the prime, and all DOE flow down terms and conditions consistent with DOE sub-recipient requirements have been incorporated into the subcontracts.

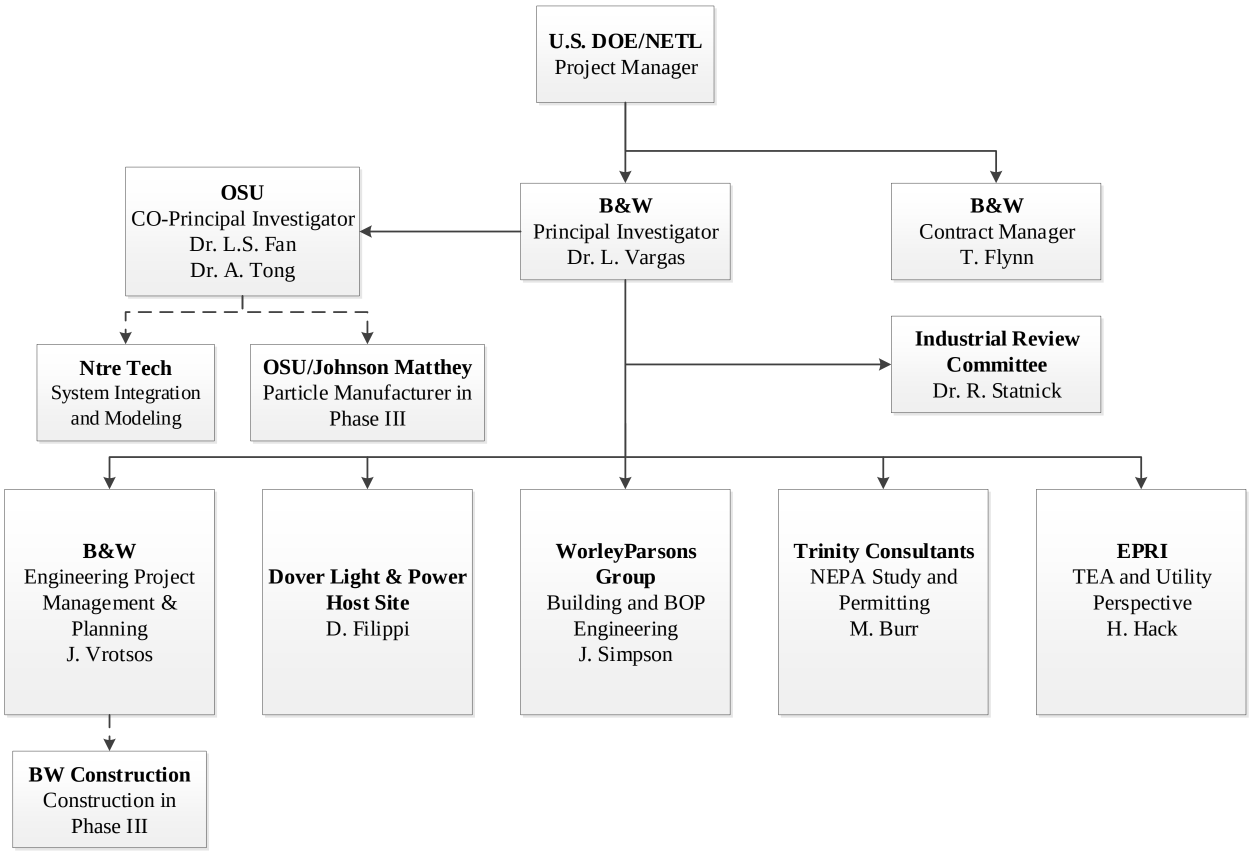


Figure 17. Project Team Organization Breakdown

Key personnel from the FEED organization, B&W (**Luis Velazquez-Vargas**, **Thomas Flynn**, and **Jeffery Vrotsos**) and OSU (**Professor L.S. Fan** and **Andrew Tong**), have been introduced in MRC-2B. During Phase II, BWCC will participate in the engineering activities to coordinate and sequence the engineering with the construction in Phase III. During Phase III, B&W Construction will have a major role as the on-site coordinator of all construction activities by all vendors and subcontractors. **Dave Filippi**, Plant Superintendent at the **DL&P** facility, has already engaged with the team by providing information on the plant. **WorleyParsons** is a large engineering company with extensive experience in the design of power plants and industrial processes from conceptual to detail engineering. Under the leadership of **James Simpson**, they will provide engineering services for the balance-of-plant to integrate the CDCL equipment into the host site. **EPRI** is a non-profit organization whose mission is to conduct research and development in energy and related fields. They have a strong team of experts, led by **Horst Hack**, in coal-fired power generation and will update B&W's TEA, evaluate TRL, and provide utility perspectives for this project. **Trinity Consultants** has previously performed services at the proposed host site and will be providing environmental consulting services including assistance with the EIV and NEPA study. An Industrial Review Committee (IRC) chaired by **Dr. Robert Statnick** of **Clear Skies Consulting** and consisting of the above participants and AEP, Duke Energy, CONSOL Energy and our project sponsors (NETL and Ohio Development Services Agency) will continue to provide industrial representation and guidance throughout the development effort. **JM**, a world leader technology company and catalyst manufacturer, will support the efforts of large-scale oxygen carrier manufacturing in Phase III. **Ntre Tech LLC**, founded by Bartev Sakadjian, will be responsible for the system integration and steam cycle simulation. It will provide review of the sequence of operation including transient operation and participate in the HAZOP analysis. Both JM and Ntre Tech will be OSU's subcontractors. Resumes for the new key personnel **Jeff Vrotsos (B&W), Horst Hack (EPRI), Jim Simpson (WorleyParsons) and Mike Burr (Trinity Consultants)** have been included with the proposal submission. Resumes for the other key personnel were submitted as part of the Phase I proposal.

E. AVAILABILITY OF PERSONNEL, FACILITIES AND EQUIPMENT TO PERFORM PROJECT TASKS

B&W's, OSU's and DL&P's personnel, facilities and equipment will be available to support activities in Phase II and Phase III of this project.

B&W – B&W will dedicate senior personnel to perform relevant design and engineering work, and provide technology expertise. B&W's Research Center facilities in Barberton, OH will be available to carry out the required activities in support of accomplishing the overall program objectives. The 250 kW_t CDCL pilot facility and the environmental control equipment that has been commissioned in the Research Center will be available to support this program.

OSU – Select graduate students, post-docs and undergrads from OSU will be available to perform laboratory work and fluid modeling required to support the activities in the project. OSU's two facilities located at two lab sites on campus, i.e., the Main Lab and West Lab, are available for completing proposed work. The West Lab facility provides a 1600 square foot, 25 feet high bay with compressed air and steam supplies. The Center for Electron Microscopy and Analysis is also located across from the west lab and provides analytical characterization equipment such as XRD, SEM and EDX to analyze the samples collected from the 250 kW_t CDCL and/or 10 MWe pilot plants. The Surface Chemistry Lab and analytical equipment (TGA, flow reactor, gas metering and gas analyzers) will be available to evaluate and characterize oxygen carrier or solvents performance and obtain valuable design data for the 10 MWe pilot plant. Office space for graduate students, postdoctoral fellows and research scientists with personal computers is available. The full license of software including FLUENT, MATLAB, Aspen Plus® and TRAX will be available and installed on each computer in the facility to perform necessary simulation and data analysis for the 10 MWe CDCL plant.

The B&W and OSU test facilities are available, but in compliance with the DOE proposal requirements, no testing is included as part of the DOE-funded Phase II FEED Study scope.

DL&P – DL&P's superintendent, operators and technicians will coordinate the engineering design activities in Phase II and provide mechanical support and maintenance for activities in Phase III. The steam turbine and balance-of-plant equipment are available for Phase II and III efforts.

F. COMPLETENESS OF FINANCIAL INFORMATION AND CONSISTENCY WITH THE FUNDING REQUIREMENTS FOR PHASE II

Letters of financial commitment and support by the prime participants and members of the IRC are attached as Other Project Information. Cost-share contribution from each participant for Phase II can be found in SF-424 budget file, and is reflected in Table 16.

G. LIKEHOOD OF THE TEAM TO SECURE COST SHARE FOR PHASE III

The current team members are interested in participating in Phase III and contributing cost share. DL&P is planning to use their property purchased for this project, such as the steam turbine, as in-kind cost share for Phase III. They are also talking with the Dover city council for potential funding support for this project. Ohio Development Services Agency (ODSA) has been supporting the CDCL technology over the past few years through multiple projects. OSU is submitting a sister proposal to ODSA to provide additional testing on B&W's 250 kW_t pilot facility scope outside of this DOE project, as well as cost share for the engineering scope on the proposed DOE project. They are also very likely to provide financial support for Phase III. The power industry survey conducted by EPRI shows that there are at least three organizations (AEP, Southern Company, and Tri-State) with potential interest in providing cost share and letters of support for this project. B&W will reach out to these and other identified power industry organizations during Phase II. Other new team members and cost-share sources will be identified during Phase II to secure the required amount of cost share for Phase III.

MRC-3. TECHNICAL APPROACH AND UNDERSTANDING

A. ADEQUACY AND FEASIBILITY OF THE APPLICANT'S APPROACH

B&W and OSU's overall objective for the CDCL technology is to complete the design, construction and successful operation of a 10 MWe CDCL large pilot plant unit by 2025. The existing 10 MWe Pre-FEED project (DE-FE0027654), along with another DOE-sponsored project (DE-FE0029093), provide supportive operation of the 250 kW_t CDCL small pilot test unit with the coal commonly used by the Dover plant and thermal integration of the proposed 10 MWe CDCL plant with the steam cycle data supplied by the host site. Three test campaigns have been conducted on the 250 kW_t small pilot unit. The CDCL technology has been successfully validated in small pilot scale and is ready for large pilot demonstration. Design data required for the 10 MWe plant, including temperature and pressure profiles, particle and coal residence times, coal conversion, particle-to-coal ratio, particle attrition, emissions, as well as operation sequences have been obtained from previous test campaigns. Based on the experimental data from small pilot testing, the project team has developed a detailed heat-and-mass balance spreadsheet. Accordingly, the main CDCL components, inlet and outlet ducting, downstream environmental equipment, coal preparation and feeding system, heat exchanger surfaces and utility requirements have been preliminarily specified and sized, as documented in mechanical functional specifications. A general arrangement of the large plant specific to the Dover site has been laid out in 3D SolidWorks, as shown in Figure 10. The 3-D layout will be updated as the design changes and will be used for directing the FEED study in Phase II. Systems for P&IDs have been identified. The conceptual design of P&IDs for the 10 MWe CDCL plant and control specifications has been initiated and will be finalized during Phase II. All of the preliminary design effort has been accomplished under the existing Pre-FEED projects. In Phase II of this project, the project team will be regathered and complete the design and specifications by integrating the CDCL plant into the existing host site setup. Start up, shut down, load change and modular integration will be incorporated into the final design as well. A comprehensive work breakdown structure for Phase II has been developed in Phase I and shared among the team members for cost breakdown and estimation. This work breakdown structure will be used for each team member to follow throughout Phase II.

In addition to the Pre-FEED Study and Feasibility Study, B&W and OSU have two other related DOE-sponsored projects that are providing important elements to the technology development. Under DE-FE-0026334 "Advanced Control Architecture and Sensor Information Development for Process Automation, Optimization and Imaging of Chemical Looping Systems", OSU and B&W have developed the control algorithms to optimize metal-oxide circulation rates to optimize performance. This algorithm will be incorporated into the B&W FocalPoint rules-based optimizer that will be installed on the facility to optimize performance of the modular system. Under DE-FE-0029093 "Heat Integration Optimization and Dynamic Modeling Investigation for Advancing the Coal-Direct Chemical Looping Process", OSU and B&W have completed or have nearly completed three important technology development activities. First, OSU is developing a multi-phase model of the combustor including the imbedded tube bundle. This model will be used to optimize the arrangement of the tube bundle within the bubbling-bed combustor to optimize flow distribution of solids through the tube bundle and maximize heat transfer. Second, OSU and B&W performed a pinch analysis to optimize the thermal integration of the sources and sinks within the CDCL system to optimize steam generation and maximize efficiency. Third, B&W and OSU have developed a dynamic model in ProTRAX linking the chemical looping primary components with the steam cycle and downstream heat recovery components such as gas heaters. OSU had the primary responsibility to develop the dynamic model of the CDCL components and B&W to develop the dynamic model of the steam cycle, including the turbine and balance-of-plant components associated with the turbine. These two dynamic models have been merged and will be used to study start up and shut down scenarios, black plant trips and the load following response of the system. In addition, B&W will contract with TRAX Energy Solutions, the vendor of the ProTRAX dynamic model software, to develop a simulator for the plant personnel based on the coupled B&W and OSU dynamic models.

B&W Construction Co. and WorleyParsons have both visited the Dover host site. Terminal points and scope of work have been clarified. BWCC has developed a construction sequence and strategy that will allow the later installation of CDCL modules 2, 3 and 4 after module 1 and the balance-of-plant equipment, especially the environmental equipment, are installed as part of Phase III Part A scope.

B&W and Trinity Consultants have identified the required permits in Phase I and will complete the permit-to-install and permit-to-operate applications from the State of Ohio EPA and Region V U.S. EPA in Phase II. The EIV study completed in Phase I will provide the essential information for NEPA study and permitting purposes.

The current host site agreement, covering the entire period of the project, signifies a firm commitment of DL&P to both Phases II and III. If new clauses are identified during Phase II, the host site agreement will be modified and resigned by B&W and DL&P. In addition, DL&P is helping B&W obtain cost share from the City of Dover to support this project. DL&P is planning to use the property installed for this project, such as the steam turbine and upgrades to the bus-duct electrical distribution to the idle bays where the new equipment will be installed, as in-kind cost share contribution for Phase III. The current team members have shown continuous interest in participating in Phase III. If awarded for Phase II, B&W will further secure the team commitment and sources for potential cost share from existing and new team members, industry partners and the state of Ohio, for Phase III.

The preliminary TEA of a 550 MWe CDCL commercial plant developed by B&W will be provided to EPRI for reviewing and updating during Phase II for a first-of-a-kind commercial plant. EPRI will also provide comparisons to relevant baselines and perform sensitivity studies of importance. A Level 1 plan and schedule of tasks in Phase II is shown in Figure 16. The full detailed plan and schedule (10-page schedule) is provided in the Project Management Plan.

As described above, the proposed project will leverage the groundwork established from the existing 10 MWe CDCL Pre-FEED project to ensure the tasks for Phase II are completed on schedule and within budget. The technical approach for this proposed project is designed such that the tasks in the Pre-FEED project are complementary and not redundant with the proposed work. The tasks proposed in Phase II aim to finalize the FEED study, obtain all required environmental permitting, secure team and cost-share commitment for Phase III and identify and complete any remaining work required to ensure a smooth transition into Phase III without delay. Since B&W has a strong working relationship with each project team member, the proposed tasks are highly feasible and attainable. ***Since each team member is already under contract, work can begin immediately upon notification of award.*** Combined with the tasks in the existing 10 MWe CDCL Pre-FEED, the project team is confident in achieving the objectives of the FEED study and demonstration of the large pilot plant at the host site.

B. FEASIBILITY, APPROPRIATENESS, RATIONALE, AND COMPLETENESS FOR THE PROPOSED STATEMENT OF PROJECT OBJECTIVES

The team is fortunate to already have in place a project to prepare a Pre-FEED study (DE-FE0027654). Consequently, only the tasks specifically identified in the funding opportunity announcement and not covered under the existing Pre-FEED study need to be proposed. Therefore, the proposed SOPO identifies complementary scope, and no redundant scope of the current Pre-FEED study is included. Since the proposed work is complementary in nature and adheres to the rationale behind the sponsored Pre-FEED study, the feasibility, appropriateness and completeness of the combined scope have been rigorously examined.

C. ADEQUACY AND COMPLETENESS OF THE PROJECT MANAGEMENT PLAN

A detailed Project Management Plan is submitted separately in this proposal, which discusses the project objectives, the complete detailed schedule through the end of Phase III, organization, risk management, funding and cost profile, milestone and success criteria in detail.

The proposed project activities are organized according to major tasks and subtasks. Some planned activities will progress sequentially, while others will be done in parallel to ensure that the proposed work can be completed properly within the project's performance period. Task leaders and project collaborators with unique qualifications and specific expertise are responsible for their assignments.

Potential risks due to uncertainties in the technical scope, resources, management, schedule, and budgetary have been identified. For each risk element, a probability and an impact value have been assigned and will be reviewed and updated as needed throughout the project. Regardless of the source, a risk management plan will be put into action to mitigate or manage each risk scenario and assess its impact on the overall forecast. Contingency plans for medium- to high-risk elements will be developed to avoid recurrence. Monitoring of the risks will continue through the entire project. Clear milestones are also identified for tracking the progress and adherence to the project schedule and deliverables. In the end, the successful criteria will be gauged against the DOE's stated objectives for the design, construction, and operation of a large-scale pilot of transformational coal technologies aimed at enabling step change improvements in coal powered system performance, efficiency and COE.

Figure 16 shows a detailed schedule and timeline for Phase II, including a high-level scope of work. The milestones of the Phase II project are shown in Table 17.

Table 17. Milestone Log

Task	Milestone Description	Planned Completion Date	Verification Method
2	FEED Study Report	9/31/2020	Phase II Topical Report
3	Final NEPA Documentation	6/30/2020	Delivered to DOE
4	Phase III Cost Estimation and Schedule	9/31/2020	Phase II Topical Report
4	Phase III Cost Share Commitment	9/31/2020	Phase II Topical Report
5	Updated TEA	9/31/2020	Phase II Topical Report
6	Phase II Topical Report	9/31/2020	Delivered to DOE

The project cost summary is provided in Table 18. The total project value is $4,189,710 with $1,189,710 (28.40%) provided as cost share by the participants and $3,000,000 provided by the DOE.

Table 18. Cost Summary

	10/1/2019 - 9/30/2020		
Entity	**Federal Share**	**Cost Share**	**Total**
Babcock & Wilcox Company	$2,003,994	$197,811	$2,201,805
The Ohio State University	$288,000	$700,000	$988,000
Electric Power Research Institute	$136,847	$34,210	$171,057
Dover Light & Power	$0	$200,000	$200,000
Worley Parsons	$259,953	$26,000	$285,953
Trinity Consultants	$129,510	$14,390	$143,900
SSOE	$62,500	$0	$62,500
ClearSkies	$69,196	$17,299	$86,495
B&W Construction Company	$50,000	$0	$50,000
Total	**$3,000,000**	**$1,189,710**	**$4,189,710**
Percentage of Total	**71.60%**	**28.40%**	**100.00%**

End of Topical Report Content
(Limit 75 Pages)

APPENDICES TO THE TOPICAL REPORT

APPENDIX A: Environmental Information Volume

Due to the size of this appendix, the Environmental Information Volume is attached as a separate PDF file (Topical_Report_Appendix_A-EIV.pdf). Please refer to this document for the Environmental Information Volume.

APPENDIX B: Bibliography and References

Cost and Performance Baseline for Fossil Energy Plants Volume 1a: Bituminous Coal (PC) and Natural Gas to Electricity Revision 3, The Department of Energy National Energy Technology Laboratory, DOE/NETL-2015/1723, July 6, 2015

Weeks SA, Dumbill P. Method speeds FCC catalyst attrition resistance determinations. *Oil Gas J*. 1990:88:38-40.

Abad A, Mattisson T, Lyngfelt A, Johansson M. The use of iron oxide as oxygen carrier in a chemical-looping reactor. *Fuel*. 2007:86:1021-1035.

APPENDIX C: Facilities & Other Resources

The Ohio State University: The 2.5 kW_t Coal Direct Chemical Looping (CDCL) bench unit is a solid moving bed system that has been used to experimentally verify the reducer reactions in a countercurrent moving bed system. The bench unit is in Koffolt Laboratory on OSU's main campus. The system consists of a nondispersive infrared gas analyzer, a thermal conductivity gas analyzer, a gas chromatograph, a steam generator, a gas mixing panel, a 208 V service panel for heating and a computer that serves the purpose of controlling the temperature of the reactor, collecting temperature and gas concentration data, and controlling the gas mixing panel. OSU also has a quartz tube fixed/integral bed reactor and differential bed reactor. All OSU's reactors can operate up to 1050 °C at atmospheric pressure.

The 25 kW_t CDCL sub-pilot unit located in the Research Center, one mile west of OSU's main campus, is a fully integrated chemical looping unit that demonstrates the main reactions in both the reducer and combustor reactors in a circulating fluidized bed setup. The equipment available for gas flow and analysis includes an air compressor, 6 mass flow controllers (0-150 L/min), four 180 L liquid nitrogen tanks, 10 variable area flow meters, six nondispersive infrared gas analyzers and a gas chromatograph. The reactor has two identical coal feeders that can flow up to 200 g/min of coal. The heating equipment for the system includes seven sets of radiant furnace heaters that go up to 1050°C, a 208 V three phase service panel with breaker for each heater. Equipment used to monitor the pressure balance and provide control loop feedback in the system includes 15 absolute and differential pressure transducers. The data acquisition and process control systems consist of industrial grade programmable logic controller (PLC, Allen-Bradley) and compatible logic/human-machine-interface programming software (Rockwell). The server connected to the PLC monitors and records the temperature, pressure and gas composition as well as control the gas flows and external heat input into the reactor systems. A baghouse collects the fines that are expelled from the reactor. Further analysis can be performed after tests by taking samples and testing them with a thermogravimetric analyzer at the Research Center. Below is a photograph of the 25 kW_t sub-pilot CDCL unit at OSU.

Figure 18. OSU's 25 kW_t CDCL Sub-Pilot Facility

The Babcock & Wilcox Company (B&W): A 250 kW_t coal-direct chemical looping (CDCL) pilot facility is located in Barberton, OH. It consists of a counter-current moving bed reducer, a bubbling fluidized bed combustor, a riser for pneumatical solid transportation, a disengagement zone for particle separation, a standpipe with zone seal for gas sealing, and a non-mechanical L-valve for solid flow control. The combustor is heated up with three pre-heaters (30 kW, 75 kW, and 10 kW) on the air supply line and a start-up burner (250 kW) located in the combustor. After the combustor reaches the auto-ignition temperature of natural gas (1100 °F), natural gas input is gradually switched from the start-up burner to the injection nozzle at the combustor bottom. The reducer is heated up with preheated air before 500 °F and hot circulated particles after 500 °F. The maximum operating temperature of the facility is 2012 °F. Pulverized coal is fed into the bottom moving bed reducer through a screw feeder and a rotary valve. Weight of the coal hopper is recorded on line for estimating the coal feeding rate. The maximum coal feeding rate is 70 lb/hr. Enhancer gas, CO_2 and/or steam, is introduced into the bottom moving bed reducer through a house-made gas distributor. The inlet steam is controlled at 350 °F while CO_2 is at ambient temperature. Nitrogen is applied at the zone seal and the L-valve. The solid circulation is controlled by the aeration rate of N_2 at the L-valve. Isokinetic Feeder (IKF) device, designed and patented by B&W, is used to measure the solid circulation rate and make up particles into standpipe upstream of the L-valve during operation. Pressure across the entire facility is monitored on line as an indicator of the solid and gas flow condition during operation. Hot exhaust gas is quenched by air supplied from a blower before passing the baghouses, the ID fan, and the stack. Particle fines collected by baghouses are recorded during operation for the evaluation of attrition rate. Gas is sampled from sampling probes at the top moving bed reducer and thermocouple ports across the reactor loop. Concentrations of CO_2, CO, NO_x, SO_2, and O_2 in the sampling gas are analyzed by multiple gas analyzers. Up to date, successful long-term test campaigns under coal have been accomplished. The facility is ready and available for additional chemical looping testing.

Figure 19. 250 kW_t CDCL Pilot Facility at B&W Research Center

Other capabilities at B&W's facilities include:

- Adequate space for subsystem or fully integrated system installations,
- Available utilities to satisfy the facility needs,
- Onsite coal storage and handling equipment,
- Onsite VFD air compressor and steam generator,
- Existing environmental control and monitoring systems.

Dover Light & Power (DL&P): DL&P is the primary host site. DL&P has been in the business of providing dependable, reliable electricity for its residents for nearly a century. Located in the City of Dover, Ohio, DL&P delivers reliable and affordable energy to nearly 14,000 residents and almost 1,000 businesses in the region. DL&P has a stoker coal-fired boiler with a maximum steaming capacity of 165,000 lbs/hr at 875 psig and 900 °F leaving the superheater. Steam temperature control is by means of an attemperator. Changes to this 1960 era boiler include addition of two 37.5 MBtu/hr gas burners, with one on each sidewall; installation of a baghouse for particulate control; and installation of a Detroit Stoker under throw feeders for improved coal distribution. DL&P is planning to install a recently refurbished steam turbine (20 MW_e) and the associated BOP before Phase III of this project. The newly added steam cycle equipment and the existing BOP equipment are available for the proposed project.

The Electric Power Research Institute, Inc. (EPRI): EPRI, with principal facilities in Charlotte, North Carolina and Palo Alto, California, conducts research and development on technology, operations and the environment for the global electric power sector. EPRI's members represent over 90% of the electricity generated in the United States. EPRI has extensive knowledge and contacts in the electric power industry that provide a perspective on coal-fired power generation using more novel technologies, including chemical looping cycles.

APPENDIX D: Equipment

Software

- Aspen Plus™
- MATLAB
- DAQ FACTORY
- FactoryTalk SE
- RSLogix 5000
- ProTRAX
- Fluent
- MFIX