Advanced Pressurized Fluidized Bed Coal Combustion with Carbon Capture

Conceptual Design Report

Concept Area: With Carbon Capture/Carbon Capture Ready

Contract: 89243319CFE000020

CONSOL Pennsylvania Coal Company LLC
1000 CONSOL Energy Drive, Suite 100, Canonsburg, PA 15317-6506
Point of Contact: Daniel Connell
Phone: (724) 416-8282
danielconnell@consolenergy.com

July 14, 2019

Business Case

Market Scenario

The overall objective of this project is to design an advanced coal-fueled power plant that can be commercially viable in the U.S. power generation market of the future and has the potential to be demonstrated in the next 5-10 years and to begin achieving market penetration by 2030. Unlike the current U.S. coal fleet, which was largely installed to provide baseload generation at a time when coal enjoyed a wide cost advantage over competing fuels and when advances in natural gas combined cycle, wind, and solar technologies had not yet materialized, the future U.S. coal fleet must be designed to operate in a much more competitive and dynamic power generation landscape. For example, during 2005-2008, the years leading up to the last wave of new coal-fired capacity additions in the U.S., the average cost of coal delivered to U.S. power plants ($1.77/MMBtu) was $6.05/MMBtu lower than the average cost of natural gas delivered to U.S. power plants ($7.82/MMBtu), and wind and solar accounted for less than 1% of total U.S. power generation. By 2018, the spread between delivered coal and natural gas prices ($2.06 and $3.54/MMBtu, respectively) had narrowed to just $1.48/MMBtu, and renewables penetration had increased to 8%. [1] (References in Appendix A) EIA projects that by 2030, the spread between delivered coal and natural gas prices ($2.22/MMBtu and $4.20/MMBtu, respectively, in 2018 dollars) will have widened marginally to $1.98/MMBtu, and wind and solar penetration will have approximately tripled from current levels to 24%. [2]

In this market scenario, a typical new advanced natural gas combined cycle (NGCC) power plant without carbon dioxide capture would be expected to dispatch with a delivered fuel + variable O&M cost of $28.52/MWh (assuming a 6,300 Btu/kWh HHV heat rate and $2.06/MWh variable cost) and could be built for a total overnight cost of <$1,000/kWe (2018$). [3] By comparison, a new ultra-supercritical pulverized coal-fired power plant would be expected to dispatch at a lower delivered fuel + variable O&M cost of ~$24.14/MWh (assuming an 8,800 Btu/kWh HHV heat rate and $4.60/MWh variable cost), but with a capital cost that is ~4 times greater than that of the NGCC plant. [4] The modest advantage in O&M costs for the coal plant is insufficient to outweigh the large disparity in capital costs vs. the NGCC plant, posing a barrier to market entry for the coal plant. This highlights the need for advanced coal-fueled power generation technologies that can overcome this barrier and enable continued utilization of the nation's valuable coal reserve base to produce affordable, reliable, resilient electricity.

Against this market backdrop, we believe that the commercial viability of any new coal-fueled power generation technology depends strongly upon the following attributes: (1) excellent environmental performance, including very low air, water, and waste emissions (to promote public acceptance and alleviate permitting concerns), (2) lower capital cost relative to other coal technologies (to help narrow the gap between coal and natural gas capex), (3) significantly lower O&M cost relative to natural gas (to help offset the remaining capital cost gap vs. natural gas and ensure that the coal plant is favorably positioned on the dispatch curve across a broad range of natural gas price scenarios), (4) operating flexibility to cycle in a power grid that includes a meaningful share of intermittent renewables (to maximize profitability), and (5) ability to incorporate carbon capture with moderate cost and energy penalties relative to other coal and gas generation technologies (to keep coal as a competitive dispatchable generating resource in a carbon-constrained scenario). These are generally consistent with or enabled by the traits targeted under DOE's Coal-Based Power Plants of the Future program (e.g., high efficiency, modular construction, near-zero emissions, CO_2 capture capability, high ramp rates and turndown capability, minimized water consumption, integration with energy storage and plant value streams), although our view is that the overall cost competitiveness of the plant (capital and O&M) is more important than any single technical performance target. In addition, the technology must have a relatively fast timeline to commercialization, so that new plants can be brought online in time to enable a smooth transition from the existing coal fleet without compromising the sustainability of the coal supply chain.

Pressurized fluidized bed combustion (PFBC) provides a technology platform that is well-suited to meet this combination of attributes. A base version of this technology has already been commercialized, with units currently operated at three locations worldwide: (1) Stockholm, Sweden (135 MWe, 2 x P200, subcritical, 1991 start-up), (2) Cottbus, Germany (80 MWe, 1 x P200, subcritical, 1999 start-up), and (3) Karita, Japan (360 MWe, 1 x P800, supercritical, 2001 start-up). These installations provide proof of certain key features of the technology, including high efficiency (the Karita plant achieved 42.3% net HHV efficiency using a supercritical steam cycle), low emissions (the Vartan plant in Stockholm achieved 98% sulfur capture without a scrubber and 0.05 lb/MMBtu NOx emissions using only SNCR), byproduct reuse (ash from the Karita PFBC is used as aggregate for concrete manufacture), and modular construction. Several of these installations were combined heat and power plants. This also highlights the ***international as well as domestic market applicability of the technology***.

The concept proposed here builds upon the base PFBC platform to create an advanced, state-of-the-art coal-fueled power generation system. Novel aspects of this advanced PFBC technology include: (1) integration of the smaller P200 modules with a supercritical steam cycle to maximize modular construction while maintaining high efficiency, (2) optimizing the steam cycle, turbomachine, and heat integration, and taking advantage of advances in materials and digital control technologies to realize improvements in operating flexibility and efficiency, and (3) integrating carbon dioxide capture via the Benfield process, which affords lower cost and energy penalties relative to conventional CO_2 capture technologies.

In addition, while the base design, performance estimates, and economics presented here are based on a greenfield Midwestern U.S. plant taking rail delivery of Illinois No. 6 coal, as specified in the Common Design Basis for Conceptual Design Configurations, the most compelling business case for the PFBC technology arises from taking advantage of its tremendous fuel flexibility to use fine, wet waste coal as the fuel source. Conceptual plant flowsheets and conceptual plant layouts for the base case and the waste fuel option are shown in Appendix B. The waste coal, which is a byproduct of the coal preparation process, can be obtained either by reclaiming tailings from existing slurry impoundments or by diverting the thickener underflow stream (before it is sent for disposal) from actively operating coal preparation plants. It can be transported via pipeline and requires only simple mechanical dewatering to form a paste that can be pumped into the PFBC combustor. As shown in the estimate in Appendix C, there is broad availability of this material, with an estimated 34+ million tons produced each year by currently operating prep plants located in 13 coal-producing states, and hundreds of millions of tons housed in existing slurry impoundments. CONSOL's Bailey Central Preparation Plant in Greene County, PA, alone produces close to 3 million tons/year of fine coal refuse with a higher heating value of ~7,000 Btu/lb (dry basis), which is much more than sufficient to fuel a 300 MWnet advanced PFBC power plant with CO_2 capture. This slurry is currently disposed at a cost. As a result, it has the potential to provide a low- or zero-cost fuel source if it is instead used to fuel an advanced PFBC power plant located in close proximity to the coal preparation plant. Doing so also eliminates an environmental liability (slurry impoundments) associated with the upstream coal production process, improving the sustainability of the overall coal supply chain.

Market Advantage of the Concept

The market advantage of advanced PFBC relative to other coal-fueled generating technologies, then, stems from its unique ability to respond to all five key attributes identified above, while providing a rapid path forward for commercialization. Specifically:

1. Excellent Environmental Performance – The advanced PFBC is able to achieve very low NOx (<0.05 lb/MMBtu) and SO_2 (<0.117 lb/MMBtu) emission rates by simply incorporating selective non-catalytic reduction and limestone injection at pressure within the PFBC vessel itself. After incorporation of an SO_2 polishing step before the CO_2 capture process, the SO_2 emissions will be <0.03 lb/MMBtu or <0.256 lb/MWh. As mentioned above, the PFBC can also significantly improve the environmental footprint of the upstream coal mining process if it uses fine, wet waste coal as a fuel source, and it produces a dry solid byproduct (ash) having potential commercial applications.
2. Low Capital Cost – The advanced PFBC in carbon capture-ready configuration can achieve >40% net HHV efficiency at normal supercritical steam cycle conditions, avoiding the capital expense associated with the exotic materials and thicker walls needed for higher steam temperatures and pressures. Significant capital savings are also realized because NOx and SO_2 emission targets can be achieved without the need for an SCR or FGD. Finally, the P200 is designed for modular construction and replication based on a single, standardized design, enabling further capital cost savings.
3. Low O&M Cost – By fully or partially firing fine, wet waste coal at low-to-zero fuel cost, the advanced PFBC can achieve dramatically lower fuel costs than competing coal and natural gas plants. This is especially meaningful for the commercial competitiveness of the technology, as fuel cost (mine + transportation) accounts for the majority (~2/3) of a typical pulverized coal plant's total O&M cost, and for an even greater amount (>80%) of its variable (dispatch) cost. [5]
4. Operating Flexibility – The advanced PFBC plant includes four separate P200 modules that can be run in various combinations to cover a wide range of loads. Each P200 module includes a bed reinjection vessel to provide further load-following capability, enabling an operating range from <20% to 100%. A 4% ramp rate can be achieved using a combination of coal-based energy and natural gas co-firing.
5. Ability to Cost-Effectively Incorporate Carbon Capture – The advanced PFBC produces flue gas at 12 bar, resulting in a greater CO_2 partial pressure and considerably smaller gas volumes relative to atmospheric boilers. The smaller volume results in smaller physical sizes for equipment. The higher partial pressure of CO_2 provides a greater driving force for CO_2 capture and enables use of the commercially-available Benfield CO_2 capture process, which has the same working pressure as the PFBC boiler and affords lower regeneration energy requirements than typical amine scrubbing processes. Because of the fuel flexibility afforded by the advanced PFBC boiler, there is also an opportunity to co-fire biomass with coal to achieve carbon-neutral operation.

The timeline to commercialization for advanced PFBC is expected to be an advantage relative to other advanced coal technologies, because (1) the core P200 module has already been designed and commercially proven, and (2) the main technology gaps associated with the advanced PFBC plant, including integration of carbon capture, integration of multiple P200 modules with a supercritical steam cycle, and development of a suitable turbomachine for the carbon capture-equipped configuration, either involve the use of commercial technology (i.e., the Benfield CO_2 capture process) or are considered to be well within the capability of OEMs using existing materials and technology platforms (in the case of the turbomachine and supercritical steam cycle). The concept of firing a PFBC with fine, wet waste coal (thickener underflow) was demonstrated in a 1 MWt pilot unit at CONSOL's former Research & Development facility in South Park, PA, both without CO_2 capture (in 2006-2007) and with potassium carbonate-based CO_2 capture (in 2009-2010), providing evidence of its feasibility. We believe that the first-generation advanced PFBC plant, capable of achieving ≥40% HHV efficiency in CO_2 capture-ready configuration and incorporating 90% CO_2 capture and compression with ≤22% energy penalty, would be technically ready for commercial-scale demonstration in the early 2020s. We propose to evaluate CONSOL's Bailey Central Preparation Plant as a potential source of fuel (fine, wet waste coal) and potential location for this demonstration plant. Additional R&D in the areas of process optimization, turbomachine design, advanced materials, and/or heat exchange fluids could enable a ≥4% efficiency point gain in Nth-of-a-kind plants and a ~4 percentage point improvement in the energy penalty associated with CO_2 capture, although it will likely only make sense to pursue efficiency improvement pathways that can be accomplished while maintaining or reducing plant capital cost.

Estimated Cost of Electricity Establishing the Competitiveness of the Concept

A summary of the estimated COE for the base case advanced PFBC with CO_2 capture is presented in Table 1. (Additional details of the economic analysis are presented in Appendix D). These estimates are preliminary in nature and will be revised via a much more detailed analysis as part of the pre-FEED study. As discussed above, our base case economic analysis assumes a first-generation advanced PFBC plant constructed on a greenfield Midwestern U.S. site that takes rail delivery of Illinois #6 coal, as specified in the Common Design Basis for Conceptual Design Configurations. Capital cost estimates are in mid-2019 dollars and were largely developed by Worley Group, Inc. by scaling and escalating quotes or estimates produced under previous PFBC studies and power plant projects. Costs for coal and other consumables are based on approximate current market prices for the midwestern U.S.; the delivered coal cost of \$50/ton includes an assumed FOB mine price of \$40/ton plus a rail delivery charge of \$10/ton. For purposes of this conceptual estimate, it was assumed that PFBC bed and fly ash are provided for beneficial reuse at zero net cost/benefit. Also, because our base plant design includes 90% CO_2 capture, we have assumed that the captured CO_2 is provided for beneficial use or storage at a net credit of \$35/ton of CO_2, consistent with the 2024 value of the Section 45Q tax credit for CO_2 that is stored through EOR or beneficially reused. Otherwise, the cost estimating methodology used here is largely consistent with that used in DOE's "Cost and Performance Baseline for Fossil Energy Plants Volume 1: Bituminous Coal and Natural Gas to Electricity." The first-year cost of electricity (COE) values presented in Table 1 are based on an 85% capacity factor (see discussion below) and 12.4% capital charge factor (CCF), consistent with the DOE bituminous baseline report assumption for high-risk electric power projects with a 5-year capital expenditure period.

To better understand the potential competitiveness of the advanced PFBC technology, preliminary estimates for several other cases are also summarized in Table 1: (1) a carbon capture-ready PFBC plant based on current technology firing Illinois No. 6 coal, (2) a carbon capture-ready PFBC plant based on advanced technology (4-point efficiency improvement + 15% reduction in capital cost) firing fine, wet waste coal, and (3) a PFBC plant with 90% CO_2 capture based on advanced technology (same as above, plus 4-point reduction in CO_2 capture energy penalty) firing fine, wet waste coal. Use of waste coal in cases (2) and (3) is assumed to result in a fuel cost of $10/ton as compared to $50/ton in the base case. (This cost could be even lower depending on proximity to the waste coal source, commercial considerations, etc.) The improvements in efficiency are assumed to be achieved through process optimization and resolution of the technology gaps identified above and later in this report. The improvements in capital cost are assumed to be achieved through process optimization, adoption of modular construction practices, and learning curve effects.

Table 1-Cost of Electricity Projections for Advanced PFBC Plant Cases

	Base Case: IL No. 6 coal 90% capture current tech	**Case #1 IL No. 6 coal capture-ready current tech**	**Case #2 fine waste coal capture-ready advanced tech**	**Case #3 fine waste coal 90% capture advanced tech**
Net HHV efficiency	31%	40%	44%	36%
Total Overnight Cost ($/kW)	$5,725	$3,193	$2,466	$4,189
Total Overnight Cost ($/MWh)	$95.33	$53.17	$41.07	$69.76
Fixed O&M Cost ($/MWh)	$24.34	$18.08	$16.44	$20.96
Fuel Cost ($/MWh)	$23.57	$17.93	$3.26	$4.06
CO2 Credit ($/MWh)	($36.48)	--	--	($31.42)
Variable O&M Cost ($/MWh)	$10.16	$7.73	$7.03	$8.75
TOTAL COE ($/MWh)	$116.92	$96.91	$67.80	$72.12

Based on the initial projections in Table 1, it is possible to highlight several competitive advantages of the advanced PFBC technology vs. other coal-fueled power generation technologies. First, although capital costs are expected to present a commercial hurdle for all coal-based technologies relative to natural gas-based technologies, the total overnight cost (TOC) range of $2,466/kW to $3,193/kW presented above for a capture-ready PFBC plant compares favorably with the expected TOC of ~$3,600/kW for a less-efficient new supercritical coal plant. [6] Second, the fuel flexibility of the PFBC plant provides an opportunity to use fine, wet waste coal to achieve dispatch costs that are expected to be substantially lower than those of competing coal and natural gas-based plants. As illustrated by Cases #2-3, a PFBC plant firing $10/ton waste coal is expected to achieve total fuel + variable O&M costs of $10-13/MWh, far better than the $24-29/MWh range for ultra-supercritical coal and natural gas combined cycle plants cited in the 2030 market scenario above. This should allow a PFBC plant firing waste coal to dispatch at a very high capacity factor, improving its economic viability. Finally, with a $35/ton credit for CO_2, and assuming a net zero-cost CO_2 offtake opportunity can be identified, the COE for an advanced PFBC plant with 90% CO_2 capture is expected to be reasonably similar to the COE for a capture-ready plant. We anticipate that the economics and performance of a first-generation PFBC plant with 90% CO_2 capture will fall between those presented in the Base Case and Case #3 above. A major objective of the project team moving forward will be to drive down COE through value engineering utilizing a combination of (i) process design and technology optimization and (ii) optimization of fuel sourcing and CO_2 offtake.

Plant Concept Description and Important Traits

Proposed Plant Concept Description

The proposed Coal-Based Power Plant of the Future concept presented herein is based on a pressurized fluidized bubbling bed combustor providing heat of combustion to a gas turbomachine (Brayton Cycle) and a steam generator providing steam to a steam turbine generator (Rankine Cycle) in parallel operation. The plant described is configured to fire Illinois No. 6 coal, and plant performance and characteristics discussed are based on this fuel. The PFBC is capable of firing a wide range of carbonaceous fuels, including waste coals and biomass. Plant performance firing these fuels may vary somewhat from what is presented herein as firing of waste coals in particular, which are typically available at very low cost, may not require aggressive steam conditions for optimum economic performance.

The bubbling bed combustor operates at elevated pressure of approximately 12 bar in the P200 module. This pressure enhances the combustion and sulfur capture reactions in the fluidized bed due to the elevated partial pressure of the reactants. Earlier versions of this technology that are not carbon capture-ready incorporated some feed water heating for the Rankine cycle by utilizing waste heat from the turbomachine exhaust. This feature is not used in the carbon capture or capture-ready versions of the technology.

The pressurized fluid bed is contained inside a pressure vessel that also encloses steam generating boiler tube surfaces. The combustion gases provide heat transfer to the steam generating surfaces for feed water/steam heating in a once-through type steam generator. The heated gas exits the pressure vessel at elevated pressure and temperature (12 bar/1550 ^{0}F) after two stages of cyclones to pass through a gas cooler, a high-efficiency metallic filter, and then (in the capture-ready case) on to a gas turbomachine expander.

The offered technology is unique and innovative in this major respect: it utilizes a carbon capture process that is capable of reducing the typical large parasitic load (electric or steam) on the base thermal cycles. The well-known Benfield process using potassium carbonate as a solvent is used at elevated pressure in the gas path to capture CO_2. This carbon capture feature is optional and may be added to a capture-ready plant configuration without major rework or compromise to plant operating characteristics and with little interruption to the operation of the capture-ready plant.

Ability to Meet Specific Design Criteria

The ability of the proposed plant design to meet the specific design criteria is described below:

- The PFBC plant is capable of meeting a 4% ramp rate using a combination of coal-based energy and co-fired natural gas energy up to 30% of total Btu input. Higher levels of natural gas firing may be feasible and can be evaluated. The PFBC design incorporates a bed reinjection vessel inside the main pressure vessel that stores an inventory of bed material (fuel and ash solids) during steady state operation. When a load increase is called for, this vessel reinjects a portion of its inventory back into the active bed to supplement the bed inventory. Natural gas co-firing using startup lances, over-bed firing, or a combination thereof is used to supplement the energy addition to the fluid bed to support the additional steam generation that supports the increase in power generation during the up-ramp transient. During down-ramp excursions, the bed reinjection vessel can take in some of the bed inventory to assist in maintaining the heat transfer requirements. Coal flow is reduced during a down-ramp transient. Steam bypass to the condenser may also be used in modulating a down-ramp transient.

- The PFBC plant requires 8 hours to start up from cold conditions on coal. Startup from warm conditions requires from 3 to 6 hours, depending on the metal and refractory temperatures existing when a restart order is given. These start up profiles are given in Appendix E. Startup from hot conditions (defined as bed temperature at or near 1500 ^{0}F, and main steam pipe temperature above approximately 800 ^{0}F) requires less than 2 hours on coal; this time is reduced to approximately 1 to 2 hours with natural gas co-firing. It should be noted that very short startup times are not compatible with use of a supercritical steam cycle with high main and reheat steam design temperatures. There are two compelling factors that mitigate against very fast starts for this type of steam cycle: first are the severe secondary stresses induced in heavy wall piping and valves necessary for supercritical steam conditions. Longer warmup times are necessary to avoid premature material failures and life-limiting changes in the pressure part materials for the piping, valves, and high-pressure turbine components. The second limiting factor on rapid startup times is the feed water chemistry limitation inherent in supercritical steam cycles. After a complete shutdown, condensate and feed water chemistry typically requires some length of time to be returned to specification levels. Assuring long material life and preventing various kinds of corrosion mechanisms from becoming an issue requires that water chemistry be brought to the proper levels prior to proceeding with a full startup from cold, no-flow conditions. Resolution of this entire bundle of issues could be viewed as a "Technology Gap" of sorts, requiring investigation to see if any realistic remedies can be developed.
- The PFBC can turn down to the required 20% load and below by reducing the number of modules in operation. A 20% power level can be achieved by operating one of four P200 modules at approximately 80% load or two modules at about 40% load each. Operation is expected at full environmental compliance based on known previous operational experience.
- The PFBC technology offered employs 90% CO_2 capture, but it can also be offered as fully CO_2 capture-ready without the capture equipment installed. The addition (construction) of the CO_2 capture equipment may be performed while the plant is in operation without interference, and the switch-over to CO_2 capture, after construction is completed, can be made by opening/closing specific valves to make the transition while at power. This is accomplished one PFBC module at a time to minimize any impacts on system operation.
- The proposed PFBC plant will incorporate a Zero Liquid Discharge system. The plant design will be integrated with the fuel preparation facility to incorporate internal water recycle and to reuse water to the maximum extent. This will minimize the capacity, and thereby the cost, of any required ZLD system.
- Solids disposal is characterized by two major streams of solids: bed ash and cyclone and filter ash. The ash material has mild pozzolanic properties, and it may be landfilled or used in a beneficial way to fabricate blocks or slabs for landscaping or light-duty architectural applications. The ash products are generally non-leachable as demonstrated by PFBC operations in Sweden and Japan.
- Dry bottom and fly ash discharge: PFBC ash (both bed and fly) is dry. Discharge is made through ash coolers that provide some heat recovery into the steam cycle condensate

stream. The cooled ash is discharged into ash silos and then off-loaded into closed ash transport trucks for ultimate disposal or transport to a facility for use in manufacture of saleable end products, as noted above.

- Efficiency improvement technologies applicable to the PFBC will include neural network control features and learning models for plant controls balancing air supply against fuel firing rate (excess air), ammonia injection for SNCR, bed performance removing sulfur, and other opportunities to optimize overall performance.
- The limitation of air heater outlet temperatures is not applicable to PFBC technology.
- High-efficiency motors will be used for motor-driven equipment when and where applicable. Electric generators will be specified to be constructed to state-of-the-art efficiency standards.
- Excess air levels will be maintained at appropriate levels to optimize the operation of the overall PFBC Brayton and Rankine cycles, and the sulfur capture chemical reactions in the bubbling bed. A 12% excess air limit may or may not be applicable to this technology. Further evaluation is required. The PFBC technology does not include any component similar to a PC or CFB boiler air heater. However, attempts will be made to minimize leakage of hot gas that could result in loss of recoverable thermal energy.
- The consideration of sliding pressure vs. partial arc admission at constant throttle pressure will be made during Phase II.
- A self-cleaning condenser will be employed for the steam cycle. The attainment of consistent 1.5 in Hg backpressure is achievable on an annual average basis for the proposed site location. However, summer peak backpressures are likely to reach 2.0 inches or more. This is a consequence of the statistically highly probable occurrence of high ambient wet bulb temperatures above 70 ^{0}F. Using aggressive design parameters for the heat sink, including a terminal temperature difference of 5 °F for the condenser, 7 or 8 ^{0}F for the cooling tower approach, and a 17 or 18 ^{0}F range for the circulating water system results in a condensing temperature of at least 99 or 100 ^{0}F at 70 ^{0}F ambient wet bulb temperature, which corresponds to a backpressure of 2.0 in Hga. Therefore, any time ambient wet bulb temperatures exceed 70 ^{0}F, back pressure will exceed 2.0 in Hga. A back pressure of 1.5 in Hga (in the summer above 70 °F wet bulb temperature) might be maintained by use of a sub-dew point cooling tower technology. This is a relatively new innovation that promises to reduce the cooling water temperature produced by an evaporative cooling tower by adding the necessary components of the sub-dew point system to a relatively conventional evaporative cooling tower. Although the efficacy of the system to reduce cold water temperatures produced by an evaporative tower appears theoretically sound, the full economics of employing this type of system remain to be demonstrated in a commercial setting.
- The use of an add-on FGD system is not required for PFBC technology to meet the stated sulfur removal target, as all sulfur capture is performed in the bubbling pressurized bed to achieve the specified 97.3% sulfur capture. When CO_2 capture is employed, additional sulfur capture is required ahead of the Benfield capture process. This additional polishing step reduces sulfur emissions to a level characterized by greater than 99.5% removal.
- Other low-cost solutions will be identified as applicable during the Phase II pre-FEED study.

Proposed PFBC Target Level of Performance

Expected Plant Efficiency Range at Full and Part Load

The expected plant efficiency at full load for a CO_2 capture-ready advanced PFBC plant is shown in Table 2. The proposed PFBC technology is modular and couples to steam turbine generators of varying size. The efficiency varies with the size of the plant, as the selected steam conditions will vary. For almost a century of progress in the development of steam turbine cycles and equipment, the selected steam turbine throttle and reheat conditions have shown a strong correlation to size, as expressed in the table below. This is based on well-established design principles arrived at by the collective experience of turbine generator manufacturers. The steam temperatures are selected to be somewhat aggressive to maximize efficiency.

Table 2-Output and Efficiency for Modular PFBC Designs

No. of P200 Modules	Total Unit Output, MWe, net	Efficiency, HHV	Steam Cycle Parameters
1	89	36.0	1600/1025/1025
2	187	37.6	2000/1050/1050
3	287	38.6	2400/1075/1075
4	397	>40.0%	3500/1100/1100

Note: the 4-module plant is selected as the case described in the remainder of this report.

Part-load efficiency for the 4 x P200 advanced PFBC plant in CO_2 capture-ready configuration is presented in Table 3. The values in the table reflect the PFBC plant operating with the number of P200 modules at the stated load.

Table 3-Part Load Efficiency Table for 4 x P200 PFBC Plant

Percent Load	No. Modules in Operation	MWe, net	Estimated Efficiency %, net, HHV
100	4	397	>40%
80	4	318	39.2
60	3	238	38.4
40	2	159	36.6
20	1	79	32.0

The reduction in efficiency at part load will vary depending on how the plant is operated. Detailed modeling is required to estimate accurate impacts on thermal efficiency at part load. For example, the impact with 4 x P200 modules operating at 50% load may be different from the result obtained with only 2 x P200 modules operating at 100% load for a total plant output of 50%. Detailed definition of plant performance under these conditions will be evaluated in the next phase.

For cases involving the addition of CO_2 capture to the completely capture-ready plant, two scenarios are presented below. Table 4 shows different levels of CO_2 capture for the 4 x P200 module plant. Each case is based on applying the Benfield technology at a 90% capture rate to one, two, three, or all four P200 PFBC modules. These cases are all at full load for each module and for the entire plant.

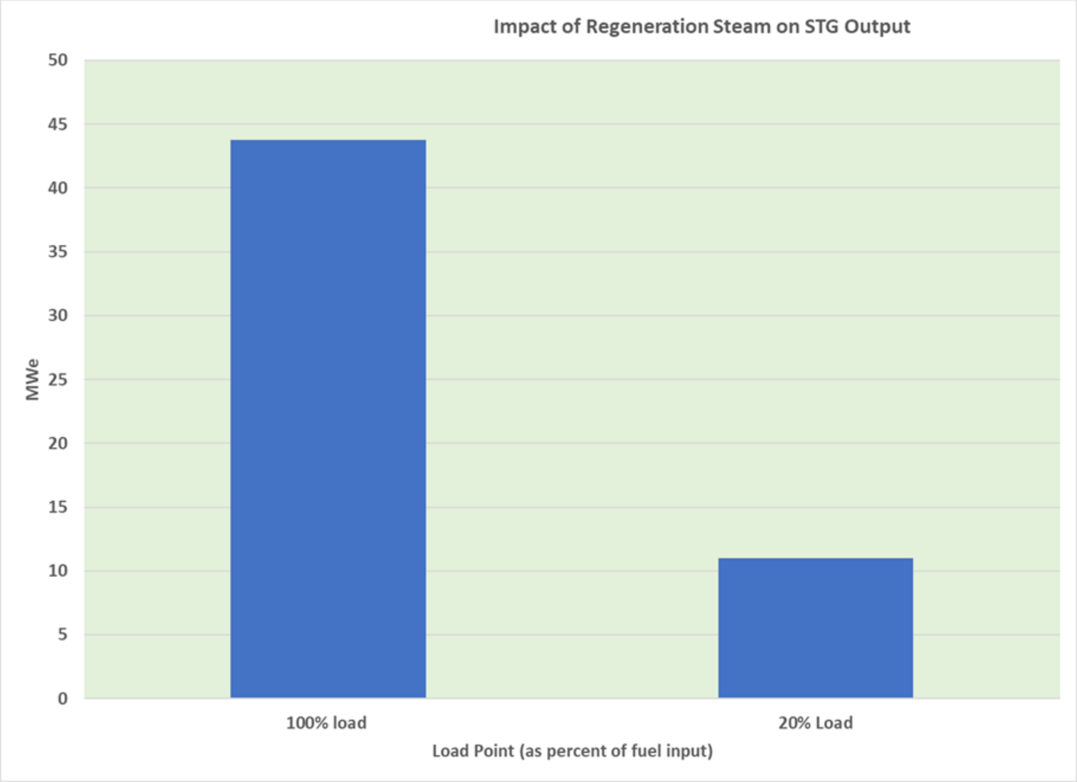
The first efficiency column ("Current State-of-the-Art") presents estimated efficiency values for the configuration described in the Heat/Mass Balance diagrams in Appendix F. This configuration is based on currently available materials of construction, design experience, and heat transfer fluid availability. The data in this column are based on the use of a new turbomachine in lieu of the GT35P, which is not configured to be compatible with CO_2 capture as designed. In all other respects, the efficiency levels in this column reflect the use of current technology materials and practices. The second efficiency column ("Advanced State-of-the-Art") is based on resolution of Technology Gap #4 identified in the section "Technology Development Pathway Description." The principal advance that would contribute to the higher efficiency levels is the use of advanced steam cycle alloys allowing use of the higher steam temperatures, including the use of double reheat. Resolving the "Other Gaps" identified in the "Technology Development Pathway Description" may contribute additional improvements vs. the Advanced State-of-the-Art case, but defining these would require additional effort beyond the scope of this preliminary assessment.

Table 4-Efficiency with CO_2 Capture for 4 x P200 PFBC Plant

No. of Modules with Capture	% Capture, Total Plant	Estimated Efficiency, %, HHV, Current State-of-the-Art	Estimated Efficiency, %, HHV, Advanced State-of-the-Art
0	0	>40	>44%
1	22.5	37.8	42
2	45.0	35.5	40
3	67.5	33.3	38
4	90.0	31	36

The impact of extraction steam from the steam turbine generator (STG) for the purpose of regeneration of CO_2 solvent is shown graphically at the 100% and 20% load points in Figure 1. These load points are defined as 100% rated steam turbine throttle flow and 20% steam turbine throttle flow. Linear interpolation is acceptable between the load points presented as a reasonable first approximation for intermediate load points. The impacts shown are the delta MWe decrease in STG output due to steam extraction for solvent regeneration. The impact is not constant in terms of percent of MWe output across the load range because as STG power output is reduced, steam extraction pressures after the first (control) stage will decrease. Since the solvent regeneration process requires steam input at essentially a constant pressure and enthalpy, it is necessary to either introduce a controlled extraction valve into the steam turbine or to shift to progressively higher extraction points as load decreases. Taking extractions from higher stages has a larger impact on the steam cycle; the introduction of a controlled extraction will also have an impact and also increase capital costs and control complexity. The graph below is based on the use of a control valve in the IP/LP crossover to maintain pressure entering the LP turbine section.

Figure 1-Impact of Regeneration Steam on STG Output



Emissions Control Summary

Air emissions for the PFBC technology are dependent on the coal and/or supplementary fuels fired. For the Illinois No. 6 coal selected for the case presented herein, targeted emissions are presented in Table 5. For different fuels and different sites, which may have widely varying emissions limits, additional measures may be required to meet these more stringent limits. The control of emissions to the limits stated in the DOE solicitation is accomplished as follows.

SO_2 is controlled by capture of sulfur in the pressurized bubbling bed. Limestone sorbent is incorporated in the fuel paste feed. The calcium in the limestone reacts with the sulfur in the coal to form calcium sulfate; the high partial pressure of oxygen in the pressurized bed assures that the material is sulfate (fully oxidized form) instead of sulfite. To achieve 97.3 % sulfur removal, in-bed capture is sufficient. When CO_2 capture is applied to the PFBC plant or if higher levels of sulfur capture are required, a polishing step is added to the gas path to achieve >99.5% sulfur capture.

Table 5-Expected Emissions for P200 Module Firing Illinois No. 6 coal

Pollutant	DOE Target, lb/MWh	DOE Target, lb/MM Btu	PFBC, lb/MM Btu	Comments
SO_2	1.00	0.117	<0.03	Based on 97.3% capture in-bed, with added polishing step (required by Benfield process)
NOx	0.70	0.082	0.05	Catalyst not required
PM (filterable)	0.09	0.0105	0.001 with metal filter (per Mott Inc. quote 2015)	Based on metallic filter
Hg	3×10^{-6}	0.35×10^{-6}	$<0.35 \times 10^{-6}$	Activated carbon bed in gas path.
HCl	0.010	0.0012	<0.0012	Cl capture of 99.5% is required based on the high Ill. 6 Cl content.

The bed functions at a constant 1550 ^{0}F temperature, a temperature at which the NOx forming reactions are very slow (kinetically) and do not lead to any meaningful thermal NOx production. NOx that is formed is largely a product of fuel-bound nitrogen, as thermal NOx creation is minimized. The use of selective non-catalytic reduction (SNCR) reduces any NOx to very low levels (< 0.05 lb/MM Btu).

In this version of the PFBC technology, a metallic filter is used to capture particulate matter (PM). The gas path leaving the PFBC vessel first encounters two stages of cyclones, which remove approximately 98% of the PM. The metallic filter removes over 99.5% of the remaining PM, resulting in very low PM emissions. This also enables the gas to be reacted with CO_2 capture solvent and to be expanded in conventional gas expanders. The use of special expander materials and airfoil profiles is not required.

The fate of Hg and Cl requires detailed evaluation in Phase II. However, at this time, the following rationale is offered in support of our belief that these elements will be controlled to within regulatory limits. A significant portion of the Hg and Cl will be reacted to form a solid compound and will be captured by the two stages of cyclones inside the PFBC vessel and the metal gas filter (external to the vessel) operating at 99.5% plus efficiency. That leaves Hg and Cl in the vapor phase. The gas will pass in succession through the following:

1. A sulfur polishing stage using an alkaline sorbent such as sodium hydroxide
2. A deep bed of activated carbon for capture of elemental Hg
3. The UOP Benfield potassium carbonate CO_2 capture scrubber.

It is believed that the two stages of scrubbing and the activated carbon bed, in series, will capture a very high percentage of the Hg and Cl that remained in the gas after the cyclone/filter stages. The Hg concentration in the flue gas after the carbon bed is estimated at <0.001 ppb by volume. The HCl concentration in the flue gas after the sodium hydroxide SO_2 scrubber and UOP

Benfield process is estimated to be in a range representing 99.5%+ removal, or <0.0012 lb/MM Btu. For both Hg and HCl, therefore, it is expected that emissions will be below the DOE specified values of 3×10^{-6} lb/MWh and 0.010 lb/MWh, respectively.

CO_2 Control Strategy

The CO_2 capture strategy employed for the proposed advanced PFBC plant is to couple the Benfield process with the P200 gas path to capture CO_2 at elevated pressure and reduced temperature. Regenerative reheating of the gas is utilized to recover most of the thermal energy in the gas to maximize energy recovery and improve thermal efficiency. The CO_2 capture is applied in a modular manner, so that the quantity of CO_2 captured may be tailored to the needs of each specific project. Performance is presented herein for a 90% capture case.

Brief Description of the Proposed System

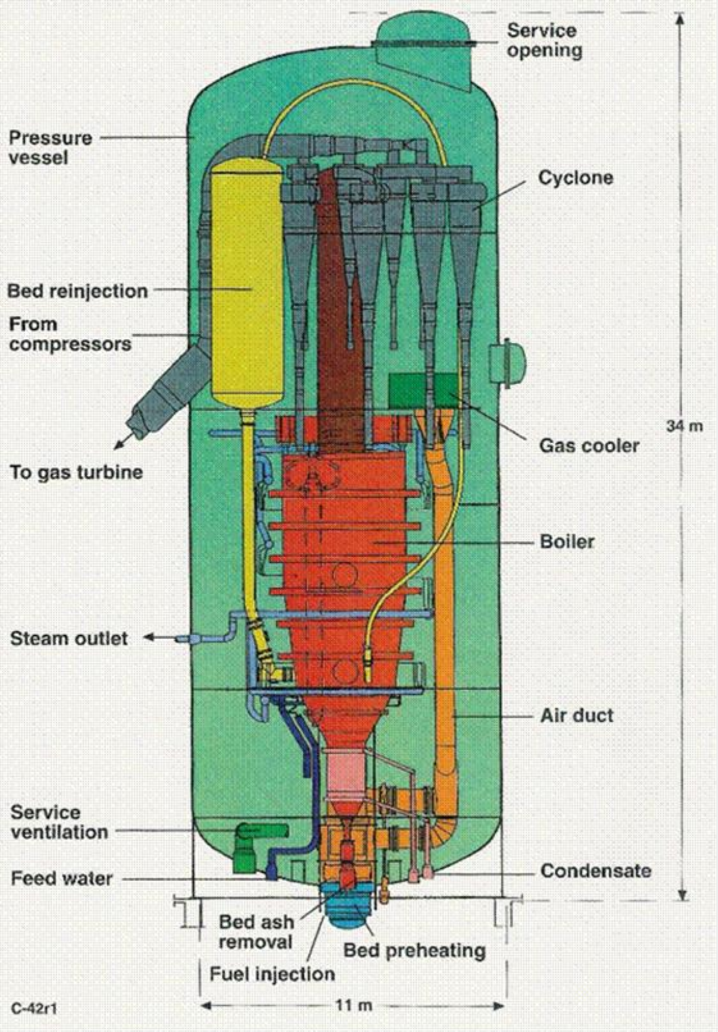
Size of the Commercial Offering

The base case advanced PFBC plant proposed herein includes 4 x P200 modules with a net output of 302 MWe with 90% CO_2 capture (or 397 MWe net in the carbon capture-ready configuration). However, the size of the commercial PFBC power plant can vary as explained above under Proposed PFBC Target Level of Performance. Table 2 shows performance for four different size plants (in the CO_2 capture-ready configuration) using different numbers of P200 modules. (Total unit output does not increase linearly in proportion to the number of modules as the efficiency of the steam cycle increases as the unit size is increased. More aggressive steam throttle pressures and temperatures are selected as unit size increases to take advantage of different steam cycle parameters.)

Advanced Technology Aspects

Advanced technology aspects of the proposed PFBC plant include the incorporation of the Benfield process at elevated pressure and reduced temperature to capture CO_2 from the combustion product gases. The PFBC plant with multiple P200 modules is coupled to a commercial state-of-the-art supercritical steam cycle to maximize thermal efficiency. Prior P200 applications have utilized sub-critical steam cycles. The control system for the entire plant will employ state-of-the-art system architecture and components to maximize performance and minimize emissions. A cut-away illustration of the P200 PFBC vessel is shown in Figure 2 below.

Figure 2-Cut-away view of P200 PFBC Pressure Vessel



List of Components not Commercially Available

The components comprising the PFBC power plant are presented in the section entitled Technology OEMs. The only component that is not currently commercially available is the gas turbomachine that replaces the GT35P gas turbine. Baker Hughes General Electric has provided a letter of cooperation (see Appendix G) for design and delivery of a replacement turbomachine tailored to the requirements of the P200 PFBC with CO_2 capture. Other qualified vendors may also offer solutions but have not offered a commitment letter as of the time of this submittal.

Block Diagram of Integrated System

The system is presented in a series of three block diagrams. A block diagram of the gas path for the integrated Base Case PFBC system (in CO_2 capture-ready configuration) is presented in Figure 3. The system with CO_2 capture installed is shown in Figure 4. Figure 5 presents the steam cycle as it relates to the PFBC vessel and gas turbomachines. Heat and mass balance diagrams for the 4 x P200 plant with capture and in a capture-ready configuration are presented in Appendix F. In addition, the heat and mass balance diagrams are given for part-load cases for the capture-ready plant and for PFBC plants of different sizes (1 x P200, 2 x P200, and 3 x P200 - all capture ready).

Figure 3-PFBC without CO_2 Capture (Capture-Ready Configuration)

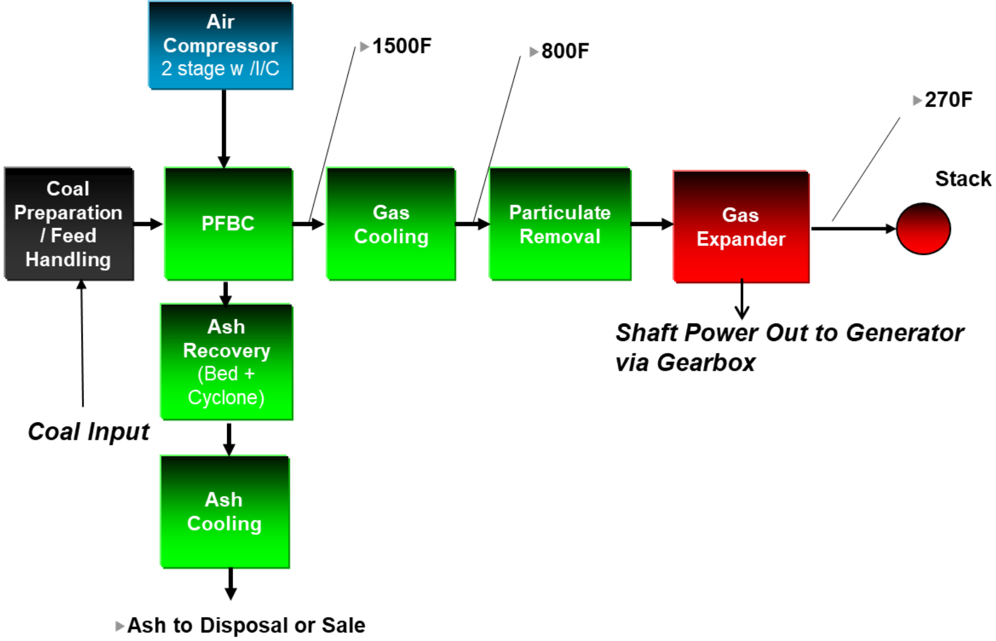


Figure 4-PFBC with CO_2 Capture

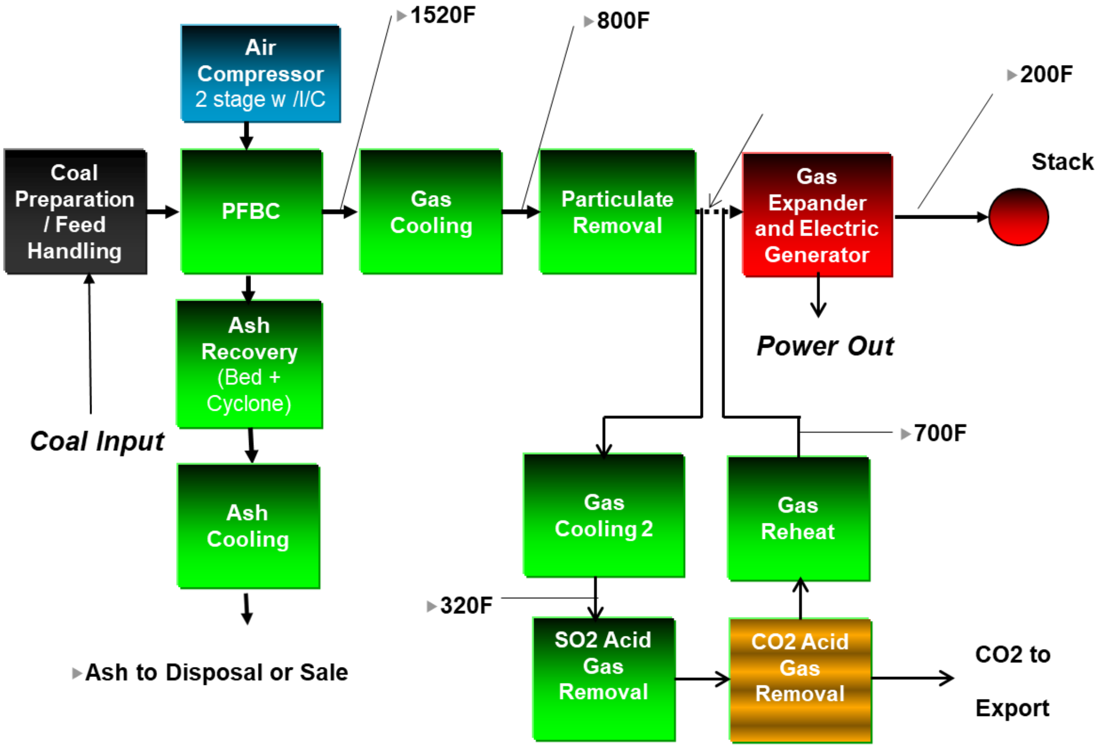
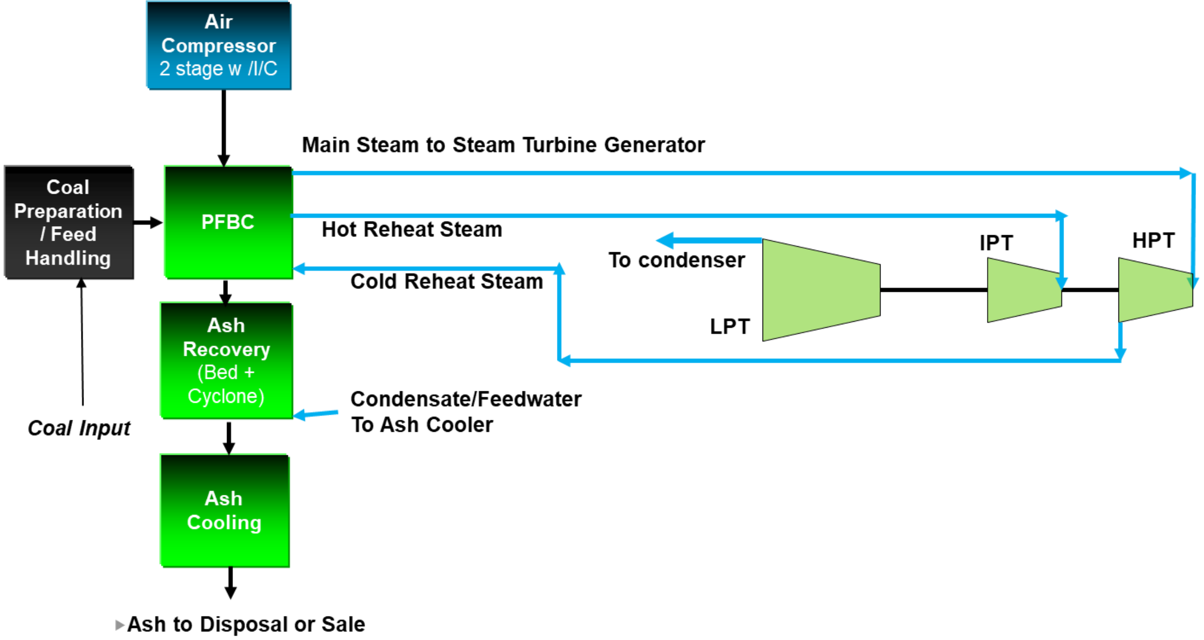
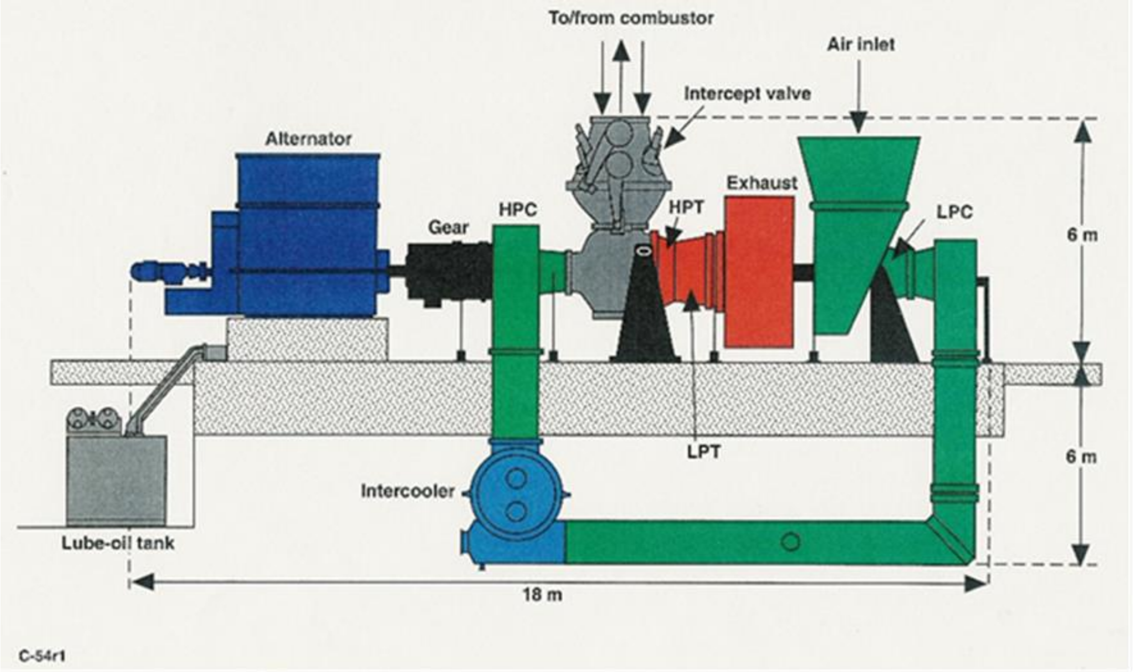


Figure 5-Steam Cycle Block Diagram Related to PFBC (simplified)



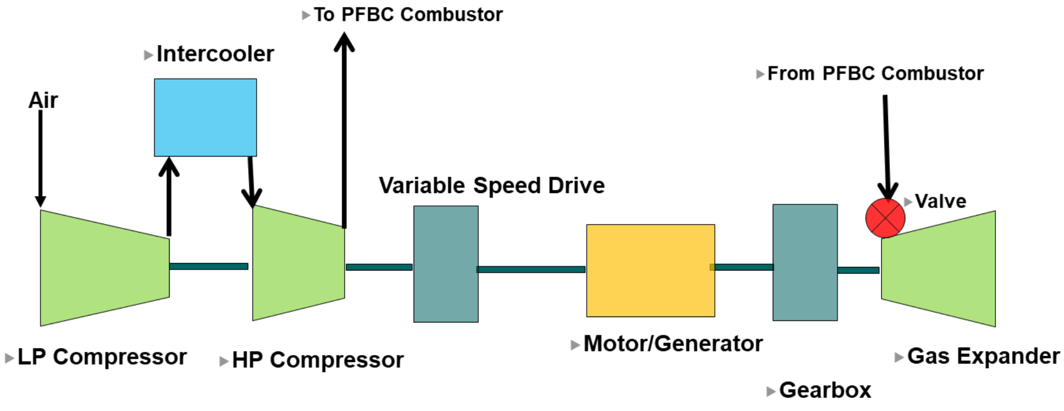
The original gas turbomachine used in early P200 configurations without carbon capture is the ABB GT35P shown in Figure 6. This machine is employed in plants still in operation located in Cottbus, Germany, and Stockholm, Sweden.

Figure 6-Elevation View of GT35P Gas Turbine



The new PFBC configuration described herein requires a new machine for two reasons: first, the GT35P is no longer in production and restoring production would require a major commercial investment. Second, the addition of CO_2 capture requires that certain modifications be made to the machine, extensive enough that a new design is most likely a preferred option. The new machine required is presented in Figure 7 below.

Figure 7-Schematic Diagram of New Turbomachine for P200 Module (one required per module)



Four (4) turbomachines required/1 shown

For total 395 MWe PFBC Power Plant

Description of Each Process Block

A brief description of each block incorporated in the block diagrams follows:

- **Coal Preparation and Feeding**
  - The coal preparation and feeding systems used by the reference plant configured for firing Illinois No. 6 coal consist of conventional coal receiving and unloading equipment, also incorporating a stacker-reclaimer and primary coal crushing equipment. The crushed, reclaimed coal is sent to fuel preparation for milling to final size and mixing with ground limestone to form a pumpable paste with nominal 26% moisture by weight.
- **PFBC**
  - The PFBC pressure vessel contains a complete fluidized bed boiler and gas path components inside a large pressure vessel. There are several ancillary components as well, related to startup, shutdown, and accommodation of transient operation. The principal parts of the boiler are the fluidized bed furnace and the various heat transfer tube bundles for economizer, boiler, superheat, and reheat. The gas path includes a down-comer to convey the compressed air to the bottom of the fluidized bed, and gas piping to and through the cyclones and then to the PFBC gas exit. Also incorporated into the PFBC vessel are the hot gas cyclones (two stages) that separate 98% plus of the particulate matter from the hot flue gas exiting the PFBC vessel. The hot gas leaves the PFBC vessel and passes to the gas cooler.
  - The gas cooler is a shell and tube type heat exchanger (gas on the shell side) providing supplementary superheating and reheating for the steam cycle.
  - The gas expander is a part of the special turbomachine presented in Figure 7 above. This expander operates at a relatively low temperature of 790 ^{0}F for the capture-ready

case and can therefore utilize inexpensive materials and uncooled design more typical of steam turbine design parameters than of gas turbine design parameters. The expander design quoted by Dresser Rand for a recent PFBC study was in fact prepared by their steam turbine production unit and not their gas expander production unit.

- The exhaust gas from the expander in this design configuration is sent directly to the plant stack for exhaust to the atmosphere. The gas temperature is approximately 270 ^{0}F at this point in the gas path for the capture-ready case, an appropriate temperature for discharge. The discharge temperature for 90% capture case is approximately 200 °F.
- The air compressor is comprised of two types of units. The low-pressure compressor is a multi-stage centrifugal design, while the high-pressure unit is an axial flow design with variable inlet guide vanes. A shell and tube intercooler is used between the compressors to reduce the air temperature and thereby reduce compressor power consumption.
- Particulate removal is performed in a metal multi-element filter contained in a pressure vessel rated for the hot gas design conditions (downstream of the gas cooler, pressure is ~12 bar, temperature is ~800 ^{0}F). The filter is backpulsed to clean the filter elements, one at a time, while on line. The PM blown from the filter is sent to join the cyclone ash (fly ash) in its respective handling system.
- The heat transfer loop (in the CO_2 capture-equipped case) is comprised of two shell and tube heat exchangers coupled by a circulating loop of Dowtherm A that regeneratively cools and then reheats the gas (shell sides of the heat exchangers).
- The UOP Benfield Process (in the CO_2 capture-equipped case) is comprised of a sulfur scrubbing subsystem followed by the potassium carbonate scrubber and regenerator, and related miscellaneous components. The Benfield process removes a nominal 90% of the CO_2 from the pressurized, cooled gas. The reheated gas (from one of the pair of heat exchangers noted above) passes to the gas expander for power generation.

Use of Other Fuels in Conjunction with Coal

The proposed PFBC plant is capable of firing other solid fuel in addition to bituminous coal. The Process Test facility in Finnspong, Sweden, has fired the following solid materials as part of a validation program. Polish Coal (fired at Vartan, Sweden)

- Spanish Lignite fired at Escatron, Spain (high moisture, high ash, high sulfur)
- Brown Coal fired at Cottbus, Germany (typical brown coal)
- Petroleum Coke
- Anthracite
- Olive Pips
- Palm Nut Shells
- Wood chips
- Oil Shale
- Sewage Sludge

Additional solid fuels, including wet, fine waste coal from CONSOL's mining operations in Northern Appalachia, were fired at the PFBC-EET/CONSOL test facility in South Park, PA.

The selection of paste feed vs. dry feed is made based on the moisture content of the fuel plus other characteristics. For this proposed application, a paste feed has been selected to allow for the potential to incorporate wet, fine waste coal as a low-cost fuel feedstock.

Description of Integrated Energy Storage

The PFBC technology incorporates energy storage in the form of a bed reinjection vessel that stores a portion of the fluid bed material during normal operation. The bed material provides a buffering effect for load changes - it ingests bed material during a load reduction and reinjects the material into the bed during a load increase. This enables the integrated fluid bed/boiler combination to respond rapidly to load transients in both directions. Although the energy storage is small in relation to the output of the plant, it provides the “bridge” between instant output and long-term energy storage in the fuel. Should all of the bed material be held in the reinjection vessels, there would be about 84 MMBtu of energy stored per P200, as stated, a small amount.

Power System Working Fluid and Process Conditions

The power system working fluids are air/gas (combustion products) and steam/feed water. The system operates by utilizing a Brayton cycle and a Rankine cycle in parallel. Although this involves use of a gas turbomachine and a steam turbine, the cycles are not integrated in a cascade as in a typical gas turbine combined cycle. The traditional combined cycle coupling is not advantageous for the PFBC configuration with CO_2 capture wherein the cycles operate in parallel but are not coupled. The use of the Brayton cycle integrated with the rest of the PFBC plant provides the pressurized gas conditions that make the Benfield process advantageous for CO_2 capture. Refer to the block diagrams above and the heat/mass balances in Appendix E for more information on process conditions.

Features that Minimize Water Consumption

The task of minimizing water consumption is influenced by the site selection and the fuel that is to be fired in the PFBC. The largest consumer of water in a thermal power plant is typically the evaporative cooling tower, where this is employed as a heat sink. Another significant user of water is steam cycle makeup for a typical Rankine cycle. Also of interest is makeup water for an evaporative cooler for the inlet of a gas turbomachine, as employed in this PFBC technology application. Finally, a significant amount of water can be required for fuel preparation where paste feed (as opposed to dry feed) is used for the PFBC.

The overall concept to be employed in the PFBC plant design is to recycle water internally within the facility and minimize the need for makeup water. Starting with the evaporative cooling tower, the use of higher cycles of concentration (up to 5 or 6) will minimize the quantity of blowdown and makeup required.

The use of paste feed for an application involving utilization of pond fines and/or tailings can be configured to recycle the water from the fines in the fuel preparation plant. The fuel preparation process can, therefore, minimize the need for makeup water.

Steam cycle makeup water use can be minimized by limiting blowdown from the steam cycle by using a condensate polisher and using steam cycle blowdown for other purposes, such as diversion to the cooling tower as makeup to that system.

The use of evaporative cooling for the gas turbomachine would be utilized during periods of high ambient temperature to maintain the mass flow of air to the PFBC, and thereby maintain total power output. Water quality for this purpose must be maintained at relatively high levels to avoid fouling the compressor with mineral deposits.

Considering the factors described above, an integrated water usage and recycling plan will be accomplished for the proposed plant when definitive site and makeup water characteristics are properly defined.

Techniques to Reduce Design, Construction, and Commissioning Schedules

Modularization

Reductions of cost and schedule parameters for the PFBC technology include the inherent modular nature of significant portions of the design. The most significant feature of the PFBC design is the P200 module. This module is used in multiples to achieve larger unit sizes. Each module is identical and based on a single set of drawings, specifications, etc. In constructing a multi-module plant, reduction of costs is achieved by quantity discounts and reliance on a learning curve effect. Sequencing and scheduling of work crews will take advantage of the learning curve to reduce costs and schedule time for complete build-out of the plant.

Within any individual PFBC vessel, components will be shop-fabricated to the maximum extent and shipped to the job site ready to be installed. This includes heat transfer surfaces, piping and valves, etc. The PFBC vessel will be field-erected in most cases; this work will be scheduled when access is not required for installation of internal components. For sites that are accessible by water (coastal or river), it is possible to completely construct the PFBC vessel and most of its internals and ship this to the site by barge.

A significant portion of the PFBC plant is scalable rather than modular. This includes the steam turbine building and components within it, the fuel preparation facility (located nearby), the water treating building and equipment, and typical ancillary facilities such as a site warehouse, administration building, etc. However, all these items may utilize modular fabrication and assembly techniques to reduce cost and speed up installation time. The construction site will be organized and optimized to accept deliveries to a staging or laydown area, then a pre-assembly area, and then allow for installation or erection with minimal handling and lifting.

Advanced Process Engineering

The PFBC plant described herein utilizes advanced process engineering in the coupling of the PFBC gas path to the Benfield cycle. The Benfield process operates efficiently and at moderate cost at elevated pressure (12 bar) and reduced temperature (300 ^{0}F). These gas conditions are achieved by cooling the gas in a shell and tube heat exchanger, passing it through the Benfield process vessels, and then regeneratively reheating the gas in a second shell and tube heat exchanger. A high temperature fluid such as DowTherm A circulates between the two heat exchangers to accomplish the required heat transfer. This fluid is commonly used in concentrated solar thermal applications to generate steam for a Rankine cycle.

Technology Development Pathway Description

Current State-of-the-art with Shortcomings, Limitations and Challenges

The current focus for developing new coal-fired power plants with CO_2 capture seems to indicate that either a supercritical PC unit with an amine-based solvent for CO_2 capture or an IGCC with a physical solvent (such as Selexol) are considered state-of-the-art technology. The shortcomings of these technologies include a relatively large energy penalty, especially for the supercritical PC plant, high capital cost, especially for the IGCC plant, and high variable operating and maintenance costs that impede the ability of the plant to economically dispatch. These technologies also have limited operating and fuel flexibility, further challenging their ability to operate economically, and are not particularly well-suited for small-scale, modular construction.

PFBC Overcomes the Shortcomings, Limitations and Challenges

As has been discussed, the PFBC technology meets most of the requirements in the Performance Work Statement and has proposed means for filling any gaps. Among others, it has high plant efficiency (>40% HHV in capture-ready configuration), is modularized, has near-zero emissions, and is capable of achieving high ramp rates.

Already in its current state, the PFBC technology offers a pathway to efficient, low-emission, modular, cost-competitive coal combustion technology with post-combustion CO_2 capture for small-to-medium size power plants. Some of the specific features are:

- Excellent fuel flexibility (handles low Btu fuels, wet fuels, and fines efficiently)
- Typical combustion efficiencies close to 100%
- High plant efficiency and high carbon burnout (low CO and loss on ignition)
- Compact boiler design to significantly lower the required quantity of expensive materials
- Useful ash products
- Low water consumption
- Readiness for CO_2 capture
- Low emission levels without use of catalyst or polishing stages. (However, the Benfield process, when added, will in most cases require additional SO_2 removal to meet process requirements).

Pending availability, carbon-neutral biomass fuel can be mixed in with the coal. PFBCs have combusted up to a 40% biofuel/coal mix, meaning that they can achieve near-zero carbon emissions while capturing less than 90% of the emissions from the combined biofuel/coal blend. Such a fueling strategy can help to improve the capital cost, operating cost, and emissions performance of the plant relative to competing technologies.

Ash from a PFBC boiler contains virtually no free lime and no sulfites or sulfides, making it easy and safe to handle. The ash is self-binding with water without any additives. If water is added the ash will harden like concrete. The hardened ash product is water resistant and has a very low permeability, making it suitable for synthetic gravel, landfill preparation, building material, and aggregate for manufacture of concrete. This is a major benefit attributable to PFBC operations with coal as it creates the potential to generate revenue from byproducts and/or to minimize disposal costs.

The PFBC boiler is provided with an insulated bed reinjection vessel storing hot bed material for fast load changes by controlling the bed mass level to benefit the load-following resources. The need for dispatchable generation, critical ancillary services, and grid reliability in the future all point to opportunity for advanced coal-fired power generating plants such as the advanced multi-module PFBC plant. This type of plant is capable of achieving high efficiencies, operating flexibly and reliably, minimizing capital cost requirements, taking advantage of low-cost fuel sources, achieving very low emission rates, and complying with potential future restrictions on carbon dioxide emissions.

One of the challenges we have is to design an efficient PFBC gas/ boiler steam cycle combined with a CO_2 capture process. A major disadvantage with atmospheric boilers and CO_2 capture processes is the volume of exhaust gasses that needs to be handled. In post-combustion capture configurations, amines have been the solvent of choice for CO_2 removal because of their fast reaction rates and high capacity for absorbing CO_2. The drawback for MEA and other amines is their high heat of absorption and tendency towards thermal and oxidative degradation and corrosive action. The post-combustion Benfield potassium carbonate CO_2 capture system, utilized by the PFBC, uses potassium carbonate as a solvent with the benefit of low heat of absorption with lower energy penalties, low solvent cost, no degradation, and low corrosion. A potential disadvantage with potassium carbonate is the slower reaction rate with CO_2 requiring a larger surface for the absorber. This is mitigated in the PFBC by the elevated pressure, which increases the partial pressure of all reactants. Compared to atmospheric processes, the combined pressurized PFBC/Benfield process results in a net size advantage.

The complete system includes a metallic filter ahead of the Benfield process to protect the process, along with the gas expander. The metallic filter also enables the P200-based plant to meet stringent air emissions limitations for PM.

Technical Risks/Issues and Assessed Technology Gaps and R&D Needed for Commercialization

This section describes the technology gaps identified as needing resolution to support successful further development of the PFBC combustion technology. The commercial P200 module has a demonstrated record of application in Europe, Japan, and the US over the last three decades. However, the future viability of this technology relies on resolution of several “technology gaps” in order to continue to be technically and commercially relevant. These gaps and proposed solutions are discussed herein.

Gap 1 - Turbomachine

The first and most important gap lies in the fact that the previously applied gas turbomachine, the ABB GT35P, is no longer available as a commercial production item. It is also the case that even if it were to be made available now, this machine is not well suited for adaption into the P200 gas path with CO_2 capture using the UOP Benfield process.

Recent studies dating back to 2015 and earlier have focused on design and development of a new turbomachine that could operate in the P200 gas path and perform the necessary functions. Based on design studies performed for DOE in the early 2000s, a relationship was developed with Dresser Rand to design and manufacture a new turbomachine to meet PFBC requirements. At this time, the commercial landscape has changed, and it must be recognized that the intellectual property rights to the GT35P machine reside with Siemens. However, Dresser Rand is now also under the Siemens corporate umbrella. While Dresser Rand has expressed interest in designing a new machine to supplant the GT35P, to date, discussions with Dresser Rand are in an exploratory stage. The CONSOL team reached out to General Electric, specifically Baker Hughes GE, which handles the types of components required to build a replacement to the GT35P that is compatible with integration with the UOP Benfield process. As a result, Baker Hughes GE has provided an expression of interest and a letter of support (Appendix G).

The new machine will be comprised of low-pressure and high-pressure compressors, a hot gas expander, a motor-generator, and necessary gearboxes, couplings, and variable speed drive components. This machine must be able to operate with CO_2 capture turned on or off, as gas flow rates and temperatures at the expander inlet will vary significantly between the two conditions.

The gas expander and motor generator operate at a fixed speed, with the expander running at higher rotational speed than the motor generator (which runs at synchronous speed of 3,600 rpm). The gas expander will likely operate at a higher speed to obtain better efficiency (rotational speed is correlated with flow capacity, which in turn is related to machine diameter). For the size of this application, an expander speed of 4,500 to 6,000 rpm is expected.

The compressor train (low and high pressure units) is likely to operate at the same speed as the motor generator at full load. However, at reduced loads and during startup and ramp-up, the compressor speed is reduced to ensure stable operation. Dynamic compression machines (axial flow and centrifugal flow) do not turn down (provide reduced flow rates) very well, and other solutions such as bleeds and blow-offs are required to manage the machine. The provision of a variable speed device resolves this problem and allows stable operation at the best efficiency at part load.

The definitive resolution for this technology gap is for Baker Hughes GE and/or Dresser Rand to design a new machine to meet the specifications of PFBC-EET and Worley Group Inc. A conceptual sketch of this machine was presented in Figure 7.

Gap 2 Integration of UOP Benfield Process

This gap involves the incorporation of the UOP Benfield process into the gas path while preserving the air compression capability of the compressor train and the expansion capability of the hot gas expander as an integrated machine throughout the load range and for startup, shutdown, and trips. The incorporation of the UOP Benfield process requires that sulfur compounds be removed to a very low level, estimated to be in the very low ppm or even down to the ppb range (as measured by volume or mole fraction). This is accomplished by introducing an alkaline (sodium hydroxide) scrubber, operating at the prevailing gas pressure and temperature, to remove the sulfur. As an adjunct to this process, a deep bed of activated carbon is introduced after the sulfur scrubber to remove mercury in the gas path in vapor form. Compounds of mercury that are in solid form are removed upstream of the sulfur scrubber in a highly-effective metallic element gas filter.

The integration of the UOP Benfield process with the P200 PFBC therefore requires the following steps, in sequence:

- Cooling of the hot particulate-laden gas exiting the PFBC from 1550 °F to ~800 °F. This is achieved by means of a gas cooler that performs superheat and reheat duty for the steam cycle as an adjunct to the thermal duty performed inside the PFBC vessel in the PFBC boiler.
- Filtration of the gas at ~800 °F to remove remaining particulate matter at a 99% plus effectiveness. This is achieved by the hot gas filter. (Quote received from Mott during the last round of PFBC plant studies, circa 2015).
- Further cooling of the gas to ~250 °F in a regenerative gas cooler/reheat loop utilizing shell and tube heat exchangers and a thermal heat transfer fluid as used in solar thermal technology applications.
- Induction of the gas into the alkaline scrubber for SO_2 removal.
- Passage of the gas through the activated carbon filter for removal of mercury.
- Induction of the gas into the UOP Benfield process for CO_2 capture.
- Reheat of the gas using the second heat exchanger (part of a pair that performs the regenerative cooling and reheating) back up to ~700 °F.
- Expansion of the gas from ~12 bar to 1 bar, producing shaft power for the turbomachine described above.
- Exhaust of the gas to the plant stack.

The definitive resolution of this gap is the detailed design of the entire gas path, including the turbomachine, SO_2 and UOP Benfield scrubbers, etc. This is not a technology gap, per se, but a design gap.

Gap 3 Redesign of the P200 Boiler for Supercritical Steam Conditions

This gap is resolved by detailed design of the boiler steam coil surfaces inside the PFBC vessel for supercritical steam conditions. This will likely require replacing a considerable amount of tube surface now made of T22 material with heavier wall tube made of T91 material (to handle the increased pressure and temperature). This involves all the tube surface, since even the economizer surface and primary superheat surface will have to deal with significantly increased pressure, and the finishing superheat surface and reheater surface will have to deal with the higher temperatures selected for the supercritical case. This gap will be resolved by detailed design and specification of alternate, commercially-available materials relative to what is in the existing P200 boiler design.

Gap 4 Design of the PFBC Boiler for Advanced Steam Conditions

This gap has much in common with advanced pulverized coal (PC) steam plant technology gaps in terms of steam cycle pressures and temperatures. In this regard, advances can be viewed as a continuous process, particularly with respect to temperature. Designing for higher steam cycle pressure (up to 5000 psi or higher) is accomplished by increasing tube wall thickness and piping thickness. However, higher temperatures, particularly above ~1100 °F, require careful consideration of life cycle/duty cycle issues, ASME Code acceptance, economic justifiability, and other potential factors.

This gap is likely to be resolved in an incremental fashion in a series of small steps. As improved high-temperature alloys become available as commercial products, they are likely to be introduced into the design/fabrication chain slowly over time. Issues related to weldability, the need for post-weld heat treatment and welder qualification, non-destructive examination techniques and acceptability thresholds for indications will take time to resolve to the satisfaction of the applicable codes (ASME Section 1, ASNI B31.1, etc.) and insurance and finance underwriters.

Other Gaps

A few relatively minor gaps can be identified as having potential for performance improvement, if resolved. These include the following:

- Use of higher-temperature heat transfer fluids for the regenerative cooling/reheat loops. Resolution of this gap by use of higher-temperature fluids (such as molten salts as used in certain solar thermal applications) could increase cycle efficiency (for the gas path). Cycle studies must be performed first in order to quantify the performance benefits that might be expected to accrue from the higher gas temperatures used in the gas path prior to induction to the gas expander.
- Use of a gas-to-gas regenerative heat exchanger in lieu of the shell-and-tube heat exchangers combined with the thermal heat transfer fluid. This development path is likely to be a difficult one, if history is any guide. The development of high-temperature gas-to-gas heat exchangers has been challenging in the past, and some of the units in question operated at lower temperatures relative to the PFBC cycle and were smaller in size (volumetric gas flow). Nonetheless, if a breakthrough were to be achieved in this area, it would be useful to incorporate into the PFBC gas path for the carbon capture design case.

Summary

The principal technology gap requiring resolution for PFBC technology to advance, with or without CO_2 capture, is the provision of a replacement machine for the GT35P. There is every expectation that this can be accomplished with the participation of a large, technically qualified organization such as Baker Hughes General Electric. The other gaps can also be resolved with time and technical effort. We believe that the PFBC technology is capable of deployment in the early 2020s to meet the DOE Coal FIRST time frame, and that overcoming the principal technology gaps will not require pilot testing of any components. These are design and optimization activities accomplished by modeling techniques readily available to the project team or through the cooperation of the OEMs.

Technology Original Equipment Manufacturers (OEM)

The equipment required to construct a 300 MWe net advanced PFBC power plant with 90% CO_2 capture is described in this section. The equipment is categorized into major divisions based on association with the functional characteristics of each system and its components. Where non-standard equipment is required, Worley Group Inc. has had discussions with leading suppliers of this equipment and has received assurances of cooperation in a detailed design phase. Letters from PFBC-EET and GE are included in Appendix G.

P200 PFBC Vessel and Internals (Commercial Equipment)

The AE firm, Worley Group Inc., has worked with PFBC-EET (license holder of the PFBC technology) and Nooter Ericson in previous design studies of multi-module P200 power plants. A detailed preliminary design and cost estimate were prepared, but the project did not proceed to construction. A second example is a repowering of two out of three PC steam electric power plants in Moundsville, WV, for using two blocks of three P200 PFBC modules. This project did not proceed to construction. The P200 equipment division includes the equipment physically located inside the PFBC pressure vessel, all of which is commercially available. This vessel and its internal components will be supplied and assembled at the site by Nooter Ericson. This includes: the PFBC pressure vessel, PFBC boiler system, cyclones, bed reinjection system, bed preheating system, ammonia injection system, PFBC fuel, sorbent, and ash systems. The scope of these systems includes components that are largely internal with some items external to the PFBC vessel. The systems interface with the external fuel and sorbent receiving, storage, handling, and preparation system; and the bed ash and cyclone ash removal, depressurization, cooling, and storage systems. All components internal to the PFBC vessel are supplied by Nooter Ericson; external components are supplied by PFBC-EET and by balance of plant suppliers.

Fuel and Sorbent Receiving, Handling, Storage, and Preparation System (Commercial Equipment)

The AE firm, Worley Group Inc, has worked with Farnham & Pfile on previous design studies of multi-module P200 PFBC power plants. The subject equipment division receives fuel from outside sources and prepares the fuel for injection in paste form into the PFBC boiler bed. Sorbent (limestone for this application) is also received, prepared, and mixed with the fuel paste prior to injection into the PFBC boiler fluidized bed. Individual components comprising this system, all of which are commercially available from a number of suppliers, are:
Dry Fuel Receiving, Handling, and Sizing Subsystem - bottom dump hopper and pan feeder, conveyors, breaker/crusher for rough coal sizing to 2” x 0.
Fuel Storage and Reclaim - reclaim conveyors, scales, sampling system, mobile yard equipment
Sorbent Receiving, Handling, and Sizing Subsystem - receiving hopper, conveyors, covered storage/reclaim dome, stacker, tram, rake, rod mills, pneumatic conveying system, sampling system
Fuel/Sorbent Preparation and Forwarding - sliding frames, weigh feeders, bins and rotary feeders, transfer conveyors, paste mixer sumps and agitators, prepared fuel sumps and agitators, prepared fuel transfer pumps
Paste Fuel Feed System - buffer silos with mixers, paste feed pumps (Putzmeister type pumps, commercially available)

Ash Handling Systems (Commercial Equipment)

The ash handling system components, which are commercially available from a number of suppliers, include recovery of bed ash from the bottom of the PFBC boiler, as well as cyclone ash recovery from the cyclone down-legs. Both types of ash pass through tubular ash coolers that provide some heat recovery to the condensate system. The fine PM recovered from the hot gas metallic filter will contain a very limited amount of usable thermal energy (due to the limited quantity). This material is mixed with the cyclone ash prior to storage in the fly ash silo, from which it is loaded onto trucks for disposal or alternative beneficial use.

Gas Turbomachine (Equipment requiring R & D)

The gas turbomachine will be a new design, tailored and optimized to the requirements of the PFBC cycle with CO_2 capture. The AE firm, Worley Group Inc., has worked extensively in the past with Dresser Rand (now part of Siemens) and General Electric in numerous previous gas turbine and steam turbine power plant designs. These efforts are documented in several DOE-sponsored reports, prepared under DOE AM26-99FT 40465. The reports are titled "Land Based PFBC Power Plants" and "Barge Mounted PFBC Power Plants," both circa year 2000 to 2002. The gas turbomachine is a custom-designed machine that provides compressed air to the PFBC boiler, and expands the hot gases after they have been filtered and the CO_2 has been absorbed. The turbomachine function is very different from the way a typical gas turbine would operate. The turbomachine components, arranged on a common shaft, are as follows:

- Compressor (low pressure, high pressure), expander, speed reducing gearbox, electric motor/generator, intercooler (non-rotating component, off-skid)

The OEM supplier for the turbomachine has not been determined at this early stage. It will likely be any of the major suppliers of such equipment such as General Electric, Dresser Rand, MAN Turbo, or possibly others. Baker Hughes General Electric has responded to an inquiry for Worley Group that included a "mini-spec" and data sheet with a statement that they have the capability and interest to support the project needs in a detailed design with a view to manufacture the required equipment. This letter is presented in Appendix G.

Hot Gas Filter and Regenerative Cooling and Reheating (Commercial Equipment)

The AE firm, Worley Group, Inc., has worked with Mott and Pall, suppliers of hot gas filters (at elevated pressure), and with Nooter, who will supply the heat transfer equipment. Worley Group, Inc., has worked with high temperature thermal heat transfer fluids in numerous studies for EPRI for solar thermal augmentation projects for existing coal and oil-fired steam electric power plants. Examples of detailed design studies include solar thermal augmentation at steam electric power stations for Hawaiian Electric, (Kahe Power Plant, Units 5 and 6, oil-fired steam electric stations); Carolina Power and Light (Mayo Station, coal-fired station); and Tri-State Transmission and Generation Association, Inc. (Escalante Generating Station, coal-fired station). The hot gas filter and regenerative heating/cooling equipment are commercial equipment. However, it would be desirable to seek and utilize advanced materials in the equipment comprising this subsystem to improve thermal performance of the overall PFBC power plant. This system conditions the hot gas exiting the PFBC vessel on the way to the UOP CO_2 capture system and the gas expander (part of the turbomachine mentioned above.) The AE firm, Worley group, Inc., has worked with Nooter and UOP on previous design studies involving the PFBC technology, and on CO_2 capture utilizing the Benfield process.

Hot Gas Cooler

The hot gas cooler reduces the PFBC gas exit temperature from 1525 ^{0}F to approximately 800 ^{0}F. The gas passes through the hot gas filter for PM removal. The gas cooler recovers the gas thermal energy by providing superheat and reheat for portions of the steam cycle.

Hot Gas Filter

The hot gas filter removes remaining particulate matter (PM) from the hot gas exiting the PFBC boiler. This filter is comprised of a group of metallic mesh filter elements arranged in a pressure vessel. The filter operates at a gas temperature of 800 ^{0}F and thus can use conventional low-alloy steel materials. The filter is equipped with a back-pulse cleaning system to remove filter cake and discharge it to the ash handling system. Suppliers of this equipment can include Mott Corporation and Pall Corporation.

After the hot gas filter, the gas path can take one of two configurations, as follows: *For a CO_2 capture-ready PFBC module*, the 800 ^{0}F gas is routed directly to the turbomachine expander for expansion and energy recovery. The gas bypasses the regenerative cooling and reheating heat exchangers, sulfur polishing and CO_2 capture stages described below for the case equipped with CO_2 capture. The gas exit temperature from the expander is about 270 ^{0}F in the CO_2 capture-ready configuration, and the gas is routed directly to the stack with no other processing or interactions.

Regenerative Gas Cooler

For a PFBC module equipped with CO_2 capture, the gas is routed to the Regenerative Gas Cooler and to a sulfur polishing step before being sent to the Benfield CO_2 Scrubber System. The Regenerative Gas Cooler is a shell and tube heat exchanger, which cools the gas further to ~320 ^{0}F prior to entering the sulfur polishing step. The sulfur polishing is required prior to induction of the gas into the UOP CO_2 scrubber. This is accomplished by a wet scrubber stage utilizing a regenerable solvent. Parasitic loads (electric and steam) are expected to be modest since most of the sulfur is captured in the PFBC bed. This will minimize the need for steam to regenerate the solvent. The regenerative gas cooler transfers heat to a circulating loop of high temperature thermal fluid (Dowtherm A or similar). The recirculating thermal fluid also reheats the gas emerging from the Benfield CO_2 capture scrubber to ~700 ^{0}F in a companion shell-and-tube gas reheater before it reports to the expander part of the turbomachine for generation of shaft power that assists in driving the compressor. The two heat exchangers (one for gas cooling and one for gas reheating) will be supplied by Nooter Ericson. The thermal fluid circulating pumps may be provided by any significant pump supplier for general service centrifugal pumps.

UOP Benfield CO_2 Scrubber System (Commercial Equipment)

The AE firm, Worley Group, Inc. has worked with UOP on numerous studies for EPRI and DOE involving carbon capture from coal-fired power plants. The entire Benfield CO_2 capture process system is supplied by UOP and is commercially available. The system includes a scrubber vessel, a sorbent regenerating vessel (stripper column), and related tanks, pumps, piping, valves, controls, etc. The system described herein is designed to remove a nominal 90% of the CO_2 from the gas path of each PFBC module. It is expected that UOP would offer the entire system package, including vessels, pumps, valves, instruments and selected piping (but excluding foundations and electrical support such as switchgear, auxiliary transformers, etc.) Major equipment identified by UOP includes:

- Absorber, regenerator, LoHeat flash drum, reflux drum, condensate reboiler, carbonate reboiler, acid gas condenser, lean cooler
- Pumps: lean pump, reflux pump, condensate pump (two pumps of 100% capacity each). These are typical centrifugal pumps required to circulate and transfer fluids in the scrubber system.

A similar complement of equipment is also required for the sodium hydroxide pre-scrubber to remove SO_2 from the gas to prescribed levels for feed to the Benfield process. This system can be provided by any purveyor of scrubbing systems.

Steam Turbine Generator and Steam Cycle Equipment (Commercial Equipment)

The AE, Worley Group, Inc., has worked with essentially all vendors of any significance in the power generation field for 100 years. The steam turbine generator and related equipment are fully conventional in all respects, except for the aggressive steam cycle design parameters selected for this application. The steam cycle will use 3500 psig/1100 ^{0}F/1100 ^{0}F as the design condition. The steam turbine generator supplier may be General Electric or Siemens. The cycle will include six feedwater heaters, including one deaerating heater. The condensate system will include a full flow polishing system located in the low-pressure, low-temperature part of the system. System pumping will include conventional motor-driven condensate pumps, motor-driven feed water booster pumps, and steam turbine-driven feed water pumps. Suppliers of the steam cycle equipment can include typical industry participants. The main condenser will be a standard shell and tube design, with titanium alloy tubes, and split waterbox design. Circulating water piping will most likely be reinforced concrete pipe, conforming to appropriate specifications (AWWA C-300-301). Circulating water pumps will be motor-driven vertical turbine type pumps from typical industry suppliers. The mechanical draft evaporative cooling tower will be primarily of fiberglass construction resting on poured concrete basins. Feedwater heaters will be shell and tube construction with standard power plant materials of construction (carbon steel, stainless steels).

Electrical Equipment

This four-module PFBC configuration will require one generator step-up transformer for the steam turbine generator. The gas turbomachines will likely be designed to generate power at an intermediate voltage likely to coincide with the medium voltage used within the power plant for large motors (above 250 hp). This voltage is tentatively set at 6900 volts. Standard medium and low voltage switching equipment, cable, etc. will be used in the electrical power distribution system, which is expected to be comprised of three principal divisions (6900V 3-phase, 480V 3-phase, and 120 V single phase). In addition, a DC system at 125 VDC and uninterruptible AC (120 V single phase) will also be provided. The overall plant control system will utilize a distributed control system (DCS) based on commercially available equipment such as the Emerson Ovation or the Foxboro EVO systems. Additional typical steam cycle power plant equipment (all commercially available) will include water treating equipment, chemical addition to cooling tower water and condensate, fire protection equipment and structural features, and instruments.