Advanced Pressurized Fluidized Bed Coal Combustion with Carbon Capture

Performance Results 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

January 27, 2020

TABLE OF CONTENTS

LIST OF EXHIBITS

1 Concept Background

This section presents the concept background including the following:

- Coal-fired power plant scope description
- Plant production/facility capacity
- Plant location consistent with the NETL QGESS
- Business case from conceptual design

We also provide a discussion of the ability to meet specific design criteria and the proposed PFBC target levels of performance to round out this discussion.

1.1 Coal-Fired Power Plant Scope Description

The Advanced PFBC project team has adopted an alternate configuration utilizing an amine-based CO_2 capture system instead of the UOP Benfield capture system utilized in the Conceptual Design Phase (Phase 1) work. As such, with the exception of Section 1.4 (Business Case from Conceptual Design), the plant description and performance presented in this report are now for an amine-based CO_2 capture configuration. We present the amine-based configuration performance results in Section 2.

The proposed Coal-Based Power Plant of the Future concept 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 or fine, wet waste coal derived from CONSOL's bituminous coal mining operations in southwest Pennsylvania. Plant performance and operating characteristics will be evaluated separately for each design fuel, and certain plant components, such as the ash handling system, will be uniquely sized and optimized to accommodate each design fuel.

The offered technology is unique and innovative in this major respect: it has inherent fuel flexibility with the capability of combusting steam coal, waste coal, biomass, and opportunity fuels and has the ability to incorporate carbon capture systems while maintaining relatively high efficiency. Carbon capture may be added to a capture-ready plant configuration without major rework and with little interruption to the operation of the capture-ready plant. The essential feature of the capture-ready plant is the provision of additional space for housing the additional components, along with space for supporting auxiliaries (electrical cabinets, piping, etc.) The Base Case plant will be designed to fire Illinois No. 6 coal, while the Business Case plant will be designed to fire waste coal while also being fully capable of accommodating typical thermal coal products.

The complete scope of the proposed power plant includes a fuel preparation plant co-located with the power generating plant. The power generation process is described in Section 1.4 and includes all necessary features to receive prepared fuel/sorbent mixture and fire this mixture to generate electricity and carbon dioxide as a co-product. The electric power generated is conveyed on a branch transmission line to the grid. The CO_2 is compressed for pipeline transport for storage or utilization. For the Illinois No. 6 coal case, the CO_2 is compressed to 2215 psig. For the Business Case, with CO_2 as a potentially saleable coproduct, the CO_2 may be compressed to a lower pressure to suit alternative disposition.

The fuel preparation plant includes coal receiving and storage, limestone sorbent receiving and storage, and, optionally, biomass receiving and storage. Each of these materials are sized and mixed to form a paste with controlled water content for firing in the PFBC power generating plant.

The PFBC power generating plant includes a heat sink (evaporative cooling tower), a water treatment facility to prepare several different levels of water quality for use in various parts of the power generating process, a waste water treatment facility to treat waste water streams for beneficial reuse within the complete facility (power generating plant or fuel preparation plant), and necessary administrative and maintenance facilities.

1.2 Plant Production / Facility Capacity

The plant production capacity for the PFBC plant is set primarily by the number of PFBC modules as the PFBC design is essentially fixed. The overall plant production capacity with four (4) PFBC modules firing Illinois No. 6 coal is set at a nominal 404 MWe net without CO_2 capture (but in complete capture ready configuration) and 313 MWe net with CO_2 capture operational at a rate of 97% of all CO_2 produced based on the amine capture system. When operating at this fully rated capacity (313 MWe) the CO_2 available for delivery at the plant boundary is ~7700 tons/day of pure CO_2 mixed with small amounts of other gases.

The annual production of electricity for delivery to the grid is 2.33 million MWh at 85% capacity factor. The annual production of CO_2 for export at 85% capacity factor is 2.4 million tons/year.

1.3 Plant Location Consistent with NETL QGESS

As discussed above, the Base Case PFBC plant is being designed to fire Illinois No. 6 coal at a Midwestern site. A Business Case alternative will be designed to fire waste fuel available to CONSOL Energy in southwestern Pennsylvania. As such, we are developing separate designs for the two cases being considered: (1) the Base Case based upon the Midwestern site and Illinois No. 6 coal and (2) the Business Case based upon the southwestern Pennsylvania (or northern West Virginia) site and wet, fine waste coal fuel. In documenting the site conditions and characteristics for plant location, we have followed the NETL QGESS [**1**] and have presented the site information in Section 3 of the Design Basis Report. Wherever possible, we have utilized available site information in lieu of generic information.

1.4 Business Case from Conceptual Design

The business case and underlying performance estimates and economics presented in Section 1.4 are based on the work performed during the Conceptual Design Phase, which assumed that the Benfield Process was used for CO_2 capture. The project team is updating this information during the current pre-FEED study to reflect the best overall plant design, which will be based on an amine-based CO_2 capture process.

This business case presents the following:

- Market Scenario
- Market Advantage of the Concept
- Estimated Cost of Electricity Establishing the Competitiveness of the Concept

1.4.1 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 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% [**2**]. 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% [**3**].

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 operating and maintenance (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\$) [**4**]. 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 about four times greater than that of the NGCC plant [**5**]. 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, (3) integrating carbon dioxide capture, and (4) incorporating a new purpose-designed gas turbomachine to replace the earlier ABB (Alstom, Siemens) GT35P machine.

In addition, while performance estimates and economics are presented here for 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. 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. 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 MW net advanced PFBC power plant with CO_2 capture. This slurry is currently disposed of 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.

1.4.2 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, based on work performed during the Conceptual Design Phase:

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. [**6**]
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%/minute 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 11 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 can enable the use of the commercially-available Benfield CO_2 capture process, which has the same working pressure as the PFBC boiler. However, during this pre-FEED study, it was determined that an amine-based system operating at atmospheric pressure to capture CO_2 from the flue gas provides a more cost-effective overall design, even considering the specific process advantages of the Benfield process, due to the unrecoverable losses in temperature and pressure encountered when integrating the Benfield process with the PFBC gas path. In addition, 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 integration with the PFBC gas path, are considered to be well within the capability of OEMs using existing materials and technology platforms. 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 or incorporating 90% CO_2 capture (increased to 97% in the pre-FEED study) 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 an approximately four 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.

1.4.3 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 Exhibit 1-1, again based on work performed during the Conceptual Design Phase. 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 No. 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 Conceptual Design 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 enhanced oil recovery (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 Exhibit 1-1 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 three other cases are also summarized in Exhibit 1-1: (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.; a revised assumption will be developed as part of the pre-FEED phase.) 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.

Exhibit 1-1. Cost of Electricity Projections for Advanced PFBC Plant Cases - Benfield

	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	$4.06
CO_2 Credit ($/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

Note: Data above are based on the Benfield CO_2 capture process, as presented in Conceptual Design Report.

Based on the initial projections from the Conceptual Design Phase in Exhibit 1-1, 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 pulverized coal plant [**7**]. 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.

1.5 Ability to Meet Specific Design Criteria

The ability of the proposed plant design to meet the specific design criteria (as spelled out on p. 116 of the original Solicitation document) 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. Startup from hot conditions (defined as bed temperature at or near 1500 °F, and main steam pipe temperature above approximately 800 °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 work 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 determine if realistic, cost-effective 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 described employs 97% 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 power plant portion of the facility will be integrated with the fuel preparation portion of the 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 zero liquid discharge (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 ash) 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, balancing bed performance against the performance of the caustic polishing scrubber for 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 excess air for the base design case is 16%. 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 3.
- 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 °F. Using aggressive design parameters for the heat sink, including a 5 °F terminal temperature difference for the condenser, a 7 or 8 °F cooling tower approach, and a 17 or 18 °F range for the circulating water system results in a condensing temperature of at least 99 or 100 °F at 70 °F ambient wet bulb temperature, which corresponds to a backpressure of 2.0 in Hga. Therefore, any time ambient wet bulb temperatures exceed 70 °F, the 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.
- When CO_2 capture is employed, additional sulfur capture is required ahead of the capture process. This additional polishing step reduces sulfur emissions to a level characterized by greater than 99.75% removal.
- Other low-cost solutions are being evaluated as applicable during this pre-FEED study.

1.6 Proposed PFBC Target Level of Performance

This section presents information on the following topics.

- Expected Plant Efficiency Range at Full and Part Load
- Emissions Control Summary
- CO_2 Control Strategy

1.6.1 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 Exhibit 1-2. (Note that information is presented with the amine configuration for various plant sizes, which vary according to the number of P200 modules installed.) 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.

Exhibit 1-2. Output and Efficiency for Modular PFBC Designs (Capture Ready – Amine Configuration)

No. of P200 Modules	Total Unit Output, MWe, net	Efficiency, HHV	Steam Cycle Parameters
1	88	37.0	1600/1025/1025
2	185	39.0	2000/1050/1050
3	285	40.0	2400/1075/1075
4	404	>42.0%	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 Exhibit 1-3. The values in the exhibit reflect the PFBC plant operating with the number of P200 modules at the stated load.

Exhibit 1-3. Part Load Efficiency Table for 4 x P200 PFBC Plant (Capture Ready – Amine Configuration)

Percent Load	No. Modules in Operation	MWe, net	Estimated Efficiency %, net, HHV
100	4	404	>42%
80	4	323	40.7
60	3	242	39.4
40	2	162	37.1
20	1	81	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 Phase 3 (FEED study).

For cases involving the addition of CO_2 capture to the completely capture-ready plant, two scenarios are presented below. Exhibit 1-4 shows different levels of CO_2 capture for the 4 x P200 module plant. Each case is based on applying the amine technology at a 97% capture rate to one, two, three, or all four P200 PFBC modules (the Conceptual Design Report used 90% and Benfield technology). 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 Block Flow Diagram (BFD) in Exhibit 2-4. This configuration is based on currently available materials of construction, design experience, 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" in the Conceptual Design Report. 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.

Exhibit 1-4. Efficiency with CO_2 Capture for 4 x P200 PFBC Plant (Amine Configuration)

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	>42	>44%
1	24.25	40.1	42
2	48.5	37.7	40
3	72.75	35.3	38
4	97.0	32.9	36

1.6.2 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, targeted emissions are presented in Exhibit 1-5. Predicted emissions values may vary slightly for the waste coal case but will be within the stated DOE target values. 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. The design will achieve 90% capture in the bed at a calcium to sulfur (Ca/S) ratio of 2.5. In addition, a polishing step is added to the gas path to achieve a nominal overall 99.8% reduction of sulfur in the gas. The addition of the caustic scrubbing polishing step is driven by the limitation of sulfur in the gas feed to the CO_2 capture process. This has the added advantage of reducing SO_2 in the stack gas which makes the air permitting process easier, and also reduces limestone consumption and costs. The optimal value of total costs for limestone and caustic is expected to be in the range of the parameters described.

Exhibit 1-5. Expected Emissions for P200 Module Firing Illinois No. 6 Coal

Pollutant	DOE Target, lb/MWh	Control Technology / Comments
SO_2	1.00	Target is achievable with ~97% capture in-bed for capture-ready case. Target is achievable with 90% capture in-bed and added polishing step (required by CO_2 capture process) for capture-equipped case.
NOx	0.70	Catalyst not required. Target is achievable with SNCR.
PM (filterable)	0.09	Cyclones and metallic filter will achieve target. Metallic filter is required to protect the turbomachine.
Hg	3 X 10-6	Particulate removal and GORE® mercury removal system will achieve target.
HCl	0.010	Cl capture of 99.5% plus is required based on the high Illinois No. 6 Cl content. Target is achieved by high level of PM capture.

The bed functions at a constant 1550 °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 III. However, at this time, the following rationale is offered in support of our belief that these elements will be controlled to within regulatory limits particularly for the capture-equipped case. 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 in solution or as elemental species. The gas will pass in succession through the following:

1. A sulfur polishing stage using an alkaline solvent such as sodium hydroxide
2. The CO_2 capture absorber vessel
3. A mercury removal system for removal of elemental Hg

It is believed that the two stages of scrubbing and the mercury removal system, in series, will capture a very high percentage of the Hg and Cl that remained in the gas after the cyclone/filter stages.

1.6.3 CO_2 Control Strategy

The initial CO_2 capture strategy employed for the proposed advanced PFBC plant was 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 was utilized to recover most of the thermal energy in the gas to maximize energy recovery and improve thermal efficiency. However, it was determined during the performance results generation process that using an amine-based system operating at 1 atmosphere pressure on the back end of the flue gas path yielded higher plant efficiency with minimal impact on plant capital costs. 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 for a 97% capture case (again, the Conceptual Design Report used 90%). For this 97% capture case, each P200 PFBC module is coupled to a separate amine process train for CO_2 capture. The system for CO_2 compression and drying utilizes two 50% capacity (relative to 100% plant capacity) component trains; therefore, each train serves two P200 PFBC modules.

As mentioned above, the project team evaluated a PFBC configuration based on the amine process and has adopted this process for completion of the remaining scope of work.

2 Performance Results

The following sections present performance results for the advanced PFBC coal-fueled power plant with CO_2 capture. These results are based on a PFBC plant that is designed to use an amine-based CO_2 capture process (as opposed to the Benfield process, which was considered in the Conceptual Design Report).

Results are being developed for two cases:

1) **Case 1:** The **Base Case** based on the Midwestern site and **Illinois No. 6 coal**, and
2) **Case 2:** The **Business Case** based upon the southwestern Pennsylvania (or northern West Virginia) site and **wet, fine waste coal**.

Each case has two subcases (A and B), as follows:

A – Capture-Ready, and

B – Carbon Capture-Equipped

The four (4) cases are summarized in Exhibit 2-1.

Exhibit 2-1. PFBC Case Matrix

Case Definition	Capture-Ready (Subcase A)	Capture-Equipped (Subcase B)
Illinois No. 6 (Case 1)	Case 1A	Case 1B
Waste Coal (Case 2)	Case 2A	Case 2B

All of the cases are based on the relevant information from the Design Basis Report for this project. The Capture-Ready cases represent an optimized steam turbine cycle. The Capture-Equipped cases are based on the same steam turbine running off-design. Integration of the carbon capture system is optimized.

This Performance Results Report presents the Illinois No. 6 based cases (Cases 1A and 1B) only. All four cases will be presented in the final report for the pre-FEED study, which will include Cases 2A and 2B as the Business Case for our proposed commercial PFBC project. (To emphasize this, the waste coal cases are highlighted in grey in the matrix above).

2.1 Plant Performance Model

The primary software used to perform the heat and mass balance (H&MB) calculations for this study is Thermoflex V28. Thermoflex is a modular program with a graphical interface developed by Thermoflow, Inc. of Southborough, MA, USA. The program covers both design and off-design simulation and models all types of power plants, including combined cycles, conventional steam cycles, and renewables. It can also model steam plants, chilled water plants, general thermal systems, and steam networks.

The PFBC power plant is modeled using the standard equipment icons available in the Thermoflex model, including the following major equipment:

- PFBC boiler

- Combustion air compressor
- Gas expander & generator
- Steam turbine & generator
- Condenser
- Cooling tower
- Emission control systems, including CO_2 capture
- Heat exchangers
- Pumps
- Interconnection piping

In order to simplify the set up and use of the model, Thermoflex software was used to create one complete PFBC train, including the boiler, air compressor, gas expander, heat recovery and emission control equipment. The steam/water flows to and from the one PFBC train are multiplied by a factor to represent the total flow to/from all four PFBC trains. The design parameters for each piece of equipment are based on vendors' inputs, public references, and industry standard practice. The following are the major references and assumptions used in the H&MB modeling:

1) PFBC Performance: Based on original ABB H&MB for the P200 PFBC.
2) Steam Turbine and Generator: Based on GE’s quotation and adjusted accordingly for the required steam flow.
3) Compressor & Expander: Assuming 88% polymetric efficiency for both compressor and expander. Actual performance will be verified with the vendors.
4) Condenser and cooling tower: Optimized based on industry practice for improved overall plant efficiency.
5) CO_2 capture system: Energy consumption for CO_2 capture is based on the DOE baseline study for bituminous coal power plants [**8**] and adjusted for 97% CO_2 capture efficiency. The energy requirement will be verified based on vendors’ inputs.

2.2 Illinois No. 6 PFBC Plant Cases 1A & 1B

This section presents both Illinois No. 6 cases, Case 1A (Capture-Ready) and Case 1B (Capture-Equipped).

2.2.1 Process Description

2.2.1.1 Case 1A Process Description

In this section, the Case 1A PFBC process without CO_2 capture is described. The description follows the block flow diagram (BFD) in Exhibit 2-2 and the stream numbers reference the same exhibit. Exhibit 2-3 provides the process data for the numbered streams in the BFD.

Compressed air (Stream 2) and coal and limestone paste (Streams 3 & 4) are introduced into the PFBC vessel and into the PFBC bed. Note that the coal and limestone paste feed streams are shown separately for information. In the actual feed to the PFBC vessel and bed, the coal and limestone paste feed is a single stream. Prior to the power plant, the coal preparation and feeding systems consist of conventional coal receiving and unloading equipment, also incorporating a stacker-reclaimer and primary coal crushing equipment. The crushed, reclaimed coal is then milled to final size and mixed with ground limestone to form a pumpable paste with nominal 26% moisture by weight.

Feed water (Stream 16) enters the PFBC where supercritical main steam is produced (Stream 11) and is fed to the supercritical HP steam turbine. Cold reheat steam (Stream 12) returns to the PFBC vessel where it is reheated and is fed to the IP Steam turbine as hot reheat steam (Stream 13). The steam expands in the IP turbine before crossing over (Stream 14) to the LP steam turbine. Turbine exhaust steam (Stream 15) is condensed before continuing to the condensate and feed water heating train. The reader should note that there are four PFBC modules and one steam turbine. As such, some of the stream quantities are presented on a per PFBC basis, while others are presented on an overall plant basis. A row in the stream table indicates the flow basis of each stream (i.e., per PFBC or overall plant basis).

Flue gas exits the PFBC bed and cyclones (Stream 5) prior to being cooled to 1450 °F (Stream 6). The slightly cooled flue gas passes through the high temperature metallic filters (Stream 7) prior to entering the turbo-expander. Fly ash from the cyclones (Stream 18) and metallic filters (Stream 19) is forwarded to the fly ash silos for short-term storage. The gas leaving the gas expander (Stream 8) passes through HP and LP economizers before entering the mercury removal process and then exiting the plant stack (Stream 9).

2.2.1.2 Case 1B Process Description

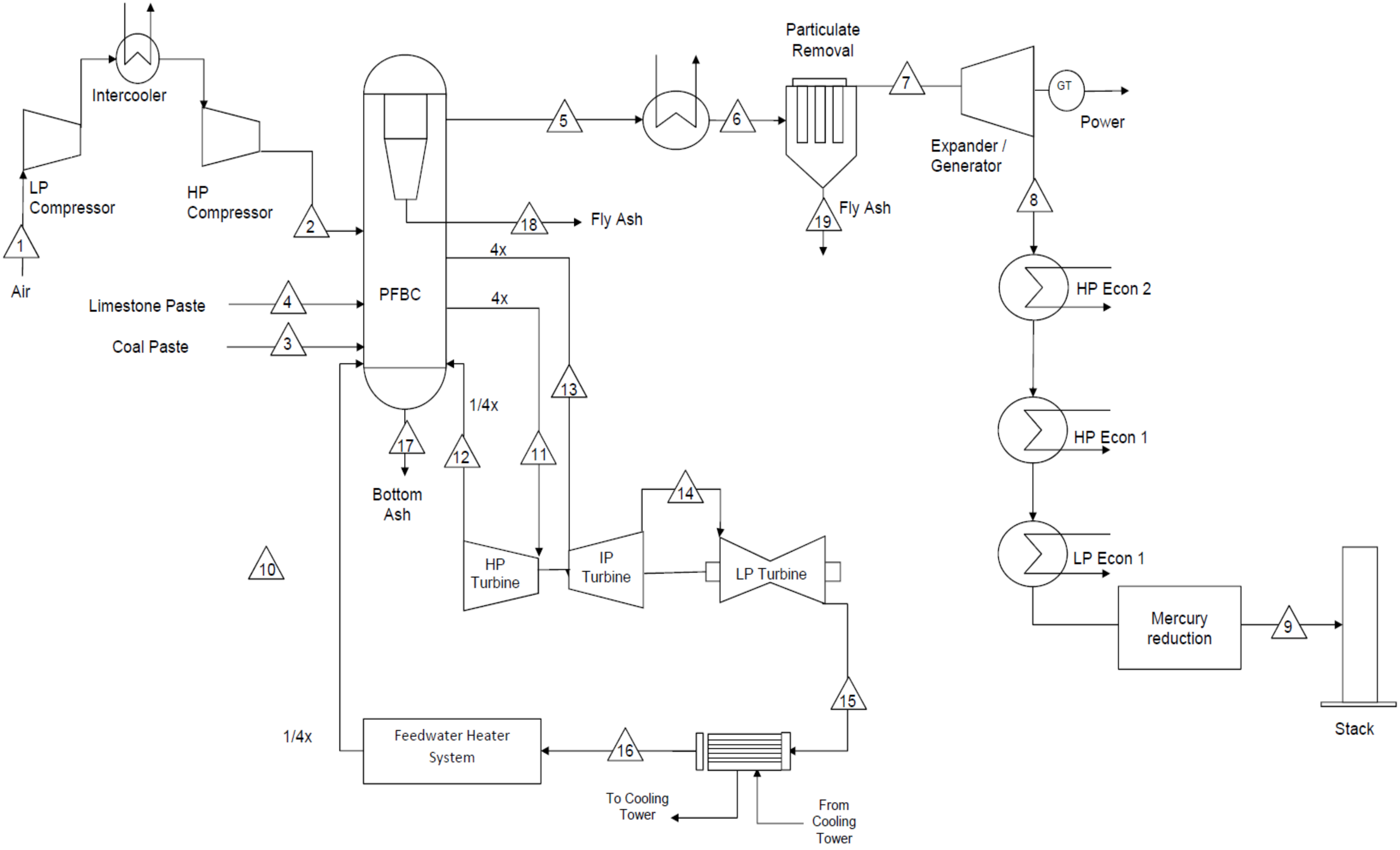
In this section, the Case 1B PFBC process with CO_2 capture is described. The description follows the BFD in Exhibit 2-4 and the stream numbers reference the same exhibit. Exhibit 2-5 provides the process data for the numbered streams in the BFD.

Compressed air (Stream 2) and coal and limestone paste (Streams 3 & 4) are introduced into the PFBC vessel and into the PFBC bed. (As indicated above, the coal and limestone paste feed streams are shown separately for information. In the plant, the coal and limestone paste feed is a single stream.) Feed water (Stream 16) enters the PFBC where supercritical main steam is produced (Stream 11) and is fed to the supercritical HP steam turbine. Cold reheat steam (Stream 12) returns to the PFBC vessel where it is reheated and is fed to the IP Steam turbine as hot reheat steam (Stream 13). The steam expands in the IP turbine before crossing over (Stream 14) to the LP steam turbine. Turbine exhaust steam (Stream 15) is condensed before continuing to the condensate and feed water heating train. The reader should note that there are four PFBC modules and one steam turbine. As such, some of the stream quantities are presented on a per PFBC basis, while others are presented on an overall plant basis. A row in the stream table indicates the flow basis of each stream (i.e., per PFBC or overall plant basis).

Flue gas exits the PFBC bed and cyclones (Stream 5) prior to being cooled to 1450 °F (Stream 6). The slightly cooled flue gas passes through the high temperature metallic filters (Stream 7) prior to entering the turbo-expander. Fly ash from the cyclones (Stream 18) and metallic filters (Stream 19) is forwarded to the fly ash silos for short-term storage. The gas leaving the gas expander (Stream 8) passes through HP and LP economizers. At this point, the carbon capture configuration begins to differ from the carbon capture-ready configuration.

The stream leaving the LP economizer (Stream 9) enters the caustic scrubber to polish the SO_2 levels to minimize amine solvent degeneration. The polished flue gas (Stream 20) passes through an activated carbon bed for mercury removal and passes to the amine carbon dioxide scrubber (Stream 21). The scrubbed flue gas exits the plant stack (Stream 24), while the captured CO_2 (Stream 22) is compressed in a multi-stage intercooled compressor and dried in preparation for export (Stream 23).

Exhibit 2-2. Case 1A Block Flow Diagram (BFD), PFBC without CO_2 Capture



Note: There are four PFBC units and one steam turbine in the plant. Streams for PFBC are for each unit.

Exhibit 2-3. Case 1A Stream Table, PFBC without CO_2 Capture

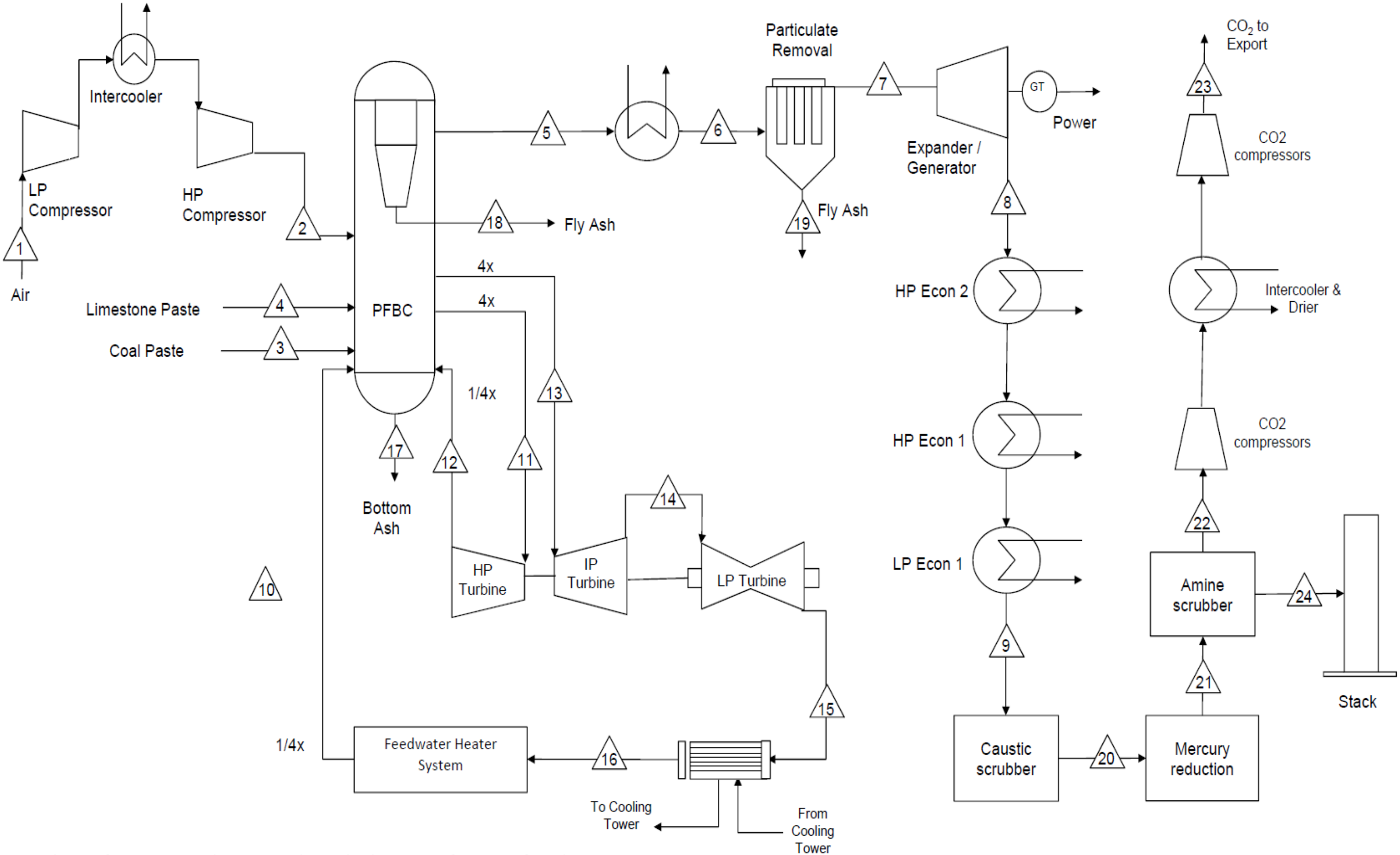
V-L Mole Fraction										
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Ar	0.0093	0.0093	0.0000	0.0000	0.0084	0.0084	0.0084	0.0084	0.00841	0.0000
CO_2	0.0003	0.0003	0.0000	0.0000	0.1377	0.1377	0.1377	0.1377	0.13773	0.0000
H_2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.00000	0.0000
H_2O	0.0101	0.0101	0.0000	0.0000	0.1287	0.1287	0.1287	0.1287	0.1287	1.0000
HCl	0.0000	0.0000	0.0000	0.0000	0.0002	0.0002	0.0002	0.0002	0.00022	0.0000
N_2	0.7729	0.7729	0.0000	0.0000	0.6991	0.6991	0.6991	0.6991	0.69907	0.0000
O_2	0.2074	0.2074	0.0000	0.0000	0.0258	0.0258	0.0258	0.0258	0.0258	0.0000
SO_2	0.0000	0.0000	0.0000	0.0000	0.00006	0.00006	0.00006	0.00006	0.00006	0.0000
SO_3	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total	1.0000	1.0000	0.0000	0.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
V-L Flowrate (lbmol/hr)	24,640	24,640	-	-	27,278	27,278	27,278	27,278	27,278	26,515
V-L Flowrate (lb/hr)	711,000	711,000	-	-	794,786	794,786	794,786	794,786	794,786	477,800
Solids Flowrate (lb/hr)	-	-	83,470	34,676	379	379	8	8	8	8
Flow Basis per PFBC/Plant	PFBC	PFBC	PFBC	PFBC	PFBC	PFBC	PFBC	PFBC	PFBC	PFBC
Temperature (°F)	59.0	576.2	77.0	77.0	1500.0	1450.0	1448.1	721.8	270.1	610.9
Pressure (psia)	14.7	186.4	159.7	159.7	159.9	156.6	155.9	15.3	14.7	3823.3
Steam Table Enthalpy (Btu/lb) [A]	-	-	-	-	-	-	-	-	-	621.7
Density (lb/ft^3)	0.076	0.484	-	-	0.222	0.223	0.222	0.035	0.055	43.900
V-L Molecular Weight	28.8560	28.8560	-	-	29.137	29.137	29.137	29.137	29.137	18.02

[A] Steam table enthalpy is referenced to zero at 32 °F (0 °C) with H_2O as liquid.

V-L Mole Fraction									
	11	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**
Ar	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO_2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H_2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H_2O	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.0000	0.0000	0.0000
HCl	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
N_2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
O_2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
SO_2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
SO_3	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.0000	0.0000	0.0000
V-L Flowrate (lbmol/hr)	106,065	95,122	95,122	82,214	75,117	84,345	-	-	-
V-L Flowrate (lb/hr)	1,911,300	1,714,100	1,714,100	1,481,500	1,353,600	1,519,900	-	-	-
Solids Flowrate (lb/hr)	-	-	-	-	-	-	8,123	18,575	371
Flow Basis per PFBC/Plant	Plant	Plant	Plant	Plant	Plant	Plant	PFBC	PFBC	PFBC
Temperature (°F)	1100.1	67498.0	1100.1	547.7	91.7	92.8	-	-	-
Pressure (psia)	3515.0	766.7	698.3	81.4	0.7	2.5	-	-	-
Steam Table Enthalpy (Btu/lb) ^{A}	1496.7	1324.9	1570.6	1304.9	987.2	60.8	-	-	-
Density (lb/ft^3)	4.319	1.256	0.769	0.138	62.091	62.079	-	-	-
V-L Molecular Weight	18.02	18.02	18.02	18.02	18.02	18.02	-	-	-

A Steam table enthalpy is referenced to zero at 32 °F (0 °C) with H_2O as liquid.

Exhibit 2-4. Case 1B Block Flow Diagram (BFD), PFBC with CO_2 Capture



Note: There are four PFBC units and one steam turbine in the plant. Streams for PFBC are for each unit.

Exhibit 2-5. Case 1B Stream Table, PFBC with CO_2 Capture

V-L Mole Fraction										
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Ar	0.0093	0.0093	0.0000	0.0000	0.0085	0.0085	0.0085	0.0085	0.0085	0.0000
CO_2	0.0003	0.0003	0.0000	0.0000	0.1385	0.1385	0.1385	0.1385	0.1385	0.0000
H_2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H_2O	0.0101	0.0101	0.0000	0.0000	0.1232	0.1232	0.1232	0.1232	0.1232	1.0000
HCl	0.0000	0.0000	0.0000	0.0000	0.0002	0.0002	0.0002	0.0002	0.0002	0.0000
N_2	0.7729	0.7729	0.0000	0.0000	0.7034	0.7034	0.7034	0.7034	0.7034	0.0000
O_2	0.2074	0.2074	0.0000	0.0000	0.0260	0.0260	0.0260	0.0260	0.0260	0.0000
SO_2	0.0000	0.0000	0.0000	0.0000	0.00020	0.00020	0.00020	0.00020	0.00020	0.0000
SO_3	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total	1.0000	1.0000	0.0000	0.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
V-L Flowrate (lbmol/hr)	24,643	24,643	-	-	27,116	27,116	27,116	27,116	27,116	27,192
V-L Flowrate (lb/hr)	711,100	711,100	-	-	792,066	792,067	792,068	792,069	792,070	490,000
Solids Flowrate (lb/hr)	-	-	83,510	22,878	298	298	6	6	6	-
Flow Basis per PFBC/Plant	PFBC	PFBC	PFBC	PFBC	PFBC	PFBC	PFBC	PFBC	PFBC	PFBC
Temperature (°F)	59	576.3	77	77	1500	1449.7	1447.5	742.0	269.3	616.1
Pressure (psia)	14.70	186.80	160.32	160.32	160	157.1	156.4	16.5	15.9	3839.9
Steam Table Enthalpy (Btu/lb) ^{A}	-	-	-	-	-	-	-	-	-	628.7
Density (lb/ft^3)	0.076	0.485	-	-	0.223	0.224	0.223	0.037	0.059	43.510
V-L Molecular Weight	28.86	28.86	-	-	29.210	29.210	29.210	29.210	29.210	18.02

^{A} Steam table enthalpy is referenced to zero at 32 °F (0 °C) with H_2O as liquid.

V-L Mole Fraction										
	11	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
Ar	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0081
CO_2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.1332
H_2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H_2O	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.0000	0.0000	0.0000	0.1573
HCl	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.000002
N_2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.6764
O_2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0250
SO_2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.000004
SO_3	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.0000	0.0000	0.0000	1.0000
V-L Flowrate (lbmol/hr)	108,768	97,209	97,209	45,871	45,694	54,728	-	-	-	28,214
V-L Flowrate (lb/hr)	1,960,000	1,751,700	1,751,700	826,600	823,400	986,200	-	-	-	811,400
Solids Flowrate (lb/hr)	-	-	-	-	-	-	6,390	14,612	292	0
Flow Basis per PFBC/Plant	Plant	Plant	Plant	Plant	Plant	Plant	PFBC	PFBC	PFBC	PFBC
Temperature (°F)	1100.0	680.1	1100.0	525.9	78.9	80.7				162.7
Pressure (psia)	3515.0	781.9	711.8	75.0	0.5	1.6				15.3
Steam Table Enthalpy (Btu/lb) A	1496.7	1327.1	1570.2	1294.6	992.8	48.7	-	-	-	-
Density (lb/ft^3)	4.320	1.276	0.785	0.130	0.002	62.204	-	-	-	0.066
V-L Molecular Weight	18.02	18.02	18.02	18.02	18.02	18.02	-	-	-	28.759

A Steam table enthalpy is referenced to zero at 32 °F (0 °C) with H_2O as liquid.

V-L Mole Fraction										
	21	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**
Ar	0.0081	0.0000	0.0000	0.0108						
CO_2	0.1332	1.0000	1.0000	0.0053						
H_2	0.0000	0.0000	0.0000	0.0000						
H_2O	0.1573	0.0000	0.0000	0.0555						
HCl	0.000002	0.0000	0.0000	0.0000						
N_2	0.6764	0.0000	0.0000	0.8954						
O_2	0.0250	0.0000	0.0000	0.0331						
SO_2	0.000004	0.0000	0.0000	0.0000						
SO_3	0.0000	0.0000	0.0000	0.0000						
Total	1.0000	1.0000	1.0000	1.0000						
V-L Flowrate (lbmol/hr)	28,179	3,626	3,642	5,765						
V-L Flowrate (lb/hr)	810,400	159,600	160,300	160,300						
Solids Flowrate (lb/hr)	0	0	0	0						
Flow Basis per PFBC/Plant	PFBC	PFBC	PFBC	PFBC						
Temperature (°F)	162.7	95.0	95.0	95.0						
Pressure (psia)	15.1	14.7	2215.0	14.7						
Steam Table Enthalpy (Btu/lb) [A]	-	-	-	-						
Density (lb/ft^3)	0.065	0.109	16.420	0.069						
V-L Molecular Weight	28.759	44.01	44.01	27.805						

[A] Steam table enthalpy is referenced to zero at 32 °F (0 °C) with H_2O as liquid.

2.2.2 Plant Performance Summary

The Case 1A (Capture-Ready) plant produces 404.25 MW net at a net plant HHV efficiency of 42.53%. The Case 1B (Capture-Equipped) plant produces 312.84 MW net at a net plant HHV efficiency of 32.90%.

The overall plant performance is summarized in Exhibit 2-6. A breakdown of the auxiliary loads is provided in Exhibit 2-7 for both Cases 1A and 1B. Exhibits 2-6 and 2-7 present the performance both with and without the inclusion of a ZLD system to comply with the requirements of the Coal FIRST program (which include the use of a ZLD system), and to facilitate performance comparisons to other plant configurations that do not include the use of a ZLD. It is noted that the pulverized coal cases (i.e., Cases 11A, 11B, 12A, and 12B) in the NETL Cost and Performance Baseline report do not include ZLD [**8**].

Exhibit 2-6. Cases 1A & 1B Plant Performance Summary

	CASE 1A	CASE 1B
Total Gross Power, MWe	421.08	363.87
CO_2 Capture/Removal Auxiliaries, kWe	0	11,700
CO_2 Compression, kWe	0	22,000
Zero Liquid Discharge System (ZLD), kWe	2,500	2,500
Balance of Plant, kWe	14,329	14,830
Total Auxiliaries [excluding ZLD], MWe	14.33	48.53
Total Auxiliaries [including ZLD], MWe	16.83	51.03
Net Power [excluding ZLD], MWe	**406.75**	**315.34**
Net Power [including ZLD], MWe	**404.25**	**312.84**
HHV Net Plant Efficiency [excluding ZLD], %	**42.80%**	**33.17%**
HHV Net Plant Efficiency [including ZLD], %	**42.53%**	**32.90%**
HHV Net Plant Heat Rate [excluding ZLD], Btu/kWh	7,973	10,288
HHV Net Plant Heat Rate [including ZLD], Btu/kWh	8,022	10,370
Condenser Duty, MMBtu/hr	1,346	872
Amine-based AGR Cooling Duty, MMBtu/hr	0	1,081
As-Received Coal Feed, lb/hr	277,992	278,097
Limestone Sorbent Feed, lb/hr	25,660	16,930
HHV Thermal Input, kWt	950,401	950,760
Raw Water Withdrawal, gpm/MW_{net}	6.9	13.7
Raw Water Consumption, (gpm/MW_{net})	5.2	9.1
Excess Air, %	16.0	16.0

Exhibit 2-7. Case 1 Plant Power Summary

Power Summary		
	CASE 1A	**CASE 1B**
Steam Turbine Power, MWe	351.29	300.64
Turbomachine Power, MWe	69.80	63.24
Total Gross Power, MWe	421.08	363.87
Auxiliary Load Summary		
	CASE 1A	**CASE 1B**
Ash Handling, kWe	400	400
Circulating Water Pumps, kWe	2,380	2,380
CO_2 Capture/Removal Auxiliaries, kWe	-	11,700
CO_2 Compression, kWe	-	22,000
Condensate Pumps, kWe	890	740
Cooling Tower Fans, kWe	1,600	1,600
Fuel & Sorbent Preparation, kWe	4,000	4,000
Metallic Filter, kWe	40	40
Miscellaneous Balance of Plant[A,B], kWe	1,500	1,500
PFBC Combustion Air Compressor, kWe	-	-
PFBC loads	1,120	1,120
Polishing Flue Gas Desulfurizer, kWe	-	800
Steam Turbine Auxiliaries, kWe	300	300
Transformer Losses, kWe	1,099	95
Water Treatment System, kWe	1,000	1,000
Zero Liquid Discharge (ZLD) loads, kWe	2,500	2,500
Total Auxiliaries [excluding ZLD], MWe	**14.33**	**48.53**
Total Auxiliaries [including ZLD], MWe	**16.83**	**51.03**
Net Power [excluding ZLD], MWe	**406.75**	**315.34**
Net Power [including ZLD], MWe	**404.25**	**312.84**

[A] Boiler feed pumps are turbine driven

[B] Includes plant control systems, lighting, HVAC, and miscellaneous low voltage loads

[C] Includes raw water, demineralized water, and waste water systems.

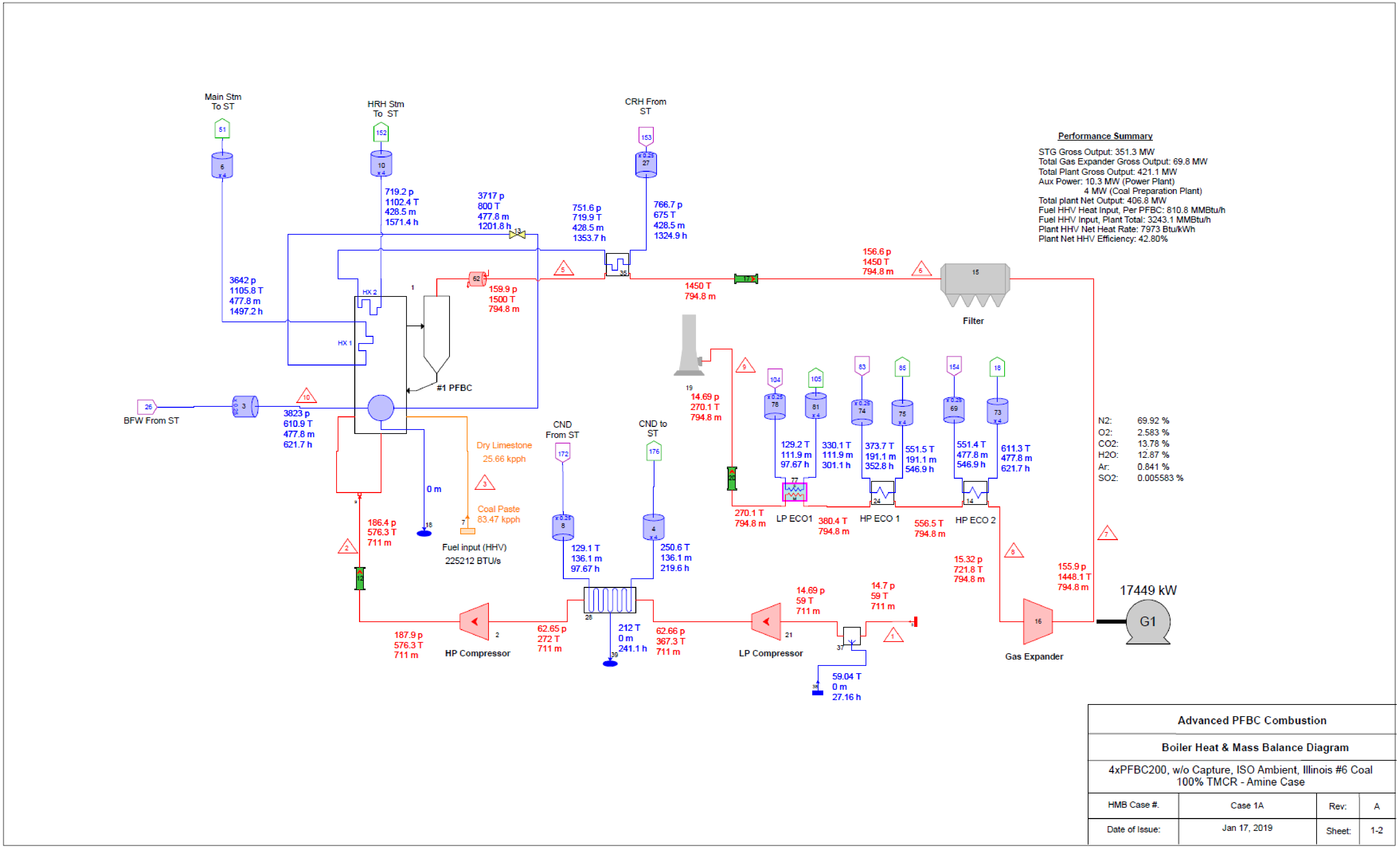
2.2.3 Heat and Mass Balances

In this section the Heat and Mass Balances (H&MB) are presented in two process sheets:

- PFBC Process
- Rankine Cycle

The PFBC H&MB covers the fuel, sorbent, boiler feed water, and air feed into the PFBC, steam generation and reheating, combustion gas cleanup and expansion, and economization of the feed water. The Rankine cycle H&MB covers the complete steam cycle. The Case 1A H&MB diagrams are presented in Exhibit 2-8 and Exhibit 2-9 for the PFBC and Rankine cycles, respectively. The Case 1B H&MB diagrams are presented in Exhibit 2-10 and Exhibit 2-11 for the PFBC and Rankine cycles, respectively.

Exhibit 2-8. Case 1A PFBC Process H&MB Diagram



Performance Summary

STG Gross Output: 351.3 MW
Total Gas Expander Gross Output: 69.8 MW
Total Plant Gross Output: 421.1 MW
Aux Power: 10.3 MW (Power Plant)
4 MW (Coal Preparation Plant)
Total plant Net Output: 406.8 MW
Fuel HHV Heat Input, Per PFBC: 810.8 MMBtu/h
Fuel HHV Input, Plant Total: 3243.1 MMBtu/h
Plant HHV Net Heat Rate: 7973 Btu/kWh
Plant Net HHV Efficiency: 42.80%

N2:	69.92 %
O2:	2.583 %
CO2:	13.78 %
H2O:	12.87 %
Ar:	0.841 %
SO2:	0.005583 %

Advanced PFBC Combustion			
Boiler Heat & Mass Balance Diagram			
4xPFBC200, w/o Capture, ISO Ambient, Illinois #6 Coal 100% TMCR - Amine Case			
HMB Case #.	Case 1A	Rev:	A
Date of Issue:	Jan 17, 2019	Sheet:	1-2

Legend
P – psia
T – F
m – kpph
h – Btu/lb

Exhibit 2-9. Case 1A Rankine Cycle H&MB Diagram

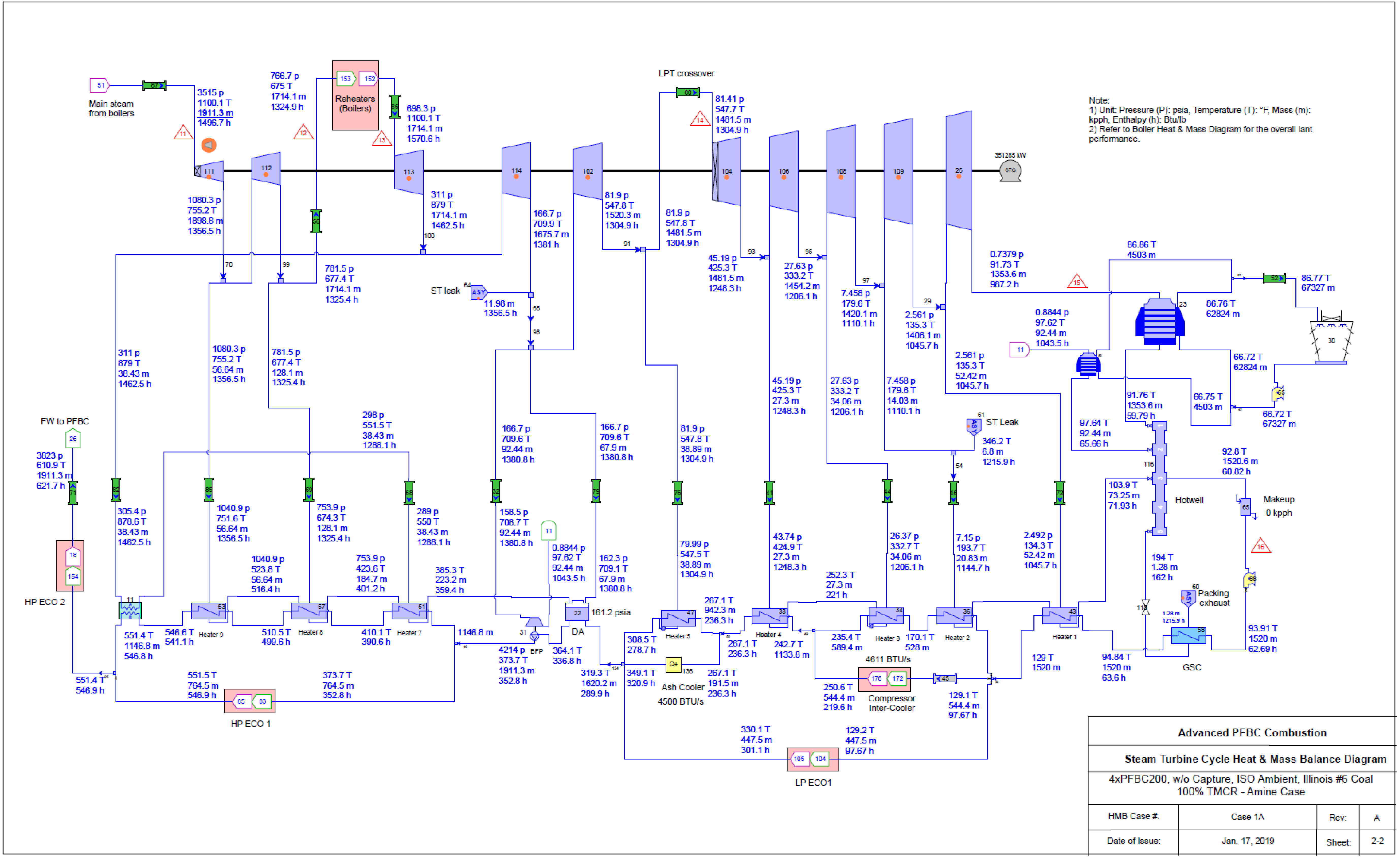
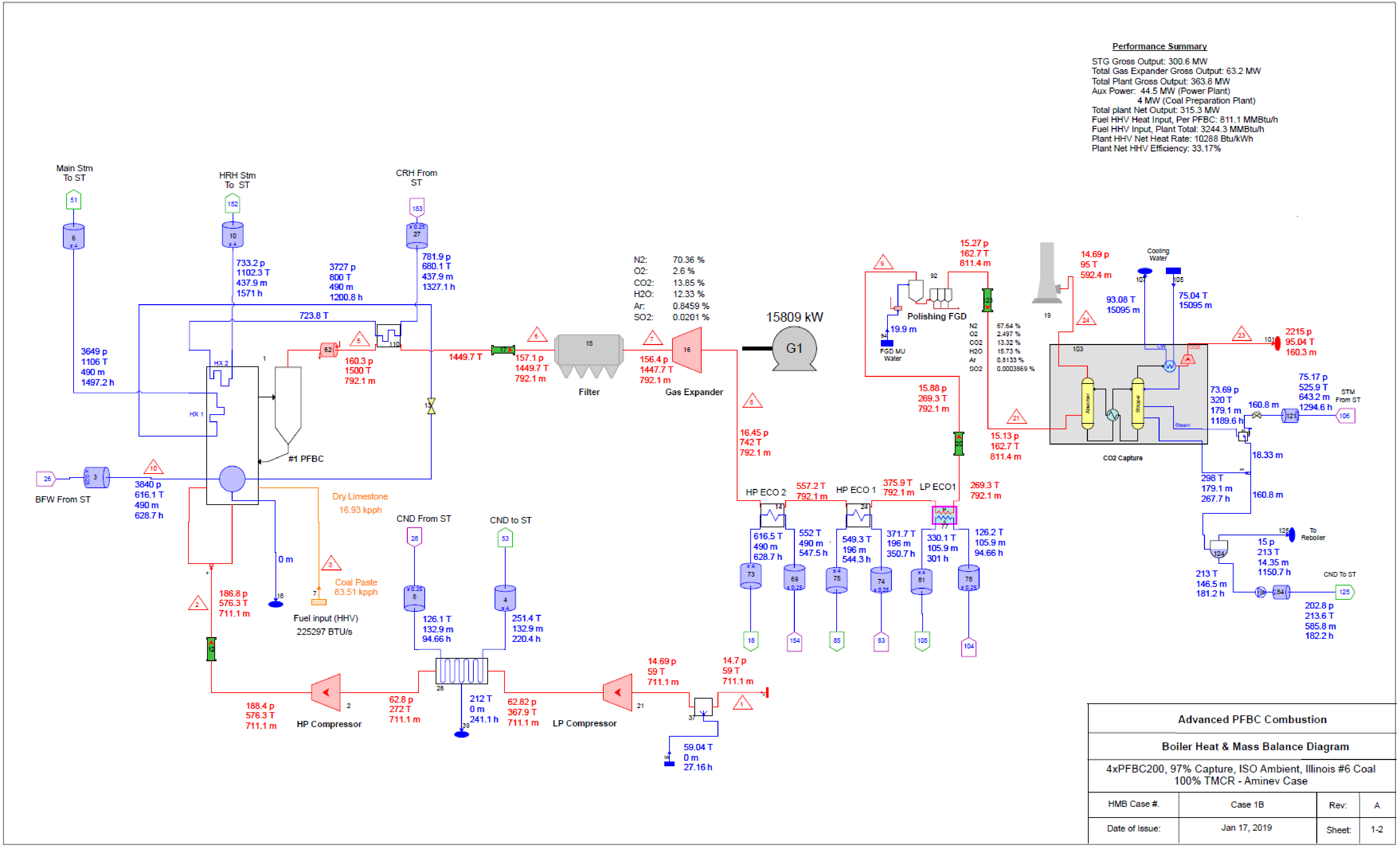


Exhibit 2-10. Case 1B PFBC Process H&MB Diagram



Performance Summary

STG Gross Output: 300.6 MW
Total Gas Expander Gross Output: 63.2 MW
Total Plant Gross Output: 363.8 MW
Aux Power: 44.5 MW (Power Plant)
4 MW (Coal Preparation Plant)
Total plant Net Output: 315.3 MW
Fuel HHV Heat Input, Per PFBC: 811.1 MMBtu/h
Fuel HHV Input, Plant Total: 3244.3 MMBtu/h
Plant HHV Net Heat Rate: 10288 Btu/kWh
Plant Net HHV Efficiency: 33.17%

Legend
P – psia
T – F
m – kpph
h – Btu/lb

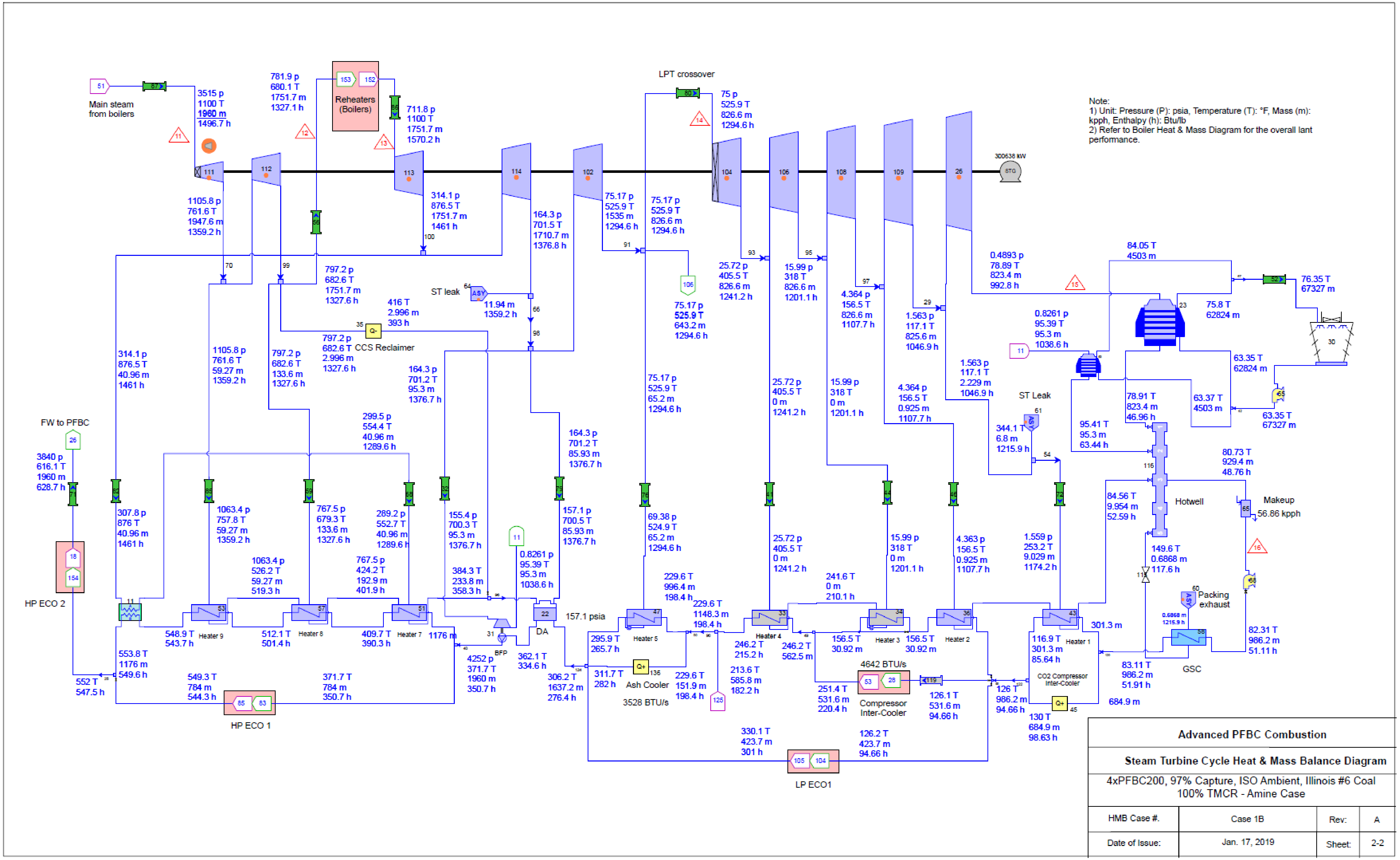
Advanced PFBC Combustion

Boiler Heat & Mass Balance Diagram

4xPFBC200, 97% Capture, ISO Ambient, Illinois #6 Coal
100% TMCR - Aminev Case

HMB Case #.	Case 1B	Rev:	A
Date of Issue:	Jan 17, 2019	Sheet:	1-2

Exhibit 2-11. Case 1B Rankine Cycle H&MB Diagram



Note:
1) Unit: Pressure (P): psia, Temperature (T): °F, Mass (m): kpph, Enthalpy (h): Btu/lb
2) Refer to Boiler Heat & Mass Diagram for the overall lant performance.

Advanced PFBC Combustion

Steam Turbine Cycle Heat & Mass Balance Diagram

4xPFBC200, 97% Capture, ISO Ambient, Illinois #6 Coal
100% TMCR - Amine Case

HMB Case #.	Case 1B	Rev:	A
Date of Issue:	Jan. 17, 2019	Sheet:	2-2

An overall plant energy balance for Case 1A is provided in tabular form in Exhibit 2-12. An overall plant energy balance for Case 1B is provided in tabular form in Exhibit 2-13. The power out is the steam turbine and the gas turbomachine power prior to generator losses.

Exhibit 2-12. Case 1A Overall Energy Balance (32 °F reference)

	HHV	Sensible + Latent	Power	Total
Heat In (MMBtu/hr)				
Coal	3,243.1	4.4	–	3,247.5
Air	–	37.0	–	37.0
Raw Water Makeup	–	47.9	–	47.9
Limestone	–	0.6	–	0.6
Caustic (NaOH) solution (50%)		-		0.0
Auxiliary Power	–	–	31.5	31.5
TOTAL	**3,243.1**	**90.0**	**31.5**	**3,364.5**
Heat Out (MMBtu/hr)				
Bed Ash	–	1.7	–	1.7
Fly Ash	–	4.0	–	4.0
Stack Gas	–	447.5	–	447.5
$NaHS0_3$	–	1.7	–	1.7
Motor Losses and Design Allowances	–	–	20.0	20.0
Cooling Tower Load[A]	–	1345.8	–	1345.8
CO_2 Product Stream	–	–	–	0.0
Blowdown Streams and Deaerator Vent	–	4.4	–	4.4
Ambient Losses[B]	–	81.1	–	81.1
Gross Power	–	–	1,459	1458.7
TOTAL	–	**1884.5**	**1,479**	**3363.2**
Unaccounted Energy[C]	–	–	–	1.3

[A] Includes condenser and miscellaneous cooling loads

[B] Ambient losses include all losses to the environment through radiation, convection, etc. Sources of these losses include the boiler, reheater, superheater, and transformers

[C] By difference

Exhibit 2-13. Case 1B Overall Energy Balance (32 °F reference)

	HHV	Sensible + Latent	Power	Total
Heat In (MMBtu/hr)				
Coal	3,244.3	0.0	–	3,244.3
Air	–	37.0	–	37.0
Raw Water Makeup	–	70.7	–	70.7
Limestone	–	0.4	–	0.4
Caustic (NaOH) solution (50%)		0.1		0.1
Auxiliary Power	–	–	148.7	148.7
TOTAL	3,244.3	108.2	148.7	3,501.2
Heat Out (MMBtu/hr)				
Bed Ash	–	1.4	–	1.4
Fly Ash	–	3.2	–	3.2
Stack Gas	–	108.7	–	108.7
$NaHS0_3$	–	0.1	–	0.1
Motor Losses and Design Allowances	–	–	35.0	35.0
Cooling Tower Load[A]	–	1991.4	–	1991.4
CO_2 Product Stream		-35.1	–	-35.1
Blowdown Streams and Deaerator Vent	–	4.5	–	4.5
Ambient Losses[B]	–	97.3	–	97.3
Gross Power	–	–	1,261	1260.6
TOTAL	0	2171.5	1,296	3467.0
Unaccounted Energy[C]	–	–	–	34.1

[A] Includes condenser and miscellaneous cooling loads

[B] Ambient losses include all losses to the environment through radiation, convection, etc. Sources of these losses include the boiler, reheater, superheater, and transformers

[C] By difference

2.2.4 Environmental Emission

The environmental limits for emissions of SO_2, NOx, particulate, and Hg were presented in the Design Basis Report. A summary of the plant air emissions for Case 1A is presented in Exhibit 2-14 and for Case 1B in Exhibit 2-15.

For NOx, particulate, and Hg, these limits have been utilized as targets. The SO_2 emissions represent the expected emissions based on sulfur removal in the PFBC fluidized bed and/or removal in the scrubbers. In the implementation phase of the project, the determination of the emissions limits will require more detailed knowledge of the emissions attainment status of the region in which the plant is located and the applicability of Best Available Control Technology (BACT) and/or Lowest Achievable Emissions Rate (LAER) emission standards on a pollutant-by-pollutant basis. LAER standards are required when a new stationary source is located in a non-attainment air quality region. BACT is required on major new or modified sources in attainment areas. The selection of BACT control technologies and limits allows the consideration of costs and specific costs (i.e., cost/ton). The selection of LAER control technologies does not allow for the consideration of cost. BACT and LAER are determined on a case-by-case basis, usually by State or local permitting agencies. This determination will be part of the FEED phase activities. For the emission estimate herein, the environmental limits have been treated as environmental targets.

Exhibit 2-14. Case 1A Air Emissions

	lb/MMBtu	**ton/year [A]**	**lb/MWh [B]**
SO_2	0.120	1,455	0.93
NOx	0.091	1,097	0.70
Particulate	0.012	141	0.09
Hg	3.89E-07	0.005	3.00E-06
CO_2	202.5	2,445,266	1,560
CO_2[C]		-	1,615
	mg/Nm^3		
Particulate Concentration [D,E]	15.5		

[A] Calculations based on an 85 percent capacity factor

[B] Emissions based on gross power except where otherwise noted

[C] CO_2 emissions based on net power (Excluding ZLD) instead of gross power

[D] Concentration of particles in the flue gas after the metallic filter

[E] Normal conditions given at 32 °F and 14.696 psia

Exhibit 2-15. Case 1B Air Emissions

	lb/MMBtu	**ton/year [A]**	**lb/MWh [B]**
SO_2	0.000	0	0.00
NOx	0.079	948	0.70
Particulate	0.010	122	0.09
Hg	3.37E-07	0	3.00E-06
CO_2	6.1	73,492	54
CO_2[C]		-	63
	mg/Nm^3		
Particulate Concentration [D,E]	13.5		

Notes A-E are per Exhibit 2-14 above.

For the capture-ready case (Case 1A), SO_2 emissions are controlled using limestone injection into the PFBC bed that achieves a removal efficiency in excess of 97% with a Ca/S molar ratio of 3.8. The byproduct calcium sulfate is removed with the PFBC bed ash and fly ash.

For the capture case (Case 1B), SO_2 emissions are controlled using limestone in the PFBC bed and a caustic polishing scrubber ahead of the amine carbon capture unit. The PFBC bed achieves an SO_2 removal efficiency of 90% with a Ca/S molar ratio of 2.5, while the polishing scrubber achieves an additional 98% SO_2 removal efficiency. The capture case has an overall SO_2 removal efficiency of 99.8%.

For both Cases 1A and 1B, NOx emissions from the PFBC are controlled to about 0.70 lb/MWh using the inherently low combustion temperature of the PFBC bed and SNCR.

Particulate emissions are controlled using cyclones within the PFBC vessel and external metallic filters. The two stages of cyclones remove approximately 98% of the particulates. The metallic filter removes over 99.5% of the remaining particulates. Overall, the cyclones and metallic filter operate at an efficiency of approximately 99.99%. Case 1B (capture case) will also likely receive an addition modest reduction in non-condensable particulate loading based on the operation of the SO_2 polishing caustic scrubber and amine-based capture system.

Reduction in mercury emission is achieved via process conditions (creating oxidized mercury) and combined control equipment (PFBC, cyclones, metallic filter, wet caustic FGD, and final mercury removal system). The GORE® mercury removal system located in the flue gas duct in route to the stack is capable of removing both oxidized and elemental mercury, eliminating concerns related to the effects of changing process conditions and mercury speciation.

For Case 1A, the CO_2 emissions represent the uncontrolled discharge from the process.

For Case 1B, 97% of the CO_2 in the flue gas is removed in the carbon dioxide removal system.

The carbon balances for the Case 1A and 1B plants are shown in Exhibit 2-16 and Exhibit 2-17, respectively. The carbon input to the plant consists of carbon in the coal, carbon in the air, and carbon in the limestone reagent used in the PFBC. Carbon in the air is not neglected here since the Thermoflex model accounts for air components throughout the gas path. Carbon leaves the plant mostly as CO_2 through the stack in Case 1A, and through the captured CO_2 stream in Case 1B; however, unburned carbon remains in the bottom ash.

Exhibit 2-16. Case 1A Carbon Balance

Carbon In		Carbon Out	
	lb/hr		lb/hr
Coal	177,220	Stack Gas	179,127
Air (CO_2)	387.8	Fly Ash	17,161
Limestone	26,035	Bed Ash	7,355
		CO_2 Product	0
		CO_2 Dryer Vent	0
		CO_2 Knockout	0
Total	**203,643**	**Total**	**203,643**

Exhibit 2-17. Case 1B Carbon Balance

Carbon In		Carbon Out	
	lb/hr		lb/hr
Coal	177,287	Stack Gas	5,384
Air (CO_2)	387.9	Fly Ash	10,740
Limestone	17,178	Bed Ash	4,603
		CO_2 Product	174,109
		CO_2 Dryer Vent	16
		CO_2 Knockout	0.4
Total	**194,852**	**Total**	**194,852**

Exhibit 2-18 and Exhibit 2-19 show the sulfur balance for the Case 1A and 1B plants, respectively. Sulfur input comes solely from the sulfur in the coal. Sulfur output includes the sulfur recovered as calcium sulfate ($CaSO_4$) in the PFBC bed ash and fly ash and as sodium bisulfate ($NaHSO_3$) in the polishing scrubber, as well as sulfur emitted in the stack gas. For the Case 1B plant, the amine scrubber will further polish SO_2 out of the flue gas along with the removal of CO_2.

Exhibit 2-18. Case 1A Sulfur Balance

Sulfur In		Sulfur Out	
	lb/hr		**lb/hr**
Coal	6,978	PFBC & Filter Ash	6,782
		Polishing Scrubber Product	0
		Amine AGR	0
		Stack Gas	195.4
Total	**6,978**	**Total**	**6,978**

Exhibit 2-19. Case 1B Sulfur Balance

Sulfur In		Sulfur Out	
	lb/hr		**lb/hr**
Coal	6,980	PFBC & Filter Ash	6,282
		Polishing Scrubber Product	684
		Amine AGR	14.0
		Stack Gas	0.0
Total	**6,980**	**Total**	**6,980**

2.2.5 Water Use and Balance

Exhibit 2-20 and Exhibit 2-21 show the overall water balance for the Case 1A and 1B plants, respectively.

Water demand represents the total amount of water required for a particular process. Some water is recovered within the process and is re-used in internal recycle. The difference between demand and recycle is raw water withdrawal. Raw water withdrawal is defined as the water removed from the ground or diverted from a Publicly Owned Treatment Works (POTW) for use in the plant and was assumed to be provided 50 percent by a POTW and 50 percent from groundwater. Raw water withdrawal can be represented by the water metered from a raw water source and used in the plant processes for all purposes, such as FGD makeup, BFW makeup, and cooling tower makeup. The difference between water withdrawal and process water discharge is defined as water consumption and can be represented by the portion of the raw water withdrawn that is evaporated, transpired, incorporated into products, or otherwise not returned to the water source from which it was withdrawn. Water consumption represents the net impact of the plant process on the water source balance.

Exhibit 2-20. Case 1A Water Balance Table

Water Use	Water Demand	Internal Recycle	Raw Water Withdrawal	Process Water Discharge	Raw Water Consumption
	gpm	gpm	gpm	gpm	gpm
Fuel & Sorbent Prep	130		130		130
FGD Process Makeup	–	–	–	–	–
CO_2 Drying	–	–	–	–	–
CO_2 Capture Recovery	–	–	–	–	–
CO_2 Compression KO	–	–	–	–	–
Deaerator Vent	–	–	–	7.6	-7.6
Condenser Makeup	**9.6**	**–**	**9.6**	0	**9.6**
BFW Makeup	9.6	–	9.6	0	9.6
Cooling Tower	**2,663**	**–**	**2,663**	**666**	**1,997**
Total	**2,803**	**–**	**2,803**	**674**	**2,129**

Note: Process water discharge excludes ZLD.

Exhibit 2-21. Case 1B Water Balance Table

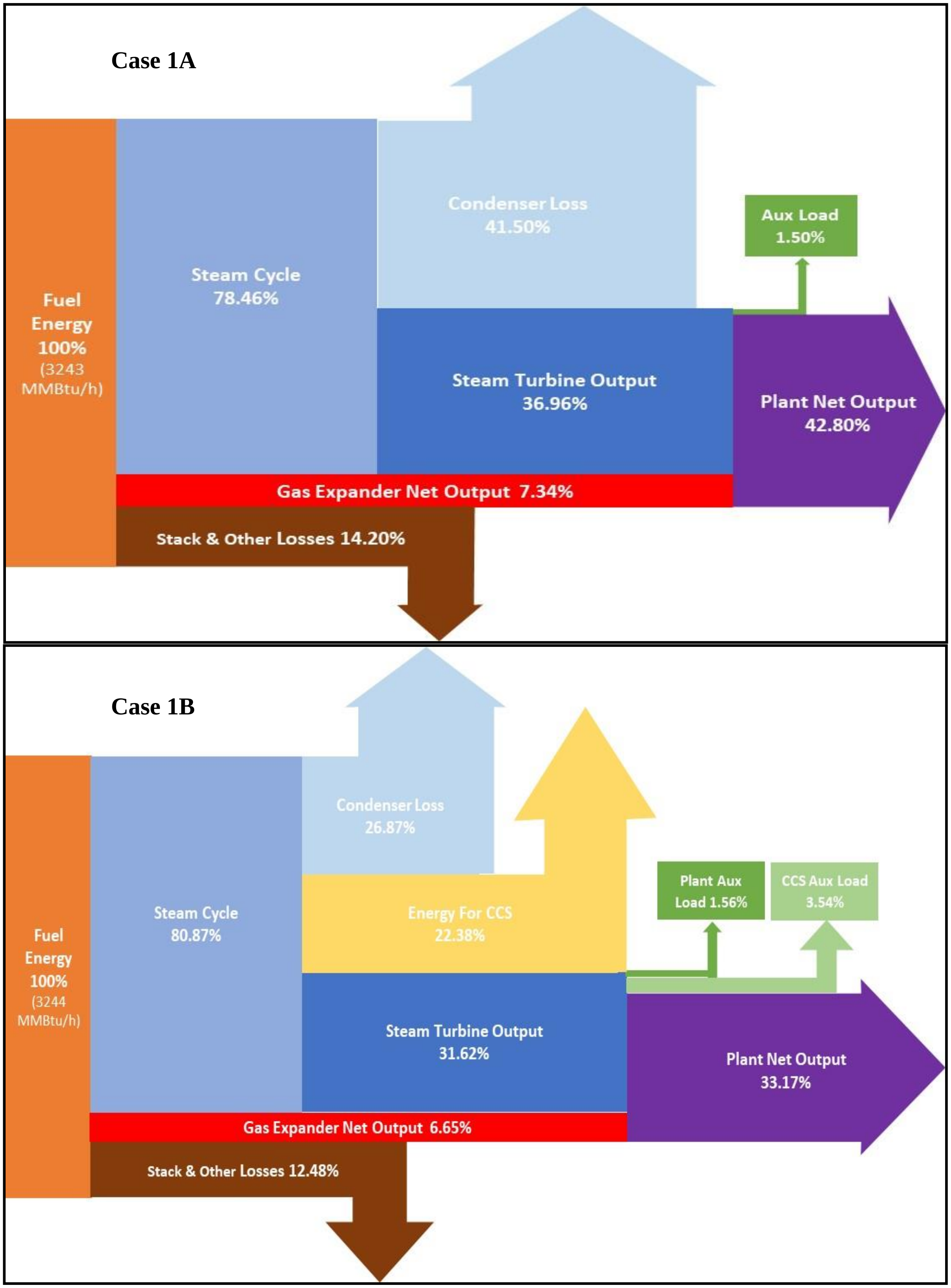
Water Use	Water Demand	Internal Recycle	Raw Water Withdrawal	Process Water Discharge	Raw Water Consumption
	gpm	gpm	gpm	gpm	gpm
Fuel & Sorbent Prep	124		124		124
FGD Process Makeup	159	–	159	–	159
CO_2 Drying	–	–	–	6	-6
CO_2 Capture Recovery	–	–	–	453	-453
CO_2 Compression KO	–	–	–	10	-10
Deaerator Vent	–	–	–	7.8	-7.8
Condenser Makeup	**113.2**	**–**	**113.2**	0	**113.2**
BFW Makeup	113.2	–	113.2	0	113.2
Cooling Tower	**3,929**	**–**	**3,929**	**982**	**2,946**
Total	**4,325**	**–**	**4,325**	**1,459**	**2,866**

Note: Process water discharge excludes ZLD.

2.2.6 Sankey Diagrams

Sankey diagrams for the Case 1A (capture-ready) and 1B (capture-equipped) cases are presented in Exhibit 2-22. These Sankey diagrams exclude the ZLD auxiliary loads.

Exhibit 2-22. Sankey Diagram for PFBC Cases 1A & 1B



2.3 Waste Coal PFBC Plant Cases 2A & 2B

This information will be provided with final report.

2.4 Performance Relative to Flexibility Metrics

This section presents the flexibility metrics of ramp rate, startup times, and turndown.

2.4.1 Ramping

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%/minute ramp rate can be achieved using a combination of coal-based energy and natural gas co-firing.

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 compressor train (comprised of 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 may be 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 potentially resolves this problem and will be evaluated in the Phase III FEED study.

2.4.2 Cold Start

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 were given in Appendix E of the Conceptual Design Report. Startup from hot conditions (defined as bed temperature at or near 1500 °F, and main steam pipe temperature above approximately 800 °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 work 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.

2.4.3 Turndown

The four separate P200 modules can be run in various combinations to cover a wide range of loads, allowing the PFBC plant to be turned down quickly to a low level.

For example, a single P200 module operating at 80% can allow the PFBC to operate at 20% load. Multiple configurations can be envisioned for higher load points. For example, the 40% load point can be achieved by 2 x P200 modules each operating at 80% load, or three P200 modules each operating at 53.3% load.

A summary of estimated plant performance under various operating conditions was presented in Section 1.6.1; more detailed modeling results will be developed and presented later in the pre-FEED and FEED studies.

2.5 Equipment Summary (Commercial vs that Requiring R&D)

Major equipment and systems for the supercritical PFBC plant are shown in the following tables. A single list is used for both the capture-ready and capture-equipped configurations. Items that only relate to the capture-equipped configuration are highlighted in light green in Account 5 (Flue Gas Cleanup). The accounts used in the equipment list correspond to the account numbers used in the cost estimates being generated for the project. The commercial status for the major equipment/systems has been identified with one of following three designations:

1. Commercial
2. Custom Design
3. R&D needed

Exhibit 2-23. Case 1A & 1B – Account 1: Coal and Sorbent Handling

Equipment No.	Description	Type	Commercial Status
	DRY FUEL HANDLING		
1	Dry Fuel Dumper / Hopper	Field Erection	Commercial
2	Feeder System	Belt	Commercial
3	Conveyor #1 with Scale / Magnet	Belt	Commercial
4	Dry Fuel Sizing Building Screens / Crusher-Pulverizer	Enclosed	Commercial
5	Dry Fuel Sampling System	Two Stage	Commercial
6	Conveyor #2	Belt	Commercial
7	Conveyor #3 to Storage Dome	Belt	Commercial
8	Storage Dome	Enclosed	Commercial
9	Storage Dome Reclaim	Vibratory	Commercial
10	Reclaim Conveyor #4 with Scale	Belt	Commercial
11	Dry Fuel Sampler	Swing Hammer	Commercial
12	Conveyor #5 to PFBC Fuel Prep System	Belt	Commercial
	SORBENT HANDLING		
13	Sorbent Dumper / Hopper	Field Erection	Commercial
14	Feeder System	Vibratory	Commercial
15	Conveyor #1 to Sorbent Dome Storage with Scales	Belt	Commercial
16	Sorbent Sampling System	Two Stage	Commercial
17	Sorbent Storage Dome	Enclosed	Commercial
18	Storage Dome Reclaim	Auger	Commercial
19	Reclaim Conveyor #2 with Scale to Sorbent Sizing System	Belt	Commercial
20	Sorbent Sizing Building (Day Hopper Feeder/Screens/Pulverizer/Dust Control)	Enclosed	Commercial
21	Sorbent Sampler	Enclosed at Transfer	Commercial
22	Sorbent Handling System to PFBC Fuel Prep	Enclosed	Commercial

Exhibit 2-24. Case 1A & 1B – Account 2: Coal and Sorbent Preparation and Feed

Equipment No.	Description	Type	Commercial Status
	FUEL PREP BUILDING	**ENCLOSED**	
1	Fuel Receiving Bin Sliding Frames	Shop Fab / Field Erected	Commercial
2	Fuel Weigh feeders (4) to Paste Mixers	Belt	Commercial
3	Sorbent Bin	Shop Fab / Field Erected	Commercial
4	Sorbent Bin Rotary Feeders (4)	Rotary	Commercial
5	Sorbent Weigh Belts (4)	Belt	Commercial
6	Paste Sumps / Mixers / Moisture Control	Mixers	Commercial
7	Prepared Fuel Sumps (4) with Agitators	Shop Fab	Commercial
8	Putzmeister Transfer Pumps (8) to PFBC Feed System	High Density Solids Pumps	Commercial
9	Buffer Silo Sumps with Agitators (8)	Shop Fab	Commercial
10	Putzmeister Feed Pumps (24) to PFBC Lances (48)	High Density Solids Pumps	Commercial

Exhibit 2-25. Case 1A & 1B – Account 3: Feed Water and Miscellaneous Balance of Plant Systems

Equipment No.	Description	Type	Commercial Status
1	Demineralized Water Storage Tank	Vertical, cylindrical, outdoor	Commercial
2	Condensate Pumps	Vertical canned	Commercial
3	Deaerator and Storage Tank	Horizontal spray type	Commercial
4	Boiler Feed Pump/Turbine	Barrel type, multi-stage, centrifugal	Commercial
5	Startup Boiler Feed Pump, Electric Motor Driven	Barrel type, multi-stage, centrifugal	Commercial
6	LP Feed water Heaters	Horizontal U-tube	Commercial
7	HP Feed water Heaters	Horizontal U-tube	Commercial
8	Auxiliary Boiler	Shop fabricated, water tube	Commercial
9	Closed Cycle Cooling System	Shell and tube HX & Horizontal centrifugal Pumps	Commercial
10	Raw Water System	Stainless steel, single suction	Commercial
11	Service Water System	Stainless steel, single suction	Commercial
12	Demineralized Water System	Multi-media filter, cartridge filter, RO membrane assembly, electro-deionization unit	Commercial
13	Liquid Waste Treatment System	ZLD	Commercial

Exhibit 2-26. Case 1A & 1B – Account 4: PFBC Coal Boiler and Accessories

Equipment No.	Description	Type	Commercial Status
1	PFBC	P200, supercritical, SNCR	Custom Design (supercritical)
2	SNCR Ammonia Storage & Feed System	Horizontal tank, centrifugal pump, injection grid	Commercial

Exhibit 2-27. Case 1A & 1B – Account 5: Flue Gas Cleanup

Equipment No.	Description	Type	Commercial Status
1	Hot Gas Metallic Filter	Pressure vessel with replaceable filter elements, back-pulse cleaning	Custom Design
2	Mercury Control system	GORE® Sorbent Polymer Catalyst (SPC) composite material	Commercial
3 Capture only	SO_2 Polisher Absorber Module	Counter-current pack column Absorber, caustic solvent	Custom Design
4 Capture only	CO_2 Absorber System	Amine-based CO_2 capture (e.g., CANSOLV capture technology)	Custom Design
5 Capture only	CO_2 Dryer	Triethylene glycol (TEG)	Custom Design
6 Capture only	CO_2 Compression system	Integrally geared, multi-stage centrifugal compressor	Custom Design

Exhibit 2-28. Case 1A & 1B – Account 6: Turbo-Machines

Equipment No.	Description	Type	Commercial Status
1	Gas turbo machine	Integrated compressor, expander, and motor/generator	Custom Design

Exhibit 2-29. Case 1A & 1B – Account 7: Ductwork and Stack

Equipment No.	Description	Type	Commercial Status
1	Stack	Reinforced concrete with FRP liner	Custom Design

Exhibit 2-30. Case 1A & 1B – Account 8: Steam Turbine and Accessories

Equipment No.	Description	Type	Commercial Status
1	Steam Turbine	Commercially available advanced steam turbine	Custom Design
2	Steam Turbine Generator	Hydrogen cooled, static excitation	Custom Design
3	Surface Condenser	Single pass, divided waterbox including vacuum pumps	Custom Design

Exhibit 2-31. Case 1A & 1B – Account 9: Cooling Water System

Equipment No.	Description	Type	Commercial Status
1	Circulating Water Pumps	Vertical, wet pit	Commercial
2	Cooling Tower	Evaporative, mechanical draft, multi-cell	Commercial

Exhibit 2-32. Case 1A & 1B – Account 10: Ash and Spent Sorbent Handling System

Equipment No.	Description	Type	Commercial Status
1	Ash handling system	-	Custom Design
8	Bottom Ash Storage Silo	Reinforced concrete	Custom Design
12	Fly Ash Silo	Reinforced concrete	Custom Design

Exhibit 2-33. Case 1A & 1B – Account 11: Accessory Electric Plant

Equipment No.	Description	Type	Commercial Status
1	STG Transformer	Oil-filled	Commercial
2	Turbo-machine Transformer	Oil-filled	Commercial
3	High Voltage Transformer	Oil-filled	Commercial
4	Medium Voltage Transformer	Oil-filled	Commercial
5	Low Voltage Transformer	Dry ventilated	Commercial
6	STG Isolated Phase Bus Duct and Tap Bus	Aluminum, self-cooled	Commercial
7	Turbo-machine Isolated Phase Bus Duct and Tap Bus	Aluminum, self-cooled	Commercial
8	Medium Voltage Switchgear	Metal clad	Commercial
9	Low Voltage Switchgear	Metal enclosed	Commercial
10	Emergency Diesel Generator [TBC]	Sized for emergency shutdown	Commercial
11	Station Battery and DC Bus		Commercial
12	120 AC Uninterruptible Power Support		Commercial

Exhibit 2-34. Case 1A & 1B – Account 12: Instrumentation and Control

Equipment No.	Description	Type	Commercial Status
1	DCS - Main Control	Monitor/keyboard; Operator printer (laser color); Engineering printer (laser B&W)	Custom Design
2	DCS -Processor	Microprocessor with redundant input/output	Custom Design
3	DCS - Data Highway	Fiber optic	Custom Design

2.6 Assessment of Available Data for Commercial Equipment & Vendor Contacts

Exhibit 2-35 reviews the status of the available data for commercial equipment and vendor contacts for the major equipment unique to the PFBC Power cycle.

Exhibit 2-35. Assessment of Available Data for Commercial Equipment

Equipment	Vendor / OEM	Contact	Notes
P200 PFBC Module	• PFBC-EET • Nooter/Eriksen • GE (Alstom)	✓ ✓ ✓	PFBC-EET is providing PFBC knowledge and design information. N/E is providing cost for the supercritical PFBC module for everything inside the PFBC Pressure vessel. The N/E design is based on the Cottbus bed and cyclone design parameters. GE (now the owner of the Alstom PFBC design) is onboard with the PFBC project.
High-temperature particulate filter	• Mott • PALL	✓ ✓	Contact made with both OEMS. Mott will provide performance and cost based on custom design. Mott design can accommodate 1450 °F.
Turbomachine	• GE Baker Hughes • Siemens	✓ ✓	Contact made with both OEMS. GE Baker-Hughes will provide performance and cost based on custom design.
Supercritical STG	• GE • Siemens	✓ ✓	Contact made with both OEMS. GE will provide performance and cost.
SO_2 polishing scrubber (Caustic)	• Dürr Megtec	✓	Dürr Megtec is providing the performance and costs for the caustic scrubber. It is possible that the SO_2 polisher can be combined with the CO_2 capture system, depending on the vendor.
Amine Carbon Capture	• Numerous vendors offer such a system	Using NETL data	We are presently utilizing the performance and cost information from the DOE Baseline study as a reference for the CANSOLV carbon capture system extended to 97% capture. We plan to contact amine capture system vendors later in the pre-FEED phase.
Benfield	• UOP	✓	UOP has agreed to cooperate. However, we have moved away from the Benfield system toward the amine system based on the enhanced performance.
Hi-temperature Heat Exchanger (*for Benfield cycle only*)	• Schmidtsche Schack	✓	To maximize the cycle performance with the Benfield carbon capture process, a high-temperature heat exchanger (Hot Gas: 1450 °F to 500 °F, Cold Gas: 250 °F to 1350 °F) is required. Schmidtsche Schack has provided preliminary performance, design, and cost data. This information will be retained for reference, as the design now relies on amine CO_2 capture.
Fuel Handling Mixer / Paste Pump	• Putzmeister	✓	Putzmeister is providing support for performance and cost data.

References

1 National Energy Technology Laboratory, "Quality Guidelines for Energy System Studies for Process Modeling Design Parameters," U.S. Department of Energy, Pittsburgh, PA, June 2019, NETL-PUB-22478.

2 U.S. EIA, Short-Term Energy Outlook Data Browser, Available: https://www.eia.gov/outlooks/steo/data/browser/

3 U.S. EIA, Annual Energy Outlook 2019 (Reference Case), Release date: January 24, 2019, Available: https://www.eia.gov/outlooks/aeo/

4 U.S. EIA, Cost and Performance Characteristics of New Generating Technologies, Annual Energy Outlook 2019, January 2019, Available: https://www.eia.gov/outlooks/aeo/assumptions/pdf/table_8.2.pdf

5 U.S. EIA, Capital Cost Estimates for Utility Scale Electricity Generating Plants, November 2016, Available: https://www.eia.gov/analysis/studies/powerplants/capitalcost/pdf/capcost_assumption.pdf

6 Connell, D. Opportunities for New Technology in Coal Mining and Beneficiation; In Proceedings of the National Coal Council Annual Spring Meeting 2018, Washington, DC, April 2018. Available: http://www.nationalcoalcouncil.org/page-Meeting-Presentations.html

7 U.S. EIA, Capital Cost Estimates for Utility Scale Electricity Generating Plants, November 2016, Available: https://www.eia.gov/analysis/studies/powerplants/capitalcost/pdf/capcost_assumption.pdf

8 National Energy Technology Laboratory, "Cost and Performance Baseline for Fossil Energy Plants Volume 1: Bituminous Coal and Natural Gas to Electricity," September 24, 2019, NETL-PUB-22638.