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Technical Paper

State of the Art of Oxy-Coal Combustion Technology for CO_2 Control from Coal-Fired Boilers

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Presented to:
32nd International Technical Conference on Coal Utilization & Fuel Systems
(aka Clearwater Coal Conference)
June 10 - 15, 2007
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State of the Art of Oxy-Coal Combustion Technology for CO_2 Control from Coal-Fired Boilers:

Are We Ready for Commercial Installation?

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Abstract

The research and development of oxy-coal combustion for CO_2 capture from coal-fired boilers has been the subject of numerous studies. Recently, The Babcock & Wilcox Company (B&W) and Air Liquide (AL), with sponsorship of the U.S. Department of Energy (DOE), have finished a pilot-scale evaluation of the technology at 1.5 MW_{th} (5 MBtu/hr) using scale model commercial boiler equipment. The oxy-coal combustion flame stability, boiler and convective pass heat transfer, boiler thermodynamic performance and NO_x emission levels compared favorably to the air/coal firing conditions. A steam generating plant engineering and economic evaluation also showed that oxy-coal combustion is a technically feasible and economically viable technology. B&W and AL are currently, with sponsorship from the U.S. DOE, undertaking a project to significantly broaden the applicability of oxy-coal combustion technology to the existing fleet of coal-fired boilers. Upon successful completion of this development effort, pilot-scale oxy-coal combustion test data will be available for application and scale-up to both wall-fired and Cyclone™ furnace boilers that burn bituminous, sub-bituminous or lignite coal. This paper will describe the research performed to date, future pilot-scale and scale-up of the technology to full-scale commercial operation.

Introduction

Over half of the electric power generated in the United States comes from coal and almost one-third of the manmade carbon dioxide emitted comes from that same coal combustion. Over the next twenty-five years, an additional 147,000 MW_e of new coal-fired generating capacity will be added in North America to meet an economy-wide electricity demand growth rate of 1.6%, as reported by the Energy Information Administration's (EIA) International Energy Outlook 2006, while at the same time increasing coal's market share. Today, over 310,000 MW_e of coal-fired generating plants are in service, operating at ever-increasing capacity factors, in the U.S.

The Intergovernmental Panel on Climate Change's (IPCC) Summary for Policymakers (SPM), February 2007, recognizes that the continuous annual release of carbon emissions at the gigaton level is likely to affect the climate, and that these effects can now be resolved and modeled at the decadal level. Plausible predictions of climate change may now be made for a few decades, perhaps more. In addition, they acknowledge that anthropogenic greenhouse gas (GHG) emissions appear to be contributing to a near-term warming trend. Carbon dioxide is just one of several of these greenhouse gas emissions (along with methane, nitrous oxides, and halocarbons); however, it represents 63% of the radiative forcing causes (21% from coal) associated with anthropogenic sources.

The need for carbon emission regulatory budgets, while temporal in nature, requires development for the U.S. and must be developed in context, and in concert, with the global efforts to manage carbon. Carbon reduction budgets need to span the breadth of the economy, as this is a challenge that cannot be met by a single sector. The presence of budgets, both near and long term, will then enable long-term planning decisions to be made, decisions that impact billions of dollars in energy and electricity system assets, both existing and future.

The power industry has successfully met the challenge of reducing sulfur dioxide, oxides of nitrogen, particulate matter and more recently mercury. Carbon dioxide challenges the industry in a new way because the quantities are vast and the technologies are still under development. The Babcock & Wilcox Company (B&W) and Air Liquide (AL) have been leaders in one such technology, Oxy-Coal Combustion (OCC), which is now ready for commercial demonstration. The OCC process allows for the isolation of CO_2 from the combustion process without the need for a separate carbon capture process, and is the pathway to a Near Zero Emissions Power (NZEP) plant.

B&W and AL have been actively involved in the development of oxy-coal technologies for power generation for the past ten years. From earlier participation in various consortia focused on these technologies, AL and B&W have become major players and have been leading several projects in this field. Together, B&W and AL performed pilot-scale oxy-coal combustion tests on a 1.5 MW_{th} pulverized coal (PC) boiler, economics of full-scale 500 MW_e PC power plants and preliminary oxy-coal advanced boiler design. Following very promising results, the efforts moved toward more detailed engineering studies at full-scale (300-500 MW_e) along with feasibility studies at demonstration scale (22 MW_e and 30 MW_{th}). These studies are about to be completed providing extended understanding on some critical technical points of the oxy-coal technology. Worldwide, several studies have also concluded showing great interest in the oxy-coal technology for CO_2 capture from coal-fired power plants.

Background/previous work

Oxy-coal combustion for enhanced oil recovery was evaluated by B&W initially in 1979 at the request of a major oil company. Since the late 1990s, B&W has been a member of the CANMET oxy-coal combustion consortium and participated in 1-million Btu/hr tests in Canada. AL has likewise been a leader worldwide with extensive R&D and subject patents and has collaborated with B&W in North America. They have been, in particular, involved in developments and industrial implementation of oxycombustion processes on many diverse industrial processes such as in metals production or glass melting for more than 40 years. In addition, they have been a leader in Air Separation Units design and operation for many years, in particular for energy production including from coal gasification.

The historical perspective of oxy-coal combustion has been reported by Santos.(1) The concept was first proposed by Abraham in publicly available literature.(2) The process was then investigated by Argonne National Laboratory (ANL) through a series of techno-economic, pilot-scale and demonstration plant studies.(3,4,5,6,7) During the 1990s, the technology gained more interest for CO_2 capture and additional work was performed by a research consortium led by the International Flame Research Foundation (IFRF).(3,8,9) B&W and AL work on oxy-coal combustion started in the late 1990s and has provided the means for assessing the potential of the technology for application to coal-fired power boilers to the point of near commercialization.

Recent pilot-scale evaluations

Pilot-scale development of the technology for coal-fired boilers began several years ago at B&W in collaboration with AL.(10,11,12,13) Highlights of the pilot-scale oxy-coal combustion experience are described below.

Description of the test facility

Shown in Figure 1 is B&W's 1.5 MW_{th} (5 MBtu/hr) Small Boiler Simulator (SBS-I) facility used in oxy-coal combustion development work. Pulverized coal (PC) flow from a storage bin is measured and controlled by a calibrated weigh feeder. The coal is then transported by heated primary oxidant (PO) at about 150F to the burner. Secondary oxidant (SO) flow is preheated indirectly to 600F by a gas-fired heater. For staged combustion, the 600F tertiary oxidant (TO) is directed to overfire ports located above the main combustion zone. The SBS is shown here in the PC mode but the unit can be converted for Cyclone firing. The oxygen levels in the primary and secondary streams and convection pass exit gas are measured with oxygen sensors. For safety purposes, boiler permissives and interlocks are set to limit the oxygen concentration in the flue gas at 25% for secondary and 21% for the primary zones using the oxygen sensors and the oxygen flow controls.

Liquid oxygen from an onsite 9,000-gallon (34,000 liters) oxygen tank was vaporized and regulated to an appropriate pressure for delivery to the SBS via a copper line. The oxygen delivery control system was integrated into the boiler safety interlock system. Flue gas was sampled continuously from the convection pass exit and the concentrations of O_2, NO_x, CO, CO_2, and SO_2 were measured on a dry basis by calibrated gas analyzers. The stack flyash was isokinetically sampled and analyzed for carbon content to determine carbon utilization.

Results

The oxy-coal combustion technology has been successfully demonstrated and characterized in the pilot facility while burning a low-sulfur sub-bituminous coal and high-sulfur eastern bituminous coal. The overall oxy-coal combustion characteristics were comparable to the air-firing case even

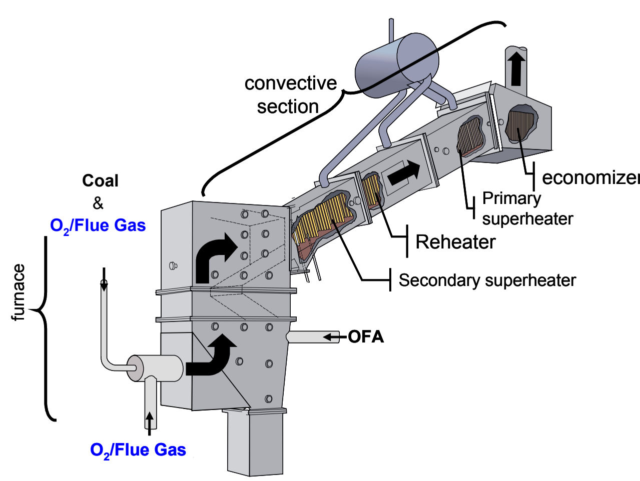

Fig. 1 B&W small boiler simulator (SBS-I).

with the change in oxidant composition from air to oxygen-enriched flue gas. The NO_x emissions from oxy-coal combustion were significantly lower (65% less) than the air-fired case. The thermodynamics and heat transfer in the furnace and the convection pass changed only modestly. In commercial applications, site-specific studies will determine the boiler performance, but based on this pilot-scale study, no heat transfer surface changes are anticipated. Air infiltration into the boiler under oxy-coal combustion conditions was reduced to the equivalent of 5% of the overall stoichiometry. Substitution of combustion air with oxygen and recycled flue gas increased the CO_2 concentration from 15% to 80% at the boiler exit. Boiler upgrades can further reduce the air infiltration and increase the flue gas CO_2 concentration. With oxy-coal combustion, the flue gas volume exiting the boiler is reduced by 70% relative to air-fired operation, downstream of the recycle take-off point, thus minimizing additional processing or treatment that may be necessary to prepare the CO_2-rich stream for permanent storage.

Technical and economic analysis

After the successful pilot development effort, the technical and economic barriers to the technology were evaluated to apply the technology to existing and new boiler applications.

Previously, extensive simulations and cost assessments were performed on the subcritical PC plant; here the scope was extended to assess the oxy-coal combustion technology with supercritical (SC) and ultra-supercritical (USC) steam cycles with more engineering and manufacturer's data input.

Below are some of these technical and economic results and items requiring further study.

Technical evaluation

Our joint development efforts have been performed with an eastern bituminous and a sub-bituminous coal, at the 1.5 MW_{th} (5 MBtu/hr) pilot, equipped with a wall-fired burner. To broadly commercialize the oxy-coal combustion technology, we need to widely expand the applicability of the technology to other boiler types and coal ranks, and demonstrate the technology at a larger scale.

Coal rank

Previous development efforts have been performed with an eastern bituminous coal and a sub-bituminous coal. Similar to normal air-blown combustion, the major differences in coal properties (e.g., heating value, ash and moisture content and ash elemental composition) affect the coal pulverization, flame stability, flyash unburned combustibles content, convection pass deposition and heat transfer. To expand the applicability of the technology, lignite testing and characterization need to be performed.

Combustion and boiler equipment

The development effort has been performed using a scale model of a B&W low-NO_x burner that was modified for oxygen firing. The oxy-coal combustion process needs to be adapted for application to Cyclone-equipped boilers and lignite fuel PC burners. Cyclones operate in a slagging mode that requires modifications of oxy-coal combustion technology before it can be used in these boilers. This technology provides a means for CO_2 control from existing Cyclone boilers. An added benefit of the oxy-coal combustion process, especially for Cyclone units, is that it provides reduced NO_x emissions from the boiler. Thermal NO_x is reduced since there is less molecular nitrogen in the oxidant stream. In addition, some of the NO_x in the recycled flue gas will be reduced to molecular nitrogen via reburning by hydrocarbon radicals in the flame. As a result, the high NO_x levels that have been characteristic of Cyclone boilers will be much lower when Cyclones are retrofitted with oxy-coal combustion. Oxy-coal combustion will be adaptable for applications to Cyclone boilers, but due to the unique Cyclone slagging mode of operation, the wall-fired experience will not be directly applicable.

Oxygen/recycled flue gas mixing and control, oxygen levels

Oxy-combustion provides a challenge of coordination of the combustion system and the air separation unit (ASU) equipment to the design engineers. In other words, it is not enough that both systems function; they need to be adaptable and work in harmony with each other. AL and B&W have completed an engineering study on a 22 MW_e PC boiler retrofitting the unit to oxy-coal technology.(16) During the progress of the project, many technical issues were identified and resolved that were never addressed in any paper or engineering study. Below are some of the items requiring special attention, generic to any PC boiler operation in oxy-coal combustion mode.

- The ASU should not be considered separately from a power plant while designing the oxy-coal power plant. The ASU has to be customized to the specific needs of this application for safety, reliability, and efficiency. In the course of the technology development, AL and B&W have come up with key insights on how to optimize an oxy-coal power plant.
- The ASU mode of operation when supplying oxygen to a power plant is different from other traditional applications. Those specifics need to be addressed during the ASU design phase.
- Boiler startup and transition between air combustion and oxy-coal combustion modes is critical with respect to safety and technicality. AL and B&W have developed this expertise during pilot scale tests and are applying the knowledge to 30 MW_{th} and 300 MW_e oxy-coal boilers.
- Mixing of oxygen with recycled flue gas should be addressed and carefully designed. AL has patented O_2 injectors and has extensive expertise in this area over many years.
- Interaction of the ASU with other parts of the power plant, other than the boiler, was identified as critical and needs to be addressed.

Near full-scale oxy-coal combustion pulverizer-burner performance

The challenge of retrofitting the oxy-coal combustion system to an existing coal-fired boiler is to simplify the oxy-coal combustion technology and to minimize the boiler heat transfer surface changes. Our research and development efforts have shown that by appropriately designing the process, the expensive pressure part modifications can nearly be avoided. Therefore, boiler modifications are limited to recycled flue gas duct, and oxygen introduction to the process, monitoring, and control. The application of oxy-combustion in a new boiler provides the designers with an opportunity to potentially reduce the size of the boiler and, therefore, reduce cost.

In the oxy-coal combustion process, oxygen is mixed with recycled flue gas to replace the normal combustion air at the pulverizer. This primary stream consists of CO_2, oxygen, and water vapor and its density is higher than the normal air. The pulverizer performance is affected by flue gas composition and may require more recycle gas than air to maintain acceptable performance, especially with low-rank coals. More development in this area is needed on the mill performance, which directly affects the burner design and operation.

Our research and development was conducted with a 1.5 MW_{th} (5 MBtu/hr) scale version of a commercial B&W low-NO_x burner. Although the burner performed satisfactorily in our pilot with a bituminous coal and a sub-bituminous coal, a near full-scale burner development is needed to reduce the risk of scale-up directly from a small burner, which will be explained below.

To address these technical barriers, B&W has initiated two projects:

- Under sponsorship of US-DOE, NETL (National Energy Technology Laboratory) award No. DE-FC26-06NT42747, a pilot-scale evaluation project has been initiated to address the effect of coal ranks and boiler types. This will be discussed in the section titled *Oxy-coal combustion for retrofitting coal-fired boilers*.
- Scale-up is being pursued in B&W's existing 30 MW_{th} pilot facility, which features a near-full scale commercial oxy-coal combustion burner fed directly by an on-line pulverizer. This will be explained in the section titled *CEDF oxy-coal combustion campaign*.

Economic evaluation

Oxy-coal combustion can be used for retrofit or new boiler applications. As a retrofit option for existing coal-fired boilers, engineering and economic evaluations have shown that oxy-coal combustion retrofits for carbon dioxide capture are technically more straightforward and less expensive than other technologies (amine scrubbing). For oxy-coal combustion to be considered as an original equipment manufacture (OEM) technology option for new supercritical boilers (SC), it has to be competitive with integrated gasification combined cycle (IGCC), amine scrubbing, and other alternative combustion systems such as circulating fluidized bed (CFB).

AL, B&W, and WorleyParsons, under sponsorship of the U.S. DOE, performed the following economic study.(14) Air Separation Unit (ASU) design, boiler design and its modifications, and CO_2 compression and purification train design were carried out with fine details along with the cost estimations. Analyses were done looking at cost of electricity (COE), net plant efficiency, and avoided cost of carbon dioxide.

Approach and assumptions

The gross power was adjusted to generate 550 MW_e net power output for all studied cases. The design and cost estimation of the oxy-coal and PC boilers was conducted by B&W in conjunction with AL, who provided the ASU and CO_2 compression system designs and WorleyParsons who performed overall balance of plant design and cost estimates. Major economic and financial assumptions are presented in Table 1.

The environmental approach for the study was to evaluate each case on the same regulatory design basis, considering differences in technology. Based on the EPA (Environmental Protection Agency) Green Book Non-attainment Area Map (http://www.epa.gov/oar/oaqps/greenbk/mapnpoll.html), relatively few areas in the Midwestern U.S. are classified as "non-attainment." Thus, for the design scenarios considered in this study, environmental control equipment is defined to meet presumptive BACT (Best Available Control Technology) emission rates shown in Table 2.

Steam conditions for the Rankine cycle cases were selected based on the NETL Advanced Materials for Supercritical Boilers program. The goals of the program dictated the steam conditions selected for the study:

- For supercritical (SC) cycle cases - 3500psig/1110F/1150F (242 bar abs/599C/621C)
- For ultra-supercritical (USC) cases - 4000psig/1350F/1400F (277 bar abs/732C/760C)

Cases studied

A summary of the different plant configurations considered in this study is presented in Table 3.

<u>CO_2 Specification A</u> - Flue gas composition exiting system with 95 mol% O_2 oxidant after drying to specified moisture

Table 1 Major Economic and Financial Assumptions

Capacity Factor	85%
Costs Year Constant US Dollars	2005 (January)
Illinois # 6 Delivered Cost	\$1.27/10^6 Btu (\$4.33 /MWh)
Design/Construction Period	4 years
Plant Startup Date	2015 – 2020*
Land Unit Cost	\$1,500 /acre
Project Book Life	20 years

* The ASU proposed in this study is designed and quoted using today's commercially available technology

Table 2 Presumptive BACT Values

Pollutant	Emission Limit	Control Technology
PM/PM_{10}	0.015 lb/10^6 Btu (0.023 Kg/MWh)	Fabric Filter or ESP (99.5 to 99.8% efficiency)
SO_x	0.1 lb/10^6 Btu (0.16 Kg/MWh)	FGD (98% reduction)
NO_x	0.07 lb/10^6 Btu (0.11 Kg/MWh)	LNB/OFA/SCR for air combustion, LNB/OFO for oxy-fuel
Hg	90% removal	Activated Carbon Injection

Table 3 Study Matrix				
Case	Steam Cycle	Oxidant	Product CO_2	Product Purity
1	SCPCRef	Air		
2	USCPC	Air		
3	SCPC-OC	95 mol% O_2	Spec. A	Saline Formation
4	SCPC-OC	95 mol% O_2	Spec. B	Saline Formation
5	SCPC-OC	95 mol% O_2	Purify to meet Spec. B	Saline Formation
6	SCPC-OC	95 mol% O_2	Spec. C	EOR
7	USCPC-OC	95 mol% O_2	Spec. A	Saline Formation
8	USCPC-OC	95 mol% O_2	Spec. C	EOR

content (Moisture<30 lb/10^6 cf CO_2). These oxy base cases provided good cost/benefit ratio.

CO_2 Specification B - Flue gas composition exiting system with 99 mol% O_2 oxidant after drying to specified moisture content (Moisture<30 lb/10^6 cf CO_2).

CO_2 Specification C – Flue gas purified to meet EOR spec: $CO_2 \geq 95\%$; $N_2 + O_2 < 5\%$; (Moisture<30 lb/10^6 cf CO_2).

The results of the air-fired SC and USC boilers compared with amine scrubbing and SC and USC oxy-coal combustion cases are presented below (Figure 2). Impact on efficiency shows 11% and 12% (absolute) efficiency decrease for SC and USC cases, respectively.

When comparing COE increase and CO_2 avoided cost for amine scrubbing and SC and USC oxy-coal combustion cases, oxy-coal combustion seems to be the lowest cost CO_2 capture technology (Figure 3).

The cost reduction potential for CO_2 capture oxy-coal combustion technology was evaluated. If the FGD is eliminated (for coals with <1% of sulfur), the COE increase can be reduced for the USC case from 44% to 36% which represents a CO_2 avoided cost reduction from \$30 to \$24 per metric ton.

The technical results are as follows:

• Conversion of air blown supercritical and ultra-supercritical designs to oxy-coal combustion to facilitate carbon dioxide capture and storage resulted in net plant efficiency (HHV) penalty of 11 and 12 percentage points, respectively.

• Presumptive BACT NO_x emission rates were met in all oxy-coal design cases without a post combustion NO_x control system (SCR).

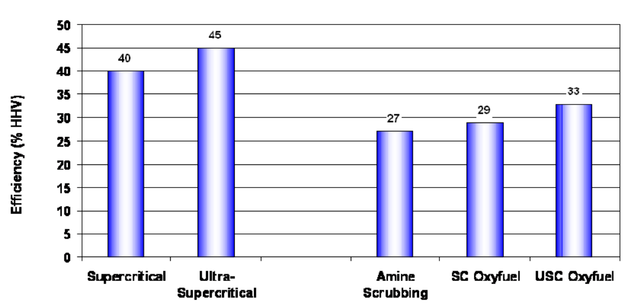

Fig. 2 Efficiency impact for different scenarios.(14)

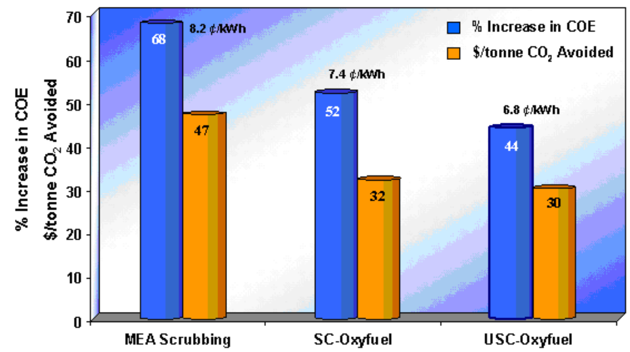

Fig. 3 COE and CO_2 avoided for amine scrubbing and oxy-coal combustion. [14]

• No air emissions were released in design cases modeled to meet CO_2 specification A (no specific CO_2 purity targeted), i.e. NO_x, SO_x and PM were removed in bulk with the CO_2.

• It was concluded that the utilization of 95% mole oxygen with compression and purification treatment is most economical as compared to 99% mole oxygen, for the same CO_2 specification (EOR).

NPV versus IRR

An additional analysis was done by B&W, and presented late last year, to evaluate the various capture alternatives from an investment standpoint, looking at net present value (NPV) and internal rate of return (IRR).[15] A total of eleven cases were evaluated. The NPVs are summarized here.

The goal that management sets, and the way that goal is measured, can make a difference in the operation of a power plant. Many comparisons of generating technologies use the "Cost of Electricity" (COE) as the best way to compare different generating technologies. B&W often works with the owners of the power plants, who are in the business of generating electricity. For these owners, "Cost of Electricity" is only part of their objective. Whether or not the power plant is subject to price regulation, the owners aim to recover their full costs, including the cost of capital. The owners also aim to make an economic profit, in addition to covering their costs. B&W's customers often judge the success of a power plant by whether it provides a positive Net Present Value (NPV) and whether the project's Internal Rate of Return (IRR) meets their goals for such a large capital investment.

For estimates of the price of electricity and the cost of fuels, the writers used recent studies from the U.S. Department of Energy, including the supplemental regional forecasts from the Energy Information Administration's *Annual Energy Outlook 2006*, to define the business environment in four representative regions of the country, to the year 2030.

The various technologies for carbon management are mixed in their rankings (far right column in dollars) on Net Present Value in Table 4 (rank column refers to IRR results). No one combustion technology appears to dominate the returns at this early stage of development, and gasification currently is the least attractive due to a higher capital cost and lower availability. Based on what is known now, it is

Table 4 Economic Comparison of Technologies Net Present Value (NPV) equity financed, 30-year service life			
Rank	Case	Description	$000s
1	1	Conventional Supercritical w/out Carbon Management	839,545
2	2	IGCC without Carbon Management	265,742
4	7	Ultra Supercritical with Oxy-Fuel (95% O_2)	227,674
3	11	Supercritical with CO_2 Scrubber AC	212,651
6	8	Ultra Supercritical with Oxy-Fuel (EOR quality)	175,609
7	4	Conventional Supercritical with Oxy-Fuel (95% O_2)	(12,594)
8	5	Conventional Supercritical with Oxy-Fuel (99% O_2)	(24,084)
9	6	Conventional Supercritical with Oxy-Fuel (EOR quality)	(24,795)
10	10	Supercritical with CO_2 Scrubber KS-1	(27,789)
5	3	IGCC with Carbon Management (Achieved Availability)	(124,697)
11	9	Supercritical with CO_2 Scrubber MEA	(595,524)

appropriate to invest in research and development for a range of technologies for carbon management of coal.

If a power company were to invest in a new plant with expensive carbon management, while none of the other power companies did, then the low-carbon investor would also have a higher price of electricity for sale to the grid. As a result, that low-carbon plant would be dispatched less often. Power companies are not as likely to invest in carbon management technologies until there is assurance that competing power companies will also invest in carbon management technologies, or until incentives encourage it. However, some power companies are pursuing programs, which include carbon management. A few are well located, to provide carbon dioxide for enhanced oil recovery (EOR). Others intend to master the technology of carbon management, in preparation for the time when that may be a key competitive competence.

Oxygen production and CO_2 treatment

The following section describes key elements of the overall oxy-coal combustion feasibility and competitiveness. They relate to O_2 production and CO_2 treatment developed and provided by AL and resulting from its historical technology focus on applications developed for more than a century.

Oxygen Production

Technology

For the quantities required by oxy-coal combustion in a commercial scale plant (several thousand metric tons of oxygen), the only available technology today is cryogenic distillation. Other available technologies for air separation like pressure swing adsorption (PSA), vacuum swing adsorption (VSA) or polymeric membranes cannot compete economically for such quantities and also in terms of achievable oxygen purity (above 95%). Ceramic membranes (oxygen ion transport membranes) are not yet available for such quantities and therefore it is still hard to compare them to cryogenic distillation both in terms of investment and performance.

Specification for oxy-coal combustion

The main characteristics of the ASU for oxy-coal combustion are: large size (typically beyond 8000 tpd for industrial-scale plants), low pressure (between 1.3 and 1.7 bar abs) and possible low oxygen purity. Low oxygen purity means a value in the range of 95-98% O_2 content compared to the typical 99.5-99.6% O_2 content of the high purity content normalized to 100 in energy scale. This allows significant savings in power consumption in the ASU as shown in Figure 4.

The key parameter in the optimization of an ASU is the trade-off between capital expenses (CAPEX) and operation expenses (OPEX). In other words, the question is: how much am I ready to invest (CAPEX) in order to save power consumption (OPEX) for the ASU? This depends primarily on the cost of power. Figure 5 illustrates the flexibility in the design of an ASU in terms of trade-off CAPEX vs OPEX. This typical curve shows that by increasing by 25%

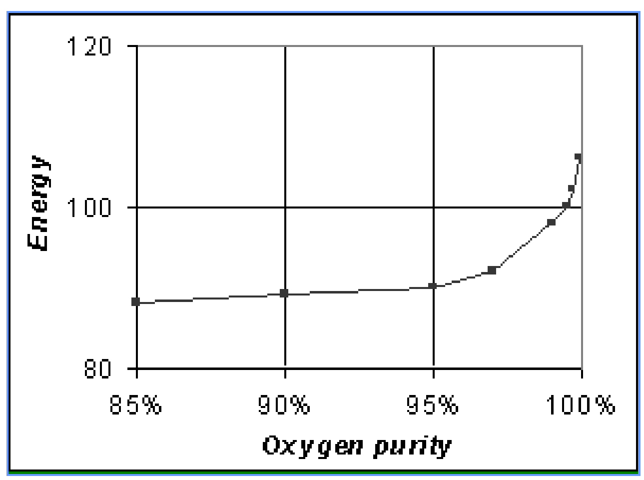

Fig. 4 Air separation unit (ASU) power requirement.

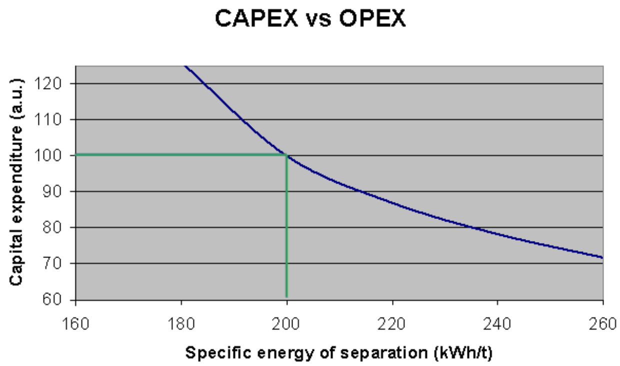

Fig. 5 Trade-off of CAPEX and OPEX in ASU design.

the capital expenditure, it could be possible to decrease by 10% the power consumption of the ASU (for example from a specific energy of separation of 200 kWh/metric ton) or to decrease the capital expenditure by 15% by increasing the power consumption by 10%.

Process scheme

An ASU consists of the following equipment:

- air compressor
- precooling system
- purification unit to remove water and CO_2 prior to entering the cryogenic section
- heat exchangers
- distillation column

Up to 5000 metric tons/day, AL proposes a process scheme with a double column dual vaporizer scheme with no duplication of equipment: one purification unit for water and CO_2 removal with its proprietary radial bed design, one high pressure (HP) column and one low pressure (LP) column.

CO_2 compression and purification unit (CPU)

Technology

For oxy-coal combustion plants, the best solution to purify the flue gas coming from the boiler is a low temperature (around -56C) partial condensation scheme as soon as O_2 removal is considered.

Specification for oxy-coal combustion

The CO_2 specification is one of the main topics to be addressed in order to design the CO_2 CPU. It depends on the application: enhanced oil recovery (EOR), saline aquifer, or enhanced coal bed methane (ECBM). However, other considerations such as transport specifications and regulations may have an impact on the CO_2 specification.

Process scheme

Low pressure flue gas from the boiler is compressed to a typical pressure of 30 bar abs, precooled and dried. It then enters a "cryogenic" section where it will be partially condensed in one or several steps to obtain a product enriched in CO_2 and a non-condensable stream containing N_2, Ar and O_2. A distillation column can be added to have a product with a lower O_2 content. The product enriched in CO_2 is further compressed, condensed and pumped to a supercritical pressure (typically between 100 and 200 bar abs).

Oyx-coal combustion for retrofitting coal-fired boilers

After determining the technical and economic barriers of the oxy-combustion technology, the following two projects were initiated: 1) significantly broaden the scope of the technology to different coal ranks and boiler types, and 2) scale-up the technology. The former is discussed below and the latter will be discussed in the section titled *CEDF oxy-coal combustion campaign*.

Under sponsorship of the U.S. DOE, B&W and AL will further develop the oxy-coal combustion technology for commercial retrofits in wall-fired and Cyclone boilers. As it was explained before, previous development efforts have been performed with an eastern bituminous coal and a sub-bituminous coal. This project expands the applicability of the technology to lignite firing; in addition, oxy-coal combustion will be adapted in this program for application to Cyclone-equipped boilers.

Upon successful completion of this development effort, pilot-scale oxy-coal combustion test data will be available for application and scale-up to both wall-fired and Cyclone boilers that burn bituminous, sub-bituminous or lignite coal. This project significantly broadens applicability of oxy-coal combustion technology to the existing fleet of coal-fired boilers. Our approach to expand the applicability of the technology is:

- To perform pilot-scale R&D, both wall-firing and Cyclone
- To develop specifications for storage, transportation, and compression train, and to minimize the equipment required for emissions control, CO_2 capture, and storage
- To further reduce the increase in cost of electricity through system integration
- To perform an engineering and economic evaluation for a wall-fired and a Cyclone boiler to assess the impact of oxy-coal combustion on electric generation cost

The tests will be conducted in a new 1.8 MW_{th} facility. The Small Boiler Simulator (SBS-II), illustrated in Figures 6 and 7, is a combustion and fuel handling facility that allows B&W to evaluate various fossil fuels, combustion processes, emission control devices, and associated hardware for potential commercial use. The 1.8 MW_{th} (6 MBtu/hr) vertical furnace of the SBS simulates the geometry of front-wall fired commercial boilers. With waterwall construction and insulation, it yields gas temperatures and residence times representative of commercial units.

The unit will be fired by a scale model of B&W's commercial low-NOx burner (DRB-4Z®). This allows B&W to examine flame shape and stability, flame temperature, and staged combustion with low-NO_x burners and overfire oxidant (OFO) to ensure the pilot facility is operating similar to commercial coal-fired boilers. Pulverized coal is prepared offline to the same fineness as commercial boilers (usually 70 %< 200

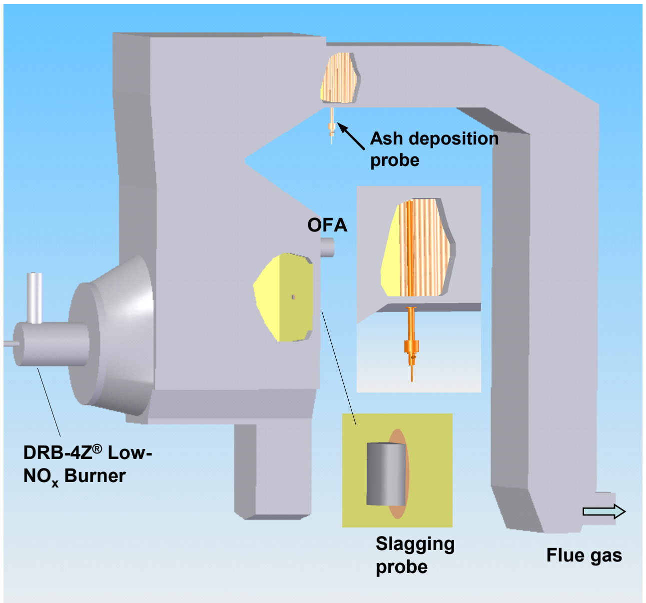

Fig. 6 B&W 1.8 MW_{th} small boiler simulator (SBS) II.

mesh) and transported by a weigh belt feeder for indirect firing applications. The convection pass design produces a flue gas time/temperature history that is representative of commercial boilers. The facility is equipped with a baghouse, dry or wet scrubber, and a condensing heat exchanger.

The facility is currently under construction at the newly relocated Babcock & Wilcox Research Center (BWRC) located at the B&W main campus. AL will relocate their 9,000-gallon (34,000 liters) liquid oxygen tank and its oxygen control skids to the new location. The facility is expected to be in operation in October 2007.

CEDF oxy-coal combustion campaign

As discussed earlier, scale-up of the oxy-combustion burner was one of the technical barriers that will be discussed here. The largest test facility in the world that has operated under oxy-coal combustion conditions with pulverized coal to date is B&W's 5 MBtu/h (1.5 MW_{th}) facility in Alliance,

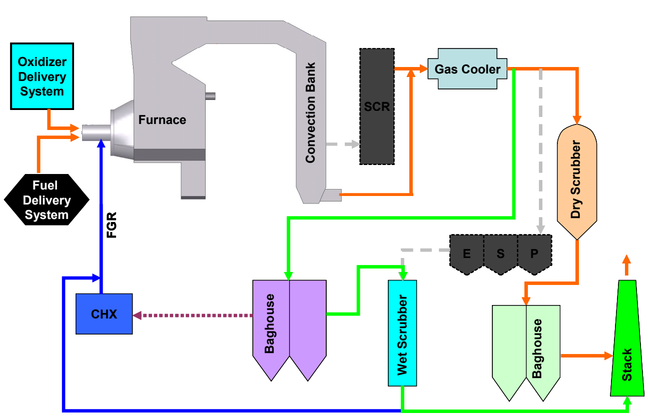

Fig. 7 SBS-II general layout.

Ohio, U.S.A. Others are proposing test facilities including the 30 MW_{th} Vattenfall project in Germany and the 30 MW_e Callide project in Australia. With the need to support design of commercial scale projects, B&W and AL decided in late 2006 to convert B&W's existing 30 MW_{th} Clean Environment Development Facility (CEDF) in Alliance, Ohio to an oxy-coal combustion system.

The objective of this project is to demonstrate oxy-coal combustion technology at 30 MW_{th}. The project will demonstrate the following main elements:

- Near-full-scale burner fed directly by an on-line pulverizer
- Pulverizer performance is affected by flue gas composition
- Pulverizer may require more recycle gas than air to maintain acceptable performance especially with low-rank coals
- New burner designs to be evaluated for various coals
- Three coals will be tested: lignite, sub-bituminous, and eastern bituminous
- Will demonstrate B&W's novel concept for controlling flue gas moisture content via a wet scrubber with integrated cooling
- Support the commercial project development that will be explained below

A test campaign will be conducted in summer 2007.

Developing a 300 MW_e commercial oxy-coal boiler

During the next 20 to 30 years, Saskatchewan Power Corporation Inc. (SaskPower), Saskatchewan, Canada, will be making major decisions concerning the refurbishment or replacement of virtually its entire fleet. Saskatchewan's 300 year supply of mineable lignite coal remains the most cost-efficient and stable-priced fuel for base load generation but there are environmental concerns.

For several years, SaskPower has been involved in evaluation of technologies for carbon dioxide management in coal-fired power plants. Recently they announced a Clean Coal Project development that will capture over 90% of the carbon dioxide produced from coal combustion. This project would result in a power plant that not only produces 300 net megawatts (MW_e) of electricity but also will capture 8,000 tons of CO_2 per day to extract more oil from Saskatchewan oil fields through enhanced oil recovery (EOR). Additional emissions-control technologies will also be incorporated, bringing the Clean Coal Project to near zero emission plant (NZEP) status.

After evaluation of the technology options and selection of oxy-coal, SaskPower, Babcock & Wilcox Canada (B&W) and AL came to an agreement in late 2006 to jointly develop oxy-coal technology as the core process for the unit to be located at the Shand facility near Estevan, SK, Canada. Figure 8 shows an artist's rendering of the future oxy-coal combustion plant at Shand. Marubeni Canada and Hitachi will supply the turbine generator set. The oxy-coal technology nearly eliminates emissions of combustion byproducts, including greenhouse gas emissions, and may be the world's first near

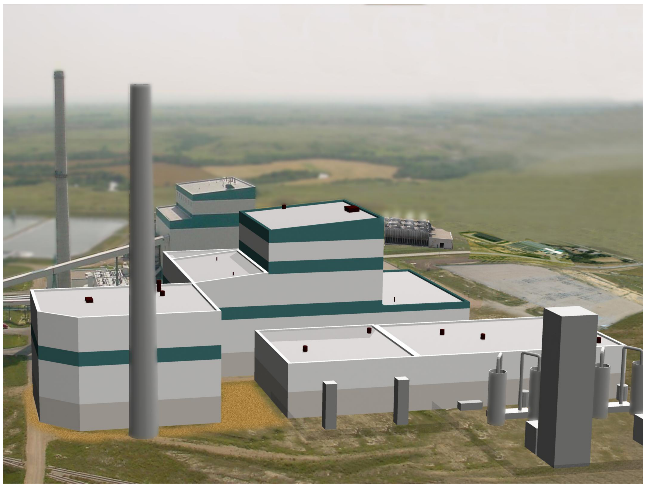

Fig. 8 Artistic rendering of oxy-combustion plant at Shand.

zero emissions (NZEP) pulverized coal unit.

In deciding on oxy-coal, SaskPower thoroughly examined and researched both oxy-coal and the post-combustion clean-up processes. Based on the current state of both technologies and project-specific parameters, they selected oxy-coal and expect it to provide the best environmental performance and lowest cost.

In 2006 SaskPower, B&W, and AL came to an agreement to develop the plant with B&W supplying a system based on a supercritical boiler and AL providing the air separation plant and CO_2 compression system. Significant design work and costing is underway to assess whether SaskPower should proceed to the construction phase. That decision is expected in mid-2007 to support an in-service date in 2011.

When successful, this power plant will be the first of its kind in a utility scale application. In support of this effort, B&W has also decided to convert its existing 30 MW_{th} Clean Environment Development Facility (CEDF) located in Alliance, Ohio for oxy-coal testing in summer 2007.

Summary

The ability to capture CO_2 from power plants is feasible in advanced modes of current technology and with new technologies under development with significant industry-driven R&D underway. Technologies are not decades away, but are some number of years away and can support a regulatory process that meets carbon management objectives.

As an industry, we have been and will continue to work hard to absorb and analyze the impact of GHG stabilization policy on the power generating industry and deliver timely, effective and economic solutions.

B&W has been designing and supplying steam generating systems for electric power generation for more than 140 years. B&W continues to advance the technology in ultra-supercritical boiler applications and advanced environmental emission controls meeting the requirements of today and into the future.

Over the previous few decades, B&W has developed many new environmental control technologies and helped the power generation industry to significantly reduce its NO_x, SO_2 and particulate matter from coal-fired boilers. Our current R&D efforts on oxy-combustion as well as other post-combustion technologies are enabling us to provide utility boiler operators a solution when CO_2 emissions are regulated. B&W is confident that with our new development efforts, PC boilers will operate in an environmentally friendly manner in a carbon constrained world.

Further, economic evaluation carried out by AL, B&W and the DOE indicates that oxy-combustion is an economically viable technology for retrofitting existing boilers as well as new pulverized coal boilers. Supercritical boilers have proven reliability and show a promise of much higher efficiency when they are used in ultra-supercritical steam cycle conditions. B&W believes that the combination of proven reliability, higher efficiency and ultra low emission of NO_x, SO_2 and particulate matter provide us with a base technology that we should pursue for carbon capture (along with other newer technologies).

Oxy-combustion technology requires introducing some new equipment such as the ASU and the CO_2 CPU to power plants. AL has designed the largest ASU which is operated at a capacity of 4000 tons/day of oxygen and is currently offering plants of capacities around 5000 metric tons/day. A single industrial site exists with cumulative oxygen production of approximately 40,000 metric tons/day. Studies have also been performed for an air separation unit of 7000 metric tons/day.

Further, AL has more than 50 years of experience in the purification and liquefaction of CO_2. AL operates 67 plants worldwide. However, a commercial scale plant (more than 10,000 t/d of CO_2) for oxy-coal combustion is much larger than any of the existing liquefaction plants. Nevertheless, technologies to be used in this CO_2 compression and purification unit (CO_2 CPU) are very close to those used in an ASU: centrifugal compressors, dryers, heat exchangers and distillation columns. AL has just completed the basic design of a 10,000 t/d CO_2 CPU.

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Key Acronyms

LNB	Low NOx Burner	FGD	Flue Gas Desulfurization
OFO	Overfire Oxygen	PC	Pulverized Coal
OFA	Overfire Air	EOR	Enhanced Oil Recovery
FGR	Flue Gas Recirculation	ASU	Air Separation Unit
SCR	Selective Catalytic Reduction	ESP	Electrostatic Precipitator