Technical Paper

Oxy-Combustion in Pulverized Coal Power Plants for Carbon Dioxide Concentration

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The case favoring the use of coal as the primary fuel for power generation in the U.S. is overwhelming. Coal is the most abundant domestic fuel and it remains the lowest cost fuel for power generation. A direct relationship has also been shown between electricity cost and the Gross Domestic Product per capita. Current margins between electricity production and demand are at their lowest levels and significant economic growth is projected resulting in a steady increase in the use of coal. Though the severity of the impact of carbon dioxide (CO_2) on global warming remains under debate, coal is the most carbon intensive fuel, making an economical means of carbon management essential to ensure coal's continued use.

Several options for concentrating and disposing of or utilizing carbon dioxide are under investigation by The Babcock & Wilcox Company (B&W) and many others in the power generation industry. Currently, the three front running approaches are scrubbing CO_2 from the flue gas of pulverized coal (PC) fired boilers before discharging the remaining constituents up the stack using an amine or other solvent, employing oxygen combustion with PC boilers to concentrate the CO_2, and integrated gasification combined cycle (IGCC) employing a water-shift reactor and hydrogen-fired gas turbine. None are inexpensive and all three significantly degrade net plant efficiency. The options with PC boilers offer the ability to address the existing fleet through retrofit applications while the IGCC option requires a greenfield site.

This paper briefly discusses the current economics and efficiency of the three options as well as their key advantages and disadvantages, then focuses on oxygen combustion. It describes the oxygen combustion process and B&W's efforts to move forward with its commercial application.

Introduction

Over 310 GW, or over half of the electricity generated in the United States today, results from coal combustion. This represents almost 33% of the U.S. anthropogenic carbon dioxide emissions. Current concerns about global climate change are expected to lead to carbon emission controls in the U.S. in the very near future. Though it is recognized by many that these controls will have insufficient impact on global emissions unless developing nations such as China and India implement controls as well, the developed nations are expected to lead in development of the necessary technologies. Based on the power generation industry's successful and economical response to sulfur dioxide, oxides of nitrogen, particulates and more recently mercury emissions from pulverized coal, it is highly likely an appropriate solution for carbon dioxide will be developed and many original equipment suppliers, including B&W and Air Liquide (AL), are working diligently to do so.

In the U.S., nuclear fuel, natural gas, and coal are the only indigenous resources in sufficient abundance to supply major portions of the domestic electrical demand. Natural gas price volatility and limited supply force it to be used for higher value needs making it unattractive for expanded electricity generation. Imported liquified natural gas (LNG) does not strengthen our national energy security and recent forecasts indicate it will not be available in large enough quantities to address domestic electricity needs. Nuclear will undoubtedly be further deployed in the years to come but projections continue to show coal as the primary resource for power generation for several decades; most recent new generation plants have been pulverized coal combustion based. According to the Energy Information Administration's International Energy Outlook 2006, an additional 147 GW of new coal-fired capacity is expected to be added over the next two decades.

A direct connection between the cost of electricity and the Gross National Product has been shown and significant costs and efficiency reductions have been projected for all carbon emission control technologies. To truly impact carbon emissions while preserving national energy security and our economic standard, it is imperative that practical and economical ways to deal with the carbon emissions from coal combustion be developed and implemented. In addition, sequestration strategies and accepted uses beyond enhanced oil recovery (EOR) are urgently needed.

The Babcock & Wilcox Company is deeply engaged in both post-combustion and oxy-coal combustion (OCC) development. For ten years B&W has been actively collaborating with Air Liquide to develop OCC. Prior work with AL has included testing of both bituminous and subbituminous coals at 1.5 MW_{th} scale in B&W's Small Boiler Simulator, participation in several commercial plant evaluations and cost studies, membership in CANMET, development of a detailed design and costs to retrofit the City of Hamilton 25 MW_e facility as a demonstration in Ohio, U.S., our current effort to convert B&W's Clean Environment Development Facility (CEDF) to full oxygen combustion capability (without CO_2 compression and sequestration), and a commercial opportunity to build a 300 MW_e net OCC plant in Canada that provides CO_2 for EOR. This paper will describe B&W and AL's OCC technology, the status and plans for conversion of the CEDF and the potential commercial 300 MW_e project.

Technology choices

To address pending legislation to control carbon emissions there are currently three technologies that are viable: Integrated Gasification Combined Cycle (IGCC), flue gas scrubbing with an Amine such as monoethanolamine, and OCC. All three current and viable means of managing CO_2 emissions produce a concentrated stream of CO_2 for compression and transportation to a point of use or sequestration (disposal).

Of the three, amine scrubbing is technologically the most mature but requires significant scale-up. Between IGCC and OCC, neither have been built or operated in a mode that manages CO_2. All three add significant capital cost to the plant in addition to a 20 to 30% reduction in net plant efficiency due to parasitic power or low grade steam requirements. OCC uses already commercially available equipment and requires no equipment scale-up or proof of any of the contributing technologies except oxygen mixing, control of the flue gas flow–oxygen mixture (similar to air flow which is already controlled), and the combustion and heat transfer performance with the different flue gas composition. IGCC requires major scale-up of the water-shift reactor and hydrogen burning gas turbine as well as proof of reliability of the gasification island. Therefore, B&W and AL believe OCC could be more readily deployable than IGCC for CO_2 capture and storage.

Cost studies have been made by several organizations. In 2001 the Canadian Clean Power Coalition (Fluor) with assistance from B&W for OCC compared all thee and concluded IGCC was lowest cost and highest efficiency, OCC second, and amine scrubbing last. In 2005 a study by DOE (Parsons) [1] with OCC information provided by B&W and AL showed OCC to have lower cost and higher efficiency (Figure 1) compared to amine scrubbing. In 2006 the Electric Power Research Institute (EPRI) performed a study for CPS Energy[2] using PRB coal and concluded the same. Also in 2006, SaskPower (Neill & Gunter) did what is believed to be

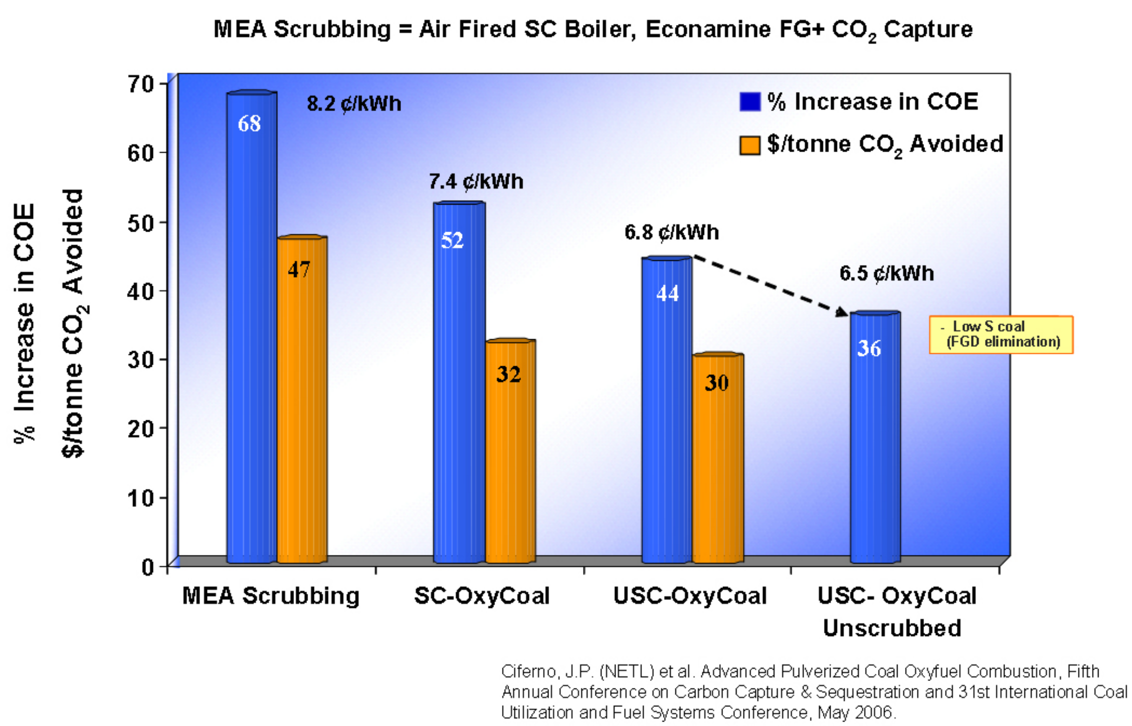

Fig. 1 Comparison of oxy-coal vs. amine scrubbing costs.

the most thorough study comparing B&W/AL's OCC design with amine scrubbing (they excluded IGCC) and selected oxy-combustion for their next plant (pending confirmation of costs). Several other studies in Europe and Japan have produced similar conclusions that OCC is likely to be as efficient and low cost as IGCC and post-combustion methods are currently less favorable, though significant development is in progress in that arena.

What is oxy-coal combustion?

OCC is a means of replacing the nitrogen in air with flue gas, which is predominately CO_2, in order to significantly increase the CO_2 concentration and facilitate its disposal. Typical flue gas from coal combustion contains about 13% CO_2 by volume making it difficult and costly to remove by post-combustion scrubbing methods. By concentrating it in the flue gas stream, it is more easily utilized or disposed.

In the current first generation form (Figure 2), which presents the least risk, the coal plant is started up using air in the same manner as is currently used and employs a 'synthetic air' approach to mixing oxygen with recycled flue gas. Once at a minimum stable load, the exit stream is controlled to force the flue gases to be recycled to replace the air and the air inlet is gradually closed. Nearly pure oxygen is introduced into the recycled flue gas to maintain safe and optimal combustion conditions in the boiler. Additional oxygen may be introduced at each burner or elsewhere to further enhance combustion and reduce NO_x. Once the air intake is fully closed and the boiler is operating on recycled flue gas and oxygen, load can be raised.

As the process proceeds, the lack of nitrogen as a diluent naturally concentrates the CO_2 and other constituents by a factor of about 3.5 times compared to air firing. The coal analysis, oxygen purity, air-in leakage, and combustion efficiency will determine the degree of CO_2 concentration that can be achieved in the flue gas, typically about 80% on a mass basis. In addition to increasing the concentration of CO_2, the concentrations of all other constituents are similarly increased. This means that unless removed in the process, even low sulfur and low moisture coals will produce significantly higher concentrations in the flue gas potentially adversely effecting corrosion and combustion. Since only coal and oxygen are added to the process, the flue gas flow extracted from the process for final cleaning and compression prior to disposal is relatively small, about 25% of the flow to the stack for an air-fired unit of the same steaming capacity.

The air quality control system (AQCS) for an OCC unit can be designed to treat all of the flue gas leaving the boiler or just the gas that is to be sequestered. The concentration of NO_x, particulate, Hg, H_2O, SO_3, SO_2, and O_2 resulting from combustion of the specific coal; the emission limits; concerns for combustion, corrosion, erosion; and the cost of further gas cleaning in the compression stage required to meet the limits for the end use of the CO_2 dictate the best arrangement.

Although the properties of the flue gas differ from those with air firing due to the lack of nitrogen, it has been found that with the proper recycle ratio, an existing boiler can be converted to OCC without changing heat transfer surfaces and only experiencing a small impact on fuel efficiency in the boiler island. For new units, optimized arrangements are

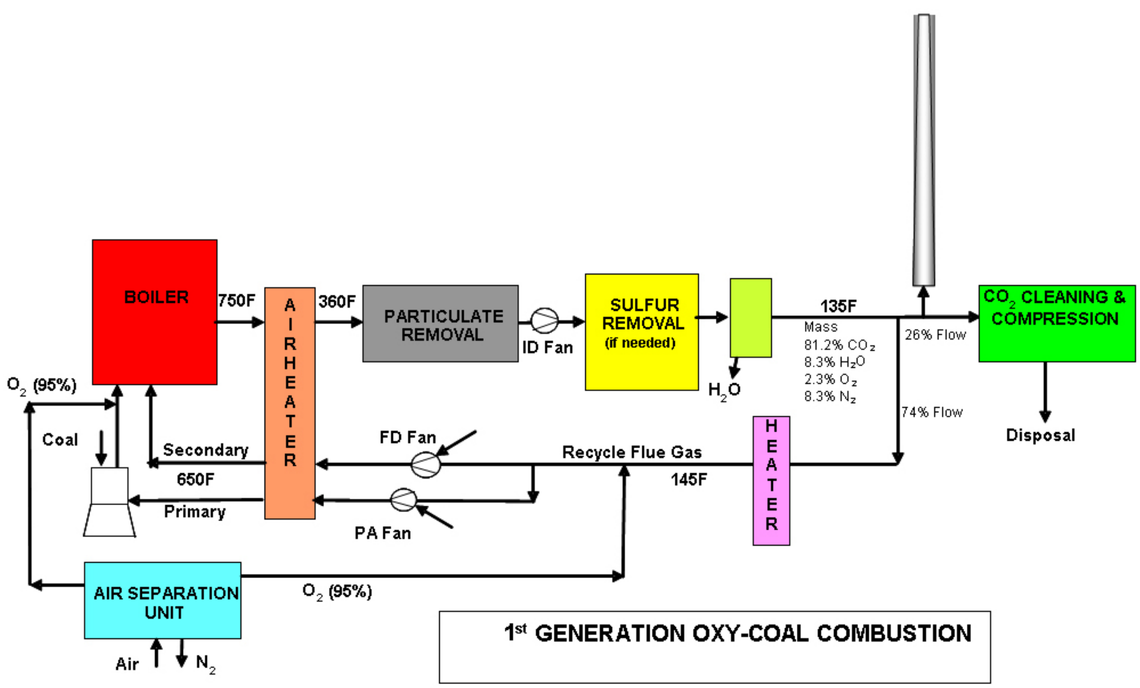

Fig. 2 Typical oxy-coal combustion process.

being studied that offer some reduction in equipment size and improved performance.

The first generation of full-scale units is intended to require as little change to the conventional power plant as reasonable to allow retrofit application and minimize risk for initial greenfield units. Evolution of the technology to eliminate or reduce the size of equipment in the gas path while providing the desired steam generation is being developed. Some of the features under consideration are higher steam temperatures, reduction in recycle flow to reduce boiler and gas path equipment sizes, simpler and more economical means of partial removal of constituents, air heater options, and oxygen introduction optimization and simplification. Improved air separation technologies and optimization of the product gas specification and the cleanup/compression process are also expected to improve both performance and cost.

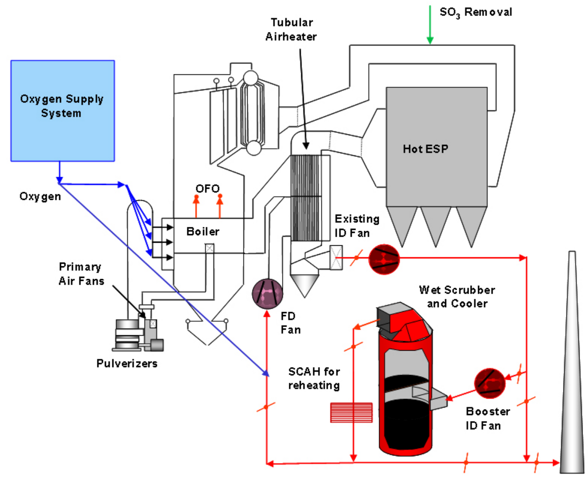

Fig. 3 City of Hamilton retrofit.

Prior work by B&W and AL

Historically, oxy-coal combustion has been reported by Santos[3] and the concept was first proposed by Abraham in publicly available literature.[4] The process was then investigated by Argonne National Laboratory (ANL) through a series of techno-economic, pilot-scale and demonstration plant studies.[5,6,7,8,9] Oxy-coal combustion for enhanced oil recovery was first evaluated by B&W in 1979 at the request of a major oil company. 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). [5,11,12] In the late 1990s B&W became a member of the CANMET's oxy-coal combustion consortium and participated in 1 MBtu/hr testing in Canada. During that time B&W began developing OCC technical expertise and participated in early techno-economic studies. AL has also performed extensive R&D leading to several key patents and has been collaborating with B&W in North America for the past decade. B&W and AL collaborative work on OCC combustion began in the late 1990s. Funded in part by the U.S. Department of Energy (DOE), pilot-scale development at B&W's 1.5 MW_{th} Small Boiler Simulator began in 2000 in collaboration with AL [12,13,14,15] with encouraging results burning eastern bituminous and subbituminous coals.

Several techno-economic studies were also undertaken including a study by B&W for the Canadian Clean Power Coalition in 2001, a similar study by Air Liquide and B&W with Worley-Parsons for DOE in 2005-2006,[1] and an evaluation by B&W of various capture alternatives from an investment perspective.[16] Partially funded by a DOE contract and primarily funded by B&W and AL, a detailed design and cost estimate to retrofit the 25 MW_e Stirling Power Boiler at the City of Hamilton, Ohio, plant was undertaken in 2005 (Figure 3). In 2006, proposals were submitted to several funding sources to proceed into the installation and testing phase but were not successful. Also in 2006, additional testing sponsored by DOE for both pulverized coal and cyclone firing to be conducted in B&W's new 1.8 MW_{th} Small Boiler Simulator II (Figure 4) was proposed and selected for funding by DOE. Meanwhile B&W was approached by SaskPower requesting evaluation of OCC for a new plant they are planning to build in Saskatchewan, Canada.

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. Conversion is in progress with testing currently scheduled to begin in June 2007.

Why is SaskPower interested in OCC?

In 2001 SaskPower participated in the Canadian Clean Power Coalition (CCPC) which B&W assisted in a study of IGCC, amine scrubbing and OCC. During that study B&W made some contacts in SaskPower and had opportunity to discuss and promote the potential of OCC.

Prior to 2004 SaskPower had decided they need to add 300 MW_e of electrical capacity to their provincial system to meet future needs (Figure 5). Since they are a government utility, and because Canada has signed the Kyoto Accord, there are financial incentives in place in Canada for projects addressing greenhouse gases. SaskPower is also interested in doing something in regard to CO_2 use. Fortunately, there is a significant local use for CO_2 for enhanced oil recovery (EOR) in the Weyburn oil field. When considering technologies for producing concentrated CO_2 for EOR, SaskPower decided they wanted a technology that was PC based (not IGCC) so they began looking at amine scrubbing and OCC and they came to B&W/AL for the latter.

Considerable investigations have been done in regard to use of CO_2 for this purpose and Encana is already purchasing CO_2 as a byproduct from the Dakota Gasification Company's synthetic natural gas plant in Beulah, North Dakota. That product is being piped 320 km to the oil field.

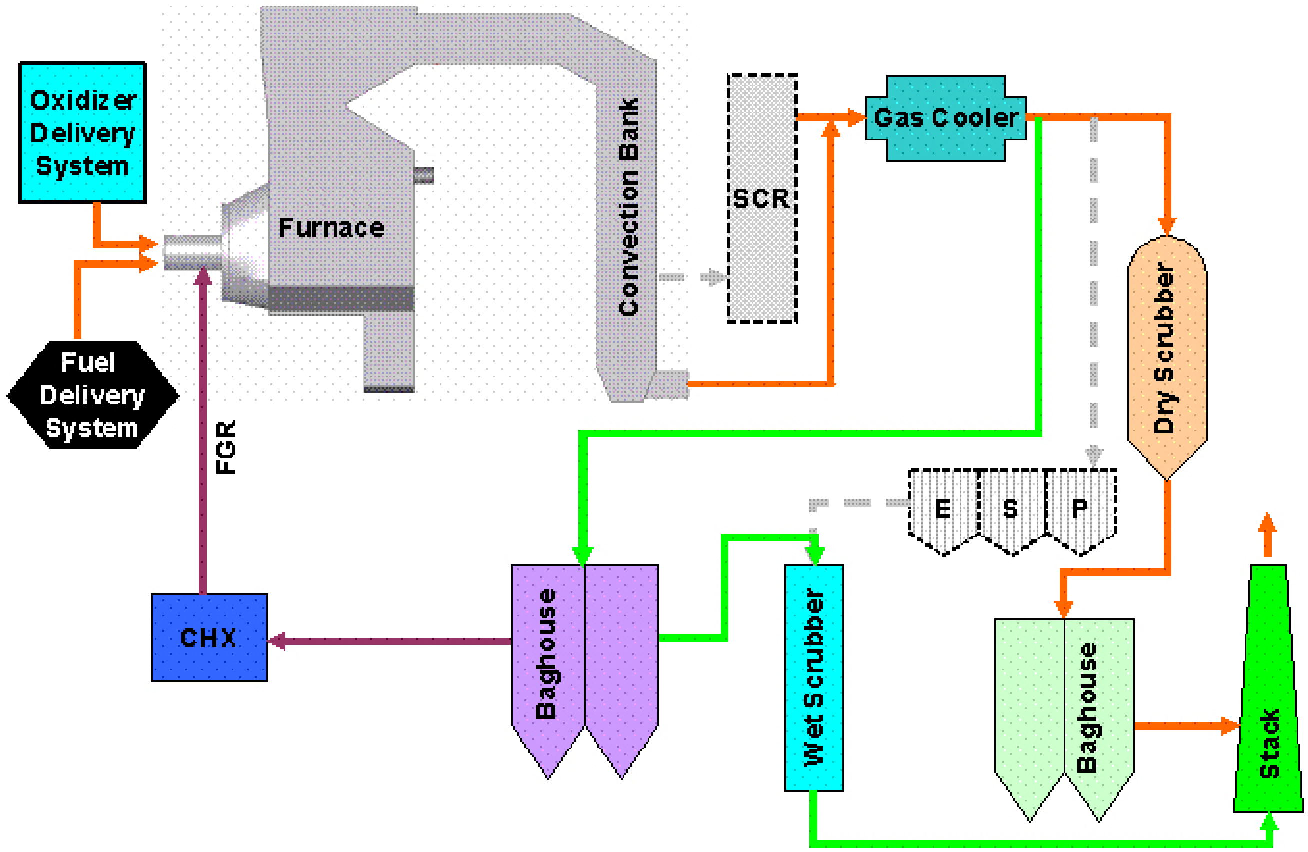

Fig. 4 B&W 1.8 MW_{th} Small Boiler Simulator II.

In late 2004, B&W was approached to consider design of a 66 MW_e demonstration at their Boundary Dam site followed by a decision for their new coal plant. After exploration of a study for Boundary Dam including an engineering estimate and meetings with SaskPower and their engineering contractor Neill & Gunter to discuss fuel and options, SaskPower decided in early 2006 not to proceed with the demonstration but to develop a commercial plant. Based on their financial analysis, the plant could be viable based on the value of 300 MW_e net of electricity and sale of the CO_2 for EOR.

SaskPower initiated a pre-feasibility engineering and cost estimating program in the late spring of 2006 with B&W and AL assisting. In parallel, SaskPower also developed a plant employing amine scrubbing for CO_2 concentration with another technology supplier. These studies were completed in August 2006 and in late September 2006 SaskPower announced selection of B&W/AL's OCC design. Upon selection B&W generated a firm proposal which was submitted in mid March 2007.

SaskPower Project

During the next 20 to 30 years, SaskPower will be making major decisions concerning the refurbishment or replacement of virtually its entire power generation 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 $1.5 billion Cn, Clean Coal Project to that will capture over 90% of the carbon dioxide produced from coal combustion. This Project will result in a power plant that not only produce 300 net megawatts (MW) of electricity but will capture about 8,000 tonnes of CO_2 a day to be used to extract millions of new barrels of oil from Saskatchewan oilfields through enhanced oil recovery. Additional emissions-control technologies will also be incorporated, bringing the Clean Coal Project to near zero emission status.

After evaluation of the technology options and selection of OCC, SaskPower, Babcock & Wilcox Canada (B&W) and Air Liquide came to an agreement in late 2006 to jointly develop OCC technology as the core process for the unit to be located at their Shand facility near Estevan (Figure 6). Marubeni Canada and Hitachi will supply the turbine generator set. The OCC technology nearly eliminates emissions of combustion byproducts, including greenhouse gas emissions and may be the world's first near zero emissions pulverized coal unit.

In deciding on OCC, SaskPower thoroughly examined and researched both OCC and the post-combustion clean-up processes. Based on the current state of both technologies,

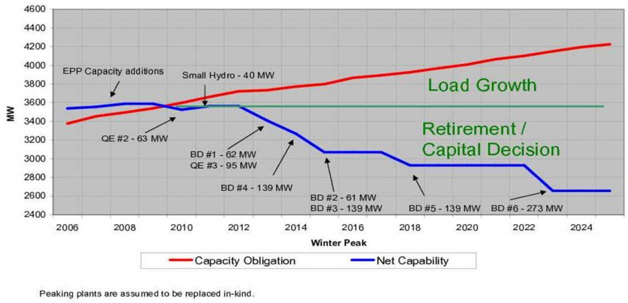

Fig. 5 SaskPower capacity plan.

and project-specific parameters, they selected OCC and expect it to provide the best environmental performance and lowest cost.

In 2006 SaskPower, B&W, and Air Liquide came to an agreement to develop the plant with B&W supplying a system based on a supercritical boiler and Air Liquide providing the air separation plant and CO_2 Compression and Purification Unit (CPU). Significant design work and costing are 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 our existing 30 MW_{th} Clean Environment Development Facility (CEDF) located in Alliance, Ohio, for OCC testing in early summer 2007.

CEDF conversion to OCC

The largest test facility in the world that has operated under OCC conditions with pulverized coal to date is B&W's 5 MBtu/h (1.5 MW_{th}) Small Boiler Simulator currently being relocated from Alliance to Barberton, Ohio. Others are proposing test facilities including the 30 MW_{th} Vattenfall project in Germany and the 30 MW_e Callide project in Australia. Since B&W and Air Liquide's demonstration at the City of Hamilton was not funded and with the need to support design of the SaskPower project, a decision was made in late 2006 to convert B&W's existing 30 MW_{th} Clean Environment Development Facility (CEDF) in Alliance, Ohio, to an OCC system.

The CEDF was built with funding from B&W, the U.S. DOE and the Ohio Coal Development Office and was started up in 1993 (Figure 7). It was initially designed as a combustion facility with provisions for performing emissions control and air toxics testing. As such, the furnace and convection pass were designed to provide a time-temperature characteristic equivalent to a large utility boiler. It also included an EL-56 pulverizer for coal preparation and an indirect coal feed system, full flow dry scrubber, fabric filter, and electrostatic precipitator (ESP). Over the years it has been used in support of the U.S. DOE's Combustion 2000 program, the "Advanced Emissions Control Development Program" as well as early air toxic and mercury testing, and has produced excellent data in support of three generations of pulverized coal burners and variations for specific applications. In 2005, in cooperation with Air Liquide, it was also used to test oxygen enhanced pulverized coal firing.

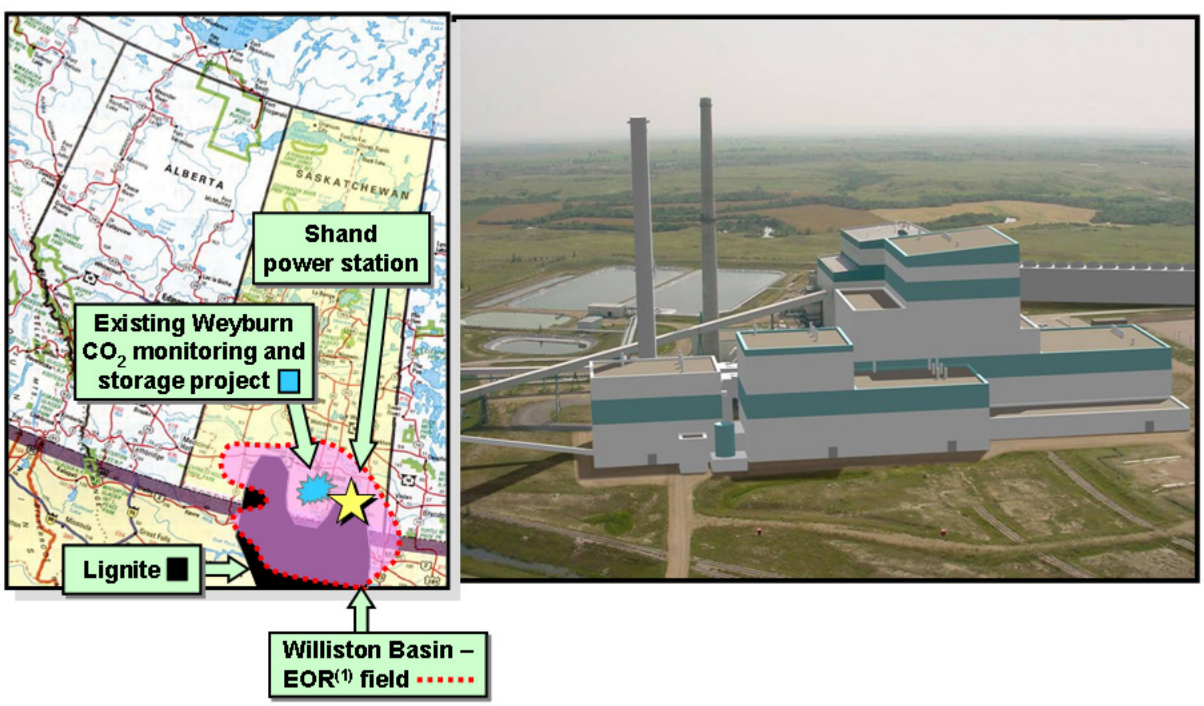

Fig. 6 SaskPower's Shand Station.

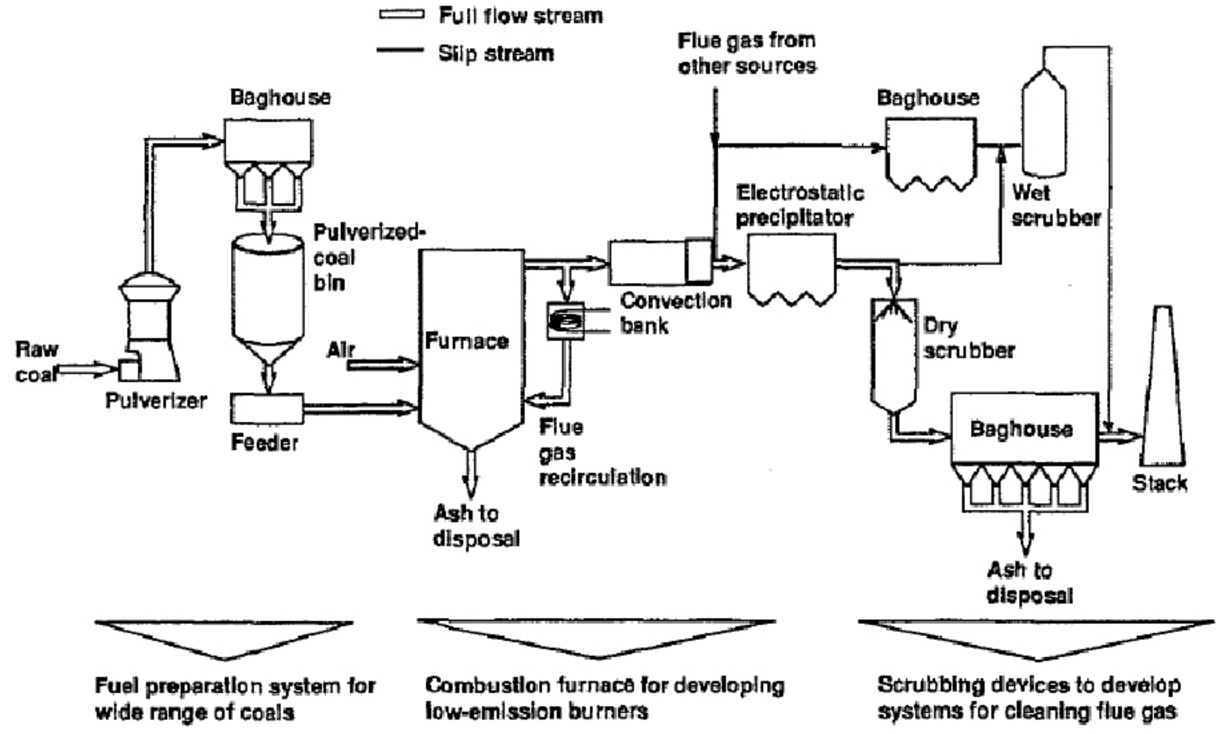

Fig. 7 As-built Clean Environment Development Facility process flow diagram.

In September 2006 a program to convert the facility to full OCC was initiated with a target first re-firing in June 2007. To permit full OCC (without CO_2 compression or sequestration), additional flues, an oxygen supply, oxygen mixers, a full-flow wet scrubber, additional coal preparation equipment, and controls and instrumentation are being added. In addition, the combustion system is being converted to direct firing to test the entire fuel preparation and firing system with either air or full OCC operation while burning Estevan lignite or subbituminous. Direct firing capability will also be preserved with minor redirection of the flow paths.

The testing will address the impact of both OCC and the various coals on coal preparation, ESP and wet scrubber performance and operation with the different flue gas composition, test control concepts for transitioning from air to OCC and OCC to air firing, load changing and major trips including Master Fuel Trip, and will support nearly full-scale testing of a new oxy-burner for lignite. In addition to testing with Saskatchewan lignite, it will be operated with eastern bituminous and with subbituminous coal.

This first campaign will test the configuration and conditions in support of the SaskPower Project including;

- Near-full-scale burner fed directly by an on-line pulverizer
  - ° Whether pulverizer performance is affected by flue gas composition
  - ° Whether pulverizer will require more recycle gas than air to maintain acceptable performance especially with low-rank coals
  - ° Whether new burner design is necessary
- Three coals will be tested: lignite, subbituminous, and eastern bituminous
- It will also demonstrate B&W's novel concept for controlling flue gas moisture content
- It supports the commercial project development that will be explained below.

In the conversion process, existing capability will not be diminished and, with minor modification, it will be capable of testing other configurations including combinations of dry scrubber, baghouse, wet scrubber and electrostatic precipitator in either full air or full OCC mode in later campaigns.

The engineering is completed, the equipment has been purchased, and manufacturing and installation are in progress. Following startup and shakedown in both air and OCC modes with indirect firing of an eastern bituminous fuel, the unit will be shut down briefly to convert to direct firing. The testing will commence firing lignite and then a subbituminous coal.

Conclusion

B&W in collaboration with Air Liquide is moving forward rapidly to commercialize oxy-coal combustion for pulverized coal-fired boilers. To minimize risk, the first plants will be very similar to conventional pulverized coal-fired systems with the addition of an air separation plant, CO_2 compression

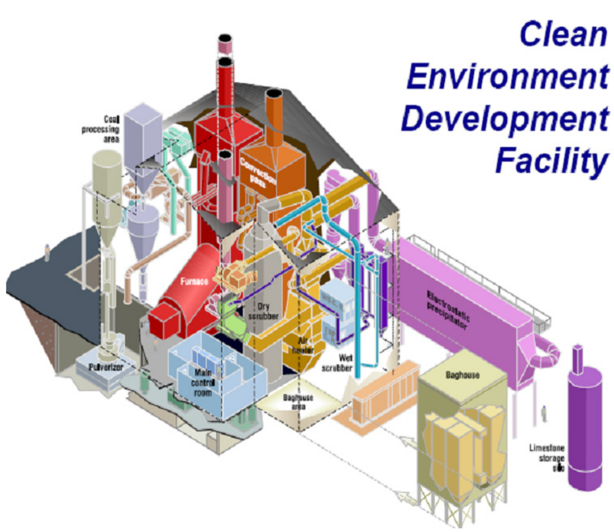

Fig. 8 The B&W Clean Environment Development Facility.

and purification system, and flue gas recycle. B&W-AL's approach is to utilize a mixture of recycle flue gas and oxygen as the oxidant and employ as much standard, conventional, reliable and available equipment as possible while taking into account the additional requirements imposed by the OCC process and flue gas properties and composition.

B&W is on track to successfully perform the largest scale testing of this technology ever accomplished in the world in the summer of 2007 at B&W's newly converted CEDF OCC facility located in Alliance Ohio. B&W is also looking forward to initiating project engineering this summer for SaskPower's 300 MW_e net Shand OCC plant, the first commercial plant of this type in the world.

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