# OXYGEN-FIRED CIRCULATING FLUIDIZED BED BOILERS FOR GREENHOUSE GAS EMISSIONS CONTROL AND OTHER APPLICATIONS

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**Paper Presented at the**
**Third Annual Conference on Carbon Capture and Sequestration**

May 3-6, 2004
Alexandria, VA, USA

## ABSTRACT

ALSTOM Power Inc. (ALSTOM) has conducted numerous studies on $CO_2$ capture from fossil fuel fired power plants. These studies show that an oxygen-fired circulating fluidized bed (CFB) steam power plant is a viable option for near-term $CO_2$ capture for enhanced oil recovery (EOR), sequestration, and other industrial applications. In this technology, a modified CFB boiler is fired with pure oxygen plus recirculated flue gas (mainly $CO_2$) instead of atmospheric air, resulting in a flue gas stream with a high $CO_2$ concentration. Consequently, $CO_2$ can be separated from the flue gas stream relatively easily. A CFB is ideal for application of oxygen firing because the CFB process recirculates a large stream of cooled furnace solids that aids in the control of combustion temperature. Other advantages of an oxygen fired CFB include fuel flexibility, good emissions performance, boiler island cost savings as compared to PC and Stoker firing, and ease in scale up from a few MWe to over 500 MWe. Furthermore, this technology is a near-term solution because it uses commercially available technologies including oxygen production and $CO_2$ stream gas processing. With regards to economics, the captured $CO_2$ and $N_2$ by-products can be sold for oil field stimulation and pressurization, respectively, to offset the cost of $CO_2$ capture.

ALSTOM, in collaboration with the U.S. DOE/NETL (DOE), is currently conducting a comprehensive two-phase greenhouse gas (GHG) emissions control study, evaluating the technical and economic feasibility of alternative $CO_2$ capture technologies applied to coal-fired power plants. Thirteen cases, representing various levels of technology development, were evaluated in Phase I. They encompassed combustion cases in CFB-type equipment, Integrated Gasification Combined Cycle (IGCC)-based systems, and Gasification Chemical (GCL) Looping (Marion, et al., 2003). Phase II entails the evaluation in a pilot-scale CFB plant of the oxygen-fired concept, and refinement of the equipment designs and economic models developed in Phase I on this concept.

As a part of the Phase-II workscope, ALSTOM has modified its 9.9 MM-Btu/hr CFB pilot plant to operate with $O_2/CO_2$ mixtures of up to 70 % $O_2$ by volume. Tests that vary fuel types, including the use of two different coals and one petroleum coke, are currently being conducted. The test objectives are to determine the impacts of utilizing oxygen firing, with different fuel types and test conditions, on heat transfer, bed dynamics (i.e., potential agglomeration), and gaseous (NOx, $N_2O$, $SO_2$, CO) and particulate

emissions. The test data will be used to refine the performance and economic models developed in Phase-I for two $O_2$-fired CFB scenarios including retrofit and Greenfield power plants. The commercialization pathway of this technology will also be discussed. This paper provides a review of commercial applications for $O_2$ fired CFB's and a progress report of ongoing Phase-II work.

## INTRODUCTION

Given that fossil fuel fired power plants are among the largest and most concentrated producers of $CO_2$ emissions, recovery and sequestration of $CO_2$ from the flue gas of such plants has been identified as one of the primary means for reducing anthropogenic $CO_2$ emissions. Burning fossil fuels in mixtures of oxygen and recirculated flue gas (principally $CO_2$) essentially eliminates the presence of atmospheric nitrogen in the flue gas. The resulting flue gas is comprised of primarily $CO_2$. Oxygen firing in utility scale Pulverized Coal (PC) fired boilers has been shown to be a more economical method for $CO_2$ capture than amine scrubbing (Bozzuto, et al., 2001). Additionally, oxygen firing in Circulating Fluidized Bed (CFB) boilers can be more economical than in PC or Stoker firing, because recirculated gas flow can be reduced significantly (Marion, et al., 2003). Oxygen-fired PC and Stoker units require large quantities of recirculated flue gas to maintain acceptable furnace temperatures to avoid slagging and fouling related problems. Oxygen-fired CFB units, on the other hand, can accomplish this by additional cooling of recirculated solids. The reduced recirculated gas flow with CFB units results in smaller boiler island components and significant Boiler Island cost savings.

## OXYGEN FIRED BOILER APPLICATIONS

The early implementation of the European Trading System for greenhouse gases in January 2005 is creating an intensive development of $CO_2$ capture and sequestration technologies. In addition to European Union (EU) States programs, several EU Framework 6 programs involving ALSTOM as a major partner are actively addressing the technical and economical issues of these major challenges with a target of reaching a 15-20 €/ton of $CO_2$ capture cost. The European context offers a unique opportunity for $CO_2$ sequestration, since depleted offshore oil wells in the North Sea, which might be removed from operation after 2006 might be upgraded with recovered $CO_2$ from European power plants. The corresponding $CO_2$ needs might reach 40 to 60 millions of tons on this medium term basis, as expressed at the European Power Plant Supplier Association (EPPSA) workshop (Advanced Fossil Fuel Technologies for a European Carbon Management Strategy) held in Brussels on March 2004.

For the short-term, ALSTOM recommended, at the end of the GHG Phase I study, to the DOE the development of Oxygen-Fired CFB technology for capturing $CO_2$ from coal or delayed petroleum coke for Enhanced Oil Recovery (EOR) applications (Marion, et al., 2003). The replacement of combustion air with high purity oxygen in a CFB can, as an additional benefit, significantly reduces the gas flow throughout the Boiler Island equipment. With $O_2$ firing a cryogenic Air Separation Unit (ASU) supplies the oxidant (99 percent pure oxygen) for the combustion of fuel rather than direct utilization of ambient air. Since the size and cost of much of the equipment contained within the boiler island (combustor, cyclones, backpass heat exchangers, air heater, fans, ductwork, baghouse, etc.) is strongly gas-flow-dependent, significant cost savings have been shown for the boiler island of this concept as compared to the comparable air-fired CFB unit. Figure 1 shows the plan and side elevation views for an air fired 210 MWe-gross CFB boiler. Similarly, Figure 2 shows the plan and side elevation views for an $O_2$ fired 210 MWe-gross CFB boiler. This boiler was designed to use an oxidant stream with 70% $O_2$ by volume with the remaining 30% being recirculated flue gas (mainly $CO_2$).

The air-fired and $O_2$-fired boilers were designed for the same coal and both units produce the same steam flows and steam conditions. A comparison of the plan views of these boiler islands (left side of Figure 1 and Figure 2) shows the $O_2$ fired unit occupies about 51 percent of the area of the air fired unit.

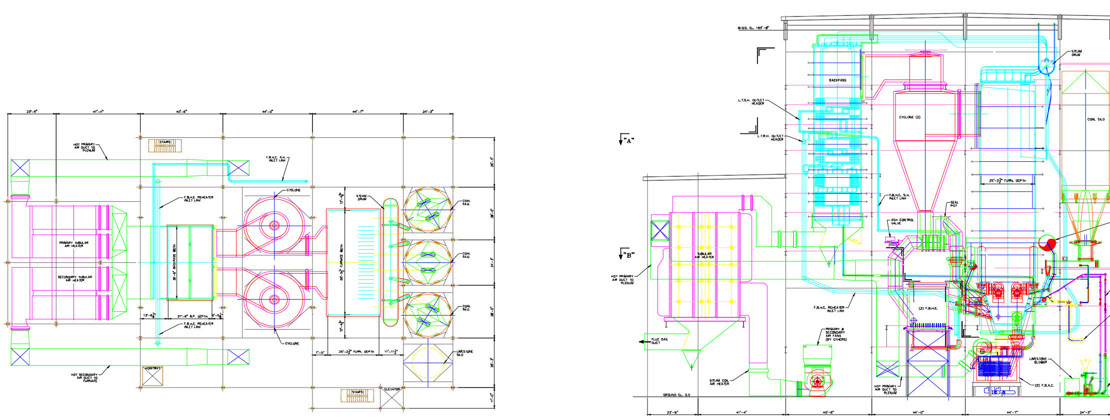

**Figure 1: Air Fired 210 MWe CFB – Plan View and Side Elevation**

Similarly, a comparison of building volumes indicates the $O_2$ fired unit occupies about 56 percent of the air-fired unit volume and the total boiler weight is about 65 percent. The smaller $O_2$ fired boiler results in a boiler cost savings of about 32 percent as compared to the air-fired boiler. This saving is an advantage for CFB boilers as compared to PC or Stoker firing which must re-circulate much larger quantities of flue gas to avoid slagging and fouling related problems.

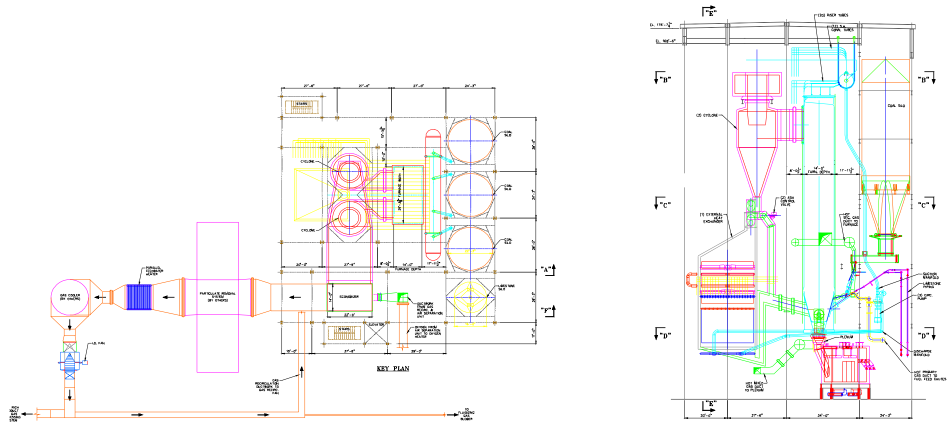

Figure 2: $O_2$ Fired 210 MWe CFB – Plan View and Side Elevation

The results from the Oxygen-Fired CFB analysis led to the conclusion that further development work was justified. In summary this recommendation was made to the DOE for the following reasons:

- The Oxygen-Fired CFB is the most near-term solution (~5-year horizon), as it uses enabling technologies, which are available commercially, for example:
  - Oxygen production by cryogenic air separation unit
  - $CO_2$ capture, purification, compression and liquefaction

- Significant boiler cost savings for $O_2$ fired CFB as compared to $O_2$ fired PC or Stoker.

- Preliminary economic analyses look viable for commercial EOR applications.
  - $CO_2$ product credit for oil field stimulation
  - $N_2$ by-product (from ASU) credit for oil field pressurization

- $CO_2$ in the flue gas is highly concentrated (~90 percent vs.~15 percent), thus making the processing of this stream to achieve the required $CO_2$ purity for EOR applications cheaper.

- Oxy-fuel firing in CFB's offers added emissions benefits over air firing, as had been preliminarily shown through combustion testing in an ALSTOM bench-scale fluidized bed combustor (Marion et al., 2003):
  - Typically low NOx emissions in combustion-staged air-fired CFB's are further reduced due primarily to elimination of thermal NOx.

- $SO_2$ emissions are reduced up to 90 percent. Sorbent utilization should not be negatively impacted if the bed temperature is maintained the same as in air firing. Furthermore, ALSTOM has a commercial product called "Flash Drier Absorbent (FDA)," which has been successfully demonstrated in the multi-use test furnace (MTF) to reduce $SO_2$ emissions by as much as 99 percent.
- Unburned carbon (UBC) loss should not be negatively impacted.
- A simplified gas processing system (GPS) design (drying and compression only) allows a "zero gaseous emission plant" although product gas purity would not be acceptable for EOR applications.

The DOE concurred with ALSTOM's recommendation of developing the $O_2$ fired CFB technology for capturing $CO_2$ and, hence, authorized the implementation of Phase-II of the current project. Phase-II, which started on May 16, 2003, entails the testing of two coals and one delayed petroleum coke in ALSTOM's pilot-scale MTF at firing rates in the 2.6 – 7.4 MM-Btu/hr range. The information obtained from the testing will be used to refine the design, performance, and economic analyses of the commercial-scale $O_2$ fired CFB concepts.

### Enhanced Oil Recovery (EOR) – an Early Opportunity for $O_2$ Firing

The three areas of particular importance to the oxy-fuel fired CFB technology for commercial EOR application are: (1) Potential early EOR project for applying this technology; (2) Technical and economic viability potentials of the technology; and (3) Timeline vision for commercialization of the technology.

#### Potential Early EOR Project

Lost Hills Oil field, located about 45 miles northwest of Bakersfield, CA (Figure 3) was discovered in 1910 (Walker and Perri, 2002). There are 2.2 billion barrels of oil in place in the Belridge Diatomite in Lost Hills. While this diatomite has high oil saturation and high porosity, it has low permeability, which has led to low primary oil recovery. Consequently, to date only 112 million barrels of oil have been produced (i.e., 5 percent of the original oil) from the Belridge diatomite.


**Figure 3: Location Map of Major Oil Fields in Southern San Joaquin Valley, CA. Lost Hills is Highlighted (from Walker and Perri, 2002)**

Chevron initiated a pilot diatomite water injection flood project in 1992, which has increased the oil production rate by more than 50 percent (i.e., from about 6,400 to 10,400 Bbl/day). In 2000, Chevron initiated a pilot $CO_2$ flooding of Lost Hill diatomite, because $CO_2$ injection is two to three times more effective than water or steam. This is due mainly to two favorable mechanisms: (1) $CO_2$ reduces the reservoir's oil viscosity; and (2) it increases fluid expansion. This pilot work is being carried out under the auspices of the U.S. Department of Energy to address two main economic uncertainties associated with $CO_2$ injection, namely, oil response and $CO_2$ utilization required for such response.

This proposed project, referred to as the Bakersfield Project, is located on/or near AERA Energy LLC oil production property (a Limited Liability Corporation for oil production in California for Exxon/Mobil and Shell Oil companies). It presents an opportunity whereby relatively cheap delayed petroleum coke from oil refineries owned by AERA LLC partners could be used to generate $CO_2$ for EOR.

Plasma, Inc. (PLASMA), a project developer with expertise in oil/gas production projects (Schuller 2002), has provided ALSTOM with information from the $CO_2$ Users Coop Group and financial data on $CO_2$ use for EOR, particularly with respect to the Bakersfield, CA, project. Furthermore, PLASMA has requested, on behalf of its clients, that ALSTOM propose CFB boiler designs that are in sufficient detail to get material take-off cost estimates. These designs would be done for a 20,300 ton/day steam production and ~210 MWe power generation from the combustion of 3,000 tons/day delayed petroleum coke. These designs would also include marketable $CO_2$ recovery using a "near zero-emission" boiler design. At the completion of this work PLASMA should be able to determine the boiler system required and to finalize the emission profile needed for permit application purposes. Based on favorable results from a bench-scale FBC study performed under the auspices of Plasma, Inc., ALSTOM recommended that work on the next phase of Plasma's overall plan proceed. This involved design studies of commercial air-fired and $O_2/CO_2$-fired CFB boilers in sufficient detail to permit material take-off cost estimates to be made.

Performance and Economic Analyses for an $O_2$ fired CFB for EOR Applications

A performance and economic analysis (Marion, et al., 2003) is shown in this section for an $O_2$ fired CFB power plant retrofitted for an EOR application where $CO_2$ product and $N_2$ by-products are utilized (Case 2a). A comparison of the $O_2$ fired EOR unit to a typical air fired CFB power plant (Case 1) is also shown.

Table 1 shows the $CO_2$ product purity specification that was used as a design guideline for the Gas Processing System (GPS) of Case 2a. The gas processing system (GPS) performance met or exceeded all component purity specifications listed except for $O_2$ and $N_2$. The nitrogen concentration specified is < 300 ppmv. According to Charles Fox of Kinder Morgan (Fox, 2002), this specification is very conservative as his company specifies a maximum nitrogen concentration of 4 percent (by volume) to control the minimum miscibility pressure.  In Case 2a the nitrogen concentration in the liquid product was 11,800 ppmv. The exact reasoning behind the very low nitrogen specification listed in Table 1 is not clear.

A very low concentration of oxygen (< 50 ppmv) in particular is also specified in Table 1 for meeting current pipeline operating practices, presumably due to the corrosive nature of the oxygen.  Hence, for Case 2a whereby the final $CO_2$ liquid product was found to contain 11,400 ppmv of $O_2$, the design of the transport pipe to the EOR site would have to take this characteristic under consideration.

Table 1: Dakota Gasification Project's $CO_2$ Purity Specification for EOR

| Constituent | Unit | Typical |
|---|---|---|
| $CO_2$ | Vol.% | 96.0 |
| $H_2S$ | Vol.% | 0.9 |
| CH4 | Vol.% | 0.7 |
| C2+HCs | Vol.% | 2.3 |
| CO | Vol.% | 0.1 |
| $N_2$ | ppm by Vol. | < 300 |
| $H_2O$ | ppm by Vol. | < 20 |
| $O_2$ | ppm by Vol. | < 50 |

The specifications for the $CO_2$ product are very dependent on the final $CO_2$ use either for sequestration or for EOR with miscibility aspects, including $CO_2$ transportation issues. The acceptance of trace elements in the $CO_2$ appears critical in terms of process complexity and associated costs if too strict limitations have to be met. In particular, the detailed fate and removal of nitrogen oxides, CO, $N_2O$ and $SO_2$ / $SO_3$ along with residual $O_2$, $N_2$ and heavy metals from the original solid fuel, appears challenging and requires detailed thermodynamic investigations and validations. It appears that not enough focus has been given to these aspects, which might significantly affect cost issues.

*Performance Analysis:*

Table 2 summarizes the Net Plant Heat Rates and Net Plant Outputs obtained from Case 1 (Air-Fired CFB power plant without $CO_2$ Capture), and Case 2a (CFB power plant Retrofit for $O_2$-Firing w/$CO_2$ Capture for EOR). The Net Plant Heat Rates (HHV basis) of the air fired CFB and the retrofitted $O_2$ fired CFB are 9,611 and 14,660 Btu/kWh, corresponding to net plant efficiencies of 35.5 and 23.3 percent (Marion, et al., 2003).

Table 2: Summary of Performance for Air and $O_2$ fired CFB Cases

| Study Case | | Fuel-Type and Cost | | Net Plant Heat Rate, Btu/kWhr | Net Plant Output, kW |
|---|---|---|---|---|---|
| # | Description | Type | Cost, $/MMBtu | | |
| 1 | Air-Fired CFB w/Pet. Coke, w/o $CO_2$ Capture | Delayed Petroleum Coke | 0.65 | 9,611 | 193,037 |
| 2a | $O_2$-Fired CFB Retrofit w/Pet. Coke, w/ Captured $CO_2$ & $N_2$ Credits | Delayed Petroleum Coke | 0.65 | 14,660 | 128,075 |

The energy penalty for Case 2a is therefore about 34 percent as compared to Case 1. There are two primary reasons for the energy penalty associated with Case 2a. First, the integration into the power plant of the Air Separation Unit (ASU) to provide combustion oxygen, and second, the Gas Processing System (GPS) to, purify, compress, and liquefy the $CO_2$ product. Both these systems consume large quantities of auxiliary power as shown in Figure 4.

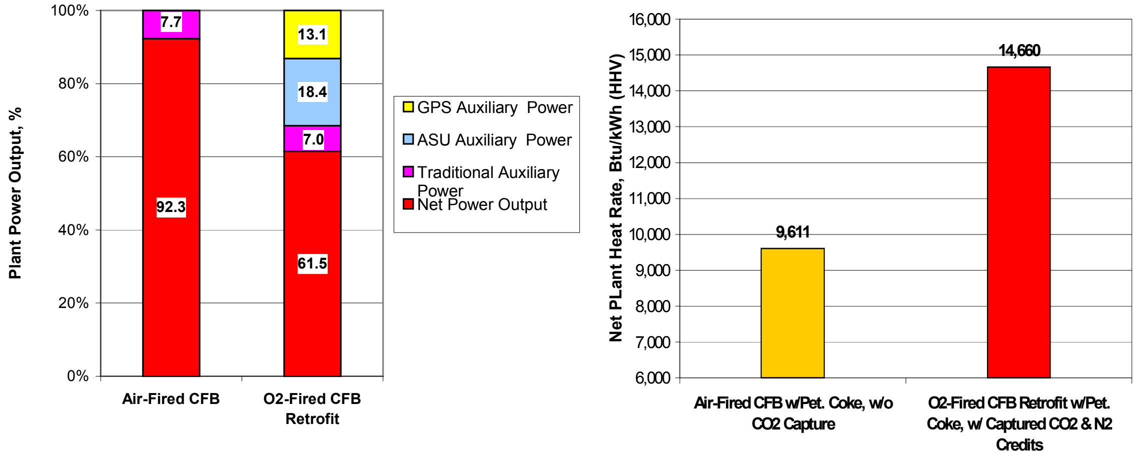


Figure 4: Auxiliary Power and Net Plant Heat Rate Comparison between Air-Fired and Oxy-fuel Fired CFB Plants

The ASU and GPS consume about 18% and 13% of the gross output, respectively, while the traditional auxiliary power consumption is about 8%. Figure 4 also shows a comparison of Net Plant Heat Rates between Case 1 and Case 2a.

*Economic Analysis:*

The financial assumptions shown in Table 3 were used for both the air-fired and $O_2$-fired cases in this study. These parameters are typical for an electric utility financing scenario.

Table 3: Economic Evaluation Study Assumptions

| | CFB Systems - Cases 1, 2a |
|---|---|
| **POWER GENERATION** | |
| Net output (MW) | Case Sensitive |
| Capacity factor (%) | 80% |
| Net plant heat rate, HHV (Btu per kWh) | Case Sensitive |
| Degradation factor (%) | 0.0% |
| **TIME FRAME** | |
| Construction period (months) | 30 |
| Depreciation Term (years) | 30 |
| Analysis Horizon (years) | 30 |
| **PROJECT COSTS** | |
| EPC Price ($1000s) | Case Sensitive |
| Fixed O&M costs ($ per kW) | Case Sensitive |
| Variable O&M costs (cents per kWh) | Case Sensitive |
| Owner's EPC Contingency | 0.0% |
| Initial spares and consumables | 1.0% |
| Insurance | |
| Insurance during Construction | 1.0% |
| Insurance during first year of operation | 0.5% |
| Development Costs | |
| Development Costs & Fees | 4.0% |
| Reimburseable Dev't Costs | 3.0% |
| Advisory Fees | 3.0% |
| Financial and Legal Fees | 3.0% |
| Start-up Fuel | 0.5% |
| Fuel Stock Pile | 0.5% |
| Other Costs | 0.5% |
| Total Initial Project Costs (% of EPC) | 17.0% |

| | CFB Systems - Cases 1, 2a |
|---|---|
| **FUEL COST** | |
| Coal Price ($ per MMBtu) | 1.25 |
| Natural Gas Price ($ per MMBtu) | 4.00 |
| Delayed Petroleum Coke Price ($ per MMBtu) | 0.65 |
| **PROJECT CREDITS** | |
| $CO_2$ Sell Price ($ per ton) | 17.00 |
| $N_2$ Sell Price ($ per ton) | Calculated |
| **ESCALATION FACTORS** | |
| Fuel Price | 0.0% |
| Variable O&M | 0.0% |
| Fixed O&M (including payroll) | 0.0% |
| Consumer Price Index | 0.0% |
| **FINANCING ASSUMPTIONS** | |
| Equity | 50.0% |
| Debt | 50.0% |
| **TAXES** | |
| Corporate Tax | 20.0% |
| Tax holiday (years after commissioning) | 0.0% |
| Customs Duty | 0.0% |
| Customs Clearance Fee | 0.0% |
| **COST OF CAPITAL ASSUMPTIONS** | |
| Discount Factor | 10.0% |

| | | CFB Systems - Cases 1, 2a |
|---|---|---|
| **DEBT PORTFOLIO** | | |
| Interest Rates (Financed) [1] | | |
| During Construction | | |
| Base Rate | | 1.32% |
| Swap/Reinvestment cushion | | 1.28% |
| Fixed Rate Margin | | 3.00% |
| All-In Fixed Rate | | 5.60% |
| During Operation | | |
| Base Rate | | 1.32% |
| Swap/Reinvestment cushion | | 1.28% |
| Fixed Rate Margin | | 2.50% |
| All-In Fixed Rate | | 5.10% |
| Up-front Fee (Financed) | | 2.0% |
| Commitment Fee | | 1.0% |
| Grace Period (months) | | 0 |
| Loan Tenor (years after construction) | | 30 |
| **PROGRESS PAYMENT SCHEDULES** | | |
| | Month | |
| | 1 | 10% |
| | 8 | 15% |
| | 17 | 25% |
| | 22 | 20% |
| | 26 | 20% |
| | 30 | 10% |
| | Total | 100.0% |

[1] Wall Street Journal, 4/23/03, London Interbank Offered Rate (LIBOR) Swap Curve

The total EPC (Engineered, Procured, and Constructed) plant costs for Cases 1 and 2a are 1,304 and 2,776 $/kWe-net, respectively as shown in Table 4 and Figure 5. The high EPC cost of Case 2a is a direct result of the integration of the ASU and GPS into the power plant. It should be recognized that the boiler island cost savings resulting from minimizing flue gas recirculation resulting in smaller boiler island components, as described previously, are not applicable to Case 2a since this is assumed to be a retrofit of an air fired CFB to $O_2$ firing. By comparison, if Case 2a was a Greenfield case it would be expected to cost about 2,450 $/kWe-net (Marion et al., 2003).

Table 4: Summary of Investment Costs and Economic Results For the Air and $O_2$ fired CFB Cases

| Study Case | | Total EPC Investment Costs, $/kW | Levelized Cost of Electricity (Cents/kWh) | | | | | |
|---|---|---|---|---|---|---|---|---|
| # | Description | | Total O&M | Financial | Fuel | $CO_2$ Credit | $N_2$ Credit | Total |
| 1 | Air-Fired CFB w/Pet. Coke, w/o $CO_2$ Capture | 1,304 | 0.83 | 2.49 | 0.62 | 0.00 | 0.00 | 3.95 |
| 2a | $O_2$-Fired CFB Retrofit w/Pet. Coke, w/ Captured $CO_2$ & $N_2$ Credits | 2766 | 1.88 | 5.25 | 0.95 | -2.41 | -1.72 | 3.95 |

Levelized costs of electricity for these two cases are also presented in Table 4 and Figure 5. For the retrofit (Case 2a), credits of 2.4 and 1.7 cents/kWh were calculated for $CO_2$ and $N_2$ by-products, respectively. These numbers are equivalent to specific product costs of about17 $/ton of $CO_2$ and 4 $/ton of $N_2$. It should be noted that $CO_2$ is the product stream leaving the gas processing system, and $N_2$ is a by-product of $O_2$ production in the air separation unit. In the analysis of Case 2a, the $N_2$ credit (4 $/ton of $N_2$) was a back calculated value. The $N_2$ value calculated was the cost required to make the calculated cost of electricity (COE) for Case 2a equivalent to the Case 1 (air-fired electricity production only) COE (i.e., 3.95 cents/kWh). In other words, the breakeven $N_2$ value was calculated. As stated above, the required $N_2$ credit was about 4 $/ton of $N_2$. By way of comparison, the current value of $N_2$ is about 11 $/ton (Schuller, 2002).

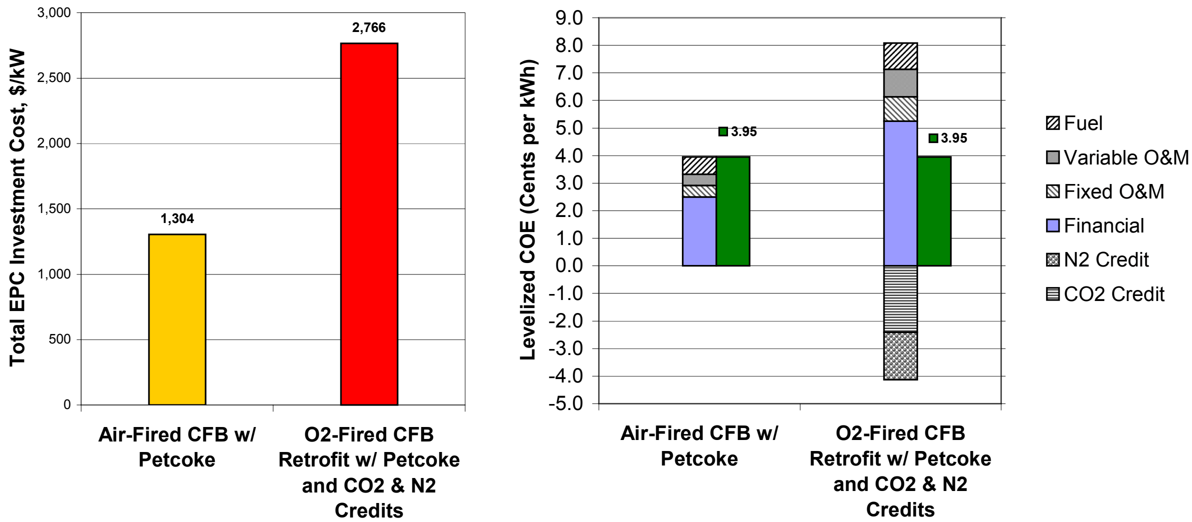


**Figure 5: Total EPC Investment Costs and Levelized Costs of Electricity for Air Fired and $O_2$ Fired EOR Application with Credits** ($CO_2$ @ $17/ton, $N_2$ @ $4/ton)

The fact that delayed petroleum coke was used as a fuel as opposed to coal in this analysis has very little impact on the overall result. In fact if coal were used instead of delayed petroleum coke, the calculated breakeven $N_2$ value would have been about 5 $/ton of $N_2$ instead of 4 $/ton.

Vision of Commercial Development Pathway

Figure 6 depicts a vision of a development pathway for a commercial oxy-fuel fired CFB with $CO_2$ capture, covering a time period of about five years. A logical first step is the implementation of the Phase-II work scope between mid 2003 and end 2004. At this point, there would be sufficient maturity to prepare proposals to demonstrate this technology at a commercial-scale (50-100 MWe range), envisioning a timeline between 2006 and 2008. Following a successful demonstration project, it would then be feasible to start commercial plant offerings (i.e., after year 2008).

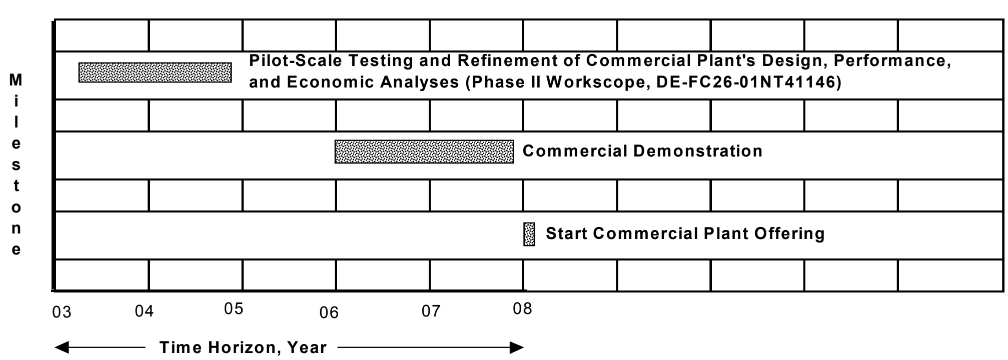


Figure 6: Commercialization Pathway

ALSTOM has also taken a first step of defining an $O_2$ fired CFB demonstration plant in Europe. A size between 20 to 50 MWe was chosen in order to achieve a balanced project in terms of risk mitigation and financing issues. To prepare for commercial introduction in 2008, ALSTOM has already performed a detailed study of a 40 MWe demonstration plant using oil residues and is targeting a capture cost less than ~20 €/ton, using an integrated CFB concept.

## Future Oxygen-Fired Boilers

### Integration of Oxygen Transport Membranes for Coal Firing

Figure 7 depicts a simplified process flow diagram (PFD) of an oxygen transport membrane (OTM) integrated with a circulating moving bed (CMB™) boiler (Marion, et al., 2003). Many other configurations are possible including CFB applications. The shaded components comprise the OTM and its support equipment. The OTM requires a supply of high pressure, and high temperature air (Stream 26) to be provided to the membrane. This is done with a system which includes an air compressor and a high temperature air heater located within the moving bed heat exchanger of the CMB™ boiler. Additionally a low-pressure, low oxygen content stream (Stream 16) is used as a sweep gas stream to pick up the oxygen, which is transported across the membrane, and supply it to the combustor. The basic concept is that combustion air is replaced with oxygen in a CMB™ combustor thereby creating a high $CO_2$ content flue gas stream for usage or sequestration.

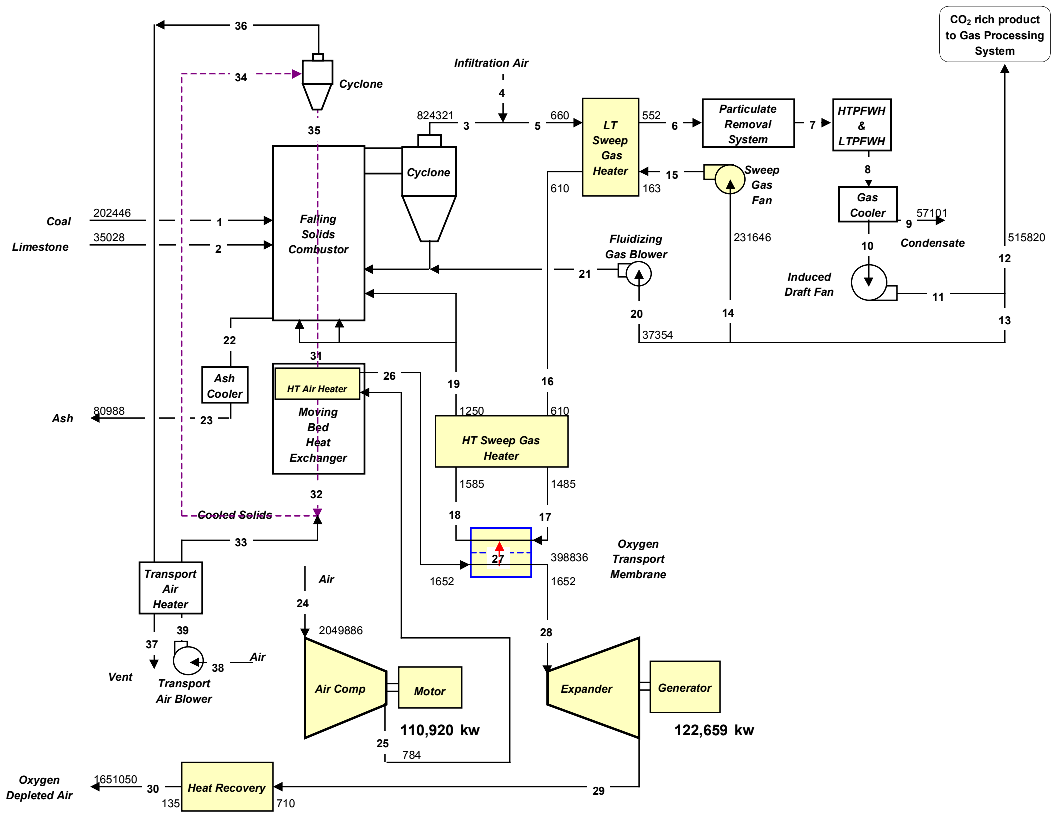

Figure 7: Simplified PFD of an Oxygen Transport Membrane Integrated with a CMB™ Boiler

## Other Future Oxygen-Fired Boilers

The $CO_2$ Capture project (CCP) and the European Commission have supported a project by BP (UK), Chalmers University of Technology (Sweden), Consejo Superior de Investigationes Cientificas (Spain), Vienna University of Technology (Austria) and ALSTOM. This project was intended to prove the concept of chemical looping combustion (CLC) technology for boiler applications to facilitate the capture of $CO_2$. The work was completed in the period from January 2002 to December 2003 and included development of particles that act as oxygen carriers, fluidization and modeling investigations, study of the design and economics of a future industrial unit and the demonstration of a laboratory scale chemical looping combustor. A conceptual design for an industrial CLC boiler has been developed by ALSTOM. It appears that there are no show stoppers in terms of technology, which utilizes mostly existing CFB technology. The oxygen carrier is the main issue in terms of cost and durability.

CLC technology using CFB boilers should appear as a longer term leading technology in terms of competitiveness for $CO_2$ removal and access to the market after a long term prototype operation and a demonstration unit operation.

## OXYGEN FIRED BOILER PILOT SCALE TESTING

The test objective is to determine the impacts of different fuel types and test conditions on heat transfer, bed dynamics (i.e., potential agglomeration), gaseous (NOx, $N_2O$, $SO_2$, CO) and particulate emissions. The test data obtained will be used to refine the performance and economic models previously developed during Phase I of this project (Marion, et al., 2003). The models examined two $O_2$-fired CFB scenarios including retrofit and Greenfield power plants. The results of this study will be used to bring the $O_2$-fired CFB boiler technology to near-term commercial readiness by addressing critical gaps in the knowledge required to design and conduct a commercial demonstration plant.

### Specific Objectives

The specific objective of the Phase II workscope is to generate a refined technical and economic evaluation of the oxygen fired CFB concept, with the benefits from pilot-scale testing of the same concept. Phase II workscope has been developed based upon the findings from Phase I and will specifically address both retrofit (moderate $O_2$ enrichment/ high flue gas recirculation) and Greenfield applications (high oxygen enrichment/low flue gas recirculation). The objective of the pilot-scale testing is to generate detailed technical data needed to establish advanced CFB design requirements and performance when firing coals and delayed petroleum coke in $O_2/CO_2$ mixtures. Firing rates in the pilot test will range from 2.6 to 7.4 MM-Btu/hr (0.8-2.2 $MW_{th}$). Pilot-scale testing is currently being performed at ALSTOM's Multi-use Test Facility (MTF). Outputs from this testing will address key technical parameters including: Flue gas quality, and bed dynamics, heat transfer to the waterwalls, flue gas desulfurization, NOx emissions reduction, other pollutants' emissions ($N_2O$ and CO), bed and ash characteristics (e.g., potential bed agglomeration).

### Test Facility Description/Modification

The 9.9 MM-Btu/hr Multi-Use Test Facility (MTF, Figure 8), being used in this study, is located at ALSTOM's Power Plant Laboratories in Windsor, CT. This circulating fluidized bed (CFB) facility, which was built in 1997, has since accrued more than 5,000 hours in operation with a wide variety of fuels under a broad range of process conditions. Detailed process and design information from this facility has been applied to commercial CFB contracts as well as development initiatives for process improvements and new technologies. The combustor is sufficiently large (I.D. of 40 inches (in), overall height > 60 feet (ft)) to minimize wall effects and provide representative hydrodynamics, which are critical to the evaluation of combustion performance, sulfur capture, heat transfer, and emissions. The facility is equipped with all major components used with commercial CFB's including external fluidized bed and moving bed heat exchangers, waterwall test sections, and a downstream baghouse/Flash Drier Absorber (FDA) test system. Extensive instrumentation allows measurement and control of mass and energy flows, gas analysis and other process conditions. A state-of-the-art data acquisition and control system provides operational control, monitoring, and on-line trending for real-time data evaluation.

The MTF has been modified to test fire the fuels in air and various $O_2/CO_2$ mixtures, as follows:

- Installation of the infrastructure to supply mixtures of $O_2$ and $CO_2$ for firing at concentrations up to 70% $O_2$ by volume. This includes piping, instrumentation and control skids for oxygen and $CO_2$ supplied from rented tanks.

- Reduction of the furnace inner diameter from 40-in. to 21-in. Since the facility is permitted to fire a maximum of 9.9 MM-Btu/hr, the reduced gas flow associated with oxygen firing would result in unreasonably low combustor fluidizing velocities. The reduction to 21-in. diameter yields representative combustor velocities (about 15 ft/sec) at 70% oxygen firing.

- Replacing some furnace components for service at elevated oxygen content. This includes the combustor bottom, fluidizing grid, and overfire air injection system.

- Installation of additional heat transfer surfaces to extract the extra heat that is normally carried away by the nitrogen in the flue gas with air firing.

- Modification of the fluidized bed heat exchanger (FBHE) to minimize re-carbonation of the circulating solids (i.e., $CaO + CO_2 \rightarrow CaCO_3$). As depicted in Figure 8, the air used in place of $CO_2$ to fluidize the solids was vented off to prevent nitrogen dilution.

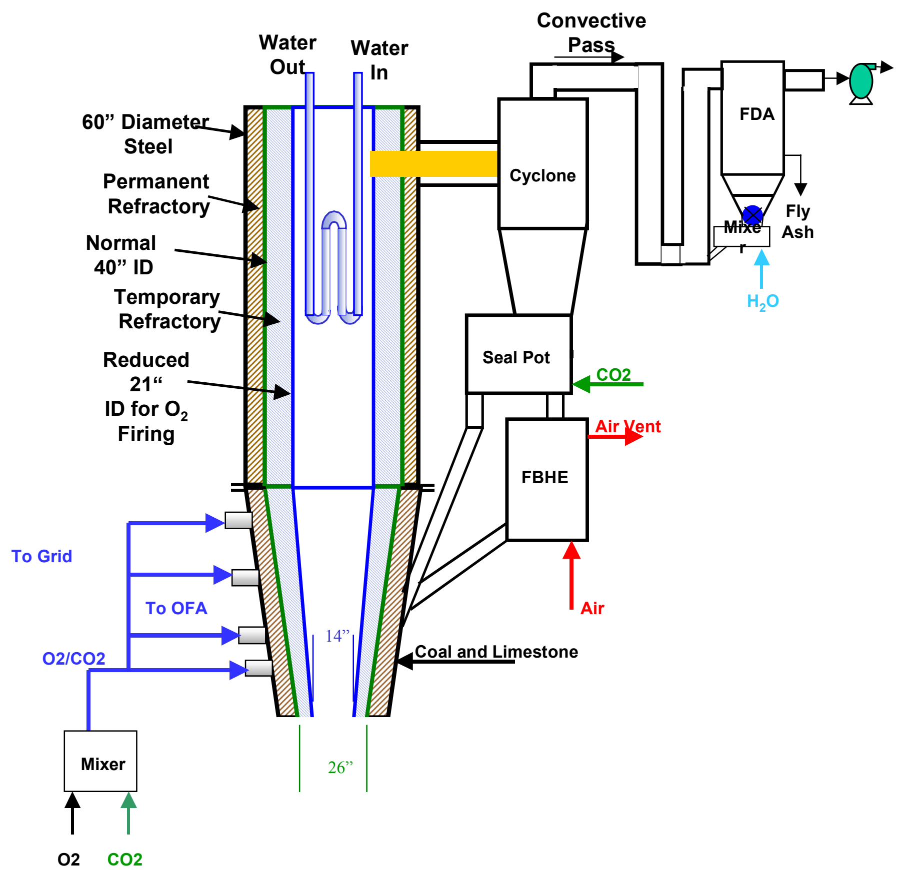


Figure 8: Schematic of the Multi-use (MTF) Test Facility Depicting Modifications for $O_2$ Firing

## Test Matrix

Table 5 shows the test matrix followed during the first campaign. Following an initial period of 24 hours for refractory curing with natural gas-air flame and facility shakedown, start-up conditions were set up on natural gas and still using air as a combustion medium. The furnace was transitioned to the Base Case CFB coal (an Eastern US bituminous coal) with air firing, after reaching operating temperatures; approximately 20 hours were needed to fully transition to this coal and stabilize at desired test conditions. During warm-up, transition, and stabilization many other tasks were accomplished. They included adapting and tuning the furnace control system, and making test personnel familiar with the new equipment. The first, baseline, combustion test with air firing was completed, and the necessary gas and solid data were collected.

Combustion testing of the Base Case coal in $O_2/CO_2$ mixtures, starting with Test 2, required set-up and fine tuning of the $O_2/CO_2$ delivery system and other furnace components as follows:

- The $O_2$ and $CO_2$ delivery system needed to be shaken down under full test conditions. This required the optimization of the vaporizers, synchronization of the control/mixing skid with the MTF's control system, and the refinement of the overall control logic.

- Transition of furnace ancillary equipment such as seal pot, aspirators, transport-assist lances, and grease airs to operate on compressed $CO_2$.

Table 5: MTF Test Matrix for Campaign 1

| Test # | Test | Planned Time (hours) | Planned Firing Rate (MM-Btu/hr) |
|---|---|---|---|
| | Curing and Shakedown | 24 | |
| | Start-up | 20 | |
| 1 | Base Coal - Air Fired | 16 | 2.6 |
| 2 | Base Coal - 21% O2 | 16 | 2.6 |
| 3 | Base Coal - 30% O2 | 24 | 3.9 |
| | Transition to Pet Coke | 6 | |
| | | | |
| 4 | Pet Coke - 30% O2 | 16 | 3.9 |
| 5 | Pet Coke - High O2 | 24 | ~5 |
| | Shutdown | | |

Due to the time consuming nature of the tasks described above, only Tests 1, 2, and 3 (Table 5) were completed in the first campaign. The research team carrying out this work feels that the valuable lessons learned during this test campaign will enable an effective execution of test Campaign 2. These lessons learned include the following:

- The liquid $O_2$ supply tank needed to be set-up to deliver and maintain a more consistent pressure. The root cause of the pressure fluctuations encountered has been identified and corrected. No additional problems in this area are anticipated in the second test campaign.

- It appears that fluidizing the sealpot with pure $CO_2$ may have caused a recarbonation of the CaO, leading to a poor fluidization in the sealpot. An intermediate solution entailed using a mixture of air and $CO_2$ to fluidize the sealpot, and steam cooling the dip-leg (a transition between the cyclone and seal-pot). Air and/or a mixture of air with $CO_2$ will be used during test Campaign 2. For commercial application, a re-design of the sealpot will be implemented to minimize the air-dilution of the flue gas.

## Initial Observations

The analysis of data obtained from these tests is proceeding. In the meantime the following preliminary observations can be made:

- *Bed Dynamics:* Firing the base case CFB coal in $O_2/CO_2$ mixtures containing up to 40% vol. $O_2$ in the primary combustor zone (i.e., upstream of the lowest overfire air port) presented no bed agglomeration related problems.

- *$SO_2$ Emissions.* In order to get efficient limestone calcination, the bed temperature was operated at about 1650°F (See Figure 9). For most fuels this temperature is above the optimum for sulfur capture, so emissions would be higher for the same Ca/S. Compared to air firing at the same temperature, the emissions may be comparable if calcination is complete. In our test the $SO_2$ emissions were lower with air firing at the same high temperatures as the 21% and 30% $O_2$ (in $CO_2$ balance), but the solids inventories were different. Quantitative analysis of this data will be completed in conjunction with the solids analysis and other operating parameters.

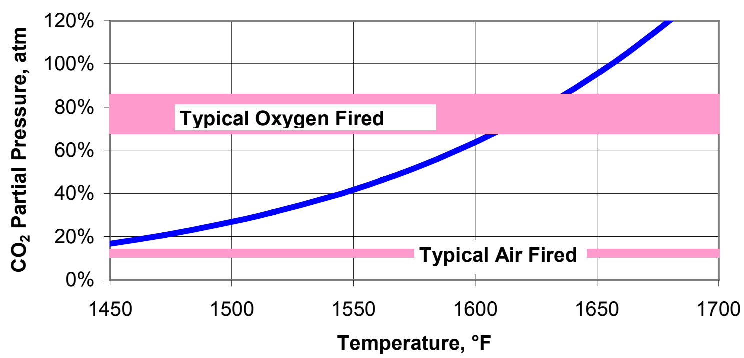


**Figure 9: Limestone Calcination Equilibrium Curve as a Function of Furnace $CO_2$ Partial Pressure and Temperature**

- *$NO_x$ Emissions:* $NO_x$ emissions were lower with the $O_2$ firing, but the staging scenarios have not yet been fully analyzed. The quantitative analysis of this data is in progress.

- *CO Emissions:* CO emissions may be higher with $O_2$-firing due to higher $CO_2$ partial pressure in the flue gas. At comparable bed temperatures, for example, CO emissions were 0.085 lb/MM-Btu for air firing as opposed to about 0.1 to 0.15 lb/MM-Btu for 21 and 30% $O_2$ firing (in $CO_2$ balance), respectively. Again, the analysis of this data is proceeding.

### Next Steps

*Test Campaign 2.* Table 6 shows the tests that are planned for Campaign 2 on the two coals and a pet coke.

Table 6: MTF Test Matrix for Campaign 2

| Test # | Test | Planned Time (hours) | Planned Firing Rate, MM-Btu/hr |
|---|---|---|---|
| | Start-up | 20 | |
| 6 | Base Coal - Air Fired – overfire air | 6 | ~5 |
| 7 | Base Coal - 21% - overfire air | 6 | ~5 |
| 8 | Base Coal - 40% $O_2$ | 12 | 5.3 |
| 9 | Base Coal - High $O_2$ | 12 | 7.2 |
| | Transition to Pet Coke | 6 | |
| 10 | Pet Coke - 40% $O_2$ | 12 | 5.3 |
| 11 | Pet Coke - High $O_2$ | 12 | 7.4 |
| | Transition to Pitt 8 | 6 | |
| 12 | Pitt 8 - 40% $O_2$ | 12 | 5.3 |
| 13 | Pitt 8 - High $O_2$ | 12 | 7.2 |
| | Shutdown | | |

## CONCLUDING REMARKS

Work carried out by ALSTOM has shown that the oxygen-fired CFB concept is a viable technology, requiring a short-term development horizon. This technology is short-term, because it is designed to use mostly commercially available enabling technologies (e.g., oxygen production by cryogenic air separation, and gas processing). It is economically feasible in a niche situation such as enhanced oil recovery, whereby the $CO_2$ product and $N_2$ by-product from the air separation unit are sold for EOR and oil field stimulation and pressurization, respectively. It is anticipated that one of the logical steps following the completion of the MTF pilot-scaled testing will be to start the design of a commercial-scale CFB boiler (~50 MWe) for demonstration of the oxygen-fired CFB concept in the USA.

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