Advanced Coal-Based Power Generation: Technical Developments and Outlook

Discussion Paper No 3

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Department of Primary Industries and Energy

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FOREWORD

Australia has a strong interest in ensuring the sustained use of coal in domestic and international markets in an economically efficient and environmentally acceptable manner. We are the world's largest exporter of coal, the sixth largest producer of black coal, and a significant brown coal producer.

Coal has over recent years been at the centre of the environmental debate, especially in the context of acid rain and climate change. Overseas and domestic perceptions on these issues can be important influences on the outlook for our exports, and for domestic use where 80 percent of electricity generation is coal-based.

This paper discusses new coal technologies which are close to commercial application, and which have the potential to improve the environmental performance of coal based electricity generation through raising thermal efficiency. These technologies are being developed in parallel with continuing improvement of conventional technology. It is clearly important that Australian coal, electricity, and allied industries appreciate and exploit the opportunities created by developments in all areas of coal utilisation, particularly where they impact on Australia's coal export trade. This paper is intended to assist with informed public debate on these issues by outlining relevant literature on the new technologies for power generation.

The discussion paper does not necessarily reflect government views, nor should it be read as a complete evaluation of the subject, but it is intended to stimulate discussion on the implications and opportunities for Australia.

SIMON CREAN
Minister for Primary Industries and Energy

MICHAEL LEE
Minister for Resources

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SUMMARY

Black and brown coal currently meet about 80% of Australia's electricity needs and are likely to continue to dominate electricity production here and overseas for the foreseeable future.

The major challenge facing coal based electricity generation in Australia and overseas is to meet the growing demand for electricity as reliably and cheaply as possible, while achieving increasingly stringent standards relating to emissions of particulates, sulphur and nitrogen oxides, carbon dioxide and solid residues.

Pulverised fuel (PF) combustion is the dominant technology for power generation from black and brown coal. The paper describes the pollution control measures relevant to this technology, including pre-combustion cleaning of coal, control during combustion, post-combustion treatment of flue gases, and solid wastes management.

The most advanced coal based power generation technologies, by integrating pollution control in the overall process, offer an improved alternative to PF technology. Additionally, concerns about climate change will favour such technologies with their capacity for higher thermal efficiencies and therefore lower emissions of carbon dioxide per unit of output. Moreover, the likely trend towards decentralisation and privatisation in the power generation industry will tend to favour the moderate sizes and higher efficiencies of the advanced technologies compared with the fairly large scale PF plants.

The paper briefly describes and assesses the advanced technologies such as atmospheric fluidised bed combustion (AFBC), pressurised fluidised bed combustion (PFBC), and integrated gasification combined cycle (IGCC). Integrated gasification humid air turbine (IGHAT), direct coal fired turbine, integrated gasification fuel cells (IGFC), and magnetohydrodynamics (MHD) are also considered, but their technical viability is yet to be established.

The paper concludes that advanced black coal PFBC and IGCC systems have the potential to achieve efficiencies as high as 45% in the near term, thus reducing carbon dioxide emissions by about 20% per unit of electricity compared with modern PF plants. Current IGCC systems are capable of the most superior performance in respect of sulphur and nitrogen oxide emissions and solid wastes.

Electricity costs are lowest from PF units that do not need extensive flue gas treatment for removal of sulphur and nitrogen oxides. Pollution control devices for flue gas treatment can add about 20-25% to the installed capital cost of PF plant. Electricity costs for advanced IGCC are projected to be lower than that for PF with emission controls, AFBC and PFBC. Currently, however, the IGCC demonstration plants, based on state-of-the-art component technologies, are not economic.

The paper concludes that AFBC, PFBC and IGCC will all be demonstrated at about the 250-350 MWe scale later this decade, paving the way for commercial application. IGHAT may not be very far behind, but IGFC and MHD are unlikely to be considered for commercial application until 2010.

In Australia, the economic and environmental pressures driving the development of advanced coal powered technologies have not been as great as in some other OECD countries. However, developments related to technological advances, modular construction of combined cycle plant for incremental power requirements, efficiency improvements and environmental standards may jointly provide the framework for future commercialisation of the advanced technologies.

The paper summarises research carried out in advanced coal based power generation by the major electric utilities and Government research establishments in Australia. Attention is specifically drawn to the need for joint Government/industry support for demonstration in Australia of the most promising technology to facilitate introduction into domestic and overseas markets.

1. INTRODUCTION

1.1 Role of Coal in Power Generation

Electricity is a very versatile and clean energy form as far as its end use is concerned. It is no surprise that electricity is the fastest growing form of energy use in the world. Whereas electricity generation within OECD is forecast to grow at a modest 2% per annum over the next decade (IEA, 1992), growth in developing countries is estimated at about 6.6% per annum (Malhotra, 1991).

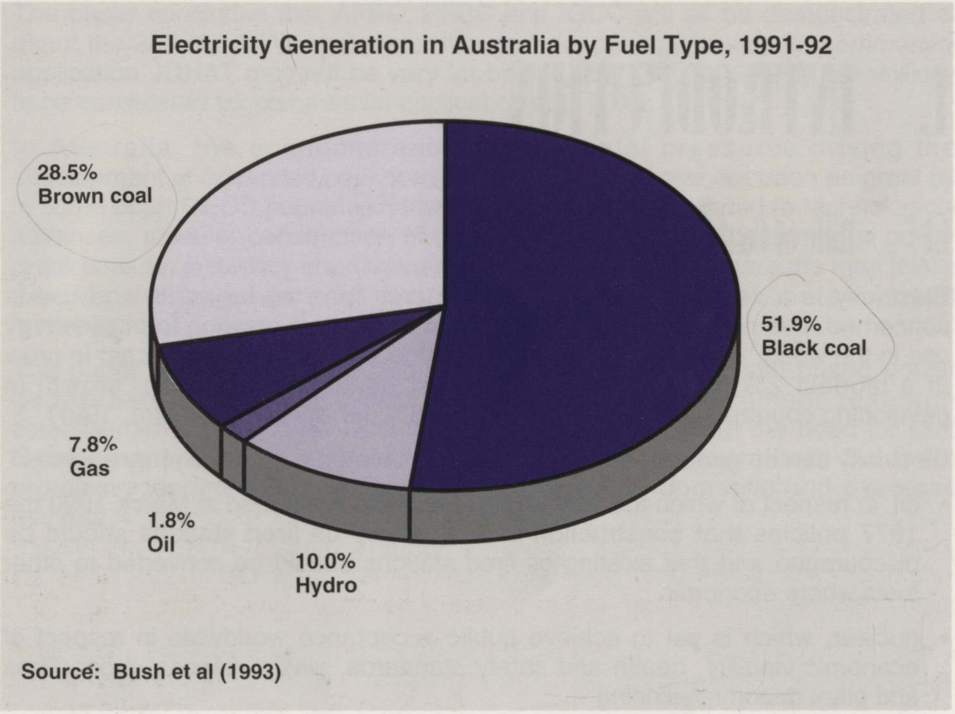
Electricity can be generated from a broad and diverse range of energy sources:

- oil, in respect of which the IEA Energy Ministers reaffirmed in March 1990 the 1977 policies that construction of exclusively oil fired stations should be discouraged and that existing oil fired stations should be converted to other fuels where economic
- nuclear, which is yet to achieve public acceptance worldwide in respect of economic viability, health and safety standards, waste disposal procedures and plant decommissioning
- hydro, which has potential which is often limited by considerations related to resource protection and environmental compatibility
- other renewable sources, such as wind, tidal, solar power and biomass, which are yet to be demonstrated for their economic viability at the required scale
- black and brown coals, which continue to dominate electricity production because of the large resource base, widespread availability and competitive prices
- natural gas, which will provide strong competition for coal over the next decade and more, provided resources are readily accessible and prices remain moderate.

Coal is, however, likely to continue to dominate electricity production here in Australia and overseas for the foreseeable future.

For the OECD as a whole, coal is the pre-dominant fuel for electricity generation, with its share of electricity generation currently at 40%. By comparison, coal currently provides about 80% of electricity in Australia.

The share of coal use for electricity generation in OECD is forecast to decrease to 38% by 2000 (IEA, 1992), mainly as a result of competition from natural gas. In Australia, coal is forecast to maintain its share to 2000 and beyond (Bush et al, 1993).



For non-OECD countries, electricity demand is forecast to increase sharply and will be as high as in OECD countries early next century. Whereas this increased demand will be met by a range of primary energy sources, the role of coal will assume greater significance.

85-90% of the new coal based electricity generation capacity is scheduled to come on stream in non-OECD countries by 2000, with the bulk of this capacity destined for the rapidly developing economies of the Asia-Pacific region.

The major challenge facing the coal based electricity industry is to meet the growing demand for electricity as reliably and cheaply as possible, while achieving increasingly stringent emission standards. The main environmental concerns emanating from the current coal based electricity generation stock are

- acid rain, based on emissions of sulphur oxides (SO_X) and nitrogen oxides (NO_X), which is of major concern, especially in the developing countries which are gearing up to expanding coal based power generation capacities
- solid residues, which include collected particulates or fly ash exiting with the flue gas, furnace bottom ash, and other residues, the disposal of which is becoming a significant issue
- carbon dioxide, an important greenhouse gas, which may impact on increased coal use in the long term.

Coal's higher carbon-to-hydrogen ratio relative to other fossil fuels means that coal produces more carbon dioxide per unit of energy delivered than other fossil fuels. New and improved coal utilisation technologies are the key to the efficient and environmentally acceptable use of coal in power generation.

A 1% increase in absolute efficiency of power generation from coal results in a 2-4% reduction in carbon dioxide emissions.

While existing capacity will continue to contribute to output, the need for new generating capacity is inevitable. Increasingly this will depend on the development and deployment of advanced clean coal power technologies.

1.2 Status of Current Pulverised Fuel (PF) Technology

For some decades coal based power generation has used PF technology, in which finely powdered coal is fed through a high velocity air stream into a pre-heated combustion chamber, where it ignites. Tubes in the combustion chamber capture the heat generated and convert the water in the tubes into high pressure steam that is used to generate electricity through turbines.

PF technology is used for electricity generation from hard coal, lignite and peat. PF plants are designed to handle a specific coal or coal blend within a determined range of coal properties, and thus are somewhat inflexible; a variation in the coal feedstock often results in loss of optimal availability and rated output. Economies of scale have favoured the evolution of fairly large-scale PF plants (up to 660 MWe). The plant size and the comparatively long start-up times after shut-downs has meant that PF plant is better suited to baseload, rather than peak-load or load following duties.

Pollution control technologies designed to be used with PF include:

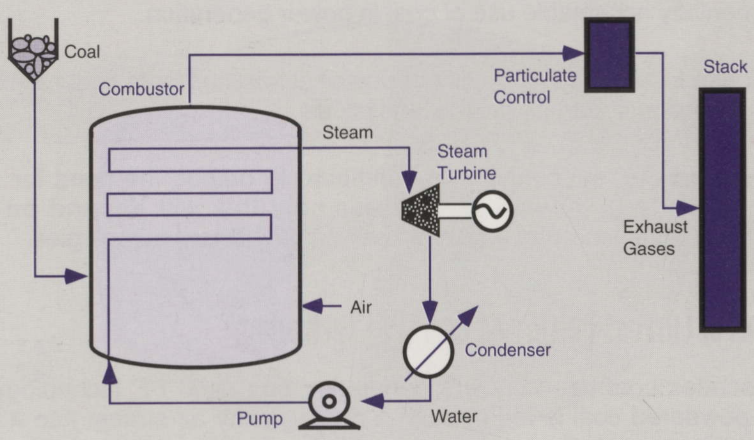
- pre-combustion cleaning of coal
- combustion control through in-furnace modifications or additions
- post-combustion treatment of flue gas for particulates (fly ash), SO_X and NO_X
- solid residues management.

No one pollution control technology or combination of technologies is appropriate for all situations. The ultimate choice of technology or set of technologies depends on the coal type and the prevailing emissions standards.

(i) Pre-Combustion Cleaning

Raw coal can be cleaned before use to reduce not only undesirable mineral matter, such as sulphur and ash, but also the coal's bulk, thus lowering transport and handling costs. Whereas coals with ash contents as high as 30%

Conventional PF Based Electricity Generation



and more have been used for PF power generation, there is an increasing trend, especially overseas, towards using coals with ash contents of 10% or lower.

The conventional physical cleaning process involves the crushing and screening of the raw coal, which is then washed to produce a lower ash product. Physical cleaning does not remove organic sulphur in the coal.

With chemical or biological cleaning, it is possible to remove ash and sulphur from coal. The cleaning costs are substantially higher than for the conventional process. In Australia, ultra-clean coal with an ash content less than 1% has been produced using chemical cleaning; commercial production is, however, unlikely until a market for this high cost product emerges.

(ii) Combustion Control

During combustion, emissions can be controlled by modification of combustion conditions or injection of a suitable sorbent into the furnace, eg limestone to trap the sulphur.

Combustion modifications have been extensively employed in commercial applications for NO_X control. The production of NO_X depends on factors such as the combustion temperature, the amount of oxygen in the furnace, and the combustion sequence, which vary with furnace and combustion system design. Modern PF burners are larger than old ones and are better designed to control coal and air flows and mixing rates during combustion. In addition, low NO_X burners, staged combustion and flue gas recirculation have been employed to specifically reduce NO_X emissions.

Emissions Reduction through Combustion Control Technologies

	% SOx reduction	% NOx reduction
Low NO_x burners	-	30-50
Staged combustion	-	30
Flue gas recycling	-	< 30
Lime injection	30-50	-
Limestone injection multistage burners	50-60	50

Sources: IEA, 1988; Bos, 1989; US Department of Energy, 1992

Furnace sorbent injection has been successfully applied for control of SO_x emissions. The technology involves injection of limestone or lime at or near burner to capture the sulphur in coal.

While these combustion control technologies achieve reduction in SO_x and NO_x emissions, they are not appropriate for application if the emission standards are so stringent that a higher reduction level is necessary.

(iii) Post-Combustion Treatment

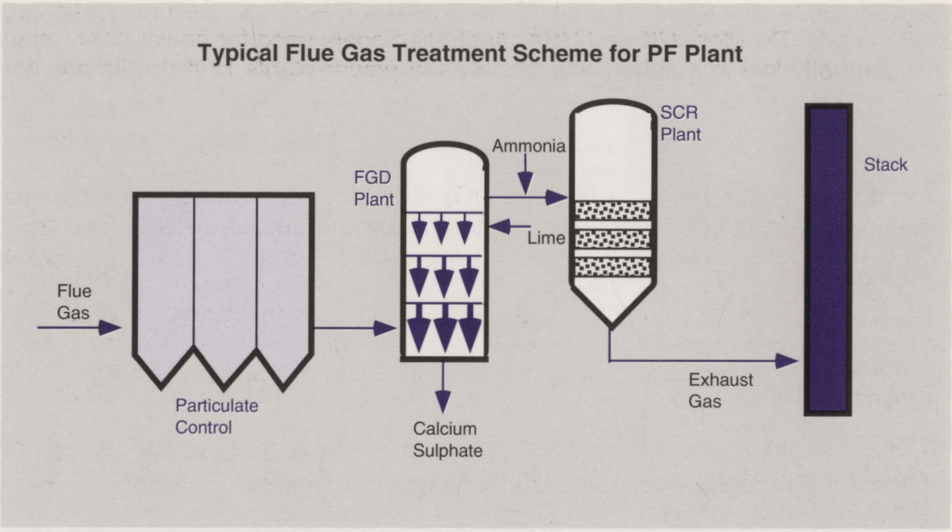
Proven technology can remove over 99% of particulates, over 95% of SO_x emissions and about 90% of NO_x emissions from the flue gases of conventional coal fired plant.

Post-combustion devices are often complex to operate, can create problems of waste disposal, can add substantially to costs, and lower the overall efficiency of the plant.

Advances in materials and manufacturing technology for equipment to control SO_x, NO_x and particulates continue to lower costs and improve reliability. This equipment can be retrofitted easily at conventional plant, thus allowing PF stations to continue to burn coal and improve their environmental performance. Indeed, most of the coal-fired capacity that will be commissioned this decade will be PF based and will increasingly include flue gas treatment for SO_x and NO_x removal.

Particulate control

In large modern PF power plants, about 80-90% of the ash in coal emerges as particulate matter in the flue gas. There are two standard particulate control



methods used in the electricity generation industry: electrostatic precipitators and fabric filters.

The electrostatic precipitators are based on applying an electric charge to the particles, which are attracted to one another and adhere to metal plates for subsequent dis-lodgement and disposal. Precipitators can remove 99.5% or more of particles by weight, but have a low level of efficiency of extraction for the very small particles.

Fabric filters, or baghouses, remove a substantial fraction of small particles, and have overall efficiencies exceeding 99.9%. The fabric filter system consists of a number of cylindrical bags which collect the particulates from flue gas.

Australian black coal power plants are mostly equipped with electrostatic precipitators, with an increasing preference for fabric filter installations in New South Wales. The brown coal power plants are fitted exclusively with electrostatic precipitators.

SO_X removal

SO_X can be removed by flue gas desulphurisation (FGD) systems, many types of which are in use or under development. One typical design is based on the use of limestone sorbent to trap SO_X; the resulting gypsum can be used in the construction industry.

The chief advantages of FGD systems are that they can be retrofitted to existing power stations and can reduce the SO_X emitted by around 95%. The disadvantages are that they entail a significant capital cost, and reduce the overall efficiency of a power station. This increases the cost, as well as increasing the amount of carbon dioxide emitted, per unit of electricity generated.

FGD systems are used extensively in Austria, Denmark, Germany, Japan, Netherlands, Sweden, UK and USA. Australian coals used for power generation are generally low in sulphur, and coal based power plants in Australia are not equipped with FGD facilities.

PROBS.

NO_X removal

Post-combustion devices to reduce NO_X emissions are based on selective catalytic reduction (SCR) or selective non-catalytic reduction (SNCR) systems. SCR systems use ammonia and a catalyst, usually a metallic oxide, to reduce NO_X to nitrogen and water vapour. NO_X removal efficiencies as high as 90% are achieved by SCR systems. SNCR systems use ammonia or urea, but without a catalyst, to reduce NO_X at a much higher temperature than SCR systems. SNCR systems are less efficient, but cost less than SCR systems and are generally easier to retrofit.

SCR systems are used in Austria, Denmark, Germany, Italy, Japan, Netherlands, Sweden and USA. Australian power plants are not fitted with post-combustion NO_X removal systems.

PROBS

Carbon dioxide removal

Whereas technology for removing carbon dioxide from PF plant flue gas is available, commercial application is not economically viable. Substantial capital investment is required for carbon dioxide removal from the flue gas, compression, transport and disposal.

An Electric Power Research Institute study has estimated that power generation costs will more than double if carbon dioxide removal is to be applied at PF plant (Torrens, 1991).

Means of reducing costs associated with carbon dioxide removal and disposal (or utilisation) are the subject of extensive research overseas. Potential technologies for removing carbon dioxide include chemical absorption, molecular sieve adsorption, cryogenic separation and membrane separation. Disposal techniques include discharge into the ocean or storage in salt domes and depleted natural gas and oil fields. Alternatives to carbon dioxide disposal are also being investigated, including biological fixation, chemical synthesis and other industrial applications.

(iv) Solid Wastes Management

PF power plants generate three types of waste: collected particulates or fly ash, bottom ash which is collected from the bottom of the furnace, and FGD wastes. These solid wastes can become a major constraint to increased coal use in countries where suitable land for disposal is not readily available.

In Australia, about 8 million tonnes of ash is produced annually, almost 90% of which is fly ash. Only about 0.8 million of the fly ash is currently used, mainly in the building and construction industries. The remaining ash is mostly slurried with water prior to disposal in an ash pond, although there is now an increasing preference for dry disposal by landfill. Leaching of trace elements from the ash needs monitoring as it has the potential to contaminate adjacent groundwater.

Most FGD systems in commercial application overseas use wet processes with lime or limestone. The resultant sludge can be processed to yield gypsum which is suitable as a material for the building industry. Where there is no market for this gypsum, the sludge is thickened and disposed.

2. ADVANCED COAL BASED POWER GENERATION OPTIONS UNDER DEMONSTRATION

The initial impetus for the development of advanced coal based power technologies came not from a primary focus on efficiency, but rather from the difficulties experienced in the USA and Europe in adapting conventional PF technology to increasingly demanding requirements for low emissions of SO_x NO_x and particulates. In fact, modification of the basic PF technology, to incorporate emission controls, lead to increased costs and lower efficiencies. The more advanced coal based power generation technologies, by integrating pollution control in the overall process, offer an improved alternative. Moreover, in the longer term, pressures to reduce carbon dioxide emissions will favour such technologies with their capacity for higher thermal efficiencies and therefore lower emissions of carbon dioxide per unit of output.

In the USA considerable efforts have been made to demonstrate a new generation of clean coal technologies. The combined commitments by the US Federal Government and the private sector to the demonstration program amount to US$6.9 billion, of which US$5.1 billion was allocated to advanced coal based power generation systems.

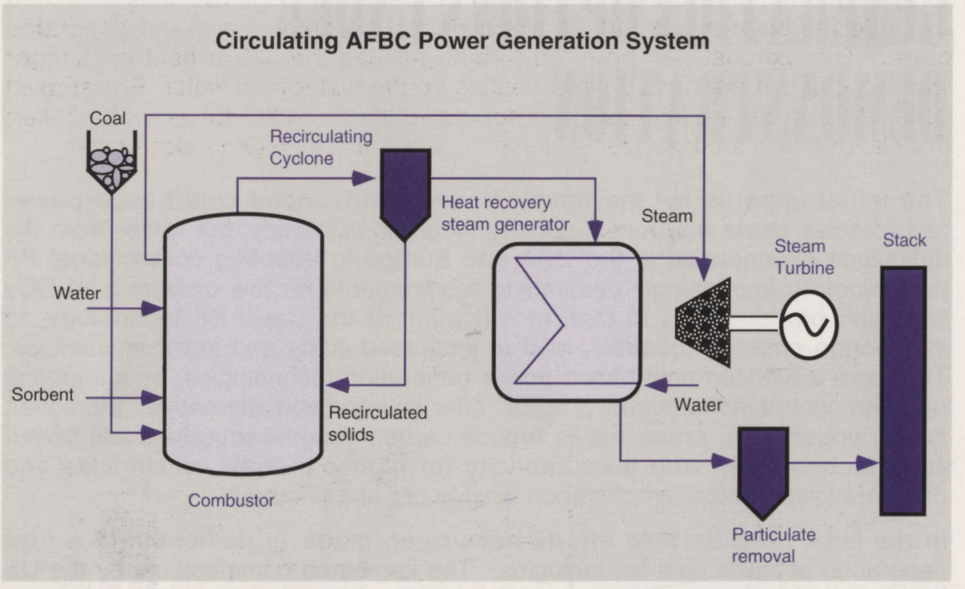
Another factor favouring the introduction of the advanced power technologies is the realisation that the economies of scale associated with current PF systems may no longer exist, making centralised large scale power stations supported by extensive transmission lines unnecessary. The new generation of advanced coal based power generation technologies, which are amenable to moderately sized modular construction, offer advantages related to shorter construction times, lower risk associated with load loss, and greater flexibility in matching capacity additions and retirements with changes in demand. The likely future trend in the power generation industry is towards decentralisation and incremental additions to capacity.

These new technologies are already finding commercial application in countries where stringent environmental standards dictate that new PF capacity needs incorporation of FGD and SCR facilities.

2.1 Atmospheric Fluidised Bed Combustion (AFBC)

AFBC is the most developed of the advanced coal combustion technologies. This involves the injection of limestone and coal into a bed of hot particles (usually sand) suspended or 'fluidised' by a stream of air from nozzles at the bottom of the combustion chamber. SO_x formed during combustion reacts with the limestone to form calcium sulphate, which falls to the bottom of the furnace.

SO_x removal efficiencies of 90-95% can be achieved (IEA, 1988). Moreover, because the combustion temperature is low at around 800-950^{o}C compared with 1600^{o}C for PF systems (McIntosh, 1990), the amount of NO_x formed is less.



Circulating AFBC technology, in which coal and bed material circulate together through the plant to ensure complete combustion, is suitable for power generation. The air stream carries the solids through a hot cyclone where the solids are separated and a portion recirculated to the combustor. The hot gases from the cyclone enter the convective section where heat exchange occurs for steam raising. Steam generated in the combustor and the convective section is used to generate power. The flue gases pass through a bag filter or electrostatic precipitator before passing to the stack.

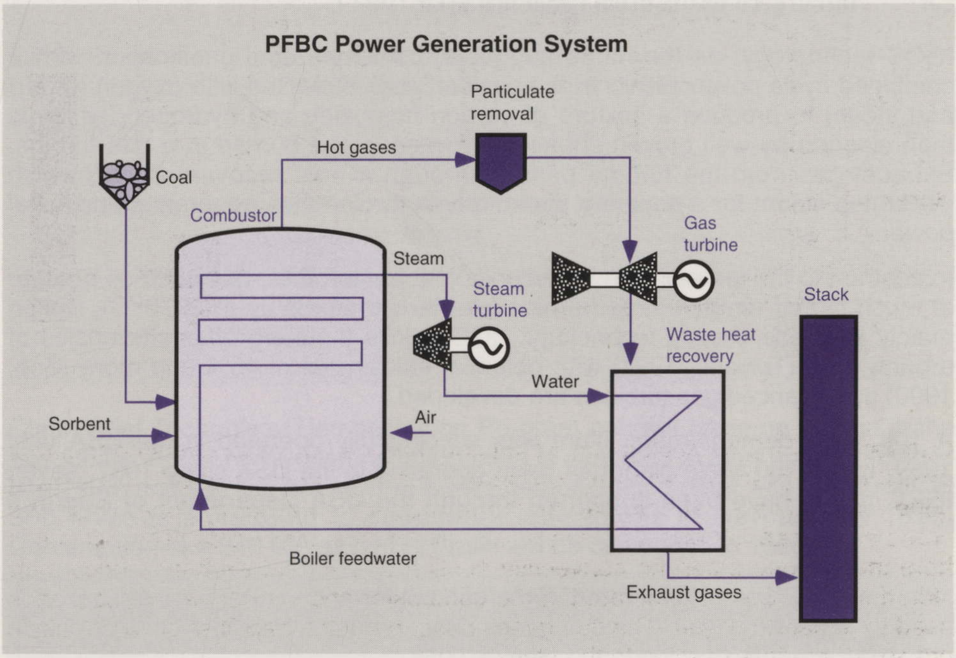
Circulating AFBC technology can operate on a relatively wide range of coals, and for a given physical size has a higher capacity, and a much quicker start-up time, than a PF unit. Circulating AFBC plants are suitable for base load, fluctuating load and load following conditions.

The biggest AFBC units being used for power generation have electrical output capacities of around 125 MWe. Larger units will have outputs of more than 250 MWe but are still to be demonstrated (Lucat, 1992; US Department of Energy, 1992).

Circulating AFBC units promise to be viable alternatives to conventional coal fired units in situations where NO_x emission standards are not so strict as to require flue gas treatment. Compared with conventional units, AFBC wastes are greater because of limestone injection and often need upgraded particulate control for capture from the flue gas stream.

2.2 Pressurised Fluidised Bed Combustion (PFBC)

In PFBC coal is burnt in a bubbling fluidised bed at a pressure typically of 12-16 atmospheres and temperatures of around 850^{o}C (Jansson, 1991; McIntosh, 1990). The hot, pressurised flue gases are cleaned through cyclones, and then expanded through a gas turbine which drives the compressor and generates power. The exhaust gas from the turbine passes through a heat exchanger where the gases are cooled while heating up the boiler feed water. Pressurised boiler feed water is converted to superheated steam in the tubes in the boiler; this steam drives a conventional steam turbine which also generates power.



The use of both a gas turbine and a steam turbine (combined cycle) means that PFBC technology can attain efficiencies of 40% or better (Torrens, 1991), resulting both in lower fuel costs and lower carbon dioxide emissions per unit of electricity compared with large PF plant. It also has the other advantages of fluidised bed combustion, namely low SO_x and NO_x and a measure of fuel flexibility, but it is more complex than AFBC.

PFBC units with capacities of 70-80 MWe are currently operating in Spain, Sweden and USA, with another unit to be operational in Japan this year (Tornerefelt, 1992). Higher capacity PFBC plants at 350 MWe are likely to evolve, with the advantages of higher efficiencies, lower fuel costs, higher environmental performance and compact physical size. The compactness means that PFBC units are well suited to space-constrained sites and modular construction.

The environmental characteristics and compactness of PFBC offers advantages in terms of retrofitting or repowering, allowing outdated coal power plants to be cleaned up while their output and efficiency are simultaneously increased. However, large scale application of PFBC requires further developments in the areas of hot gas cleaning by filtration under pressure and materials improvement to minimise corrosion and erosion. Flue gas treatment for NO_x removal may also be necessary for PFBC units if NO_x emissions are to be reduced by 90% or more.

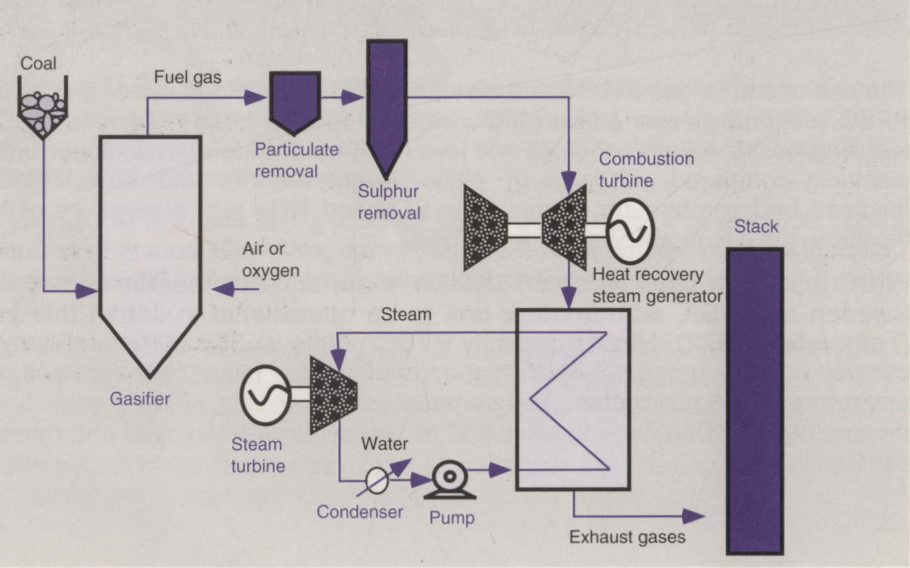
2.3 Integrated Gasification Combined Cycle (IGCC)

IGCC technology, as the name suggests, combines coal gasification with a combined cycle power plant. In the gasifier, coal is reacted with oxygen (or air) and steam to produce a mixture of carbon monoxide and hydrogen, which is then cleaned by well proven chemical processes and burned in a gas turbine. Exhaust gas from the turbine passes through a heat recovery boiler, which generates steam for a separate steam-driven turbine thus generating additional power.

In contrast to the temperature limitations of steam turbines, gas turbines operate at much higher temperatures (turbine inlet temperatures up to 1270^{o}C), limited mainly by blade cooling technology. IGCC units therefore offer efficiencies of around 42% (Torrens, 1991) with potential efficiencies of 45% and more (Zon, 1990) as advanced gas turbines are developed.

A 100 MWe demonstration plant was successfully operated in the USA until 1989, and a 160 MWe plant has been operating in the USA since 1987; seven IGCC plants have been supported through the USA Department of Energy's

IGCC Power Generation System



USA Clean Coal Technology Demonstration Program - IGCC Projects

Project	Location	Capacity (MWe)
Camden	Duke Energy Corporation Station, Camden, New Jersey	480
Cleveland	Centerior Energy Corporation COREX Plant, Cleveland, Ohio	150
Pinon Pine	Sierra Pacific Power Company's Tracy Station, Reno, Western Nevada	80
Polk Power	Tampa Electric Company's Polk Power Station, Lakeland, Florida	260
Springfield	City Water, Light and Power's Lakeside Station, Springfield, Illinois	65
Toms Creek	ANR Coal's Toms Creek Mine, Coeburn, Virginia	55
Wabash River	PSI Energy's Wabash River Station West Terre Haute, Indiana	265

Clean Coal Technology Demonstration Program and will come on stream in the late 1990s. A 250 MWe demonstration plant is expected to start up in Holland in late 1993, and the first brown coal based demonstration plant with a capacity of 300 MWe is scheduled to commence operations in Germany in 1995. Construction of a 340 MWe plant in Spain will be completed in 1996.

IGCC has the best near-term potential for clean use of coal and reduction of SO_x and NO_x per kWh generated. Its environmental performance is exceptionally good, with very low SO_x and NO_x emissions.

Its solid waste products in the form of inert vitreous slag have a number of applications in the construction industry, and the sulphur is recovered in the marketable form of pure sulphur or sulphuric acid.

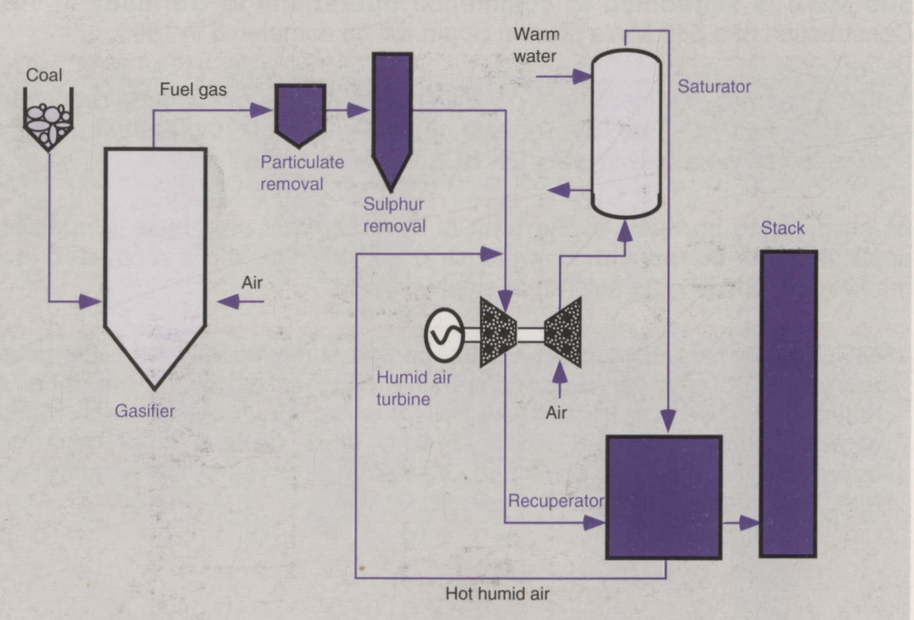
IGCC plants have the added advantage that current combined cycle units run on natural gas can be switched to run on gasified coal if the price of natural gas rises enough to make it worthwhile. Such an approach would allow the utilities to obtain capacity quickly, since the lead time required to build a natural gas-fired combined cycle plant (2-3 years) is less than that for a complete IGCC plant (3-4 years).

3. FUTURE ADVANCED COAL BASED POWER GENERATION OPTIONS

3.1 Integrated Gasification Humid Air Turbines (IGHAT)

IGHAT is similar to IGCC except that in the former a single gas turbine replaces the gas and steam turbines of IGCC. In IGHAT, rather than having air pass directly from the compressor stage of a gas turbine into the combustion stage, it is diverted into a cooler and then into a vessel known as a saturator. The compressed air flows upwards against a stream of water that has been heated using the gas turbine exhaust, the compressed air cooler, and any other sources of low-level heat. When the air leaves the top of the saturator it has been humidified to between 10% and 40% water vapour. This humidified air is then further heated by the turbine exhaust and sent to the combustor, where fuel is added and burned. IGHAT gains efficiency by greatly increasing the mass flow through its expansion stage for a given amount of air flowing through the compressor and by having a higher input temperature to the combustor, relative to IGCC.

IGHAT Power Generation System



IGHAT could achieve efficiencies of 42% (Torrens, 1991; Cook et al, 1991), without using a steam bottoming cycle but still reclaiming low-level heat that would be difficult for other cycles to utilise. In addition, the capital cost of IGHAT is expected to be around 20% lower than IGCC. This is because IGCC needs expensive coolers to cool the coal gas for steam raising: instead with IGHAT the coal gas could simply be quenched with water.

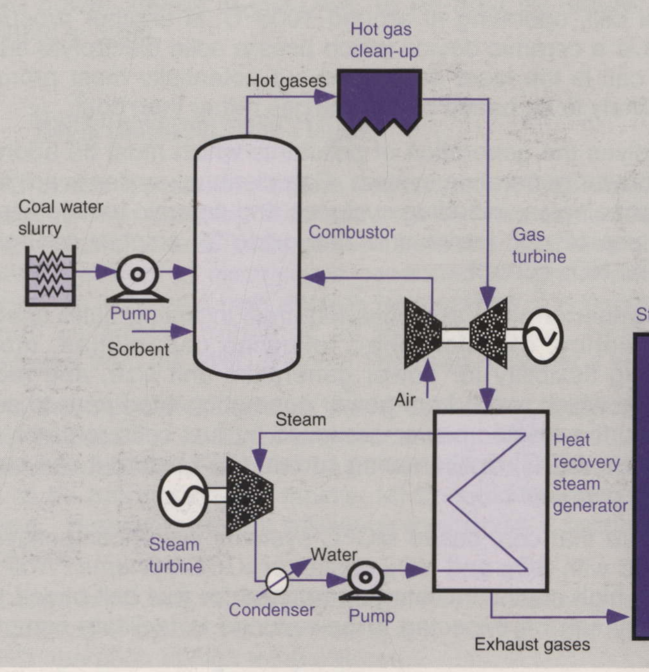
IGHAT is currently being developed in the USA. Full scale demonstration is not expected until 1996.

3.2 Direct Coal Fired Turbines

Combustion turbines have historically been limited to burning the traditional clean fuels such as natural gas and oil. Efforts to burn coal directly have been frustrated by erosion, corrosion and ash deposition problems of the turbine blades. With advances in coal cleaning and combustion technologies, there has been a revival of interest in direct coal firing of turbines.

Considerable research effort is underway in the USA by Solar Turbines, General Motors (Allison), Westinghouse and General Electric to investigate utility and cogeneration applications. The power generation cycle comprises a pressurised slagging combustor, hot gas clean-up, and a combustion turbine exhausting to a heat recovery steam cycle. Efficiencies in the order of 43% (Scalzo et al, 1991) have been estimated.

Direct Coal Fired Turbine Power Generation System



Initial results from the slagging combustor fired with coal and coal-water mixtures have been promising (Bannister et al, 1992), as have results from a 4 MWe turbine fuelled with coal-water mixtures (Wilkes, 1992). However, considerable additional research is anticipated for improved ash removal, hot gas clean up, combustion turbine configurations and integrated operation.

Most developers agree that current development programs will need to be successful prior to demonstration at about the 50 MWe scale to establish technical and economic viability. Commercial application therefore seems unlikely before the year 2000.

3.3 Integrated Gasification Fuel Cell (IGFC)

IGFC combines coal gasification with a fuel cell that converts the chemical energy of the fuel gas into electrical energy by a direct electrochemical process. Basically, a fuel cell consists of an electrolyte in contact with a porous anode and cathode. The fuel gas combines electrochemically with oxygen ions to form water, carbon dioxide and electricity.

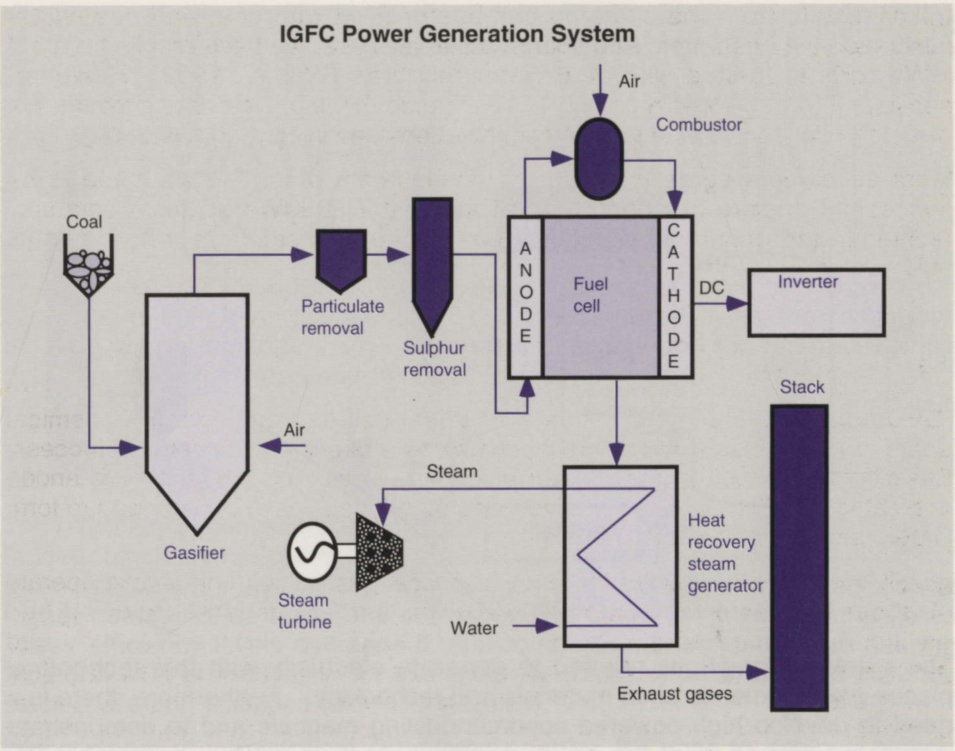
Ideally the fuel cell selected for use with a coal gasification unit should operate at about the same temperature as the gasifier. In general, fluidised bed gasifiers produce fuel gas in the 650 - 1000^{o}C range while entrained bed gasifiers produce gas at 1000^{o}C and more. One choice of fuel cell is the molten carbonate fuel cell (MCFC), with an electrolyte of lithium and potassium carbonates, operating at around 650^{o}C. Unconverted fuel from the cell is combusted, and this heat, along with heat generated from the gasification process, can be recovered in the steam bottoming cycle which produces additional electricity.

The solid oxide fuel cell, operating at around 1000^{o}C, is another prospective alternative. The cell is a ceramic device which uses a solid electrolyte such as yttria-zirconia. The cell is the least developed but potentially most promising. Initial application is likely to be based on natural gas rather than coal.

The use of coal involves the generation of pollutants which must be addressed in an overall IGFC power generation system. Gas clean up systems are similar to those of other technologies, including cyclones and ceramic candle filters for particulate control; use of zinc ferrite and zinc oxide for sulphur control; and staged combustion for NO_x control.

Fuel cells have a number of other attractive features, including quiet operation, high part-load efficiency, excellent load following capabilities, modular construction providing flexibility for power generation unit size, and reduced losses in transmission which result from power generation sited near to centres of demand. However, the electric power produced by fuel cells requires costly inversion of direct current (DC) to alternating current (AC) before it can be used by present distribution systems.

Current indications are that coal based MCFC systems are uncompetitive with PF systems equipped with SO_x and NO_x control or IGCC systems (Wolk et al, 1991). However, the high capital investment required for fuel cell based power generation technology can be expected to be reduced to facilitate commercial application.



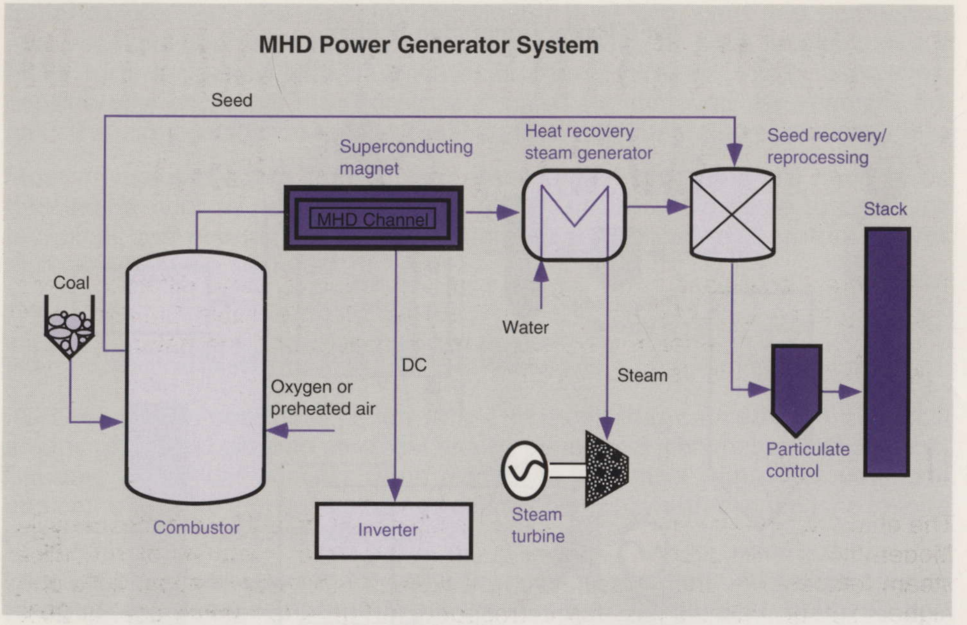
Fuel cells are still in the pilot plant stage and it is unlikely that IGFC will become commercially available before 2005. The largest planned MCFC test facility is a 2 MWe power station in the USA, to be fired by natural gas, which will be completed in 1994.

3.4 Magnetohydrodynamics (MHD)

In MHD power generation, coal is combusted at 2000-2500^{o}C. The hot gases are seeded with potassium compounds to form an ionised plasma that can conduct electricity, and finally passed between the poles of a superconducting magnet. A current of electricity is generated at right angles to the direction of gas flow. To achieve a high enough temperature, it is necessary to use oxygen enriched air and/or preheated air for combustion. Heat can be recovered downstream from the MHD channel and used to power a steam cycle.

MHD is the only advanced coal power technology that can burn and use coal directly without the need for pre-processing. MHD would appear to be quite flexible in its ability to respond to power system requirements. Because of its ability to be brought on-line rapidly, MHD could be most suitable for fast load following. However, its high efficiency may make it suitable also for base load applications.

Coal based MHD has recently undergone initial testing in a 1.5 MWe unit in the USA. Extensive emissions monitoring and control data are still to be collected for MHD operation at high temperatures.



The extreme conditions needed to generate electricity with this technology places great demands upon materials and technology. Furthermore, there is a need to develop high powered superconducting magnets and to demonstrate integrated operation of the entire power system. Like fuel cells, only DC electricity can be produced, thus requiring costly conversion to AC. This means that MHD is not expected to reach commercialisation until well into the next century.

4. COMPARATIVE ASSESSMENT OF CURRENT AND NEW TECHNOLOGIES

The different coal based power generation technologies serve different needs, according to the size of plant required, the type of fuel available, the desirability of using waste material, the physical area available and the nature of other power generation plants in the system.

4.1 Efficiency

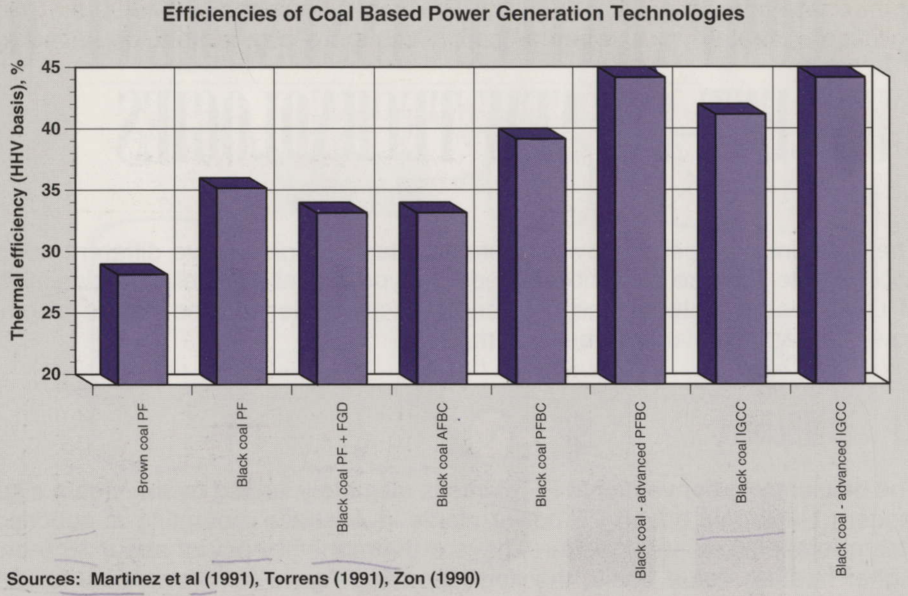
The efficiency in conventional PF plants is ultimately limited by the steam cycle. Modern black coal based PF power plants in Australia, operating at subcritical steam temperature and pressure, have a thermal efficiency of about 36% on a higher heating value basis; the corresponding figure for brown coal is 29%. These efficiency levels decrease if post-combustion treatment of flue gas for SO_x and NO_x is necessary; for example, the efficiency level drops to 34% for black coal plant, equipped with FGD facilities.

Using steam at supercritical conditions enables PF units to achieve higher efficiencies, although this poses challenges for turbine metallurgy. New working fluids to replace steam, eg ammonia/water mixtures (as in the Kalina cycle), have also been proposed to increase efficiencies, but considerable research will be necessary to introduce these fluids to coal based power generation and to ensure compatibility with materials and equipment.

For AFBC, efficiency at about 34% for black coal plant is comparable with current PF plant, equipped with FGD facilities. With PFBC, the use of both a gas turbine and a steam turbine in combined cycle operation enables efficiency levels of 40% or better to be achieved for black coal; an increase to 45% or more is possible using a topping cycle incorporating additional firing of products from a coal gasifier to raise the inlet temperature to the gas turbine.

IGCC systems currently offer efficiencies of around 42% for black coal, but are capable of efficiencies of 45% and more with advances in hot gas clean-up and high efficiency gas turbines.

> Advanced PFBC and IGCC systems therefore have the potential to achieve efficiencies as high as 45% in the near term for black coal, thus reducing carbon dioxide emissions by about 20% per unit of electricity compared with modern PF plants.



Sources: Martinez et al (1991), Torrens (1991), Zon (1990)

The advanced coal based technologies such as IGHAT, direct coal-fired turbines, IGFC and MHD are also considered to offer opportunities for increased efficiency, but their technical viability has not been established beyond the current conceptual stages. In the case of IGHAT and direct coal-fired turbines, efficiencies are unlikely to exceed 45% but costs may be lower than for PFBC and IGCC. For IGFC, conversion efficiencies of around 45-50% have been estimated (Hishinuma and Abe, 1991; Torrens, 1991); and for MHD, overall efficiencies of 50-60% are anticipated (Messerle, 1991; Morrison, 1993).

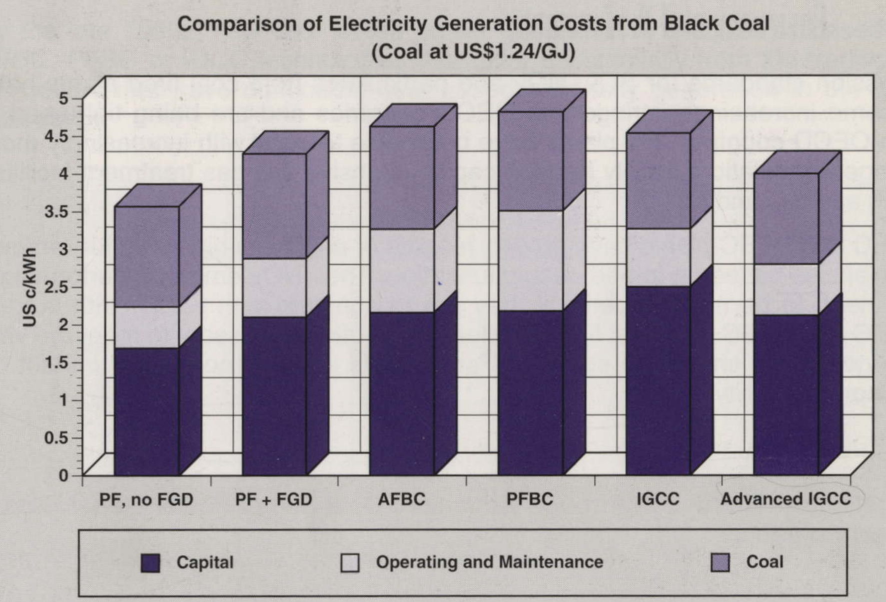
4.2 Costs

Currently, PF units burning low-sulphur coals generate the cheapest electricity. The cost advantage of PF technology depends critically on the environmental performance the plant must achieve and the quality of fuel to be burned.

Once SO_X and NO_X devices are added to a PF unit, its cost advantage diminishes considerably. The cost of electricity from PF units increases as these pollution control devices are added, mainly due to increases in the capital cost component and to a lesser extent from increases in the operating and maintenance costs.

Pollution devices for control of particulates, SO_X and NO_X can add 25-30% to the installed capital cost of conventional coal fired plant.

The overall electricity generation costs from AFBC plants are expected to be somewhat higher than that from the PF plants equipped with SO_X and NO_X pollution control devices; whereas capital costs are comparable, operating and



Source: Wolk et al (1991)

maintenance costs are higher. The prospects for circulating AFBC technology are greatest for repowering of existing plant which needs to meet new emission standards and where site area is not adequate for additional facilities for SO_X and NO_X control; in repowering applications, plant life can be extended by use of existing coal and waste handling equipment and steam turbine assembly.

Electricity generation costs from PFBC plants are even higher, mainly because of the higher capital costs and higher operating and maintenance costs, compared with PF plants equipped with SO_X and NO_X pollution control equipment. PFBC plants are very compact due to pressurised operation and will increasingly find application in retrofitting existing plants where available space is very limited and new more stringent environmental regulations apply.

The overall electricity generation costs projected for advanced IGCC are lower than that of PF with SO_X and NO_X emission controls, AFBC and PFBC, mainly because of the higher efficiency of IGCC relative to the others. Currently, however, the IGCC demonstration plants, based on state-of-the-art component technologies, are not economic.

Whereas cost estimates for IGHAT, IGFC and MHD concepts have been put forward, a meaningful comparison is not possible because of the very preliminary nature of these estimates in the absence of construction or operational experience.

4.3 Environmental Performance

Emission standards for SO_x, NO_x and particulates from coal fired plants have become increasingly stringent in OECD countries and are being tightened in non-OECD countries. PF plants have been able to cope with increasingly more stringent regulation, mainly through capital intensive flue gas treatment facilities such as FGD and SCR.

AFBC and PFBC plants have proven records of achieving high sulphur removal efficiencies based on in-bed desulphurisation. Their NO_x emission performance will need to be more superior if they are to compete with IGCC; with current AFBC and PFBC systems, flue gas clean up is often necessary to meet the very stringent NO_x emissions standards and this is likely to negatively impact on economic viability.

Emissions Reduction through Advanced Coal Based Power Generation Technologies

	% SOx reduction	% NOx reduction
PF + FGD + SCR	95+	90
AFBC	90	50
PFBC	90+	50+
Advanced PFBC	95+	80+
IGCC	98	95
Advanced IGCC	99+	95+

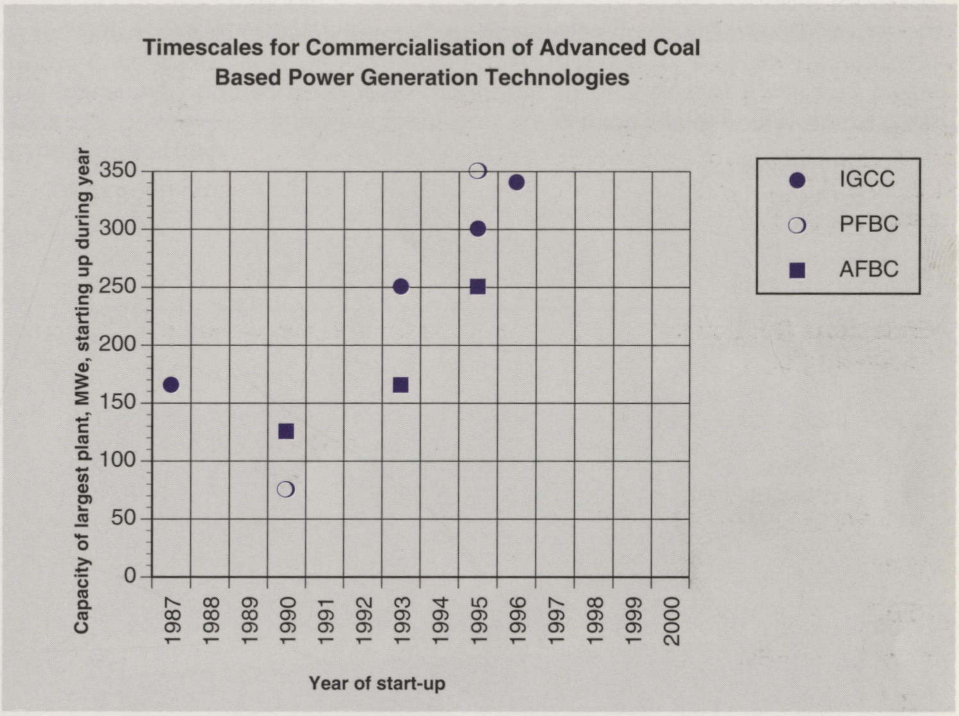
Source: US Department of Energy, 1990

Current IGCC systems are capable of the most superior performance in respect of SO_x and NO_x emissions. They also result in the least amount of solid wastes, as there is no need for use of lime or limestone to capture sulphur dioxide within the combustion system or in the flue gas.

IGHAT and IGFC technologies have the potential for achieving even greater reduction in emissions.

4.4 Timescale for Deployment

By the late 1990s, new coal based power generation is likely to be based on AFBC, PFBC or IGCC technologies that differ substantially from the traditional PF boilers that have dominated coal based electricity generation in the past decades.



AFBC, PFBC and IGCC technologies will all be demonstrated at about the 250-350 MWe scale later this decade, paving the way for commercial application.

IGHAT may not be very far behind, but IGFC and MHD are unlikely to be considered for commercial application until 2010 (Hishinuma and Abe, 1991; Messerle, 1991; Morrison, 1993).

5. THE AUSTRALIAN CONTEXT

In the Australian context, black and brown coals are the dominant fuels for electricity generation. Two-thirds of the total 35 GWe installed generating capacity is based on coal. A total of 17 GWe generating capacity is based on black coal and 6 GWe on brown coal, and all use PF technology.

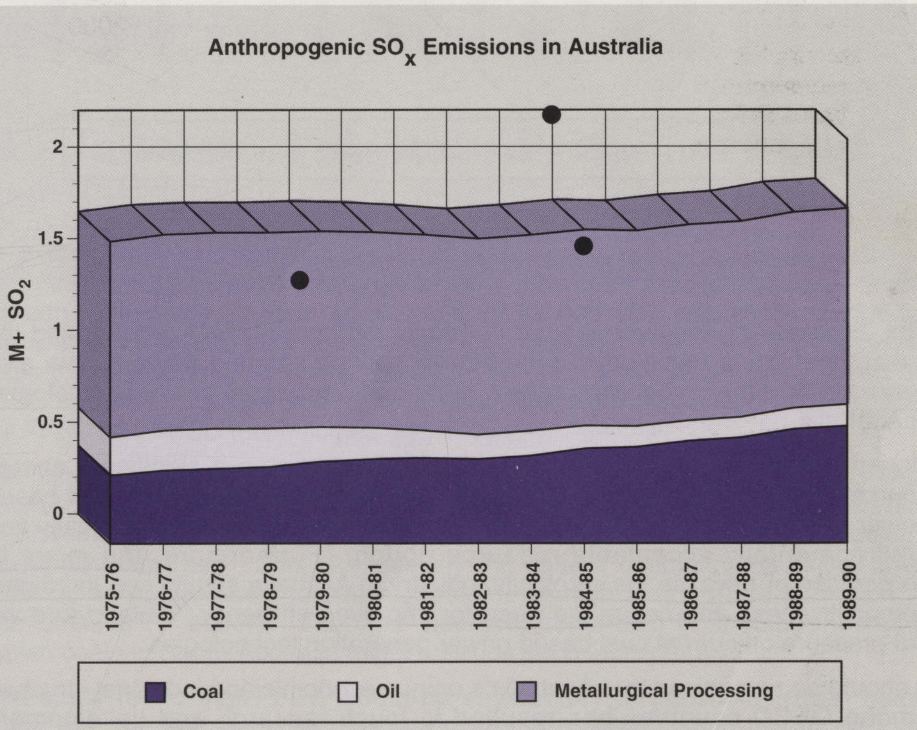
Coal Based Electricity Generation Capacity (MWe) in Australia

New South Wales (black coal)	
Bayswater	2640
Erraring	2640
Liddel	2000
Mount Piper	1320
Munmorah	600
Vales Point	1320
Wallerawang	1000
Queensland (black coal)	
Callide B	700
Gladstone	1650
Swanbank	678
Tarong	1400
South Australia (brown coal)	
Northern Units 1 & 2	500
Thomas Playford B	240
Victoria (brown coal)	
Hazelwood	1600
Loy Yang A	2000
Morwell	170
Yallourn W	1450
Western Australia (black coal)	
Muja	1040

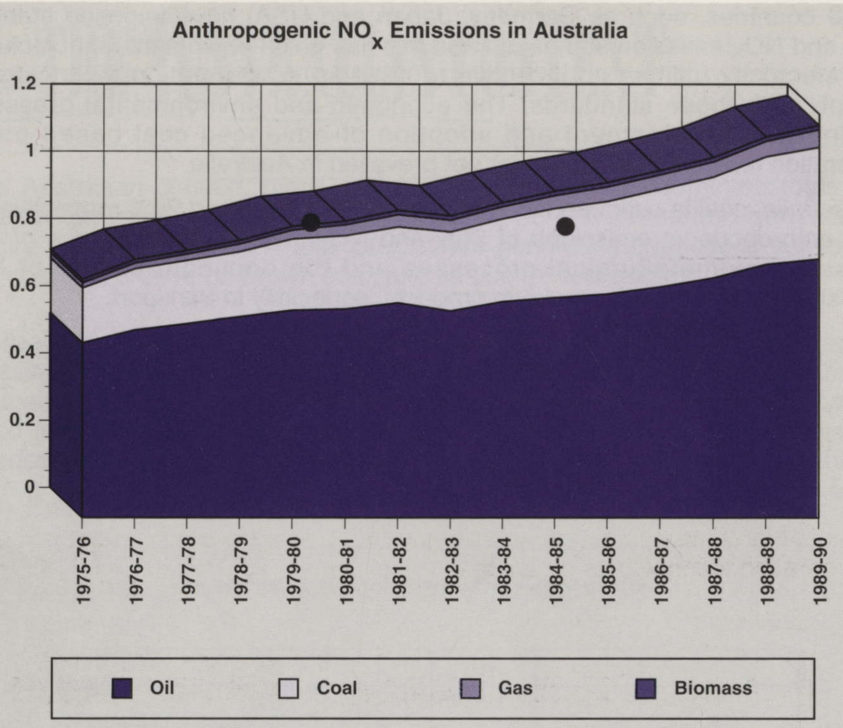
Some countries, such as Germany, Japan and USA, have imposed stringent SO_X and NO_X emission standards, and this has given equipment manufacturers and electricity utilities an incentive to develop power station technology to comply with those standards. The economic and environmental pressures driving this development and adoption of advanced coal based power generation technologies has so far not prevailed in Australia.

In Australia, coal is estimated to account for about 25% and 20% respectively of total anthropogenic emissions of SO_X and NO_X. The principal source of SO_X emissions is metallurgical processes and the dominant source of NO_X emissions is the use of petroleum products, especially in transport.

Unlike other OECD countries, where SO_X and NO_X emissions from fossil fuel based electricity generation have been or are being reduced, these emissions will increase in Australia with increased fossil fuel use for electricity generation; the emissions need to be closely monitored to ensure that fossil fuel based electricity generation capacity expansions are compatible with the environment at the regional level.



Sources: Varhelyi (1985) for 1979 emissions data point; Australian Environment Council (1989) and one of its references for 1984-85 emissions data points



Source: Hameed and Dignon (1988) for 1980 emissions data point; Australian Environment Council (1989) for 1984-85 emissions data point

The existence of adequate electricity generation capacity in Australia, and the substantial costs involved in prematurely retiring existing plant, have also served to limit the introduction of new higher efficiency coal power technologies in Australia.

Nevertheless, because of coal's position in Australia as a significant energy source, both for domestic requirements and for export, advanced coal based power generation technologies will help to make coal a more economically and environmentally acceptable resource option. Furthermore, the move to corporatise or privatise the electricity industry in Australia should see increased competitiveness and hence the need for improved efficiency. This in turn will put pressure on current coal based power generation technologies.

It should be recognised that Australia's unique economic and industrial structure among OECD countries has resulted in much research and development associated with power generation being more appropriately performed elsewhere. Because of the costs involved in undertaking research and development in this area, Australia has generally been an importer of the technologies, although there is a possibility of being involved in the supply of some components in niche markets.

The long lead times in developing these technologies to commercialisation and the considerable financial commitments involved are often beyond the financial capabilities of many individual nations. International energy research cooperation is necessary not only for these reasons, but also to avoid unnecessary duplication, to achieve economies of scale and scope, and to pool resources. Much of the research, development and commercialisation of advanced coal based power generation technologies has involved huge joint efforts by the private and public sectors.

Users of the advanced coal based power generation technologies in Australia may require the construction of demonstration plants in order to establish reliability and performance characteristics. These demonstrations would also facilitate the export of the technologies to developing countries in the region. Demonstrations are critical to achieving commercialisation, but are costly and pose a significant financial risk, eg the 250 MWe IGCC demonstration plant in Holland has been estimated to cost US$ 462 million (1989 dollars). Accordingly, Government and industry could justifiably share the risk to accelerate the introduction of these new technologies. This has certainly been the case under the US Clean Coal Programme.

Australia is carrying out research into advanced coal based power generation technologies on a number of fronts.

5.1 Commissioned Study into Alternative and Advanced Power Generation Technologies

In August 1991, Ewbank Preece Sinclair Knight reported on a study of alternative and advanced power generation options for the Australian electricity industry. The study, carried out at a cost of A$ 400 000, was jointly funded by the Energy Research and Development Corporation (ERDC) and the Electricity Supply Association of Australia. Although detailed investigations were based on IGCC applications for black and brown coals, the study also assessed prospects for AFBC and PFBC technologies.

The study indicates that if it were necessary to generate electricity from a high sulphur coal in Australia, where coal costs are generally low, and efficiency improvements are not a major goal, a change to circulating AFBC technology would be warranted. This is especially the case if contaminants in the coal, such as salts, are likely to cause problems of high temperature corrosion in conventional PF boilers. Thus, for example, generation from sulphur-bearing brown coals in South Australia might well use such technology.

The study found that PFBC would be satisfactory for most Australian black coals, but that the electricity cost (approaching 6 c/kWh) using this technology would be significantly more than that using PF technology (3-4 c/kWh), where the PF plant does not need FGD facilities. There may be some situations in which PFBC could make viable the use of cheap coal with heavy fouling tendencies and/or high sulphur content. There is no experience of the use of PFBC with Victorian brown coal.

The study also found that on cost and performance grounds IGCC plants are not likely to be immediately attractive for Australian black or brown coals.

Electricity generation costs are likely to exceed 5 c/kWh. However, special forms of IGCC tailored to Australian coals and conditions, with simplified gas clean-up, but which would meet present and likely future SO_x and NO_x emission standards in Australia, could be more competitive. Furthermore, IGCC technology lends itself to cost savings from phased construction from peak, through intermediate and finally to base load uses, allowing capacity to be brought on stream progressively.

5.2 Electricity Industry Research

The major electric utilities in Australia are all carrying out research into advanced coal based power generation technologies.

The Electricity Trust of South Australia (ETSA) is assessing the suitability of circulating fluidised bed combustion technology for salty brown coals such as Lochiel coal. The pilot scale facility, located at Osborne, will determine the performance of Lochiel coal under circulating AFBC conditions and the long-term behaviour of refractories and metals located in the high temperature zones. ETSA is also maintaining an interest in coal gasification.

Pacific Power has a significant interest in IGCC which is being pursued through its sponsorship of an Advanced Technology Centre at the University of Newcastle. This Centre will deal with power engineering technology, including IGCC. Pacific Power is also considering a program of investigations culminating in construction of a demonstration plant, including studies into technical feasibility, power systems implication, and prototype design.

The State Electricity Commission of Victoria (SECV) is conducting a strategic program into new technologies for power generation from brown coal. The program has included steam fluidised bed drying, hydro-thermal drying, direct coal fired turbine, and integrated gasification combined cycle. Steam fluidised bed drying technology, which reduces the moisture content of brown coal from 60% to 15%, was successfully tested by the SECV. The technology is the basis for the development, by Lurgi, of the 150 000 tonnes per year dried coal which will be used by SECV as auxiliary fuel. Hydro-thermal drying technology has been tested at pilot plant scale, producing 400 kg per hour of coal-water slurry, to facilitate experiments with a 200 kW gas turbine. Whereas the coal-fired turbine has produced promising results, the most prospective power generation technology for the near future would appear to be IGCC, and SECV has already achieved satisfactory gasification results with its 200 kg per hour process development unit.

5.3 Government Research

In 1992, the Government announced the establishment of a Cooperative Research Centre for new technologies for power generation from low rank coal, aimed at research into process design and optimisation, coal beneficiation and combustion, and fluid bed drying, gasification and combustion processes. The Centre will involve cooperation between SECV, ETSA, Monash University, University of Adelaide, CSIRO Division of Mineral and Process engineering, ICAL Ltd, and Lurgi (Australia) PTY Ltd. The Centre will receive funding of about $2 million a year over seven years.

The CSIRO Division of Coal and Energy Technology is involved in IGCC research aimed at investigating the behaviour of Australian black coals under gasification conditions. The research is mainly aimed at identifying issues which may arise for IGCC applications and seeking improvements. Specific research topics include the slagging of ash in the gasifier, the use of fluxing agents to assist slagging, and the pyrolysis and reactivity of coal in the high pressure conditions within the gasifier.

The CSIRO Division of Materials Science and Technology is carrying out research into the solid oxide fuel cell system. Within three years, the researchers aim to perfect methods of stacking cells in series for a 100We module. An all Australian owned company, Ceramic Fuel Cells Ltd, comprising BHP, CSIRO, ERDC, Pacific Power, SECV and Strategic Research Foundation, has been established to commercially develop the technology.

Research is also underway in selected aspects of advanced power generation technologies at Monash University, University of Adelaide and University of Newcastle. The emphasis is on fundamental research into reaction mechanisms, inorganic matter behaviour and mathematical modelling.

6. CONCLUSIONS

Australia is well equipped with modern PF plants and it is unlikely that future demand will warrant the building of new power stations based on the advanced coal based power technologies before 2005. In the longer term, new coal fuelled power stations will increasingly be based on the new generation of advanced power production technologies such as AFBC, PFBC and IGCC.

Whereas the advanced coal based power generation technologies are not currently economic in the Australian context, developments related to technological advances, modular construction of combined cycle plant for incremental power requirements, efficiency improvements and environmental standards may jointly provide the framework for their future commercialisation.

The use of these higher efficiency technologies will help to increase value adding in both the coal and electricity industries, while at the same time offering environmental benefits. However, given the advanced state of development of these technologies overseas and the costs associated with such developments, Australia may have no choice but to import these technologies although it could possibly be involved in the supply of some components in niche markets.

There is scope for joint Government/industry support for demonstration of the most promising coal based advanced power generation technology in Australia to facilitate introduction into domestic and overseas markets. Early Australian involvement in such a development will be a far-sighted contribution not only in support of the domestic coal and electricity sectors but also to sustain and enhance exports of Australian coals and power station design, engineering, manufacturing and consultancy services to the rapidly growing power sectors in the dynamic Asian economies.

It is likely that some countries which are Australia's traditional coal markets, such as Japan, Korea and some European countries, will otherwise introduce these advanced coal combustion technologies ahead of Australia. To safeguard these markets and to develop new opportunities, it is essential as a minimum that the suitability of Australian coals for the new technologies be continually assessed.

In addition, there could be opportunities for new industrial niche markets based on developments in advanced coal power technologies such as IGFC. IGFC's potential for high efficiency, modular, decentralised power generation makes it an attractive alternative to grid supply for some consumers here and overseas. These factors, coupled with Australia's expertise and resource endowments in the area, make IGFC one of the most promising technologies for local development and manufacture.

REFERENCES

Australian Environment Council, Acid rain in Australia: a national assessment, Report No 25, 1989

Bannister, R L, Wiant, B C, Newby, R A, Jensen, A R, Mach, F V, Claeson, E U, Raatikka, L M, Diehl, R C and Eppich, H M, Coal firing gas turbines for combined cycle applications, Modern Power Systems, pp 39-45, September 1992

Bos, H G, Advanced NO_x reduction burners, Modern Power Systems, pp 53-58, December 1989

Bush, S, Leonard, M, Bowen, B, Jones, B, Donaldson, K and Trieu, L H, Energy demand and supply projections Australia 1992-93 to 2004-05, ABARE Research Report 93.2, 1993

Cook, D T, McDaniel, J E and Rao, A D, HAT cycle simplifies coal gasification power, Modern Power Systems, pp 19-25, May 1991

Hameed, S and Dignon, J, Changes in the geographical distributions of global emissions of NO_x and SO_x from fossil fuel combustion between 1966 and 1980, Atmospheric Environment, Vol 22, No 3, pp 441-449, 1988

Hishinuma, Y and Abe, T, Molten carbonate fuel cell power generation system combined with coal gasification, International Conference on Coal, the Environment and Development: Technologies to Reduce Greenhouse Gas Emissions, Sydney, 18-21 November 1991

International Energy Agency, Emission controls in electricity generation and industry, Paris, 1988

International Energy Agency, Energy Policies of IEA Countries, 1991 Review, Paris, 1992

Jansson, S A, Status and development potential for PFBC plants, International Conference on coal, the Environment and Development: Technologies to Reduce Greenhouse Gas Emissions, Sydney, 18-21 November 1991

Lucat, P, CFB scaled up to 250 MWe for Provence, Modern Power Systems, November 1992

Malhotra, A K, Financing of energy projects in developing countries - requirements and options, International Conference on Coal, the Environment and Development: Technologies to Reduce Greenhouse Gas Emissions, Sydney, 18-21 November 1991

Martinez, J A, Snow, G C and Maibodi, M, Costs for advanced coal combustion technologies, United States Environmental Protection Agency, 1991

McIntosh, M, Pressurised fluidised bed combustion, Symposium on Clean Coal Technologies and Australia's Export Markets, Sydney, 26 October 1990

Messerle, H K, Magnetohydrodynamic electrical power generation, International Conference on Coal, the Environment and Development: Technologies to Reduce Greenhouse Gas Emissions, Sydney, 18-21 November 1991

Morrison, G F, Recent developments in MHD, Power Generation Technology, 1993

Scalzo, A J, Amos, D J, Bannister, RL and Garland, R V, Coal fuelled gas turbine programmes gather pace, Modern Power Systems, pp 53-59, June 1991

Tornerefelt, J, PFBC heads for Czechoslovakia, Modern Power Systems, pp 37-38, November 1992

Torrens, I M, The greenhouse gas performance of power sector coal utilisation technologies, International Conference on Coal, the Environment and Development: Technologies to Reduce Greenhouse Gas Emissions, Sydney, 18-21 November 1991

US Department of Energy, Tidd: The nation's first PFBC combined cycle demonstration, March 1990

US Department of Energy, Clean Coal Technology Demonstration Program, February 1992

Varhelyi, G, Continental and global sulphur budgets - I. Anthropogenic SO2 emissions, Atmospheric Environment, Vol 19, No 7, pp 1029-1040, 1985

Wilkes, C, Gas turbine passes the coal test, Modern Power Systems, pp 43-47, May 1992

Wolk, R H, Preston, G T and Spencer, D F, Advanced coal systems for power generation, IEA Conference on Technology Responses to Global Environmental Challenges, Kyoto, 6-8 November 1991

Zon, G D, IGCC future under test at Buggenum, Modern Power Systems, pp 39-45, August 1990

LIST OF ABBREVIATIONS

AC	Alternating current
AFBC	Atmospheric fluidised bed combustion
DC	Direct current
ERDC	Energy Research and Development Corporation
ETSA	Electricity Trust of South Australia
FGD	Flue gas desulphurisation
HHV	Higher heating value
IEA	International Energy Agency
IGCC	Integrated gasification combined cycle
IGFC	Integrated gasification fuel cells
IGHAT	Integrated gasification humid air turbine
kWh	Kilowatt-hours
MCFC	Molten carbonate fuel cells
MHD	Magnetohydrodynamics
MWe	Megawatts electrical
NO_x	Nitrogen oxides
OECD	Organisation for Economic Cooperation and Development
PF	Pulverised fuel
PFBC	Pressurised fluidised bed combustion
SCR	Selective catalytic reduction
SECV	State Electricity Commission of Victoria
SNCR	Selective non-catalytic reduction
SO_x	Sulphur oxides

vanced Coal-Based Power Generation A Discussion Paper

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