Chapter 7

CATALYSIS FOR ELECTRICITY APPLICATIONS

G. Alexander Mills and Jens Rostrup-Nielsen

7.1 OVERVIEW: SCOPE, STATUS, ENVIRONMENTAL ISSUES, RESEARCH OBJECTIVES

This chapter defines the status and opportunities for new catalytic technology, to provide more efficient and economic generation of electricity from carbonaceous fuels and, particularly, to provide enhanced environmental protection. Not included in this discussion are fuel cell catalysis and non-catalytic research by DOE and others to improve efficiency by (hot) stack gas cleanup or turbine improvements.

While the application of catalysis to electricity generation is relatively recent, it has assumed growing importance and shows much potential. A driving force for the provision of new technology is increasingly severe requirements for environmental protection, particularly those limiting emission of oxides of nitrogen and sulfur in combustion gases. Carbon dioxide emissions pose a serious concern as well, and may assume major importance in the future.

Electricity generation and use represent a major segment of our energy activity. About one-third of the world's energy fuels are consumed in generating electricity, and this proportion represents a wide variety of fuels. In contrast, virtually only one fuel, petroleum, is used in the transportation energy sector. A variety of fuels offers a range of important technical opportunities, including the chance to use our non-petroleum resources — coal, gas, and biomass. Another significant difference between the electrical and transportation sectors is the difficulty in importing electricity, except from Canada, compared to the relative ease of shipping liquid petroleum from abroad. Two-thirds of the fuels' heating value is lost in the generation of electricity; hence, there is an important opportunity to improve energy efficiency.

New U.S. government regulations are having a major impact on technology used by utility companies. Compliance with some new regulations faces industry with profound economic consequences. Currently, in some states a utility company must purchase electricity from an outside source if this is cheaper than electricity that would be generated in a newly constructed plant. Also, electrical transmission companies are required to transmit electricity through/over their systems in return for a fee for their services. This is done to provide the public with the most economic electricity available.

New environmental regulations, driven by a desire for environmental improvements, are causing profound *technological* changes. The Clean Air Act Amendments of 1990, CAAA, are broad-based, applying not only to acid rain (the primary target) but also to ozone nonattainment, air toxics, and visibility. Electric utilities, mobile and industrial sources are all subject to emissions control provisions within the CAAA. The electric utility industry is most affected in the near term by the reduction of SO_2 and NO_x, required to meet acid rain provisions (Title IV), and by control of NO_x for ozone nonattainment (Title I). However, provisions for air toxic emissions in Title III and visibility in Title VIII may have significant impacts, especially in the longer term.

The CAAA requires reduction of SO_2 to half of 1980 levels. By the year 2000, annual SO_2 emissions must be reduced to 8.5 million tons and placed under a permanent emissions cap. During the first phase, 1995-9, the highest SO_2 emitters, a group of 110 power plants, must limit their emissions to below 2.5 pounds per million Btu of fuel. Beginning in the year 2000, all remaining generating units greater than 25 MW in size will be affected (Torrens *et al*, 1990) with emissions reduced further. The impact of the CAAA on utilities presents a host of new technical challenges, introduces business risks, changes the cost of electrical generation, and calls for organizational responses. The costs of clean air compliance are major in magnitude. The costs of acid rain control requirements are estimated to approach $7 billion annually, once fully implemented in the year 2000.

There are fundamental differences in the chemistry of NO_x and SO_2 and consequent options for their pollution alleviation. NO_x is derived in part from nitrogen contained in the fuel and in part from the reaction between air nitrogen and oxygen in the high temperature combustion chamber. While low-NO_x burners can minimize NO_x formation, at present the main NO_x control technology is achieved by both catalytic and non-catalytic reduction of NO_x by NH_3 in stack gas treatment. Sulfur oxides are derived from sulfur in the fuel. Sulfur must be removed at some point, since sulfur is objectionable in air in any form. Two approaches have been used to control emissions: pre-combustion fuel cleaning or post-combustion stack gas cleaning.

Increasingly stringent environmental regulations have prompted a fundamental change in the approach to pollution control. Specifically, this represents a change from catalytic remediation of pollutants, produced in the present technology, to the devising of a new catalytic process that prevents or minimizes pollutant formation. Research objectives for catalytic research relating to electricity generation include the provision of new and improved technology:

- To achieve pollution abatement not only by removal of pollutants but also by catalytic processes that prevent pollution formation.
- To achieve higher energy efficiency in electricity generation.
- To achieve more economic generation (lower plant operating and particularly plant investment costs).
- To make available economical processes for use of the abundant national fuel resources - coal, gas, biomass.

7.2 PRODUCTION OF CLEAN FUELS

7.2.1 Clean Gaseous Fuels

7.2.1.1 IGCC - Integrated Gasification Combined Cycle

There is growing interest in manufacturing a clean fuel gas from solid fuels to be used for generating electricity in an Integral Gasification Combined Cycle system (Figure 1). In IGCC, gasification consists of reacting coal, biomass, or petroleum coke with steam and oxygen or air at a high temperature to form a fuel gas, consisting mostly of CO and H_2. The gas is cooled and purified. In the combined cycle plant section, the highly purified gas is burned and the hot combustion gas is routed through a gas turbine to generate electricity. Then, the residual heat in the exhaust is recovered in a steam boiler for use in a conventional steam turbine generator to produce additional electricity. A promising alternative is the use of the purified gas to generate electricity, employing a catalytic fuel cell, a technology not included in this study because it is the subject of a separate forthcoming Research Needs Assessment by the Office of Program Analysis.

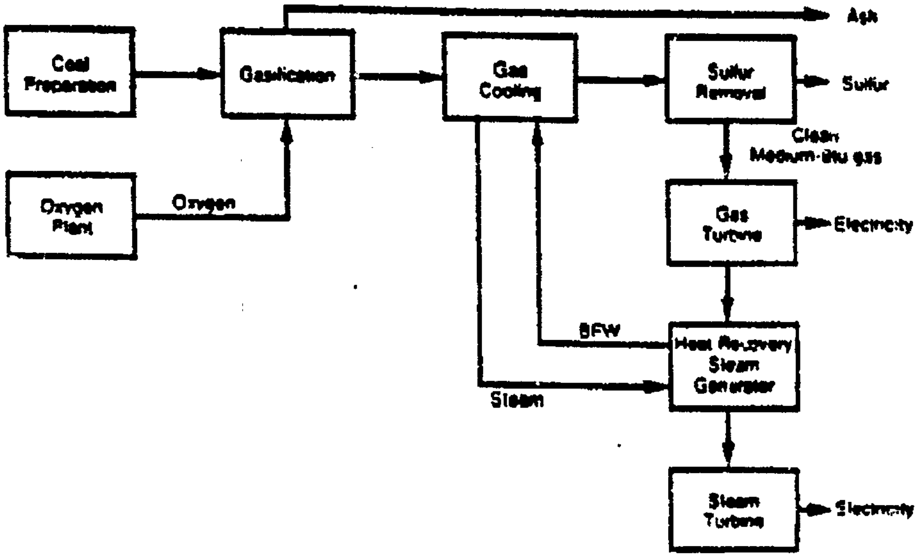

Figure 1. Integrated Coal Gasification Combined Cycle. (Alpert, 1991)
BFW = boiler feed water

IGCC has important environmental and energy efficiency advantages

- The H_2S and NH_3 in fuel gas can be removed to a greater extent than is practical for removal of SO_2 and NO_x from combustion gases which, because of the addition of nitrogen introduced in combustion air, are much larger in volume. In IGCC operations, sulfur removal levels of over 99% have been demonstrated on a plant scale. Emissions are well below the existing NSPS emission standards of 90% removal for new plants.

- Interest in IGCC is heightened by increasingly stringent environmental restrictions, particularly those regulating sulfur emissions.
- The clean gas is highly suitable for use in high-efficiency gas turbines. Electricity is produced with greater energy efficiency than in pulverized coal-fired plants. Hence, CO_2 emissions are reduced.
- Essentially any solid carbonaceous feedstock can be used in modern gasification plants.
- Combined-cycle plants can be composed of standardized modules, sized for large and small utilities.
- Studies have shown the possibility of capturing and sequestering CO_2 from IGCC by adding shift and sequestering stages to process flow sheets. New imaginative approaches are needed.
- Opportunities exist to develop catalytic technologies to co-produce electricity and fuels/chemicals and improve gas purification processes.

Of particular importance in advancing technology to commercialization is the development of several improved gasifiers that have been demonstrated in the IGCC operation. These are summarized in Table 1.

What will be the world's largest IGCC plant (Commission of European Communities, 1992) in Puertollo, Spain, is scheduled to begin operations in 1996. It will produce 305 MWe at 45% efficiency with emissions of SO_2 of < 10mg/Nm^3 and of NO_x of < 60 mg/Nm3.

Table 1.
Integrated Gasification Combined Cycle Demonstration Plants

Name	Demonstration Location	Tons of Coal per Day	MW Electricity
Texaco	California	1200	135
Dow	Louisiana	1700	160
British Gas/Lurgi	Scotland	500	
Royal Dutch/Shell*	Netherlands	2000	250

* *Construction completed July 1993. Fall start-up. (Salzman et al., 1992)*

Additional IGCC variations will be demonstrated under the DOE Clean Coal program, funded jointly by industry and DOE (Table 2). Of further interest is the IGCC plant planned for Delaware. This facility will charge about 2400 tons per day of high-sulfur petroleum coke to a Texaco gasifier and generate 125 MWe electricity. It has also been announced that a 260 $\mathrm{MW_e}$ IGCC plant based on coal will be built in Florida. In addition, an agreement has been signed to install the IGT U-Gas process in China.

It is fair to say that IGCC is a combination of modern technology process units, well engineered to meet new needs. There are opportunities to provide further improvements using the advanced catalytic processes discussed below. Opportunities also exist to improve processes for catalytic conversion/removal of H_2S and NH_3 from syngas.

7.2.1.2 Co-Production of Electricity and Chemicals/Fuels

In an IGCC plant in which a purified mixture of CO + H_2 is manufactured, it may be advantageous to use part of this gas to generate electricity and part to manufacture chemicals/fuels such as methanol, ammonia, or hydrogen, according to recent proposals. Such a facility has been termed a *powerplex*, EPRI, 1992. Coal gasification is required to produce a mixture of CO and H_2 , known as synthesis gas (syngas). Synthesis of chemicals and fuels from syngas has had a long industrial history. At present, this includes production of methanol and the large-scale production of hydrocarbon transportation fuels by SASOL in South Africa. Various technological suggestions have been advanced for the co-production of chemicals/fuels and electricity, designed to take advantage of the IGCC situation. Coal-based power plants are capital intensive. An advantage for IGCC co-production plants would accrue from operating the gasifier at capacity all the time and, when electricity needs are low, manufacturing methanol with part of the syngas. This methanol can be marketed or used for "peak shaving" generation of electricity.

Economic evaluation studies, carried out for EPRI, have led to the design of a plant that is integrated to both electricity and methanol production (Fluor, 1982; EPRI, 1987; Chem Systems, 1990; Houston LP, 1992). Included is base load to cycling operation, that is, full electricity to full methanol production. The potential economic advantage of co-production of electricity and methanol is significant. It is projected that the cost of electricity would be lowered by 10% (Kern *et al.*, 1991; Bauman *et al.*, 1991). In other studies, the co-production of electricity and ammonia and urea is being explored, with an emphasis on environmental benefits (Bradshaw and Wetherington, 1991). Interest in IGCC is heightened by the recognition that the price of gas could increase greatly, whereas coal prices are expected to be relatively stable.

A recent study (Houston L&P, 1992) concluded that co-production of chemicals such as methanol or urea can result in significant reduction in the cost of electricity. if the selling price of chemicals escalates at a rate greater than inflation. The price of methanol and urea are tied closely to the price of natural gas. It is also reported that a better knowledge of the integration of gasification plants with combined cycle power generation holds the potential for further improvements and capital cost savings, making IGCC and co-production more competitive in the future. A highly integrated plant in which the combustion turbine compressor supplies one-half the air required for the oxygen plant has been estimated to produce electricity at 40-45 mills/kwh (EPRI, 1993). Opportunities for new catalytic technology to improve integration of catalytic synthesis of fuels/chemicals into IGCC operations are discussed below.

Table 2.
DOE Clean Coal Technology IGCC Projects
(Various stages of development, 1993)

Project	Technology
Wabash River Coal Gasification Repowering Project West Terre Haute, Indiana	Destec, slurry feed, oxygen-blown, two stage entrained flow (entrained flow, slagging first stage and non-slagging second stage) gasifier (265MW)
TAMCO Power Partners Toms Creek IGCC Demonstration Project Coeburn, Virginia	IGT/Tampella U-Gas, air-blown, fluidized bed with zinc titanite and ceramic candle filter hot gas clean up (107 MW/55 MW net coal based)
Sierra Pacific Power Piñon Pine IGCC Power Project Reno, Nevada	MW Kellogg, air-blown fluidized-bed gasifier with limestone injection and zinc ferrite and ceramic candle filter hot gas clean up (80 MW)
Air Products Commercial Scale Demonstration of Liquid-Phase Methanol (LPMEOH) Process Daggett, California, or other site	Texaco, slurry feed, oxygen-blown, single state entrained flow gasifier providing synthesis gas to the LPMEOH system (150 tons/day)
Combustion Engineering IGCC Repowering Project *Springfield, Illinois*	ABB CE *dry feed*, air-blown, *entrained bed*, gasifier with limestone injector and *moving-bed zinc ferrite hot gas clean up* (65 MW)
Tampa Electric Company IGCC Demonstration Project Lakeland, Florida	Texaco, oxygen-blown, entrained-flow gasification system with moving-bed solid sorbent hot gas clean up (260 MW)
Camden Clean Energy Project IGCC Demonstration Project Camden, N. J.	British Gas/Lurgi Fixed Bed Oxygen-blown Gasifier High Sulfur W. Virginia Coal (480 MW)

7.2.1.2.1 Slurry-Catalyst Synthesis

Methanol synthesis is highly exothermic. In order to prevent harmful temperature increases, low conversion per pass is accepted, necessitating costly recycling of unreacted gas. The use of catalysts slurried in inert liquid provides a concept of heat management, which has been extensively tested in a 10 year, $25 million program. During this time some 7000 hours of operation were carried out in a 10 ton-per-day plant in La Porte, TX (Brown *et al.*, 1990). An advantage of about 10% has been estimated for liquid phase methanol synthesis; LPMEOH, using syngas from coal, over conventional vapor-phase technology.

Once-Through Synthesis

In this process, all or part of the syngas is passed through a bed of methanol synthesis catalyst on a once-through basis, that is, without recycling unreacted CO and H_2. The unreacted syngas then goes to the combustor. In this way, methanol synthesis avoids the cost of recycling (EPRI, 1987). A once-through operation, using a slurry-catalyst reactor at the IGCC plant at Cool Water, CA, has been proposed. The process is shown in the flow diagram in Figure 2 (Brown *et al.*, 1990).

Co-Production of Methanol and Dimethyl Ether

Much interest has been aroused by novel technology (Brown *et al.*, 1991; Hansen *et al.*, 1991; Lee, 1992; Lewnard *et al.*, 1993) being developed for the conversion of syngas to a mixture of methanol and dimethyl ether in a single reactor in which the following reaction sequence occurs:

$$2\,CO + 4\,H_2 \rightarrow 2\,CH_3OH \qquad \text{methanol synthesis catalyst}$$

$$2\,CH_3OH \rightarrow CH_3OCH_3 + H_2O \qquad \text{dehydration catalyst}$$

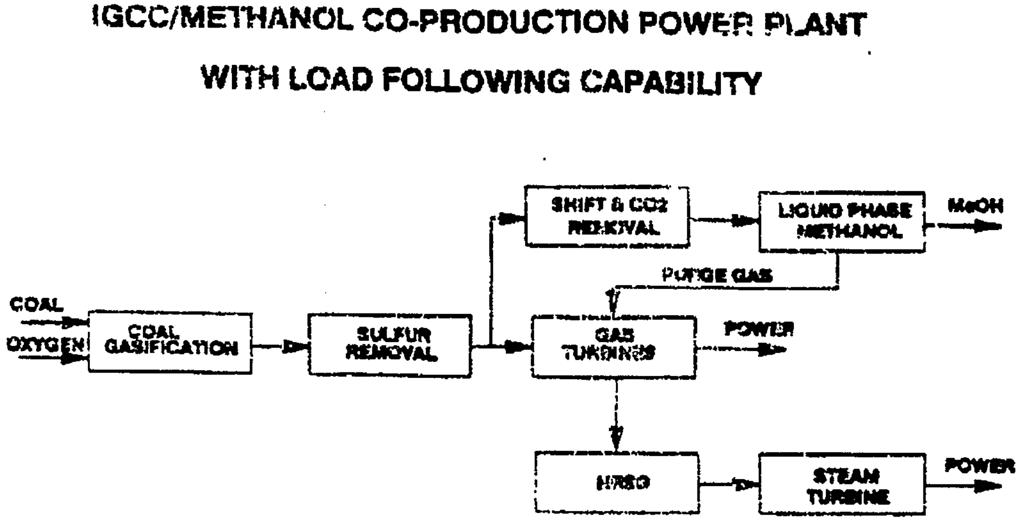

Figure 2. IGCC/LPMEOH Methanol Production Flow Diagram. (Brown *et al.*, 1990)

A combination of two types of catalysts makes this reaction sequence possible. The water gas shift, WGS, reaction

$$H_2O + CO \rightarrow H_2 + CO_2$$

can also be carried out simultaneously, using a water gas shift catalyst. Then the overall net reaction is

$$3\ H_2O + 3\ CO \rightarrow CH_3OCH_3 + CO_2$$

Co-production of methanol and dimethyl ether offers an opportunity for increased syngas conversion per pass. The effect of the combination of these reactions is essentially to avoid unfavorable thermodynamic limitations for methanol synthesis. Methanol, a product of the first reaction step, is consumed in the second reaction, forming dimethyl ether and water. The water is used in the third reaction, generating carbon dioxide and hydrogen, the latter being used for methanol synthesis. Thus, the product of each step is a reactant for another, creating a strong driving force for the overall reaction (Hansen and Joensen, 1991; Brown *et al.*, 1990; Lee, 1992). The slurry catalyst reactor system has been tested for conducting the simultaneous synthesis of MeOH, DME and WGS. Process development has focussed on the use of coal-derived syngas that is rich in CO (Brown *et al.*, 1990).

Improved Synthesis Catalysts

Intensive research has resulted in a wide variety of improvements in catalysts and process systems for synthesis of methanol and related chemicals/fuels (Mills, 1993). It is expected that improved catalyst systems can be incorporated in the co-production of electricity and chemical manufacturing.

7.2.1.3 Catalytic Gasification

Manufacturing synthesis gas from methane is a highly developed catalytic process, used internationally for the large-scale production of chemicals. Syngas production by gasification of coal has been used extensively. Tennessee Eastman currently uses the process to manufacture methanol, and it is also used at Great Plains, North Dakota, to produce methane. Coal gasification, the partial combustion of coal in the presence of steam, is a non-catalytic process carried out at temperatures which range from about 1000 ° to 1500° C. Various attempts have been made to devise a practical process that could operate at lower temperatures.

It has long been known that alkali hastens the critical slow reaction

$$C + H_2O \rightarrow CO + H_2$$

The chemistry of base-catalyzed carbon-steam reactions involves the formation of hydrogen and a phenoxide whose structure has been determined (Mims and Pabst, 1982). The phenoxide can be decomposed at low temperatures, using a transition metal oxide as catalyst (Heinemann and Somorjai, 1992; Pereira *et al.*, 1990). Mixtures of alkali and transition metal oxides can serve as catalysts for continuous steam gasification of coal or chars at temperatures below 600°C. Mixtures of alkali and alkali earth oxides are almost as effective as the alkali transition metal oxides, and they are not easily sulfur poisoned. Electron microscope studies show that alkali compounds attack carbon in the presence of water in a solid edge recession. Alkali transition metal oxides form a low melting eutectic, resulting in a liquid film that hastens the gasification by edge recession.

Catalyst mobility can be important for reactions involving a solid reactant. Providing catalyst mobility for effective catalyst performance is a new concept. Extensive laboratory and pilot plant studies demonstrated that, by the addition of potassium salts, gasification could be carried out at commercially useful rates at temperatures some 100°C lower than previously required (Penner and Wiesenhahn, 1987; Exxon, 1981). Recovery of most of the potassium entrapped in the ash from minerals in the coal was a key consideration. The development of improved catalytic gasification could provide an important step forward in developing a process for integral gasification/fuel synthesis.

7.2.1.4 IG/S Integral Gasification/Synthesis

Integral Gasification/Synthesis is the concept of carrying out simultaneous gasification of coal or biomass and synthesis to desired hydrocarbons or oxygenates. The gasification temperature, pressure, and other conditions must be such that the synthesis product is thermodynamically possible. A synthesis catalyst is present during gasification. In practical terms, for integral gasification/synthesis to function, it is required that gasification be carried out at considerably lower temperatures than usual. It should be pointed out that the reaction $C + H_2O \rightarrow CO_2 + CH_4$ is almost thermally neutral and is thermodynamically favorable. Therefore, it should be possible to trade C for CH_4 at no energy cost! It is encouraging to note that in coal gasification it has been demonstrated that methane synthesis can occur to a certain extent. *There is a challenge to synthesize methanol, less thermodynamically stable than methane, under IG/S conditions.*

7.2.1.5 Utilization of Methanol

A novel concept for improving efficiency in methanol fuel use involves the catalytic decomposition of methanol to produce a fuel gas. The reaction is highly endothermic. The heating value of the syngas is greater than that of the methanol from which it was derived. If waste heat is utilized to supply the needed energy, there is an expected gain of 20% in energy efficiency (Yoon *et al.*, 1985). The use of catalysts *to enhance fuel-use efficiency* presents opportunities of considerable potential. This is a research area which has been relatively neglected.

7.2.2 Liquid Fuels from Coal

By 1970, new concern for environmental protection had focused attention on air pollutants away from combustion of coal used for generating electricity. New regulations that were imposed made many U.S. coal deposits unsuitable for use in many existing plants because of their high sulfur content. Sponsored by industry and government, intensive research and development programs were carried out to develop technology for the manufacture of a clean liquid fuel from coal, suitable for use in generating electricity. Several direct hydroliquefaction processes were developed and tested on a tons-per-day scale. These included processes known as Solvent Refined Coal, Donor Solvent, H-Coal, Two-Stage Liquefaction, and a German process at Bottrop (Elliott, 1981; Meyers, 1984).

Sulfur in coal is present in both inorganic sulfides, mainly as pyrite, and in organic compounds, mainly as thiophenes. A significant factor in producing a low sulfur liquid from coal is that, while the pyrites are fairly readily removed, removal of the organically bound sulfur is more difficult. Moreover, as desulfurization proceeds, removal becomes increasingly more difficult so that it is not practical to go to very low sulfur levels without subsequent product refining.

By 1976, it was becoming apparent that advanced coal hydroliquefaction technology was economically unattractive compared to flue gas desulfurization, FGD. It is possible to remove 95-98% of SO_2 with flue gas desulfurization technology.

Flue gas desulfurization processes have been installed extensively. At present, the technology used to manufacture liquid fuels for electricity generation is not deemed attractive, although it may have merit in certain circumstances (Commission of European Communities, 1992). Instead, research interest in coal hydroliquefaction has been directed to the production of transportation fuels. Considerable technical and scientific progress in this area has been made, as noted in Chapter 9. However, interest in production of a coal-derived fuel gas for generating electricity has greatly increased.

7.2.3 Chemically Recuperated Gas Turbine (CRGT)

A new method for generating electricity from natural gas has been proposed by the California Energy Commission (Janes, 1990). The process allows for the recovery of high-temperature heat from the exhaust of an advanced gas turbine. Heat transfer is accomplished by utilizing the endothermic catalytic methane-steam reforming reaction. The recovery of heat is accomplished more efficiently by chemical means than by using heat transfer in a steam boiler. The chemically recuperated gas turbine (CRGT) consists of three major components (Figure 3):

- Advanced gas generator equipped with an intercooler
- Steam cooled power turbine equipped with a reheat combuster

- A partial methane steam reformer

Desulfurized natural gas reacts with steam over a nickel-based catalyst at about 815°C, producing a fuel gas containing hydrogen and carbon monoxide. The normal exhaust temperature from a gas turbine is about 540°C. The most effective way to elevate the exhaust temperature is to reheat before the power turbine. Some of the high-temperature heat is used to partially convert natural gas to hydrogen and carbon monoxide. The natural gas/H2+CO mixture leaves the reformer as a hydrogen-rich, low-Btu fuel gas mixture. Combustion can be expected to result in low NO_x when fueling the gas generator combuster. Manufacturers of reforming catalysts have evaluated operating conditions and concluded that a combination of catalysts currently in use can be expected to perform according to CRGT design. However, a more active catalyst is needed for reforming below 680°C, which would be advantageous. Detailed process engineering and cost calculations have been performed by the CA Energy Commission and checked by engineering and equipment manufacturers.

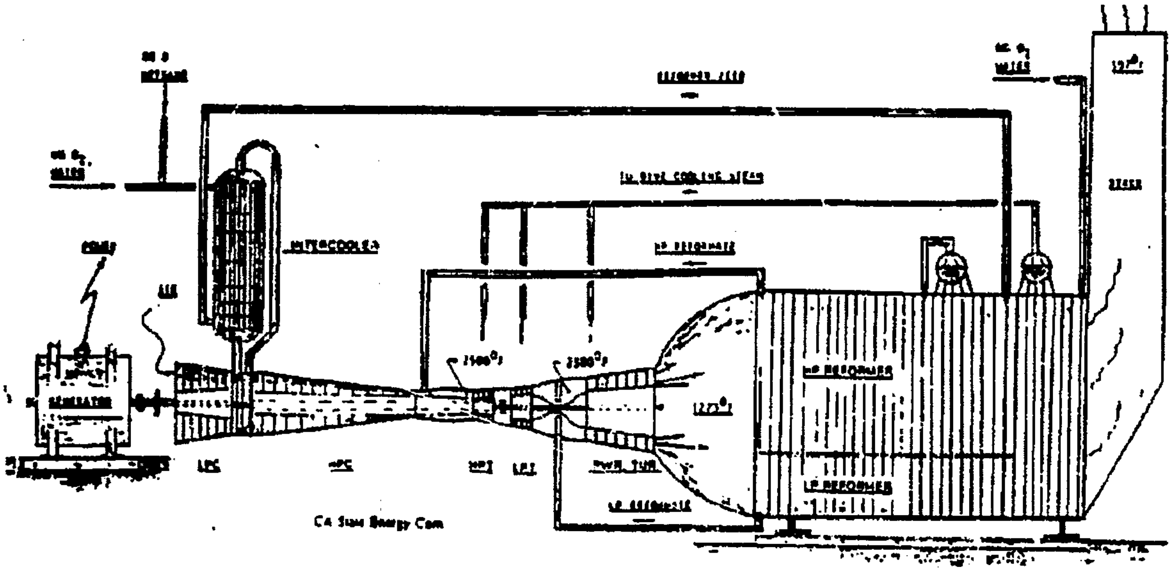

Figure 3. Chemically Recuperated Gas Turbine with Intercooler and Reheat.
(Janes, 1990)

In the current combined cycle system for generation of electricity, the exhaust heat from the gas turbine is removed to drive a conventional steam turbine. The combined gas and steam turbines are able to convert 51% of the energy in natural gas to electricity. Average utility efficiency is about 33% for conventional gas and oil-fired boilers in operation. A projected thermal efficiency of the chemically recuperated gas turbine, CRGT, has been estimated to be 60%, about 10% higher than for the gas-fired turbine alone. The substantial increase in projected energy efficiency, employment of near-standard equipment, favorable cost estimates, and expectations of low NO_x emissions make CRGT an attractive technology. A combination of present industrial catalysts is deemed capable of functioning adequately, but there is a need for a steam reforming catalyst capable of functioning at lower temperatures than conventional.

Since the price of natural gas is expected to rise to its former level, in the long term, synthetic natural gas, SNG, from mine-mouth coal may be a wiser investment than natural gas. Improved processes for manufacturing methane from coal have been developed and offer this long-range option. It should be added that, while manufacturing syngas from methane is a highly developed commercial catalytic process, recent results of a different approach, direct partial oxidation of methane, offer considerable promise for improvement (Hickman and Schmidt, 1993).

7.3 POLLUTION REMEDIATION

7.3.1 CO_2 Emissions

Increased absorption of the sun's rays by increased concentrations of light-absorbing molecules in the atmosphere surrounding planet earth and the consequent rise in temperature has been termed *the Greenhouse Effect. Global warming could melt present ice caps, raising sea levels* and significantly decreasing land area in the U.S. and elsewhere. There is concern that increasing the presence of CO_2 in the atmosphere generated by increased combustion of fossil fuels will increase the Greenhouse effect.

The technology and economics of capture, utilization, and disposal of carbon dioxide from fossil fuel-fired power plants has been critically examined recently (M.I.T./DOE - 1993). This study finds that direct capture and disposal would likely increase the cost of electricity by about a factor of two or more for the case of retrofit of current coal-fired power plants and by 50% or more for the case of successful development of advanced, high efficiency power plants (such as IGCC or fuel cells) *that are specifically configured to integrate* CO_2 capture.

If a requirement for full or near-full cessation of CO_2 emissions from power plants is envisioned, certain research discussed here by Spencer, 1991 and in the M.I.T./DOE report is believed warranted. Opportunities for CO_2 utilization include enhanced oil recovery, plastics manufacture, production of biomass fuel (utilizing sunlight to convert CO_2 and H_2O photosynthetically by microalgae) and chemical conversion of CO_2 to fuels.

Chemical conversion of CO_2 to fuels, for example, by the reaction

$$CO_2 + 3H_2 \rightarrow CH_3OH + H_2O$$

would require a significant energy source for hydrogen production that could be used several fold more efficiently by directly serving power plant end-markets. The fundamental question is the source of hydrogen. Hydrogen can be generated by electrolysis of water which requires 312 kJ/mol of H_2. *To avoid generation of more* CO_2 *in the hydrogen production process, a non-*fossil energy source is needed. The most likely solution is to produce the H_2 from solar or nuclear sources of energy. However, if solar or nuclear energy sources are available, they could be used directly to displace fossil fuel and reduce the amount of CO_2 produced in the first place. However, there are additional considerations in the production of transportation fuels. Specifically, due to our current infrastructure, liquid transportation fuels are more desirable than electricity or hydrogen because of fuel storage and transportation considerations. However, as pointed out in the M.I.T./DOE report, the efficiency loss is probably too large a price to pay using present technology. This provides an opportunity for catalytic research for more economical and energy efficient conversion of CO_2 to fuels.

7.4 RESEARCH RECOMMENDATIONS

Technology objectives for catalytic research relating to the generation of electricity:

- to achieve pollution abatement, not only by removing pollutants but also by devising catalytic processes which prevent pollution formation
- to achieve higher energy efficiency in electricity generation
- to achieve more economical generation (lower plant operating and particularly plant investment costs)
- to make available economical processes for use of abundant national fuel resources — coal, gas, and biomass.

Improved Manufacture of Electricity (* indicates highest rating)

* IGCC. Research is proposed to provide synthesis catalysts for advanced processes which combine Integrated Gasification Combined Cycle generation of electricity and fuels/chemicals manufacture. Synthesis catalysts are needed, specifically designed for load-following; for a "once-through" synthesis operation; for slurry-catalyst systems. Synthesis catalysts of interest include those for manufacture of methanol, of methanol/dimethyl ether mixtures, of ammonia, and of hydrogen. Particular consideration should be given to hydrogen co-production because of its growing critical requirements.

* IGCC Coal + Biomass. Processes using a combination of these two fuel substances can provide special opportunities to prevent or lessen CO_2 emissions. Various process flow sheets have been proposed. Catalysts are needed to meet the conditions of projected applications.

Research is needed to improve energy utilization efficiency for methanol and/or dimethyl ether synthesis by developing systems for their catalytic conversion to a *fuel gas* of increased fuel content, using waste heat. Manufacturing synthesis gas by direct selective catalytic oxidation appears to be a promising new target. Research is recommended

Research is recommended for integral gasification/fuel synthesis, utilizing opportunities presented by recent advances in catalytic gasification.

CRGT (Chemical Recuperated Gas Turbine).

t has been concluded that a combination of existing catalysts could function under the proposed conditions of temperature, pressure, and contact times. However, it is believed that research could provide specifically designed catalyst modifications which would improve the process.

REFERENCES

Alpert, S. B. 1991. Clean Coal Technology and Advanced Coal-Based Power Plants. *Annual Review of Energy and the Environment*. Palo Alto, Annual Reviews. 16:1-23.

Bauman, P. D. and M. Epstein. 1991. Coal Gasification-Based Integrated Coproduction Energy Facilities. Paper read at Tenth Annual EPRI Conference, October 15, Palo Alto, CA.

Bradshaw, W. D. and R. W. Wetherington. 1991. Introduction to a Novel Approach to Coal Gasification: Coproducing Electricity and Fertilizers. IGCC/F. 10 th Annual EPRI Conference on Gasification Power Plants, October 15, Palo Alto, CA.

Brown, D. M., B. L. Bhatt, T. H. Hsuing, J. J. Leonard, and F. J. Waller. 1991. Novel Technology for the synthesis of Dimethyl Ether from Syngas. *Catalysis Today*. 8:279-304.

Brown, D. M. and J. L. Henderson. 1991. Methanol Synthesis from CO-rich gas for use in gasifier combined-cycle power plants. Proceedings: Fifteenth Annual EPRI Conference on Fuel Science. EPRI GS-7434, August.

Brown, D. M., J. L. Henderson, T. H. Hsing, and D. W. Studer. 1990. LPMEOH. Beyond LaPorte - Next Steps to Commercialization. Paper read at Fifteenth Annual EPRI Conference on Fuel Science and Conversion, June 19-21, Palo Alto.

Chem Systems Optimization of Electricity-Methanol Coproduction. 1990. EPRI GS-6869, project 2771-1, June.

Commission of European Communities. 1992. Coal Can Be Green. Directorate General for Energy, rue de la Loi 200, B1049, Brussels, Belgium.

Elliott, M. A., ed. 1981. *Chemistry of Coal Utilization. Second Supplementary Volume*. New York: Wiley-Interscience.

EPRI 1987. Once-Through Methanol for Power Generation. Technical Brief. EPRI, APS 23.10.87.

EPRI 1992. Powerplex, DOE to Sponsor Four New GCC Projects Under the Clean Coal Program. AFPS Developments, Issue 9, Winter, p 4.

EPRI 1993. IGCC Economics, AFPS Developments, Issue 13, Spring. p. 3.

Exxon Catalytic Coal Gasification Development Program. 1981. Final Report, FE 2777-31.

Fluor Engineers and Constructors, Inc. 1982. Economic Evaluation of the Coproduction of Methanol and Electricity with Texaco Gasification-Combined-Cycle Systems. EPRI, AP-2212, project 239-2.

Hansen J. B. and F. Joensen. 1991. High Conversion of Synthesis Gas to Oxygenates. In *Proceedings Natural Gas Conversion Symposium*, 1990, pp.457-467. Oslo:Elsevier.

Heinemann, H. and G. A. Somorjai 1991. Fundamental Studies of Catalytic Gasification. LBL-30015, UC-109, Lawrence Berkeley Laboratory, University of California, Berkeley.

Houston Light and Power Company. 1992. Evaluation of Coal Gasification Coproduction Energy Facilities. eds. E. E. Kern, S. D. Havemann, and R. G. Chmielewski. EPRI TR-101789, Project 3226-04.

Janes, J. 1990. Chemically Recuperated Gas Turbines. California Energy Commission.

Kern, E. E., R. G. Chmielewski, S. D. Havemann, and S. D. Baumann. 1991. Coal Gasification-Based Integrated Coproduction Energy Facilities. Paper read at Tenth Annual EPRI Conference, October 15, Palo Alto, CA, Final Report TR 101,789.

Lee, S. 1992. Updates of Methanol, Dimethyl Ether, and Gasoline Process Development. Proceedings of Sixteenth Annual Conference on Fuel Science, EPRI TR-100632, project 832-99, 21992, April.

Lewnard, J. J., T. H. Hsiung, J. F. White, and B. L. Bhatt. 1993. Liquid Phase Process for Dimethyl Ether Synthesis. U.S. Patent 5,218,003, issued June 8.

Meyers, R A , ed. 1984. *Handbook of Synfuel Technology*. New York: McGraw Hill.

Mills, G. A 1993. Status and Future Opportunities for Conversion of Synthesis Gas to Liquid Energy Fuels. DOE/NREL Contract HZ-11208-1; NREL/TP-421-5150; NTIS-DE93010025.

Mims, C. A. and J. K. Pabst. 1982 Role of Surface Salt Complexes in Alkali-Catalysed Carbon Gasification. Paper read at International Symposium on Catalytic Coal and Carbon Gasification, Sept., Amsterdam.

M.I.T./DOE - 1993. The Capture, Utilization, and Disposal of Carbon Dioxide from Fossil Fuel-Fired Power Plants. DOE/ER-30194, Vols. I & II.

Penner, S. A. and D. F. Weisenhahn. "Coal Gasification", *Energy,* Vol. 12(8/9), pp. 747-763.

Pereira, P., R. Csencits, G. A. Somorjai, and H. Heinemann. 1990. Steam Gasification of Graphite and Chars at Temperatures <1000 K over Potassium-Calcium-Oxide Catalysts. *J. of Catalysis*. 123:463-76.

Salzman, D. S., D. F. Guyot, and R. Isernhagen. 1992 *Summary of the 1992 Shell* Gasification Process/Combined Cycle (SCGP/CC) Design. Eleventh EPRI Conference on Gasification Power Plants. October.

Spencer, D. F. 1991. A Preliminary Assessment of Carbon Dioxide Mitigation Options. *Annual Review of Energy and the Environment*. Palo Alto, Annual Reviews. 16:259-73.

Torrens, I. M., J. E. Cichanowicz, and J. B. Platt. 1992. The 1990 Clean Air Act Amendments: Overview, Utility Industry Response, and Strategic Implications. *Annual Review of Energy and Environment*. Palo Alto, Annual Reviews. 17:211-33.

U.S. Department of Energy. Clean Coal Technology - Advanced Power Generation. 1992. Brochure.

Yoon, H., M. R. Stouffer, P. J. Dudt, F. P. Burke, and G. P. Curran. 1985. Methanol Dissociation for Fuel Use. *Energy Progress* 5:78-83.