Power Gas and Combined Cycles: Clean Power from Fossil Fuels

ENERGY

In the search for new ways to produce clean electric power from fossil fuels, generating systems that combine gas and steam turbines are playing a central role. To meet increasing demand for electricity in the next few years, combined gas and steam cycle systems offer a relatively cheap and—more importantly—immediately available option. Approximately 15 units with a total capacity of nearly 4500 megawatts have been ordered in the last 18 months, and the first is due to be delivered in mid-1973. These systems are attractive to the utility industry now because of delays in construction of nuclear facilities, difficulties in siting large generators, and pressures to use clean fuel. Combined-cycle systems may be even more attractive in the future because they offer the promise of greater efficiency than conventional stations. The new units are designed to burn natural gas and oil distillates, but could also burn other gasified fuels.

Ten or fifteen years from now, when natural gas and low-sulfur oil are expected to be in very short supply, combined-cycle systems may be the key to clean production of electricity from coal, a very plentiful resource. Coal gasification to make power gas appears to be one of the cheapest methods of eliminating the sulfur from coal combustion, and combined-cycle systems are conveniently symbiotic with systems for coal gasification. The combined-cycle system can be fired with the products of the coal gasification process, and the gasifier can draw compressed air from the combined-cycle system. Thus combined-cycle technology may be as important for long-term planning of energy resources as for the short-term solution of a planning lapse.

No processes for making power gas from coal have been developed by U.S. companies. A clear distinction must be made, however, between power gas, which has a rather low heating value [about 150 British thermal units (Btu) per standard cubic foot (scf)], and synthetic natural gas, which has a high heating value (about 1000 Btu/scf). Research on four processes for making synthetic natural gas from coal (*Science*, 6 Oct. 1972) has been funded by the Department of the Interior since 1961.

Unlike natural gas or its synthetic substitutes, power gas has such a low heating value that it cannot be economically transported very far; it must be converted to more useful forms of energy near the site of production. However, the synthesis of power gas is far simpler than the synthesis of natural gas, a process that one engineering consultant has called the toughest problem in chemical development he has ever known. One station for electrical power generation with a combined-cycle system fueled with power gas (low-Btu gas from coal) has just begun operating at Lünen, Germany. Hence there is little indication yet to show just how expensive such a process will be.

Combined Cycles More Efficient

Gas turbines that could be used for power generation were an offshoot of the development of turbines for military aircraft in World War II. The performance of aircraft turbines has continued to improve as metallurgists have found a series of metals that withstand ever higher temperatures. Historically, new developments in the turbines of military aircraft have become available to civilian aircraft 2 or 3 years later, and have been reflected in the design of stationary turbines for industrial applications about 5 years later. The turbine engines in the military aircraft of World War II could withstand maximum inlet temperatures of only about 500°C, but, because of new metals and new techniques for cooling the turbine blades, aircraft turbines can now operate at almost 1200°C. Turbines for electrical power generation now operate steadily at 1000°C.

The advantage of a combined-cycle system is that it has the potential of greater efficiency than either a gas turbine or steam turbine alone. Much of the heat entering a gas turbine is wasted when the exhaust gases escape at relatively high temperatures (typically 445°C for a turbine with a 1000°C inlet temperature). The losses are relected in relatively low efficiencies for converting fuel energy into electricity. (Generators powered by gas turbines alone have been used for several years by the U.S. utility companies to meet power requirements at times of peak loads. They have efficiencies of about 25 percent.) If the exhaust gas of the gas turbine is channeled into a boiler rather than allowed to escape, the waste heat can be used to produce steam (at 390°C) that would also produce electricity. The efficiency of combined gas and steam turbine systems is now comparable with the efficiency of the best existing steam-power installations—about 39 percent.

For any gas turbine, the efficiency of power production increases with the temperature of the hot gases that turn it. The efficiency gained by operating a combined-cycle system at high temperatures is even greater. According to a report by the United Aircraft Research Laboratories (*1*), temperatures of 1220°C should be attainable by the mid-1970's, and 1440°C by the early 1980's. At the latter temperature, the efficiency of the combined cycles is projected to be 50 percent.

It may be possible to extend the efficiency of a turbine system even further by adding another cycle, because the efficiency of any thermal cycle is improved by increasing the differential between inlet and exhaust temperatures. Systems that add an extra turbine at the high temperature are called topping cycles, and those that add an extra turbine at the low temperature are called bottoming cycles.

One proposal for a topping cycle is a potassium vapor cycle. Liquid potassium would be heated in the primary boiler to form potassium vapor that would drive a turbine. As proposed by Arthur J. Fraas of the Oak Ridge National Laboratory, the exhaust of combustion would power a gas turbine and the waste heat from the potassium turbine would power a steam turbine. A study of the proposal, which assumes a particular fluidized-bed process for combustion of coal, projects an efficiency of the entire system of 51 percent.

A fluid, such as isobutane, with a much lower boiling point than steam could be the heat-transfer medium for a bottoming cycle. A prototype of an isobutane turbine is being developed for production of electricity from geothermal sources (*Science*, 15 Sept. 1972).

If combined-cycle systems are to play a role in power generation later in this century, new fuels must be found. Most observers expect that it will be possible to produce power gas from coal, though neither the best method nor the cost is yet clear. It is also possible to produce power gas from residual fuel oil (the relatively inexpensive dregs of the refining process) by methods that are thoroughly developed and available for license.

Power Gas from Oil

Residual fuel oil with a low sulfur content—no more than 0.3 to 0.5 percent by weight is allowed as fuel for power stations in Maryland, Connecticut, and New York—has now replaced coal for power generation in most states east of the Mississippi River. The demand for low-sulfur residual fuel oil is growing and its price is rising. Residual fuel oil with a high sulfur content (2.6 percent) is readily available from Venezuela, and is considerably cheaper (45 cents per 10^6 Btu versus 75 cents per 10^6 Btu or more). If residual fuel oil is introduced into a mixture of steam and air at high pressure, the residual oil can be partially oxidized to produce a raw fuel gas consisting mostly of carbon monoxide, hydrogen, and nitrogen. The sulfur originally present would be converted into hydrogen sulfide. The raw fuel gas could be scrubbed with water to remove carbon and soot particles and passed through an absorption system to remove the sulfur compounds. The desulfurized gas would then be burned in the primary boiler of a combined-cycle system. The sulfur compounds would be processed to retrieve elemental sulfur. For coal the process would be similar, but complicated by problems of handling a sticky solid that burns to form a troublesome ash.

The technology for partial oxidation of liquid hydrocarbons was developed for the production of synthesis gas, especially for making ammonia. It originated in the early 1950's from the Texaco Development Corporation in the United States and the Shell Internationale Petroleum Maatschappi N.V. in the Netherlands. Now both Texaco and Shell have processes for producing low-Btu power gas from residual fuel oil.

In a recent evaluation of the Shell gasification process, the authors concluded that the unit power cost of electricity in a combined-cycle plant fueled with power gas from residual oil would be about 9 mills per kilowatt-hour, assuming the improvements of turbine temperatures projected for the mid-1970's and assuming the cost of oil to be \$2 per barrel. This is higher than the current electricity rates (7 or 8 mills per kilowatt-hour), but the current costs will certainly rise as low-sulfur fuel sources become scarcer.

Since the chief advantage of gasification technology for electrical power generation is its effectiveness for high-sulfur fuels, the process by which sulfur compounds are removed from the gas must be very effective. Much data about the removal of hydrogen sulfide from hydrocarbon gases is available, most of it from the experience of the nature gas industry. Since most natural gases must be transported very far through pipelines, reliable methods were found to remove corrosive gases, such as hydrogen sulfide and carbon dioxide. Two such systems look very attractive for cleaning power gas, one with hot potassium carbonate and one with various amines as the chemical solvent. In these "wet" processes, the chemical solvent reacts with the carbon dioxide and hydrogen sulfide to form complex compounds, which are retained until the temperature and pressure are changed and then released as the complex compounds decompose. One way to dispose of the hydrogen sulfide is to selectively oxidize it to form elemental sulfur by a system invented by C. F. Claus in 1880. The Claus system is particularly attractive because elemental sulfur is the by-product that a power station can most readily market, and it is also the easiest to stockpile.

Proven Method of Sulfur Removal

The processes for removing hydrogen sulfide from power gas are expected to be so highly effective (98 to 99 percent removal) that sulfur emissions from the power plant would be almost completely eliminated. The study by Shell projected the sulfur concentration in the power gas would be only 5 parts per million, far less than the current limit on stack emissions and less then most estimates for future emission standards.

As a method for removing the sulfur from dirty fossil fuels, gasification appears to be superior to the major alternative—removing sulfur dioxide from the stack gases of a conventional power station. Though much research money has been spent on the problem of sulfur dioxide removal, the techniques available appear to have major problems. Furthermore, gasification may be cheaper. According to Arthur Squires, of the City College of the City University of New York, hydrogen sulfide can be removed from power gas for about \$20 per kilowatt, whereas it costs about \$70 per kilowatt to remove sulfur dioxide from stack gases.

According to Shell, the gasification process is also expected to produce little emission of nitrogen oxides because the nitrogen from the fuel forms N_2 most of the time, and with careful gas turbine design little nitrogen from the air forms oxides. Some observers think a combined-cycle plant could reduce nitrogen oxide emissions by two orders of magnitude, but this has not been demonstrated. Other observers are more skeptical.

The combined-cycle plant would have absolutely no emmissions of dust or soot, and the advanced combined-cycle designs would reduce thermal pollution by 25 percent compared to conventional power stations. At such a reduced level of thermal pollution, cooling stacks would be far cheaper, and it is possible that no dumping of hot effluents into natural waterways would be necessary. The problems would be the disposal of ash (which would be 50 percent vanadium if Venezuelan residual oil is used) and unburned carbon. Shell estimates the carbon waste would be less than 3 percent of the fuel input. Less than 1 percent is highly desirable.

Power Gas from Coal

Although many consultants, such as Squires and the research team at United Aircraft Research Laboratories, have urged immediate consideration of power generation with the new combined-cycle systems fueled by low-Btu power gas from residual fuel oil, the feedstock for which an effective gasification process will be most urgently needed in the future will be coal. The basic chemistry of coal gasification is very similar to gasification of residual fuel oils: partial combustion at high pressures with air and steam. However, coal is much more difficult to handle and transport because it is a solid. Furthermore, the composition of coal varies widely in different parts of the country. A process which works satisfactorily for coal from the East Coast may not work for coal from Illinois or Montana. Another major problem is separating the ash from the coal and disposing of it.

Very little research on gasification of coal for low-Btu fuel has been done in the United States. For the production of high-Btu gas from coal four well-defined processes exist. By substituting air for oxygen in the initial step of any one of these four processes, a low-Btu gas can be made. However, the best process for pipeline gas may not be the most suitable for power gas (a large methane yield is desirable for high-Btu gas but not for low-Btu gas). There are so many options available for each step in low-Btu coal gasification that a very great number of different complete processes are imaginable. Coals melt and become sticky; at least seven ways to deal with this problem have been proposed. At least three approaches are available for the problem of gasification. Then there are six or seven ways to remove ash after gasification (it should preferably be removed with no carbon). Clearly a very large tableau would be necessary to describe all the options of different approaches to the three problems of coal handling, gasification, and ash removal.

Few of the possible coal gasification options have been studied. The only system that is now commercially available was developed in Germany in the 1930's. It is a "gravitating bed" gasifier, manufactured by Lurgi Gesellshaft für Mineralöltechnik GmbH in West Germany. The Lurgi system has several important limitations. The products of combustion of the Lurgi power gas contain large amounts of water vapor, the coal particles must not be smaller than 3 millimeters in diameter, and the size of the gasification unit appears to be quite small for the scale of U.S. power generation. More than 20 Lurgi gasifiers of the current design would be needed for a 1000-megawatt power station.

However, Lurgi gasifiers are available now, and the company is putting into operation at Lünen, Germany, an installation to supply power gas to a combined-cycle system, which has a gas turbine that will generate 74 megawatts of electricity and a steam turbine that will generate 98 megawatts. In the United States, the Commonwealth Edison Company of Chicago has plans to install three Lurgi units to gain experience with coal gasification, but the power gas will not be used to fuel a combined-cycle system.

The possibility of coal gasification to make a low-Btu power gas has been heavily publicized in the United States in the last year, and the Office of Coal Research of the Department of the Interior is now considering proposals for the development of such a process. But the first new experiment on a gasifier to supersede the Lurgi design will almost certainly be performed in Europe. In Paris, France Albert Godel is planning to test a new design for a gasifier in early 1973. A coal gasifier called the Ignifluid boiler was developed by Godel and Babcock-Atlantique 17 years ago. The unit has been widely used (except in the United States), and successfully makes low-Btu gas with a fluidized-bed, a method for burning coal that has several advantages over a fixed bed. Air and steam are injected rapidly enough to buoy up the granular material (coal that is not carefully sized can be used). Because the fluidization allows easy movement of the solids from one part of the boiler to another, the temperature of the fluidized bed is uniform. Because steam is utilized much more efficiently in a fluidized bed than in a fixed bed, almost no steam appears in the power gas. However, because of the design of the grating on which coal rests, the Ignifluid boiler cannot be operated at high pressures. The new design, soon to be tested by Godel, has a different grating that is suitable for high pressure operation.

Other proposals for fluidized-bed processes have been studied on paper (or with small bench-scale experiments), but have never been tested. Arthur Squires and his colleagues at City College have proposed an elaboration of Godel's design that would treat fine carbon particles and ash differently. The City College gasifier would be shaped so that the fine particles would form a turbulent fluidized bed (called a "fast" fluidized bed) in the high velocity gases rising from a fluidized bed composed of larger coal sizes. The City College gasifier would incorporate Godel's ingenious discovery, used in the Ignifluid boiler, to collect the coal ash. Squires and his colleagues are also studying ways to clean hydrogen sulfide from power gas at high temperatures. The methods discussed earlier for cleaning power gas from residual fuel oil could be used for cleaning power gas from coal, but require that the gas be cooled.

Environmental Damage from Mining

Although coal is so plentiful the U.S. supply may last 500 years, it cannot be removed from the earth without paying a high price for the upheaval of topsoil, the pollution of streams, and the safety and health of miners. Deep mining is one of the most dangerous jobs in the country, and the U.S. techniques for deep mining are very inefficient compared to European methods. Deep mining causes subsidence of the land, apparent throughout Appalachia, and severe pollution of streams because the "run off" water from mines is heavily laden with acid. Most of the lands that have been strip-mined in the United States have not been reclaimed, and many observers question how effective any reclamation program can be. Demand for coal from western states such as Montana is growing because of its low sulfur content (about 1 percent versus 4 percent for many eastern coals), and strip-mining techniques are being used now to "open" the western coal fields. Some observers argue that reclaiming land in the plains will be relatively easy and effective compared to the difficulties of reclaiming hillsides in West Virginia. However, much of the West is underlaid with a hard cap-rock that would be broken by extensive mining, and environmentalists are afraid that the water table might fall significantly as a result of strip-mining.

Limited Funds for Coal Research

Nevertheless, the rate of progress of research in coal gasification could be very important for supplying energy in the future. Coal may be the only fuel available after gas and oil are depleted, especially if the output of nuclear power stations is limited by technical or environmental problems. But the total amount of money spent on coal degasification (about $40 million in the last 11 years) is less than one-third the amount spent on fission every year.

Through various coincidences of history, economics, and politics, coal research has been badly neglected in the United States. The program for production of high-Btu gas at the Office of Coal Research has still not produced a working pilot plant, and research on low-Btu gas production was simply not funded until $3 million was provided for initial studies last summer. The shortage of natural gas is here, and the shortage of low-sulfur fuel is imminent. Coal gasification techniques to replace these fuels are needed, but so far the options are not available.

—William D. Metz

References

1. A. J. Giramonti, "Advanced power cycles for Connecticut electric utility stations," Report L971090-2 prepared for the Connecticut Development Commission by United Aircraft Research Laboratories, East Hartford, Connecticut (1972).