28 August 1970, Volume 169, Number 3948 **SCIENCE**

Clean Power from Coal

Recovery of sulfur will be a mere incidental in new systems for burning coal to produce electricity.

Arthur M. Squires

In 1969 the United States power industry discharged to the atmosphere about 7×10^6 tons of sulfur in the form of SO_2. In the absence of controls other than tall stacks, the discharge in 1980 will be about 18×10^6 tons. Not long ago, the industry apparently hoped to rely primarily upon tall stacks to disperse its gaseous wastes (*1*), but the vast ecological experiment implied in the projected emissions is unlikely to occur. In early 1968, New Jersey issued rules that call for sulfur levels in coal and residual oil below 0.2 and 0.3 weight percent, respectively, after October 1971. Fuel suppliers, unable in 1968 to conceive where fuels of such low sulfur levels might be found, were skeptical that the rules would be applied. Other jurisdictions now give signs that they can be expected to follow Jersey's lead, and fuel users are beginning to understand that SO_2 emissions must soon be sharply limited.

What will be the technological response? In a word, I believe the response may work to make power cheaper.

It must be said at once that application of means now generally put forward for controlling SO_2 (*2*) would add significantly to the cost of electricity. Environmentalists would reply that the added cost is a small price for clean air. Yet the attempt to weigh costs of control versus benefits is a premature and probably silly exercise if it is carried out before the technological community accepts the idea that controls are imperative.

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There is a suggestive historical parallel. Before 1863, British alkali works poisoned the air with massive discharges of HCl gas. Under pressure from neighbors, managers of the works experimented with water scrubbing to absorb HCl, with indifferent success. The Alkali Act of 1863, passed by Parliament in spite of expert testimony to the difficulties, required a 90 percent reduction in HCl emissions. Soon sophisticated gas-scrubbing towers appeared, exceeding the Act's requirement. For a while much of the hydrochloric acid produced by the towers was taken to sea and dumped, but profitable markets for the acid developed. Most significantly, perhaps, the Alkali Act appears to have stimulated invention. Chlorine gas was a curiosity before Weldon and Deacon filed their patents (in 1866 and 1868, respectively) disclosing chlorine processes which soon turned HCl gas formerly wasted into profits.

In this article I have two purposes:

- to persuade that paths of technological development exist that could lead to suppression of SO_2 from coal and at the same time to a lower cost of power;
- to argue that a massive injection of money into *coal engineering* is the immediate ingredient necessary to open up these paths of development.

The combustion of coal at high pressure in the presence of a desulfurizing agent and the generation of power by a combination of gas- and steam-turbine cycles represent, together, a major opportunity.

The questions arise, What combustion technique? and What desulfurizing agent?

The first question is the more difficult. Efforts that shed light on the question, motivated simply by a desire for cheaper power, have been under way for some time. It will be well first to review these efforts and later to look at agents for the capture of sulfur.

Rethinking Coal Combustion

All of our great power-generating stations based upon coal use pulverized-fuel (PF) firing. Although PF boilers have reached the giant sizes needed for power generation at the 1000-megawatt scale, they are basically quite simple. A number of burners inject pulverized coal and air into a large rectangular box that has walls composed of vertical tubing filled with boiling water. The firing chamber must be huge not so much to allow sufficient combustion volume as to provide sufficient tube surface for transfer of heat to the boiling water.

Much of the inorganic matter in the coal leaves the chamber as fly ash, generally to be collected by an electrostatic precipitator. Some stations in metropolitan settings have installed precipitators to provide collection efficiencies exceeding 99 percent. To handle fly ash from a low-sulfur coal, such a precipitator costs about $10 per kilowatt of capacity (*3*). Although few existing stations are equipped with such precipitators, the power industry will find it hard in the future to escape such costs for fly ash control.

Power engineers adopted PF firing in the mid-1920's, when they began to require steam flows larger than earlier grate-combustion techniques could readily provide. Engineers of the day, accustomed to worrying about grit emissions from the earlier techniques, welcomed the finer dust that the PF boiler discharged. Herington (*4*) wrote in 1920:

It is quite true that perhaps 60 per cent of the ash goes up through the stack. This ash is of such light flocculent nature that it is dissipated over a wide area before precipitation occurs and no trouble can be expected from this source, although the amount of tonnage put out through the stack per day seems great.

The engineer of 1920 soon heard from nearby housewives who found "soot" on their wash, but the insults to lung tissue by fine matter were as yet unknown. Would PF firing have seemed so attractive for development if engineers had felt something like today's concern about fly ash?

Schemes to control fly ash and sulfur from PF combustion have a makeshift, tacked-on aspect. The time is at hand to rethink the problem of burning coal, with air pollution as a first rather than a last consideration. If the engineer of 1920 had been as much concerned with fly ash as with grit, he might well have concentrated upon ways to increase the burning capacity of his familiar grate devices.

An idea was at hand. Figure 1 is copied from the specification of Winkler's historic patent (*5*), filed in Germany in 1922 and put into commercial practice there in 1926. Winkler's idea was to increase the rate of gas flow upward through a granular bed to and beyond the point at which each particle in the bed was buoyed by the rising gas. When the pull of gravity upon each particle was canceled by the upward drag of the current of gas, the particles flowed freely, and the bed took on the character of a boiling liquid. A decade later, American engineers coined the term "fluidization" to denote Winkler's procedure.

It does not detract from the simple beauty of Albert Godel's idea to wonder why no one before him thought to fluidize a bed of coal upon a traveling grate. This idea led Godel during the 1950's to his "Ignifluid" boiler, seen in cross section in Fig. 2 (*6*). Godel made the remarkable discovery that the ash of almost all coals is self-adhering at a temperature in the vicinity of 1100°C, no matter how much higher the ash-softening temperature may be. Godel exploits this discovery to burn a wide range of coals in his fluidized bed (see Fig. 2). Coal is supplied in sizes up to 2 centimeters. As a coal particle burns, ash is released. Ash sticks to ash and not to coal, and agglomerates of ash are formed. They sink to the grate, which carries them to an ash pit. Godel's bed operates adiabatically, except for radiation from the upper surface. He limits the bed to the desired ash-sintering temperature by maintaining a high inventory of carbon in the bed, so that combustion is incomplete. Carbon appears as CO in the gas leaving the bed, and sulfur appears as H_2S. Godel admits secondary combustion air to the space above the bed, where CO and H_2S burn to CO_2 and SO_2, respectively.

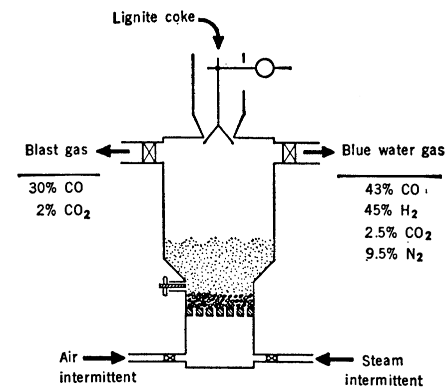


Fig. 1. Winkler's historic idea for partial combustion (that is, gasification) of coal in a "fluidized" bed [from his patent application filed in 1922 (*5*)].

As a result of the high velocity of fluidizing gas (about 3 meters per second) and the low air-to-fuel ratio, the coal-treating capacity of Godel's traveling grate is roughly ten times greater than that of previous grate-combustion devices.

Godel originally thought his Ignifluid system to be useful only in small boilers and for special fuels of low reactivity or high ash content. He believes he lost many years through failure to realize that his system might go into large utility boilers. A mature technique, such as PF firing, tends to become surrounded by an aura of inevitability that inhibits invention and protects it from competitive ideas.

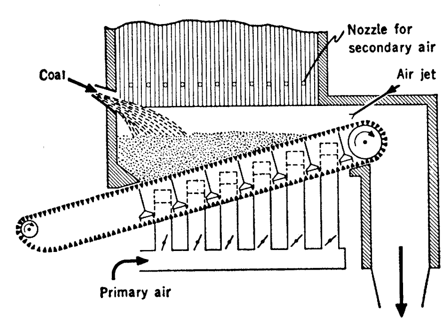


Fig. 2. Cross-sectional view of "Ignifluid" boiler developed by Albert Godel (*6*) and Babcock-Atlantique (*7*).

Recently, Babcock-Atlantique has promoted use of the Ignifluid boiler in large stations (*7*). A 60-megawatt unit is in operation at Casablanca, and negotiations are well advanced for a 275-megawatt unit to burn and remove accumulations of anthracite wastes in northeastern Pennsylvania. The owner of the unit, UGI Corporation, will benefit from a low fuel price, between 12 and 15 cents per million Btu (British thermal units), and the waste supplier, Blue Coal Corporation, will recover valuable urban land. The waste has a high ash content, and Godel's system is uniquely capable of dealing with it.

Another approach to fluidized combustion of coal is receiving worldwide attention. The U.S. Office of Coal Research (OCR) has sponsored large-scale trials conducted by Pope, Evans, and Robbins at Alexandria, Virginia (*8*). The U.S. Bureau of Mines and groups in England and Australia are doing similar work (*9*). The fluidized bed is operated nonadiabatically, the inventory of carbon is very small, and combustion is complete. The bed itself generally comprises the larger particles of ash matter in the coal. The bed is in contact with boiler tubes which hold the temperature to a level where ash does not sinter, generally below about 1000°C.

Although fluidized beds have been built in huge sizes for other purposes, it is nevertheless not yet clear that this work can lead to a boiler that challenges the PF furnace in cost for power generation at the 1000-megawatt scale.

Combustion at High Pressure

A large-scale experiment with fluidized combustion at 6 atmospheres and 800°C is under way at BCURA Industrial Laboratories (formerly the British Coal Utilisation Research Association) at Leatherhead, England (*10, 11*). If the competitive advantage of a fluidized-bed boiler operating at atmospheric pressure is uncertain, there is little doubt that such a boiler at elevated pressure can be much cheaper than a conventional furnace. Figure 3 illustrates the dramatic reduction in boiler size that might be achieved. No electrostatic precipitator would be needed, and the saving might run well beyond $10 per kilowatt.

BCURA's concept is that the hot gases from the bed would be expanded in a gas turbine. Another cost saving would arise from the fact that a gas-turbine power plant costs less than a steam plant by about $30 to $50 per kilowatt. The gas turbine would provide about 20 percent of the power from BCURA's system. Utilities have used gas turbines primarily to supply peak-load power, because the efficiency of an open-cycle gas turbine that operates independently of a steam plant is poor. Such a turbine discharges a hot gas directly to the atmosphere. In a few installations, a gas turbine discharges hot gas to a steam boiler, and such cooperative use of gas-turbine and steam power equipment can provide base-load power at outstandingly low cost (*12*).

The drive for higher performance in aircraft engines will continue, and experience from such engines can be expected to maintain the historic upward trend of temperature of gases at the inlet of industrial gas turbines. As this temperature rises, the proportion of the total power provided by the gas turbine of a combined-cycle system should logically increase. Systems can be envisaged in which the gas turbine would provide more than one-half of the power. With temperatures that might reasonably be achieved within a decade, such systems could provide electricity-generating efficiencies approaching 50 percent (*13, 14*). Adoption of the systems would greatly reduce the quantity of heat rejected to the environment from the steam cycle condenser.

In BCURA's experiment, about 70 percent of the heating value of the coal is transferred to steam in boiler tubes passing through the bed. The remaining heat appears as sensible heat in the hot combustion gases. If the gas turbine is to play a larger role, more energy must be converted to sensible heat in combustion gases. This can be accomplished by substituting a carbon-rich bed for the carbon-lean bed of the BCURA concept, since partial combustion occurring in the carbon-rich bed can provide CO for combustion outside the bed and ahead of a gas turbine.

A problem arises from the fact that dust carry-over from a carbon-rich bed contains a high percentage of carbon, which would represent a serious carbon loss if it is not used. Carbon in the dust carry-over cannot be consumed simply by returning the dust to the carbon-rich bed. There is a tendency for the dust to be blown out of the bed again quickly, and, as the dust "ages," its carbon tends to sinter to an inactive coke.

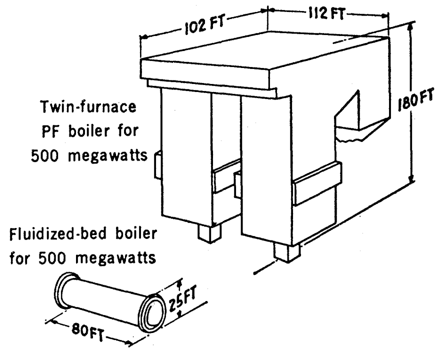


Fig. 3. BCURA's projection of size of fluidized-bed boiler at 15 atmospheres compared with conventional PF boiler (*10*).

Pope, Evans, and Robbins' success in burning carbon in fines blown from their experimental boiler (*8*) suggests a solution to this problem. They provide an auxiliary bed to which air is supplied in greater than stoichiometric amount for combustion of fines charged to the bed. Figure 4 illustrates how such a carbon burnup bed might cooperate with a partial combustion bed to supply gases at high temperature to a gas turbine. BCURA's temperature, 800°C, is probably too low for a partial combustion bed, and the carbon-rich bed in Fig. 4 should operate at a temperature above 900°C.

Carbon burnup in a partial combustion bed becomes less of a problem if the temperature is raised into the ash-sintering range, above about 1050°C. The Ignifluid traveling grate might be modified for use at high pressure. Jéquier and collaborators at the Centre d'Études et Recherches des Charbonnages de France operated an agglomerating fluidized bed of a design suitable for high pressure (*15*). Jéquier's design might be combined (*16*) with Lurgi's "circulating fluid bed" (*17*) to provide equipment of outstandingly large coal-treating capacity.

BCURA chose 800°C for its test at high pressure to limit the quantity of volatilized alkali salts in gases reaching the gas turbine. Problems with alkali corrosion of turbine blades may be expected if a fuel gas is produced much above 900°C. In planning the strategy for development of a fluidized-bed, partial combustion process for power generation, it will be important to establish upper limits for alkali entering the gas turbines which are expected to become available in the late 1970's. A safe plan would be to provide these turbines with gas that has been cooled and scrubbed free of alkali. Scrubbing with a heavy oil at about 370°C would be preferable to scrubbing with water at a lower temperature, so that heat may be rejected from the scrubber to boiler tubes, raising prime steam. There will be an advantage in keeping the quantity of gas to be scrubbed as small as possible. This will favor schemes in which the coal is devolatilized first, so that the gasification bed must deal only with coke (*18*).

It is hard to escape the feeling that PF combustion might never have been developed, other than for cement-making, if Winkler's work and the chemical engineer's interest in fluidization had appeared sooner. This proposition is, of course, not worth arguing, but the aura of inevitability that has colored much recent thinking about PF combustion and the SO_2 problem should be dispelled by concrete developments now appearing: the Ignifluid boiler to be built in Pennsylvania, BCURA's test of fluidized-bed combustion at high pressure, and Lurgi's application of its historic high-pressure gas producer to power generation (*19*).

A technique as mature as PF firing, practiced on so large a scale, will be difficult to displace. To enjoy the advantages of the combination of gas-turbine and steam power equipment, we must find a way to burn coal at high pressure in equipment of large capacity. A reasonable target would be a technique able to handle the coal for 1000 megawatts in a single unit, or at most in a few units. Development costs are certain to be large, since only expensive large-scale trials could satisfy those responsible for outlays for new power plants. I believe that fluidized-bed art offers the best hope, but I should note that Babcock and Wilcox have faith in a PF partial combustion technique (*20*). Texaco piloted such a technique in the late 1950's (*21*) but published no results. A scale-up of Lurgi's gravitating-bed gasifier would be difficult and uncertain.

Dealing with Sulfur Oxides

Work on alternative techniques for burning coal would be justified simply for the prospect of cheaper power. A special urgency in the effort arises from the opportunity to direct these developments into paths that will lead to a combustion technology in which sulfur is dealt with early in the coal-treating process rather than at its end.

The National Air Pollution Control Administration (NAPCA) has seized this opportunity. It has supported work to explore the possibility of using limestone or dolomite in a fluidized-bed boiler to absorb SO_2, and it has engaged Westinghouse Electric Company to direct a broad effort toward development of nonpolluting fluidized-bed boilers. Under a NAPCA contract, United Aircraft has explored advanced power generation concepts that incorporate gas and steam turbines and coal gasification equipment (*14*).

Atmospheric-pressure tests conducted so far suggest that appreciably more $CaCO_3$ must be injected than just the stoichiometric amount required to react with SO_2 to form $CaSO_4$, if this control technique is to meet New Jersey's requirement for October 1971—that is, a maximum allowable emission equivalent to 0.2 percent sulfur in coal. $CaSO_4$ has a larger molecular volume than either $CaCO_3$ or CaO, and a shallow layer of the first $CaSO_4$ reaction product seals off the interior of a particle (*22*).

If $CaCO_3$ must be used in an amount far greater than stoichiometric, the economics of the operation are improved, particularly in a station of large size, if the resulting sulfur-laden solid is treated for recovery of a valuable sulfur product by a technique that restores the solid to a form suitable for reinjection into the boiler. In atmospheric-pressure tests, Consolidation Coal Company has burned coal in a fluidized bed consisting substantially of particles of calcined dolomite, with good sulfur retention by the bed (*23*). The $CaSO_4$ formed was regenerated to CaO by a roast under slightly reducing conditions. Sulfur was evolved from the roast in a gas containing SO_2 at a concentration adequate for manufacture of sulfuric acid in a contact plant. British Esso (*24*) has conducted similar tests on absorption of SO_2 from the complete combustion of residual oil.

In a system for combustion at high pressure, an agent derived from limestone or dolomite may advantageously capture sulfur during a first coal-processing step. For this step, there are three cases to consider:

• complete combustion, using air in excess of stoichiometric;

• partial combustion, using between about one-third and one-half of the stoichiometric air and yielding a fuel gas containing CO and H_2;

• a carbonization yielding low-sulfur coke as well as fuel gas, heat for the carbonization being supplied by a partial combustion which consumes about 10 to 15 percent of the stoichiometric air (*25*).

Volume of high-pressure equipment would be roughly proportional to the air rate, and carbonization has the advantage that it can provide a low-sulfur fuel product that can be stored and shipped. We will look at this option in more detail shortly.

The CO_2 partial pressure in gas leaving BCURA's fluidized bed for complete combustion at 6 atmospheres and 800°C is sufficiently great that $CaCO_3$ in limestone or dolomite added to the bed would not decompose. Although limestone would not be reactive toward SO_2, half-calcined dolomite would react readily:

$$[CaCO_3 + MgO] + SO_2 + 0.5\,O_2 = [CaSO_4 + MgO] + CO_2$$

Kinetics for this reaction, apparently on account of half-calcined dolomite's porosity, are favorable at temperatures even as low as 600°C (*26, 27*). A way exists to regenerate $[CaCO_3 + MgO]$ from $[CaSO_4 + MgO]$ while liberating H_2S for sulfur manufacture (*27*).

Partial combustion and carbonization have the advantage that sulfur as H_2S can be removed from gas more readily than sulfur as SO_2. It is far easier to prepare sulfur in elemental form from H_2S than from SO_2, and sulfur would be a better by-product than sulfuric acid, since only the former can be stored or economically shipped long distances.

Recent experiments at the City College of the City University of New York (*25*) show that the reaction of H_2S and CaO in calcined dolomite to form CaS occurs homogeneously throughout the particle.

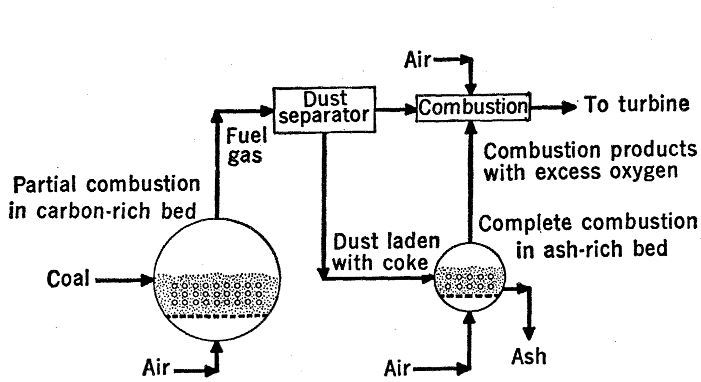
At least three techniques (given below) are available for recovering sulfur values from CaS.

1) The historic Claus-Chance process, introduced about 1880, treated CaS wastes of alkali works with water and a gas containing about 40 percent CO_2.

$$CaS + H_2O\ (\text{liquid}) + CO_2 = CaCO_3 + H_2S$$

In a countercurrent system, the reaction was substantially quantitative, yielding a gas containing 40 percent H_2S, which could be readily oxidized to sulfur in a Claus system. Pintsch Bamag has worked recently on a version of the Claus-Chance method to act in conjunction with partial combustion of residual oil with air at atmospheric pressure (*28*).

2) Consolidation Coal Company (*29*), British Esso (*24*), and FMC Corporation (*30*) have worked on various procedures, each amounting to a controlled oxidation of CaS to release SO_2, which would be converted to sulfuric acid.



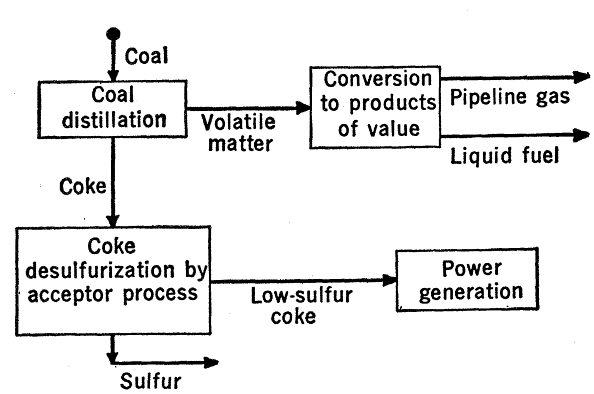


Fig. 4 (left). Scheme to supply CO for combustion ahead of a gas turbine.   Fig. 5 (right). A "Coalplex."

$$CaS + 3/2\ O_2 = CaO + SO_2$$

3) The City College is studying a technique for desorbing sulfur from CaS at high pressure by reacting the solid with steam and CO_2 (*31*).

$$CaS + H_2O\ (\text{steam}) + CO_2 = CaCO_3 + H_2S$$

The Claus-Chance procedure has the disadvantage that heat from the reaction of CaS with water and CO_2 is wasted; also, $CaCO_3$ is recovered as a wet slime difficult to reuse except at another penalty in thermal efficiency. The oxidative procedures have the appeal of simplicity, if sulfuric acid is an acceptable product or if H_2S is available from another operation in a fuel-treating complex (*30*) to react with SO_2 to yield sulfur. Of the several procedures, the high-pressure desorption is probably best suited to provide a regenerated $CaCO_3$ in a form suitable for repeated cyclic use.

Chemical species other than CaO exist, of course, which are capable of removing H_2S from a fuel gas at high temperature. Consolidation Coal Company has worked on the problem of providing MnO in a form suitable for this purpose (*32*), and the Bureau of Mines has studied sinters containing iron oxide (*33*).

Although operation at high temperature has the advantage of affording better thermal efficiency, the art of scrubbing a fuel gas with an alkaline liquor to absorb H_2S is highly developed, and this alternative may be preferred in the immediate future (*19*).

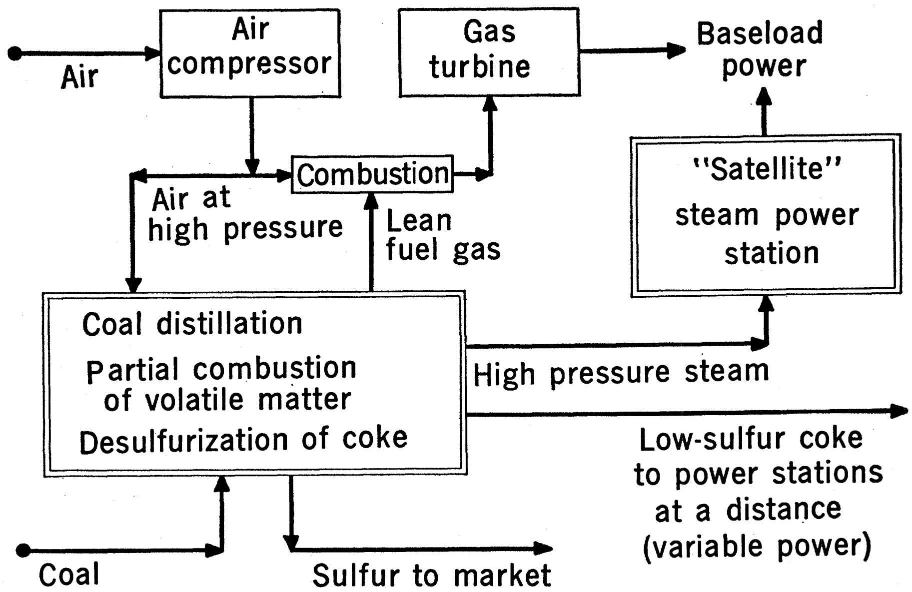


Fig. 6. A pioneering Coalplex (*25*) directed toward recovery of sulfur and generation of clean power.

Perspective for Coal

The country's and the world's reserves of hydrocarbonaceous matter largely reside in coal fields. Our own reserves of natural gas are insufficient for our growing needs, and arrangements have already been made to bring liquified gas from abroad at costs that bring sharply into view the alternative of converting volatile matter in coal into synthetic gas. Someday even the oil of Alaska's North Slope will be gone, and domestic supplies of liquid fuel will be desired.

An "obvious" response to these developments is illustrated in Fig. 5. Behnke (*34*) has called attention to the need to study the feasibility of integrated chemical extraction and power-producing complexes. In recent years OCR has supported work directed toward this goal (*35, 36*). The "Coalplex" depicted schematically in Fig. 5 is a logical choice for study. Volatile matter in coal may be converted by relatively simple procedures into synthetic pipeline gas or liquid fuel. Fixed carbon is converted to products of value only with much more difficulty, but Consolidation Coal Company (*35, 37*) has shown how easily the fixed carbon may be desulfurized through the cooperative action of H_2 gas and a solid acceptor for sulfur in the form of H_2S, such as CaO. FMC Corporation (*30, 38*) has operated a pilot unit demonstrating this procedure for producing a low-sulfur coke. Scientific Research Instrument Corporation (*39*), working under a NAPCA contract, has demonstrated the favorable kinetics for evolution of H_2S from coal distilled in the presence of H_2.

The term "coal distillation" in Fig. 5 should be understood in a broad sense. A pyrolysis at high temperature, preferably under a substantial partial pressure of H_2, can probably lead to a Coalplex of lowest capital cost and highest thermal efficiency. If the product mix from such a Coalplex does not have a proper balance of gas, liquid, and electricity, the yield of liquid may be increased and that of electricity reduced by adopting more expensive procedures for the initial treatment of at least a portion of the raw coal. For example, the treatment could be conducted at lower temperature and higher H_2 pressure and in the presence of catalysts.

Pulverized-fuel combustion is unsuited to handle the low-sulfur coke that will emerge from a Coalplex. Not only would an electrostatic precipitator be expensive, but the coke would need to be supplemented by a volatile fuel to maintain a stable flame. Work to develop fluidized-bed combustion techniques can be amply justified simply for the reason that they will be needed to deal with low-sulfur coke, which is certain to become available in large amounts.

In the near term, a less ambitious complex producing simply power and low-sulfur coke could play a useful role. Figure 6 depicts broadly a scheme under study at the City College (*25*). This pioneering Coalplex would generate base-load power from combustion of volatile matter and would ship low-sulfur coke. Heat to distill volatile matter would be provided from its partial combustion, and these steps, as well as coke desulfurization, would occur within a single vessel housing three fluidized-bed zones. Air flow to the partial combustion would be only 11 percent of the stoichiometric air for complete combustion of the coal, and the gases that result from the partial combustion would be at high pressure (such as 21 atmospheres). Hence, the volume of gases undergoing treatment would be only a tiny fraction of the volume that must be handled in a stack-gas cleaning operation. A single process vessel could treat coal for power generation at a rate of 1000 megawatts. The vessel would be approximately 25 meters in height. Its diameter would be about

5.5 meters over roughly 8 meters of the height, and about 3 meters elsewhere. The cost of the coal-treating equipment should be more than offset by revenues from sulfur and savings in cost of power-generating equipment (such as lower boiler cost and lower cost of gas turbines versus steam plant).

The scheme might advantageously be installed at a riverside location to process coal on, for instance, the scale of 13×10^6 tons per year, providing sulfur-free fuel for 5000 megawatts of power and typically shipping 4×10^5 long tons per year of sulfur. Such an installation would enjoy economies of scale in coal processing and sulfur production. Elliott (*40*) has called attention to the role which low-cost fluidized-bed boilers might play in supplying peak-load power, and the availability of low-sulfur coke to such boilers would relieve their owners of the need to install equipment for sulfur recovery.

A natural evolution is foreseen:

- The first Coalplexes would be justified simply for their economy in dealing with sulfur.
- Later, modifications would cream off limited amounts of pipeline gas and liquids from volatile matter.
- Further evolution would increase production of gas and liquids.

Ultimately, in an economy powered principally by breeder reactors, a Coalplex would evolve for which power might be a relatively minor by-product, and fixed carbon would be shipped mainly for metallurgical or electrochemical use.

Reordering Coal Engineering's Priority

There exist paths of technological development that can lead to clean and cheaper power. The missing ingredient is money. Lack of money increases the degree to which an aura of inevitability protects PF combustion from competitive ideas. When money is short, the "practical" man tends to prefer projects aimed at adjusting the mature art, and it is hard to get serious attention for ideas that are not a tack-on to the old.

I envy nuclear engineers in many respects, and not least in the obvious fact that no aura of inevitability will arise to protect the light water reactor. The breeder concept holds out the hope of an efficiency some 50 to 80 times greater than the efficiency of this primitive device, if efficiency is related to our total natural supplies of both fissile (uranium-235) and fertile (uranium-238 and thorium-232) materials. The light water reactor's aboriginality is appreciated if it is recalled that Watt's engine had an efficiency roughly one-tenth that of a modern power station. In a mature power economy based upon breeder reactors, the cost of uranium or thorium will matter very little. The light water reactor is sensitive to the price of uranium, and so also will be the cost of initiating a breeder power economy. I have seen no responsible opinion that the light water reactor, at the commonly projected growth of nuclear industry, can have any competitive standing beyond about 1990, for there simply is not enough low-cost uranium now in sight to fuel this reactor in the 21st cenutry. It is this fact and the uncertainties of the breeder development program that provide powerful arguments for a reordering of priorities for nuclear versus coal engineering. Benedict (*41*) wrote recently:

> Development of the sodium-cooled fast breeder reactor will be difficult and time consuming, and it is not certain that power costs will be low enough to permit them to compete with plants burning fossil fuel at today's price. Nevertheless the potential value of having available a practically unlimited source of energy [is] so great as fully to justify the effort now going into this development.

Equally justified is a vigorous effort to maintain coal's competitive position vis-à-vis the light water reactor, so that some low-cost uranium-235 will remain even if the breeder is delayed beyond present hopes.

Coal engineers need "fun" money, such as nuclear engineers have had, to pursue curiosities. It is a shame that no Godel Ignifluid unit can yet be seen here. An anecdote suggests what we may have missed on account of its lack. In the mid-1930's, M. W. Kellogg Company and Esso were at work on a technique for cracking distillate oils by passing oil vapor together with a fine clay catalyst through a heated coil. Results obtained in a small coil were good, but a larger coil performed badly. Examination of the flow of catalyst and air in a glass coil of the larger size revealed that the greater centrifugal force in the larger coil caused the catalyst to separate from the bulk of the air and to move in a ribbon along the outer diameter of the coil. As it happened, a team of Kellogg and Esso engineers had just returned from a trip to Germany, where the team had visited a Winkler gasifier much like the one shown in Fig. 1. One of the men suggested putting the catalyst in a bed and passing oil vapor upward into the bed to cause it to fluidize. This was done, and within a few weeks a pilot unit was in operation. The tremendous fluid cat cracker of today has a look of inevitability, but, if the men had not seen the Winkler gasifier, how long might it have been before fluid-cracking, so important during World War II, had been invented? How long before the chemical engineering profession awoke to the potential of fluidized-bed art?

It is a shame that no Jéquier unit has been built here, no Szikla-Rozinek unit (*42*), no Secord slagging-grate gasifier (*43*), no Winkler generator of the East German tuyere-blown, pear-shaped design (*44*), no Ruhrgas-Lurgi carbonization unit (*45*), or no plant-scale version of the dilute-phase carbonization unit for agglomerating coals developed by the Grand Forks Station of the Bureau of Mines (*46*). A theme of this article has been the need for a search for equipment of the highest possible coal-treating capacity. Experience with these novelties might have carried us far along a road now only dimly apparent. I have tried to indicate my view of the best paths of work, but it is proper to wonder how many ideas are missing for lack of the chance to see their physical embodiments.

Coal engineers also need the spectaculars, like the nuclear electric power station at Shippingport, which were so important to nuclear engineers before they could offer competitive equipment. The last coal spectacular was the coal-to-oil unit at Louisiana, Missouri, on which something over $100 million was spent after World War II. President Eisenhower canceled the experiment in 1953 for what then seemed proper reasons. In some respects the plant was obsolete even when built, and by 1953 two sad facts were evident: oil from coal would not be competitive for at least two decades, and by that time a far better job could be done. Yet I wonder how many good minds were turned away from coal engineering by Louisiana's closing. Senior men were forced to scramble to keep themselves occupied with responsible tasks, and at least a half-generation of inventors looked elsewhere than at coal's problems.

Spectaculars are important not only for a field's self-esteem and to attract recruits, but also for a reason more subtle. A development engineer is seriously handicapped if he works for years under no great urgency to provide engineering designs for a full-scale plant that he knows will actually be built. There is a coziness in this circumstance hard to resist, which leads to the temptation to resort to dodges convenient for getting on with small-scale work not suited for use in the field. A flaw of some coal development programs in recent years has been too little concern with seeking and testing designs affording coal throughputs per unit volume which are realistic for the commercial scale.

Above all, coal engineers need more coal engineering establishments—and more coal engineers! It has taken a great deal of money to generate the headlines, to produce the fellowships and fine work at colleges, and to support the symposia and demonstrations, reaching even into secondary schools, which have drawn the first-class minds who have carried forward our space and nuclear programs. It will be important to the nation's welfare that coal engineering during the 1970's at last receive its proper share of these inducements (*47*).

Summary

Nuclear engineers have a vision whose fulfillment will make plutonium-239 and uranium-233 the "dirty, cheap" fuels and will make coal the fuel of esteem. It will be valued for derivative chemicals and clean fuels and for metallurgical and electrochemical uses of its fixed carbon. In a coal technology devised to exploit these values, the recovery of sulfur will be a mere incidental. An immediate, properly financed effort to develop means for coping with sulfur can give us clean air with profit, help to conserve our limited supply of vital uranium-235, and take us a large step toward a coal technology for the 21st century.

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2. J. R. Garvey, testimony to Joint Committee on Atomic Energy, U.S. Congress (25 February 1970). Stack gases of a 1000-megawatt power station flow at 1300 m^3/sec and typically contain SO_2 at 0.2 to 0.3 percent by volume. Chemical treatment of such a vast throughput for removal of a constituent present in such small amount is bound to be costly. Since the 1930's, development teams have worked upon many ingenious ideas for capturing SO_2 from stack gases. The history of many of these efforts is depressing: initial enthusiasm followed by abandonment when the economic facts became clear. At the moment, some half-dozen or so schemes are alive. Two have reached field trials at a scale greater than 100 megawatts. The Tennessee Valley Authority is conducting trials of a dry limestone-injection technique in the hope of obtaining 40 to 60 percent removal of sulfur oxides through application of twice the stoichiometric amount of stone for absorption of the total sulfur [A. V. Slack and H. L. Falkenberry, *Combustion* **41**(6), 15 (December 1969)]. The hoped-for result would not meet New Jersey's requirement for October 1971. Combustion Engineering, Inc., is testing a wet limestone system which uses substantially the stoichiometric amount of stone. First trials ran into difficulties at the Meramec Station of Union Electric Company. A different design has given better results in preliminary operation at Lawrence Station of Kansas Power & Light Company [*Electrical World* **172**(23), 38 (8 December 1969)], and the technique may represent the best hope for early control of SO_2. The Cat-Ox system of Monsanto Company [J. G. Stites, Jr., W. R. Horlacher, Jr., J. L. Bachofer, Jr., J. S. Bartman, *Chem. Eng. Progr.* **65**(10), 74 (October 1969)] appears ready for a field trial at the +100-megawatt scale. Several other schemes are perhaps also ready for such trials. An overblown heralding of these systems could lead to pressure for their application on an imprudently wide scale. The history of classic disasters of engineering—for instance, the Great Eastern, the post-World War II Fischer-Tropsch synthesis, the Fermi reactor—should teach caution in applying new technology on a giant scale. Too much money and hope committed to multiple installations of inadequately tested systems could make it difficult to fund work on more advanced schemes for control of sulfur oxides. A distinguished panel of engineers recently concluded that efforts to force the broad-scale installation of unproven processes might delay effective SO_2 emission control (Report COPAC-2, prepared by Ad Hoc Panel on Control of Sulfur Dioxide from Stationary Combustion Sources, Committee on Air Quality Management, Committees on Pollution Abatement and Control, Division of Engineering, National Research Council, Washington, D.C., 1970).
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48. Work at the City College on desulfurization of fuels by calcined dolomite is supported by Research Grant No. AP-00945 from the National Air Pollution Control Administration, Consumer Protection and Environmental Health Service. This article is adapted from a paper presented 28 December 1969 at the Boston meeting of the AAAS in the symposium entitled "Power Generation and Environmental Change," arranged by the AAAS Committee on Environmental Alteration.

Cancer Viruses in Primates

Newborn simians are inoculated with viruses and neoplastic cells in an attempt to induce leukemia.

Roy Kinard

In 1962 the National Cancer Institute assigned high priority to the inoculation of newborn simians with oncogenic viruses as a part of the intramural viral oncology program. Gordon Zubrod, then the Institute's director of intramural research, introduced the concept of establishing breeding colonies in the United States to supply newborn simians for this purpose. Zubrod and Ray Bryan insisted that a reliable source of newborn simians would be necessary, and argued that, even if the search for human cancer viruses failed, the animals would be a valuable asset to other National Institutes of Health programs. Contracts to begin production and inoculation of newborn rhesus monkeys, baboons, and marmosets were arranged in 1962 and 1963. In 1964, the Special Virus-Leukemia Program, headed by Frank Rauscher, took over the support and direction of the existing contract projects.

In 1968 the program was renamed the Special Virus Cancer Program and was expanded to include the study of other neoplasms, but the projects described here are still directed mainly toward induction of leukemia in simians. The administrative functions of the program are to plan and coordinate projects so that the total effort will converge toward attaining the objectives listed below. This article is written in an effort to prevent unnecessary duplication of effort and to solicit the cooperation of individuals who may be considering similar work (*1*). Some general background and rationale is presented, then the work of the various collaborative projects is described.

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Program Rationale

The original program was based on the convictions that at least one virus is essential for the induction of human leukemia and that sufficient knowledge and technical competence was then available to achieve the following objectives: (i) induce leukemia in an experimental primate host; (ii) recover the responsible virus; (iii) establish laboratory passage strains of the isolated virus in animals or tissue cultures; (iv) confirm the pathogenicity of the virus for humans by seroepidemiological survey of leukemia patients and their contacts, whether human or animal; and (v) develop an effective vaccine or other control measure.

The knowledge underlying the convictions, and the techniques that can be used to attain these objectives, have been recently reviewed in detail (*2–4*). Viruses are known to be the primary cause of several forms of leukosis in chickens, mice, and cats (*5*). Viruses are probably responsible for various forms of leukemia in dogs and cattle, as well as for many transmissible and transplantable neoplasms of other vertebrates. Most viral leukemias in mice are preventable by vaccines. The leukosis viruses of chickens are a complex of related viruses one of which, the Rous sarcoma virus, causes malignant sarcoma in *Saguinus nigricollis* (a marmoset) and benign fibroma in the rhesus monkey. Simians of the family Cercopithecidae (macaques, baboons, and some other African monkeys) are susceptible to many cytolytic viruses of humans and have been used for experimental work, including the production and testing of vaccines, on many