Oak Ridge National Laboratory

review

Winter 1980

THE COVER: This issue is, with the exception of the departments, entirely devoted to coal research and its impacts. Much of the information covered extends beyond ORNL to include the national picture. Work being performed at the Laboratory is highlighted in red.

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DEPARTMENTS

OAK RIDGE NATIONAL LABORATORY
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COAL: THE UNDERUTILIZED RESOURCE

The doubling in world oil prices during the past year and recent events in the Middle East have again turned public attention to energy. However, we seem not to have awakened fully to the tenuousness of our energy situation and, in particular, the risks that accompany our dependence on imported oil. Execution of an effective energy program is still before us.

Many studies over the past decade have concluded that the expanded use of coal must be a cornerstone of an effective energy program. Clearly our large coal reserves can fill much of the nation's energy needs until longer term solutions are put to use. Burned directly, coal provides heat for warmth or industrial processes. It can be converted into low, medium, and high energy-content gases for a variety of applications or can be made into liquids matching the multitude of fuel and chemical products now obtained from crude oil. Transformed into electricity, energy from coal is delivered reliably to millions of individual users.

Nevertheless, we have been turning to greater use of coal with hesitation. The growth rate since the 1973 oil embargo has averaged only half that needed to meet the goal of doubling by 1985, and industrial use of coal has actually decreased over that period. In spite of a number of proposals dating back to before the embargo, the largest coal gasification plant operating or under construction in the U.S. processes only 150 tonnes of coal per day, and the largest liquefaction plant, now in shakedown, will process only 600 tonnes per day. (These sizes should be contrasted with commercial-scale plants which are expected to have capacities of around 30,000 tonnes per day.)

Our failure to embrace a rapid increase in the use of coal as a fuel and as a raw material for producing other fuels has many reasons: recognition that for some time synthetic fuels will be more expensive than petroleum and natural gas; uncertainty about future conditions, including future government regulations, which inhibits private capital investment in mines, transportation networks, and utilization facilities; serious environmental concerns joined recently by the danger of the "greenhouse effect" from increased atmospheric CO_2; the difficulty of making decisions when a large number of parties with competing views are involved; and finally, the slowness of establishing an overall national policy on energy.

In our view, acceptable ways to resolve these issues must be found so that we can increase the level and diversity of coal use. For example, it seems likely that available technologies will permit increased use of coal for a while without significant damage to the environment. These technologies are not as good or as cheap as we would like; but we need to observe them in use, and we can expect improvements as development programs go forward. The CO_2 problem will require continued watching so that we, and the rest of the world, can begin to curtail use of fossil fuels if future research shows that to be necessary.

Production of synthetic gases and liquids is costly now, but the gap between natural and synthetic fuels should close as oil and natural gas costs rise. The lower costs that are expected to accompany a fully developed industry can only be demonstrated by building and operating several industrial-sized plants.

Some of the hesitation of industry about conversion to coal and investment in expanded use can be removed by establishment of clear and lasting national policies and regulations. And finally, we must find ways to reach agreement about actions that are in the national interest even though they involve costs and risks as well as benefits.

ORNL's early conviction about these matters led us in 1974 to establish the Fossil Energy Program as a major Laboratory activity and to begin to create a broad program in coal R&D. Since then, significant fractions of our basic physical sciences and health and environment programs have been redirected towards work related to coal combustion, liquefaction, and gasification; and we have undertaken studies and development programs on a variety of coal technologies. Today these activities represent 11% of the total Laboratory budget and involve staff members in 14 divisions.

As a result of our feelings about the necessity for expanded coal use and of ORNL's increasing activities in this area, this issue of the *Review* is devoted solely to coal. This deviation from the usual *Review* format has permitted us to treat many aspects of coal production and use. By this means we hope to provide the readers of the *Review* with a broad perspective as well as an understanding of ORNL's growing involvement.

—L. E. McNeese and M. W. Rosenthal

Energy Supply and Demand

By BLYNN PRINCE and JOHN McGAUGH, Strategic Planning Department of UCND's Operation Analysis and Planning Division.

Coal is the nation's most abundant fossil fuel resource. The primary thermal energy that can be obtained by direct combustion of identified reserves of coal in the United States is about 300 times the present annual U.S. primary energy consumption rate.

How best to exploit this natural resource is not a simple problem, however. Coal is also the fossil fuel with the greatest potential for damaging the environment and producing safety and health hazards in its mining, transportation, conversion, and combustion. Moreover, the nation's demand for primary energy continues to increase as the population and economy grow, thereby making these environmental limitations loom even larger in the future.

It becomes important, therefore, to gain a more precise understanding of how coal may fit within the nation's overall future energy supply and demand picture.

History

From 1850 to 1975, there was a growth of demand for total primary energy from all sources, including fossil fuels (coal, oil, and natural gas), solar-based renewable sources (wood, work-animal feed, wind, and hydropower), and nuclear fission energy, which just began to penetrate toward the end of this period. Over most of this 125-year period, total primary energy requirements have tended to grow at a rate of about 3% per year, with the exception of the dramatic drop during the Great Depression in the 1930s.

Electricity is a relative latecomer in this historical period, with significant penetration into the energy supply system only by the 1920s. Since then, primary energy allocated to electric generation has tended to grow about 2.7% faster than the total primary energy demand. In 1850, over 90% of primary energy was derived from wood and work animals; by 1975, the nation relied on petroleum and natural gas for about 75% of its energy. Of these, transportation accounts predominantly for the petroleum consumption, and household, commercial, and industrial uses for the natural gas. Coal supplied only about 18% of U.S. primary energy in 1975, most of which was used in electricity production.

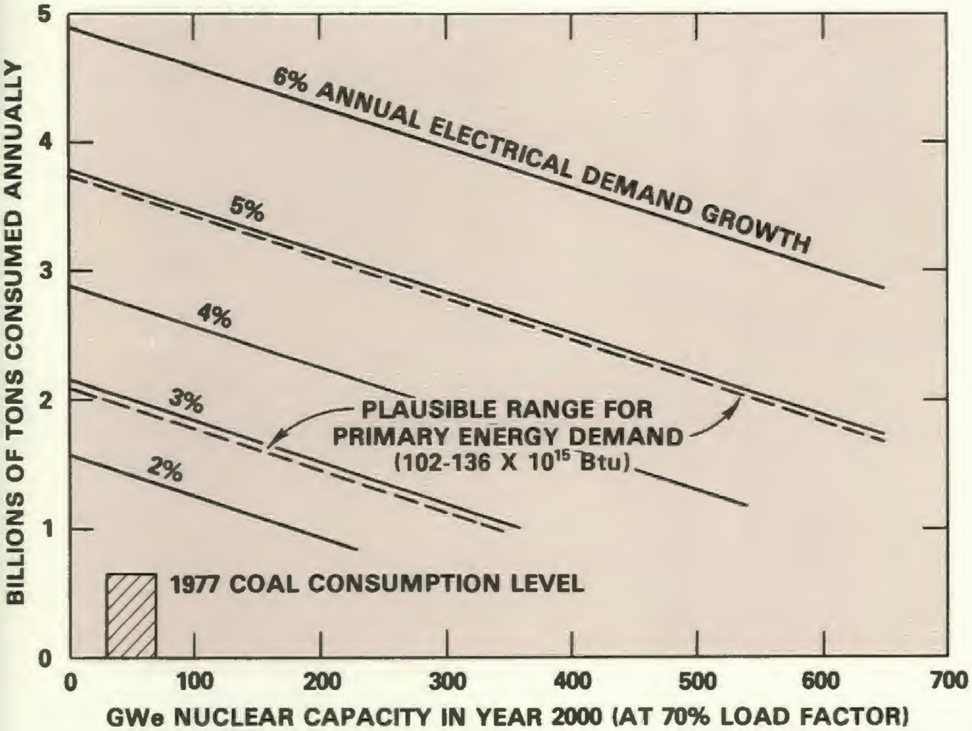
The Future

In projecting future trends, there is the temptation to estimate demand growth by simple extrapolation, concluding a demand for about 170 quads per year of total primary energy by the end of the century, of which slightly over one-half would be used in electric generation. There are a number of reasons, however, for suspecting this estimate to be too high, and to project average growth in demand over the next two or three decades to be significantly less than was experienced in the past.

For instance, the 1970s marked the end of a long period in which the real price of energy had been steadily declining. During that decade, new constraints appeared that tended to counter that trend. By around 1970, domestic production of petroleum peaked out and began to decline, giving rise to increasing dependence on imported petroleum. Today, over 40% of the country's total petroleum consumption relies on importation. At the same time, natural gas production has stopped increasing, and has declined slightly through the decade. Although imports of gas are not yet a significant fraction of supply (~5%), the trend is in this direction.

But another force emerged during the early '70s that shows no indication of abating. The past decade has been a kind of watershed marking the development and growth of a national environmental consciousness. Federal and state legislation has been enacted that is

Blynn Prince



In 1977, U.S. consumption of coal was about 750 million tons. By 2000, if the country were to have no nuclear capacity, and if the growth in demand were to be kept to 2%, some 1.5 billion tons would be needed to fill the demand. Both hypotheses, however, are implausible. The plausible range of demand growth is considered to be somewhere between 2.9% and 4.9% by 2000. The amount of coal required for that range will depend on the extent to which nuclear power is available.

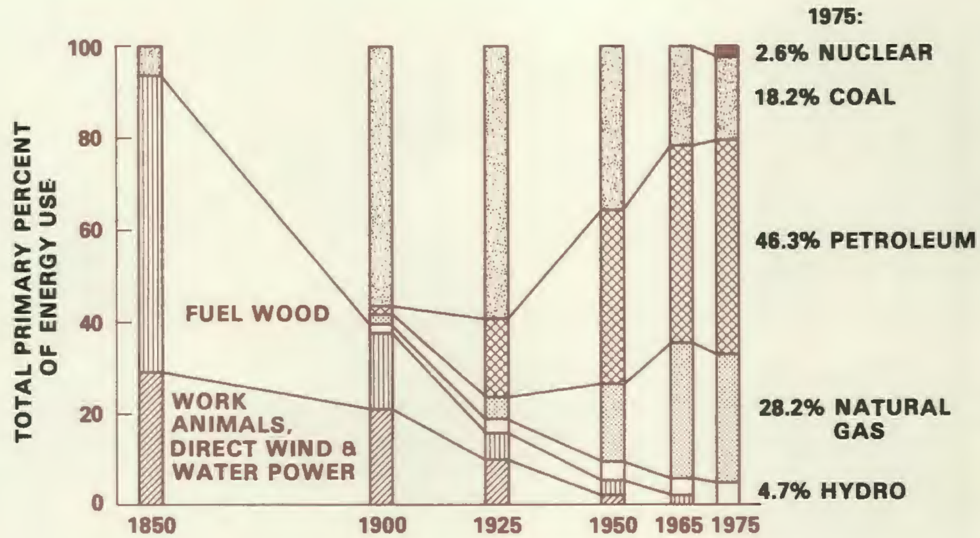
aimed toward controlling sources of air and water pollution and managing certain uses of land resources. The price of meeting these environmental objectives has been added to the price of imported oil imposed by OPEC, resulting in the beginning of a turnaround in the real price of energy. Moreover, there is no indication that this trend will soon be reversed. As a consequence, the nation is confronted with new economic incentives for using energy more efficiently than in the past.

This new interest in conservation, the strategy of reoptimizing energy use so as to reduce the amount required to obtain various goods and services without undue loss of amenities, promises to have a substantial impact on the long-run growth of energy demand. There are, however, still other factors to consider in future projections. Changes, such as the increasing average age of the population, are taking place in the U.S. demographic and economic structure that also point toward reduced growth rates. Economic growth also depends on trends in productivity improvement; as energy becomes more expensive, there may be a gradual shift away from certain energy-intensive manufacturing activities, which have traditionally had high productivity growth rates. We have already seen a growth in service-oriented activities (e.g., education, health, communications) which tend to be less energy-intensive but have slower productivity growth.

The potential impacts of all these phenomena on the demand for energy have been explored in a number of energy policy studies made during the past several years, under the auspices of such organizations as the Ford Foundation, the National Research Council, ERDA and the Department of Energy, and the Electric Power Research Institute. While they all tend to agree that the average growth of primary energy demand is likely to be lower between now and the turn of the century than in the past, estimates differ on how much. Striking a balance among these differences, we can conclude that a 20–40% reduction in historical extrapolation seems plausible. This would put demand by the year 2000 in the range of 102–136 quads, instead of the projected 170.

John McGaugh

Several historical transitions have taken place in reliance on various primary energy sources. These distributions among sources, given here as percentages of total primary energy, are indicated for several years selected over a 125-year period.



Compared to the historical 3% growth rate, energy demand over the last quarter of the century would be 2.6 to 1.5% per year.

For the present, we believe that more precise estimates of demand growth are unwarranted, and that planning for energy supply expansion must be flexible enough to accommodate this range of possibilities. What is wanted is the continuing orderly integration of the energy supply and demand without unduly disrupting the functioning of the economy.

Guidelines

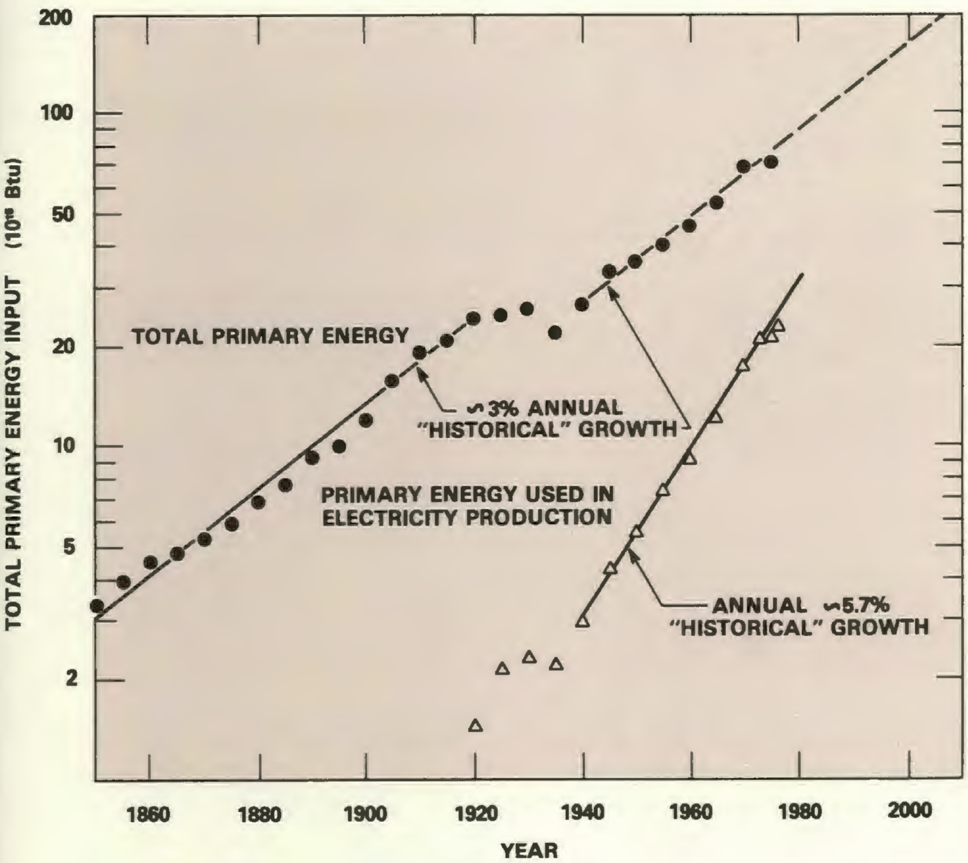
Using these estimates of demand growth as a point of departure for examining the problem, certain guidelines in planning have been offered by the studies mentioned. Some of their conclusions are:

- The U.S. needs to shift its degree of dependence on petroleum to other sources of primary energy as rapidly as possible.
- Successful efforts at applying conservation technologies and policies can have substantial impact in moderating future energy demand growth, without unduly restricting amenities derived from economic growth.
- Possibilities for expanding natural gas production at rates that would be desirable to help substitute for certain uses of petroleum appear tenuous.
- Coal and nuclear power appear most likely to be the primary energy sources which can provide the residual supply expansion needed between now and the turn of the century.

Let us construct a "baseline" scenario by assuming that domestic production of petroleum and natural gas can be maintained at current levels for the remainder of the century. Furthermore, we will assume that it is desirable to restrict any further net increase in dependence on imported petroleum. The prospects for tradeoffs by year 2000 between moderating demand growth through conservation and expanding energy supplies via coal and nuclear power can then be quantified. Let us make two additional assumptions: (1) Electrical generation will account for 75% of all primary energy growth requirements after 1977; also, there are no significant increases in thermal-electric generation efficiencies. (2) Coal provides for the remaining 25% of primary energy growth through various nonelectric uses. The effective thermal equivalent is assumed to be 20 million Btu per ton.

Using the above assumptions, we can conclude that the range of 102–136 quads of total primary energy would correspond to an average annual growth of electrical demand between about 3–5%. Thus, for example, if the U.S. has 300 GW(e) of installed nuclear capacity in operation by year 2000, the total coal consumed annually for all purposes (electric and nonelectric) might range between 1.2 and 2.8 billion tons. By comparison, the total coal consumed in 1977 was 670 million tons; and nuclear power generation was equivalent to 43 GW(e). Without any backup from nuclear generation, the total coal required in year 2000 would be considerably higher, ranging from 2.2 to 3.8 billion tons. Unquestionably, the upper ranges of these requirement estimates would be difficult production targets to achieve.

The magnitude of these projections gives some weight to the question of how realistic the



Long-term historical growth of total primary energy input for the U.S. has averaged about 3% per annum, except for years during the 1930s depression. Primary energy used to generate electricity has tended to grow at nearly twice this rate since 1940.

assumptions are that led to them. The extent to which electricity will continue to penetrate the energy supply system and substitute for direct uses of fuel is a matter of controversy in all energy policy evaluations. However, assumption (1) appears to characterize reasonably well the range of possibilities considered in the studies examined. The qualifying assumption that no net improvements in generating efficiencies will occur could prove conservative, if commercial applications of cogeneration, fuel cells, or MHD generation technologies become significant, within this time frame. Assumption (2) may ultimately prove somewhat optimistic in terms of the effective thermal equivalent, when all losses incurred in coal cleaning and conversion are accounted for.

The baseline scenario could also be subject to change. If the U.S. is able to develop unconventional, high-cost resources of natural gas or oil shale, or to make direct application of solar energy on a sufficient scale to displace some end uses of fuel, less coal production would be required by year 2000. In the other direction, coal production requirements could increase if they are also called upon to displace current direct industrial uses of petroleum and natural gas.

The message that seems to emerge from all this is that high priority needs to be placed on all programs aimed at facilitating safe, reliable, and environmentally acceptable uses of both coal and nuclear energy, and on making energy conservation policies effective.

Energy Use in the United States, 1975

Primary fuel	Total energy used (10^{15} Btu)	Percent direct use by sector			
		Household & commercial	Industrial	Transp.	Electric utility generation
Petroleum & natural gas liquids	32.72	17.6	17.3	55.2	9.9
Natural gas	19.95	38.0	42.9	3.0	16.1
Coal	12.83	1.9	29.8		68.3
Hydropower	3.23				100.0
Nuclear	1.83				100.0
Total	70.56				

By 1975, the transportation sector accounted for the majority of petroleum uses, with the remainder divided approximately equally between the industrial and household/commercial sectors. The latter accounted for nearly all uses of natural gas, while coal was used primarily for electricity generation.

The Market for Coal

By E. C. FOX and R. L. GRAVES

In the United States, coal is abundant, accessible, and relatively cheap. It is so abundant, in fact, that in some parts of the country all you have to do is remove a little soil to reach coal in abundance. Today, as the world's largest coal producer, the United States mines 770 million tons of coal a year, but that fact is not so impressive when you consider that we mined 700 million tons per year sixty years ago (1920). Why have we been turning away from coal and what is coal's future in the American energy market? We can obtain a fairly good perspective of our predicament if we understand how and why we got into it.

Sixty years ago coal was the primary purchased fuel; about 80% of the energy used in 1920 came from coal. At that time there were basically only two fuel sources—coal and wood. The supply of wood was limited and coal was seemingly inexhaustible, so coal won by default.

When oil and gas were first introduced, these fuels won rapid acceptance. Unlike today, when the oil price more closely represents its value, past pricing reflected production costs plus profit. Since 1915, gas has been a favorite of industry. Demand was so high that two-thirds of the early industrial gas supply was synthesized from coal since the natural gas fields in Pennsylvania and Ohio (which were the first developed and were close to the industrial market) were inadequate to meet the needs. By World War II, a transportation network was constructed that could move the gas long distances from the large fields in Texas and Louisiana, so the consumption of gas escalated. Gas proved to be the perfect fuel for industrial and residential heating because it is clean, easily handled by modest equipment, and was inexpensive. In fact, except for the last few years, natural gas has always been cheaper than coal, although regulation of natural gas price at artificially low values has been a major factor. Because gas and oil were cheap, easy to use, and met the eventual environmental restrictions better than coal, coal took a back seat to gas and oil.

National energy policy calls for a reduction of imported oil and replacements for gas. Other energy sources that must fill the void which will result from restricted use of oil and gas are nuclear energy, conservation, and coal. Determining the share of the energy market for which coal can compete is most easily accomplished by looking at each major energy-consuming sector; namely, utilities (electricity production), industry, transportation, and residential/commercial consumers. The Engineering Technology Division of ORNL has investigated the market for coal-based energy systems both in DOE-funded studies and as a part of their internal strategic planning effort.

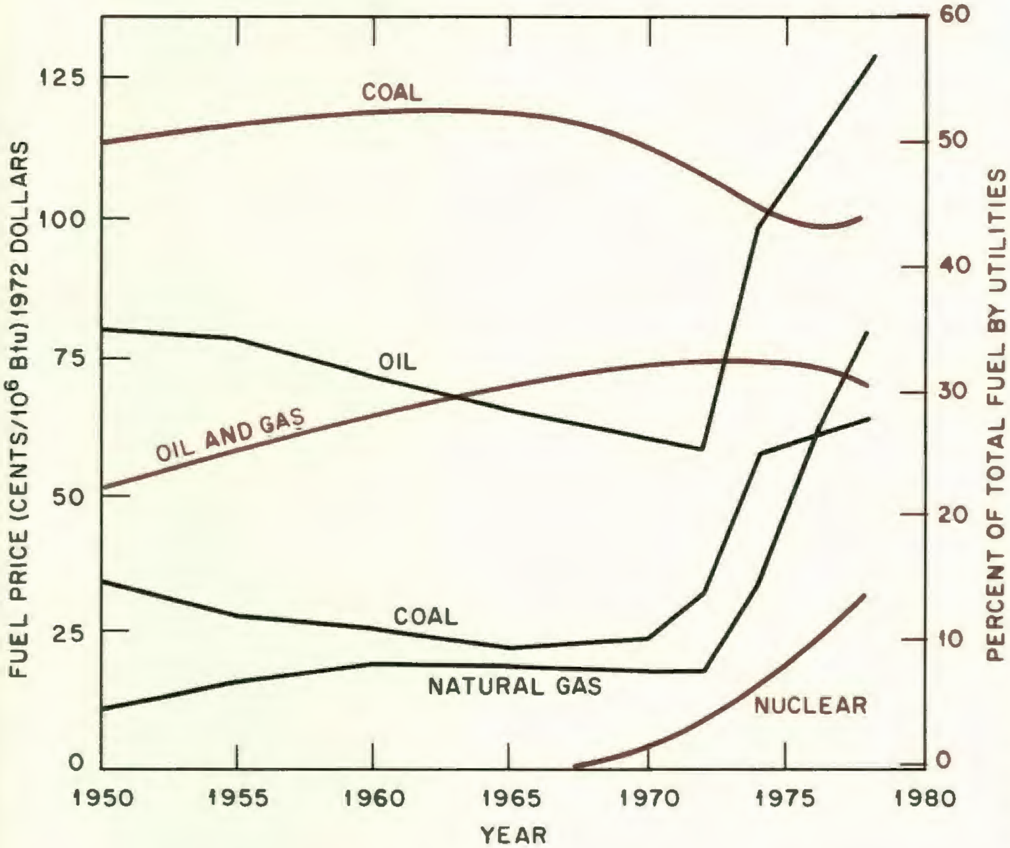
Coal and Electricity

Production of electric power is one of the most attractive applications of coal because most electric power plants are large enough to take advantage of an economy of scale, and in such plants coal is used to generate steam, a technically developed application for coal. Coal presently plays a major role in the production of electricity with 45% of United States electric power coming from coal-fired plants. In recent years, however, coal has received less attention due to the emergence of less expensive nuclear power, continually tightening emissions standards, and greater use of oil and natural gas.

The demand for coal by the utilities is characterized by a retrofit market and an expansion market. The existing oil- and gas-fired power plants constitute the retrofit market—that is, the plants whose boilers and other components must be replaced with proper equipment so that they can burn coal. The retrofit market represents six quads of energy, about half of which is oil (16% of imported oil). By the year 2000, however, the annual fuel use by utilities is predicted to increase by about 50 quads, making the expansion market the real target for coal.

The geographic distribution of utilities that are largely dependent on oil may have a pronounced effect on the retrofit market for coal. About 60% of the oil consumed by utilities is used in California, the Northeast, and the deep South. Questions concerning the logistics and cost of moving coal to these areas have not been resolved.

Prices (in 1972 dollars) of oil, coal, and gas are shown here for the third quarter of the 20th century, compared with utilities percentage use of coal, oil and gas, and nuclear in the same period.



Emissions regulations may also present a problem in these locations since an increase in coal use is generally accompanied by increased levels of particulates, nitrous oxides, and sulfur dioxide (SO_2) in the atmosphere. The deep South, however, presently has very low levels of atmospheric SO_2 and particulates; therefore this area may have fewer difficulties in using coal rather than oil.

The future market for coal in the utilities is very large, and a great deal of effort is being expended in determining the most suitable technologies to fill this need. Exclusive of the coal-burning device, the geographic distribution of the future market is of great importance in determining the applicability of coal. The largest growths are to occur in the Southeast, East, West, and, to a lesser extent, in the Southwest. The close proximity to coal sources and the present existence of coal-fired plants make the East and South appear to be likely candidates for coal utilization in the future. However, coal is generally not used and not readily available in parts of the West (California); therefore, direct combustion of coal is perhaps less feasible in this area. It should be noted, however, that a coal-fired electric plant being planned near San Francisco by Pacific Gas and Electric will be supplied with coal from Utah.

The problems of burning coal in areas which may already be in near noncompliance with emissions standards for a particular atmospheric pollutant weigh as heavily in the expansion market as in the current retrofit market. New methods of getting energy from coal, such as fluidized-bed combustion and coal gasification, are seen as viable measures to lessen the environmental impact of expanded coal use.

In fact, the development work on advanced coal utilization systems for power generation may have its greatest value in producing less expensive, environmentally acceptable power plants. Efforts directed toward developing cheaper and more efficient coal power plants are certainly worthwhile, but may not have a significant impact on the growth rate of coal use in the utilities. This is because the economics of power generation plants strongly favor even conventional coal plants over oil- or gas-fired plants. Hence new advanced systems will not tend to cause a shift to coal in the utilities, but would provide power to the consumer at lower cost while still meeting emissions requirements.

It is interesting to note that the median overall thermal efficiency of power generation in the United States was about 32% in 1977—that is, 68% of the heat produced was rejected to the environment while only 32% was converted to electricity. That trend has been downward since 1975. Hence, the introduction of the atmospheric fluidized-bed steam power plant, operating at about 35 to 36% efficiency, would represent a noteworthy improvement. Continued development of the other concepts, such as pressurized fluidized beds and gasifiers coupled to combined cycles, should produce a plant with an efficiency of over 40%, which will be increasingly advantageous as fuel costs escalate. Improvements in coal technology will also help assure a place for coal in a market being pursued by other technologies such as nuclear energy.

Industrial Energy Market

Industry in the United States uses about 40% of the total input of primary energy. It is not only the major energy-consuming sector, but is also a large user of oil and the largest user of natural gas. While the types of processes that use this energy are thousands in number, the market can be characterized largely by two general types: steam generation and nonsteam process heat. These two broad categories account for about 80% of industrial energy use.

In April 1977, President Carter announced in his National Energy Plan that utilities and industries would be required to shift from the consumption of oil and natural gas to the more abundant supplies of coal. In 1978, Congress passed the Power Plant and Industrial Fuel Use Act which provides criteria for utilities and industries to convert to coal. But the decision to convert to coal is largely in the hands of the industrial energy user. For example, there are no regulations that would force an industrial energy user, who is presently burning gas or oil and does not have coal burning capabilities, to convert to coal. The present Fuel Use Act relates primarily to new installations. Unlike the utility sector, the major opportunity for increasing the use of coal is in replacing existing oil- and gas-fired equipment. One implication is that the near-term market is relatively insensitive to industry's growth. But a more important implication is that the conversion to coal will take place only if coal has merits relative to alternatives as judged by the user. Since the major market is in replacement—not in expansion—and replacement of existing oil and gas equipment by coal equipment is not generally covered by government mandate, the potential user has some options. One obvious option is to continue to use existing equipment and fuels. In general, this is what is happening at the present time. To gain some perspective on the quantity of coal that would be required for a total shift to coal in industry, the oil and gas presently being used represents the energy equivalent of 550 million tons per year of coal. Although the present production of coal is somewhat lower than the mining capacity, this added production would require nearly doubling the present capacity.

Direct Coal Combustion

For much of industry, direct coal combustion is an unfamiliar, complicated and perplexing energy option. Unlike buying another oil- or gas-fired boiler or process heater, the decision to switch to coal involves important and complicated issues such as environmental constraints, financing constraints, and economic feasibility.

The environmental issues are important because, while it may not be illegal under the present energy legislation to continue burning oil and gas, in many instances industries converting to direct coal combustion will end up violating a number of environmental laws that govern the ambient air quality and restrict the emissions from industrial sources. The ambient concentrations for one or more pollutants in most heavily industrialized regions of the country are equal to or greater than the ambient limits. Areas such as these, which are in noncompliance, must offset any new source with an equal or greater decrease in another source within that region. The prospect of dealing with such complicated legal maneuvers is particularly severe for small industries that do not have large legal and technical staffs. Direct coal use is thus discouraged, especially in an application that is apart from a company's primary product.

When considering the prospect of converting gas- or oil-fired systems to coal, the question of economics is the most relevant and easiest to quantify. The capital resources needed to complete a conversion to direct coal firing are three to four times greater than the cost of oil or gas systems. Also, because of the economy of scale, the addition of coal boiler capacity a little at a time is not economically attractive. Thus, in contrast to the past practice with package oil and gas units that could be added in increments to accommodate growth and replace obsolete units, the decision to switch to coal usually involves the replacement of a major portion of the capacity at one time.

Although most companies would be able to raise the capital required for new coal facilities, all companies have finite capital resources. They must choose between investing in these energy projects or in developing their primary product. A company is motivated to convert to coal either because it is forced to through legal orders or because it perceives that the operational savings will offset the capital investment. Since for most, the present legislation does not require conversion, most decisions will be based on the economic merits.

We examined the aggregate market for direct combustion by estimating what the voluntary market would be if all boiler installations which could economically justify shifting to coal did so. The economic market potential for coal was judged relative to the cost of oil in industrial boilers. Unlike oil- or gas-fired boilers, coal equipment is very capital-intensive. For this reason, the total product cost of steam is a strong function of the size of the installation and the use or capacity factor. Since coal type, quality, and price vary throughout the country, the analysis was performed regionally to take some of these variations into account. These relationships were then combined to give a perspective of the direct coal-combustion market in regard to meeting simple economic acceptance as a function of oil price. The actual world oil price is somewhere between $26 and $30/bbl (at present writing) while the typical delivered cost of oil to industries is about $30/bbl. Therefore, at today's prices, few industries would perceive that the savings would be enough to justify building a coal-combustion system.

Presently there are several advanced combustion systems that are being developed for industrial applications. Some advanced systems, such as industrial fluidized-bed combustors, are felt to be capable of decreasing the capital required for the boiler equipment by as much as 25%. If such systems were commercially available today, our analysis shows that 10 to 30% of industries could economically justify switching to coal.

Synthetic Fuels as an Option

One alternative to converting an industrial facility to coal firing is to continue to burn oil or natural gas. In the event that gas or oil is not available or their prices rise to a high enough level, substitute synthetic fuels could begin to capture part of the industrial energy market. The price and availability of fuels are interrelated; as the supply decreases and the demand grows, the price rises. However, throughout recent history the United States government, in an attempt to institute certain domestic policies, has to some extent regulated both the price and supply of oil and natural gas.

In a narrow sense, the market for synthetic fuels will be similar to that for oil and gas. Synthetic products that can technically be substituted directly for gas and oil must be priced the same as gas or oil to achieve market penetration. Since present estimates of synthetic fuel prices are in the range of 50 to 100% higher than present natural fuel prices, the present market is small. However, future prices of oil and gas should increase at a faster rate than prices of synthetic fuels. As a result, at some time in the future, these fuels will penetrate the market.

Recent analysis indicates that by the year 2000, synthetic liquid fuels could capture as much as 50% of the new industrial market. If gas and oil are unavailable, the industrial energy options become limited. In fact, for the near term, most industries would limit their choices between direct coal combustion and burning synthetic fuels. Assuming that an industry would make a choice and not merely postpone their investment decision, the choice would be between investing in new coal combustion equipment and buying synthetic fuels for either new or retrofitted applications. The market can then be represented by the price of synthetic fuel that would compete with the investment in combustion equipment. It can be inferred from this that in the absence of oil and gas, and with synthetic fuel prices consistent with current estimates of synthetic fuel costs ($25 to $50/bbl), there is technically a large market for these fuels.

Transportation Market

The transportation sector is the largest user of oil and it is one of the most important in respect to the "energy crisis." If we break down the "energy crisis" to its key ingredients, we find that the crisis is really distillate fuel shortages and waiting lines. Ninety-three percent of the fuel used for transportation is distillate fuel, which represents 54% of the total oil used in the United States.

In an open market, synthetic coal products will have to be priced competitively to make any penetration. However, estimates of acceptable processes indicate that the cost of producing gasoline would be somewhat higher than $1.50/gal. Although the price of petroleum-derived fuel is approaching the synthetic costs, there is still too much uncertainty in price for a commercial enterprise to invest the immense capital required for the conversion facilities. Strong government support is needed before any of the market can be captured. This could be in the form of government loans, direct investment, or subsidies. But without government action, the market penetration of synthetic motor fuels will be very small.

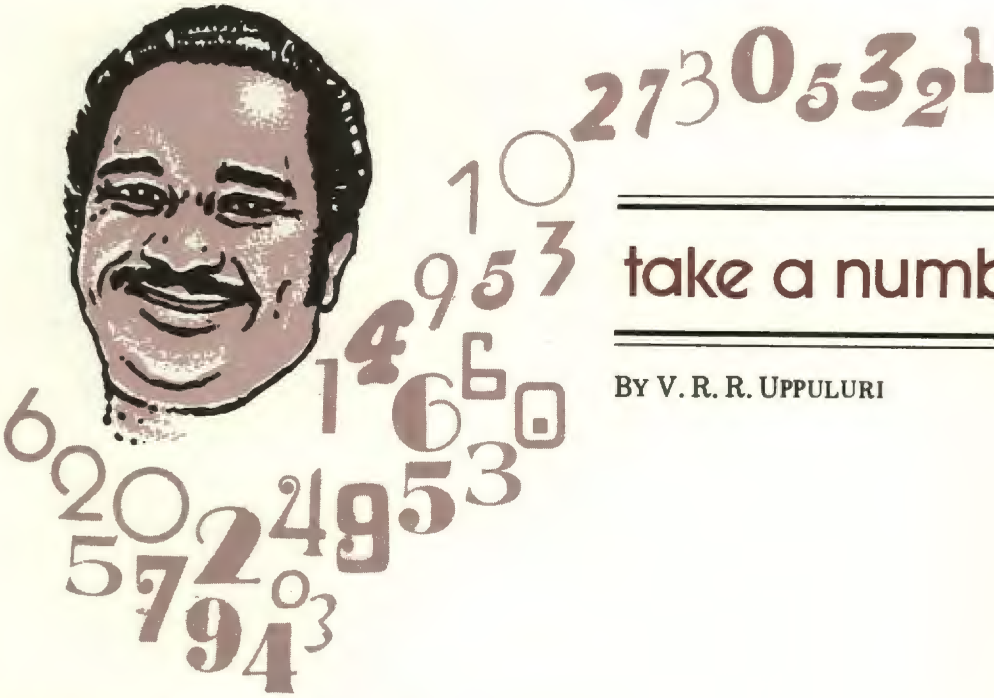
Residential/Commercial Market

As recently as 1947, nearly 50% of the energy used in the residential and commercial sector was derived from coal. But by 1977, only 2% of such energy came from coal. It isn't hard to understand why this change has taken place, and it's clear that a reversal is not imminent. A strong shift to direct coal combustion is not practical for several reasons. First, there are not commercial combustors available that would be environmentally acceptable if a wide-scale conversion to coal took place in the residential sector. The systems that are available have no means of capturing either the sulfur or ash that is emitted in the flue gas. Second, equipment required to burn coal is three to four times more expensive than that required to burn oil or gas. The use to which coal would be put in this sector is basically space heating, and because equipment use is so low (<30%) for this application, coal is a poor economic choice. These factors, plus the low growth rate projected for residential/commercial energy demand, imply that the fuel choice in the near term will be essentially as it is now. Therefore, the best use of coal in homes and commercial buildings is as a substitute fuel, either an oil or a high or intermediate Btu gas.

The Outlook for Coal

The major market for direct coal combustion is in the utility sector and to some extent in large industrial applications. For the other sectors, synthetic fuel production appears to be the best approach. In an open market, the cost of synthetic fuels is presently too high to compete effectively in any sector. If natural fuels become unavailable as the Fuel Use Act is imposed upon industry, the market for synthetic fuels will be high. To gain any substantial market impact for coal, it is essential that the federal government institute a balanced, coordinated, and long-range plan that includes consistent environmental regulations, equipment development and demonstration, and price regulations and financial support.

Ted Fox, left, and Ron Graves are in the Fossil Energy Technology Section of the Engineering Technology Division



take a number

BY V. R. R. UPPULURI

An Optimal Apportionment

A prisoner is given 50 white and 50 red balls and asked to distribute the 100 balls into two identical urns in any way he chooses. The prisoner is told that the urns will be brought back the next morning, and he will be allowed to choose one of the urns at random and pick one ball at random from the chosen urn. If the chosen ball is white, the prisoner gets to go free. If the chosen ball is red, he will be shot. The problem is to determine the apportionate distribution of the white and red balls into the urns, so that the prisoner will have the maximum chance of getting out free.

Because of the symmetry of the problem, at first it may seem that, no matter what the prisoner does in distributing the balls, the probability of drawing a white ball will equal the probability of drawing a red ball, so that his chance of getting out free is $1/2$. Surprisingly, the prisoner can improve his chance of getting out free from $1/2$ to $74/99$, simply by putting one white ball alone in one urn and 49 white balls and 50 red balls together in the other urn.

The Extraction of Coal

By E. R. PALOWITCH, Acting Director, Pittsburg Mining Technology Center

It is clear that if the nuclear power industry does not grow as predicted—whether (1) because of the concern over the adverse environmental effects of nuclear reactors or radioactive wastes, (2) because of the failure to develop the breeder reactor, or (3) because the development of such "soft" technologies as geothermal, solar, and biomass fail to provide significant quantities of energy—fossil fuels will have to fill the nation's major energy requirements in the immediate and short-term future. And of the domestic fossil fuels, coal is the most abundant.

The U.S. Geological Survey has recently identified a coal resource base of some 1,600 billion tons, with a postulated additional 1,600 billion tons yet to be identified. Of this total resource, about 437 billion tons may be in deposits of a type recoverable with present technology: either underground or surface mining. A little over half of this last amount, approximately 240 billion tons, is so-called "high-rank coal," consisting of anthracite and bituminous deposits that can provide energy at the rate of up to 26×10^{12} Btu per million tons.

The low-rank coal is the approximately 200 billion tons of subbituminous and lignite deposits that provide less than 15×10^{12} Btu per million tons. A high percentage of this coal occurs in thick beds in Montana and Wyoming, and contains less than one percent sulfur. Furthermore, about a third of these coals are recoverable by low-cost surface mining methods. Thus, the demand for low-cost, low-sulfur coals for direct firing in steam generating plants will be in demand in the Great Plains states, particularly Montana and Wyoming.

At the present time, regulations set by the Environmental Protection Agency decree that stationary steam plants burning fossil fuels may not emit more than 1.2 pounds of sulfur dioxide per million Btu/hr. This means that the sulfur content of high-rank coal containing 12,000 to 14,000 Btu per pound must be kept below about one percent. (For newly constructed power plants, the EPA's New Source Performance Standards impose even more stringent limits.) Almost half of the nation's coal resources contains less than this amount of sulfur and is consequently usable for direct combustion in steam generating plants without costly processing to meet EPA standards. Furthermore, the washability of much of the coal that contains more than one percent sulfur is such that it can be upgraded by current technology to meet these standards.

Extraction

Coal is mined either by surface or underground methods. The method used depends on many factors: the characteristics of the coalbed; the amount of water or gas present; the proximity of adjacent coalbeds, etc. But the method selected will be the one that provides the greatest health and safety assurance for mine personnel, the lowest investment and operating cost per ton of product, the maximum recovery of resource, the maximum salable product, and the least adverse environmental impacts.

Where coal lies under cover too deep to be mined economically by surface methods, it must be reached by horizontal entries, inclined slopes, or vertical shafts for either partial or full extraction. In partial extraction, entries are driven, 10–20 feet wide, to distances of up to several thousand feet, with connecting crosscuts to provide ventilation and to accommodate the mining machinery. It is the actual driving of these entries and crosscuts that produces the coal. The intervening pillars of coal provide the support needed to keep operations accessible and workable. Partial extraction methods can be conventional, using explosives to free the coal from the coalbed, which is then mechanically loaded into shuttle cars and hauled to the surface by mine cars and/or conveyor belts. Where conditions permit, a continuous mining machine is used to rip the coal from the coalbed and load it onto shuttle cars. Where geologic conditions are favorable, the coal left standing as pillars can be extracted after a section of the mine has been fully developed, thus raising coalbed recovery by as much as 40 percent.

Full extraction methods involve subdividing the coal into large blocks or panels which are then mined out totally, allowing the roof to collapse as the operation

Coal is mined here at the Falcon Coal Company's South Fork mine near Jackson, Kentucky.

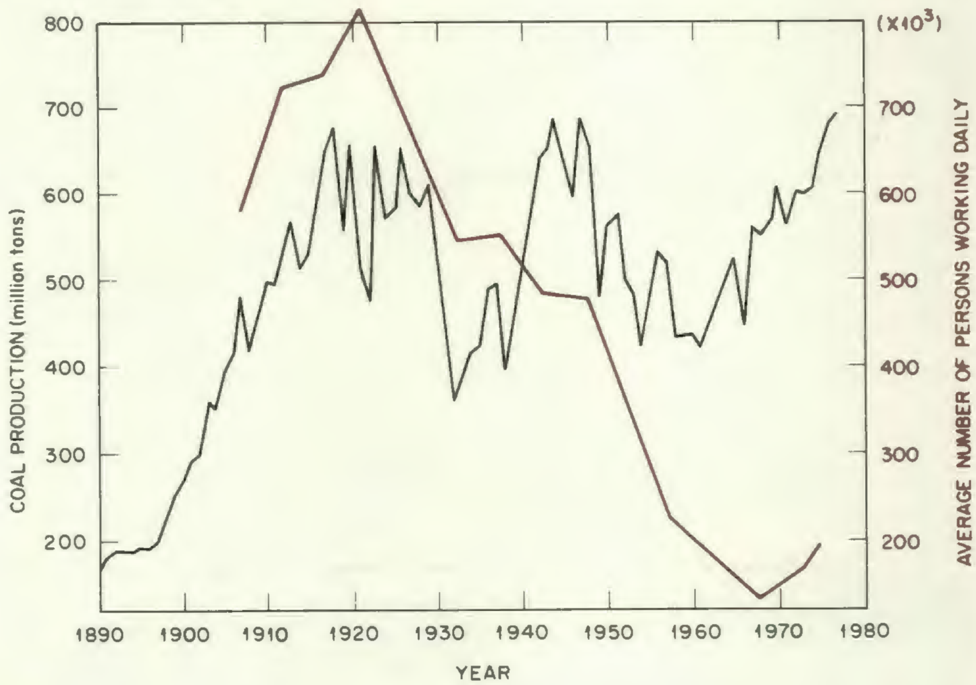
retreats. Full extraction methods are either longwall or shortwall. In the former, vertical panels of coal are blocked out in dimensions of 400–600 feet wide by 2000–5000 feet long, and the coal is extracted by a "plow" or shearing machine that rides on a flexible chain conveyor and extracts a web of coal 4–30 inches deep as it is hauled back and forth across the face. The broken coal is carried off the face by a flexible chain conveyor. The roof over the face is supported by self-advancing hydraulic chocks, which are advanced after each cut of coal is removed.

The shortwall method is similar except that the panels are only about 150 feet wide and successive slices, 8–10 feet wide, are taken from the short side of the panel with a continuous mining machine. Shuttle cars are used to haul the broken coal from the face. As in the longwall method, the roof is supported by self-advancing chocks.

Surface mining methods are used where coalbeds outcrop or lie under less than 150 feet of cover. Depending on the nature of the topography, mining follows either area or contour methods. Area mining is used where the coalbed and terrain are relatively flat. Parallel cuts are taken in the overburden which is removed to expose the coal. It is then drilled and blasted lightly, and the shattered coal is loaded by a small power shovel into trucks for transportation to the preparation plant or railhead. As the coal from each cut is removed, the overburden from the next successive cut is placed in the void of the previous cut. Reclamation of the disturbed land follows closely behind the mining operations. Depending on the slopes of the surface and the coalbed, additional parallel cuts may be made.

When the coal lies under hilly-to-mountainous terrain and outcrops on the hillsides, the overburden is removed from over the outcropping coalbed by a stripping shovel to expose a 40- to 50-foot wide section of coal. This exposed coal then is drilled, blasted, and loaded into trucks for hauling from the pit to a preparation plant or railhead. Depending on the steepness of the hillside, additional cuts may be made parallel with the outcrop; the newly excavated overburden is placed in the void left by the previous cut. Mining ceases when the height of the highwall created

As technology for mining coal has improved, production has mounted in the face of a marked decrease in the number of mining industry employees.



exceeds the digging capacity of the stripping shovel. As with area mining methods, reclamation follows coal extraction to meet required standards.

Coal under the highwall that is too deep to mine by surface methods may, under some circumstances, be extracted by augering into the highwall with large-diameter horizontal drills. Although highwall augering seldom recovers more than about 25% of the coalbed, the technique often can recover portions of a coalbed that would otherwise be lost totally.

Surface mining has been growing at the rate of about 15 million tons per year for the past decade. In 1978, more than 60% of all coal mined in the United States was mined by some form of surface method. The amount of coal surface-mined is expected to double in the eastern and central states and increase almost eightfold in the western states by 2000, although the percentage of coal mined by surface methods is expected to level off at about 60.

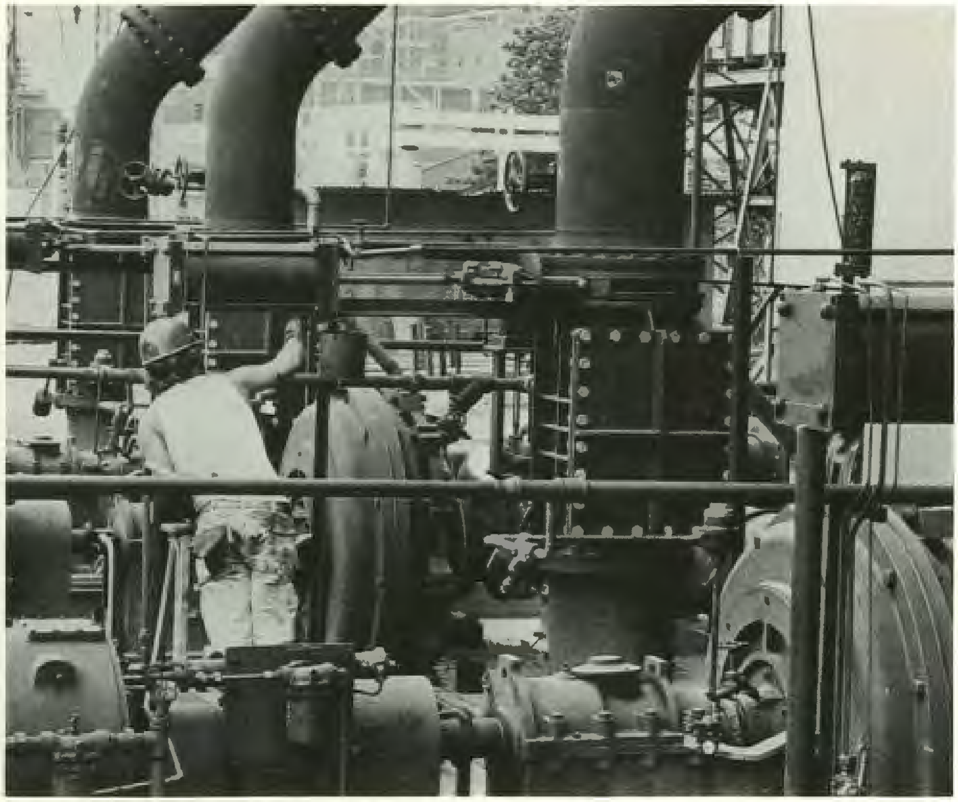
Prices

During the 25-year period 1945 to 1970, when the Wholesale Price Index climbed from 54.6 to 110.4, the retail price of coal remained at around $5 per ton, principally because of the development of post-war technology. In the next five years, however, the price of coal leaped to $20 a ton. This inordinate price surge was primarily a result of the quadrupling of the cost of imported oil. Nonetheless, coal still provides energy at about half the cost of imported oil.

Coal prices tend to have low elasticity, i.e., sudden increases in demand produce rapid increases in price. And, as about 70% of the coal produced annually is used to supply about 40% of the nation's electric power needs, the electric utilities play a dominant role in establishing retail prices of coal. Because the electric utilities cannot easily adjust their generating capacity, nor can they easily switch from one type of fossil fuel to another (e.g., coal to oil) in the short term, they are forced to pay whatever price the market place demands. Their ability to pass these costs on to their customers via automatic fuel adjustment clauses has enabled them to accommodate to higher coal prices.

Productivity

The remarkable stability of the cost of coal during periods of high inflation and increasing production costs was accomplished by modernization and mechanization of the industry



At TVA's Widows Creek coal-fired steam plant, this limestone scrubber removes up to 94% of the sulfur dioxide from a large unit.

following World War II. Worker productivity more than tripled in the years between the late 1940s and 1960s. Since then worker productivity has dropped, however, to 2.4 tons per man-hour for surface miners, and 1.1 tons for underground workers, down 35% from the 1969 peak.

Because of the steady increase in the industry-wide worker productivity up to 1969, the number of workers employed by the industry dropped steadily from a high of 820,000 in 1922 to a low of 140,000 in 1968. Over that period, annual coal production moved from a low of 360 million tons to a high of 690 million tons.

It is generally conceded that the dramatic decrease in underground productivity that began in 1969 is the result of a number of developments which have occurred during the past several years—passage of the Federal Coal Mine Health and Safety Act of 1969; deteriorating labor-management relations; increased number of young and untrained miners; chronic overcapacity; and pricing policies. Productivity of surface workers also has been affected adversely by implementation of the Surface Mining Control and Reclamation Act of 1977.

The President's National Energy Plan II projects a doubling of coal production by 1985 and requires 254 new mines by 1985 and an additional 571 new mines in 2000. This coal will have to be produced from deeper, thinner, dirtier, and gassier coalbeds, and in a manner that will guard the health and safety of its workforce, minimize adverse environmental impacts, and conserve our finite coal resources. And it must meet all of these requirements at a cost competitive with foreign oil, domestic oil and gas, and nuclear energy.

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? Coal Quiz

How much do you know about coal and its history? Try this multiple-choice test for fun and see. Write the letter of the correct answer on the space before each question.

__ 1. One of the following is *not* a type of coal: (a) lignite (b) charcoal (c) anthracite (d) bituminous (e) none of the above.

__ 2. One of the following elements is *not* an important component of coal: (a) carbon (b) nitrogen (c) uranium (d) silver (e) sulfur.

__ 3. Coal is sometimes called (a) buried sunshine (b) black gold (c) black diamonds (d) graphite (e) all of the above (f) *a*, *b*, and *c* only.

__ 4. The first country to use coal in large quantities was (a) China (b) England (c) Germany (d) Egypt (e) South Africa.

__ 5. Anthracite coal is found in (a) Illinois (b) Pennsylvania (c) Wyoming (d) Colorado (e) West Virginia.

__ 6. England has been mining and burning coal for (a) 600 years (b) 800 years (c) 900 years (d) 1200 years (e) none of the above.

__ 7. In 1306, King Edward I of England (a) wrote the nursery rhyme "Ole King Coal" (b) invented a special furnace in which to burn coal (c) declared that burning coal is a crime punishable by death because coal smoke is poisonous (d) suggested that coal should be put in the Christmas stockings of children who misbehave (e) personally visited one of England's first coal mines.

__ 8. In the seventeenth century, England began to use coal on a large scale because (a) strip mining was invented (b) the country was deforested and desperately short of wood for its navy's shipbuilding needs (c) soot from burning wood was giving chimney sweeps cancer of the scrotum (d) England decided to use more wood for making Chippendale furniture (e) England decided to use more wood for paper to publish the works of its poets and playwrights.

__ 9. The first American soft-coal mine was opened in Virginia in 1787. The first people to use American coal were the (a) American Indians (b) schoolmasters (c) blacksmiths (d) pilgrims (e) steamboat captains.

__10. A famous English scientist who invented the first safety lamp for coal miners was (a) Humphrey Davy (b) Isaac Newton (c) John Dalton (d) William Harvey (e) William Henry Perkin.

__11. Coal is generally *not* transported by (a) airplanes (b) boats (c) railroad trains (d) slurry pipelines (e) trucks.

__12. The following metal that is *not* found in significant quantities in most coal ash is: (a) iron (b) titanium (c) aluminum (d) gold (e) chromium.

__13. In the nineteenth century, coal gas was (a) made by heating coal without any air (b) used for lighting streets and houses before the electric lamp was invented (c) often wasted when produced by heating coal to make coke (d) all of the above (e) none of the above.

__14. The number of by-products of coal tars and gases is in the order of more than (a) 50 (b) 200,000 (c) 400 (d) 8,000 (e) 1,000,000.

__15. The following is *not* a coal tar product: (a) nylon (b) rayon (c) vitamins (d) food flavorings (e) perfumes.

__16. The following is *not* a coal gas product: (a) fertilizer (b) synthetic rubber (c) plastics (d) cleaning fluids (e) facial tissue.

__17. Peat is (a) a brown, slimy material that contains plant remains (b) burned as fuel in Ireland (c) found in the Florida Everglades (d) *a* and *b* only (e) *a*, *b*, and *c*.

__18. Electric utilities burn what fraction of the coal used in the United States? (a) one-fourth (b) one-third (c) one-half (d) three-fourths (e) four-fifths.

__19. It is estimated that the United States has enough coal (if mined and burned at the current rate) to last (a) 100 years (b) 30 years (c) 700 years (d) 1000 years (e) 1500 years.

__20. It is estimated that the United States has what fraction of the world's coal resources? (a) one-fourth (b) one-third (c) one-half (d) two-thirds (e) four-fifths.

__21. Sixty-five years ago, four-fifths of the energy used in the United States came from coal. Yet in 1973, coal's share of the energy consumed was only (a) one-sixth (b) one-fifth (c) one-fourth (d) one-third (e) one-half.

__22. Coal mining is dangerous work due to cave-ins, explosions, and poisonous gases. In 1930, coal mine accidents caused 1600 deaths and 70,000 injuries. In the early 1970s, on the average, coal mine accidents annually caused (a) 1400 deaths and 60,000 injuries (b) 1250 deaths and 55,000 injuries (c) 1100 deaths and 44,000 injuries (d) 630 deaths and 29,000 injuries (e) 240 deaths and 10,000 injuries.

__23. To detect the presence of deadly gas in the coal mine before there was enough to overcome the mine workers, miners once used (a) rotting fish (b) a gas detector invented by Isaac Newton (c) canary birds (d) a candle flame (e) none of the above.

__24. Coal has been carried out of mines by (a) elevators (b) mule carts (c) continuous miners (d) women toting baskets (e) all of the above.

__25. One of the pollutants produced by burning coal is sulfur dioxide. This pollution may be reduced by (a) cleaning crushed coal in magnetic separators before it is burned (b) using flue-gas desulfurization equipment in boiler smoke stacks (c) burning the coal in fluidized beds containing limestone (d) all of the above.

(see answer key on page 52.)

He hung up on me! All I said was we're into synfuel work out here ...

Coal Cleaning

By CAROLYN KRAUSE

Coal is far from a perfect fuel. It is loaded with impurities, including inorganic contaminants, that reduce its heating value when it is burned raw. It contains rock and moisture that add to its mass and increase shipping costs. It has minerals that cause an assortment of problems: (1) they are hard on pulverizers that crush the coal into fine particles for feeding into steam boilers; (2) they escape burning coal as fly ash, a pollutant that must be removed by electrostatic precipitators; and (3) they form molten ash that coats and fouls boilers, causing unscheduled outages, maintenance difficulties, and a lower level of electricity production at coal-fired power plants. In addition, coal contains sulfur.

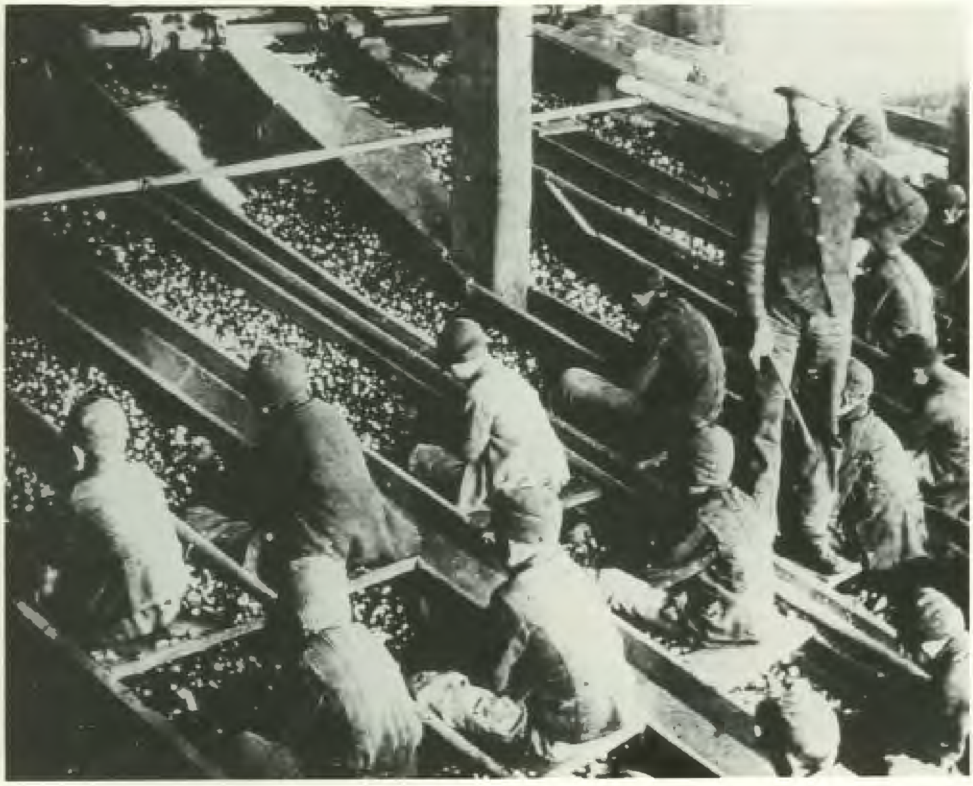
Sulfur is not only bound organically in the coal but also is present in inorganic constituents including iron disulfide and sulfur-bearing pyrites. Sulfur is a problem because it is released to the air as sulfur dioxide (SO_2) when coal is burned. Sulfur dioxide is classified as a mild irritant which can aggravate the health problems of people with respiratory difficulties. Some SO_2 is transformed in the air to sulfuric acid, which erodes buildings and statues and can make soils acidic. Hence, the Environmental Protection Agency has issued stringent standards requiring severe reductions in SO_2 emissions from boilers fired with fossil fuels.

There are three ways of reducing SO_2 emissions from burning coal: cleansing the coal of sulfur before it is burned and removing the sulfur dioxide after the coal is burned. The third way, during combustion, is achieved via the fluidized bed. In most boilers, the SO_2 is scrubbed from the flue gas before it leaves the stack by flue-gas desulfurization (FGD) equipment. Many utilities have started to use scrubbers to meet EPA standards. But cleaning coal by physical removal of sulfur-bearing inorganics may be a cheaper method of minimizing SO_2 emissions, and it may be the only way of making high-sulfur coals usable under new EPA standards even with scrubbing. Furthermore, coal cleaning may soon become an economic as well as an environmental necessity because studies show that substituting clean coal for raw coal reduces power plant operating costs by far more than cleaning costs.

Why is coal cluttered with contaminants? The answer goes back some 300 million years when vast, swampy forests became buried and compressed into peat that was later metamorphosed into coal during the Carboniferous Age. Silts containing inorganic substances were co-deposited in the swamp along with the lush vegetation ultimately transformed into coal. Pyritic sulfur and most ash-producing minerals were either present in the swamp silts or were deposited later in the coal bed by groundwater that had leached minerals from the overburden. Another source of such inorganic contaminants as shale, slate, sandstone, and limestone is the roof and floor of the coal mine.

Since the 19th century, many methods have been tried to remove contaminants from coal to improve its efficiency as a fuel. These methods go by several names: coal cleaning, coal preparation, or beneficiation. The material that is easiest to identify and separate from coal is the slate and other matter that comes from the mine floor and roof. In early coal preparation plants, "slate pickers" had the tedious job of manually separating this material from coal. Today these contaminants are easily removed by gravity separation—that is, the impurities have a higher specific gravity than does coal so they settle out at a faster rate. Most coal cleaning processes in use today rely on the principle of gravity separation.

Coal preparation traditionally has been used to improve the appearance and fuel value of coal employed in home heating and to make coal more suitable for metallurgical purposes. The coke industry has long used beneficiation to make coal low in sulfur and ash content and to render it uniform (the physical and chemical properties of coal vary from mine to mine). A uniform product is essential to the efficient operation of blast furnaces and foundry cupolas. Coke, or carbonized coal, is used



In early coal preparation plants, boys known as slate pickers had the tedious job of separating coal from slate and other material that comes from the floor and roof of the coal mine.

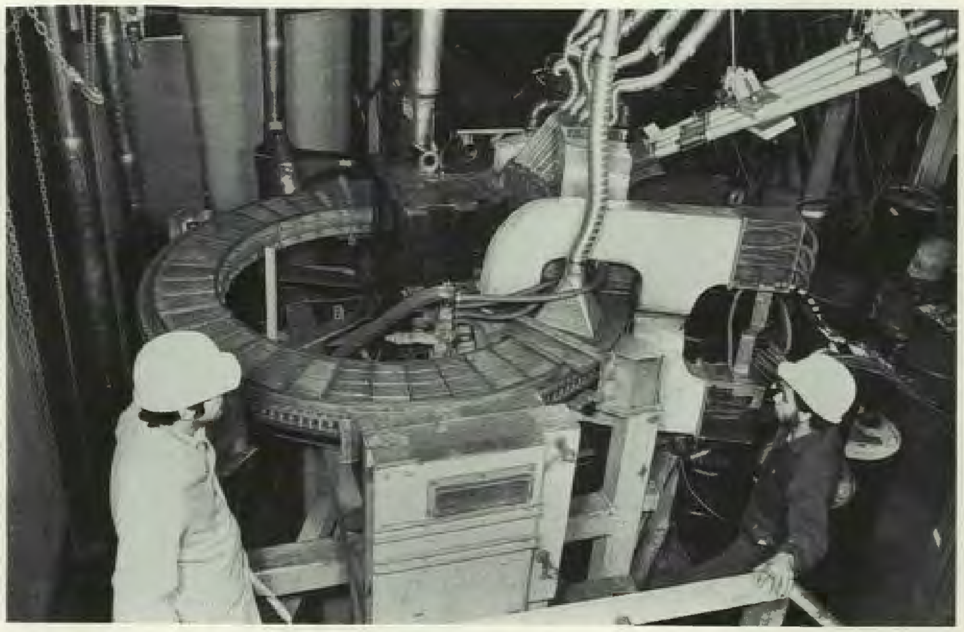
in smelting furnaces for making iron and steel.

Wet Processes

The coal preparation technology in use today was developed to improve coals for the manufacture of coke. Much of this technology involves mechanical methods of washing coal—wet processes. Such a method was introduced by the Germans in the 1830s with the invention of a manually operated batch-processing jig. In 1848 a Frenchman named Berard patented the first continuous jig washer. Over the years, the jig has been a popular device for cleaning coarse coal. In 1976 jigs accounted for 46.7% of all the cleaned coal produced in the United States. The jig works by pumping pulses of water up through a screen plate on which the coal rests. While the pulsating of the coal by water is repeated up to 50 times a minute, the coal particles, which are less dense, tend to rise to the top of the liquid mixture, while the more-dense refuse particles tend to sink. The efficiency of the jig, however, is limited when the specific gravities of the coal and some of its refuse are nearly the same.

More efficient than the jig for cleaning coal are the heavy-media vessel and heavy-media cyclone, which operate on the principle of gravity separation and are able to separate coal from refuse particles with similar specific gravities. Before coal is fed to these devices, it is usually reduced in size by breakers and crushers, which crush the soft coal but only knock off the harder rock and mineral impurities. The coal is then placed on sizing screens which separate it into different sizes. The largest lumps can be handled by the heavy-media vessels, which use a flowing medium of water and magnetite for separating the less-dense floating coal from the sinking impurities. Medium-sized lumps are often sent to heavy-media cyclones, which combine centrifugal force and gravity to achieve separation of coal from impurities. While being whirled in a stationary cone by a watery medium, the more dense refuse collects at the sides of the cone and leaves at the bottom and the less dense coal swirls up and out the top. In 1976 dense-medium processes were used to clean 32.1% of the total clean coal. Heavy-media technology is an outgrowth of the dense-medium process, which was first applied to coal in 1858 and was patented in 1853 by Sir Henry Bessemer, the British engineer who ushered in the Age of Steel with his invention of the blast furnace.

Fine coal particles, which represent 10 to 30% of all coal mined by today's techniques, are the hardest to clean by conventional wet-cleaning processes. In many wet processes, the "fines" are carried along with the aqueous process stream, are not recovered, and are ponded as waste. One of the more successful wet processes for cleaning the fines is froth flotation, which was first applied to coal washing in 1920 in Spain and France. Froth flotation makes use of surface properties rather than specific gravities to achieve separation. Coal attracts oil and repels water, whereas refuse repels oil and attracts water. So if coal is treated with an oil-based agent and then placed in water in a froth flotation tank which



Continuous separation of coal from inorganic materials in a carousel separator at Sala Magnetics Inc. plant in Cambridge. The raw pulverised coal is carried over expanded mesh metal mesh trays through a strong magnetic field and air flushed to receptacles below. When the material leaves the magnets, the inorganics are then dropped.

undergoes mechanical agitation, the induced air bubbles will attach themselves to the oil-coated coal particles and lift them to the surface in a froth. The refuse, being attracted to water and repelled by oil, stays in the slurry and is removed as tailings. The process has a problem in that fine pyrite particles, which tend to repel water, often rise with the clean coal particles. Flotation produced only 4.3% of the coal cleaned in 1976, but there is evidence that increasing proportions of coal are being cleaned in flotation tanks.

In the United States, coal washing was first practiced on a large scale in the states of Alabama and Pennsylvania, starting around 1923. Today, about 50% of the coal mined is washed in many of the 500 coal preparation plants in the United States. But wet processes have a drawback. Excess moisture in coal adds to shipping costs, can cause the coal to freeze in stockpiles or railroad cars in wintery weather, and reduces fuel value because burning coal uses some of its energy to evaporate the moisture. Hence, additional energy must be consumed in dewatering or drying coal, using such devices as vibrating screens, centrifuges, and thermal dryers. None of these devices works well with fine coals.

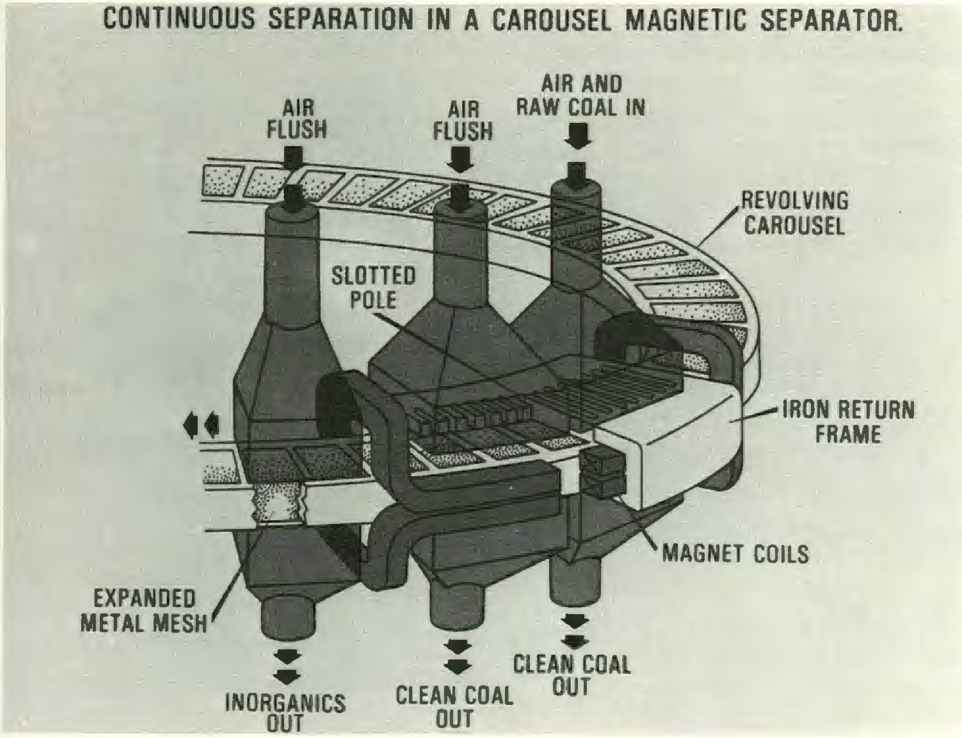
Dry Processes

After coal has been mined and handled, up to 30% of the coal will have been reduced to fine particles, which are difficult to clean and costly to dry. Some of these fines are produced by crushing the coal to liberate minerals. Many coal preparation plants have chosen to discard these fines before they become a dust problem and a fire hazard. But throwing away these fines wastes money and a potential energy source, so a possible solution would be the development of efficient dry processes to clean the coal fines.

The dry cleaning of coal is an American invention. In 1874 the Korm pneumatic jig was patented in this country. Similar air jigs now in commercial operation use pulsating currents of air to achieve gravity separation of coal from impurities. Other dry methods under development include electrostatic separation, use of heavy organic liquids as heavy media, and magnetic separation (which has also been tried on wet coal). These methods are not likely to be commercialized until their efficiencies are improved.

At Oak Ridge National Laboratory, two promising schemes for dry-cleaning coal have been developed using magnetic separation. The objective of the ORNL program is to develop these methods into commercial processes. The principle behind magnetic separation is that sulfur-bearing iron pyrites and ash-forming minerals are weakly attracted by a magnetic field while coal particles are mildly repelled by the field. ORNL was the first to demonstrate that high- and open-gradient magnetic separation are efficient methods of cleaning coal fines. These methods can remove almost all of the liberated ash and pyritic sulfur while recovering 90% of the energy content of the feed coal.

The study of high- and open-gradient magnetic separation techniques for dry coal cleaning was initiated by David Eissenberg of the Engineering Technology Division as a result of discussions with Hugh Long (Energy Division), who had tried earlier to start a similar program. Using DOE/Fossil Energy program development funds, ORNL's dry magnetic separation program was begun in 1976. Under Eissenberg's direction, Larry Dresner performed



In a continuous high-gradient magnetic separator, the revolving ring, containing wedge-shaped cannisters of expanded metal mesh, moves continuously through the cavity magnetized by the magnet coils and iron flux return frame. Coal is fed down through the mesh where the minerals having a positive magnetic susceptibility are retained, while the clean coal passes through. As the mesh leaves the cavity, the magnetically trapped minerals are released and fall out.

theoretical calculations, and Mike Silverman conducted laboratory experiments to demonstrate feasibility of the dry open-gradient scheme. Feasibility studies of dry high-gradient magnetic separation of coal were subcontracted to Auburn University in 1977–78. Arguing that wet processes left coal fines unsuitable for use by electric utilities, Eissenberg, John Jones, and Eugene Hise obtained funding from DOE for the magnetic separation developments at ORNL in fiscal year 1978. Since then engineers Hise and Allen Holman, assisted by technician Marshall McPhee, have been solving the problems of making these schemes feasible for commercial coal preparation.

The high-gradient magnetic separator consists of a solenoid that generates a magnetic field of 20,000 gauss. In the solenoid core is a tube containing a wire mesh consisting of discs of expanded metal stacked alternately with spacers. Each filament or wire of this mesh becomes a magnet whose small but high-gradient magnetic field attracts and holds the inorganic materials present in pulverized coal. When coal fines are fed through this separator, the inorganics are retained on the wire mesh, letting the clean coal pass through. With the batch-type machine used for experimental work, the clean coal is collected first and then the power to the magnet is turned off so that the magnetically trapped material falls out of the mesh and into a refuse collector. For production processing, machines capable of continuous separation of several hundred tons per hour of feed have been commercially developed for other mineral separation applications. These machines can be adapted to dry magnetic separation of coal. In late 1979 ORNL began demonstrating continuous separation of one ton per hour of coal by high-gradient magnetic separation at the Sala Magnetics Inc. plant in Cambridge, Massachusetts.

ORNL engineers have also shown in the laboratory that it is possible to perform coal-impurity separations in an open-gradient magnetic separator. Unlike the high-gradient separator, this device contains no mesh but simply deflects the particles in accordance with their magnetic susceptibility as they pass through an open cavity having a magnetic field of particular characteristics. Such a device is commercially available for laboratory separations of small quantities of material. The feed can be passed through the magnetized cavity on an adjustable inclined vibrating tray or metered through an orifice to fall freely and vertically through the cavity. In either case the stream of particles is spread into a spectrum from greatest negative susceptibility to greatest positive susceptibility. Flow splitters can be placed at any point along that spectrum to divide it into two or more streams. When the magnet is off, the coal particle stream exiting at the bottom has the diameter of a pencil. But when the magnet is energized, the coal stream spreads out like a fan almost an inch and a half wide. The relatively clean coal particles are deflected away from the maximum field strength as much as the mineral particles are attracted to it. Separations performed in this free-fall mode have been the most selective of any process tested.

The open-gradient separation is still very much in the laboratory stage. The means by which the existing machine creates the desired magnetic force does not appear capable of extrapolation to large production units, nor have literature searches and consultation revealed any suitable machines or designs. Because the free-fall, open-gradient magnetic separator is in concept similar, in principle more versatile, and, in the tests performed at ORNL, more successful, there is a strong incentive to develop such a machine.

Hise and Holman have performed a large number of separations by gravimetric (using the principle of gravity separation), high-gradient magnetic, and open-gradient magnetic methods on western Kentucky and Pennsylvania coals in four size fractions ranging from 600 microns to 10 microns in particle diameter. The purpose of these experiments was to compare and correlate the three methods. They concluded that, for those coals tested, the magnetic processes can remove the liberated minerals as effectively and with as high a Btu recovery as the laboratory gravimetric process.

Following the demonstration of continuous high-gradient magnetic separation at one ton per hour on a commercial machine, ORNL will proceed in collaboration with the Tennessee Valley Authority and possibly coal producers and other utilities to develop this process to commercial viability through appropriate demonstration plants.

The New Economics

In the past, electric utilities could burn raw or run-of-mine coal in their furnaces relatively cheaply. But new federal environmental standards require drastic reductions in sulfur dioxide and ash emissions. And recent economic analyses indicate that cleaned coal reduces power-plant operating costs by far more than cleaning costs. Hence, coal cleaning is becoming an environmental and economic necessity.

The electric utility industry, which is the largest coal consumer in the United States, burns about three-fourths of the nation's total coal output. But only about 21% of the coal consumed by utilities has been cleaned by physical methods. The rest of the steam coal used is raw coal that costs \$22 to \$26 per ton (by contrast, prepared metallurgical coal used by the coke industry now sells for \$48 to \$52 per ton).

However, the electric utility industry is now converting to the view that it pays to use more expensive, cleaned coal. The mechanization of mining, the mine safety and environmental regulations, and changing economics have together led to a marked decrease in steam coal quality in recent years. This poor coal quality has in turn resulted in power plant deratings and outages, increased operating and maintenance costs, higher shipping costs, and increased system heat rates, all of which mean higher generating costs and higher electric bills for consumers. Another contributor to high generating costs is EPA's stack emission standards restricting particulate and sulfur emissions. While these standards were becoming more stringent, more and more of the steam coal available contained increased amounts of sulfur and ash. Thus, more stack scrubbers and increased electrostatic precipitator capacity are required, adding to utilities' capital and operating costs and boosting generating costs.

Much of the coal mined in the Appalachian and Midwestern regions is extremely high in sulfur and ash content. New coal-fired power plants using this coal may not be able to comply with EPA's revised New Source Performance Standards using scrubbers alone. Hence, coal cleaning may have to be combined with flue-gas desulfurization to meet new environmental standards. Studies have shown that precombustion cleaning also can reduce the capital investment and operating costs for the scrubber's absorbent handling and preparation systems and for sludge disposal. In general, these savings offset the cost of cleaning in a coal preparation plant.

Demonstration Tests

Several utilities are showing interest in testing advanced physical methods of cleaning coal. Aided by financial and technical support from EPA and the Electric Power Research Institute, General Public Utilities and New York State Electric and Gas Company are testing a 1200 ton/hr advanced cleaning plant using a dense-medium cyclone process at Homer City, Pennsylvania. The first of its kind in coal beneficiation technology, this plant is designed specifically to reduce pyritic sulfur. The Homer City facility yields an ultra-clean product that is low enough in sulfur to meet the EPA sulfur emission standard for new utility boilers without the need for expensive scrubbing of the stack gases. And the sulfur content of the plant's middling product is also low enough to meet the SO_2 emission standard for existing boilers without stack gas scrubbing.

TVA, the nation's largest

consumer of coal, is also interested in demonstrating advanced coal cleaning techniques. Currently, 19.4% of coal used by TVA is washed. A small amount of this coal comes from TVA's Breckinridge coal preparation plant, a jig facility located near Morgantown, Kentucky. TVA is now building a 2000 ton/hr coal preparation plant at its Paradise Steam Plant near Drakesboro, Kentucky. When this heavy-media plant goes into operation in 1981, it is expected to supply about 11.8% of TVA's coal consumption (compared with the .86% provided by the Breckinridge plant). Another coal preparation plant is being built at TVA's Cumberland Steam Plant in Middle Tennessee. TVA also plans to buy more beneficiated coal from the East, which costs no more than low-sulfur coals from the West after transportation costs are taken into account.

TVA's interest in using more prepared coal to meet environmental standards and to increase electricity generation from existing units has prompted it to start a coal cleaning demonstration program in which ORNL is participating. The program is being conducted jointly with DOE's Pittsburgh Mining Technology Center. Program objectives are to determine the impact of coal cleaning on power plant operation and maintenance and to establish the commercial viability of new processes for ash and sulfur removal from coal prior to combustion.

For example, TVA proposes to compare the costs and benefits of using cleaned vs run-of-mine coal at one of its coal-fired steam plants. TVA plans to feed prepared coal to one boiler and use run-of-mine coal that is high in sulfur and ash content in the other boilers. The object of this test is to determine the extent to which cleaned coal can help TVA avoid the problems of power derating and loss of peaking capacity as well as higher maintenance and operating costs. In general, poor quality coal has forced power plants to reduce their level of power production, thus driving up generation costs.

In collaboration with TVA, ORNL and DOE are proposing the incorporation of magnetic separation for dry cleaning of coal fines at a proposed TVA coal cleaning demonstration plant. TVA plans to incorporate appropriate new cleaning technologies developed by DOE and its subcontractors in the agency's facility for commercial demonstration.

Gene Hise pours pulverized coal into an open-gradient magnetic separator which removes almost all of the liberated ash and pyritic sulfur from the coal while recovering 90% of the Btu's.

Coal is dirty but it can be made clean. And as environmental protection agencies seek to protect the public health, utilities try to hold down costs, and consumers lobby for lower electric bills, the nation is just beginning to realize the benefits of beneficiation.

Transportation of Coal

By CAROL OEN, Fossil Energy Information Program

Coal is mined and coal is consumed, all too frequently at different places, which gives rise to the problem of getting it moved, one way or another. Even though nearly 700 million tons of coal, the most in history, were mined in the United States in 1977, use of even more coal, in place of oil, is in the national interest in order to reduce dependence on imports of foreign oil. By 1985, coal production is expected to reach one billion tons, an increase that will call for a national transportation policy to facilitate its movement.

It might be useful to review some basic facts about coal production and use, and look briefly at the different transportation modes used for coal, their capabilities, and some of the problems in meeting the challenge of the projected 1985 production.

History

The first bulk movement of coal was by water. The second quarter of the nineteenth century saw major canal construction and improvements in the Ohio and Mississippi rivers by the federal government, to a great extent motivated by the desire to ship large quantities of coal cheaply. However, since the canals were narrow and shallow, they did not offer a fast route for large-volume shipments. As the railroads were built, they quickly took over most of the traffic, and the use of canals for coal shipment decreased thereafter.

River traffic, too, largely lost to the railroads as they pushed westward, offering greater speed, flexibility, and long-distance capabilities. By the end of the century, when coal constituted 90% of the commercial energy supply in this country, the railroads had most of the coal traffic; but also, by 1885, they were the largest *consumers* of coal, being in transition from the wood-burning era to the introduction of diesel power.

Coastal shipping was also once a major part of the energy movement pattern in the United States, entailing a flow from the Appalachian mines to the coast—mainly Norfolk, Virginia—followed by shipment up the East Coast. Export traffic finally replaced the coastal traffic, as international demands for coal increased and domestic demands in the Northeast declined in favor of oil and gas.

The relative contribution of coal as an energy source peaked in 1910, and then steadily declined as natural gas and oil became cheap and abundant.

Thirty of the 50 states have minable coal resources, with reserves constituting several hundred times the annual production. The greatest known resources of minable coal are in Montana, Illinois, Wyoming, West Virginia, Pennsylvania, and Kentucky, in that order.

A study of production and consumption areas brings out the essentially regional nature of coal, since four of the five top states in both production and consumption are Ohio, Pennsylvania, West Virginia, and Illinois. In many cases, coal movements do not cross state boundaries, with concentration of production, transportation, and consumption being in the area along the Ohio River and up to the Great Lakes. For coal to become a national fuel, which it must, coal transportation capabilities must expand.

Electric utilities are now and will continue to be the largest consumers, with a 1976 consumption of 450 million tons, up from 405 million in 1975. Industrial use and export make up most of the balance.

Coal is moved from the mines by rail, about 65%; truck, 13%; and water, 10%. The remainder is kept at the mine mouth, either for use by the mines, for adjacent industry, or for slurry piping.

This, however, only applies to "originating" shipments, i.e., what mode the coal was loaded into at the coal-source location. Before coal reaches its ultimate destination, it may have been moved by two or more modes.

Since costs for transportation are a significant part of the cost of the coal, the health of the transportation systems has a strong bearing on the price and distribution of coal.

Railroads

Coal and railroads are critically interdependent. Railroads are the primary movers of coal, and coal is the principal commodity moving by rail, providing about a fourth of the total rail traffic. Illustrating a symbiotic relationship of long

Rows of coal hoppers line up at TVA's Kingston Steam Plant to deposit the fuel. Sixty-five percent of all coal mined is moved by railroad.

duration, the economics of the railroads encourage a high-volume traffic of such commodities, which operates throughout the year, rather than the seasonal demands of agricultural products.

During 1969, rail freight costs averaged about 62% of the mine-mouth value of the coal, demonstrating a downward trend; they were 122% of coal value in 1928. Using total cost figures (mine-mouth cost plus transporation cost), the percentage of total cost accounted for by transportation declined from 35% in 1970 to 23% in 1976. Changes in both coal prices and railroad rates can change these figures quickly. Railroads earn about 18% of their revenues from coal hauling.

Unit Trains

The "unit train" concept has been an important development in the coal-railroad relationship, referring to one or more locomotives and their train of hopper cars used exclusively for moving coal on a regular schedule between origin and destination. Such unit trains may offer discounts of 25—40% below conventional train rates, providing obvious advantages to the coal producers, the railroad operators, and ultimately the consumer, who benefits from lower fuel costs and the stable fuel supply. Cost of labor relative to tonnage is very low for coal, but is especially so for unit trains, where loading and unloading are automatic.

The Question

Can the railroads keep up with the demands for increased utilization of coal? The coal-rail relationship has remained basically stable over time, with growth in one accompanied by parallel growth in the other. Productivity increases by the railroads are primarily from unit trains, which, although there has been a small improvement with higher freight-train speeds, still average only about 20 mph. Adoption of technological advances such as automated loading and weighing, automatic car unloading, and efficient movement to and from temporary storage will be more important in contributing to improved productivity than greater speed and capacity.

The railroad industry has experienced some serious financial problems, and excess capacity is one of them; nevertheless, the railroads are fundamentally viable. They are so basic to the economy that it is likely the federal government would underwrite needed physical capabilities, should such action be required in special cases. That the railroads will retain to 1985 an economically justified rail plant, including service to active coal sources and markets, is quite certain. If one billion tons of coal production is achieved in 1985, railroads can expect to transport approximately 600-650 million tons, assuming their "normal" market share. This represents a 3.5% average annual increase, which appears to be practicable.

One study has used the railroad network model of the Federal Railroad Administration to look at the problem of potential rail bottlenecks that could affect the 1985 coal transport capabilities. Approximately 14,000 origin-to-destination links are included in the model. River and mountain crossings and other natural barriers that constrict the network to a limited number of paths between major producing and consuming areas were identified. Considering projected increases both for coal and other commodities, many links would be overloaded. Of the 16 natural barriers, 11 would have one or more overloaded links. Bypassing bottlenecks could mean much greater mileage, thus increasing the cost.

Investment in new equipment and capacity has been less than needed. In many cases, it has come from non-railroad sources, principally electric utilities. Estimates for needed capital spending are between $6 and $7 billion to meet 1985 needs, of which 65% is for locomotives and cars, and 35% for fixed plant needs—rails, fixed facilities, etc.

Social Impacts

The concerns of railroad managers in fulfilling the projected 1985 coal movement requirements have been studied. Problems anticipated in interaction with municipalities were one concern. Growth in coal traffic will result in many more long, heavy trains, giving rise to aggravated grade crossing problems, always a source of concern to railroad and municipality alike. Railroads would like to negotiate with local governing bodies before the latter write ordinances controlling crossings, and to have a government program to eliminate crossings where appropriate.

A Los Alamos Scientific Laboratory study has looked further into the impact of rail transport of coal on small western towns. Gillette, Wyoming, population 7000, and other nearby communities are in the path of unit trains carrying coal from a heavy production area. Projecting to 1985, 18 to 31 trains per day, each with as many as 100 cars, can be expected to pass through Gillette, resulting in daily traffic blockages of from five to nine hours cumulative time. But more serious than the traffic jams is the interruption of such community services as fire, police, and ambulance access. By 1985, other communities could have 62 to 125 trains per day going through. This impact could be temporary, however. By the year 2000, competition from other transport modes, such as slurry pipelines, combined gasification and pipeline, or nearby electricity production and transmission by wire, may take a portion of the traffic from the unit trains.

Water Movement

About 154 million tons of coal in 1976 traveled by combined coastal, lake, and internal waterway. Foreign exports added another 60 million tons to the amount shipped by water. Coal is the largest single commodity moving on the waterways (petroleum and petroleum products are larger as a combined group), representing about 21% of all commodities so moved, or 16% of all domestic waterborne traffic in 1976. The navigation ways are maintained by the federal government. In 1974, there were almost 25,000 miles of navigable inland waterways, including the coastal waterways of both oceans, the Great Lakes, and the Mississippi River systems. Most important are the Ohio and Mississippi River systems (some 9000 miles), which carried about 2500 towboats and over 17,000 barges in 1975, many devoted exclusively to coal.

Where water routes can be used, their low cost, only about one-third that of rail, is very attractive. In terms of energy expenditures per mile, coal hauling by barge is said to be less expensive than pipelining of natural gas and about equal to pipelining of petroleum.

Shipper projections of Great Lakes use by 1985 show a requirement for an investment of $450–500 million (1976 dollars) to increase vessel capacity. This route is especially important to the movement of coal from the western states. At least one new transshipment facility on Lake Erie would be needed along with expansion of existing facilities at Duluth and Lake Erie ports. Should user charges be imposed on Great Lakes traffic, they would not be expected to reduce current levels of lake traffic and would have a marginal impact on growth of coal traffic where rail and water rates are similar.

Rising demands necessitate enlargement and modernization of channels and navigation works, for which the Army Corps of Engineers is responsible. Environmental rulings requiring that they deposit dredged materials in special diked areas result in a severe limitation of the amount of channel and harbor maintenance performed each year.

Trucking

Trucking is the most rapidly growing transport mode for coal. From 57 million tons in 1973, about 10 million tons per year were added through 1976, the last year for which data are available, when the total was 90 million. These figures do not include quantities trucked to railroad or waterway loading areas or to mine-mouth electricity-generating plants.

In general, truck hauls are much shorter than rail or water haulage, and they are primarily localized. Relatively few interstate shipments of coal are by truck. Because trucks are the most expensive carrier per mile of operation, they are better suited to higher value commodities, especially those needing the fast point-to-point delivery system trucking offers. For short hauls (less than 50 miles), trucks may be competitive if the capital costs of rail or barges are fully considered.

The maximum weight allowed on the interstate highways is 73–80,000 pounds gross weight. The truck itself weighs at least 20,000 pounds or one-fourth the limit. A 30-ton load is small when compared to the 100-ton capacity of a modern rail hopper car. State weight limits are often lower than the interstate limits, and few mines are situated adjacent to an interstate highway.

Road damage by trucks is a major concern. It is said that it takes 2500 automobiles to equal the damage done by one 55,000-pound truck. Safety is also a great concern, as trucks have a greater

Joy Huffstetler, a staff member in Oen's program, reads a microfiche in the process of her research.

Fossil Energy Information Program

The Fossil Energy Information Program, headed by Carol Oen, provides information support services to research and development programs for the increased use of coal and synthetic fuels as alternatives to oil and gas as clean energy sources. Originally established in 1974 as the Coal Information Program, this DOE-supported program is part of the Fossil Energy Program and the Information Center Complex of ORNL's Information Division. It provides information in such areas of fossil energy as engineering, coal-conversion technology, coal combustion, health and environmental effects, and chemical characterization of fuels. It serves the needs of researchers in government, industry, and academia by offering specialized keyworded data bases, specialized directories of experts and R&D activities, and services aimed at keeping researchers abreast of new developments. The information program staff works closely with staff members of ORNL's Fossil Energy Program and Life Sciences Synfuels Program.

capacity for damage to property and life in case of accident.

The three states moving the most coal by trucks both from origin and at destination are Pennsylvania, Ohio, and Kentucky.

Coal Slurry Pipelines

Pipelining ground-up coal as a water slurry has received considerable attention in recent literature as a transportation mode. The concept is not a new one. A patent for such a method was obtained in 1891. Despite this, very few such pipelines have been built and operated. The first slurry pipeline in the United States was a 10-inch-diameter pipe that ran the 108 miles between Cadiz, Ohio, and Lake Erie. Consolidation Coal Company built it in 1957 and operated it for six years. It was closed when a reduction in rail rates changed the competitive picture. The second is the 18-inch Black Mesa Pipeline which connects the Peabody Coal Company's Black Mesa Mine in Arizona with the Mohave electrical generating plant in Nevada, 273 miles away. It has been in operation since 1971, and has a capacity of 4.8 million tons per year.

At least seven other coal slurry pipelines are planned or being studied. All but one, which would serve Florida from the Appalachian area, are in the West. Some of these would move as much as 25 or 30 million tons of coal per year.

Attractiveness of these pipelines is based on their one-time capital investment, their low direct impact on the environment, their relatively low maintenance, high reliability, and great economy of scale.

The great reserves of coal in the West are not accompanied by an abundance of water, and the water requirements for slurry pipelining are a concern. Also, the question of rights of eminent domain for coal slurry pipeline construction has not been settled.

Transport Mode Comparison

The usefulness of a transport mode depends on many factors, including the physical capabilities, costs, and adaptability. In general, flexibility of a particular mode is in inverse proportion to its economics.

Neither environmental nor safety considerations preclude any one transport mode. Accidents involving trains or trucks create public safety hazards.

Competition

In spite of a number of rate concessions, competition has and will diminish the railroads' supremacy in coal hauling for the nation.

The picture is not simple. As railroads use more unit trains, they may displace water movement. At the same time, unit trains can connect with large terminal facilities, making possible joint coal movements that would otherwise be less competitive. The influence of regulation, or the lack of it, is important.

The rail share of movement of United States coal production has fallen slightly because of water and truck competition, but large-scale diversion to other modes appears unlikely.

While basically viable, neither the coal industry nor its transporters are vigorous industries immune from problems. Labor and other difficulties at the mines and for the transporter have interrupted coal supplies.

Influences Toward Decreased Coal Transportation

At present, the total increase, both past and projected, in the use of coal by all sectors in all parts of the country dictates a parallel increase in transportation. There are emerging developments that will tend to reduce the amount of coal transportation, however. Technologies that permit the use of coal at the source, such as mine-mouth generation of electricity or in-situ gasification of coal, obviate the need for bulk coal transport.

Extra-high-voltage transmission of energy is factored into the coal transportation picture by some reviewers. That is, the electrical energy produced through the use of coal is transferred over power lines to users. As mine-mouth generation or other at-source energy-conversion technologies are used, this will be a growing factor and the relative advantages, disadvantages, and costs must be given a full accounting. Pipelines carrying coal gasification products also fall under this consideration.

Summary

The second coming of a coal-based energy economy faces many problems, not the least of which is adequate and economical transportation of the coal. In examining the likelihood of the nation achieving the needed developments in the transportation sector to move the one billion tons of coal expected to be produced in 1985, most studies are cautiously optimistic. There is a sufficient lead time even today to arrange for capital equipment to be ordered and delivered to keep abreast of growing needs. The major reason for hesitation appears to be the uncertainty of the transportation sector managers about the ability of railroads, barges, and other transportation modes to retain their fractional share of the total transportation market for coal. Should major investments be made in coal slurry pipelines, for instance, it is felt that the total proportions could be so changed that investments become risky. For this reason, there have been suggestions that the federal government offer financial incentives to the transporters to reduce the risk. With the size of the estimated needed capital spending, i.e., an estimated $6.1 billion for railroad equipment and facilities plus $1–2 billion (1976 dollars) for water facilities, such risk reduction by the government would be a positive incentive to move forward aggressively to assure capacity equal to increased coal production. A sound national transportation policy must be part of a sound national energy policy.

Carol Oen

Coal Storage

By ED DAVIS, post-doctoral assignee with the Earth Sciences Section of the Environmental Sciences Division

As a result of President Carter's April 1977 National Energy Plan (NEP), utilities and industries throughout the United States are being required to shift from the consumption of oil and natural gas to more abundant supplies of coal. To ensure a sufficient stockpile during times when coal cannot be delivered, some form of onsite storage is required. Generally, this coal storage is divided into two categories: active, or live, storage, which has a relatively short residence time and which feeds directly into the firing equipment; and reserve storage, which is onsite for longer periods of time and which ensures continuous plant operation if coal deliveries are cut off.

Giant coal-moving machines spread coal evenly in stockpiles.

The proportions of coal placed in active and reserve storage vary with the type of user. Utilities that generate electricity and, in the future coal conversion facilities that must run essentially 100% of the time, usually stockpile coal to meet 30 to 90 days of continuous nondelivery. Industrial coal users, who often have access to alternative energy sources, may have only small amounts of coal in storage, purchasing more as needed from coal-handling facilities, which stockpile large amounts to supply such industries. Considering all sources, the National Coal Association estimates that there were 141 million tons of coal in storage in the United States at the end of 1978. Projections indicate that by 1985, this amount will reach approximately 250 million tons in storage; and by the year 2000, a possible 750 million tons of coal will be stockpiled throughout the United States.

Various environmental problems will arise in the handling and storage of these large volumes of coal. Rain or snow will either penetrate or run down the outer surfaces of the pile; in either case, particulates and various inorganic and organic elements will be leached from the stockpile. Chemical analysis of the leachate from high-sulfur eastern coals indicates that it is similar in quality to the acid drainage from mines, having low pH values and high concentrations of dissolved iron, sulfate, and trace metals. In the case of coal combustion facilities, this runoff is usually directed to fly-ash storage ponds for neutralization and ultimate discharge to the nearest stream.

Not all the rainfall on a coal storage pile appears as runoff. Some of it penetrates the pile and is retained in the interior as bound water or water held against gravity, and some evaporates. Various attempts have been made to estimate runoff quantities, but such estimates are highly dependent upon stockpile configuration, coal particle size, amount and intensity of rainfall, and moisture content of the coal being stored. In general, it appears

Ed Davis, who is studying the environmental aspects of coal storage, stands near the massive coal pile of TVA's Bull Run Steam Plant.

that runoff may range from 50 to 85% of the rainfall on the pile.

Total suspended solids (TSS) and pH are the only parameters currently addressed in National Pollutant Discharge Elimination System (NPDES) permits for discharging runoff from materials storage, which includes coal-storage piles. The content of TSS in coal-pile runoff has been reported by Tennessee Valley Authority investigators to range from 8 to 2300 mg/liter, with pH values ranging from 2.3 to 3.1. NPDES criteria for releasing coal-pile runoff specify less than 50 mg/liter total suspended solids, and a pH between 6 and 9. In other words, TVA has found coal-pile runoff that is too acidic and overloaded with suspended solids, thus requiring further treatment if it is to meet federal standards.

Leachates from eastern coal-storage piles have been shown to contain extremely high concentrations of both iron and sulfur (measured as sulfate ion). Values of these two elements reported by the Environmental Protection Agency range from 0.2 to 90,000 mg/liter and 500 to 22,000 mg/liter respectively. Little information has been reported on trace elements in coal-pile runoff. Studies indicate that acidic eastern coals containing high percentages of iron and sulfur yield leachates with higher trace element concentrations than lower-sulfur western coal samples that are more basic. This is in part due to the higher trace element content in eastern coals, but also to the increased solubility of the trace elements at lower pH values.

Coal is a carbonaceous, nonhomogeneous, highly variable fossilized material. Eastern United-States coals, formed under the influence of ancient oceans, tend to contain high percentages of sulfur (1 to 4%) and to be relatively dense, whereas western United-States coals are usually lower in sulfur content (<1%) and somewhat softer. The quality of runoff from coal-storage areas (and thus its environmental effects) is obviously highly dependent on the chemical and physical composition of the coal being stored.

In the stored-solids study in the Environmental Sciences Division, Bill Boegly and I found that coal-particle size also plays a significant role in determining the quality of leachate from coal-storage piles. Fine coal presents a large surface area for water contact and microbial activity. Coarse-coal storage, now in widespread use throughout the United States, provides much less surface area for moisture contact but requires more storage space and has an increased rate of natural oxidation, thus increasing the loss in heating value during storage.

No firm criteria exist for the design and operation of coal-storage piles. The National Coal Association, however, suggests that coal be placed in one- to two-foot layers and compacted before additional coal is applied. Further, the Association recommends that storage piles should be constructed with a minimum flat area on top and with sloping sides. This will minimize penetration of rainfall into the pile and reduce the amount of leachate. These suggestions are not always followed, as many utilities prefer piles with large flat tops to simplify coal placement and removal.

One obvious way to eliminate runoff from coal-storage piles is to enclose them and prevent rainfall contact. Unfortunately, this may not be practical or economical for large storage piles and may result in considerable difficulties with fires resulting from spontaneous combustion unless oxygen is excluded from the pile.

Use of an organic (polymer) coating has been suggested to reduce rainfall penetration into the pile and also to reduce air flow into the pile, eliminating windblown coal fines. Other coatings, such as tars, have been proposed, but widespread use of this technique has not occurred to date because of the relatively short residence time for the coal in active piles. This approach would apply more to long-term, reserve coal storage.

To meet NPDES permit criteria, pH adjustment and chemical coagulation have been shown to produce releasable effluents. Considerable reduction in iron and trace-element concentration will also occur; however, these are not currently addressed in the effluent guidelines.

Solid waste and ash are not the only sources of pollutants from coal conversion and combustion plants. Leachate from increasing numbers of onsite storage piles is certain to represent a runoff problem from its trace elements and organic compounds, which will require complex treatment schemes before discharge.

letters

Dear Editor:

Your Fall 1979 issue is not clearly stated. The first sentence in O'Keefe's article on "The Politics of Energy" makes it sound as though the U.S. uses 80 quadrillion Btus of energy per day. It's bad enough on an annual basis!

Do you agree that the words "per year" at the end of this sentence would make it clearer?

James H. Heroy
Trappe, Maryland

Thank you, Mr. Heroy. Of all the people who reviewed that article in preparation for publication, and who have read it subsequently, you are the only one to have caught the error. —Ed.

Coal Combustion

By CARL B. SMITH and ROBERT S. HOLCOMB, of the Engineering and Engineering Technology Divisions, respectively.

More than three-fourths of the 565 million tons of coal that were burned in the United States in 1978 were used to produce electricity. The remaining 128 million tons (23 percent) were employed to produce heat and, to a lesser extent, chemicals that were processed into synthetic products. Today 45 percent of all electric power produced in the United States comes from combustion of pulverized coal in boilers.

The pulverized-coal boiler of today is the result of continued development from the mid-1920s through the 1970s. The first small units had output power levels in the range of 15 MW with overall thermal efficiencies on the order of 25 percent—that is, they used a quarter of the energy extracted from the coal but rejected three times as much to the environment as waste heat. Pressures of about 8.27 MPa (1200 psi) and temperatures on the order of 370°C were available then.

By the end of the 1940s, coal plant efficiencies had been increased to the order of 35 percent by elevating operating temperatures to nearly 540°C. These improvements were made possible in part by development of improved alloys and better construction techniques. Output power levels of 150 MW were achieved by the 1950s. By

ORNL Technology Development

ORNL is participating in a number of projects and activities in FBC development under the sponsorship of DOE and TVA.

The Coal Combustor for Cogeneration Development Program is a DOE program to develop the technology for an industrial cogeneration system using an FBC boiler to heat air to a high temperature to drive a gas-turbine generator and supply process heat. A contractor team of Westinghouse, Babcock and Wilcox, and Stone and Webster was selected from a number of bidders to design and build a 200-kW(e) test unit and to participate in a test program and the design of a larger demonstration plant for an industrial site. The test unit will be operated at the Y-12 Plant by the Engineering Technology Division.

The Boiler Material Test Apparatus is a test facility that has been designed for corrosion and erosion testing of boiler and superheater tube materials for industrial and utility steam generators. The facility will consist of four combustors, each with a 2 × 2 foot bed. Authorization for construction is expected from DOE in the near future.

ORNL's 10-inch-diameter FBC boiler and the 4 × 4 foot fluid-bed, cold-flow model are being used to obtain experimental data in support of the TVA program to design and build a 200-MW(e) FBC demonstration steam-power plant. A program of fundamental tests on pneumatic coal feeding has also been initiated. In addition, technical support is being provided to them in the areas of design review, system analysis, and FBC process modeling.

Another area of fluidized-bed technology in which ORNL is involved is that of pressurized fluidized-bed combustion (PFBC). ORNL is participating with DOE and TVA in planning a conceptual design study and cost estimate of an 800-MW(e) PFBC steam-power plant. In this concept, the fluidized bed would operate at a pressure of 4 to 10 atm and the flue gas would be cooled to about 590°C and routed through cyclone separators to remove most of the fly ash and dust particles. The gas would be expanded through a gas turbine that would serve to drive the compressor supplying the air to the combustor. Since the power produced by the turbine is used to pressurize the air for the fluidized bed, this concept has been given the name of the Supercharged Fluidized-Bed Combustor. It is believed that this approach offers the possibility of reducing both the capital and operating costs of FBC power plants.

Bob Holcomb (left) and Carl Smith check out the operation of the 10-inch dia Atmospheric Fluidized Bed Coal Combustor at the Y-12 Plant. ORNL's Engineering Technology Division is trying to optimize the performance of this device by changing operating temperatures, velocity, bed depth, and other parameters. This concept is environmentally attractive because it offers a way of burning coal and capturing sulfur dioxide (a pollutant) in one step.

1960 the output power level of the average boiler had increased to 200 MW, with pressures reaching 24 MPa (3500 psi) and efficiencies reaching 38 percent. At the end of the 1960s the average coal unit size had increased to 500 MW and the largest units produced 1300 MW. A typical example of a large coal-fired steam plant built in the 1960s is the Bull Run Steam Plant near Oak Ridge. This facility, operated by the Tennessee Valley Authority, produces 900 MW and has an efficiency ranging from 36 to 39 percent depending on load level.

During the 1970s the average unit size rose to 575 MW with no further increase in the maximum unit size. The number of supercritical units (boilers with pressures so high that the heated coolant is kept in the liquid rather than gaseous state) declined in the 1970s in favor of the subcritical units which have a typical pressure of 17 MPa (2500 psi). In the last two decades, design engineers concentrated on increasing reliability and size of coal-fired power plants. However, the reliability and availability of the coal units declined with increasing size. This phenomenon stems in part from the increase in the number of boiler tubes; for a given probability of a tube failure, the probability of a forced outage from a boiler tube failure increases with unit size so that boiler tube failures become a larger fraction of the total failures. Consequently, the trend toward even larger units appears to have been reversed. In particular, committed new pulverized coal units totaling 109,000 MW over the next ten years have an average size of 506 MW.

The total of all pulverized coal units in the United States produced 1,000,000 kWh of electric power in the past year. It is expected that coal combustion will continue to play an important role in producing electricity to ensure further economic growth in the United States. But changing economic and environmental priorities are likely to prompt changes in the ways in which we burn coal.

It is well known that coal combustion releases undesirable pollutants into the atmosphere. Current regulations limit the levels of sulfur dioxide, nitrogen oxides, and particulates that can be legally emitted by power plants. The latest regulations, embodied in the Clean Air Act Amendments of 1977, have prompted electric utilities to change their fuel-purchasing practices and to incorporate existing technology for cleaning up emissions. If they use low sulfur coal (including that which has been cleaned in coal preparation plants), then they need dry scrubbers to clean the flue gas. If they burn medium to high sulfur coal, then they must use wet scrubbers to clean the flue gas to meet environmental requirements. Scrubbers are expensive to build and costly to maintain; furthermore, they reduce the amount of power that would normally be obtained from the coal-fired plant.

Fluidized-Bed Combustion

Since the United States has vast reserves of high sulfur coal, there is an incentive to develop economical methods of burning coal that do not pollute the environment. A newly developing technology that appears to meet this need is fluidized-bed combustion (FBC) of coal. This method can meet environmental requirements while producing electricity at a cost that is estimated to be less than that of power plants with scrubbers. In order for FBC to be accepted by the utility industry, it is first necessary to demonstrate that the technology is feasible and that the economic benefits are real. Many utilities are skeptical about the possible economic benefits of newer technologies in light of their unhappy experience with greatly escalated costs of nuclear power plants due to changing government regulations and underestimated costs. Consequently, the federal government, which is sponsoring FBC research through the Department of Energy, has teamed up with the boiler manufacturers in industry in jointly funded projects to demonstrate the economic viability of FBC technology.

In a fluidized bed, solid particles are maintained in balanced suspension against gravity by the upward motion of either gas or liquid. In coal combustion, particles of coal mixed with crushed limestone and ash are ignited by a steady flow of heated air. At the appropriate temperature range (about 850°C), the sulfur dioxide produced by the burning coal combines with the calcium oxide produced by heating the limestone to form calcium sulfate. Thus, SO_2 emissions are virtually eliminated. The calcium oxide/calcium sulfate product is a relatively harmless solid waste; in some cases, it can be used as a soil enricher to neutralize acidic soils. The combustion temperature is low enough to keep nitrogen oxide emissions at acceptable levels. Thus, FBC of coal is an environmentally attractive concept.

The fluidized-bed concept was first investigated by Fritz Winkler in Germany in the early 1920s in an effort to gasify coal. In America, in about 1926, W. W. O'Dell began to develop the fluidized-bed concept for catalytic cracking of oil. Other limited work was accomplished in the United States by Standard Oil Company and Combustion Engineering Inc., but they were unable to develop the concept further for applications in burning coal. In 1961 Douglas Elliott, an Englishman, performed experiments which led him to rediscover the FBC boiler. The English led the Americans in development of this technology until 1965 when Michael Pope of New York City successfully operated a small FBC boiler. Pope then persuaded the U.S. Office of Coal Research to support his development of an FBC boiler designed for utility application. His experimental work was conducted at Alexandria, Virginia, in the Naval shipyards. After a few years of experimental and design work by Pope's firm, the Office of Coal Research signed a contract with Foster Wheeler Corporation, which agreed to design and build the first large FBC boiler based on Pope's concepts. In late 1976 the unit was installed and started in West Virginia at the Rivesville power station of the Monongahela Power Company. This 55-year-old power plant had turbines small enough for the testing of the 30-MW(e) FBC boiler. Since 1976 the FBC boiler has operated fairly well, but there have been problems with the peripheral systems. For example, the fuel-feed system has been plagued with clogged lines due to the use of damp coal. But the operating FBC unit has still been able to meet maximum power requirements.

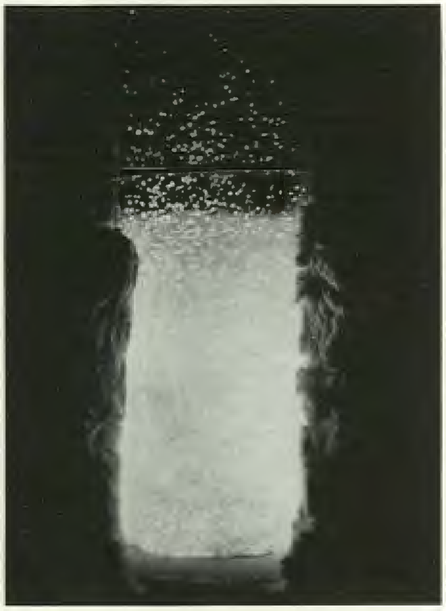
The Component Test and Integration Unit is now under construction at West Virginia University in Morgantown. It will have three FBC units stacked vertically, a configuration proposed for future boilers. Information gained from its operation will be used in the construction of the first demonstration facilities.

Current Developments

At Rivesville it was recognized that too large a step had been taken in the technology, so further developmental efforts focused on smaller scale units. DOE's Morgantown Energy Technology Center and several universities had begun analytical and experimental work, and all three major U.S. boiler manufacturers began their own work. In the current national effort a number of small FBC units ranging in size from 6 inches in diameter to as large as 4 feet by 9 feet are in operation developing the needed data. At ORNL a 10-inch-diameter FBC unit about 15 feet tall is providing data to assist the Tennessee Valley Authority in its program of designing and building a 200-MW(e) demonstration power plant in Kentucky. In a joint venture, Combustion Engineering Company has teamed up with DOE in a project to design, build, and operate a 50,000-lb/hr saturated-steam boiler scheduled for startup in 1981. Recently Foster Wheeler Corporation started up their second FBC boiler, which produces 100,000 lb/hr of saturated steam for space heating at Georgetown University. Babcock and Wilcox is operating a 6-foot-square FBC boiler at its Alliance Research Laboratory in Alliance, Ohio, for the Electric Power Research Institute. EPRI is also providing R&D and funding assistance to TVA in the 200-MW(e) demonstration program.

Morgantown Energy Technology Center is responsible for operating the Component Test and Integration Unit at West Virginia University. The CTIU is a flexible, modularized test facility that features three FBC beds

A fluidized bed coal combustor in operation.



stacked vertically in an arrangement similar to that proposed by two of three major U.S. boiler manufacturers for future utility-size boilers. The CTIU will be used to assist DOE, TVA, the boiler manufacturers, and industrial firms in solving problems with the first demonstration units. Furthermore, data from the CTIU will aid in the development of second-generation units, new equipment, and control systems for future FBC boilers. The Oak Ridge Operations Office of DOE is responsible for design and construction of the CTIU. ORNL engineers are assisting DOE in preparing the CTIU for test operation by providing technical information and project management assistance. In particular, overall project scheduling is being provided through use of a performance measurement system. Also, project cost analyses, cost projections, and reporting are being provided.

DOE projects that FBC has great potential for significant commercialization by the year 2000. Accordingly, a Program Opportunity Notice was sent to industry for obtaining cost-sharing proposals for large industrial-size FBC units with approximately 200,000 lb/hr of steam output. Proposals received in late August are being evaluated. It is anticipated that industry will provide the majority of the funding. As part of the decentralization of project management within DOE, it is planned that the Morgantown Energy Technology Center will have the lead management role for DOE on these projects.

An alternative approach for producing electric power from coal that is receiving widespread attention is the coal gasifier–gas turbine combined cycle integrated power plant. In this concept, a coal gasification system located on the power plant site supplies low- or intermediate-Btu synthesis gas to fuel a gas-turbine generator, and a steam-turbine generator is driven by steam raised by heat extracted from the hot, raw synthesis gas and from the gas-turbine exhaust stream.

This cycle offers the potential of increased efficiency over steam-power plants. The efficiency that may be realized will depend primarily upon the gasifier efficiency and the gas-turbine inlet temperature that is employed in the cycle. The range of the net cycle efficiency that is generally projected for this system is 36–39% for an assumed gasifier efficiency of 78–85% and a gas-turbine inlet temperature of 1090°C, which is about the upper limit with current technology. The High Temperature Turbine Technology Program of DOE is being carried out to make use of increased air or water cooling of the turbine blades to increase the allowable turbine inlet temperature to 1315–1425°C, which, if successful, will make possible efficiencies in the range of 39 to 42 percent.

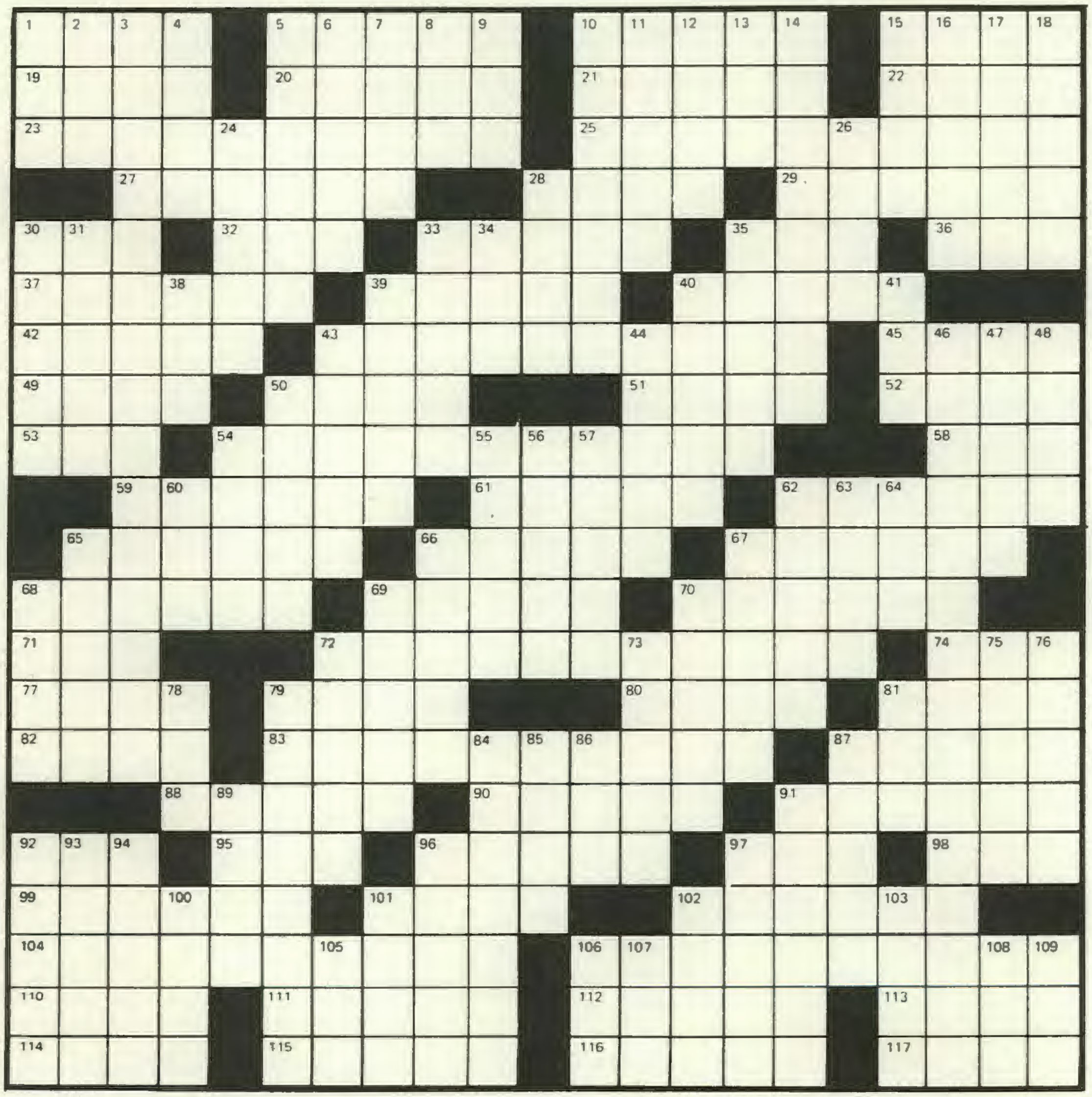
Conclusion

It has been projected that coal usage will have to increase by a factor of 2 or 3 by the year 2000 in order to meet the energy needs of the United States. A major part of this increased coal utilization will occur in conventional electrical power plants and industrial plants. There is, however, the parallel need to minimize the adverse environmental impact of increased coal use on our nation. In order to meet both of these goals, it is imperative that government and industry work cooperatively to develop improved coal combustion technologies, including FBC, that can be commercialized and provide America's energy needs without polluting the environment.

Ted's in coal combustion. He's on the fluidized bed all day, water bed all night.

BURNING ISSUES

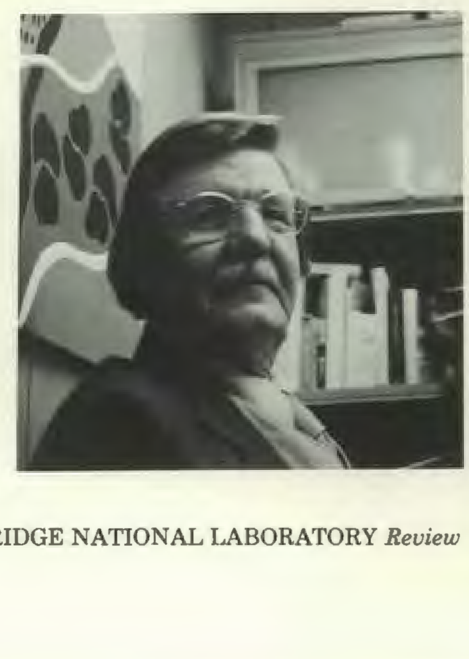
By HUME R. CRAFT



ACROSS

1 Boys
5 Victims of DDT
10 Deceptive appearances
15 Moving nuclear particles
19 Experimenter's bonus
20 Chou - - -
21 Carpet made in Afghanistan
22 Thomas - - - Edison
23 Extra point for U.S. via gasification
25 Coal mining exodontia
27 Isotope of at. wt. 230
28 Ceremonial word
29 Research job
30 - - - theory

When ORNL health physicist Hume Craft retired in 1975, he had completed over thirty years of employment at the Laboratory. Since then, he has turned a lifelong hobby into a second profession, and is today a nationally recognized free-lance crossword-puzzle constructor, turning out puzzles for the class trade, such as the New York Times Magazine *and Dell Publishing Co. Inasmuch as his output averages up to four major puzzles a month, it was generous on his part to consent to produce a puzzle for the* Review's *coal issue. If the response is favorable, he may be persuaded to do another.* *The solution to this puzzle can be found on page 74.*



32 Falstaff's forte
33 Catfish
35 Certain detector
36 "Able was I - - - I saw Elba"
37 Fortune telling cards
39 What the Pied Piper could do
40 Combustion-chamber parts
42 Make amends
43 Excitement in the fluidized bed
45 Uses an abacus
49 Balcony section
50 Spread
51 - - - Bethe
52 Certain scientist: abbr.
53 Compass point: abbr.
54 Added weights on the energy dilemma
58 Former French coin
59 Loans under Roman law
61 Baseball's Peewee
62 William - - - Fields
65 Items for chairpersons
66 Climbing plant
67 Altogether
68 Hydrocarbon in the methane series
69 Raccoon-like animal
70 Actor Omar
71 "- - - was saying"
72 Patchwork "guilt" mending in the Cumberlands
74 "Kill the - - -!"
77 Pack away
79 Me, fa, ti, do connection
80 Carlsbad Cavern sights
81 - - - dieu
82 Razor sharpener
83 Anathema to coal processors
87 Lively
88 Wire nails
90 " . . . The Queen's - - -" (G&S)
91 Pasture sight
92 Male swan
95 Hesitating sounds
96 Nosy one
97 Driver's station
98 Blockhead
99 Hindu god incarnation
101 Rider's choice
102 Mack of the Keystone Cops
104 Soft line opposed by environmentalists
106 Namesake of a red precious stone
110 Soon
111 Coach Robert - - - Neyland
112 Dollar owner
113 Owlish sound
114 Singer Horne
115 Having a portal
116 Family rosters
117 Familiar (with)

DOWN

1 Muscle spasm
2 Commotion
3 This knocks out the NO_x
4 Late comedian Jimmy
5 Hazards
6 Follow
7 Kind of chance or pickin's
8 Philippine native
9 Elmer Gantry's target
10 Jewish months
11 Emulated a witch
12 Ostentatious
13 Damage
14 Wagon and house
15 Alkaline solution
16 Elizabeth of France
17 Have: French
18 Minister's home
24 Maternally related
26 TV performer
28 Oak Ridge connection
30 Hackneyed
31 Industrialist Cyrus
33 Release, as from the army
34 Sphere
35 Diving birds
38 End of a countdown
39 Activists
40 Girl's given name
41 Give way
43 Kadiddlehopper, et. al
44 Pronoun
46 Scrubbing effect
47 TV's Howdy - - -
48 Swing around
50 Developmental stage
54 Paul Bunyan's Babe and others
55 Asian wild sheep
56 Lariat's kin
57 Cloth for overalls
60 Stowe character
62 State prior to the ordered universe
63 Bereft, old style
64 Pugilist's moniker
65 Vigor, zest
66 "Oak Ridgy"
67 Relatives of atoms
68 Gala event: Slang
69 Biologist's concern
70 Solid - - -
72 Crosses
73 Baseball's Doubleday
75 Mr. Standish
76 Jurypersons
78 Wolfe's "The - - - and the Rock"
79 Kind of partner
81 Golf tournament: abbr.
84 At ease in the studio
85 Comet's feature
86 Hail or farewell
87 Combat zone
89 Paper allotment
91 Types
92 Political group
93 Sheep-like
94 Music stick
96 Drench
97 Laugh
100 Albacore
101 Guest, for one
102 Eye trouble
105 U.S. teachers: abbr.
106 Quick to learn
107 Close by: dial.
108 Nursery tenant
109 Ike's theater: abbr.

Coal Liquefaction

By H. D. COCHRAN Fossil Energy Programs, Chemical Technology Division

The American appetite for oil is voracious. Every day each American consumes an average of 3.2 gallons of petroleum including 1.9 gallons in the form of liquid transportation fuels such as gasoline, diesel fuel, and jet fuel. Liquid fuels are also important for space heating, for industrial boilers to make process steam, and for power generation. The United States, comprising about 6% of the world's population, consumes about 40% of the world's petroleum, importing almost half its needs. As domestic and global demands for petroleum outstrip supply, prices rise and fuel supplies become uncertain, causing serious disruptions to our economy. Coal liquefaction, producing liquid fuels from our abundant coal resources, is one of the few options potentially available to alleviate this serious problem. Because of the magnitude of America's energy demand, the size of the coal liquefaction industry that would be necessary to meet a significant portion of that demand is very large. How large will be considered later in this article.

Liquefaction processes convert solid coal into liquid fuels that may range from heavy tar-like products (solid at room temperature) to lighter, more refined products like gasoline or methanol. More than 60 different coal liquefaction processes have been identified involving various chemical reactions that often occur at high temperatures and pressures. Hydrogen is generally consumed in these processes to produce fuels of higher quality and to remove impurities containing sulfur, nitrogen, and oxygen. Most processes produce several liquid products and by-products, and the slate of products may vary greatly among processes.

This article presents the description, history, status, and economic prospects of three broad classes of coal liquefaction processes—direct, pyrolysis, and indirect. Direct processes are characterized by dissolution and hydrogenation of coal slurried in a process-derived solvent. Pyrolysis involves subjecting dry coal to high temperatures without solvent in a reducing atmosphere. Indirect processes for producing liquid fuels from coal involve gasification of the coal with steam and oxygen to produce synthesis gas (carbon monoxide and hydrogen) that may be reacted to form liquids.

Direct Liquefaction

In the 1920s the German chemist Friedrich Bergius discovered a method for combining coal with hydrogen under pressure. This hydrogenation, which earned Bergius a Nobel Prize in chemistry in 1931, is the forerunner of all direct liquefaction processes. The first commercial coal hydrogenation plant was started in Germany in 1927 by the I. G. Farbenindustrie A.G. at their Leuna works. More than a dozen commercial plants based on Bergius hydrogenation were built prior to and during World War II in Germany, Poland, Czechoslovakia, Italy, Japan, and Great Britain. Peak production in Germany during this period exceeded 100,000 barrels per day, which sustained Hitler's war machine during the latter part of World War II when Germany found itself blockaded from its overseas oil supply. After the war, direct liquefaction plants were operated in the Soviet Union and in the United States by Union Carbide Corporation at Institute, West Virginia, and by the U.S. Bureau of Mines (Department of Interior) at Louisiana, Missouri.

While none of these plants is operating today, technological descendents of the Bergius process are the focus of the U.S. Department of Energy's liquefaction R&D program. In these procedures, ground coal is mixed with a process-derived solvent, pumped to pressure (1500–3000 psi), mixed with hydrogen gas, heated to reaction conditions (about 800°F), and reacted for periods up to about one hour. The product mixture is then cooled, depressurized, separated, purified, and upgraded into marketable fuel products. The process-derived solvent is separated from the product mixture and recycled to the process. Hydrogen consumed in the reaction is produced by gasification of a carbon-containing stream of little economic value. Four direct liquefaction processes are the main effort of DOE's liquefaction R&D program. They

Richard Forrester, (left) Royes Salmon, and Al Irvine of the Chemical Technology Division discuss a process flow sheet for a coal liquefaction plant. These three men lead a group of engineers who perform technical and economic evaluations of coal liquefaction processes. The Liquefaction Technology Assessment effort now under way is aimed at a comparative evaluation of different liquefaction processes to assist DOE in policy decisions.

are two Solvent Refined Coal (SRC) processes, which use no added catalyst; the H-Coal process, which uses a solid catalyst directly to promote reactions of the coal slurry with hydrogen in an ebullated-bed reactor; and the Exxon Donor Solvent (EDS) process in which the recycle solvent (not the coal/solvent slurry) is catalytically hydrogenated so that the solvent can donate hydrogen to the coal fed to the process.

The SRC-I process yields as its principal product a clean, solid fuel (a tar-like product which melts if heated to about 350°F). This process has been successfully tested by Gulf Mineral Resources Company in a 50-ton-per-day (tpd) pilot plant at Fort Lewis, Washington, and by the Southern Company and Catalytic, Inc. in a 6-tpd unit at Wilsonville, Alabama. (Capacity of coal liquefaction plants is expressed either in tons per day of feed coal or barrels per day of product. Typically, one ton of coal yields about 2.7 barrels of product.) DOE has awarded Southern a contract to do preliminary engineering designs for a 6000-tpd demonstration plant, which if built is planned for operation in 1983. This large SRC-I plant (one train of a five-train commercial plant) will cost about $1.3 billion to build, and will have one of the largest hydrogen generation and handling facilities ever constructed. In spite of this magnitude the plant will produce less than 20,000 barrels per day (bpd) of fuel products, equivalent to about 0.1% of our present petroleum consumption.

Gulf has developed the SRC-II process (a variant of SRC-I that yields liquid products) and tested it at 30-tpd in the Fort Lewis plant and in a 1-tpd facility at Harmarville, Pennsylvania. Preliminary design for a 6700-tpd demonstration plant for this process is also under way.

Another direct process, the H-Coal process, has been operated in a 3.5-tpd process development unit by its developer, Hydrocarbon Research, Inc. A 200–600 tpd pilot plant being built at Catlettsburg, Kentucky, is scheduled to begin producing 750–1800 bpd of liquid fuels by the H-coal process in 1980.

The EDS process has been operated in a 1-tpd unit and will be demonstrated in a 250-tpd pilot plant at Baytown, Texas, during

1980. Exxon Research and Engineering Company, which developed this process, has designed the Baytown facility to produce 700 bpd of liquid fuels.

There are advantages and disadvantages to direct liquefaction. It converts a high percentage of the coal to liquid fuels under relatively mild process conditions and has a relatively high thermal efficiency. Direct liquefaction lends itself advantageously to the application of much petroleum-based technology such as direct catalytic hydrogenation. Handling of the coal as a slurry eases the problem of feeding solids to a high pressure system but presents other slurry-handling problems such as uncertain design and operation of fired slurry heaters, difficulties in separating solids from liquids, and problems in the handling and gasification of solids-laden liquefaction residues including serious materials problems through erosion.

The major liquefaction projects mentioned above are managed by DOE's Oak Ridge Operations Office (ORO). ORNL, which has a considerable effort focused on direct liquefaction technology, provides technical support to ORO including an assessment of ongoing R&D activities, review of designs for the two SRC demonstration projects, and technical support for the H-Coal pilot plant. Other work at ORNL relating to direct liquefaction includes studies of rheological and heat transfer properties in slurry preheaters, measurement of physical properties of liquefaction process streams, investigation of new direct liquefaction techniques, studies of solid-liquid separations, and technical and economic evaluations of coal liquefaction processes.

Pyrolysis Processes

The technology of coal pyrolysis dates from early in the 19th century when low-temperature (850–1300°F) carbonization processes were used to produce coke for the iron and steel industries. Early technology was based on small fixed or gravitating beds, which are not practical for large-scale fuel production. Fluidized-bed and entrained flow reactors, which offer the possibility of increased capacity, were the focus of development efforts in the United States and abroad shortly after World War II. The Bureau of Mines' Parry process was developed in the 1950s. FMC Corporation's FMC coke process is used in a commercial plant in Kemmerer, Wyoming, that is still operating today. Union Carbide's hydrocarbonization process operated at a pilot plant scale in the late 1950s and early 1960s. The late 1960s and early 1970s saw the operation of U.S. Steel's Clean Coke process and FMC's COED process. Union Carbide's Coalcon process was scheduled for demonstration under ERDA sponsorship from 1975 through 1977, but the project was cancelled.

Today, pyrolysis processes play only a limited role in DOE's liquefaction program. DOE's gasification program includes the COGAS process, a pyrolytic process in which roughly half the fuel value of the products is in liquid form. The COED process, which is the forerunner of the COGAS process, was operated in a 36-tpd pilot plant at Princeton, New Jersey, by FMC. A 2200-tpd COGAS demonstration plant is currently being designed by a DOE-supported consortium called the Illinois Coal Gasification Group. Rockwell International, Cities Service, and others are developing processes for rapid pyrolysis of coal under hydrogen pressure in entrained flow reactors.

ORNL's research for DOE on pyrolysis centered around operation in 1975–77 of a bench-scale hydrocarbonization reactor and technical and economic evaluation of a hydrocarbonization process. The results indicated that hydrocarbonization of western coals can produce useful fuels (solid char, oil, and substitute gas) economically that require little or no upgrading.

Pyrolysis processes have several advantages. They can be operated at lower pressures, do not require slurry handling, offer easier solid-liquid separations, and use less hydrogen. The disadvantages are that they may produce a substantial amount of solid char, often present problems in coal feeding and handling caking coals, and may produce relatively heavy liquids that require considerable upgrading.

Indirect Liquefaction Processes

In 1923 the German chemists Franz Fischer and Hans Tropsch synthesized organic liquids by reducing carbon monoxide with hydrogen over an alkalized iron catalyst. Prior to and during World War II, liquid fuels were produced commercially from coal by an indirect process in which the coal was gasified in Lurgi fixed-bed gasifiers and the synthesis gas (hydrogen and carbon monoxide) was reacted by Fischer-Tropsch technology to produce a range of liquid fuels. Peak production reached about 12,000 bpd. In the early 1950s a commercial Fischer–Tropsch plant operated in southern Texas using synthesis gas produced from natural gas.

In 1950 the South African Coal,

George Oswald (right) and Lloyd Youngblood adjust valves on the Coal Liquids Flow System at the Chemical Technology Division's Coal Conversion Facility. This system is being used to study the liquefaction of coal by slurry dissolution, similar to the Solvent Refined Coal (SRC) process now being tested in pilot plants in Alabama and Washington. ORNL researchers are studying the physical properties of coal liquids at temperatures and pressures typical of those at the SRC pilot plants. Information they obtain on viscosity, density, heat capacity, and thermal conductivity will aid engineers in designing SRC demonstration plants expected to be constructed in the 1980s under the supervision of DOE's Oak Ridge Operations.

Oil, and Gas Corporation (SASOL) was formed to produce gasoline and other fuels as well as chemicals from coal with the Fischer-Tropsch process, and by 1955 the SASOL plant was operating. Today, the SASOL plant produces 10% of South Africa's gasoline using modified Lurgi gasifiers and two types of Fischer-Tropsch reactors—the Arge fixed-bed reactor and the Synthol entrained-flow reactor.

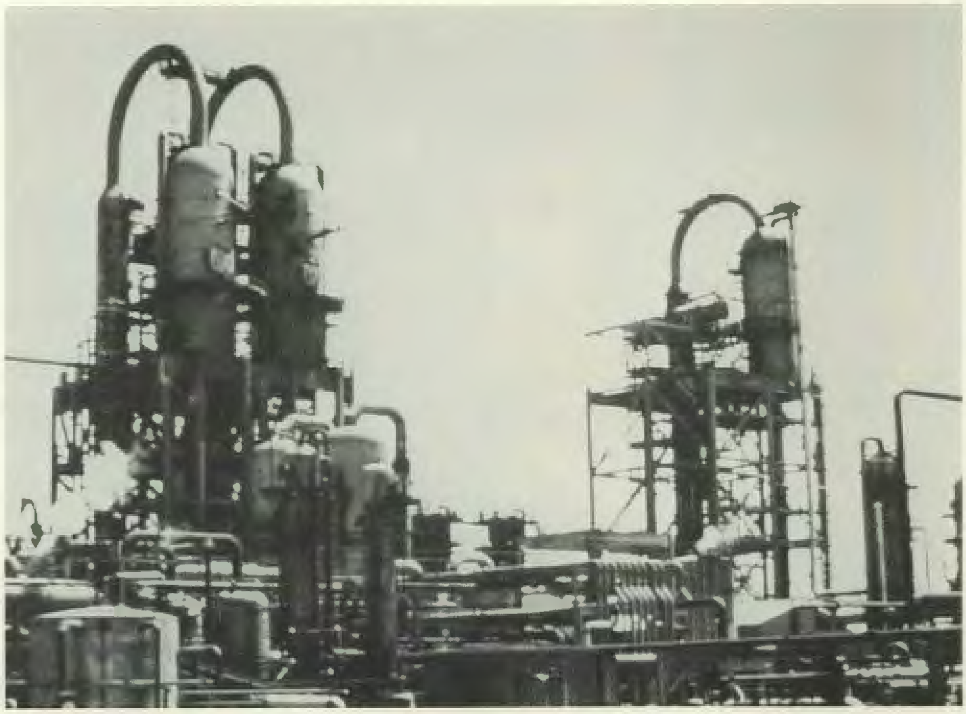
Fluor Engineers and Constructors, Inc., of Irvine, California, are building two substantial additions to the SASOL plant, each larger and more environmentally acceptable than the original plant. These two projects (having a total capital cost of $7 billion) combined with the original coal liquefaction plant will supply half of South Africa's petroleum needs by the mid-1980s.

In the United States, indirect liquefaction processes have received little attention until recently. Gasifiers specifically for indirect liquefaction are not under development, and work on synthesis technology is on a very small scale. Several European nations, often in conjunction with U.S. industries, are developing advanced gasifiers—e.g., Shell-Koppers, Saarburg-Otto, and Texaco. And one of the most exciting synthesis technologies is Mobil's M-gasoline process, which uses conventional technology to convert carbon monoxide and hydrogen to methanol and then employs a zeolite catalyst to turn methanol into gasoline. It will undergo pilot-plant testing in Germany and may be first commercialized in New Zealand.

Last July President Carter called for the creation of an Energy Security Corporation to direct the production of 2.5 million bpd of oil substitutes from coal liquids. coal gases, and other sources by 1990. It is speculated that a major portion of President Carter's synfuels initiative may be based on indirect liquefaction technology, which is commercially available today. Several plants yielding 50,000 to 100,000 bpd each may be constructed in the western United States using Lurgi gasification technology and several synthesis technologies—Fischer-Tropsch, Methanol, and Mobil M-gasoline. Other plants located in the East might use Koppers-Totzek gasifiers. It is likely that advanced gasifiers would be used in later plants due to potentially large cost savings.

To date ORNL's contribution to the national effort in indirect liquefaction has consisted entirely of technical and economic assessment studies. These studies explore the advantages and drawbacks of indirect processes. A small research program will be initiated at ORNL during the current fiscal year to explore the mechanisms of Fischer-Tropsch synthesis, particularly as they may bear on the practical problems of catalyst selectivity and catalyst deactivation. Advantages of indirect processes are these: they are commercially available today, they can produce liquid fuels requiring little or no upgrading, and they can avoid production of carcinogenic compounds found in products and wastes from direct

The Synthol synthesis reactors at SASOL with gas/oil absorption systems in foreground.



and pyrolysis processes. Generally, the most serious disadvantage of indirect liquefaction processes is thought to be an inherently lower thermal efficiency and the resultant higher cost. But thermal efficiency is strongly dependent on the gasification portion of the process so it may be amenable to substantial improvement through development of advanced gasifiers tailored to the technology.

Economics and Prospects for Commercialization

Because no commercial coal liquefaction plants exist today (except for the SASOL plant, where the economic system differs from that of many western countries), the economics of coal liquefaction must be assessed by designing conceptual plants and estimating their costs. Liquefaction is capital-intensive—a commercial coal liquefaction plant would cost at least $2 billion. Since the methods of financial analysis used in economic evaluations vary widely, estimated prices for coal liquefaction products are difficult to compare consistently. In general, most estimates indicate that coal liquefaction products will cost 1.5 to 2.5 times the present OPEC (Organization of Petroleum Exporting Countries) petroleum price, which is now about $28 a barrel. Since the present trend is toward large, frequent OPEC price increases as well as decontrol of domestic oil prices, coal liquefaction technology, while not commercially attractive today, may rapidly become so tomorrow.

Assessments generally agree that cost differences among the direct liquefaction processes are less than the uncertainties of the estimates. It has been widely believed that pyrolysis processes and indirect processes are more costly than direct processes. Recently, comparative economic assessments have been performed by the Ralph M. Parsons Company, by the Engineering Societies' Commission on Energy, and by ORNL. These studies have all been of a scoping level so that uncertainties in the projected product prices are on the order of ±30% or perhaps even larger. Further, these comparative evaluations are complicated by the variety of products produced, the differences in the type of feed-coal required, and the variations in degree of technological uncertainty embodied in the different processes. With these limitations in mind, however, it is possible to draw some preliminary general conclusions: (1) Commercially available indirect liquefaction processes appear to be marginally more costly than promising, developing processes. (2) Promising, developing processes appear to be very similar in economic attractiveness and thermal efficiency; they include representatives of all three classes of liquefaction— direct, pyrolysis, and indirect processes. (3) The potential for economic improvement shown by the developing processes with respect to the commercially available indirect technology is of the order of 30% reduction in cost. (4) Products from all coal liquefaction processes are more costly than products derived from petroleum at current prices.

In addition to technical and economic considerations, other important factors influence the prospects for commercialization of coal liquefaction. These include political, geographic, legal, financial, social, environmental, and logistic factors which, while beyond the scope of this article, will also be critical in ultimately determining the role of commercial coal liquefaction in America's energy future. Because the United States consumption of petroleum is very large, almost 20 million bpd, a future commercial coal liquefaction industry would also have to be very large to have a significant impact. Individual commercial-scale coal liquefaction plants will likely have capacities on the order of 50,000 bpd each. These plants will be very large, each occupying a land area perhaps twice the size of a moderately large (200,000 bpd) petroleum refinery. Perhaps 2000 workers would be employed in operating each plant, which would cost more than $2 billion (1979). To produce 2 million bpd, roughly 1/10th of our petroleum consumption, would require about 40 of these immense facilities.

If legal, financial, and regulatory obstacles could be overcome expeditiously (which would be a major change from the present situation), the time required for engineering, procurement, and construction of a single plant (including the necessary mine development) would be approximately five years; it is very likely that actual project completion periods would be significantly longer because of the obstacles mentioned above. After the first plant is operative, it might be possible, by a concerted, national effort that includes staggered engineering and construction schedules, to bring production capacity growth to a rate of perhaps two 50,000-bpd plants per year. It is more likely that capacity would be built more slowly, however.

H. D. Cochran

The creation of such a coal liquefaction industry (simultaneously with the construction of new power plants, refineries, shale-oil plants, coal gasification plants, and other important capital projects) might impose a serious strain on U.S. engineering, manufacturing, construction, and financial capabilities. Based on estimates by Fluor Engineers and Constructors, Inc., installing a 1.5 million bpd coal and shale liquefaction industry by the year 1990 might require as much as 40% of the present U.S. engineering/construction professional capacity, 40% of the present compressor-manufacturing capacity, 20% of pressure-vessel and tank capacity, 30% of pump capacity, 30% of heater and boiler capacity, 25% of valve capacity, and 10% of steel-casting capacity. On the other hand, pipe, structural steel, and construction trades' man-power requirements represent only 2–3% of U.S. capacity. While generation of capital for financing such an industry is not a limitation, the risk associated with such investment would be high so that financial arrangements might be difficult.

As a concluding statement, then, many suggest that coal liquefaction is not at a state of commercial readiness today. Large plants must be built and operated to reduce technical, institutional, and economic uncertainties. Because of the present market conditions, the impetus in the near-term for building large plants and approaching a state of commercial readiness will come only through government support. This will be true until petroleum prices are raised to perhaps double their present level. It may not be in the national interest to wait for the pressure of external forces before stimulating the commercialization of alternative sources for vital liquid fuels.

Glossary

Fixed-bed reactor—a reactor in which stationary solid particles come into intimate contact with fluid passing through them.

Gravitating-bed reactor—a reactor through which the solids flow with gravity.

Moving-bed reactor—a reactor through which solid particles are moved either mechanically or by gravity flow.

Fluidized-bed reactor—a reactor containing an assemblage of solid particles maintained in balanced suspension against gravity by the upward motion of either gas or liquid.

Ebullated-bed reactor—a reactor in which gas and liquid pass upward through an assemblage of solid particles which are maintained in balanced suspension against gravity.

Entrained-flow reactor—a reactor in which solid particles are carried with the flow of a moving fluid.

information meeting highlights

Metals and Ceramics, Oct. 17–18

New Alloys

ORNL metallurgists continue their traditional role of developing new structural materials that are resistant to high temperatures, chemical corrosion, neutron irradiation, and other stresses imposed by advanced energy systems. The latest development that looks promising for specific applications is a high-chromium ferritic steel that is similar to stainless steel in its ability to maintain strength at elevated temperatures. Most ferritic steels are limited by their low-strength properties at temperatures exceeding 500°C, but this new alloy is an exception. Called nine-chrome-one-moly (for molybdenum) steel, the new alloy was developed by four ORNL metallurgists and two researchers from Combustion Engineering of Chattanooga, under the leadership of ORNL's V. K. Sikka.

This modified 9 Cr–1 Mo steel was originally developed as a potential replacement for the conventional stainless steel (which is more difficult and costly to make) to pipe liquid metal in breeder reactors. The alloy is also being favored as a candidate material for coal-conversion plants, particularly in such components as advanced superheaters and steam supply systems, fluidized-bed heat-exchanger tubing, and liquefaction-plant pressure boundaries. Substituting this ferritic alloy for austenitic stainless steels would allow an all-ferritic system, eliminating the need for and uncertainty of austenitic-to-ferritic steel-weld transition joints.

This modified alloy differs from the standard alloys both in composition and in its response to heat treatment. Its composition was changed by reducing the amount of carbon and silicon present and adding niobium and vanadium. While this new alloy is comparable to two commonly used stainless steels in strength and ductility at high temperatures above 500°C, it is superior to them in its resistance to thermal shock and stress-corrosion cracking from water. Tests continue to further characterize the new alloy's strengths and deficiencies.

Radiation-resistant steel. Titanium-modified stainless steels under development in the M&C Division are now being considered as candidate materials for breeder and fusion reactors. Tests conducted here and at Hanford Engineering Development Laboratory have shown that these steels are more resistant to radiation damage than is type-316 stainless steel, which is conventionally used as a structural material in energy systems. (See ORNL *Review*, Fall 1975).

When conventional stainless steel is exposed to fast neutrons, the metallic atoms are dislodged from their lattice positions. The displaced atoms tend to collect as new planes of atoms, while the vacated sites accumulate as empty spaces called voids. Void formation causes the material to increase in volume and decrease in density. The resultant swelling makes conventional stainless steel less desirable as a structural alloy for fuel cladding and duct assemblies in breeder reactors. This is because the swelling must be allowed for by leaving enough space for bowing or warping of the fuel cladding and duct (hexagonal can containing fuel rods) so as not to restrict the flow of the liquid-sodium coolant that carries away the heat for producing steam to generate electricity. The greater the space that must be left, the less efficient is the neutron capture by the uranium-238 blanket and the less plutonium-239 (breeder fuel) is bred per fissioning atom. To help assure the efficient operation of breeder reactors. ORNL metallurgists have developed titanium-modified steels with the concentrations of other alloying elements balanced so as to minimize phase instabilities during irradiation. Tests show that the swelling in titanium-modified steels is only 20% as high as that of type-316 stainless steel, a significant improvement.

In addition to their improved swelling resistance, the titanium-modified steels possess greater resistance to irradiation embrittlement. This embrittlement, which could lead to cracking, is caused when neutrons react with the steel to form helium. Because 14-MeV neutrons are released to the first wall by heavy hydrogen plasmas in fusion devices, the rate of helium generation is 10 times as high in the fusion wall area as it is in the typical breeder-reactor environment. Thus, solving the helium embrittlement problem is essential to increasing fusion-wall lifetime and making fusion devices economical.

To simulate years of reactor-like radiation damage in a matter of hours, ORNL researchers have bombarded a range of stainless steels with nickel ions from the 5.5 MeV Van de Graaff accelerator and injected the specimens with helium. They have also studied steel samples subjected to neutron irradiation in the High Flux Isotope Reactor here and the EBR-II reactor in Idaho. They found that the stainless steels containing controlled levels of titanium and silicon are superior to type-316 stainless steel in reduction of swelling, increased creep strength, and improved resistance to helium embrittlement.

Researchers working on developing and testing these alloys that are resistant to radiation damage are Arthur Rowcliffe, M. L. Grossbeck, Phil Sklad, E. H. Lee, and P. J. Maziasz. Says Rowcliffe: "The titanium-modified stainless steels have been developed to the stage where they are prime candidate materials for the first wall of early fusion reactors and are likely to supersede type-316 stainless steel in the large breeder reactors currently under design."

LRO alloys. Ductile ordered alloys, developed by Chain T. Liu with assistance from Hank Inouye and Tony Schaffhauser, have undergone further testing; as a result, there is some good news and some bad news. The good news is that recent tests show that these long-range-ordered (LRO) alloys are highly resistant to radiation damage, steam oxidation, and liquid-metal corrosion. The bad news is that these alloys have poor air-oxidation resistance, even though the alloys show the low oxidation rate in steam.

LRO alloys based on vanadium, cobalt, nickel, and iron were developed at ORNL in 1978 because of their ability to increase in strength at the elevated temperatures typical of such advanced energy systems as fast breeder reactors, high-temperature gas-cooled reactors, fusion devices, and coal-conversion vessels. Conventional alloys tend to become weaker at higher temperatures, but LRO alloys have a unique, highly-ordered atomic structure that resists deformation with increased temperatures up to a critical ordering temperature. The traditional problem with most LRO alloys has been that it is difficult to use them to make components with complicated shapes by low-cost, conventional methods because of their poor fabricability and ductility—inability to be pulled or stretched very far before breaking. Liu and his associates found that by adding iron to the alloy composition, they could considerably improve ductility of certain LRO alloys. While iron-based alloys have better ductility, they also have a lower critical ordering temperature than other LRO alloys. Even so, iron-based LRO alloys can be used in the 500–700°C temperature environments typical of fossil-fuel, steam-turbine systems and fast-breeder and fusion reactors. Cobalt-based LRO alloys that are low in iron or iron-free can be used in 700–950°C environments, as in HTGR, fusion, process-heat, and coal-conversion applications. However, ORNL research on cobalt-based LRO alloys has been de-emphasized because of strategic supply problems and the high cost of cobalt.

Despite current funding difficulties, ORNL alloy developers hope to obtain support for research aimed at improving the air-oxidation resistance of the ordered alloys. It is expected that an addition of alloy elements could improve resistance to air oxidation and to sulfidation. Resistance to sulfidation—reaction with sulfur to form sulfide compounds that degrade the material—is essential if these alloys are to be potential candidates for coal conversion uses. In the meantime, ordered alloys developed at ORNL continue to look promising as structural materials for closed systems (not exposed to air) in advanced energy devices.

Physics, Nov. 5-6, 1979

Lining Up and Sizing Up Fleeting Nuclei

They come and they go, much faster than you can say, "Now you see it, now you don't." They are formed when a beam of heavy ions bombards a target of uranium or similar heavy element in an accelerator. They are isomers that decay by fissioning—splitting into nuclear fragments with the release of energy.

First discovered in 1962 as a byproduct of heavy-ion bombardment of plutonium, spontaneously fissioning isomers occur in the nuclides of the heaviest elements, such as uranium, neptunium, plutonium, and americium. Isomers are two or more forms of the same nuclides having the same mass and atomic numbers but different energy states and rates of radioactive decay. The ground-state isomers are relatively stable, but the 35 known fissioning isomers are short-lived species in an excited state that vanish following rapid radioactive decay. Because spontaneously fissioning isomers have short nuclear lifetimes, ranging from a thousandth to a billionth of a second, they are almost impossible to study. Now, a new technique developed at ORNL sheds some light—literally, from lasers—on fissioning isomers, their unique size and shape, and other properties of interest to nuclear physicists, such as nuclear magnetic and quadrupole moments and nuclear spin.

In their normal nuclear ground states, nuclei of actinides like americium are permanently deformed and resemble footballs, each with a long axis about 20% longer than the short axis. Fission isomeric states are thought to be larger and more deformed. The ORNL technique has found that spontaneously fissioning isomers of americium-240 are shaped much like elongated footballs, with the long axis about twice as long as the short axis.

Because of stabilizing conditions in the nuclear potential energy surface, these isomers exist at these large deformations before they fission. The first direct experimental proof for the large deformations expected for fission isomers was obtained by the new ORNL technique called laser-induced nuclear polarization (LINUP).

LINUP is a most appropriate acronym because the technique involves using a laser beam to line up nuclei so that they fission preferentially in one direction. Detection of fission fragments coming from one direction—in this case, along the laser beam—indicates that the laser is tuned to the right frequency, which differs from the normal frequency (or atomic resonance) of the americium-240 nuclei in the ground state. By determining the size of the frequency (energy) shift required in the laser beam to keep the nuclei and their fission fragments aligned along the beam, ORNL physicists can measure properties of these short-lived nuclear species which until now have defied close examination.

The LINUP technique has been developed by Curt Bemis and Jim Beene of the Physics Division, Jack Young of the Analytical Chemistry Division, and Steve Kramer of the Health and Safety Research Division. It is a technique that combines concepts of both atomic and nuclear physics because it involves exciting the atom (electrons in orbit) by laser light to better understand what is happening in an excited nucleus (spontaneously fissioning isomer).

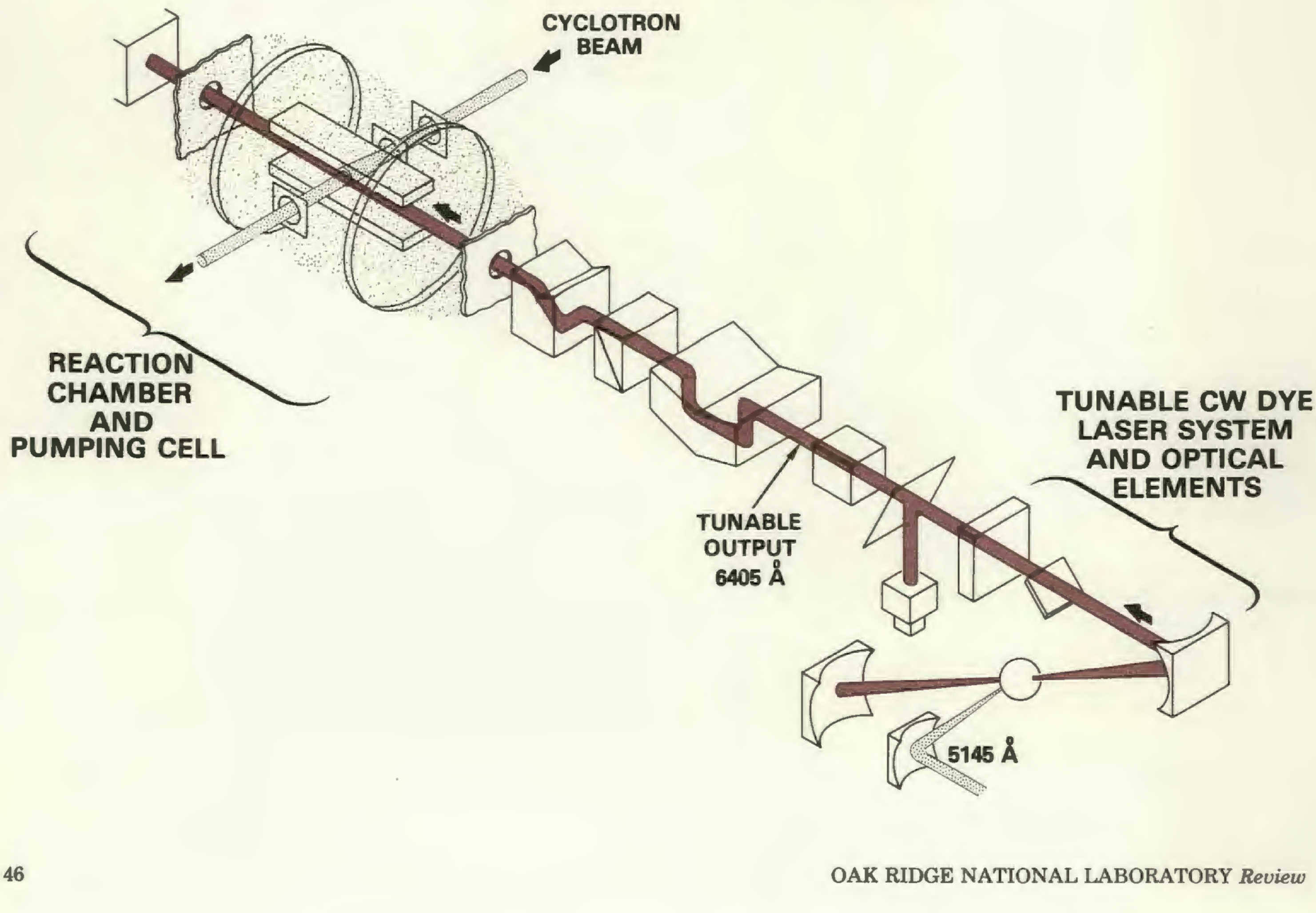
By bombarding a uranium-238 target with heavy ions of lithium-7 in the Oak Ridge Isochronous Cyclotron, Bemis and his associates can produce about 200 fissioning ^{240}Am isomers per hour, which come to rest in a chamber containing helium gas. Intersecting the cyclotron beam (and thus the thermalized-isomer recoils) at right angles is a laser beam produced by a continuous-wave dye laser, controlled by a microcomputer and pumped by an argon-ion laser. Prior to entering the optical pumping chamber, the laser beam is passed through special crystals or prisms which allow the passage of light of only a certain orientation—in this case, right-circularly polarized photons.

Before their nuclei fission, the ^{240}Am isomer atoms are subjected to optical pumping with polarized light. That is, each atom absorbs a laser photon of the right frequency (or wavelength or energy), causing an electron to jump to the next farther orbit from the nucleus and then give up this new energy by returning to its original orbit and emitting a photon. This cyclic absorption and decay continues until each ^{240}Am atom absorbs its limit of photons of the right-circular polarized kind. Eventually, the atoms reach an orientation condition where they cannot absorb another laser photon because of angular momentum selection rules. These rules permit the atom, with respect to its external axis, to occupy only certain quantized directions in space (like a compass needle designed to point in only four directions—north, east, south, and west.) The right-circularly polarized photons impart their angular momentum to the atoms absorbing these photons, and the atomic electrons in turn exert their influence on the nuclei. Thus, the ^{240}Am nuclei end up circling about or precessing the laser beam with the long axis of each pointing at a slight angle along the beam.

In 1956 the Danish physicist Aage Bohr (like his father, Niels, a Nobel laureate) hypothesized that, when nuclei fission, the fission direction is determined along the long axis of the football-shaped nucleus. If the ^{240}Am nuclei shaped like elongated footballs are lined up so that the long axis of each is pointed approximately in the direction of the laser beam, then the fission fragments are preferentially emitted along this beam, as Bohr hypothesized. Thus, if fission fragments are detected by a position-sensitive gas proportional counter located along the laser beam, the experimenters will know that the laser is tuned to the right frequency. This previously unknown frequency for fissioning isomers of ^{240}Am was determined by the LINUP technique. The difference between the known frequency for ground-state ^{240}Am and the fission isomer frequency found by the ORNL physicists is called the optical isomer shift.

"This difference in frequency or wavelength of the atomic transition is proportional to the difference in the nuclear volume," says Bemis. "The difference in the wavelength from one isomer to another is a direct measure of the change of nuclear radius or volume or deformation. Hence, LINUP is an effective technique for performing high-resolution optical spectroscopic measurements on short-lived nuclides produced by heavy-ion reactions."

LINUP PROVIDES HIGH-RESOLUTION SYSTEM FOR STUDY OF SHORT-LIVED NUCLIDES



Chemistry for Coal Liquefaction

By O. L. KELLER, director of the Chemistry Division

Coal represents 90% of the recoverable fossil energy resources of the United States. According to recent estimates, our coal will last for almost 700 years at present rates of consumption. Although the length of time coal will last will clearly be reduced as its usage increases, the sheer mass of this resource makes it our first alternative to foreign petroleum as a long-term domestically available energy source. America is aptly called "the Saudi Arabia of coal."

Our coal supply is long-term but finite. There is time and justification for fundamental research to have a decided impact on the best use of our coal resources. While current technology in coal liquefaction, gasification, and combustion is sufficient for the undertaking of a first-generation effort in these areas, chemical developments are needed to underpin the long-term production of energy, fuels, and chemical products from coal. When looked at from the point of view of the extensive chemical underpinnings of the nuclear and petroleum industries, our knowledge of the chemistry of coal is clearly inadequate.

At first sight, this inadequacy in the understanding of coal chemistry seems strange because coal processing is an old, one might even say ancient, industry. In the early 1700s, coke was already being produced from coal for use in the blast furnaces of England. Town gas, with coke as a by-product, was in commercial use around 1800. The last of the gasworks in the United States did not shut down until around 1950, the victims of cheap natural gas and petroleum. Besides coke, the gasworks produced as by-products ammonia, coal tar, and benzene. As is well known, the development of organic chemistry as a science and its application on a commercial scale depended largely on the availability of these feedstocks from coal. But what may not be widely recognized is that these chemical developments dealt little with coal itself. They only dealt with products obtained from coal by drastic reactions of carbonization at high temperatures. Thus, the coal itself remained mostly a mystery from the organic chemist's point of view.

Massive production of liquid fuels from coal started as a German industry. Indeed, it is doubtful if Germany could have mounted a credible effort in World War II without its famous coal liquefaction industry to produce the fuels for its army and air force. At the peak, near the end of the war, the Germans were producing oil from coal at the rate of 6,000,000 metric tons per annum. Most of the production employed high-pressure catalytic hydrogenation of coal to produce the desired liquid fuels. Friedrich Bergius won the Nobel Prize in chemistry in 1931 for his pioneering research that led to these processes. But it is generally conceded that we must do much better now than the World War II efforts because those plants today would be economically unattractive and environmentally unacceptable.

In addition to the direct liquefaction of coal by processes based on the work of Bergius, other processes have evolved from the work of A. Pott and H. Broche. In 1927, these German scientists developed solvent extraction approaches to coal liquefaction which used hydrogen donor solvents as an integral part of the process. A plant based on the Pott–Broche process was built and run by Ruhröl at Welheim. It had an annual capacity of 26,000 metric tons of the hydrogenated product. Difficulty in filtering the product was the main problem encountered.

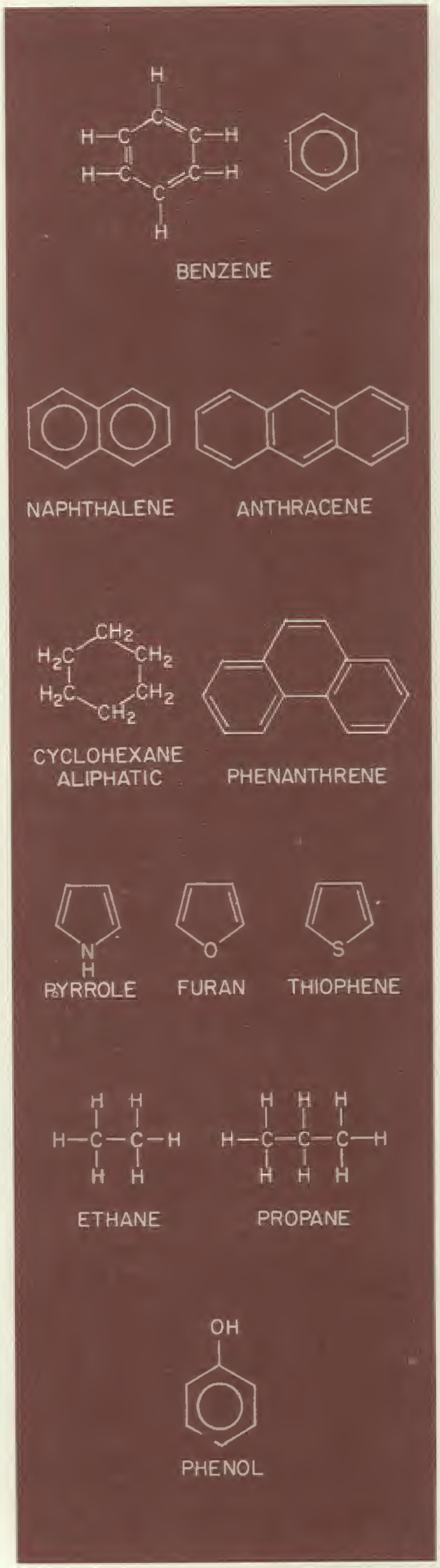
The production of town gas with coke as a by-product is not the only commercialized gasification process, either. The essentially complete gasification of coal with no coke as a by-product is possible through the use of steam. In this way, carbon monoxide and hydrogen (synthesis gas) can be produced. For example, in the 1930s, the Lurgi Company in Germany began its still continuing efforts in coal gasification, and in the mid-1920s, the Winkler process achieved the first wide-scale success of the fluidization technique in gasification reactors. In addition to the direct liquefaction approaches employing high-pressure hydrogenation of coal, the German World War II effort also produced liquid fuels indirectly by use of the coal-produced synthesis gas. Franz Fischer and Hans Tropsch developed catalysts that allowed the carbon monoxide and hydrogen of synthesis gas to react to form liquid fuels. At the present time, the indirect routes to coal liquefaction are better understood technically than the direct methods. Currently, the only commercial plant in operation producing fuels from synthesis gas is the SASOL plant in South Africa, which is based on the Fischer-Tropsch technology. The catalysts employed in such processes are still somewhat mysterious, however, and improvements in economics and in product slates are needed for applicability to the United States energy situation.

The industries of the past were based on a coal science that was largely empirically derived. It is not hard to find out why only an empirical approach of narrow applicability was possible. Coal is a rather loosely defined but well-known term covering a range of complex, solid fossil fuels consisting of a multicomponent mixture of organic and inorganic constituents. Coal is not only complex but also variable. One coal is not like another on the macro, micro, and molecular levels. The heterogeneity and variability of coals are coupled with an inaccessibility to the molecular level that renders coal, from the chemical point of view, a most challenging substance for study. We have an advantage today in that new instrumentation and new theoretical knowledge have been developed in the last few decades to help us peer into coal and catalysis in ways that were totally unavailable to early workers. It is this new instrumental and theoretical capability that gives us hope that we can now develop a new science that far outstrips that of the earlier workers, and thence may lead to new technologies.

Organic and Inorganic Research

Currently available evidence indicates that part of the organic portion of coal has a structure that consists of very large macromolecular units made up mostly of carbon and hydrogen atoms that can best be thought of as polymers, or chainlike structures. In keeping with the general nonregular and variable nature of coal, these polymers are not made up of regularly repeating units as is the case for familiar plastics like polystyrene. They differ in molecular structure and in molecular weight. Also, there is another portion of inorganic matter in coal consisting of small molecules of various sorts that are occluded in the coal matrix.

If we were able to see a more or less statistically significant representative of a coal polymer network, we would probably first of all notice the presence of large units in the polymer formed by fusing several benzene rings together. Such structures could be similar to naphthalene or anthracene, for example. Other units of the polymer might have additional hydrogens bonded to the skeletal carbon framework to make hydroaromatic structures analogous to hydroanthracene. On the other hand, if an oxygen, nitrogen, or sulfur atom replaces a carbon atom in the skeletal network itself, then a heterocyclic structure unit results. Such structures might be based on furan, pyrrole, and thiophene, for example. These polynuclear units are thought to be connected by bridging groups. Some of these bridges consist of carbon atoms in a chain bonded only to hydrogen as in ethane or propane. Such linkages are called alkyl-bridging



groups. Other possibilities include -C-O-C- and -C-S-C- ether and thioether bondings, respectively, in these bridges. Another prominent feature of the coal structure is the presence of functional groups, most especially -OH hydroxyl groups, bonded to the carbons of the polynuclear aromatic carbon skeletal framework. These -OH's give a phenolic character to the coal.

A molecular identification of the functional groups and heterocyclic structures in coals is most important. For example, the removal of organic sulfur and nitrogen is a key problem in coal utilization. If we knew their functional forms in coal, we could be in a better position to devise suitable methods for removing them.

Coals also contain inorganic constituents that come partly from the original plants that were coalified and partly from mechanisms such as mineral waters flowing through the site after the death of the plants. Clays, quartz, and metallic sulfides, chlorides, and carbonates compose most of the mineral matter in coal. Important trace elements often present include titanium, arsenic, manganese, and lead. Some low-rank coals and lignites contain up to 0.1 percent uranium, but high-rank coals are essentially non-radioactive.

Direct Liquefaction of Coal

Most current work on direct conversion of coal to fuels uses

A Brief Look at Coal Chemistry

Coal chemistry is not new; it is almost 300 years old. In 1681 King Charles II of England issued the first patent for coal-tar chemistry. Coal tar is a black, gummy material exuded by coal when it is heated in the absence of air. Although an ugly substance, it is a valuable source of organic chemicals.

In the 1840s, the German chemist August Wilhelm von Hofmann became the first to obtain benzene from coal tar. Benzene is a molecule consisting of a ring of six carbon atoms to which are attached six hydrogen atoms. Its ringlike structure was deduced in 1865 by the German chemist Kekulé while daydreaming before his fireplace. In his reverie, visions of carbon atoms danced in his head. One chain coiled on itself like a snake, and Kekulé's idea of the benzene ring was born.

Besides ring-shaped aromatic hydrocarbons of which benzene is the simplest, coal contains aliphatic compounds that consist of straight or branched carbon chains bonded to hydrogen atoms. Aliphatics include methane (CH_4), ethane (C_2H_6), propane (C_3H_8), and butane (C_4H_{10}). Over the years, chemists have found many uses for all these compounds, which are also obtained from petroleum and natural gas.

In the 1850s, the English chemist William Henry Perkin pondered Hofmann's suggestion of using coal for making quinine, normally obtained from the barks of certain trees. He thought that this medicine for treating malaria could be synthesized from chemicals derived from coal tars that collected in the chimneys of gasworks and coke ovens. He failed to make quinine, but at the age of 18 he found a way to synthesize a purple dye called mauve from coal tar. Perkin's discovery paved the way for the fast-growing coal-by-product industry.

Since Perkin's success in synthesizing a pretty dye from an unattractive material, more than 200,000 different coal by-products have been made from coal tar and coal gas. Coal-tar products include dyes, perfumes, medicines, food flavorings, vitamins, explosives, insecticides, weed killers, nylon, and various plastics. Coal gas, which forms when coal is heated to make coke for the iron and steel industries, has been used to make ammonia, synthetic rubber, cleaning fluids, fertilizers, and plastics.

At the end of World War II, oil and natural gas replaced coal as the primary sources of chemicals in the United States. At that time oil and gas were cheap and abundant, and it proved easier and less expensive to obtain chemicals from petroleum than from coal. Synthetic rubber, nylon, and many plastics are now being made from petroleum instead of coal. Natural gas rather than coal is the chief source of ammonia. In 1976 by-products from coke ovens supplied only 10% of the benzene consumed in the United States.

About 10% of American oil and gas supplies are used to produce petrochemicals. As these oil and gas supplies decline, the chemical industry will continue to use foreign oil and increasingly turn to shale oil for feedstocks. It is expected that it will be several decades before there will be a return to coal as a significant source of chemicals. This slow but necessary revival will accompany production of liquid and gaseous fuels from coal.—CK bituminous coals such as Illinois No. 6. This conversion involves adding hydrogen to the coal to make liquid fuels currently useful in the transportation area. The required hydrogen is a major expense in coal liquefaction. The cheapest place to get it is probably from the coal itself (even though coals generally contain less hydrogen than carbon on an atomic basis).

Three processes receiving considerable attention at the present time in the United States are (1) Solvent Refined Coal (SRC); (2) Exxon Donor Solvent (EDS); and (3) H-Coal. These processes are

Model Compounds and Coal Chemistry

Clair Collins, Ben Benjamin, Ed Hagaman, and Lloyd Brown have been studying reactions of coal and compounds that model coal from several points of view. One of their important contributions has given new insights into the types of chemical bonds in coal that can break most easily to produce radicals under coal liquefaction conditions. They have also developed nuclear magnetic resonance (NMR) spectroscopy equipment that allows characterization of chemical bonding and functional groups in solid coal and in coal-derived liquids, thus obtaining a "before" and "after" look to hopefully discover what happens to coal in the liquefaction reactions.

Coal Mineral Matter Catalysis

Coals contain clays, pyrite, carbonates, and quartz as their main mineral content. The clay, iron, and other minerals are intimately mixed and microscopically dispersed in coals. In liquefaction and gasification processes, the mineral matter may be important catalytically; that is, these minerals may hasten the relative rates of reactions without being altered themselves. Iron and titanium constituents might serve as hydrogenation catalysts, for example, and clays have long been known as cracking catalysts. The identity, and equally importantly the dispersion, of the mineral components of submicron dimensions found in Illinois No. 6 coal have been studied for the first time recently by Dick Strehlow, Larry Harris, and Charlie Yust.

Direct Liquefaction

The development of new approaches to liquefaction of coal is clearly an important area. John Larsen and Marv Poutsma, chemists, and Bill Rodgers and Bob Hightower, chemical engineers, are searching for such new avenues. Currently, they are using gaseous phenol to convert various coals to a soluble material without added catalysts or hydrogen. The liquid products have a higher hydrogen to carbon ratio than the original coal, the other product being a hydrogen-depleted residue. These fundamental studies thus indicate that it is possible to use hydrogen originally present in the coal structure to produce hydrogen-rich liquids for fuel.

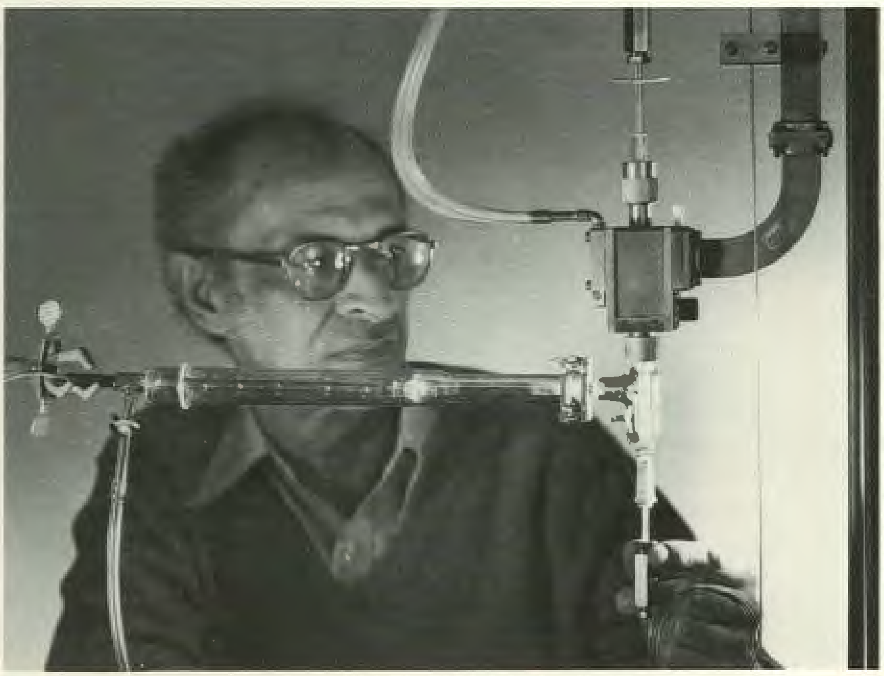
Coal Conversion and Health

Coal is dirty. It pollutes the environment unless stringent preventive measures are employed. Carcinogens and other especially bioactive effluents from coal utilization must be identified and controlled. Mike Guerin, C.-H. Ho, and Bruce Clark have obtained important results recently in this area. These investigators have separated petroleum and synthetic crude oils into chemical classes (acidic, basic, and neutral fractions) for biotesting in the Biology Division. In this way, they have discovered that basic constituents of some coal liquids, especially primary aromatic amines, are the major contributors to mutagenicity. Polycyclic aromatic hydrocarbons are still viewed as the most important mutagens and carcinogens in coal-derived syncrudes. Once the major bioactive constituents are identified by accurate and true biological test methods, such constituents may be reducible and controllable in coal processing through a better knowledge of the basic chemical reactions involved in their production.

heavily dependent on the Bergius and Pott-Broche technology developed in Germany during and prior to World War II. They handle the cleavage of easily broken bonds and the reactions of the resulting free radicals in the coal by approaches developed largely empirically during and before the war years. The catalytic influence of the mineral matter in coal itself is presumed in at least several of them.

SRC, EDS, and H-Coal all use recycled solvents to push hydrogen into the coaly matter being liquefied. These donor solvents are produced in the processes themselves and are a complex melange of many different

O. L. Keller



Ralph Livingston checks the results of an experiment using apparatus in the background to perform electron spin resonance (ESR) spectroscopy. In their application of ESR, Livingston and his colleagues have detected free radicals (molecules with unpaired electrons) produced by reactions breaking down model hydrocarbons (typical of coal) that are heated in the absence of air. ESR, which detects magnetism due to unpaired electrons, allows the chemists to identify free radicals and trace the ensuing reactions, thus providing insight into what happens in high-temperature coal reactions during pyrolysis, which is important in coal liquefaction processes.

Free Radicals in Coal Conversion

The coal "polymer" network can be "depolymerized" in various ways to make liquids. Such degradation reactions often involve the application of heat to coal, resulting in pyrolysis which produces free radicals, or molecules and atoms possessing an odd, unpaired electron. Details of the identities and reactions of these free radicals are of central importance to understanding the reactions of coal that produced them and also their subsequent reactions. The production of free radicals in coal liquefaction reactions suggests immediately that electron spin resonance (ESR) spectroscopy, which detects the magnetism due to the unpaired electron, would be an ideal way to study them. A recent development in ESR by Ralph Livingston, Henry Zeldes, and Mark Conradi has allowed for the first time the study, at the requisite high temperatures, of the pyrolysis of hydrocarbons that are models for coal. Some of the free radicals thus produced have been unambiguously identified by their ESR spectrum, and their subsequent reactions traced. For example, the benzyl radical formed by the decomposition of the bibenzyl radical has been observed, along with the reaction of the benzyl radical with the bibenzyl molecule, to form toluene. Important studies complementary to these spectroscopic ones have been carried out by Marv Poutsma through the use of kinetic and product-analysis methods. These elucidations of radical behavior are providing important clues to what is happening in high-temperature coal reactions.

chemical species. Researchers on the SRC project now recognize that chemical species can be selected from this melange which have peculiarly great donor solvent properties. The identification of these species in the superdonor solvents is clearly of the greatest importance for understanding their superdonor properties.

Liquefaction processes can be made more efficient (a) by reducing the rates of the regressive reactions that produce reactor residues and smaller polymerization products, and (b) by increasing the rates of the progressive reactions that produce desirable fluid products. The role of the inorganic constituents in coal itself as catalysts may be important in this regard. The dispersal of the mineral matter in coal may be as important as its chemical identity. Also, the kinetics of the reactions may be intimately tied to the pore-size distribution and surface properties of the coal. These factors that possibly affect the kinetics of the progressive and regressive reactions are a ripe subject for fundamental research.

Indirect Liquefaction of Coal

Carbon monoxide and hydrogen can be produced by reaction of coal with steam and oxygen. Before World War II, chemists Fischer and Tropsch developed catalysts based on iron and cobalt that could be used to convert mixtures of H_2 and CO to liquid fuels and chemicals. The Fischer-Tropsch process is an indirect way to liquefy coal.

In this country, the Mobil Corporation discovered and is still developing a two-stage indirect liquefaction process by which CO and H_2 are first converted into methanol, using commercially established technology. Methanol is then converted to gasoline with a novel zeolite catalyst. An advantage of the Mobil approach is that the zeolite catalyst produces a gasoline rich in aromatics and branched aliphatics, which increase the octane rating, whereas the traditional Fischer-Tropsch hydrocarbons are largely linear.

Catalyst research at many industrial, university, and government laboratories in this field is directed toward achieving more selectivity for desired products. Toward this end, mechanisms of complex surface reactions in heterogeneous catalysis are being investigated by spectroscopic and by sophisticated product-analysis techniques, among others. Details are being learned of the modes of CO and H_2 chemisorption as a function of catalyst composition and surface structure. A promising approach might be to employ radioactive carbon-14 to study the mechanisms of interesting reactions. As the detailed mechanisms are worked out, they should be very helpful in the design of new catalysts.

The organometallic chemists are giving strong input into the development of soluble homogeneous catalysts for CO hydrogenation reactions and other reactions in solution. Soluble hydridocarbonyl metal-cluster catalysts seem particularly popular. Their behavior may result from their similarities to metal surfaces.

As this survey makes clear, a wide range of product types is possible from synthesis gas reactions using various catalysts and process conditions. Nevertheless, the venerable Fischer–Tropsch processing has generic problems in inefficiency to methane production and the production of linear hydrocarbons of broad molecular weight distributions and low octane ratings. Sulfur poisoning and carbon deposition from low H_2:CO feed ratios are also frequent problems. Research is needed that is aimed at searching for new catalysts and understandings of catalytic mechanisms and process conditions to help achieve the necessary improvements in product specificity for fuels and chemicals to make these syntheses a commercial success.

Conclusions

Our technology and our science for coal liquefaction can build profitably on the experience of the past—especially on the great successes of the German efforts. Those efforts included the direct liquefaction of coal by the high-pressure hydrogenation approach and indirect liquefaction in which fuels were catalytically produced from coal-derived synthesis gas (carbon monoxide and hydrogen). At its peak, the German program was producing oil from coal at the rate of 6,000,000 metric tons per annum. So we are dealing with a program that has already been brought to a high technological level and has been carried out on an industrial scale. In such an area, where so much experience has been accrued, dramatic advances in technology are likely to require an increase in our fundamental understanding of what coal is and what its reactions are. Modern theory and instrumentation give us fresh hope that such advances are possible, both in coal structure and chemistry and in catalysis.

Answers to Coal Quiz, p. 16

1.b, 2.d, 3.f, 4.a, 5.b, 6.a, 7.c, 8.b, 9.c, 10.a, 11.a, 12.d, 13.d, 14.b, 15.b, 16.e, 17.e, 18.d, 19.c, 20.a, 21.a, 22.e, 23.c, 24.e, 25.d.

Coal Gasification

By HAROLD HARTMAN, Engineering Analysis Department of Engineering Division

In the 19th century, houses and streets in Europe and the United States were illuminated by a special gas. This type of gas was also used to generate electric power. By World War II, American industry was using the gas as a fuel and as a raw material for numerous chemical products such as fertilizer and plastics. This gas was not natural gas, which became so plentiful and relatively inexpensive in the middle of this century. It was gas produced from coal. As many as 10,000 small gasifiers may have been used in producing the gas.

Today coal is gasified commercially in South Africa and in several nations in Europe and Asia but it is not yet economically feasible to produce coal gas on a large scale in the United States. The energy scene, however, is rapidly changing as this country commits itself to reducing oil imports, restricting oil and natural gas to their highest priority uses, and minimizing the environmental impacts of energy sources. In anticipation of changing requirements and economics, the Department of Energy is supporting a number of projects and studies to evaluate existing and advanced coal gasification processes. The information derived from these efforts could prove useful in selecting economical and environmentally acceptable processes for commercial gasification plants, which will be needed increasingly as oil and gas prices increase and supplies become uncertain.

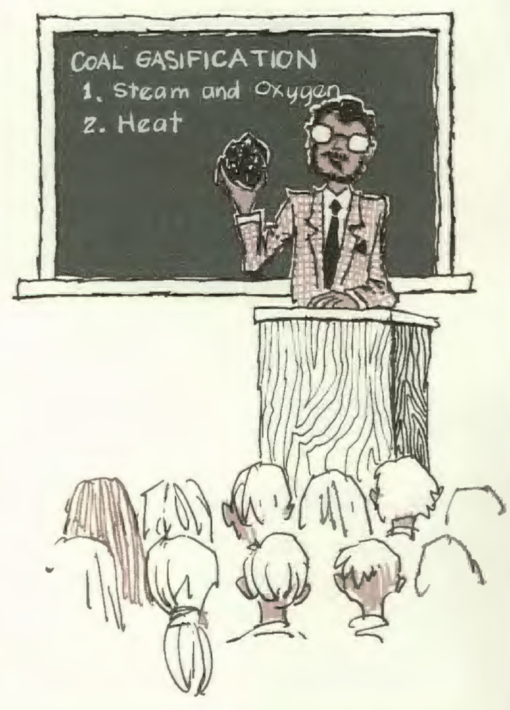
The conversion of coal to a gaseous product is effected by reacting the coal with oxygen (or air) and steam. The gas produced by the carbon-oxygen-steam reactions can be either cleaned and used as a fuel gas or processed further to a synthesis gas. Synthesis gas is composed primarily of carbon monoxide and hydrogen and can be converted to substitute natural gas, chemicals, or liquid fuels. Thus, gasification is an important part of producing both gaseous and liquid products from coal.

Applications

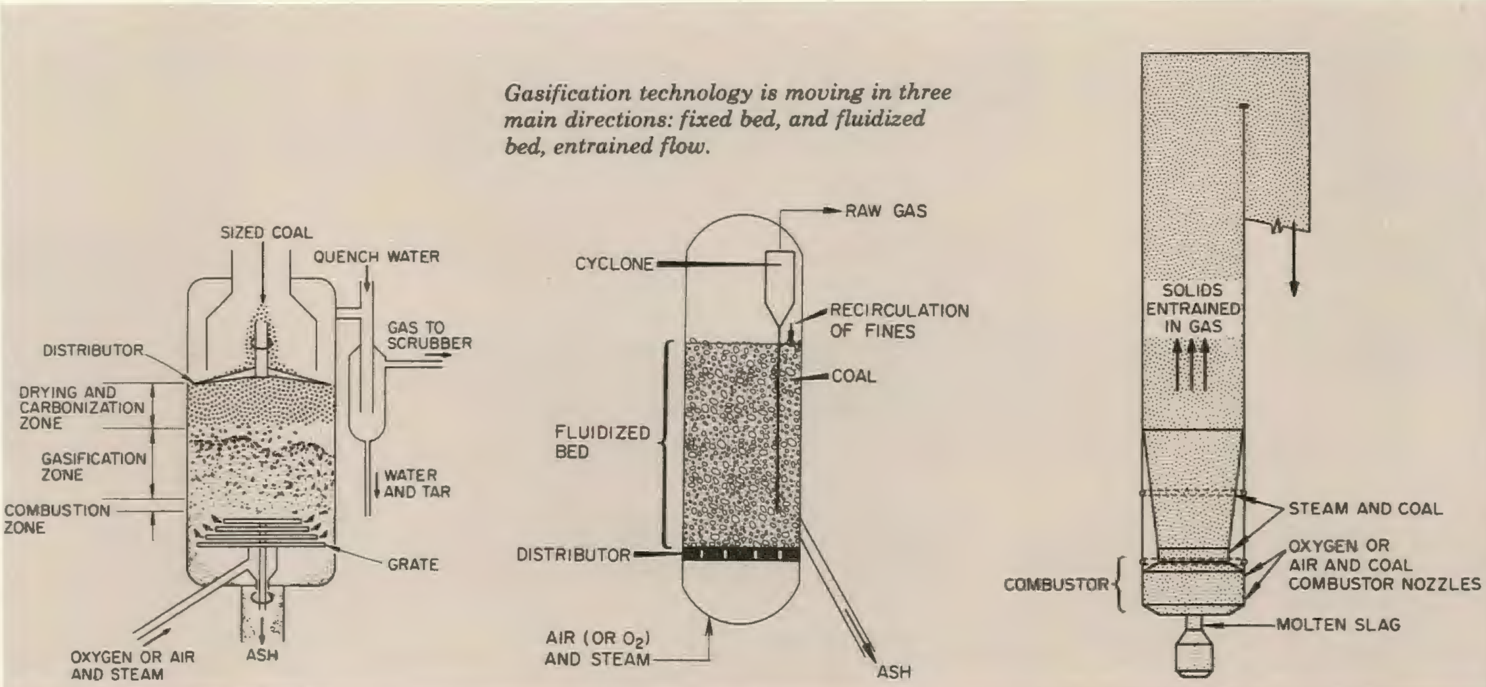
Gas produced from coal is described in general terms by its heating value, which is often expressed as the number of Btu per cubic foot at standard conditions. Natural gas has a heating value of about 1000 Btu/ft^3 (37.3 MJ/m^3), and "high-Btu" gas is similar. Medium Btu gas has a heating value that ranges from 250 to 400 Btu/ft^3; this is usually produced by gasification with steam and oxygen. Low Btu gas has a heating value of 100 to 200 Btu/ft^3 and is usually produced by gasifying coal with steam and oxygen in air; the nitrogen remaining from the air lowers the heating value of the product gas since nitrogen is not combustible.

Coal is usually brought to be gasified in a plant that is built above ground, but methods are also being developed to gasify the coal in situ, or underground. In-situ gasification has the potential to recover more coal reserves with less aboveground environmental impact. However, control of the gasification is less certain, and the gas generated may be far from potential users.

Coal gas can be used, after appropriate cleaning and processing, as either a fuel gas or a synthesis gas. Low Btu gas would be used near its place of manufacture as a fuel gas for direct combustion in power production or in process heating applications. The energy content or heating value of low Btu gas does not warrant transport for great distances as it is uneconomical. Intermediate Btu gas is more



No, Smedlock, you don't get gas from coal by swallowing it.



Gasification technology is moving in three main directions: fixed bed, and fluidized bed, entrained flow.

suitable as a synthesis gas since it contains primarily a mixture of carbon monoxide (CO) and hydrogen (H_2). The ratio of hydrogen to carbon monoxide in the gas can be adjusted by reacting part of the CO with steam (H_2O) to produce more hydrogen. The resulting gas with the proper CO/H_2 ratio can be used to prepare methane (substitute natural gas), methanol, or other substances. If required, the synthesis gas can also be converted to essentially all hydrogen, which can be used to produce ammonia or to assist in liquefying coal. Gasification of the solid residues from coal liquefaction is proposed as the hydrogen source for some liquefaction processes.

Gas Preparation

Coal for surface gasification must be mined, transported to the site, and reduced to an appropriate size. The size of the coal that is fed to the gasifier is determined by the method to be used; different kinds of gasifiers are used in response to specific needs, such as the kinds of coal available or a tar-/oil-free requirement of the product. Gasifiers can be, for example, fixed bed, fluidized bed, or entrained flow. Gasifiers of the fixed-bed type require larger coal particles (½–1½ inches or 13–39 mm). Fluidized-bed gasifiers require coal particles about ⅛ inch (3 mm) in size since the gasification occurs in a fluid bed where the solid particles are supported by the upflowing gas. Entrained-flow gasifiers require the smallest particles since the coal must be carried along with the gases. The gasification process basically involves the conversion of carbon in the coal to carbon monoxide and carbon dioxide using either pure oxygen (for medium Btu gas) or oxygen in the air (for low Btu gas). Steam is also used in the gasification process; hydrogen and carbon monoxide are formed from the carbon–steam reaction. The product-gas composition depends on the pressure, temperature, type, and size of coal, all of which are influenced by the type of gasifier used. The ash is removed in a form that depends on the combustion zone temperature in the gasifier. At high temperatures the ash melts and a slag is formed; at lower temperatures the ash is recovered in the dry form or as part of a water slurry.

Sulfur in the coal is converted mainly to hydrogen sulfide (H_2S) at the conditions determined by the type of gasifier. Gas purification processes serve to remove the hydrogen sulfide and particles that are carried over from the gasifier. Such processing steps could include scrubbing to remove particulates, gas purification to minimize H_2S and CO_2, and shift conversion (of CO to H_2) to obtain the desired ratio of hydrogen to carbon monoxide.

The types of systems selected for gasification and gas purification depend on the use of the gas and the type of coal feed available. A higher temperature gasifier, such as an entrained-flow unit, might be used to process a less-reactive coal. A synthesis gas product will require an oxygen feed and greater gas purification. Desired system pressures are influenced by the end use of the product gas; a high

ORNL Surveys

Harold Hartman, Joe Belk, and Dan Reagan of UCC-ND (ORNL) Engineering have conducted a survey of low and medium Btu coal gasification for the Department of Energy and have published their findings in a two-volume report, "Low Btu Coal Gasification Processes." In their survey, they have reviewed 102 process descriptions, briefly described 47 processes and provided a more detailed description of 21 processes. They have concluded that many processes have been proposed but only a few are likely to be used for commercial coal gasification.

Gas purification processes have been reviewed, and two reports have been published by the ORNL Chemical Technology Division for the Department of Energy. Michael Edwards (now at Mobil R&D Corp.) has described seven methods for removing hydrogen sulfide from low Btu gas in "H_2S Removal Processes for Low Btu Coal Gas." He selected each of the seven processes to represent a different category of gas treating. Jim Meyer (now at Atlantic Richfield Co.) and Edwards have reviewed processes for removing particulate matter, sulfur, nitrogen, and alkali-metal compounds from the gas in their paper, "A Survey of Processes for High Temperature, High Pressure Gas Purification." Their analysis indicates that high temperature processes will not be available for some time to purify raw product gas to the conditions required for use in gas turbines.

Reports have been issued by Chemical Technology and UCC-ND Engineering personnel for the Department of Energy under the heading "Survey of Industrial Coal Conversion Equipment Capabilities." These reports discuss valves; high-temperature, high-pressure gas purification; heat recovery and utilization; rotating components; letdown valves; mechanical piping connectors and expansion joints; equipment operating experience, prices, and development programs; and the reports are condensed in an executive summary. Reid Williams of ORNL Engineering has been coordinating this project; Chemical Technology participants were Edwards, Wally Gambill, and Jim Meyer. Besides Williams, UCC-ND Engineering contributors were Tom Andress, Bill Boudreau, Bill Bush, Dale Hatcher, Joel Horton, Bill Reed, Moshe Siman-Tov, Ed Slade, and Berdell Tolliver. They concluded that equipment should be available for all clean-stream applications, but that components for handling streams containing solid particles must be selected carefully and may need significant upgrading.

pressure use would suggest considering a pressurized gasifier.

Status

Coal gasification is in commercial practice in Europe, Asia, and Africa to produce synthesis gases, which in turn are used to prepare ammonia, methanol, and liquid fuels. Commercial units offered include the Lurgi fixed-bed, the Winkler fluidized-bed, and the Koppers Totzek entrained-flow gasifiers.

Large-scale units have been proposed in the United States but have not yet advanced to the construction phase. The Lurgi dry-ash process was selected for several projects including the Great Plains Gasification Associates Project, in Mercer County, North Dakota; the WESCO project near Farmington, New Mexico; and the El Paso Natural Gas company project in the Four Corners Area of New Mexico. A 250-billion Btu/day commercial high Btu gas plant is likely to cost 1.5 to 2 billion dollars, require four years to construct, use about 20,000 tons/day of coal, and supply about 0.5 percent of the United States' natural gas requirements.

Demonstration plant designs are being prepared, and one or more plants may be built in the next several years. Coal usage in the proposed demonstration plants could range from 2000 to 4000 tons/day. High Btu gas demonstration plants that are being considered by the Department of Energy include the British Gas/Lurgi slagging gasifier in the CONOCO project for Noble County, Ohio, and the COGAS fluidized-bed process for the Illinois Coal Gasification Group project in Perry County, Illinois. Low/medium Btu gas demonstration plants being considered are the U-GAS Institute for Gas Technology fluidized-bed process in a City of Memphis fuel-gas project; the Texaco entrained-flow process for a W. R. Grace synthesis gas-for-ammonia project in Baskett, Kentucky, and a two-stage, fixed-bed gasifier in an Erie Mining Company fuel-gas project in Hoyt Lakes, Minnesota. The Tennessee Valley Authority will use the Texaco coal gasification process to produce synthesis gas for an ammonia plant; at present,

ORNL Studies

A report, "Mathematical Model of the HYGAS Pilot Plant Reactor," has been prepared. It shows that results from a mathematical model of the HYGAS coal gasifier compare reasonably well with pilot-plant data. Participants in this work included Jim Meyer, Jim Cox (Co-op employee), George Frazier (consultant), Royes Salmon of Chemical Technology, and Jan Wells and Joe Belk of ORNL Engineering.

A report titled "Evaluation of Eight Environmental Control Systems for Low Btu Coal Gasification Plants" has been prepared by Suman Singh, John Fisher, and George Peterson of the Chemical Technology Division. In it, economic evaluations are made on gasification and raw-gas cleanup, acid-gas treatment and sulfur recovery, and wastewater treatment. The authors conclude that the cost of environmental controls can be a significant part of the cost of clean fuel gas.

Several studies have been completed by Bill Ulrich, Michael Edwards, and Salmon of Chemical Technology regarding potential applications of underground coal gasification. Low Btu gas for electricity generation, substitute natural gas, and synthesis gas are discussed in "Process Designs and Economic Evaluations for the Linked Vertical Well In-Situ Coal Gasification Process." Gasoline is featured in their report, "Evaluation of an In-Situ Coal Gasification Facility for Producing M-Gasoline via Methanol." Their results show that coal gas produced underground and used for several applications is cost-competitive with coal gas produced above-ground.

natural gas is used in the Muscle Shoals, Alabama plant. Texaco and Southern California Edison recently agreed to build a test facility to demonstrate the commercial viability of coal gasification for electric power generation near Barstow, California.

The pilot plants and process development units that have been operated involve advanced gasification concepts which usually offer some improvements over existing commercial units. All types of gasifiers have been or are being tested in process-development units or pilot plants and include fixed-bed, fluidized-bed, entrained-flow and molten-bath processes. The Department of Energy is sponsoring a Gasifiers-in-Industry Program in which currently available small gasifiers will be used to produce low Btu fuel gas. The program includes a Foster Wheeler/Stoic Gasifier for a University of Minnesota project in Duluth, Minnesota, and two Wellman-Galusha gasifiers for a Pike County, Kentucky, project.

Problem Areas

Coal-gasifier technology is proven; one of the barriers to it, however, is the cost. High Btu gas from coal is estimated to cost up to several times the price of natural gas. The cost factor is even larger if the natural gas price is regulated at a low level. Gas from coal, especially low and medium Btu gas, could still be used in situations where alternative fuels are not available. There is some risk of technical problems occurring in the more advanced gasifier technology. However, the possibility of improvements over existing commercial technology is leading some planners to prefer the advanced technology and some developers to test the advanced systems. Environmental concerns are with the disposal of solids from coal cleaning, ash from gasification, and liquid effluents and gaseous emissions. Another barrier is an institutional one; agreements have not been reached between the agencies involved in the planning, financing, and regulating of coal-gasification plants, especially regarding costs and risks. These problem areas and concerns must be carefully considered in planning a coal-gasification plant.

ORNL Work

Coal-gasification work at ORNL includes experiments, surveys, studies, and reviews. Blocks of coal are being heated in order to better understand in-situ gasification. Surveys completed include one for coal-gasification processes and gasifiers, one on gas-cleanup processes, and related surveys of coal-conversion equipment. Studies that have been done include preparing a computer model of a gasification process, evaluating environmental control gas-cleanup systems, and estimating the cost of several products prepared from gas produced at in-situ coal-gasification facilities. Specific in-depth reviews have been made for coal-gasification processes and systems.

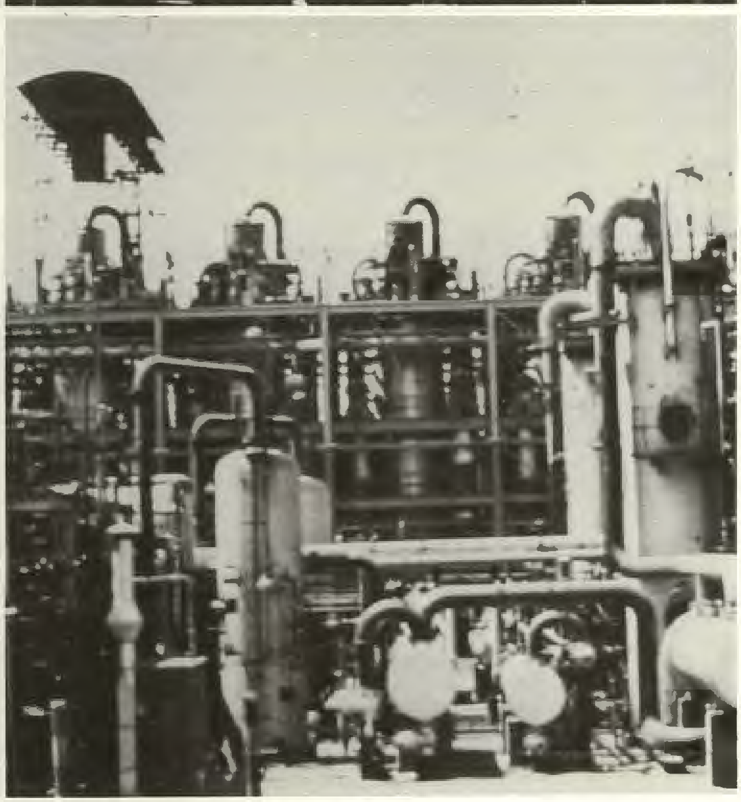
Prospects

The future of coal gasification depends on the need for coal gas as a substitute for other materials and the ability to solve the problems associated with the process. Limitations such as higher costs and institutional, technical, and environmental concerns must be overcome. Coal gasification will continue to be important in those areas outside the United States where oil or natural gas are not as available as coal. Coal gasification is likely to become important in the United States where supplies of alternative energy or such synthesis materials as oil or natural gas are prohibitive in cost or cannot be obtained at all.

Harold Hartman

SASOL, the coal gasification plant at Johannesburg, South Africa. On the left is the gasifier house.

The coal recovery and storage area at SASOL.



Synthesis unit developed by the German firm, ARGE, for the production of paraffin from coal-derived synthesis gas.

Materials Research for Advanced Fossil Fuel Systems

By R. R. JUDKINS and R. A. BRADLEY, Fuel Cycles Department of Metals and Ceramics Division

Many new processes now in development for using fossil fuels more effectively will call for materials that can withstand some unusually punishing conditions. Improvements in these construction materials or their appropriate selection can result in favorable impacts on fossil energy system economics. To assure the availability and reliability of these materials, several materials-research programs are in progress, the most pioneering of which encompass the development of metals and ceramics equal to the demands of advanced fossil fuel utilization systems in combustion and in coal liquefaction and gasification. Besides DOE, the Electric Power Research Institute and the Gas Research Institute are joining private industry in sponsoring the work conducted at universities, industrial research centers, national laboratories, and other government research laboratories.

The Assistant Secretary for Fossil Energy Programs in DOE has assigned ORNL the lead management role in a national program to develop materials technology for use in constructing fossil-fuel utilization and processing systems. Called the Advanced Research and Technology Development (AR&TD) Fossil Energy Materials Program, it addresses materials requirements for all fossil energy systems: extraction, coal conversion, oil-shale retorting, heat engines and heat recovery, combustion systems, fuel cells, and magnetohydrodynamics. ORNL's role in the AR&TD Fossil Energy Materials Program includes management of the national program, in-house R&D, and materials design support to DOE and TVA projects. In its management role, ORNL aims to ensure that the materials development program fulfills both the short- and long-term needs of DOE's Fossil Energy Programs.

Ron Bradley, who heads this national program management effort, has assembled a team of task leaders at ORNL and other national laboratories to follow the development activities both at ORNL and at other facilities participating in the national program. At ORNL, fossil energy materials research activities are centered in the Metals and Ceramics (M&C) Division. They include basic research, selection and testing, research on corrosion in liquefaction and combustion systems, pressure-vessel research, welding, development of ceramic materials for heat exchangers, and evaluation of material performance in various systems.

Fluidized-Bed Combustion

Atmospheric fluidized-bed combustion (AFBC) systems present a variety of problems with respect to selection of structural materials because of the hostile environment afforded by the combustion mixtures. In AFBC devices, sulfur released by the burning coal is reacted with limestone in the fluidized bed to produce a harmless solid waste, thus minimizing sulfur dioxide emissions. All components contacted by the fluidized bed must satisfy operating requirements that are unique relative to past operating experience for coal combustion systems. The compatibility of a fluidized bed of hot and potentially corrosive particulate material and steam generator surfaces must be better defined to establish the operational limits of the fluidized bed.

In the pressurized fluidized-bed combustion (PFBC) application, a gas turbine recovers some of the energy in the PFBC gas effluent. Here the principal concerns about materials are turbine erosion and corrosion and deposition on blades, which cause loss of aerodynamic efficiency. Cyclone collectors have been the most effective devices for gas cleanup to date, and as many as three cyclone stages may be required.

Gordon Godfrey, of Jack DeVan's materials compatibility group, leads investigation in the area of materials for fluidized-bed combustion. In order to fully assess the effects of temperature, erosion, and bed chemistry on heat-exchanger tubes, several experimental programs are planned. A Boiler Materials Test Apparatus will be constructed in the facilities of the Engineering Technology Division. The M&C

Gene Goodwin (left) and Ron Bradley examine a specimen in which expensive Type 320 stainless steel cladding is welded to cheaper 2.25 Cr-1 Mo ferritic steel. Use of the submerged arc process to weld these two alloys has been demonstrated at ORNL. Successful welding permits the use of less expensive steel in massive coal conversion vessels.

Division will conduct a materials test program to determine the limits of operating conditions for an AFBC imposed by the corrosion behavior of heat exchangers and support materials.

A materials support program for TVA's pilot and demonstration AFBC plants is also under way. This program, led by Roy Cooper, includes the review of materials of construction for the plants; metallographic studies of corrosion test samples from an FBC at Leatherhead; England, on a program sponsored by the Electric Power Research Institute, testing of alloys used for in-bed materials; and evaluation of coatings for AFBC systems.

Coal Liquefaction

To produce liquid fuels from coal, liquefaction processes under development mix coal with process solvent and hydrogen at pressures of 7–21 MPa and at temperatures on the order of 425–455°C. The various liquid process streams may cause corrosion and erosion of piping, valves, and vessels. Our knowledge of corrosion problems is based primarily on observations and studies at solvent refined coal (SRC) pilot plants. Liquefaction processes are based in large part on established oil refining techniques. Although there are added complexities in liquefaction plants due to the presence of particulates not found in oil refineries, corrosion problems downstream from the reactor vessel were expected to be somewhat similar to those of petrochemical plants. However, solids-free liquids have caused higher than expected corrosion rates in the fractionation areas of the Fort Lewis, Washington, and Wilsonville, Alabama, SRC plants; at Fort Lewis the wash-solvent column and its associated reboiler, overhead cooler, and internals have had to be replaced several times, and fractionating column internals at Wilsonville have required replacement.

The AR&TD Fossil Energy Materials Program has several projects directed toward solving materials-related problems of the coal-liquefaction plants. The task leader for these projects is Bob Swindeman of Chuck Brinkman's mechanical properties group.

A failure prevention and analysis program has been established at ORNL to investigate the effects of the various process streams on erosion and corrosion of components. Work is under way both to identify and isolate the corroding species in the process streams and to assess potential containment materials by exposing samples in the SRC plants at Wilsonville and Fort Lewis, as well as at the Exxon Coal Liquefaction Pilot Plant at Baytown, Texas, and the H-Coal Pilot Plant at Catlettsburg, Kentucky.

Battelle Columbus Laboratories is conducting erosion evaluations under conditions simulating those of high-pressure letdown valves in typical liquefaction service. Materials that exhibit the best performance in laboratory tests are being evaluated in liquefaction pilot plants. The Bureau of Mines at Albany, Oregon, is working on valve materials to improve resistance to abrasion and erosion. Several promising material combinations have been identified, and components fabricated from these materials are being evaluated in coal conversion plants. Lawrence Berkeley Laboratory is testing piping materials that are candidates for slurry containment.

At ORNL, researchers are assessing the susceptibility to general corrosion and stress-corrosion cracking of alloys that are potential structural and piping materials for coal-liquefaction plants. Primary responsibility for this effort rests with Jim Keiser, Vivian Baylor, Gene Lawrence, Elmer Lee, and Bob Crouse. In Library, Pennsylvania, the Conoco Coal Development Company is building a process development unit for a coal liquefaction process that uses zinc chloride as a catalyst. In order for this process to be economically practical, the zinc chloride must be regenerated and recycled. Nickel-base alloys were chosen as the primary materials of construction for the regeneration facility. However, subsequent experience has shown that these materials have an unacceptably high rate of corrosion under the conditions necessary for regeneration of the zinc chloride. Experiments to evaluate corrosion resistance and mechanisms of corrosion in the zinc chloride regeneration system are being designed at ORNL by Baylor, Keiser, and Lee to determine corrosion as a function of time, temperature, and composition of the environment and the alloy.

The Metal Properties Council is administering a program conducted by Southwest Research Institute on the corrosion of containment materials in process-stream fluids provided by liquefaction pilot plants.

Coal Gasification

Gasification processes require that extremely corrosive gas mixtures be contained at high pressures and temperatures. Gasification environments vary from one process to another but all contain CO, CO_2, H_2, and H_2O plus char materials of varying compositions depending on process and feedstocks. Although refractory bricks or cements will be used extensively as liners in gasifiers and ancillary components, many of the critical gas and solids handling, transport, and cleaning components must, because of their function, be constructed from heat-resistant metallic alloys. Typical components include gasifier internals such as valves, pipes, and thermowells; solids and gas transfer lines; cyclones; heat exchangers; and power-recovery turbines.

Vinod Sikka examines a large valve body casting of the modified 9 Cr–1 Mo alloy. This high-chromium ferritic steel recently developed at ORNL is like stainless steel in its ability to maintain strength at elevated temperatures. The alloy looks promising for applications in breeder reactors and coal conversion plants.

Potential materials problems associated with low-temperature (<300°C) regions of gasifiers include erosion in the coal preparation system, and in the transport lines, pumps, and valves used to introduce coal to the gasifier. Materials problems in these areas are similar to those in the comparable areas of liquefaction plants discussed earlier. Potential materials problems in the medium-to-high-temperature regions of gasifiers include erosion of transport lines, valving, and cyclones, and corrosion and erosion–corrosion in the gas cleanup and separation areas and in the handling facilities for chars, slags, and other solids.

Stainless steels and high-chromium, heat-resistant alloys will be used as critical components in process equipment for the gasification of coal. These materials will operate over a broad temperature range, 320– 980°C, in potentially corrosive and erosive environments. Particles of ash and coal char suspended in the gas, traveling at velocities of up to 46 m/s, will impinge on heated metal surfaces. Results from laboratory and pilot-plant tests indicate that several high-chromium-content stainless steels and heat-resisting alloys may be appropriate for these applications, but additional testing is required to enable prediction of materials performance in these environments.

Argonne National Laboratory is working on a multiple-phase project that is part of the AR&TD Fossil Energy Materials Program. This project includes a task on the corrosion behavior of materials for gasification systems. The objectives of the task are to evaluate the high-temperature corrosion behavior of iron- and nickel-base alloys in gas environments, evaluate deposit-induced hot corrosion behavior of heat exchangers and gas turbine materials with and without coatings, develop mechanical property data on several Fe–Cr–Ni alloys after exposure to simulated gasification-system environments, and to develop an approach for evaluating corrosion problems.

The Bureau of Mines at Tuscaloosa, Alabama, is performing studies to determine

Vic Tennery (at top) and George Wei discuss the operation of the Ceramic Recuperator Analysis Facility. Recuperators are heat exchangers designed to recover heat from hot flue gases for preheating combustion air or gases low in energy content. ORNL is studying the potential of using recuperators made of ceramic materials for cutting consumption of fossil fuels by industry.

the effect of catalytic coal-gasification environments on state-of-the-art candidate metals and refractories and to identify the attack mechanisms of coal-gasification environments on those materials.

Lockheed Missile and Space Company, Inc., has a program to develop coating systems suitable for protecting large internal components (cyclones, diplegs, thermowells, brackets, and supports) of coal gasifiers from corrosion. The program includes the selection of a coating process suitable for coating gasifier internal components, selection of coating compositions, development of selected coating compositions and processes, and testing to evaluate the coating compositions and processes.

The Idaho National Engineering Laboratory has a program to determine creep and fatigue strengths and ductilities of coal-gasifier materials when they are subjected to biaxial stresses in the presence of a simulated coal-gasifier environment.

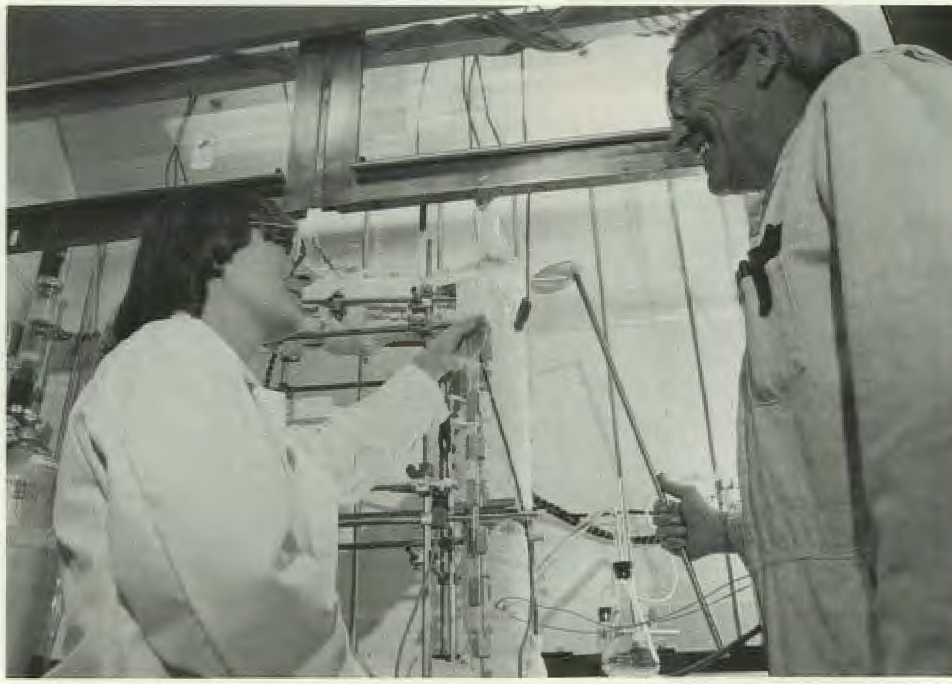
The Metal Properties Council, Inc., is engaged in a multiphase program directed towards materials for the gasification of coal. That portion of the MPC effort being sponsored by DOE includes the evaluation of the corrosion of metals and refractories in coal-gasification pilot plants and screening of alloys for resistance to aqueous corrosion environments expected in coal gasification equipment.

Coal-Conversion Pressure Vessels

Commercial coal-conversion plants will require large, thick-walled pressure vessels operating in environments rich in hydrogen, sulfur, and carbon. The chromium-molybdenum steel grades are the currently favored materials of construction for the pressure vessels. Depending upon the operating conditions, these steels may undergo changes in their mechanical properties during service. These changes can be caused by the combined effects of pressure, temperature, and environment, and can result in the degrading of the reliability and safety of these units. One area of concern is the interaction of hydrogen and carbon (termed hydrogen attack) in which methane bubbles are formed. These bubbles can decrease the steels' ductilities at operating temperatures. Further, hydrogen embrittlement can lead to a loss of fracture toughness.

Domenic Canonico and his pressure vessel technology group at ORNL are working on problems associated with pressure-vessel and piping materials for coal-conversion systems. Walt Stelzman, Robin Williams, and Ron Swain are conducting materials studies in an autoclave that can duplicate the pressures, temperatures, and hydrogen levels anticipated in conversion plants. The autoclave is also being used to determine the effect of these environments on the fracture toughness of the candidate materials. Williams is using thermodynamics calculations to predict the H_2-C interation. The accuracy of his results is being assessed by exposing candidate steels in the autoclave to H_2 environments representative of those in coal conversion systems.

The University of California at Berkeley is conducting a program to develop new alloy steels or improve current steels for coal-conversion pressure vessels. The goal is to produce an alloy of sufficient strength that the required section thickness can be reduced and of sufficient



Elmer Lee, technician, and Vivian Baylor, metallurgical engineer, prepare to replace one specimen tree with another in a zinc chloride loop. Various alloy samples are hung on the specimen tree, which is inserted in the loop to determine the alloys' resistance to corrosion caused by exposure to chemicals present during regeneration of the zinc chloride catalyst. The $ZnCl_2$-catalyzed hydrocracking process is an advanced coal liquefaction process being tested because of its potential for producing gasoline as an end product, unlike other processes that produce feedstocks which require further refining.

weldability that postweld heat treatment will not be required.

Westinghouse Electric Corporation Research and Development Center is measuring the relationships between concentrations of six elements (Mo, Cr, Mn, Si, C, P) in 2¼ Cr-1 Mo steels and susceptibility to hydrogen and temper embrittlement. The objective is an improved formulation of the 2¼ Cr-1 Mo steels. Cornell University is also pursuing a program on hydrogen attack in 2¼ Cr-1 Mo steels.

Lehigh University is conducting a program to relate the thermodynamics and kinetics of surface chemical reactions to crack-growth phenomena.

At Ames Laboratory, work is under way to measure the effects on 2¼ Cr-1 Mo steels of simultaneous exposure to coal slurry, hydrogen gas, and mechanical stress.

Development of New Steel Alloys

The use of ferritic steels in the fossil power industry is often limited by their relatively low-strength properties at temperatures greater than 500°C; therefore, austenitic steels tend to be used in higher temperature applications. Because of their good thermophysical properties, however, the high-chromium ferritic steels can be considered for such applications as advanced superheaters and steam supply systems, fluidized-bed heat-exchanger tubing, and liquefaction-plant pressure boundaries. Substitution of these materials, moreover, can eliminate the need for austenitic-to-ferritic steel weld transition joints.

ORNL and Combustion Engineering, Inc., metallurgists have developed a modified chromium-molybdenum (9 Cr-1 Mo) steel with elevated temperature strength properties similar to those of austenitic stainless steels. Laboratory experiments on this alloy suggest that it is an attractive candidate, thus fostering plans to gain industrial experience with it. Two 15-ton heats (ingots) have been made and are being processed into tubing for installation in utility-boiler superheaters. The Laboratory will make the materials available for evaluation to participants in various areas of fossil energy materials research. Plans are being made to evaluate this alloy in the heat exchanger of a Tennessee Valley Authority commercial power plant. This project, when successfully completed, will provide improved materials for conventional and fluidized-bed boilers and advanced steam systems, liquid-metal topping cycles, liquefaction plants, and gasifiers. Vinod Sikka heads this task at ORNL.

Welding Development

Formidable fabrication problems must be addressed for current designs of coal-conversion systems. The pressure vessels will require, in selected areas, stainless steel cladding to protect them against acid condensates that may form on cold spots in the systems. This cladding operation will take place at the component fabricator's shop; then the components, because of the size of the vessels, must be taken to the field for final fabrication. Dave Edmonds of Gene Goodwin's welding and brazing group has developed techniques for producing sound-clad deposits using high-heat input processes. Work is continuing on the effects of welding on clad integrity. Even higher heat input cladding techniques are desirable

Maurice Allen inspects the corroded walls and tray supports of the wash solvent column at the Fort Lewis, Washington SRC-II plant.

Jim Newsome, technician, makes final preparations for the operation of an autoclave being used to simulate coal liquefaction environments. U-bend specimens of dozens of different alloys are placed in coal liquids (similar to those found in Solvent Refined Coal pilot plants) at 450°C and 2000 psi. The objective of these tests is to screen materials for resistance to stress corrosion cracking. The tests are carried out under the direction of Jim Keiser.

for the fabrication of large vessels. Clads made by these high-heat processes will be provided by commercial vessel manufacturers and will be evaluated at ORNL, to assure the production of sound, fissure-free deposits.

For many systems, pumps and valves represent a likely problem area. Erosion–corrosion of these components is often severe, and development of fabrication and repair techniques to improve the situation is desirable.

Dissimilar-metal joints are required in many systems. For most dissimilar-metal combinations, optimized filler metals and welding procedures are not available, nor are design data for the transition weldments.

Several projects are in progress as part of the AR&TD Fossil Energy Materials Program. The Colorado School of Mines is investigating the poor toughness of as-welded electroslag weldments in 2¼ Cr–1 Mo steels, and is seeking ways of ameliorating the problem. The Babcock & Wilcox Company is conducting a program to develop an electron-beam process for field-welding steel sections up to 200-mm thick. The Westinghouse Electric Corporation is engaged in a program to develop a narrow-groove, hot-wire, gas-tungsten arc welding process for steels of the same thickness.

Joe Long of Canonico's group leads the welding development task, as well as the coal-conversion pressure-vessel task.

Refractories and Structural Ceramics

Refractories are used in fossil energy systems from about 1100°C to about 1260°C. Typical low-temperature applications include the refractory liners for dry-ash gasifiers, pressurized fluidized-bed combustors, process heaters, cyclones, and associated piping. Typical high-temperature applications include refractories for slagging gasifiers, magnetohydrodynamics (MHD) preheaters, and combustors.

Work related to corrosion, erosion, and degradation of refractories in dry-ash gasifiers has been conducted at Babcock and Wilcox Lynchburg Research Center, Iowa State University, Pennsylvania State University, Massachusetts Institute of Technology, Battelle Memorial Institute, National Bureau of Standards, Bureau of Mines–Tuscaloosa, University of Missouri-Rolla, and Virginia Polytechnic Institute. This work concluded that 50–60% alumina concretes are the preferred refractories for use in dry-ash coal gasifiers. At the Illinois Institute of Technology Research Institute, a program for the design, engineering, and evaluation of refractory liners for slagging gasifiers is in progress, with supporting projects at Argonne National Laboratory and Pennsylvania State University.

Current interest in the use of structural ceramics includes their use as combustors, rotors, and stators in high-temperature uncooled gas turbines and as the principal structural components of high-temperature, efficient, heat-exchanger devices.

The NBS is working on major materials problems that arise in coal conversion systems and affect such components as turbine blades, heat exchangers, and preheaters for MHD facilities, refractory linings in gasifiers, and let-down valves used in synthetic liquid-fuel plants. The purpose of the work is to improve our understanding of the mechanical behavior of structural ceramics, and to provide essential data on refractory materials used in fossil energy systems.

At ORNL, Vic Tennery's structural ceramics group is involved in a task to define the best materials and fuel combination conditions to provide adequate operation of ceramic heat exchangers. The motivation for development of ceramics for use in high-temperature heat exchangers for fossil-fuel-fired environments is in two applications—high-temperature gas turbines and waste heat recovery.

Existing subcontractor facilities are being used to expose ceramic materials to combustion products from concentrated coal-oil mixtures and direct coal firing. During the initial phase of this study, various types of silicon carbide ceramics are being tested. Also, materials joined by recently developed joining technology are being evaluated. Ceramographic evaluation techniques that are being used include optical microscopy, scanning electron microscopy, electron microprobe, and x-ray diffraction, as well as conventional chemical analysis. In addition, a Ceramic Recuperator Analysis Facility was constructed at ORNL and is being used to test refractory structural ceramic materials.

The success of this program could lead to the use of high-temperature ceramic heat exchangers for the recovery of up to 80% of the available heat that is currently wasted. This extracted waste heat may be used for many applications, including preheating combustion air, cogeneration, and preheating raw materials.

This national Fossil Energy Materials Program, which includes producing, testing, and fabricating materials for advanced fossil-fuel systems, will require significant efforts from the ORNL staff and the fossil energy materials community. Without these materials, though, our supply of energy in the future will be severely limited. Clearly, materials and energy availability are inextricably related, and the success of a coal-based energy program is dependent on the availability of materials that will satisfy the safety and reliability needs of modern commercial coal-conversion and utilization facilities.

Rod Judkins

Glossary

Autoclave
—a heated pressure vessel for testing the effects of high temperatures and pressures on materials.

Cladding
—an alloy material that is satisfactory for use in a corrosive environment and that is bonded to a less-expensive structural base metal.

Corrosion
—deterioration of a metal by chemical or electro-chemical reaction with its environment.

Creep
—extent to which a material is elongated at high temperatures when a load or some other pressure is exerted.

Cyclone
—a funnel-shaped device for removing particles from an air stream by centrifugal force.

Ductility
—the ability of a material to deform plastically without fracturing.

Erosion
—destruction of metals or other materials by the abrasive action of moving fluids, usually accelerated by the presence of solid particles in suspension.

Fatigue
—the phenomenon leading to fracture under repeated or fluctuating stresses having a maximum value less than the tensile strength of the material.

Fracture toughness
—resistance to failure by propagation of a crack under constant load.

Magnetohydrodynamics
—process in which hot gases from burning coal are channeled through a magnetic field. Because the gases are seeded with easily ionized elements to make them electrically conducting, their swift passage through a magnetic field produces a voltage that can drive an external circuit.

Steel, austenitic
—a stainless steel that is highly corrosion-resistant, containing 16–26% chromium, 6–22% nickel, and about 0.08% carbon.

Steel, ferritic
—a stainless steel that is corrosion-resistant, containing up to 30% chromium with low (about 0.01%) carbon content.

Thermowell
—an appurtenance that extends into a high temperature region of a system and is used to house a temperature-measuring device.

BOOKS

"Broca's Brain: Reflections on the Romance of Science," *by Carl Sagan. Random House, New York, 1979. 347 pages, $12.95. Reviewed by Carolyn Krause, ORNL* Review *staff writer.*

Broca's Brain, one of the few science books to be on the bestsellers' list in recent years, offers a revealing glimpse of the thinking going on in Carl Sagan's brain. The book is a collection of essays—some poetic and some ponderous—dealing with such subjects as pseudoscience, science fiction, planetary exploration, the search for extraterrestrial life, theories of cosmology, history of astronomy, advances in transportation and computer technologies, near-death experiences, the lives and achievements of Albert Einstein and Robert Goddard, and Broca's brain. The last topic (subject of the book's first essay) concerns Sagan's thoughts as he holds the dead brain of Paul Broca, 19th century French surgeon, neurologist, and anthropologist who collected human brains (now at Paris's Museum of Man) and studied them. Broca discovered that each area of the brain controls a specific kind of thinking, setting the stage for findings about the different cognitive activities of the left and right brain. Broca also made a landmark contribution to understanding the origins of aphasia—an impairment of the ability to articulate ideas.

The ability to articulate ideas for a mass audience certainly comes easily for Carl Sagan, as *Broca's Brain* and his Pulitzer Prize-winning book, *The Dragons of Eden,* show. Like Lewis Thomas (author of *The Lives of a Cell* and *The Medusa and the Snail*), Sagan has elevated science writing to an art form. This is a remarkable accomplishment when you consider that Sagan is foremost a scientist—professor of astronomy and space sciences and director of the Laboratory for Planetary Studies at Cornell University and a leader in establishing the high surface temperatures of Venus and in understanding the seasonal changes on Mars.

It is clear that Sagan is dedicated to making science exciting and understandable for the layman, partly because he believes it is the scientist's obligation to explain research results and partly because he thinks there is a correlation between improved public understanding of science and financial support for technological projects. He does not hesitate to make a pitch for missions that he believes would have popular appeal as well as scientific value. For example, he proposes a rendezvous with Halley's comet in 1986 by solar sailing rather than conventional rocket propulsion or the newer technology of ion propulsion. This sail-bearing spacecraft, which could be launched by the U.S. manned space shuttle and would be visible to the naked eye as a bright light, would be propelled by radiation pressure exerted by the Sun. Sagan also favors a solar probe, roving vehicles to explore Mars, and a lander on Titan, Saturn's largest moon, the largest satellite in the solar system, and the celestial object with an atmosphere of a density most similar to Earth's. While Sagan deplores the current slowdown in the space program in what he considers the "golden age of planetary exploration," he fails to consider the possibility that the public may be becoming disenchanted with planetary probes that may seem like flying white elephants because they are sending back ambiguous results that raise more questions than give answers. Questions are the scientist's bread and butter, but if the American public is hungry for anything in the world of science and technology in an inflationary age, it is solutions, not problems and questions.

The book is sprinkled with

observations, the following of which were particularly interesting to me. According to Sagan:

• The Department of Energy "can be effective only if it can maintain a distance from vested commercial interests, if it is free to pursue new options even if such options imply loss of profits."

• Our civilization is threatened more by lack of adequate fertility control than by cancer, the elimination of which would extend the average life expectancy by only a few years.

• You too may have a crater named after you someday, as space probes discover a vast number of surface features on moons and planets. Now that most dead astronomers have had their names affixed to craters, planetary nomenclature committees are looking at other groups of people for names. Mercurian impact craters, for example, will be named after composers, poets, and authors.

• Meteorites are fragments of colliding asteroids, miniature planets (or "planetoids") that are remnants of a planet that exploded or a would-be planet that failed to form due to perturbations of Jupiter's gravitational field.

• The Sun, which had been getting steadily brighter, may be in an anomalously dim period, as suggested by the fact that scientists are detecting much fewer solar neutrinos than predicted by theory.

• The first lunar landing by Apollo astronauts outraged Orthodox Muslims because the Moon has a special and sacred significance in Islam. (This is perhaps another of the many reasons why Iranians are angry at Americans.)

• The near-death experience—leaving of the body and looking down upon it, the sudden presence of a bright light, the approach of a godlike figure—may be a sudden reliving of the birth experience. There may be connections between the perinatal experience and our ideas about God and cosmology.

• Preliminary evidence indicates that the universe may not expand forever but fall back on itself as a cosmic fireball and that the universe is violent as quasars explode and obliterate more than a million worlds at a time and possibly countless forms of life.

Sagan and his colleagues estimate that a third of all stars have planets and that there could be a million technical civilizations—defined as societies capable of radio astronomy. He believes that it is scientifically valid to search for extraterrestrial intelligent life through unmanned missions and radiotelescopes, even though there is no evidence for other inhabited worlds. On the other hand, he brands as borderline science other people's beliefs in ancient astronauts and unidentified flying objects, the evidence for which is questionable.

Although Sagan's book is rich with the discoveries of planetary exploration (but out-of-date in respect to recent findings on the volcanoes of Io, one of Jupiter's 14 moons), it says very little about other fascinating astronomical subjects, such as sunspots, solar neutrinos, quasars, pulsars, and black holes. Even so, I thoroughly recommend *Broca's Brain*. Read it for its poetic statements, such as Sagan's description of the Earth as seen from great distances as a "cloudy, blue, spinning ball set like a sapphire in the endless velvet of space." Read it for stimulating ideas, some of which may be as far out as extraterrestrial life itself. Read it for its eloquent summary of Einstein's life and contributions, written in honor of the German scientist's centennial. Read it for Sagan's reliance on recent planetary findings to skillfully demolish the controversial arguments of Immanuel Velikovsky, who proposed in *Worlds in Collision* (1950) that a comet ejected by Jupiter made a grazing collision with Earth in 1500 B.C., knocked Mars into a new orbit, and ended up revolving around the Sun as the planet Venus; these catastrophic events were used by Velikovsky to explain such Biblical phenomena as the parting of the Red Sea and manna from heaven. Finally, read *Broca's Brain* to find out what a national resource is the mind of Carl Sagan.

Environmental Control Technology

By JERRY KLEIN and CHUCK SCOTT, Advanced Technology Section, Chemical Technology Division

Coincident with our present commitment to develop technologies for utilizing this nation's abundant supply of coal is our need for concurrent development of the necessary environmental control technology. This integration of the process and the controls is required to ensure the environmental acceptability of increased coal use.

Ed Arcuri, research microbiologist, makes adjustments while Sherry Gibson, technician, takes samples from the tapered fluidized-bed bioreactor used to study removal of phenols from wastewater discharged by coal conversion processes. Bacteria adhering to coal particles suspended by upwardly flowing water and air cleanse the wastewater by consuming and digesting toxic phenols. The bioreactor concept recently received an IR-100 award.

The need for controls has several reasons. The conversion of coal may involve incomplete combustion, which produces dangerous flue gases; there may be harmful materials present in the coal feedstock and these may be concentrated in the product, by-product, or waste streams; or the conversion reactions may produce toxic organics including carcinogenic and/or mutagenic compounds.

The waste materials that are of concern can come in solid, gaseous, or aqueous forms, and each form poses its unique potential problems, with, of course, its unique cleanup requirements. Solid wastes take the form of slags and ashes; sulfur and nitrous oxides, particulates, and volatile organic compounds are of concern for gaseous emissions. Wastewater occurs in processes that use water for cooling, for transportation, and occasionally for chemical interactions. However, the final nature of these materials is determined by both the designated product use and whatever cleanup technologies are employed. Often what appears to be a solution to a waste material problem may only be a transfer of the material to a different form. An example of this is flue-gas desulfurization, in which lime or limestone, in removing gaseous SO_2, produces a large quantity of a semi-solid sludge that is difficult to dispose of in an environmentally acceptable manner.

In the coal industry, there are many different kinds of environmental control technologies. Their nature depends on the problem areas to be addressed and in some cases on the history of the particular segments of the industry. For instance, in coal mining, what control technology there is is chiefly concentrated on worker protection and the small but growing area of the elimination of acid mine drainage. Similarly, for coal beneficiation and preparation there exists only a small effort concentrating on the disposal of wastewater and beneficiation sludges, and the removal of respirable particulates from the workplace environment.

However, it is in the area of coal utilization that the majority of control technologies have been applied to date and where future emphasis will be placed. For coal combustion systems, regulations have forced increased attention to flue-gas desulfurization systems. These regulations will ensure future dependence on various types of scrubbers for the removal of the harmful oxides. Past operating experience with wet lime and limestone scrubbers and the resulting sludge disposal problem is resulting in considerable interest in regenerative flue-gas desulfurization systems. An example of this is TVA's recent decision to build a 600 MW magnesium oxide regenerative system at its Johnsonville facility. The cost and complexity of such systems as this will undoubtedly lead scrubber developers to use an integrated approach for the removal of sulfur compounds, nitrogen oxides, and particulates instead of treating each contaminant independently.

For coal conversion (i.e., gasification and liquefaction) industries, however, environmental controls are at a minimum, due primarily to the small scale of the currently operating commercial processes. At present, there are but a few small gasifiers operating, with only enough installed controls to enable the gas to be consumed on site. Such controls are limited to particulate removal and water scrubbing with subsequent wastewater cleanup. Sulfur and nitrogen oxide levels are controlled by the operating parameters of the gas combustion equipment and the use of low sulfur coal.

The nature of the coal conversion processes is such that they generate airborne sulfur and nitrogen compounds and particulates. In addition, a variety of potentially toxic organic compounds may also be released. The use of aqueous scrubbing to clean up the gas streams and the condensate water that results from the partial oxidation of the hydrogen in the coal contribute to a wastewater medium for the potential transportation of these organic materials. In addition, the inorganic fraction that was present in the original coal feed will need to be disposed of in an environmentally acceptable fashion.

There are today real deficiencies in the application of environmental control technologies to the emerging coal conversion technologies. Due to the developing nature of the coal conversion industry, hard data on the characteristics of the output streams are not available. Unfortunately, this means that necessary information is lacking for the design of efficient control systems. In addition, the past history of the industry has been one of adding on the minimum amount of control technology necessary to meet permit requirements with little thought to integration of the process and the controls or to keeping records for future control development. The lack of consistent effluent guidelines, moreover, presents a moving target to developers of control technologies, who are normally familiar with fixed guidelines. It also tends to make the process developers uneasy about trying out new technology in case it may lead to tighter controls.

In order to alleviate some of the above difficulties, a number of government agencies, especially the Department of Energy and the Environmental Protection Agency, have begun to fund relevant R&D programs in this area. These programs can be grouped by the nature of the emphasis on the work in question.

Initial efforts in control technology need to be directed towards the characterization of effluent streams. Although these efforts are often not focused for the developers of control technologies, they do provide the basic data needed on the streams to be treated and on the effectiveness of currently applied technologies. Several national efforts are under way, including DOE and TVA work, to evaluate the health and environmental acceptability of a number of coal gasification and liquefaction processes. These efforts include numerous EPA subcontractors, national laboratories including ORNL, private firms, and local government agencies. A well thought out protocol for sampling, and the chemical and physical characterization of materials, including raw materials, finished products, and by-products (or effluents), provide the most comprehensive data for making an evaluation. In addition, several base-supported programs include the analysis of a wide variety of coal conversion products and waste products.

In the area of process stream modification studies, there is very little work at the present time. The Pittsburgh Energy Technology Center has investigated phenol concentrations in Synthane wastewater as a function of coal injection. Such related efforts as design of H-Coal facilities and SRC demonstration units to allow reuse of several wastewater streams can be included in this area, although more work needs to be done.

One area in which there appears to be no shortage of both willing and able firms is in the assessment of control technologies. Many such studies have been conducted across the country, including several at ORNL. Unfortunately, most of these assessments come to the conclusion that what is needed is

Jennifer Brand, of the effluent control technology department in Chemical Technology Division, monitors the stripping column in her laboratory with technician Jack Beams. She is assessing the efficiency of different methods of cleaning up coal conversion wastewaters.

more experimental data on the applicability of promising control technologies.

In the advanced technology section of its Chemical Technology Division, ORNL is heavily involved in the experimental assessment of several control technologies that look promising both for present applications and for future demonstrations. For the removal of carbon monoxide and unburned hydrocarbons from gasifier flue gases, researchers are testing a number of promising catalytic materials on actual coal pyrolysis gas. The division is also actively investigating technologies for the cleanup of the ever-present aqueous waste streams.

Considering the need for continued emphasis on the nation's use of its abundant coal resources, resulting in increasingly stringent effluent regulations with regard to the discharge of pollutants, and considering as well the escalating costs for control technology, the conclusion is inevitable that environmental control technology will be receiving a great deal of future attention. Past efforts to apply it to coal utilization have been limited to a "catch up" philosophy resulting in minimal use of such technology. Not only can increased funding be expected in support of the application and modification of existing and advanced control technologies, but other control options will gain future acceptance. In this light will be the integration of control technologies and process designs, along with the implementation of zero discharge and complete recycle concepts.

Cleaning Up Synfuel Wastewater

ORNL is proposing a waste-treatment scheme to remove the toxic organic substances in aqueous effluents from coal conversion facilities. The goal of this scheme, which includes several systems being developed and tested at ORNL, is to produce water of a purity acceptable under the stringent environmental standards anticipated for coal conversion facilities in the 1990s.

In this treatment scheme, wastewater from coal conversion processes would first be treated in an air- or steam-stripping column for the removal of two volatile gases, ammonia and hydrogen sulfide. The degassed water can then be mixed with an appropriate solvent for solvent extraction of the bulk of the toxic phenols in the effluent. The fluidized-bed, tapered bioreactor developed and tested at ORNL is used to remove residual phenols, down to a few parts per million or less. This device, which received an IR-100 award in 1979, consists of a tapered column in which upward-flowing water and air suspend coal particles to which phenol-consuming bacteria are attached. The fluidized-bed bioreactor treats a given volume of effluent five times as fast as packed-bed bioreactors and ten times as fast as activated-sludge ponds used for conventional sewage treatment.

After biological treatment, the effluent is ready for the final polishing steps. ORNL has been investigating the use of ozone (O_3) to break down potentially carcinogenic organics such as polycyclic aromatic hydrocarbons (PAH) into simpler compounds that can be easily adsorbed onto solids or easily digested by microorganisms. [Ozone, produced by exposing oxygen to ultraviolet (UV) light or to an electric discharge, is widely used in Europe for water treatment, whereas chlorine is the chief chemical treatment employed in the United States.] Early results indicate that mixing ozone with PAH-contaminated water breaks down the ring structure of the aromatics, converting them into straight-chain or branched-chain aliphatics. The disappearance of the aromatics during ozonation can be followed by a fluorometer, which measures the amount of fluorescence given off by PAHs when they are excited with UV light. Use of higher concentrations of expensive ozone would ultimately break down these organics into water and carbon dioxide, but it is not considered economically feasible to use ozonation alone for the polishing task.

Once the effluent emerges from the ozone-polishing reactor, it is further purified in a column of activated charcoal in which the simpler organic compounds are adsorbed onto the carbon particles. The various organic sludges from the process may be broken down by oxidizing the material at high temperatures and pressures. This wet oxidation process is now being investigated at ORNL—*CK*

These last concepts, although vaguely defined at the present time, will be mandated by future 1984 federal discharge regulations.

Considering ORNL's multidisciplinary approach to solving environmental concerns and the increasing attention that such concerns are receiving, the areas of environmental control technology can only be looked to as a major responsibility in the Laboratory's R&D future.

Jerry Klein

Chuck Scott

After It Has Been Burned

The Problems of Waste Disposal and Resource Recovery.

By BILL BOEGLY and JACK WATSON

Any industrial operation results in the production of solid waste which requires some form of disposal or utilization. The quantity of coal consumed in the United States makes it one of the major sources of solid waste in this country. As environmental concerns increase, waste treatment and disposal methods must be developed that will have minimal impact on the environment until techniques can be developed to recover and recycle those wastes economically. Coal contains about 5 to 20 wt % of noncombustible material which will remain as ash after the carbon is removed during combustion or conversion. Because this ash contains essentially all of the elements in the coal, it represents a potential source of metals for resource recovery and recycling. Recovery and recycling of these materials are limited today by available markets and transportation costs. As a result, most of the ash is being disposed of on land. Although the Resource Conservation and Recovery Act (RCRA) may provide the economic incentives for resource recovery, it appears that land disposal will remain the primary method of solid-waste handling for coal utilization technologies until markets are developed.

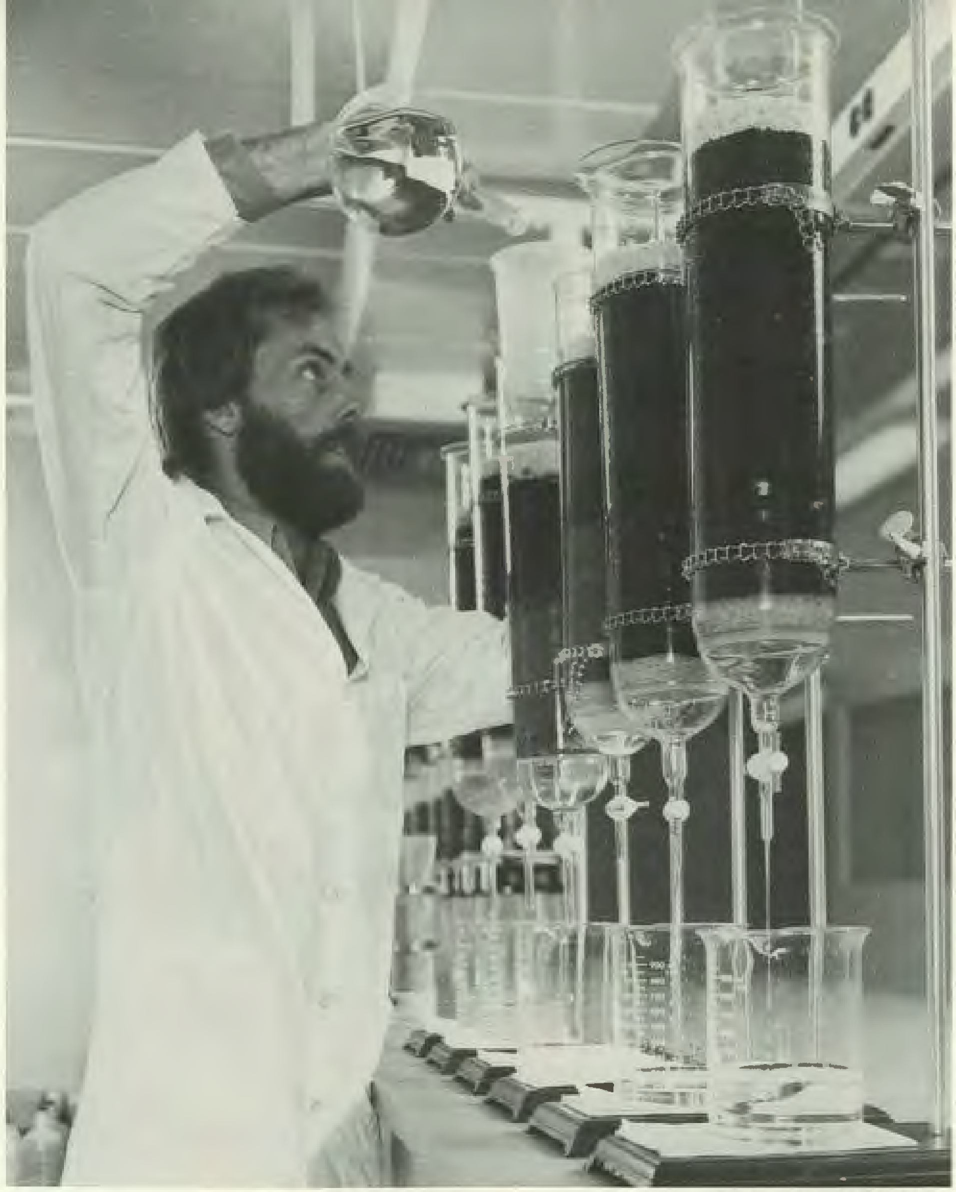
Ash Disposal

Fly and bottom ash from coal-fired power plants are currently being disposed of in ash ponds, or by some form of landfilling. Ash is allowed to settle out in ponds, and the water is either evaporated or released to the nearest watercourse. The ponds may be dredged at periodic intervals to provide additional storage area on site. However, the dredged material must still be deposited at other locations. Use of ponds may result in leaching of trace elements that are removed from the disposal area in the water overflow. Current National Pollutant Discharge Elimination System (NPDES) regulations for electric power plants do not address trace metals, although RCRA criteria on groundwater degradation do concern releases of trace metals to groundwater. The exact effect of RCRA on coal utilization facilities that use ponds for ash disposal has not yet been defined.

If ponds cannot be constructed feasibly at the power plant, some form of land disposal is used. This ranges from filling in ravines or depressions near the plant to disposal in trenches excavated for this purpose. RCRA land-disposal regulations will require that this type of operation be governed by sanitary landfill criteria. Furthermore, if utility wastes are classified as "hazardous" by RCRA testing procedures, leachate control using liners or collection systems, monitoring of wells, and detailed record keeping and reporting will be required. Rough estimates of RCRA landfill costs for such disposal indicate that it may run to \$80 to 100 a metric ton, which could cost about \$8,000 to \$10,000 per day for a power plant that uses about 1000 metric tons of coal per day. If the ash is deemed "nonhazardous," disposal costs might be in the range of \$500 to \$1000 per day. The economic impact on the electric power industries will depend on RCRA classification of the wastes, so the Electric Power Research Institute is spending considerable effort in evaluating the sampling, leaching, and analysis requirements of coal wastes to satisfy RCRA testing protocols.

When high-sulfur coal is burned, it may be necessary to use fluidized-bed combustion units or to install flue-gas desulfurization (FGD) processes to minimize sulfur dioxide emissions in order to meet environmental standards. Either of these alternatives will increase the amount of solid waste produced for each metric ton of coal burned. Normally, flue-gas desulfurization wastes are produced in slurry form and are usually deposited in a pond at the site. Fluidized-bed combustion in which ground limestone is added to the fluidized bed for sulfur removal will also result in increased solid waste production because of the limestone added; this waste, however, will be dry. Various studies are now under way to assess the possibility of using these residues for agricultural purposes.

Currently, there is considerable interest in gasification or



Henry Wilson, an environmental chemist, studies the composition and mobility of trace contaminants found in the residues from various coal conversion processes. These leaching studies provide information necessary to develop mathematical transport models which are being verified by larger field scale testing.

liquefaction of coal to produce transportation fuels and reduce imports of foreign oil. The majority of the proposed gasification or liquefaction processes generate most of their solid waste as gasifier bottom ash in an amount about equal to the inorganic residue in the coal because very little, if any, solid material is added during the processing operations. Many of the proposed gasification–liquefaction plants will remove sulfur from the gas streams, but the sulfur will probably be marketed rather than handled as a solid waste.

Although ash/slags make up most of the solid waste from a coal conversion facility, some sludges will also be produced from the liquid-waste-treatment processes and product-upgrading systems. Although there is not as much sludge as ash, the sludge may contain greater amounts of organic material, so prudence may dictate handling the two separately. Segregation of waste streams is common practice in many industrial operations, and the impact of RCRA may make it even more important to maintain segregation where large volumes of inert wastes are produced and where small, so-called hazardous, wastes may occur. The application of this procedure would result in large landfills for the high volume of those wastes deemed nonhazardous, with small, specialized landfills for wastes classified as hazardous.

If utility wastes are found to have significant leaching problems or if the site is not well suited to protecting groundwater from leachates, it may be possible to treat the waste chemically to remove toxic components or to fix or solidify the waste to minimize leaching. Fixation or solidification is also a possible mitigation measure if groundwater contamination is detected at any time after disposal.

Ash and Slag Use

Use of coal wastes where possible reduces disposal problems and sometimes decreases costs. The enormous quantity of ash produced by even a single modern coal-fired power plant means that only high-volume products with local markets can affect disposal problems significantly. Previous studies in the Chemical Technology Division have shown that production of cement from the fly-ash residue of two large steam plants in the Oak Ridge area would not only fill the local cement market but would also produce as much cement as is now being used in the entire Southeast.

The principal solid wastes from coal combustion are the bottom ash, or slag, and the fly ash collected in electrostatic precipitators or other flue-gas devices. The proportion of ash that appears as fly ash depends on the type of furnace used. Power plants built in recent years use finely ground coal, and these produce approximately 72% fly ash and 28% bottom ash and slag. Fly ash consists of high-fired, airborne

Waste Studies at ORNL

ORNL's Environmental Sciences Division has recently started research on the potential land disposal of solid wastes from coal gasification. Conducted by Bill Boegly, Chet Francis, S. Y. Lee, and Henry Wilson, this program, called the Stored Solids Study, is assessing the physical and chemical characteristics of the ash and slags, is determining their leaching properties under both batch and column conditions, and is carrying out soil attenuation experiments with different gasifier ashes.

One of the key features of the ORNL study is an evaluation of the soils' capability to attenuate the movement of trace elements from the landfill to groundwater. The provisions of RCRA cover the potential for soil attenuation but appear to rely more on the use of impermeable liners and leachate collection systems to prevent groundwater contamination. The ORNL leaching program draws heavily on the experience gained in the past 20 years during studies on the migration of radionuclides from shallow-land disposal of low-level radioactive wastes. The University of California at Riverside, the Tennessee Valley Authority, Westinghouse Electric Corporation, and R. E. Stone and Company are conducting similar studies on combustion ash, fluidized-bed combustion ash, and certain gasification wastes. Development of a full-scale gasification industry will require safe and economical methods of handling these wastes.

Both the continuing effort to increase the use of ash and the future or imminent appearance of new types of coal-waste materials have resulted in many new proposed uses of these wastes. Of particular interest are studies performed under the direction of Jack Watson of the Chemical Technology Division. The studies deal with recovering metals such as aluminum from coal wastes (see ORNL *Review*, Winter 1979). The process for recovery of the metals can also be used to remove any trace components that might interfere with economic disposal of the waste. For example, a waste termed hazardous might be converted to a nonhazardous waste by selective removal of trace elements with the additional cost balanced by reduced disposal costs. New applications for fly ash currently under consideration include several new uses as filler material, and even as sorbent media. John Moore and Earl McDaniel of the Chemical Technology Division have included fly ash in some of the cements they are testing for restoration of geologic integrity of repository sites for radioactive-waste disposal. Fly ash is added routinely in the cement-based mix used to dispose of ORNL's liquid radioactive waste. It is also used as filler in the construction and building products industries and as a grit for icy roads.

particles, usually spherical in shape. These particles contain crystalline and amorphous phases, which have been studied by Les Hulett and Bill Lyon of the Analytical Chemistry Division. The principal components of fly ash are oxides of silicon, aluminum, and iron. Moderate concentrations of titanium and magnesium are found, along with environmentally significant quantities of trace metals. The bulk composition of fly ash, bottom ash, and slag is similar, but several trace elements which potentially affect disposal hazards are more concentrated in the smaller fly-ash particles. These elements may be partially volatile under furnace conditions and later condense or adsorb onto fly-ash particles. The smaller fly-ash particles, which have larger surface-to-volume ratios, have a greater ability to collect these volatile trace elements.

Bill Boegly

Electric utilities have promoted and succeeded in increasing the use of ash. The National Ash Association, sponsored by the utility companies, promotes exchange of information and ideas

Jack Watson

on uses for ash. Bottom ash and boiler slag enjoy relatively high utilization, approximately 30% and 60% respectively. Bottom ash is used principally as a fill material for construction and can also be used as a filler material in asphalt. About 60% of the boiler slag produced is used as blasting grit, with about 30% used for the familiar roofing granules on asphalt shingles.

Fly ash constitutes about 70% of the total weight of ash produced—but less than 15% is used. The principal uses are as additives or replacement components in cement or concrete. Replacement of up to 20% of the cement with fly ash in some concrete mixtures not only lowers the cost of the concrete but also improves its properties, such as workability, long-term strength, sulfate resistance, corrosion of steel, and volume change during hardening. Fly-ash use is generated both by the need for the material and the need to get rid of the waste.

In principle, wastes from scrubbing (FGD) can be oxidized to convert the sulfite to sulfate, then dried to leave a material that is largely calcium sulfate. Japan uses FGD material in wallboard construction, incorporating wastes from oil-fired plants. Such use of FGD wastes from coal-fired plants may prove more difficult because there can be more water-soluble and perhaps toxic components in the waste. Another problem for many uses of FGD sludge is that it must compete with cheap, high-quality gypsum. FGD and fluidized-bed combustion (FBC) wastes have both been suggested for use as agricultural amendment to improve soil properties. FBC wastes in particular contain considerable excess limestone and may be most attractive for these purposes.

The problem of waste disposal has become an important issue for many technologies. No longer can disposal be based on the "cheapest" method; safety considerations have forced many industries to reevaluate their disposal systems. Beneficial uses of materials can go a long way to minimize undesirable impacts, and consideration of the back end of the fuel cycle offers challenges to the technologists to develop new and safe applications of wastes from coal use.

Tell Long-Range Planning to mark this for a future coal seam.

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Toward Non-Toxic Coal Technologies:

Guidance from Rapid Biological Tests.

Ti Ho examines chromosomes of human blood cells under a microscope to gain knowledge concerning the potential genetic threats of chemicals to man.

(This article was compiled from material contributed by ORNL biologists in the Life Sciences Synthetic Fuels Program)

Producing liquid fuels on a large scale from coal and shale has been endorsed by President Carter as a means of significantly reducing United States' dependence on foreign oil. Further conservation or, perhaps, better utilization of our own resources could also come about through the gasification of coal. However, these technologies for producing synthetic fuels bring forth a variety of environmental, health, and safety issues during their development and commercialization. Many of these issues will be common to conventional fossil-fuel utilization. Regardless, adequate programs for industrial hygiene and safeguards for the worker, the environment, and the general public should be developed.

Of primary concern to researchers in the life sciences are the long-term or profound effects of exposure to synthetic fuel products and wastes such as cancer, mutations, birth defects, and toxicity in man. Our work aims at determining the consequences of long-term, wide-level exposure to unique (or at least increased) concentrations of hazardous materials in our environment. It is prudent, therefore, that developers of coal-conversion and shale-oil processes receive feedback from health scientists on the identification and toxicity of the various chemicals produced or discharged by the processes. With this knowledge, engineers either can alter the technology to produce less toxic products or can improve waste treatment schemes. Biological results can also aid in the selection of a safer technology for the environment.

Biologists are now working in concert with engineers, analytical chemists, and ecologists to steer development of conversion technologies toward the production of nontoxic fuels and by-products. These scientists are attempting to identify materials with carcinogenic, mutagenic, or related effects. Work is concentrated on the source and control of potentially hazardous substances. Important areas of investigation involve the characterization and treatment of wastes, fugitive emissions, and effluents. Additional studies address the problems of disposal of sludges and solid wastes. Furthermore, this team effort, perhaps uniquely, is cognizant of and aiding in the development of standards and regulations. Significant programs addressing the environmental and health issues and research requirements of the emerging conversion technologies have been initiated

by the Department of Energy (DOE), the Environmental Protection Agency (EPA) along with the Electric Power Research Institute (EPRI), the American Petroleum Institute (API), and specific industrial interests. Again, the research is interconnected with the development of regulations.

Interest in the development and application of biological research to practical problems (here, the assessment of the potential health hazards of the emerging technologies) has accelerated the initiation of these "integrated" programs. Thanks to the recent development of fast, inexpensive bioassays (tests), biologists can determine rapidly whether a given product warrants additional evaluation through time-consuming, expensive tests in animals such as mice. The short-term tests are used for screening chemicals and other materials typical of the products of coal conversion processes. If the results are negative, the

The insect (Drosophila) system is a key intermediate or validating mutagenicity assay in the evaluation of energy-related chemical threats.

material is considered reasonably safe. If the results are positive, a biological red flag is raised and the material is subjected to a series of more intensive tests to determine its mutagenicity, carcinogenicity, teratogenicity, and toxicity. In short, the rapid screening tests can serve as predictors of biohazards early in the development of new synthetic fuels technologies. Rapid bioassays save time and money and also fulfill the requirements of federal regulations calling for determination of toxicities of coal-derived products and wastes. Many of these regulations are embodied in the Toxic Substances Control Act and in the Resource Conservation and Recovery Act. Coal-derived liquids, aqueous wastes, particulates, and solid wastes can be evaluated by rapid screening tests. These are complex mixtures, with potential biohazards that are perhaps common to all coal-conversion processes and conventional fossil-fuel processes.

To isolate and identify compounds in complex materials that are responsible for causing tumors or genetic changes, analytical chemists break the complex material down into simpler components. The biologists then perform short-term tests on each of the simpler, or fractionated, substances in an attempt to zero in on the compounds that are biohazards.

Besides the Ames test, biologists use other rapid-screening techniques. For example, fruit flies can be exposed to coal-derived materials and inspected for genetic change such as altered eye color or lethality in offspring. Yeast and human cells exposed to suspect mutagens are checked for gene and chromosome damage. These and other tests function as (1) predictors of long-range health effects, such as altered genes, birth defects, and cancerous tumors; (2) predictors of toxicity for man and his environment; (3) a mechanism to isolate and identify rapidly a hazardous agent in a complex material; and (4) a key to relative biological activity through correlation of control data with changes in environmental or process conditions. Much of the exploratory work in using short-term assays to predict health effects has involved fractionated natural oils and synthetic oils and wastes from coal-conversion and shale-oil processes. However, it should also be pointed out that much of the developmental biological work was initiated through our experience with the radiation problem over the last decades. Furthermore, one must realize that practical application of any research involves a fundamental understanding of biological processes. Applied research without the continued underlying quest for basic mechanisms and understanding cannot stand alone.

The possibility of using short-term bioassays to isolate and identify the potential hazards of such complex materials has been investigated jointly by teams of analytical chemists and biologists. Within the DOE research efforts, groups at Oak Ridge, Richland, Los Alamos, Albuquerque, Livermore, and Argonne have been instrumental in developing and applying the assays. Within the EPA, major efforts have been funded not only in the development of the assays but in the application to the environmental assessment of technologies. Here, the effort has not been limited to synthetic fuels but has encompassed other established industries. Furthermore, the approach has been extended to general problems such as diesel fuel emissions and airborne particulates.

In synthetic-fuel health-effects research, the following general approach has evolved. Analytical chemists have analyzed and prepared coal-derived chemicals for biological testing—cytotoxicity, mutagenicity, and carcinogenicity assays. As a prescreen for a chemical's potential to cause genetic mutations or possibly cancer, biologists have been using the *Salmonella* histidine reversion test developed by Bruce Ames of the University of California at Berkeley. The Ames test uses a mutant strain of the *Salmonella* bacteria, whose genes have been altered so that the strain is unable to make the amino acid histidine, which is essential to its growth. If the test compound is mutagenic, it will cause the *Salmonella* bacteria to revert to their normal state and start growing without a histidine supplement. By counting the number of revertant colonies produced by the test chemical, biologists can rate its mutagenicity. Many chemicals found mutagenic in the Ames test have also been found to be carcinogenic in animal tests, so the test serves as a quick way of identifying substances that deserve further examination for their cancer-producing potential.

Oils as Biohazards

Any evaluation of the health effects or hazards of a process should involve an investigation of past work in similar industries. In the case of coal liquids, tars, and soots, along with shale oils, industry's experience has been long and wide. In the late 1700's, it was first observed in England that coal tars and soots have the ability to cause cancer. Biological hazards from both petroleum and shale-oil-derived crude oils were also reported early in the development of the industries in England and Scotland. Workers in the spinning industry in Scotland sometimes developed cancerous lesions of the scrotum due to exposure to oils derived from Scottish shales; their affliction was termed "mule spinners' cancer." American workers in similar industries did not have as high an incidence of cancer, perhaps because the lubricants and fuels employed were acid-treated petroleum oils which may have been low in carcinogens. Based on these experiences in early industry, it has been generally thought that the cancer-causing potential is higher for oils distilled at high temperatures and for shale-derived oils than for petroleum-derived oils.

More recent studies have found supportive evidence for the hypothesis that carcinogenic substances are present in various oils and distillates from both petroleum and shale-derived materials. Researchers with the oil industry and the API have found carcinogenic potential in both petroleum and shale products by comparison studies in which the skin of mice was painted with test oils and then observed for tumor formation. Although the carcinogenic potential was found to be about the same for petroleum and shale products, the researchers noted that upgraded (hydrotreated) shale oil was less active. The API is continuing to investigate this comparison. In other studies, researchers assessing the Estonian shale-oil industry for potential health effects have suggested that phenols are the major toxicants and have carcinogenic potential.

In considering the potential biohazards of the developing coal conversion technologies, scientists are extending the previous comparisons of petroleum-derived vs shale-derived materials to coal-derived liquids and tars. Clarification of the question of decreased activity in upgraded oils also needs to be readdressed. The newly available techniques in short-term testing should aid in answering these questions.

The new technology of coal conversion has sparked concern about the possible occupational and public health risks of these processes. The early experiences at the Union Carbide Corporation coal conversion plant at Institute, West Virginia, probably justify this concern. In the 1950's, animal studies using Union Carbide product streams from its experimental coal-hydrogenation unit revealed that compounds produced at various points in the process were carcinogenic.

One of the oldest known substances used to produce skin tumors in experimental animals is coal tar. An active fraction was isolated from coal tar and, on further analysis, was found to contain polycyclic aromatic hydrocarbons (PAH). Much of the modern work followed from these early observations. Other laboratory, clinical, and epidemiology studies have shown the carcinogenic potential of coal-conversion process materials and the associated occupational hazards. Limited epidemiological evidence from the Union Carbide study, from coke-oven and gas-worker studies, and from the study of shale-oil workers in Colorado suggest there is an increased risk of cancer for these workers. Hopefully, more complete epidemiological studies now under way or planned in conjunction with the evaluation of the emerging coal-conversion and shale-oil industries will clarify this question.

Current Research

How do coal-derived liquids compare with shale oil and natural crude oil for carcinogenic potential? Biological research funded by DOE, EPA, and/or API is approaching this question with skin-painting assays with mice. The mice are exposed to known

quantities of coal-liquefaction products, shale oils, and natural petroleum liquids. Although the studies require more than two years for completion, preliminary results (largely at Oak Ridge National Laboratory and Battelle Pacific Northwest Laboratory) have pointed to a greater carcinogenic activity in coal liquids and shale oil than in the natural crude. The short-term tests for mutagenesis had predicted a similar array of potencies. Similarly, work funded by industry a number of years ago pointed to a reduced biological activity in upgraded (hydrotreated) oils. Current work with the short-term tests agrees

Microbiologists employ the Salmonella histidine reversion assay (Ames Test) to determine the mutagenic potential of a wide array of energy-related pollutants.

with these observations. The actual carcinogenesis trials are underway.

What materials produced in coal conversion facilities have been identified as possible threats to human health and the environment? The gaseous effluents from coal conversion facilities contain primarily ammonia, sulfur oxides, nitrogen oxides, carbon monoxide, hydrocarbons, and particulates with some trace metals and polycyclic organics. Aqueous effluents and discharges will occur as condensates, scrubber sludges, and product waters. Phenols and PAHs appear to be the major organic contaminants in process streams from coal conversion. Obviously, these toxic or carcinogenic substances in combination with such lung irritants as coal dust and fines compound the human health problem. Another health threat could be posed by coal-derived solid wastes because they contain toxic materials that could be leached out and allowed to enter the human food chain or drinking water.

While development of coal-conversion and shale-oil technologies is accelerated, the DOE and the EPA have shown well-placed urgency to assess the environmental and health effects of these processes. Along with this interest has come a further need for short-term screening assays to determine whether synthetic materials have a potential for genetic damage and toxic effects. A potential for genetic damage has been accepted as a biohazard not only as a danger to future generations but also as a possible indicator of carcinogenic potential. Toxicity data may prove predictive of possible health hazards for man as well as of potential damage to the environment.

Role of Short-Term Tests

Research within DOE Biomedical Programs and within EPA has emphasized bioassays for mutagenicity (as a possible prescreen for carcinogenesis), cytotoxicity, and teratogenicity. For example, tests using coal-derived substances have produced chromosome damage in human white blood cells, cell damage in various systems, and birth defects causing abnormal development in both amphibians and mammals. Biologists are now developing a comparable battery of short-term tests for carcinogenesis, specifically for use with complex materials or their fractions from coal conversion processes.

Mutagenicity tests are used for two kinds of mutations: somatic, in which the reproduction of ordinary tissue cells is affected, and germinal, in which the germ cells are affected, causing genetic changes that appear in offspring. Interest in using short-term assays to test for somatic mutations has been kindled by the theory that tumor production comes from somatic mutations. In addition, several researchers around the world have reported a qualitative correlation between the ability of a chemical agent to produce tumors in experimental animals and mutations in genetic testing systems. Thus, short-term genetic assays are now being used extensively as a prescreen for the detection of potential environmental carcinogens as mutagens.

Some known carcinogens such as benzo[*a*]pyrene are not in themselves mutagenic until after they have been metabolized. Thus, if a suspect carcinogen is not found mutagenic in the Ames test, it is subjected to a metabolic activation test in which an enzyme from rat liver is added as a reagent. The enzyme preparation metabolizes the chemical, transforming it into a carcinogenic and mutagenic compound in the same process used by a rat ingesting the chemical.

Biologists have used rapid-screening techniques to shorten the list of compounds that require examination by expensive, time-consuming, mammalian tests. They have found that many compounds are not mutagenic in bioassays and therefore are probably not mutagenic or carcinogenic in mammals. However, further tests are required to determine if the compounds are toxic agents or tumor promoters. The tests have shown that a number of aromatic amines and aza-arenes (nitrogen-containing compounds) are mutagenic, suggesting that they should be tested for carcinogenicity. The investigators were led to these classes of compounds through work on crude synthetic oils. Thus, we are beginning to capitalize on the integrated team approach of the chemist and the biologist.

One problem in testing coal-derived samples for mutagenicity is that the complex mixtures contain highly toxic as well as carcinogenic and mutagenic substances. To render these samples less toxic so they can be used for biological tests without being lethal to experimental subjects, the investigator breaks down the concentrated mixtures into acidic, basic, and neutral components. The acidic fractions contain phenols and carboxylic acids; the basic fractions, aromatic amines; and the neutral fractions, polycyclic aromatic hydrocarbons. By fractionating these complex mixtures and identifying the constituents of each fraction, the chemists help the biologists pinpoint which compounds are most responsible for biological activity such as bacterial mutagenesis.

Biological end-points in the short-term testing of energy-related materials have not been limited to mutagenesis assays. Tests involving cytotoxicity (cell lethality) in a number of cellular systems are being used and evaluated. It is anticipated that these assays will aid the biologist in the overall assessment of the health and environmental impacts of the processes. Teratogenic and embryotoxic end-points are also used.

The use of this battery of short-term assays does not eliminate the need to carry out classical toxicological examinations and long-term animal assays. As an aid to the industrial hygienist and in the attempt to evaluate risk for man, this type of whole-animal work is mandatory. The short-term tests simply act as a mechanism to quickly locate a potential hazard and perhaps isolate and identify the constituents. Detection of biological activity in any short-term assay will help the investigator to set priorities for further testing.

Mammalian Genetics Research

Samples that showed positive effects in these short-term assays have been studied for genetic and germ cell toxicity effects in mice by the research team at ORNL. Five types of tests are used in the mouse system—dominant lethals, heritable translocations, specific-locus, somatic mutations ("spot test") and the total reproductive capacity tests. The dominant-lethal test is a relatively rapid test for chromosomal damage. This is done by simply studying the uterine contents of females mated to males exposed to the sample. Dominant-lethal mutations lead to death of embryos early in development. The heritable translocation test measures the frequency of chromosome breakage and exchange of parts between chromosomes transmitted to the next generation. Thus, the heritable translocation procedure generates the most meaningful information for evaluating chromosome aberration hazards of test agents to the human population because it measures transmissible genetic damage. The specific-locus method is the only practical method available to detect induction of gene mutations in germ cells of mammals. By mating exposed mice to a stock carrying seven recessive markers in homozygous condition, induced mutations can be objectively detected in the first generation.

The spot test, developed by Liane Russell, uses only a few animals and produces results in about five weeks. The test involves injecting coal-derived substances into pregnant mice to see if somatic mutations are induced in the exposed embryos. If a mutation occurs in a cell that will ultimately give rise to cells that specialize in producing pigment, then the newborn mice affected will eventually grow fur with oddly colored spots. Thus, a mouse that would be normally covered with black fur might have brown or white patches.

In addition to mutagenic effects, certain germ cells of mice such as the oocytes have been shown to be sensitive to even a relatively slight insult from known mutagens. The total reproductive-capacity test detects chemicals that are toxic to female germ cells by simply determining the lifetime production of offspring of exposed females.

Future testing in animals to screen synthetic fuel components for genetic effects will be influenced by a recent discovery by Walderico Generoso and associates at ORNL. The finding raises serious questions about the dominant-lethal test in which male mice are treated with the test chemical and then mated with normal female mice to determine if a high rate of embryo deaths results from the mating. Generoso has found that egg cells in some mouse strains are able to repair genetic damage present in the sperm that have fertilized them, thus suggesting that the popular dominant-lethal test may be invalid in some cases as an indicator of a test chemical's ability to damage chromosomes significantly.

The Future

For the most part, biological tests available today seem to be valid indicators of potentially hazardous chemicals derived from coal and shale oil. Now that President Carter has proposed a crash program to produce synthetic fuels, it is fortunate that biologists and analytical chemists have the tools and techniques to launch their own crash program to provide early warnings of potential human health hazards posed by technologies under development. With biologists and technologists working together, the synthetic fuels processes adopted for the future are more likely to be considered environmentally acceptable solutions for producing energy.

Coal and Health

By WALTER PORTER and SEATON GARRETT, M.D.

Dan Schuresko peers through a fluorescence microscope as John Mrochek (left) and Bill Bostick look on. The microscope is part of the laser-microfluorometry system used in the Chemical Technology Division to determine uptake of PAH by cells.

In the last 15 years, people have become increasingly aware of the risk of developing some form of cancer from exposure to environmental insults. Sources of possible exposure include air, water, food, radiation, and certain chemicals. The recent increase in activities related to coal conversion technology has caused this level of concern to rise still further, not only among people at work but also among those in the community. It cannot be said that the concern is without foundation. However, what many do not know is that exposure to sunlight can and does induce the same types of skin cancer as those caused by contact with coal-derived materials. A similar parallel can be drawn between inhaling airborne contaminants from coal conversion and tobacco smoking. There are other potential health stresses, mostly affecting workers associated with coal conversion as opposed to community residents. But these stresses are common not only to coal-related activities but also to many other industrial and developmental processes.

History

The cause-and-effect relationship between coal-derived materials and cancer first came to light in 1775, with the discovery by British surgeon Sir Percival Pott that London chimney sweeps had an increased incidence of cancer of the scrotum. During the 1950s, Union Carbide operated a large-scale pilot plant at Institute, West Virginia, for the production of chemicals from coal hydrogenation. During the period of operation of this plant, a comprehensive epidemiological study was conducted of the workers.

Among the most significant findings in Carbide's study was an increase in the incidence of skin cancer among workers exposed to the coal hydrogenation process over that of the population of West Virginia and the United States as a whole. This study showed no evidence of increased incidence of lung cancer; to date, in follow-up studies, no positive correlation has been demonstrated with regard to either lung cancer or other types of systemic cancer.

The experience in the coke-oven industry has been quite a different story. The National Institute for Occupational Safety and Health, in the Department of Health, Education, and Welfare, has conducted epidemiological studies both in the United States and in other countries. Data compiled from these studies show significant increases in cancer rates for coke-oven workers. Not only was there an increase in skin-cancer incidence but also in cancer of the lung and respiratory system and several other organ systems as well.

Current Status

It has long been firmly established that many, if not most, of the polycyclic aromatic hydrocarbons (PAHs), volatile compounds produced by pyrolysis of coal, are cancer-causing agents. Others are strongly suspect, and some have mutagenic (chromosome-damaging) and possibly teratogenic (birth-defect-causing) effects. Because of this knowledge, industrial hygienists and other occupational health specialists have recognized the need for careful monitoring of the coal-conversion worksite, for effective engineering control measures (e.g., local exhaust-ventilation systems), and for personal protective clothing and equipment. Such techniques and equipment for controlling exposures have been in general use for years, and their effectiveness has been proven through extensive testing and actual use in the workplace. Occupational physicians and industrial hygienists are unanimous in their conviction that an industrial hygiene program must be dovetailed with a comprehensive medical surveillance program for workers involved in coal conversion. They agree that this is essential to early detection of health effects.

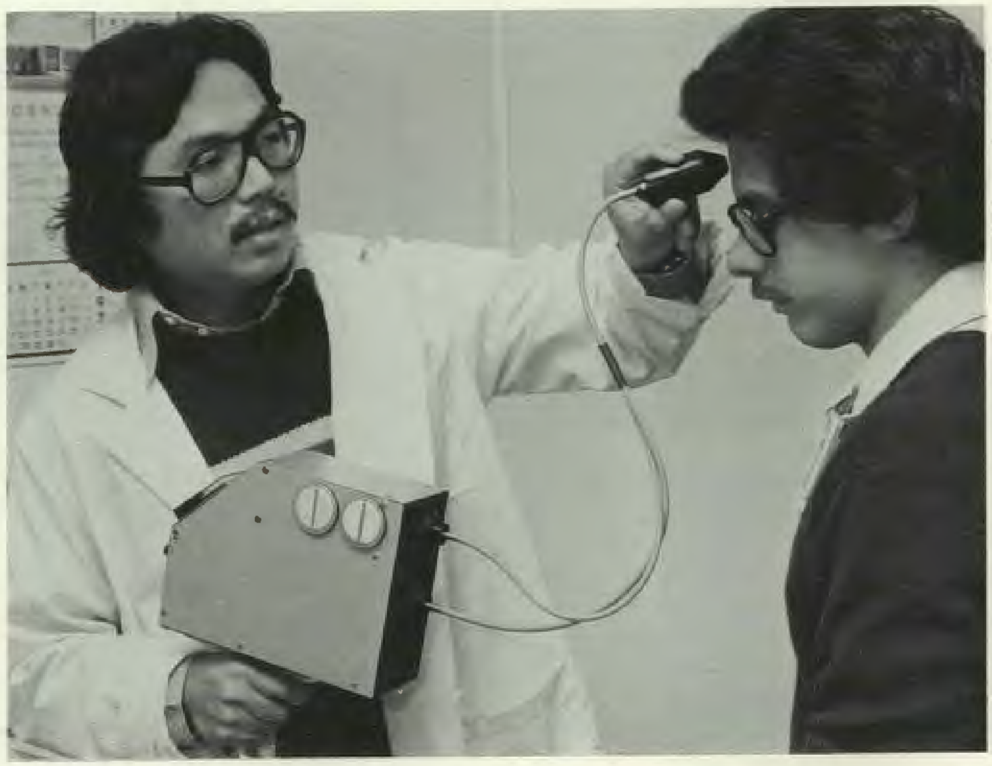
Today's Problems

Although such health effects are fairly well understood, there are more unanswered questions than answered ones. Probably the major points of uncertainty pertain to the degree of toxicity: How potent are the compounds? Will new compounds being identified prove to be carcinogenic, mutagenic, or teratogenic to humans, or will their effects ultimately show up as some combination of these? What is the minimum induction time or latent period? Which compounds are cocarcinogenic, which are tumor promoters, and which ones act synergistically or have potentiation effects? And finally, are there as yet unidentified compounds or materials that are significantly toxic other than as carcinogens, mutagens, or teratogens?

In workplace monitoring, there are further questions: In our sampling and monitoring efforts, are the materials or compounds we are measuring the ones we should be measuring? Are our sampling and analytical methods accurate and reliable enough?

Alan Anderson and Sharon Yoder affix a personnel pump monitor to senior technician Randy Gibson at the Coal Liquids Flow System in Building 2528. At the belt is an air pump that draws ambient atmosphere through a tube containing activated charcoal, clipped to his collar. By examining the organic contaminants thus collected, a quantitative analysis of the work environment can be made.

Is the forehead of Paul Martinez contaminated? Tuan Vo-Dinh uses the fiber optics lightpipe luminoscope to detect possible contamination of skin by traces of coal-derived liquids. The luminoscope uses long-wavelength ultraviolet (UV) light to induce fluorescence in potentially carcinogenic compounds in coal liquids on skin. The UV light is of such low intensity that it poses very little hazard to the skin.



At present there is only one recognized limit for employee exposure to coal-derived materials in workplace air—that for particulate PAHs, formerly called "coal tar pitch volatiles." This permissible level, known as a "Threshold Limit Value," was established by the American Conference of Governmental Industrial Hygienists and adopted by the Occupational Safety and Health Administration as a legal workplace standard. This limit may not be the most appropriate one for assessing the degree of hazard to the health of workers potentially exposed on a regular basis to airborne coal-derived materials. It may well be that we need a different limit for each individual compound, instead of one that encompasses all benzene-soluble particulates. For years, many people have doubted the adequacy of the benzene-extractable parameter; however, until someone is able to demonstrate to the occupational health community that there are better or more applicable exposure limits, we must rely on what we have.

Another deficiency in our ability to assess health effects is the scarcity of data from epidemiological studies, especially those dealing with long-term or chronic effects. Simply stated, the opportunities to follow, observe, and measure health-related changes in populations of workers involved in coal liquefaction and gasification have been few and far between. This dilemma is further compounded by the fact that workplace exposure data are almost nonexistent. That is, concentrations of airborne contaminants to which workers have been exposed simply have not been measured.

In the field of medical surveillance, the critical need is for earlier and more reliable techniques for diagnosis of health problems. To be sure, this need is common to all areas of medical practice and health care.

Protection at ORNL

From the beginning of the coal conversion activities at ORNL, our approach to the industrial hygiene and medical surveillance programs has been a very conservative one. The overriding consideration in our philosophy has been and still is that because the extent of the hazards to our employees was not known (and would not be for years), we must go to extremes in protecting them. It may be that our efforts in surveillance and employee protection will, in retrospect, be considered superfluous. However, our reasoning is that the level of protection can be reduced in the future, but past protection can never be increased. From our conservative approach, we are learning as we go, and the programs will be adjusted as new techniques are proven.

A comprehensive program of workplace air sampling has been in progress from the start of work at ORNL. Both personal (individual breathing zone) and area air samples are collected during all phases and levels of operations activity and are reviewed continuously. Samples are routinely analyzed and quantified for total airborne particulate matter, benzene-soluble materials, and 3,4-benz-pyrene, or B(*a*)P. Periodically, monitoring is conducted for other contaminants, such as phenolic compounds, benzene, toluene, hydrogen sulfide,

Monitoring Research at ORNL

At ORNL, several developments offer hope for improved monitoring and surveillance capabilities for coal technology workers. Some of these developments are based on the principle that polycyclic aromatic hydrocarbons (PAHs) and other organics produced by coal reactions absorb ultraviolet light (UV) and then fluoresce in the near-ultraviolet or visible regions of light. Using this principle, instruments are being developed to detect PAHs which in animal tests have been shown to be carcinogenic.

For example, a portable fluorescence spotter for detecting surface contamination by trace amounts of PAHs has been developed by Dan Schuresko of the Chemical Technology Division, with contributions from Bill Walker of the Plant and Equipment Division and Mike Blair, Gerry Schultze, and Martin Bauer of the Instrumentation and Controls Division. This monitor can remotely detect PAHs in chemical spills and leaks by shining UV light on areas of suspected contamination and measuring the intensity of the visible light emitted. The spotter is highly sensitive; it can detect 0.1 microgram of perylene (a PAH) at a distance of 50 cm with the room lights on, and it can locate nanogram amounts at the same distance in the dark. The spotter will be field tested in 1980 at the solvent-refined-coal pilot plant at Fort Lewis, Washington, at the Pittsburgh and Morgantown Energy Technology centers, and at the HYGAS Coal Gasification Pilot Plant in Chicago.

More specifically aimed at problems of skin contamination from spills and leaks is a development by Tuan Vo-Dinh of the Health and Safety Research Division. Called a fiber optics lightpipe luminoscope, this instrument detects contamination of skin by liquids produced from fossil fuels. When available, it will have the advantage of illuminating small areas of the skin with long-wavelength UV light with an intensity orders of magnitude less than that of a hand-held "black light." The problem with using the "black light" to induce fluorescence in PAH-contaminated skin is that prolonged exposures to UV light this intense could be carcinogenic. The lightpipe luminoscope is designed to detect potentially cancer-causing compounds on skin, without being a health threat in itself. The instrument will have the sensitivity to quantify dermal exposures where the contamination is thinly spread or still persists after wash treatment.

An instrument that can identify and quantify specific gases and vapors in the coal workers' atmosphere has been developed by Alan Hawthorne, Dick Gammage, and others in the Health and Safety Research Division. Called DUVAS—short for "derivative ultraviolet-absorption spectrometer"—this portable instrument is based on the principle that PAHs and other gaseous, coal-derived compounds each absorb UV light of a characteristic wavelength. By determining how much UV light of a certain wavelength is absorbed, the device enables researchers to ascertain how much of a specific compound is present in the air. Examples of compounds that DUVAS can monitor are PAHs; ozone, nitrogen oxides, sulfur dioxide, and ammonia. It has the potential for assessing worker exposure and warning workers of elevated concentrations of airborne pollutants due to leaks and other operational problems. The spectrometer is being field tested at the low-Btu coal gasifier operated by the University of Minnesota at Duluth and at TVA's coal-to-ammonia facility in Muscle Shoals, Alabama.

The Chemical Technology Division is also developing a biological technique for assessing coal conversion workers' exposure to and uptake of PAHs. This technique takes advantage of the observation that mammalian cells exposed to PAHs increase their production of certain enzymes capable of metabolizing PAHs. This phenomenon of induction—that is, the elevation in levels of some enzymes known collectively as "cytochrome P-450 mixed-function oxidase system"—is apparently the initial biological response of cells to aromatic toxins. Hence, it is believed that the extent of induction can serve as an excellent indicator of PAH uptake. By exposing cells to PAHs and then using a laser to induce fluorescence of the cells' PAH metabolites (which is distinct from the fluorescence of parent PAH compounds), ORNL researchers are seeking to determine PAH uptake. The experimental measurements are carried out either in batch mode, using extracts of cell homogenates, or on a single-cell basis, where the laser-excited fluorescence of PAH metabolites in single cells is measured directly using a fluorescence microscope/fluorometer. Principal developers of this technique are Dan Schuresko and Bill Bostick. Mike MacLeod and Jim Selkirk of the Biology Division provide samples, consultation, and lab facilities; Kris Dearstone of the same division provides technical assistance.—*CK*

Dr. Seaton Garrett, director of the Health Division, examines George Oswald's skin for changes that might indicate the onset of skin disease. The skin surveillance program is conducted with Dr. Charles Huddleston, consultant dermatologist to the Health Division.

or carbon monoxide.

Such measures as safe work procedures, engineering controls, and protective clothing and respiratory equipment are taken to ensure that levels of exposure are at a minimum. Jim Ealy, Alan Anderson, and Sharon Smith of the Industrial Hygiene Department have the major portion of the monitoring and surveillance responsibilities at ORNL. Of course, the real responsibility for ensuring that our employees are protected lies both with supervision and with the employees themselves. Safe practices and conscientious use of protective equipment can be accomplished only by those closest to the work.

Future Plans

At the Laboratory, several efforts are under way that offer promise of improved monitoring and surveillance capabilities (see box). Nationwide, work is proceeding on several fronts toward developing better, more accurate, and more usable instruments and techniques, as well as ones that will produce meaningful data and results. Worthy of mention is the activity of Gulf Oil Corporation at its solvent-refined coal pilot plant in Fort Lewis, Washington. Gulf is conducting a comprehensive health protection program (including industrial hygiene and medical surveillance) on its employees at this site and has several developmental projects in progress. One of the more promising is a technique for detecting skin contamination, using a solvent that removes PAHs for analysis.

Throughout the country, many variations in sample collection and analysis are being evaluated, especially those performed with sorbent materials. Passive dosimeters of many descriptions are being developed for gas and vapor sampling, and minianalyzers for practically all types of toxic air contaminants are appearing. One pocket-size personal analyzer that will monitor a worker's exposure to toxic gases is in the developmental stage. This instrument can measure as many as 10 different gases, calculating and storing the 8-h, time-weighted averages and peak concentrations of those gases.

Assaying the Effects

Medical surveillance of those employees involved in coal conversion research at ORNL consists of integrating their general medical evaluations with special tests conducted because of their individual exposure possibilities. Each general evaluation has two parts, the multiphasic and the physical examinations. The multiphasic exam occurs approximately every 18 months and includes hematology, blood chemistries, urinalysis, chest x ray, pulmonary function studies, electrocardiogram, vision testing, visual-field testing, audiometry, and tonometry (the test for glaucoma). Depending upon the individual's age or special needs, a physical examination follows either each multiphasic or every other one. The special additional studies, performed because of potential exposure to carcinogens, fall into two general categories: a system of surveillance of the skin because of the increased incidence of skin cancer observed in earlier groups involved in exposure to PAHs, and special evaluations of the respiratory system because of the risk of lung cancer.

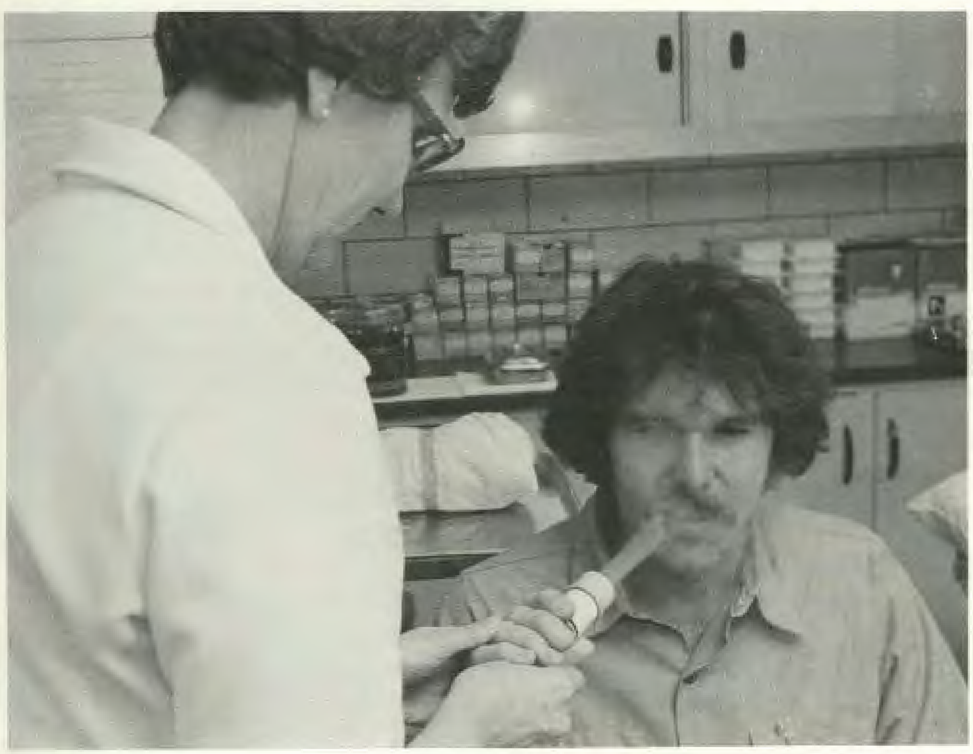
The skin surveillance program

includes an annual evaluation by Dr. Charles Huddleston, consultant dermatologist to the ORNL Health Division. In addition to the special skin examinations, we have a program of skin photography and maintain a file of serial photographs of the areas at highest risk to exposure. The 35-mm color slides are made by Jim Richmond of the photography department, who uses a special camera and has worked out techniques for excellent color and texture reproduction. These are reviewed each year at the time of the new skin examination to determine any change. Drs. Seaton Garrett, David Sexton, John Sisk, and Sam Shamiyeh, as well as physician associate Ed Wise, participate in the medical surveillance program which includes initial evaluations, termination exams, and annual surveillances (done along with Dr. Huddleston).

The special pulmonary evaluation includes chest x rays and pulmonary function studies from the multiphasic examination as well as the findings on the physical exam. Additionally, we collect sputum for evaluation by Dr. Geno Saccomanno of Grand Junction, Colorado, for the presence of—or the progression through several stages of—premalignant changes in the cells normally shed by the lung. Dr. Saccomanno and others have classified varying stages of atypical cells from mild to fully invasive cancer of the lung. Best estimates are that this, in most cases, takes somewhere between 10 and 20 years. It is hoped that finding *premalignant* cells of significant degree of abnormality can lead to intervention by advising discontinuation of smoking or removal from exposure to other carcinogens, thereby having some chance of heading off this progression prior to the invasive stage.

Collection of the sputum specimens for this purpose is supervised by Charlene Reynolds, chief nurse in the Health Division. The procedure requires the subject's inhaling a mildly irritating fog generated by an ultrasonic nebulizer from a solution of hypertonic saline and propylene glycol, designed to induce sputum production. Smokers generally produce sputum much more quickly and abundantly than do nonsmokers, but most patients are able to produce an adequate specimen within 15 to 20 minutes. Subsequent sputum is collected intermittently over the next 12 to 24 h, then is submitted to Dr. Saccomanno for cytologic evaluation. The procedure is repeated one week later, making a total of two specimens. Two specimens give a reasonable chance of studying a cell population that is representative of most and perhaps all areas of the lung. The frequency of collection of sputum for cytology is dependent upon the findings of the individual cytology, the subject's length of potential exposure to PAHs, and age.

On the experimental horizon, there are techniques that we hope will become *clinically useful* as more is learned about them. These may provide a better estimate of the actual exposure or may give some idea of how the individual is responding to the exposure. For instance, there is considerable evidence that some metabolites of materials absorbed are more carcinogenic than the materials themselves. The measurement, therefore, of metabolite level in body fluids such as urine may be



Health Division nurse Charlene Reynolds coaches George Oswald, coal researcher, as he inhales a fog produced by an ultrasonic nebulizer designed to induce production of sputum. Sputum samples are examined in Colorado for any premalignant changes in cells normally shed by the lungs.

Walter Porter, ORNL Industrial Hygienist.

possible by yet-to-be-proven techniques. This would have the considerable advantage of measuring actual exposure rather than merely inferring exposure from the atmospheric monitoring techniques that are now used. Also, some enzyme systems involved in metabolizing the substances may be increased or enhanced by exposure to the materials. If this is indeed the case, then a measure of the levels of enzyme induced by such exposure can be used as a measure of its extent, if not as evidence of how the individual is responding to the exposure.

Martin Bauer and Bill Walker watch as Gerry Schulze uses the portable fluorescence spotter developed at ORNL to check a chemical spill for PAH contamination. This monitor can remotely detect PAHs (potential carcinogens) by shining ultraviolet light on areas of suspected contamination and measuring the intensity of visible light emitted.

If these techniques and other developmental programs at the Laboratory and elsewhere prove to be clinically useful, then they will be incorporated into our program of health protection.

Ecological Impacts of Coal Utilization

By CARL GEHRS, Advanced Fossil Energy Program, Environmental Sciences Division

Greater use of coal to meet our future energy needs may result in increased environmental costs from land disturbances caused by mining and residue disposal, from atmospheric and aqueous effluents, and product spills. Ecological research is concerned with identifying the types and extents of risks to terrestrial and aquatic biota resulting from the above activities. Such research findings provide information useful in developing benefit/cost assessments and in siting and developing energy facilities where their environmental costs will be minimized. This research also provides input to the technology developer by identifying what materials require increased control or development of waste management procedures.

No matter how coal is to be used (e.g., conventional combustion, fluidized-bed combustion, liquefaction, or gasification), it must first be mined. The historical record shows greater environmental damage from surface mining than from underground mining. This is due, at least in part, to the need to disturb greater areas of the earth's surface to recover the same amount of coal. Loss of vegetation and fish and wildlife habitat; destruction of soil structure with resulting erosion, sedimentation, and changes in hydrology; and acid mine drainage have all been associated with past strip-mining activities. Most of the past environmental damage has occurred in mountainous regions of the eastern United States. Regulations set by the Surface Mining Control and Reclamation Act of 1977 are expected to minimize these types of effects in future strip-mining activities.

Although the environmental costs of underground mining are initially less visible (with the exception of acid mine drainage), we know less about their causes and how to control them.

Coal Combustion

The impact on the environment of current methods of coal utilization comes primarily from deposition and/or uptake of contaminants emitted from the stacks, although aqueous effluents

Effects of Coal-Derived Oils on Aquatic Microcosms

Pond microcosms—consisting of water, sediment, and an array of aquatic plants and animals living together under quasi-natural conditions—have been found to be more sensitive to the toxic effects of water soluble fractions of coal-derived oils than are standard bioassay organisms like algae and zooplankton. Jeff Giddings and Leon Washington of ORNL's Environmental Sciences Division found that, during two weeks after the synfuel treatment, the microcosm community showed little net growth or production, and the water lost most of its dissolved oxygen. *Elodea* (the main plant in the photo) and other plants were partially or completely destroyed, algae were eliminated, zooplankton became scarce, and snails left the water and congregated on the aquarium walls above the waterline. The protozoan *Vorticella,* however, proved resistant to the synfuel treatment and became more abundant as sensitive species disappeared. From the third to seventh week after treatment, the community showed signs of recovery, as *Elodea* sprouted new roots and eventually re-established its population, snails returned to the water and reproduced, and several species of algae replaced the diatoms that did not recover. Giddings and Washington hope to use the results for planning large-scale experiments in outdoor ponds this year.

Ecological Effects of Gaseous Effluents

Atmospheric pollutants expected from advanced fossil energy facilities may inhibit growth of vegetation in ways that may be dependent on which gaseous pollutants are mixed together. J. W. Johnson, left, and Bill Selvidge load plant exposure chambers with snap bean plants which will be exposed to mixtures of gaseous pollutants typical of stack gases expected from coal conversion facilities. Results of experiments of this type indicate that plant response to a given pollutant in a gaseous mixture may or may not be dependent upon response to other pollutants in the mixture. It has been found that plant response to sulfur dioxide and nitrogen dioxide was dependent on the presence of ozone, but the response to SO_2 was independent of NO_2. These results suggest that the siting of additional sources of SO_2 and/or NO_2 in a region currently experiencing even relatively low ozone levels permitted by current standards may result in greater-than-additive impact on growth of sensitive vegetation species.

Aquatic Transport of Organic Contaminants

Polycyclic aromatic hydrocarbons (PAHs) and other trace organic contaminants expected to appear in surface waters near coal conversion operations are released in effluents from coal coking. To test laboratory-based predictions of transport behavior of contaminants, researchers from ORNL and the Pennsylvania State Department of Environmental Resources have measured PAH concentrations in water and sediment downstream from a coking wastewater discharge in Bethlehem, Pennsylvania. Results indicate that concentrations of nine major PAH compounds, including the carcinogens benz(a)anthracene and benzo(a)pyrene, persist in water and sediments for considerable distance from a coking discharge (and presumably from a coal conversion facility also). Sediments were found to contain more than 160 different PAHs, many of which degrade slowly (with half-lives of months or years) and are at concentrations up to 100,000 times as great as the same compounds found in overlying water. Research by Dave Shriner suggests that atmospheric deposition as well as coking effluent contributes to the elevated concentrations of PAHs in sediment. Samples were collected by two Pennsylvania scientists and Steve Herbes and George Southworth of ORNL's Environmental Sciences Division. More than 100 water and sediment samples were analyzed for PAH content by Wayne Griest, Mike Maskarinec, Roberta Reagan, Sara Harmon, and Hisa Kubota of the Analytical Chemistry Division. Carol Allen (ESD) and Gary Sayler (University of Tennessee Ecology Program) conducted supplemental assays of microbial activities in the water and sediments.

and leachates from solid residues may affect local areas. These contaminants are primarily gaseous oxides of sulfur and nitrogen and, to a lesser extent, hydrocarbons, particulate materials, and trace elements. A major reason for development of advanced fossil energy systems is to capture these materials before they reach the environment. Unfortunately, removal from one medium (air) may simply transfer the material to other media (solid residues and water), giving rise to a different set of potential problems.

The most severe environmental effects of coal use that have been documented are seen in the Scandinavian countries, where deposition of materials emitted from industrial complexes in western Europe has been shown to have increased the acidity of rain in Scandinavia and has seriously decreased productivity (fewer and smaller fish, for example) of several lakes. Similar effects of coal effluents appear to have occurred in the northeastern United States and the Canadian shield (see ORNL *Review*, Summer 1979). Fallout from coal combustion emissions has also been suspected of adversely affecting the microorganisms in the soil and potentially reducing total forest productivity.

At the present time, major efforts

PAH in Terrestrial Environments

Though polycyclic aromatic hydrocarbons are found in the natural environment apparently due to synthesis by some plants, the largest amounts of these compounds—many of which are carcinogenic—are found in industrialized areas where fossil fuels are consumed. Scientists are now studying the movement of PAHs through terrestrial food chains to learn the fate and effects of these "above background levels" of PAH. In the Environmental Sciences Division, N. T. Edwards and E. Groothuis have shown that anthracene (labeled with radioactive carbon-14) is taken up by bean plant roots from solution culture and translocated to the stems and leaves. They found some evidence that this PAH was also metabolized by the bean plants and plan further research to identify the anthracene metabolites. Here, B. M. Ross-Todd prepares an experiment for determining the influence of soil on anthracene uptake by bean plants. ORNL ecologists suspect that soil will have a strong attenuating effect on uptake of PAHs in plants and plan to test how varying environmental conditions affect soil's ability to reduce uptake.

are under way in North America and Europe to develop an understanding of the transport, transformation, and effects of atmospheric emissions of coal combustion so that an accurate estimate of future problems can be made.

Coal Liquefaction and Gasification

Coal liquefaction and gasification processes make use of high temperature, high pressure, and a reducing atmosphere which gives rise to a variety of organic compounds, many of which are not currently released in kind or quantities to the environment. Included in these are polycyclic aromatic hydrocarbons (PAH), the azaarenes and arylmines in particular. Specific compounds in each of these families have shown up with various human or environmental perturbations; hence, there is substantial interest in the quantities released, their ultimate fate in the environment, and the types of ecological effects they cause.

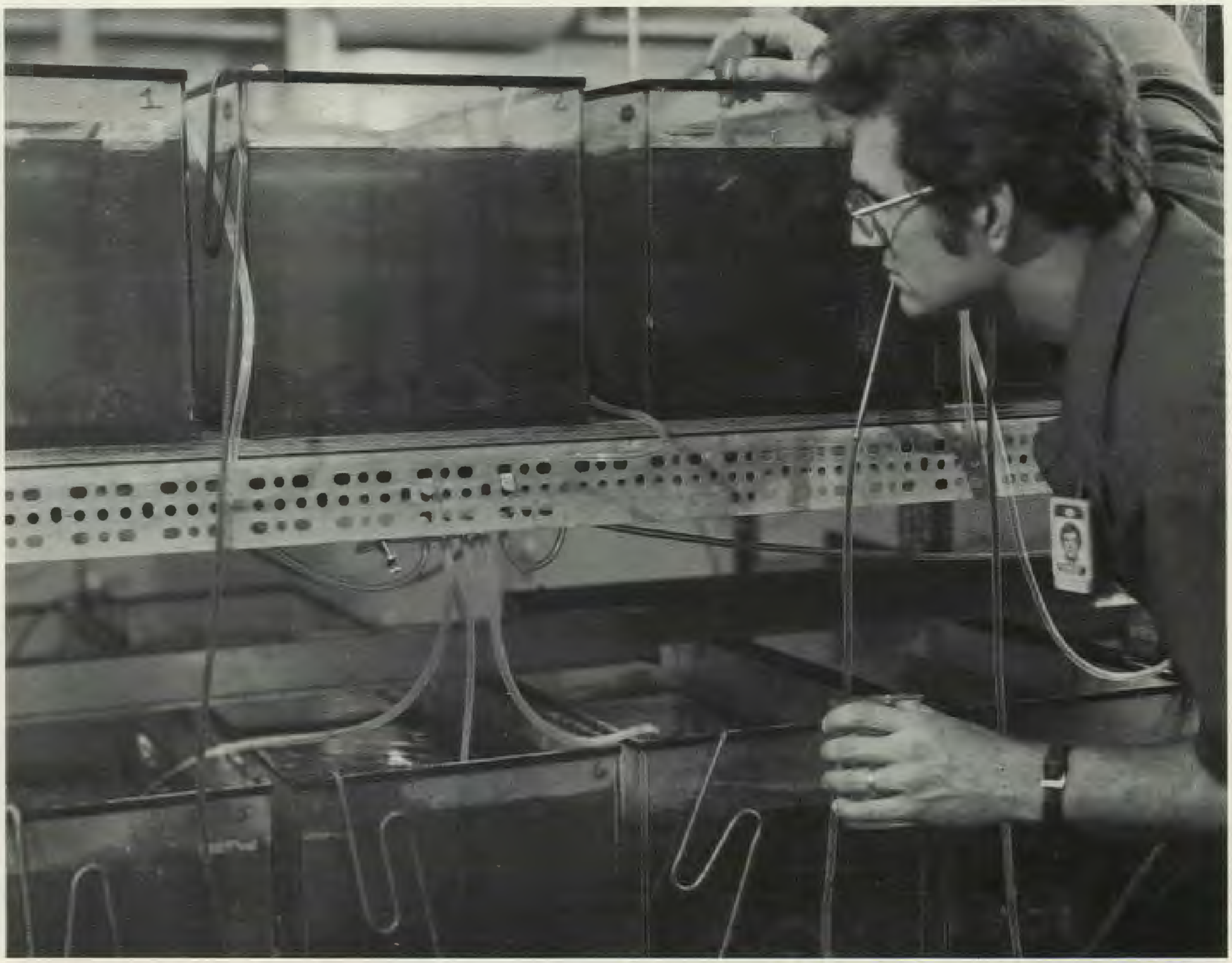
Identification and quantification of the *specific* ecological effects that may result from the various coal conversion processes is currently not possible because we don't know what, how much, or from what source (e.g., atmospheric releases as compared to solid residues) materials will reach the environment. Qualitative estimates can, however, be made.

If potential ecological effects associated with coal conversion differ from those observed with coal combustion, it will result from two factors: the unique compounds produced as a result of process characteristics and/or translocation of pollutants from one medium to another before being released to the environment.

The overriding long-range concern centers in the elevation of levels of CO_2 in the atmosphere, resulting in significant rises in average global temperature. Too much accumulation of heat could alter the global pattern of climate, leading to complex changes in the

Atmospheric Deposition to Vegetation

Sulfates and trace-element rich particles that escape the stacks of coal-fired power plants (including those equipped with particle control devices) linger in the atmosphere until deposited by gravity, wind, or rain on man-made structures, waterways, land, and vegetation. To measure the input of acidic sulfate and trace elements produced by coal combustion to a deciduous forest canopy, Steve Lindberg, Ralph Turner, Dave Shriner, Jan Coe, Philip Lowry, and Linda Mann of the Environmental Sciences Division have been involved in a large-scale field effort at the Walker Branch Experimental Watershed. Here, at left, Steve Lindberg is using a hydraulic lift to collect deposition plates in a tree canopy 20 m off the ground. He is also collecting leaves for comparison of the physical and chemical properties of deposited particles on these surfaces. At right is a scanning electron micrograph which shows particles of fly ash, emitted during fossil fuel combustion and deposited on a chestnut oak leaf. Conclusions from the initial two-year study are that (1) air concentrations and deposition rates reflect primarily regional rather than local source contributions; (2) particle settling by gravity is enhanced by the aggregation of small particles into heavier masses upon discharge from coal combustion plants; (3) particle-born trace elements can be dissolved in water to some extent, thus facilitating their movement into vegetation; (4) dry deposition contributes a significant fraction of the annual trace element transport to the forest landscape, although during heavy rainfalls the wet deposition rates can exceed dry deposition rates by 100 to 1000 times; and (5) atmospheric deposition as an external source of elements to the terrestrial ecosystem accounts for on the order of 50% of the total element transport to the forest floor.



Aquatic Effects of Coal Conversion

ORNL ecologists have been examining the toxic effects of different coal-derived materials on such aquatic organisms as *Daphnia* water fleas, fathead minnows, algae, and midges (tiny two-winged flies with aquatic larvae). Here, Ben Parkhurst checks out the system used to culture fathead minnows for screening tests. Other scientists at ORNL doing toxicity screening tests are Aubrey Bradshaw, J. L. Forte, G. P. Wright, R. E. Milleman, Jeff Giddings, Leon Washington, and R. M. Cushman. They have found that extracts from solid wastes generally are of low, acute toxicity to aquatic organisms and probably not a significant hazard. Untreated wastewaters were found to have high acute toxicities due to high concentrations of phenols. Biological oxidation can largely eliminate the phenols, but the treated wastewaters are still acutely toxic because of the presence of high concentrations of ammonia. The water soluble fractions of liquid products from coal conversion processes were found to have a much higher toxicity to aquatic organisms than similar petroleum products. These results suggest that spills of coal-derived oils could have a much more adverse impact on the aquatic environment than comparable spills of petroleum products.

generalized paths of storms and air masses (lows and highs, respectively) and to corresponding shifts in zones of natural and cultivated vegetation. These shifts will probably be detrimental, from the human perspective, in some regions and beneficial in others. Major efforts are currently under way to develop means for assessing the assimilative capability of the biosphere and predicting responses that may arise from increased CO_2 generation.

Atmospheric effluents from coal-conversion facilities will probably not cause direct significant acute effects to terrestrial ecosystems. This is a result of constraints likely to arise from EPA's New Source Performance Standards and standard and state implementation plans designed to achieve and maintain rational air quality standards. Chronic effects may occur, however, as a result of changes in pollutant mixtures (SO_x, NO_x, and ozone) as well as from products of the interactions of these substances with lesser studied pollutants such as hydrogen sulfide, carbonyl sulfide, carbon disulfide, and hydrocarbons. Probable types of effects include decreased rates of photosynthesis, increased rates of respiration, enzyme inhibition, and changes in membrane permeabilities.

Carl Gehrs

The major potential impacts on aquatic ecosystems resulting from coal conversion processes are in the areas of solid residue disposal, liquid effluents, and product (liquefaction only) spills. Primary concern with respect to residue disposal centers is in the modification of pH, the increased concentrations of trace elements, and the leachability of organic compounds in these residues. Aqueous effluents and product spills will provide the major load of organic contaminants to aquatic environments. They will also constitute the major difference in potential effects of combustion and conversion since aqueous additions from conventional combustion facilities consist primarily of ash-pond leaching. If conversion facilities can attain 'zero release' of aqueous effluents, then product-spill and residue-disposal leaching will become the major problems. Acute effects to various aquatic species will probably occur as a result, and in the vicinity, of product spills, but not from aqueous effluent releases or solid residue leachates. More widespread chronic effects may come about by the continuous addition of organic contaminants from aqueous effluents and solid residue leachates. The types of effects include decreased feeding and reproduction and increased respiration and neurological disorders, resulting in decreased productivity and potential displacement of sensitive species.

Space does not allow discussion of any of the potential environmental effects of coal utilization in depth, or even all in general. For example, a major concern of ecologists is the ultimate fate and availability of materials with potential human health effects in the environment. That area was not included in this overview. We would direct the reader to an in-depth review of the potential environmental effects of increased coal utilization included in the National Academy of Science-sponsored Second Supplementary Volume to *Chemistry of Coal Utilization* soon to be released by Wiley-Interscience.

Atmospheric Pollutants

In order to evaluate environmental impacts of an advanced fossil fuel facility such as a coal gasification plant, it is necessary to be able to predict where the atmospheric pollutants go after leaving the point source. Many proposed sites in the eastern United States are located in areas of complex terrain where existing models of atmospheric dispersion are of little aid in identifying dispersion patterns. The dispersion of a smoke bomb released at the site of a demonstration coal gasification facility under construction in eastern Kentucky has been recorded by scientists from ORNL's Environmental Sciences Division, working with meteorologists from NOAA's Atmospheric Turbulence and Diffusion Laboratory in Oak Ridge. These data will help scientists predict the patterns of atmospheric dispersion expected to occur with the plume from the operating gasifier.

Assessing Impacts of Coal Conversion:

Environmental Analyses at ORNL.

By CHARLES BOSTON, Environmental Impact Section, Energy Division

The fossil energy impacts group under Chuck Boston holds a work session in the Energy Division. From left, Roger Kroodsma, Frank Kornegay, Dick Ketelle (standing), Bob DeVault, Dick Roop, Elly Triegel, Steve Decicco, and Allen Witten.

The ORNL involvement in assessing impacts of coal conversion resulted from the confluence of two important national trends in the 1970s: the American concern about industrial assaults on human health and the environment, and renewed interest in and government support for making synthetic fuels from our abundant supplies of coal to reduce our dependence on foreign sources of oil. Environmental concerns have been translated into federal legislation, notably the National Environmental Policy Act (NEPA) of 1970. NEPA calls for environmental impact statements on federally licensed or supported projects. Thus, impact statements are required for synthetic fuels projects that are partially financed by the federal government. The proposed demonstration coal-conversion plants, which will be the step between pilot plants and full-scale commercial plants, are to be financed equally by the federal government and the industrial partner (with the understanding that DOE will withdraw from the joint venture when the operation

How ORNL Helps DOE

The Laboratory has a key role in assisting DOE in all six of its large demonstration projects to convert coal to synthetic fuels. These plants are all in the conceptual design stage and fall into three categories: high-Btu gasification, medium-Btu gasification, and liquefaction. Proposed sites are in Illinois, Kentucky, Ohio, Tennessee, and West Virginia. A liquefaction plant and a medium-Btu gasification plant are proposed for two different sites in Kentucky. Decisions on going ahead with construction will be made in the spring or summer of 1980. Demonstration plant operation may start as early as 1983-84, with commercial operation scheduled to begin in the mid to late 1980s.

By working with DOE to ensure compliance with NEPA, ORNL has had the opportunity of becoming involved in virtually all aspects of these important projects. Because ORNL has accepted responsibility for writing the environmental impact statements and because each statement must address the project in its entirety, ORNL has had access to large amounts of information ranging from highly technical process data to socioeconomic studies.

Writers of impact statements are required to address the impacts of leachates from coal-storage piles and storage areas for coal conversion ash and slag. An ORNL assessment of this problem was carried out early in the demonstration program. The assessment document, "Environmental and Health Aspects of Disposal of Solid Wastes from Coal Conversion: An Information Assessment," was prepared under the direction of Helen Braunstein and indicated a serious need for experimental work in this area. To provide the necessary data and to ensure compliance with regulations anticipated under the Resource Conservation and Recovery Act, DOE has sponsored the Fossil Energy Environmental Project's stored solids study, described by Bill Boegly elsewhere in this issue.

ORNL's initial involvement in the demonstration program produced two generic guideline documents. One of these offers guidance to potential DOE contractors on how best to respond to requests for proposals and also gives advice to successful bidders on what to include in their environmental reports. The second guideline document, "Environmental Monitoring Handbook for Coal Conversion Facilities," was prepared under the direction of Steve DeCicco and Marti Salk. It describes in detail the environmental and socioeconomic monitoring programs that should be conducted in the preconstruction, construction, and operating phases of the projects. The purpose of preconstruction (or baseline) monitoring is to provide a reference point in assessing environmental and socioeconomic impacts of construction and operation. A third document, "Environmental Analyses for Pipeline Gas Demonstration Plants," prepared early on under the direction of Lisa Stinton, provides a reference base for subsequent site-specific and process-specific impact analyses.

Later, as DOE signed contracts with various industrial partners, ORNL served in a consulting role to develop site-specific, baseline monitoring programs for each of the six demonstration plants. In each case the ORNL handbook served as the basic guidance document. For all six projects at least a year's data have been collected, analyzed, and delivered to DOE and ORNL in the industrial partner's Environmental Report at a cost of about a million dollars. This cost is borne entirely by DOE as are all other costs during Phase I (conceptual design).

As we begin the fourth year of this project, we are at a crucial stage in the entire NEPA process. As fate would have it, schedules which were somewhat staggered initially have now shifted until they virtually coincide. This overlapping has necessitated a larger commitment of personnel over the critical writing period between receipt of the environmental report and completion of the preliminary draft impact statement. We were fortunate in having highly qualified subcontractor personnel available to assist our in-house "core group" during this unusual (and unavoidable) peak in manpower demand.

The "core group" will have ultimate responsibility for the critical analyses of impacts in all environmental statements. Key individuals making up the core group, by discipline, are Steve DeCicco, project manager; Bob DeVault, socioeconomics; Dick Ketelle, geohydrology; Frank Kornegay, air quality; Roger Kroodsma, terrestrial ecology; Elly Triegel, geohydrology; Bob Reed, ecology coordinator; Dick Roop, aquatic ecology, and Alan Witten, project manager. The statements will be issued this year.

According to current schedules, draft impact statements for all six projects are to be issued in the spring of 1980. A 30-day waiting period to permit possible litigation follows issuance of the final impact statement after which construction may begin.

Coal to Synfuels Demonstration Projects

Project	Industrial partner	Process type	Process	Proposed site
CONOCO	Continental Oil Co.	High-Btu gasification	British Slagging Lurgi	Noble County, Ohio
ICGG	Illinois Coal Gasification Group	High-Btu gasification	COGAS	Perry County, Illinois
Grace	W. R. Grace Chemical Co.	Medium-Btu gasification	Texaco	Henderson County, Kentucky
MLGW	Memphis Light, Gas and Water	Medium-Btu gasification	U-Gas	Shelby County, Tennessee
SRC-I	Southern Co. Services	Liquefaction	SRC-I	Daviess County, Kentucky
SRC-II	Gulf Mineral Resources Co.	Liquefaction	SRC-II	Monongalia County, West Virginia

of the plant is proven, at which time the industrial partner will purchase DOE's portion). The environmental impacts of the proposed demonstration plants will be addressed in NEPA-required assessments and the more detailed statements.

Although it is fashionable, in some circles at least, to blame environmental regulations including NEPA for many of the country's ills, the facts according to the Council for Environmental Quality's 1978 annual report would seem to indicate otherwise. Pollution control investments, which seem enormous when viewed alone, have been running at only about 2% of the gross national product over the past few years and in 1978 amounted to less than 5% of total business investment in plant and equipment. The total cost of all federal environmental regulations (air, water, solid waste, etc.) is currently running at an annual rate of about $30 billion in 1977 dollars ($130 per capita). The benefits are very difficult to measure but are estimated for air pollution control *alone* at about $27 billion for 1980. If one adds the benefits from water quality controls, solid waste controls, and others (excluding aesthetics) it would appear that the investment is already paying off. Furthermore, as the period of backfitting draws to a close and as environmentally damaged systems continue to recover in the early 1980s, the payoff should increase dramatically.

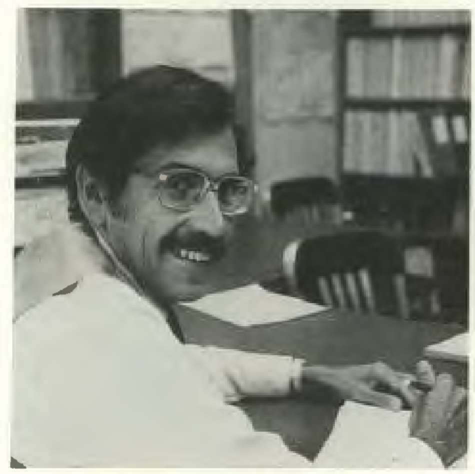
Environmental assessments and impact statements weigh the benefits of energy-producing facilities against the potential hazards of such facilities to the environment and human health. Research at ORNL has found or corroborated evidence indicating the potential hazards of certain constituents of coal gasification and liquefaction products, liquid discharges, and gaseous emissions. Low levels of aromatic amines and phenols in effluents have been found to be toxic to fish. Trace metals that may be concentrated in the human food chain can adversely affect the hatchability of fish eggs. Polycyclic aromatic hydrocarbons which may occur in products and effluents have been shown to cause cancer in animals. Gaseous emissions such as benzene and carbonyl sulfide have been found to inhibit photosynthesis in plants. Disposal of solid wastes from coal conversion facilities poses potential environmental problems due to toxic materials that may be leached out of landfills into groundwater and carried beyond the disposal site. Impact statements recommend measures needed to reduce adverse impacts on the environment.

Coal conversion plants also have social and economic impacts that must be addressed in impact statements. On the positive side, they provide jobs and may generate property tax revenue which may result in increased services and lower taxes. On the negative side, coal conversion projects may bring a large construction force into the community, imposing a heavy burden on local government services such as schools, sewage treatment, road maintenance, and police and fire protection. Other impacts include wage inflation and an increased demand for housing. All these socioeconomic impacts must be considered in the NEPA-required statements, and, if necessary, measures to mitigate negative impacts of coal conversion plants on communities should be taken.

The Fossil Energy Environmental Project in the Energy Division has been assessing the environmental and socioeconomic problems posed by siting coal conversion plants in three major coal-producing regions of the United States—Appalachia and the central and western states. Questions addressed by these assessments pertain to the availability of water, quality and quantity of coal to be used, suitability of geologic and climatic conditions, transportation problems, availability of skilled construction labor, and other socioeconomic considerations. Siting factors are often contingent on the process used or the product. For example, high-Btu gas plants should have pipelines available to transport the product, whereas medium-Btu plants should be located near industries that can use the fuel.

Since autumn of 1976, ORNL has been aiding DOE's coal conversion demonstration

Charles Boston



New Projects

In addition to providing environmental assistance to the synthetic fuels demonstration program, the Laboratory is initiating work in two other fossil-related areas. The first of these new projects, initiated by Tom Row and Bob Van Hook, is basically a key support role to DOE's Office of Plans and Technology. The Laboratory will assist in the development and implementation of the necessary environmental aspects of DOE's Fossil Energy Programs.

The second of the new fossil projects is in support of DOE's Economic Regulatory Administration (ERA) in its enforcement of regulations implementing the Industrial Power Plant and Fuel Use Act of 1977. The Fuel Use Act was passed by Congress with the intent of reducing oil and natural gas consumption by utilities and major fuel-burning installations. In carrying out this intent, ERA will be evaluating the conversion of facilities from oil and gas to alternative fuels, such as coal. These evaluations encompass the engineering feasibility of conversion, consideration of pollution-abatement equipment, fuel availability and transport, and environmental effects of conversion, among other considerations. This project promises to be a challenging venture with analysis and research activities. And, like the other efforts of the assessment programs, this work aims at simultaneously meeting national goals of energy production and environmental protection.

program in four general areas: environmental assessment, guidance to demonstration plant contractors regarding environmental obligations, experimental studies of stored solid wastes from coal conversion, and guidance to contractors in environmental monitoring. The approach historically adopted by the program has been a deliberate, step-by-step investigation to ensure a sound basis on which to proceed safely with siting, construction, and operation of large demonstration plants, which will typically consume 2000–6000 tons/day of coal.

Because the demonstration plants provide the first real test of commercial-scale equipment, they are extremely important to the development of a synthetic fuels industry that is environmentally acceptable. Plant sponsors should know in advance about environmental requirements before making their construction and operations plans or deciding on the type of environmental control technology to be included in the engineering design. Environmental control technology includes effluent treatment systems, such as devices to remove phenols and other toxic substances from waste streams. Early definition of control measures also allows the associated costs to be included in the economic evaluation of the demonstration facility.

New Regulations

ORNL has been involved in the NEPA process almost since its enactment on January 1, 1970. During the first decade of NEPA, we prepared over 200 statements and assessments primarily related to nuclear developments but also covering other areas such as geothermal wells, biomass applications, enhanced oil recovery projects, and energy policy. Our pioneering efforts in nuclear statements are now being matched by our preparation of the first statements for large, federally sponsored synfuels projects.

Our impact statements for synthetic fuels demonstration plants are pioneering efforts in another important respect. They will be our first statements prepared under the new regulations issued by the Council on Environmental Quality (CEQ), a high-level policy-making group in the White House. Previously, CEQ provided only guidelines that permitted considerable variability in the format and content of impact statements.

The new regulations, which specify what aspects should be covered and the format to be used, are now in force and should greatly improve the quality and effectiveness of environmental impact statements.

A new activity for the Laboratory as a result of CEQ regulations is our participation in what are called public scoping meetings. These public meetings may be held in advance of impact statement preparation to solicit input from, and identify concerns of, all interested parties. DOE elected to hold such meetings near the proposed sites for all six coal conversion demonstration projects. Project managers Alan Witten and Steve DeCicco participated as panel members at the public scoping meetings for their respective projects. The lead agency, in this case DOE, is responsible for conducting the meeting. The results have been encouraging. The meetings not only accomplished the stated purpose of identifying public concerns and providing input to the impact statement process but also permitted public involvement in a critical energy area. Local citizens and organizations were pleased that they were being heard at the outset of the project before the environmental impact statement was an accomplished fact.

What happens after the final impact statements are issued and the demonstration plants are under construction or operating? A natural follow-up activity that is required by the new CEQ regulations is monitoring of construction and operation. As a part of the impact statement recommendations, environmental monitoring programs are set up during construction and operation to ensure that adverse impacts do not go undetected. In many cases corrective or mitigating measures are prescribed based on the results of such monitoring. In this sense the impact statement is not just a one-shot document to aid decision making but also a promissory note ensuring continued protection of the environment and the communities affected. This is extremely important in this type of program, a goal of which is "to demonstrate environmental acceptability."

Another important follow-up activity which DOE may be willing to support is a kind of post mortem to improve assessment methodologies. Actual impacts occurring at operating plants are compared with projected impacts. Predictive models can then be refined resulting in more accurate projections in future impact statements and more realistic monitoring programs.

awards and appointments

The award for the best paper presented at the June 1979 annual meeting of the American Nuclear Society's Radiation Protection and Shielding Division went to **R. T. Santoro, R. A. Lillie, R. G. Asmiller, Jr.,** and **J. M. Barnes** for their paper, "Shielding Calculations for the TFTR Neutral-Beam Injectors."

Pete Pasqua has been named chairman of the local section of the American Nuclear Society. Vice chairman is **Mel Feldman,** and treasurer is **Don Steiner.**

LaRue Foster received the Golden Pen Merit Award in the individual writing category, editorial division, for her editorial, "... from a lack of roses," published in the ORNL *Lab News,* October 1978. The award was presented by the International Association of Business Communicators, Chattanooga chapter.

Edward C. Beahm and **Charles A. Culpepper** received an award for a technical paper making a significant contribution to materials development for the nuclear industry, "Basic Compatibility Studies of Advanced Fuels with 3D Transition Metals," from the American Nuclear Society. The paper was given at an ANS annual meeting.

C. R. Kennedy was chosen to present one of four plenary lectures given at the 14th Biennial Conference on Carbon held at Pennsylvania State University in June.

Greg Clark was awarded the Pawsey Medal of the Australian Academy of Science honoring his research on properties of solids, using nuclear techniques.

The Radiation Protection and Shielding Division of the American Nuclear Society has chosen **Fred Mynatt** and **Ward Engle, Jr.,** to receive Technical Achievement Awards for their work in solving radiation transport problems.

Jerry Swanks has been named assistant director of the Operations Division.

Ernie Silver has been appointed chairman of the Forum Committee of the American Nuclear Society.

Clair J. Collins is a recipient of the 1979 Southern Chemist Award presented by the Memphis Section of the American Chemical Society.

Nancy Johnston Dudney and **Ruth J. Maddigan** have been named recipients of Wigner postdoctoral fellowships by Herman Postma, ORNL director. This fellowship program was established in 1976 to honor Eugene P. Wigner, Nobel laureate and first director of research and development for Clinton Laboratories, predecessor of ORNL.

Steve Hamley has been certified as a radiation protection technologist by the National Registry of Radiation Protection Technologists (NRRPT).

Edward W. Hagen has been elected a Fellow of the Instrument Society of America.

Roy G. Cardwell is the recipient of the first Special Service Award presented by the Institute of Nuclear Materials Management.

The 1979 Radiation Industry Award has been presented to **John Cleland** by the American Nuclear Society for his pioneering research on the neutron transmutation doping of semiconductors, leading to its industrial application to silicon for semiconductor devices.

Chuck Coutant has been elected chairman of the Electric Power Research Institute's advisory council.

Ed Kobisk was recently elected president of the International Nuclear Target Development Society for a one-year term.

The 1979 Kirkpatrick Chemical Engineering Achievement Award, given biannually by *Chemical Engineering* to an institution that has shown outstanding group effort in new chemical engineering technology commercialized over the previous two years, went to Union Carbide Corporation for its development of a new, low-density polyethylene. Of the four Honor Awards bestowed on the same occasion, the first was given to Oak Ridge National Laboratory for its successful recovery of uranium from phosphoric acid used for fertilizer. This work, described in the Fall 1978 *Review,* and performed in the Chemistry Division, was based on an invention credited to **Fred H. Hurst, Jr., David J. Crouse, Allen D. Ryon, Wesley D. Arnold, Keith B. Brown, Charles F. Baes, Charles F. Coleman, Iran L. Thomas,** and **William B. Howerton.**

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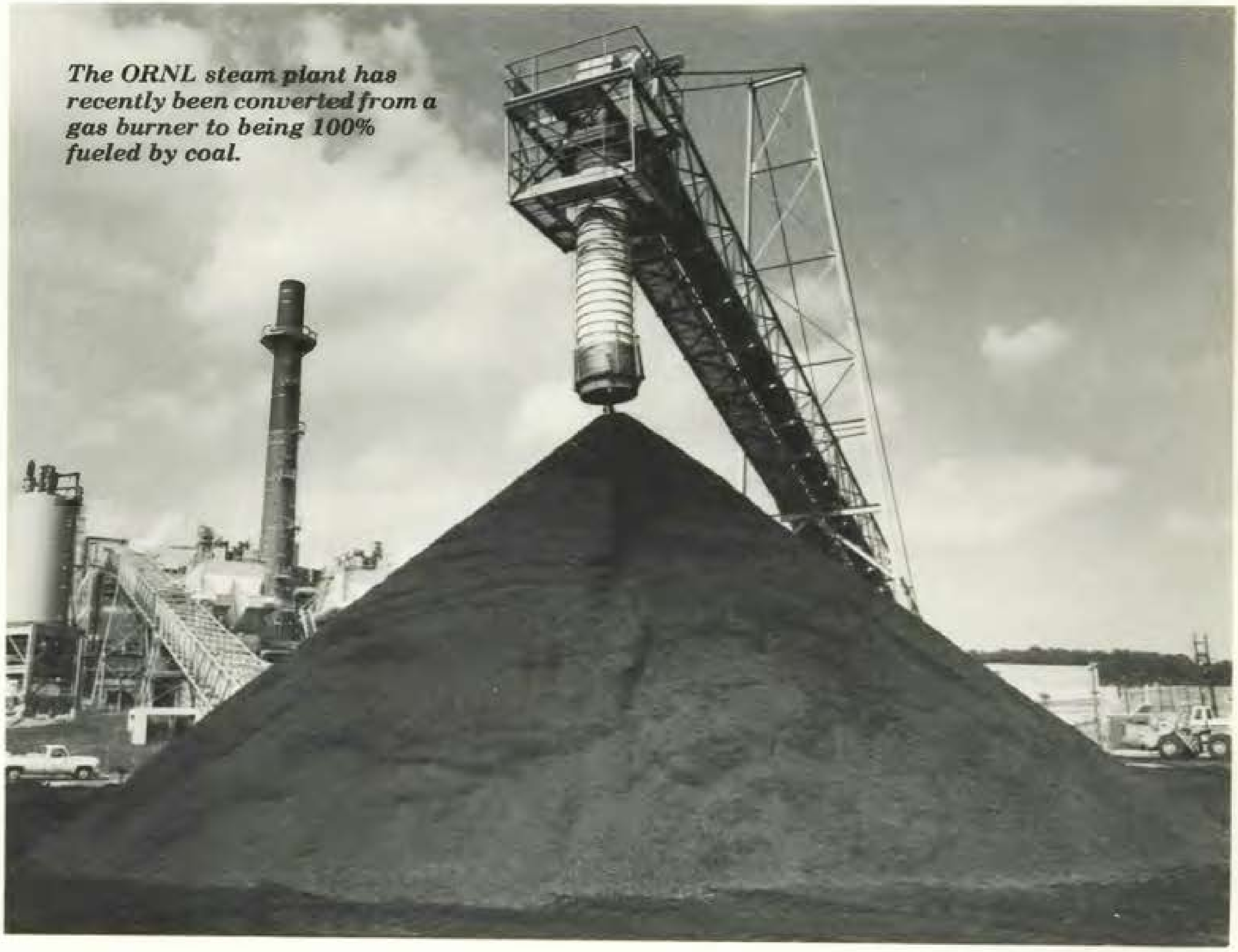

The ORNL steam plant has recently been converted from a gas burner to being 100% fueled by coal.