persed by evaporation from cannisters placed throughout the city or possibly sprayed from moving vehicles or aircraft. If a test is conducted in Jerusalem, DEHA will probably be sprayed from a truck patrolling the highways. Altshuller and others argue that Heicklen has not given enough consideration to whether the chemical would reach a great enough height to be effective. But Heicklen contends that if DEHA is released near highways, it will be transported anywhere the pollutants are carried.

Another potential problem might be the effect of DEHA on other living organisms, but Heicklen argues that there is no evidence to support such a possibility. In fact, Pennwalt is currently studying application of DEHA to the surfaces of plants as an antioxidant to prevent damage from ozone. The only major question now, he feels, is its potential toxicity to man, and that is something that can be determined only through more extensive testing.

The reaction among Heicklen's peers is mainly negative. Many, in fact, seem to want to dismiss the proposal out of hand. It is often dismissed with a vehemence that seems inappropriate in a scientific discussion, although many of the arguments unquestionably deserve further consideration. Among the foremost critics are James N. Pitts, Jr., of the University of California at Riverside, Jack Calvert of Ohio State University, and Altshuller. That their views represent those of the majority is demonstrated by a recent incident that followed Heicklen's presentation of the proposal at a scientific meeting. Heicklen's paper received only scattered applause, but Pitts' impassioned response from the audience received vigorous applause.

Pitts' primary objection to Heicklen's proposal is that the effects of DEHA and its oxidation products on humans are not known. He is particularly concerned that DEHA is structurally similar to the notorious carcinogen diethylnitrosamine [$(C_2H_5)_2N{-}NO$], and thus potentially quite dangerous. Legator's failure to find mutagenic activity, however, would seem to suggest that the resemblance between the two compounds is only superficial. Pitts argues, and Heicklen agrees, that very detailed studies of the effects of DEHA should be conducted before direct exposure of the general public is seriously considered.

Pitts also argues that extrapolation of Heicklen's results in the smog chamber to real urban atmospheres is questionable. He and Altshuller argue that the principal effect of a free-radical scavenger would be simply to delay formation of smog, and thus simply move the problem downwind. The pollutants that did not react to form ozone over the initial city would react later to form it over the suburbs, over a rural area, or perhaps even over another city. Altshuller notes that this has already happened as a result of automobile emission controls that reduce emissions of hydrocarbons, but not of nitrogen oxides. Rural ozone levels are high in some areas already, and use of DEHA might simply make the situation worse. Calvert is also concerned that DEHA might undergo unforeseen reactions downwind to produce even worse pollutants.

Pitts contends, furthermore, that exposure of everyone in a city to DEHA would be an abridgement of individual rights, since there would be no way to avoid it short of leaving the city. He rejects the analogy to treatment of water with chlorine or fluoride. In these cases, he contends, the benefits are clearly identified and the risks are equally well identified, whereas neither the benefits nor the risks are clear with chemical prevention of smog. Heicklen says that the exact same arguments can be applied against catalytic converters.

Finally, Pitts says, there is a very clear moral issue involved, since the project would involve exposing the whole population of a city to a chemical with demonstrated side effects. But it may be that the issue is not all that clear. The use of DEHA would require the same kind of delicate balancing of risks and benefits that is required, for example, for drugs, food additives, chlorine in water, or even catalytic converters. And this may be a problem that cannot be settled until those risks and benefits are more clearly defined.

There seem to be very few scientists occupying the middle ground. One of the few is Sidney Benson of the University of Southern California. Benson concedes that, at first, he thought the idea sounded "pretty idiotic." And even now he thinks that there must be a much greater investigation of potential hazards before any experiments are conducted in the atmosphere. But he thinks Heicklen has given careful consideration to most of the problems involved and has given a satisfactory response to the most important criticisms. He thinks that the concept might possibly be sound and that, at the very least, more research should be undertaken to identify and quantify the risks.

Many of the arguments may be moot. Until the question of mutagenic activity is resolved, there obviously will be no atmospheric tests. If the mutagenic question is resolved satisfactorily, it will still probably be necessary to test DEHA for carcinogenicity, and that would take at least 2 years. If DEHA is found to present a mutagenic hazard, then Heicklen must go back to square one with a new chemical. He already has a candidate, a DEHA analog that would probably not be metabolized. But Heicklen does not have the research funds to begin again with a new chemical and the disqualification of DEHA might, to the immense relief of many other scientists, sound the death knell for the concept as well.—THOMAS H. MAUGH II

Coal Research (III): Liquefaction Has Far to Go

Liquefaction is perhaps the most difficult of coal conversion techniques. Not only is it technically demanding, requiring subtle rearrangements of coal's chemical structure to incorporate additional hydrogen, but liquefaction faces economic barriers to commercial use that may well prove more difficult to overcome than those of new gasification and direct combustion techniques. Nonetheless, liquefaction of coal will clearly be needed to supplement and then supplant petroleum—perhaps before too long, although there is debate about exactly when. Domestically, oil production has been declining since 1970 and imports have climbed to 40 percent of total consumption. Worldwide, consumption of oil exceeds the rate at which new supplies are being found. Coal is by far the largest potential source of substitute liquid fuels.

Liquefaction of coal in the true sense of that term is still an unattained goal. Existing commercial processes for converting coal to liquid fuels gasify the coal first and then synthesize a liquid product. The process is inherently inefficient, since it involves high temperatures and the breaking of all the carbon-carbon chemical bonds in the coal material before putting some of them back together again. Hence new methods for liquefying coal directly or refining it to a clean fuel under conditions much less extreme than those of gasification hold considerable technical promise.

Coal is liquefied by exposing it to hydrogen gas or a hydrogen-bearing solvent under pressure and, in many processes, in the presence of a catalyst. Temperatures are kept below 900°F so that hydrocarbon molecules are not destroyed. Alternately, coal can be destructively distilled by heating in such a way that its volatile components are given off and can be condensed as a liquid. The net result is to add hydrogen or remove carbon, in the process shortening the length of the hydrocarbon molecular chains. Hydrogen is generated by gasifying a portion of the coal or of a coal residue in most schemes, and this is a substantial part of the cost of liquefaction. Sulfur content of the coal is also an important constraint, since hydrogen is also needed to remove this contaminant (as hydrogen sulfide gas) in proportion to the amount of sulfur present. In theory, it is somewhat easier and cheaper to make a heavy oil suitable for a boiler fuel than a synthetic crude oil that can be refined to gasoline, since the crude oil product requires adding about twice as much hydrogen—between 5 and 10 percent of the coal's weight. Boiler fuels may also have an economic advantage in that they would supply a regulated market—the electric utility industry that now generates about 30 percent of its power with oil and natural gas—making commercial introduction somewhat easier.

The only operating coal-to-liquids plant in the world today is located in Sasolburg, South Africa (Fig. 1). Built by a South African government corporation in the early 1950's, the plant is the prototype of a mine-mouth coal refinery. It produces synthetic gasoline and other motor fuels, along with pipeline gas, ammonia, and other products. Coal is gasified to produce synthesis gas (carbon monoxide and hydrogen) and then, using the Fischer-Tropsch process originally developed in Germany, passed over a catalyst and partially converted to a mixture of hydrocarbons. The process is relatively inefficient, especially as a source of liquid fuels, and has attracted no commercial interest in the United States, where coal prices are much higher than in South Africa. The South Africans, however, concerned about their dependence on imported oil, have announced plans to build a second and much larger Fischer-Tropsch plant capable of producing the equivalent of about 40,000 barrels a day—nearly the size that would be considered a commercial facility in the United States, and an enormous undertaking for a country the size of South Africa.

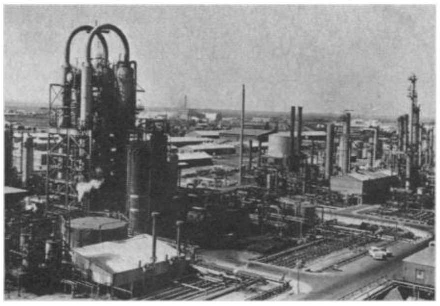

Fig. 1. Part of the Fischer-Tropsch coal-to-liquids plant, Sasolburg, South Africa. [Source: South African Coal, Oil, and Gas Corporation, Ltd.]

An alternative and equally proved coal-to-gas-to-liquids process, essentially a variation of Fischer-Tropsch with a different catalyst, converts synthesis gas from coal to alcohols, predominately methanol. The process is still inefficient and the product is consequently likely to be expensive. But it has been considered by U.S. companies as a replacement source of the methanol used in the chemical industry, which is now made from natural gas, although no plants have been announced. As a fuel, methanol is attractive because it burns cleanly, and it has been proposed as a motor fuel, either in pure form or blended with gasoline. More immediately, several electric utility companies have expressed an interest in methanol as a turbine fuel for peaking plants that operate only intermittently, where the fuel cost is less important. Most estimates, however, suggest that methanol from coal would be more expensive than imported oil and probably more expensive than the products of direct coal liquefaction processes, if and when they are available. Moreover, the prospect that oil-exporting countries might convert some of their unused natural gas to methanol adds to the economic risk, since this fuel, even after shipment to the United States, could easily undersell methanol from coal.

New Processes

The economic problems of methanol are also those faced, in large measure, by the new coal liquefaction processes being pursued by the Energy Research and Development Administration (ERDA). They will be expensive, producing synthetic crude oil or clean boiler fuels at costs probably between $3 and $4 per million Btu—roughly the equivalent of oil costing $17 to $23 per barrel. (Imported oil now reaches the United States at a price of about $12.50 per barrel.) Nearly two-thirds of this cost is attributable to the capitol costs of these complex plants; a commercial liquefaction facility producing about 50,000 barrels a day would be expected to cost about $1 billion, if built today. The key economic question for liquefaction is thus how fast the price of crude oil will rise.

To judge from the difficulties ERDA has had in getting oil companies to put up money for cooperative research efforts, the industry consensus on when crude oil will cost $25 per barrel is none too favorable for commercial liquefaction before the early 1990's. ERDA itself no longer predicts any production of coal-based liquid synthetic fuels by 1985. Moreover, coal-based liquids face competition from shale oil, for which the technology is both simpler and further advanced. There is in fact no immediate need for synthetic oil, since imports are available. But the timing could be deceptive, since large pilot plants needed to resolve a host of engineering problems have not yet been built (a capacity of 600 tons per day is usually described as the smallest that will test commercial scale equipment). Beyond these, large demonstration or first-of-a-kind commercial plants will be needed to establish economic feasibility. Some observers believe 1990 will be a hard target to meet, as things now stand.

The design for an ERDA demonstration plant to make boiler fuel from coal is essentially complete, but there appears to be considerable doubt both in government and in industry that the project will go ahead (*Science*, 20 August, p. 665). Proposed by Coalcon, a joint venture of Union Carbide and Chemical Construction Company with a consortium of industrial backers, the design is based on a process developed in the 1950's by Union Carbide. As now contemplated, coal would be destructively distilled by heating under pressure in the presence of hydrogen, giving off a liquid product that contains about half of the coal's carbon. The remainder, in the form of an unreactive char, is gasified in a separate reactor and used to make both hydrogen and synthetic natural gas (methane), so that the plant would produce about half liquid fuel and half gas.

Most observers unconnected with Coalcon believe it is a promising process for research but is premature for a demonstration plant. They point to the fact that the Coalcon process has not been operated with caking coals that tend to stick together when heated, although the plant is to be located in Illinois and is to use local, caking coals. Moreover, some critics assert that the process as a whole has not been adequately tested on a smaller, pilot-plant scale, since the current design differs substantially from what was operated in the 1950's. In any case, estimated costs for the plant have risen considerably above what was originally contemplated, and ERDA has postponed any decision to go ahead with or to cancel the project until 1977. Whether or not Coalcon survives, there are no plans for another liquefaction demonstration plant at this time, according to Philip C. White, ERDA's assistant administrator for fossil energy.

Instead, the emphasis appears to be on pilot plants—one already in operation, a second and much larger plant in the final stages of negotiation between ERDA and industry, and a third being contemplated. These are, respectively, the Solvent Refined Coal process and the H-coal process, both originally developed with support from the Office of Coal Research (OCR), now ERDA, and the Donor Solvent process developed by Exxon. Still other processes are being investigated at more preliminary stages of development.

The Solvent Refined Coal process, developed by a subsidiary of Gulf Oil, is a method of dissolving coal to remove ash, reduce its sulfur content, and lower its average molecular weight. Pulverized coal is mixed with a solvent and with hydrogen and heated until most of it dissolves. Gases including hydrogen sulfide are removed, as are ash and other undissolved solids. A fraction of the remaining liquid is recycled as the solvent, and the rest is product, a low-sulfur boiler fuel that is a solid at room temperature but melts readily at about 375°F. The ERDA pilot plant at Ft. Lewis, Washington, has operated well, treating 50 tons of coal a day. White describes it as "our most advanced liquefaction process with respect to scale and operability." A second, smaller pilot plant owned by Southern Company Services has also tested the process.

An assessment of the process by the Electric Power Research Institute (EPRI) is optimistic about its technical feasibility, although whether the product can be readily burned in power plants is still unproved. A major combustion test of the fuel is about to get under way. The cost of solvent refining, however, will not be low; EPRI estimates it at about $1 billion for a commercial plant capable of processing more than 15,000 tons of coal a day. At that cost the process is not a competitor to stack-gas scrubbing or other means of burning coal cleanly in new facilities. Rather the market for solvent refined coal appears to be as a low-sulfur fuel for old coal-fired power plants which are operated only intermittently and for which it is not economically feasible to install antipollution devices. That is still a substantial market, but observers point out that the process is a "live technology" only if certain regulatory decisions go favorably. In particular, they note, the sulfur dioxide emission standards for liquid fuels are stricter than those for solid fuels, too strict perhaps for solvent refined coal to meet unless it is classified as a solid. In addition, shipping rates for the fuel may depend on whether it is classified as coal or as a higher-tariff manufactured product, and the difference could make or break its economic feasibility.

Catalysts Play a Key Role

Solvent refining is not a catalytic process, but most true liquefaction processes such as H-coal and Donor Solvent do employ catalysts to accelerate the hydrogenation of coal. In fact, modern hydrocracking catalysts developed for petroleum refining are the major reason that the liquefaction processes now under development are far more attractive than those tried by Germany during the 1930's and operated at full industrial scale during World War II, before being later abandoned. These catalysts permit reactors operating at pressures of 150 to 200 atmospheres, compared to nearly 700 atmospheres for the German processes, and provide for more efficient utilization of hydrogen.

The H-coal process, developed by Hydrocarbon Research, Inc., converts coal to oil by hydrogenating it directly. The sequence of processing steps is essentially the same as in solvent refining except that the mixture of finely ground coal, recycled oil, and hydrogen is reacted in the presence of a catalyst. The key feature of the process is the reactor, known as an "ebullating" bed because the flow of reactants upward through the vessel suspends the granular catalyst particles and thus helps to ensure good contact with them. Spent catalyst is removed and discarded. The process can produce either synthetic crude oil or, by lowering the reactor temperature and adding less hydrogen, a heavy-oil boiler fuel. Producing the needed quantities of hydrogen as a by-product of the process itself and improving the techniques for separating unreacted solids from the product oil are among the most troublesome unsolved problems.

The H-coal process has so far operated only on a small scale. A 600-ton-per-day pilot plant—large enough to permit scaling up directly to a commercial facility—has been designed, but not yet built. Negotiations between ERDA and an industrial consortium that includes four major oil companies have stalled for months over the question of money. Normally for a pilot plant ERDA would put up two-thirds of the cost and industry the rest, but uncertainty over how soon liquefaction will be commercially feasible and concern about efforts in Congress to break up the large oil companies seems to have made industry unwilling to consider an R & D investment approaching $100 million. In an effort to get the project under way, ERDA recently offered to finance a larger portion of the plant.

Still more tentative are plans for a pilot plant based on the Donor Solvent process. The preliminary development of this process has been entirely by Exxon; ERDA began supporting operation of a small-scale unit in combination with the company only in July 1976. The process differs from H-coal in that hydrogenation of the coal is done indirectly, through a solvent that transfers hydrogen to the coal while extracting a liquid product. The solvent is regenerated by hydrogenating it catalytically in a separate reactor, which has the advantage that the catalyst material "sees" only clean liquids. Exxon is attempting to raise money from private backers for a cooperative pilot plant with ERDA, so far with little success, according to observers familiar with the project.

Even if the new pilot plant projects go ahead, liquefaction is some time away from being proved technically feasible. Eric Reichl of Continental Oil points out that the largest liquefaction reactors ever operated were German units with a capacity of processing 400 tons of coal per day. The reactors being discussed for eventual commercial use in the United States today would have capacities between 2000 and 8000 tons per day. But the largest now in operation processes only 50 tons per day and, as Reichl puts it, "solids handling is notoriously unpredictable so that we can expect some interesting extrapolation problems."

Economic feasibility—and what Reichl and others appear to view as much the same thing, political feasibility—may prove still more elusive. "It is above all," Reichl says, "a matter of national policy and not technology," pointing to the South African commitment to a new Fischer-Tropsch plant to reduce its dependence on imported oil. In the United States, however, the political climate is decidedly unfavorable to a major subsidized effort to produce synthetic oil, and the de facto policy is to buy oil abroad and damn the consequences. But it would be unfortunate if political and economic uncertainties combine to delay development of the liquefaction technologies that the country will surely need, possibly sooner than later.—ALLEN L. HAMMOND