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ENERGY TECHNOLOGY VI

RECENT DEVELOPMENTS IN COAL LIQUEFACTION IN THE UNITED STATES*

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1. INTRODUCTION

Because of the importance of liquid fuels to the economic health of the U.S., production of liquid fuels from coal is one of the major objectives of the U.S. synthetic fuels program. Our liquid fuels are obtained almost entirely from petroleum at present. The consumption of liquid fuels in the U.S. is enormous, about 17 million bbl/day, of which we currently import about half. These imports are one of the largest contributors to our balance of payments problem and the decline in value of our currency. Over half of the total consumption of liquid fuels is in the transportation sector: about 7.5 million bbl/day of gasoline, 1.1 million bbl/day of aircraft jet fuel, and about 1.3 million bbl/day of diesel fuel. Without revolutionary changes in our transportation systems, there is no alternative in sight for liquid fuels in these applications. In addition, large quantities of liquid fuels are used by the electric utility industry and by the industrial, commercial, and residential sectors. Some conversion to coal in the utility industry is possible, but there are many plants which would be impractical to convert both from a cost and an air quality point of view. Besides residual fuel oil for boilers, there is a need for lighter, more highly refined oils for combustion turbine and combined cycle systems.

In this paper we will discuss some of the recent developments in the U.S. coal liquefaction program. The order of presentation will be first, chemistry; second, process research and development; and finally, economics and commercialization.

2. CHEMISTRY

The initial development of processes for coal liquefaction has been largely empirical. This has been unavoidable because we have had very little knowledge of the chemical structure of the substances we have been trying to liquefy. However, it appears that progress is being made, and that we are now approaching the point where knowledge of chemical structure, reactivity of linkages, and specific chemical reactions can contribute toward the development of better processes. Implicit in all this work is the recognition of the relationship between structure and reactivity, which has been one of the most important advances in modern organic chemistry.

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At the 1978 Coal Chemistry Workshop sponsored by DOE and SRI at Menlo Park, California in March 1978, there were three discussion groups, one on coal structure and analysis, one on liquefaction, and one on gasification.[1] Current views on the chemical structure of coal were expressed by John Larsen, Peter Given, and others. The organic portion of coal appears to be a highly complex collection of macromolecules tied together by relatively weak linkages. The macromolecules, which have very high molecular weights, are composed of a aliphatic, aromatic, polyaromatic and substituted polyaromatic structures with a variety of functional groups, linked together in a variety of ways. The linkages between clusters include ethers and short methylene (CH_2) chains.

Coal liquefaction apparently proceeds in two stages. There is an initial rupturing of the weak bonds of the coal macrostructure which leads to large molecules that are soluble in pyridine. This is followed by cracking or hydrocracking reactions in which the large molecules are attacked at weak points including heteroatom linkages. Free radical fragments can be capped off by hydrogen leading to the production of more or less stable liquids and light gases. Or they can combine with each other leading to larger molecules and ultimately to coke. In some cases, free radicals can generate hydrogen atoms (particularly in the presence of gaseous hydrogen) which in turn can attack linkages between aromatic and aliphatic carbons. The relative roles of molecular hydrogen and donor hydrogen in these reactions is a question that has received a great deal of attention. The use of model compounds such as dibenzyl is helping to elucidate such questions.

Work at Mobil R & D Corporation and Exxon Research and Engineering Company has shown that heating coal for a few minutes at 425°C converts it into pyridine soluble material called asphaltols. In this way the coal, which is very difficult to study by chemical methods, is converted into a soluble substance more amenable to understanding. Since the asphaltols are undoubtedly intermediates for present and future liquefaction processes, their discovery and study are important for the future of this area. Research in various university, industrial and national laboratories has been influenced by initial studies at Mobil on the fractionation and characterization of conversion products of asphaltols obtained under typical solvent refining conditions. This includes work at Oak Ridge looking at the relative ease of breakage of bondings of the types thought to link the polynuclear units together in the coal polymer and also the relative abilities of various coals to donate hydrogen for capping off the radicals formed in such bond ruptures. Also at Oak Ridge radicals formed by pyrolytic bond rupture in pyrolysis of model compounds are being identified for the first time directly and in situ by electron spin resonance. The kinetics and mechanisms of these all important reactions can thus be followed and derived directly. At Exxon such mechanisms are being studied by chemical methods.

At Pittsburgh Energy Technical Center and at the University of Utah, excellent use of NMR methods has been made in studies of coal structure and reactions. At Utah, for example, NMR methods for solids, pioneered at MIT and Berkeley, have been applied with great advantage to coal itself and to coal derived liquids. These investigators find that the carbon skeletal structure of the coal polymer is substantially preserved in the coal derived liquids. The subtle differences they see are due to the breaking of the crucial bonds that allow the coal to be liquefied. So such studies, now only in their infancy, have great promise for the future understanding and development in this area.

Although the breaking down of the coal skeletal carbon structure occurs in all liquefaction schemes, in supercritical solvent extraction of coal the molecules trapped in the coal matrix assume a greater importance. These trapped molecules have been characterized at Argonne National Laboratory for several coals, including a high volatile Illinois bituminous. The main trapped molecules are found to be aliphatic, alicyclic and hydroaromatic compounds with a small admixture of heterocyclics. Importantly, the Argonne investigators studied initial pyrolysis reactions beginning at 250°C. The compounds produced by the initial pyrolysis were, in general, similar to those found in the trapped fraction with the difference that phenols made an appearance in abundance under pyrolysis although they were absent in the trapped fraction.

The Menlo Park workshop gave rise to a number of recommendations for priorities in coal research. Under coal structure and analysis, high priority was given to structure-reactivity relationships, liquefaction and pyrolysis products in chemical reactions, the chemical forms of oxygen, nitrogen, and sulfur; and the use of solid phase ^{13}C and ^{1}H nuclear magnetic resonance techniques in analyzing structure. The liquefaction discussion group gave top priorities to low severity techniques for breaking the coal structure into heavy liquids, noncatalytic methods of liquefaction, new techniques for removing nitrogen from coal liquids, the mechanisms of pyrolysis, the role of catalysts in the various stages of liquefaction, and the development of new catalysts having greater tolerance toward coking and metals poisoning.[1]

At the same meeting, the Coal Science Program of DOE's Office of University Activities was described. This Office is sponsoring university studies of coal characterization, structure, and chemistry, coal process applications, and the chemistry of coal liquids and gases. One of the large efforts is the Penn State coal sample and data bank project, which by the end of this year expects to have 1300 well-characterized samples, with data in 33 categories for each sample. Under structure and chemistry there are projects at seven universities; studies of new analytical techniques and separation methods are being supported at a number of universities; and process development applications including kinetics and mechanisms of coal process reactions are under investigation at Auburn, Penn State, Colorado School of Mines, and other locations. Other important areas currently being studied are catalyst development, upgrading of coal-derived liquids, and solid-liquid separations.[1]

We can expect that such studies will have an increasing impact on the development of improved liquefaction process sequences.

3. COAL LIQUEFACTION PROCESSES

For the purposes of this discussion, coal liquefaction processes will be divided into four categories, as shown in Fig. 1. These are (1) the direct liquefaction processes, typified by SRC-I and II, H-Coal, and Exxon Donor Solvent (EDS), in which a slurry of coal and solvent is subjected to high severity liquefaction conditions; (2) two-stage liquefaction, such as Conoco's CSF process, in which an initial dissolution at mild conditions is followed by a more severe catalytic hydrogenation-hydrocracking step; (3) pyrolysis and hydropyrolysis processes, such as COED, Cities Service, and Rocketdyne, in which coal is carbonized to produce liquids, gases, and char; and (4) indirect liquefaction, such as Fischer-Tropsch and methanol synthesis in which coal is first gasified to produce a synthesis gas which is then recombined to produce liquids.

3.1 Process Descriptions and Status

3.1.1 Direct Liquefaction

Simplified block flow diagrams for the SRC-I, SRC-II, H-Coal, and EDS processes are shown in Fig. 2 through 5. It should be noted that while these flow diagrams represent reasonable conceptual configurations, none of these processes have yet operated in a completely integrated fashion, and therefore, variations in practice may be pursued for technical or economic reasons.

These processes are all similar in that a slurry of coal in process-derived oil is subjected to fairly severe liquefaction conditions in the presence of hydrogen. The SRC-I and II processes use no catalyst, except that which is in the mineral matter of the coal, while the H-Coal and EDS processes rely on catalytic hydrogenation. H-Coal employs direct catalytic hydrogenation of the coal slurry in an ebullated bed reactor. The EDS process uses catalytic hydrogenation of the donor solvent, which is a distillate fraction, and thus avoids having the catalyst contact the heavy asphaltenes and tars and the mineral portion of the coal.

The SRC-I process is aimed at producing a fuel that can be burned by utilities for electric power generation. In addition, the SRC-I product is a building block from which liquid fuels and industrial and metallurgical coke can be produced. The reduction of sulfur content, nitrogen content, and particulate matter to regulatory levels are the principal process objectives.

In the SRC-I process (Fig. 2), the coal is slurried with a process-derived solvent and is pumped through a preheater into a dissolver. Hydrogen is added ahead of the preheater as well as downstream of the preheater. There is no added catalyst. Liquefaction conditions are in the general range of 800-900°F, about 2000 psig, and a residence time of 20-60 minutes.

A series of liquid-vapor separation steps provides recycle hydrogen, and distillation provides the recycle solvent. The solid-liquid separation step separates the main SRC product from the unreacted coal and ash. The carbonaceous portion of the residue is gasified to produce hydrogen for the process. The SRC product is a uniform, low-sulfur, low-ash solid material with a softening point of about 300°F and a heating value of about 32 million Btu/ton (16,000 Btu/lb). It can be pulverized and burned like coal, or it can be melted and burned like oil.

The SRC-II process (Fig. 3) is similar except that the hydrogenation severity is greater, the separation of solids and liquid is by vacuum distillation, and a slurry is recycled rather than a solvent. The main fuel oil products are distillate rather than residual materials. Because of the higher severity, the gas make and the hydrogen consumption are greater. But, because the products are lighter, the troublesome solid-liquid separation step can be accomplished by distillation, which is a relatively simple operation. Also, the sulfur and nitrogen contents of the fuels are lower than in the SRC-I product.

It is apparent that the mineral matter in the coal provides important catalytic activity (particularly for solvent hydrogenation reactions) in both SRC-I and SRC-II processes. It appears also that the solids recycle in the SRC-II process results in a higher inventory of catalytically-active mineral matter in the dissolver. This, as well as an increased residence time for the less volatile fraction in the dissolver, contributes to the higher degree of hydrogenation in this process relative to SRC-I.

Both SRC-I and SRC-II fuel products have undergone combustion tests in utility boilers with satisfactory results. In June 1977, 3000 tons of solid SRC-I fuel were burned successfully in a 22MW unit at Georgia Power Company's Plant Mitchell near Albany, Georgia. The pulverizers and coal feeders worked well after minor modifications, and showed a 25% increase in capacity and a 25% reduction in power consumption for a given electricity production. Stack emissions were reported to be within EPA limits. Boiler efficiency was the same as that obtained when firing coal.

In 1978, 4500 barrels of SRC-II liquid was burned successfully at a Consolidated Edison power station in New York City. NO_x levels from 175 to 300 ppm were obtained with a fuel nitrogen content of 1%. This is well within the proposed new source performance standards of 400 ppm for coal-derived liquids. Sulfur oxide and particulate emissions also were satisfactory.[2]

In the H-Coal process (Fig. 4), coal is slurried with a process-derived oil, pumped to reactor pressure, mixed with recycle and makeup hydrogen, and fed through a preheater to the ebullated bed reactor. The reactor feed and an internal liquid recycle stream enter the bottom of the reactor and cause the catalyst bed to expand and fluidize. Typical operating conditions are 2500-3000 psi and 850°F. An advantage of the ebullated bed is the high degree of backmixing which gives a more uniform temperature and makes it easier to control the exothermic heat of reaction. The reactor products leave the bed and are separated in a vapor-liquid separator for subsequent processing. The cobalt-moly on alumina catalyst remains in the bed, except for a portion which is withdrawn and replaced to maintain the desired level of catalyst activity. Catalyst consumption is estimated by HRI to be about 1 lb per ton of coal feed. A portion of the reactor effluent is hydrocloned to reduce its solids content and prepare a low-solids liquid stream for recycle to the feed slurry preparation tank. The remainder of the liquid product is vacuum distilled to produce naphtha and distillate fuel oil products plus a bottoms stream which goes to a gasifier for hydrogen production.

In the Exxon Donor Solvent (EDS) process (Fig. 5), the coal is slurried with a recycle donor solvent which has been catalytically hydrogenated to improve its hydrogen donor properties. The slurry is preheated and goes to the reactor along with recycle and makeup hydrogen. The reactor operates at about 2000 psi and 800-900°F; there is no added catalyst. The reactor effluent is distilled to obtain the recycle solvent which is then rehydrogenated in a fixed bed catalytic reactor. The liquid products are distillates; unreacted coal and ash are removed as bottoms from a vacuum distillation column and go to a Flexicoker/gasifier unit for recovery of additional liquids and production of fuel gas. Makeup hydrogen is produced by reforming the light hydrocarbon gases produced during liquefaction.

Status of direct liquefaction projects. The SRC-I process has been operated in a 6-TPD pilot plant at Wilsonville, Alabama, and in a 50-TPD pilot plant at Fort Lewis, Washington. The Fort Lewis plant has also operated in the SRC-II mode, in which case its throughput is reduced to about 30 TPD. The Fort Lewis plant is the largest operational coal liquefaction plant in the U.S. at this time.

Demonstration plants for both SRC-I and SRC-II are in the preliminary engineering stage, although it is possible that only one of these may be built. The SRC-I design is based on 6000 tons of coal per stream day, while the SRC-II design is based on 6670 tons per stream day, both using a 90% capacity factor. In 1978, DOE signed contracts with Southern Company Services and the Pittsburg & Midway Coal Mining Company for the preliminary design and cost estimation work on these plants. However, in late 1978 OMB decided to limit funding to only one of these projects. The outcome of this decision is still unresolved. At present, both Southern and P&M are proceeding with design and development studies.

Exxon is involved in an integrated R&D program which includes bench scale studies: 50 lb/day, 100 lb/day, and 1 T/day pilot plants and engineering and design studies. The program includes operation of a 250 T/day liquefaction pilot plant which is under construction and operation of a 70 T/day FLEXICOKING prototype unit, both of which are located in Baytown, Texas. The research and development program includes evaluation of lignites and subbituminous and bituminous coals as liquefaction feedstocks: coal liquids product testing and evaluation, engineering technology studies aimed at special equipment design features, and design studies for a conceptual commercial plant. Exxon includes studies of vacuum tower bottoms utilization which includes both FLEXICOKING and partial oxidation for process fuel gas and hydrogen production.[3,4]

Development and demonstration of the H-Coal process has been carried out in bench-scale units processing 25 lb of coal per day and in a process development unit handling 3.5 tons/day. Fourteen coal types have been evaluated, with a total of over 52.000 hours of operating experience. A large pilot plant is under construction at Catlettsburg, Kentucky that will have a capacity of 600 TPD in the boiler fuel mode or 200 TPD in the syncrude or high severity mode.[5]

Fig. 6 summarizes the schedules for the large pilot plants and demonstration plants of the direct liquefaction processes. The H-Coal pilot plant is scheduled to be completed in October of this year, and operations in both the boiler fuel and the syncrude mode will take place in the following two years.[5]

The 250-TPD EDS pilot plant at Baytown is now under construction and is expected to be completed by the end of 1979. Operations have been scheduled through the middle of 1982.[4]

Both the SRC-I and SRC-II demonstration plants were scheduled to be completed by the end of 1983. Phase zero conceptual design studies are underway for both plants. As indicated earlier, it is not certain that both will be built.

3.1.2 Two-stage liquefaction

In the two-stage approach to liquefaction, an initial dissolution step is followed, after removal of most of the solids, by a more severe hydrogenation to break down the large molecules and heteroatom compounds. A simplified flow diagram is shown in Fig. 7. As mentioned previously for the other processes, integrated operation has not yet been demonstrated.

Two-stage liquefaction is typified by Conoco Coal Development Company's CSF process, although a number of other companies are also doing work on the two-stage approach. The CSF process was piloted in a 20-TPD unit at Cresap, West Virginia, for several years, but pilot plant operation was discontinued around 1970. While the CSF Pilot Plant did not lead to plans for further development, demonstration, or commercialization, the potential of two-stage liquefaction remains high, and important developments in this area of liquefaction technology may be anticipated in the near future.

The rationale behind Conoco's two-stage approach is that the first stage extraction conditions can be relatively mild – about 300-500 psi, 700°F, with no catalyst or gaseous hydrogen. This step, therefore, is relatively inexpensive. Recycle solvent and donor solvent are used to achieve the initial dissolution or extraction. The depth of extraction is purposely limited so that subsequent gasification of unextracted residue will satisfy hydrogen requirements. After extraction, a rough separation of solids is achieved by settling. The settler overhead, containing about 1% solids, then goes to the second stage which is a high severity catalytic ebullated bed hydrogenation step using molecular hydrogen. Thus the expensive cobalt-moly catalyst is not exposed to most of the mineral matter and unreacted coal. This should tend to reduce catalyst consumption and make it easier to maintain catalyst activity although further experiments are still required to confirm the quantitative effects. Recent studies by the British National Coal Board and by Oak Ridge National Laboratory have indicated a significant further advantage of low severity initial extraction. If the extent of extraction is limited to below about 85 wt %, the original coal particles largely retain their integrity, minimizing the production of fines and greatly easing the solid-liquid separation step. Products from the second stage are distilled, and the vacuum tower bottoms go to gasification. In the flowsheet used by Fluor in their recent evaluation of the CSF process, the settler bottoms go to a low-temperature carbonizer for recovery of liquids, and the char from the carbonizer goes to a gasifier for hydrogen production.[6]

3.1.3 Pyrolysis processes

Liquid, gaseous, and solid fuels can be produced from coal by low-temperature pyrolysis or carbonization processes. With the use of increased hydrogen pressure such processes are generally termed hydropyrolysis or hydrocarbonization processes. Pyrolysis processes are principally thermal processes and are generally conducted in gas-solid contacting systems; fixed bed, fluidized bed, recirculating bed, and entrained flow systems have been utilized. Coal pyrolysis processes in fixed beds have a long history; recent developments have focused on fluidized, recirculating, and entrained systems and on hydropyrolysis conditions. Coal pyrolysis technology is reviewed in three subsections that follow – focusing on the rapid pyrolysis/hydropyrolysis processes, fluidized-bed hydrocarbonization processes, and carbonization/gasification processes.

Rapid pyrolysis and hydropyrolysis processes. These processes generally employ entrained-flow reactors to permit minimal exposure of volatile liquid products to the severe pyrolysis environment. Fig. 8 shows a simplified block flow diagram for hydropyrolysis. Again it should be noted that the integrated, conceptual flowsheet has not been demonstrated. The principal effort in this area is the 1 TPH process development reactor operated by Rocketdyne Division of Rockwell International with support from the U.S. Department of Energy. Others involved with rapid pyrolysis and hydropyrolysis processes include Cities Service, Occidental, IGT, City University of New York, PETC, BNL, and ORNL. The most significant recent development in this field is the successful performance of the Rocketdyne reactor.[7] The 4-in.-diam, 1-TPE reactor has achieved sustained operation for about an hour and has successfully handled caking bituminous coal.

Rockwell's process is based on the concept that high liquid yields are favored when coal is allowed to react with hydrogen at high temperature for a short period of time followed by rapid quenching. Reaction temperatures of about 1400-1900°F are achieved by mixing the coal with hydrogen preheated to about 2000°F. Overall carbon conversions of about 50-65% have been obtained. Rockwell indicates that they have achieved carbon conversion to liquid products of about 30-36%, and conversion to gases of about 20-30%. The liquid products have a high BTX content, and the gaseous products contain a high proportion of methane. In a commercial plant design, it is expected that the unreacted char would be fed to a gasifier to produce hydrogen and/or fuel gas required by the facility.

Through correlation of rapid hydropyrolysis yield results from Rocketdyne and Cities Service, Bechtel[8] has demonstrated the absence of significant reactor size effects.

Fluidized-bed hydrocarbonization processes. All effort has been curtailed on the Union Carbide/Coalcon fluidized bed hydrocarbonization demonstration plant.[9] The failure of this large project is generally attributed to uncertainties related to the handling of caking coals, the possible need for hydrotreating of the liquid products, and the overall process economics which showed no clear advantage over the slurry hydroliquefaction processes. Significant technological developments related to fluidized-bed hydrocarbonization processes in the U.S. include successful testing of two reactor concepts with caking coals – the Westinghouse recirculating bed reactor[10] and a proprietary Union Carbide reactor.[11] Also, ORNL has demonstrated[12] that caking coals pretreated with alkaline salts present no caking problems, show attractive hydrocarbonization yields, and retain the alkali salt catalyst in the char. All effort funded by the U.S. Department of Energy in fluidized-bed hydrocarbonization has been curtailed.

Carbonization/gasification processes. The COED[13] multistage carbonization process developed by FMC with gasification of the char, called the COGAS process, is one of two processes under consideration for a large (2200 TPD) demonstration plant to produce pipeline quality gas from coal. The COGAS plant if built will produce nearly half of the heating value of its products as liquid fuel. The other contender is the Conoco Coal Development Company's proposal using the British Gas Corporation-Lurgi slagging gasifier. A decision regarding the demonstration plant has been postponed by the U.S. Department of Energy at the time of this writing. Otherwise there has been little significant recent development in the pyrolysis portion of the COED process.

3.1.4 Indirect liquefaction

Indirect liquefaction, shown in Fig. 9, is carried out by first gasifying the coal to produce a syngas, which after purification can be catalytically recombined to produce liquid products.

Two routes to indirect liquefaction are currently receiving attention. The first is Fischer-Tropsch synthesis, which produces a wide variety of liquid products. The second is methanol synthesis. Both of these are in commercial operation in South Africa.

The recent development of the Mobil-M process has created new interest in the methanol synthesis route. In this process, methanol is converted to gasoline using artificial zeolite catalysts of controlled pore size.[14]

Mobil Research and Development Corporation has made process development studies of this process in fixed and fluid bed bench-scale units. Two reactors were used in the fixed bed unit. Methanol was dehydrated to an equilibrium mixture of methanol, dimethylether, and water in the first reactor. The methanol and dimethylether were converted to high octane gasoline and some lighter hydrocarbons in the second reactor. Over 200 days of successful operation were achieved in the fixed bed unit. A single reactor was used in the fluid bed unit, and a catalyst aging test of two months duration was made.[15]

Process development studies in the fixed and fluid bed bench-scale units indicated some advantages for the fluid bed over the fixed bed. Consequently, a 4-BPD fluid bed pilot plant was designed, built, and operated under a follow-on DOE contract in 1976-1978. Startup and operation of this unit were reported by Mobil to be very successful.

The fluid bed pilot plant operates at temperatures of 730 to 800°F and pressures of 20 to 40 psig. Methanol conversion is over 99.5%, producing about 44% hydrocarbons and 56% water. Of the hydrocarbons produced from the reactor, the C_5^+ gasoline fraction is about 60%. The C_3 and C_4 olefins and isobutane produced are in about the right proportions for alkylation, which brings the total 9 psi Reid vapor pressure gasoline yield up to 88% of total hydrocarbon yield. The Research Octane Number of this gasoline, unleaded, is 96. Yields from the fluid bed process are significantly higher than from the fixed bed unit. Thermal efficiency of the methanol conversion process is about 95%.[16,17,18]

Planning is currently underway for a 100-bbl/day fluid bed pilot plant sponsored by DOE, the Federal Republic of Germany, German industrial participants, and Mobil.

At present there appear to be no active DOE plans to demonstrate Fischer-Tropsch technology in the U.S. liquefaction program. The economics of this route reportedly are less attractive than the methanol-Mobil-M scheme for U.S. applications.[19,20]

3.2 Process Problems in Coal Liquefaction

There are a number of process areas in coal liquefaction on which development work is required and in most cases is going on. Some difficulties are common to almost all of the processes for coal liquefaction while others are more specific to particular processes or process types. Generic problem areas will be described first; then problems specific to the various classes of processes will be discussed. While the focus of this section is on problem areas in coal liquefaction, it should be kept in mind that ongoing development efforts appear capable of solving these problems in a timely fashion.

3.2.1 Generic problem areas

As shown in Fig. 10, areas of difficulty that are generic to coal liquefaction include the following: (1) measurement and control of process streams, (2) measurement and correlation of stream properties, (3) materials and components, (4) gasification, gas cleanup, and recycle, (5) heat recovery from dirty process streams, (6) health and safety, and (7) waste treatment.

Measurement and control of flowrates of process streams containing solids is a problem for all liquefaction processes as are liquid level detection and control. On-stream analysis of chemical and physical characteristics of process streams is important for several processes. Measurement of temperature, pressure, and differential pressure is complicated by the dirty and severe direct liquefaction environment. Dynamic control of complex processes with limited capability for holdup requires careful systems design.

Design of demonstration or commercial-size scale liquefaction plants will require estimates of properties of the process streams at process conditions. Particularly important are the rheological, heat transfer, and vapor-liquid equilibrium properties of process streams. Fragmentary data are available for most of these properties, and correlations from the petroleum industry are being extrapolated although it is recognized that petroleum-based correlations may have significant deficiencies for this application.

Almost all liquefaction processes involve service conditions that place severe demands on components and materials of construction. Erosion, erosion-corrosion, sulfidation, and stress-corrosion cracking are generic difficulties. Capability for design and fabrication of very large, heavy-walled pressure vessels is presently one limitation on the size of liquefaction trains. Concerns related to materials and components also impact plant maintenance requirements and associated plant service factors. A coordinated development program for materials and components in coal liquefaction appears to be emerging.

Almost all liquefaction processes involve the use of gasification, most commonly for the production of hydrogen. The gasification processes themselves have development needs that are beyond the scope of this paper. But gasification with associated heat recovery, gas cleanup, separation, and recycle is a very costly part of the overall liquefaction plant and presents problems and opportunities for further development.

High concentrations of polynuclear aromatic hydrocarbons (PNA) and other compounds which are suspected of causing cancer in humans are known to be present in many coal liquefaction process streams, products, and wastes. These materials require special precautions for protecting the health and safety of workers in coal liquefaction plants, although other health and safety considerations are generally similar to those found, for example, in the petroleum industry.

Federal law will require the use of best available technology for treating the wastes from coal liquefaction plants. Commercially available technology is generally applicable to treating aqueous wastes and gaseous emissions. The treatment and disposal of solid wastes may present new problems of significance as EPA implements the Resource Conservation and Recovery Act of 1976. Development and demonstration of the best available waste treatment technologies will require serious attention from government and industry. Commercially available technology is generally applicable to treating aqueous wastes and gaseous emissions, but the performance of such technology on coal-derived wastes is generally unknown.

3.2.2 Problem areas in direct and two-stage liquefaction

Fig. 11 shows some of the problems common to direct liquefaction processes. These processes all require slurry mixing, pumping, and preheating. High pressure pumps are available but their short valve life is a difficulty. Design of a fired heater for preheating the slurry to reaction temperature is difficult because of (1) highly viscous gel formation with some coals, (2) lack of adequate pressure drop and heat transfer data, and (3) potential coking problems, especially at heat fluxes greater than the very modest ones ($\leq 10{,}000$ Btu/hr ft^2) that have been used so far.

Flow distribution and stability in the liquefaction reactor have been identified by Exxon, Gulf, and Air Products as possible areas of difficulty. High-pressure letdown valves in slurry service have shown rapid wear and short life due to the erosive action of the slurry at high velocities. In a commercial plant, replacing these valves during operation could present design and operational complexities. In catalytic direct and indirect liquefaction processes, catalyst activity and life are also concerns.

Solid-liquid separation is particularly troublesome, especially for those processes such as SRC-I in which the product is too heavy to be taken overhead in a vacuum column. Recent results with the U.S. Filter at the Wilsonville Pilot Plant, however, have been very encouraging, and filtration may prove to be viable for solid-liquid separations. Approaches such as Kerr-McGee's critical solvent process and Lummus anti-solvent deashing process also show promise and these processes are being tested at Wilsonville and elsewhere. When a vacuum distillation column is used, as in SRC-II and EDS, there may still be design difficulties to avoid coking in the preheater and entrainment of solids in the distillate and provide reliable pumping of the high-solids content bottoms from the column into a high pressure gasifier. Another possible source of difficulty is achieving the necessary flow control when the vacuum bottoms is fed to an entrained flow gasifier.

Most of the liquefaction processes require a gasifier for production of hydrogen or fuel gas from the unconverted coal residue. Development of a high pressure gasifier for this application carries with it its own set of concerns, such as the pressurized feed system, nozzle design, and ash or slag removal.

In some processes, use of a high-pressure, low-temperature, fluidized bed carbonizer is contemplated as a means of recovering liquids from settler bottoms. Thus far, only near-atmospheric operation has been demonstrated.

Heat recovery from reactor effluent will be a difficult task. Shell and tube exchangers in high pressure slurry service can be expected to have an extremely high tendency toward fouling and coking. If this occurs, the removal of a tube bundle during operation could pose significant safety hazards. There is no easy solution in sight for this problem, other than omitting the heat recovery and taking a thermal efficiency penalty.

3.2.3 Problem areas for pyrolysis processes

Fig. 12 lists problems which are specific to the pyrolysis processes. Among these are the handling of dry solids at elevated temperatures and pressures. In particular the pressurized hydropyrolysis processes face difficulties with pressurizing and feeding dry coal. Lock hoppers are the best available technology for pressurization, but they are costly and inefficient and frequently experience erosion, particularly with the valves. Several advanced, pressurized coal feeder concepts are under development, but the status of continued development and testing is uncertain at this time.

Rockwell, Westinghouse, and Union Carbide appear to have developed methods for handling caking coals in pyrolysis reactors. Large-scale demonstration has not yet been attempted for any of these approaches, however.

Providing process heat to pyrolysis reactors impacts the process thermal efficiency. Burning of hydrogen with oxygen is a very costly approach. Multistage pyrolysis processes address this concern by combustion and/or gasification of char. The use of char combustion for process heat in the rapid hydropyrolysis processes is an important objective which is currently receiving little attention.

Heat recovery from reactor effluents is of greater concern for pyrolysis processes than the direct and two-stage processes because of the higher temperatures generally employed. Furthermore, the rapid pyrolysis processes require a rapid quench of the reactor effluent which complicates heat recovery.

Finally, in order to minimize the carryover of unreacted solids with the liquid product, pyrolysis processes will demand efficient gas/solid separation probably using cyclones and perhaps other techniques. Little effort is currently focused on this area.

3.2.2 Problems in indirect liquefaction

As indicated in Fig. 13, the main problems in indirect liquefaction are those connected with the gasifier. Gas cleanup, shift, and methanol synthesis technology are fairly well established. Mobil's fluidized bed reactor for the Mobil-M process may present some difficulties in scaling up to commercial size.[16]

3.3 Product Upgrading

Product research and testing have established that coal-derived liquids in the naphtha range make excellent feedstocks for upgrading to high octane gasoline blending stocks. Above the naphtha boiling range, coal liquids appear to be best suited for industrial or utility fuel oil use rather than for jet fuel or diesel fuel. This is because of the highly aromatic nature of coal-derived liquids and the high cost of hydrotreating them to jet fuel or diesel fuel specifications. Shale oil, which produces a more paraffinic mid-barrel material, is probably better suited than coal for jet fuel and diesel fuel production.

Fant and Barton of Exxon have reported[21] on the properties and end-uses of the naphtha and fuel oil products from the EDS process. The naphtha can be hydrotreated by conventional fixed-bed technology to very low levels of sulfur and nitrogen (1 ppm or less) suitable for a feedstock to catalytic reforming. The severity levels required in hydrotreating are greater than for petroleum-derived naphthas but are well within the range of conventional technology. After hydrotreating, the naphtha can be catalytically reformed to very high octane levels. Reforming yields are shown in Fig. 14. Liquid yields are higher than for petroleum-derived stocks due to the very high proportion (87%) of aromatics, naphthenes, and cyclo-olefins. For example, a yield of 88% (liquid volume) of C_5+ reformate was obtained at a

Research Octane Number of 103 clear. With the current octane difficulties being experienced by refiners due to the phase-out of lead, the availability of high-octane unleaded reformate from coal naphtha could be extremely valuable. Another favorable point is that the combination of naphtha hydrotreating and catalytic reforming showed a net positive hydrogen production of 1250 scf/bbl.

Another possible route for upgrading heavy coal-derived distillate liquids is catalytic hydrocracking. This route was chosen by Fluor in their recent study of the Conoco CSF process.[6] Fig. 15 shows a greatly simplified block flow diagram for the hydrocracking-catalytic reforming steps. It is well known in the petroleum industry that highly aromatic distillates make good hydrocracker feedstocks. The main questions to be resolved relate to the hydrotreating and cut point conditions needed to prepare the vacuum distillate for hydrocracking and whether the overall hydrotreating-hydrocracking operation will be economical in terms of yields, hydrogen consumption, and catalyst life.

Upgrading, of course, will imply some loss in yield and reduction of energy efficiency. However, it has been accepted for a long time in petroleum refining technology that yield must frequently be sacrificed to improve quality. The yield-octane curve in catalytic reforming of naphtha to high-octane reformate is a good example of this. Another is the yield loss in converting mid-barrel stocks to gasoline by fluid cat cracking.

Therefore, if the energy efficiency from coal is lower when producing gasoline than when producing fuel oil, we should not allow this to influence unduly our thinking about what products should be produced. If energy efficiency were the only criterion, the petroleum refining industry would be selling fractions right off the distillation column – or perhaps the crude oil itself. But this is not what is needed in the marketplace. Our approach to coal liquefaction should be guided by what products are needed and the quality specifications that have to be met, and the costs of upgrading should be included in our economic evaluations wherever the end use demands it.

4. ECONOMICS AND COMMERCIALIZATION

4.1 Recent Economic Studies

Most recent studies seem to indicate that the cost of synthetic liquid fuels from coal in 1978 dollars will be about \$25 to \$35 per barrel. This, of course, can vary rather widely depending on the nature of the products and the type of financing.

Economic comparisons among various processes are difficult and are frequently misleading because (1) different degrees of conservatism are used in design and cost estimation, (2) different financial ground rules are used, and (3) often no allowance is made for the fact that the processes may produce products of widely differing properties and end uses. The assumptions used in providing steam and electricity to operate the facility can have a considerable effect on the overall thermal efficiency and the product cost. Keeping these warnings in mind, some recent studies will be discussed.

As shown in Fig. 16, a design and economic study of the EDS process by Exxon resulted in an initial selling price of \$29/bbl in 1978 dollars for the liquid products. This was based on a 24,000-TPD plant producing 60,000 bbl/day of liquids from Illinois No. 6 coal. The net liquid yield thus is about 2.5 bbl/ton. Capital investment is \$1.6 billion in 1978 dollars, or \$27,000 per stream day barrel. Over half of the product price is due to the charges on capital investment. Overall thermal efficiency is 63% with sulfur and ammonia included.[22,23]

Exxon also compared the costs of liquids from SRC-II, H-Coal, and EDS, and concluded that the costs of products from all three appear to be within ± 10% of each other. In this study, Exxon used published conceptual designs and economic studies for SRC-II and H-Coal and adjusted them to the same basis Exxon used for EDS.[23]

Fig. 17 summarizes the results of a study by Hydrocarbon Research Incorporated showing an estimated cost of about $17/bbl for H-Coal liquids, with a capital cost of $14,800 per daily barrel. HRI also quoted an estimate by Ashland Oil of $20,000 per daily barrel in 1977 dollars for a pioneer plant.[24]

As indicated in Fig. 18, a comparison of the direct and indirect approaches to liquefaction was made by Harney, Mills, and Joseph. They concluded that the cost of gasoline made by the methanol-Mobil-M route is only marginally higher than that made by the H-Coal process. At a 50/50 debt-equity ratio, the costs were $1.02/gal for Mobil-M and $0.99/gal for H-Coal, or about $42/bbl. As a convenience, the fuel oil produced in the H-Coal process was given the same value as the gasoline. The estimated capital investments in 1977 dollars for 50,000 bbl/day plants were $1.64 billion for the H-Coal route and $1.76 billion for the methanol-Mobil-M route. These correspond to $32,800 and $35,200 per daily barrel respectively.[19]

A study by Max Schreiner and others of Mobil with assistance from Lurgi indicated that Mobil-M is superior to Fischer-Tropsch from the standpoint of thermal efficiency and product cost. The results are briefly summarized in Fig. 19. Estimated total facility costs for the methanol-Mobil-M system were about $41,500 per calendar day barrel or about $37,300 per stream day barrel in 1977 dollars. The plants used about 27,000 tons/day of Wyoming subbituminous strip-mined coal. Products included both liquids and SNG, about 47% liquids and 53% SNG on a thermal basis for the fluid bed Mobil-M route. With SNG and LPG valued at $6.17/million Btu, the gasoline cost was 92¢/gal or about $7.60/million Btu using equity financing at 12% rate of return after taxes and a coal cost of $7/ton. Thermal efficiency for this case was 63%. Capital investment was about $1.7 billion, and gasoline production was 23,000 bbl/day. Doubling the coal cost would raise the gasoline price by about 8¢/gal. For the Fischer-Tropsch case, the gasoline costs were from 10% to 40% higher depending on the allocation of costs among the products.[20] It should be emphasized that upgrading of the gasoline to U.S. quality specifications was one of the requirements of the study.

Fig. 20 summarizes another study of the indirect route. Badger Plants Division made a conceptual design and economic analysis of a plant producing 415,000 bbl/day of methyl fuel and methanol from 74,000 TPD of bituminous coal. They estimated a plant cost of $3.1 billion and a product cost of 18.8¢/gal on a 1977 basis with inflation at 6%/year. If inflation is eliminated, this works out to 24.5¢/gal on an instant plant 1977 dollar basis. The fact that eliminating inflation makes the price go up is a little confusing but basically it is because the same nominal rate of return on investment was used in both cases, and the effect of inflation is to reduce the real rate of return on investment. Badger's investment cost corresponds to $7500 per daily barrel of methyl fuel. If this is adjusted to fuel oil equivalent on a Btu basis, it corresponds to about $17,500 per daily barrel of fuel oil equivalent.[25] The overall thermal efficiency of the Badger conceptual facility was 59.2%. This is not much lower than the overall efficiencies estimated for direct liquefaction. If correct, this study indicates that earlier estimates of efficiency for the coal-to-methanol route were much too pessimistic.

As indicated in Fig. 21, the economics of the Conoco CSF process were investigated in a conceptual design study by Fluor Engineers and Constructors. Their design showed 66,000 bbl/day of gasoline, 15,000 bbl/day of LPG, and 78 million scf of SNG produced from 30,000 TPD of coal. Estimated plant investment was $1.7 billion excluding the coal mine, and gasoline price was $24/bbl in 1977 dollars.[6] The plant capital corresponds to $21,000 per daily barrel of liquid products. The design and cost estimate include the upgrading facilities needed to produce high quality gasoline. This was an "nth" plant design rather than a first plant, and included projected cost reductions due to the "learning curve" effect.

4.2 Commercialization

It seems clear that liquid fuels from coal are not yet competitive with imported petroleum, which now costs about $15/bbl including ocean freight.

One widely held view of commercialization is that the cost of imported oil will rise more rapidly than the cost of coal liquids, and that at some point in the future there will be a crossover, at which point it will become economically feasible to build plants for producing liquid fuels from coal. Current research and development programs are aimed at reducing the costs of these fuels, therefore hastening the point at which economic competitiveness is achieved as well as ensuring that technically feasible processes will be available at that time.

However, just when this economic crossover will occur is not clear. Around 1973 and 1974, there was a massive readjustment in the price of Middle East oil, reflecting the realities of the marketplace and the dominant position of OPEC in world petroleum supply. But since that readjustment, additional price increases have been largely keyed to the general inflation which has eroded the value of the dollars we pay to the Middle East nations.

Regarding the recent announcement by OPEC of a graduated 14.5% increase in oil prices, the Oil and Gas Journal reported this year an analysis by the Organization for Economic Cooperation and Development which states that even after this increase, oil prices in real terms will still be below the levels of early 1977.[26]

Inflation is also driving up the price of coal. Projections of the marginal mine-mouth costs of coal by Data Resources Incorporated indicate Western coal costs increasing at 8%/yr and Eastern medium- and high-sulfur coal increasing at about 9%/yr. Their projected price for Illinois coal was about $65/ton in 1990.[27] In fairness, it should be said that not all forecasters agree that coal prices will escalate this rapidly. However, coal prices will at least follow the rate of general inflation and in addition are pushed upward by environmental, health, and safety regulations and by decreases in average productivity. Also, the growth of a coal liquefaction industry cannot occur without a considerable expansion of the coal mining industry, and this expansion of demand will probably induce an appreciable rise in price.

The estimated costs of building synthetic fuel plants also have been going up rapidly. And, as pointed out by Krasts and Henkel of Conoco,[28] the rate of inflation of capital goods is higher than the rate of general inflation, because of long-established government economic policies. Moreover, when inflation is high, the rates of return demanded by lending institutions and other investors go up correspondingly, leading to still higher costs for capital-intensive synthetic fuels.

Another point to be considered is that inflation tends to generate a climate of uncertainty which discourages large capital investments, especially in a new industry.

A synthetic fuels industry of appreciable size (say 2 million bbls/day) will probably take at least 15 years to build. And this time does not start now – it starts after economic competitiveness is achieved. Also, this is without consideration of possible regulatory or environmental restrictions that could hamper the rate of growth. The expansion of the coal mining industry to provide the necessary feedstock will also have to take place during this same time period, and will compete for investment funds.

Considerations such as these tend to make us wonder whether we ought not take a more searching look at the mechanisms by which we expect the synthetic fuels industry to develop. It is not at all clear that natural marketplace forces will be able to build the industry rapidly enough to meet the demands we expect in the next 20 to 30 years. The need for governmental initiatives has been widely discussed. We wish to emphasize here the need for careful consideration of the demand-time curve for synthetic liquid fuels and of the length of time required to build an industry of the size needed.

5. REFERENCES

1. Proceedings of the 1978 Coal Chemistry Workshop, March 8-10, 1978, SRI International, Menlo Park, Calif. (published November 1978).
2. Energy Daily, November 14, 1978.
3. W. R. Epperly and J. W. Taunton, "Development of the Exxon Donor Solvent Coal Liquefaction Process," presented at AIChE 85th National Meeting, Philadelphia, Pa., June 7, 1978.
4. W. R. Epperly and J. W. Taunton, "Exxon Donor Solvent Coal Liquefaction Process Development," presented at 13th Intersociety Energy Conversion Engineering Conference, San Diego, Calif., August 20-25, 1978.
5. A. G. Comolli, C. A. Battista, et al, "Development and Demonstration of the H-Coal Process," presented at ACS Division of Petroleum Chemistry, Miami, Fla., Sept. 11-15, 1978.
6. Fluor Engineers and Constructors Report FE-2251-40, Conceptual Design for Advanced Coal Liquefaction Commercial Plant, October 1977.
7. C. L. Oberg, A. Y. Falk, and J. Silverman, "Flash Hydropyrolysis of Coal Using Rockwell Short-Residence-Time Reactors," presented at AIChE 71st Annual Meeting, Miami, Fla., November 12-16, 1978.
8. Bechtel Corp., "An Analysis of Coal Hydrogasification Processes, Monthly Technical Progress Report for the Period 1 January - 31 January 1978," FE-2565-11 (February 1978).
9. Coalcon, "Clean Boiler Fuel Demonstration Plant Program, Phase I, Task II, Hydrocarbonization Demonstration Plant Process Design Report," Vol. 5, 600-301-00-004 (June 1977).
10. L. A. Salvador, D. Keairns, "Advanced Coal Gasification System for Power Generation: Quarterly Progress Report," FE-1514-61 (January 1977).
11. B. Liss, personal communication to H. D. Cochran and J. M. Holmes (November 1977).
12. L. E. McNeese, "Fossil Energy Program Quarterly Progress Report for the Period Ending June 30, 1978," Sect. 2.1, ORNL-5444 (November 1978).
13. R. Bloom, "Illinois Coal Gasification Group Project Incorporating the COGAS Process," presented at AGA 8th Synthetic Pipeline Gas Symposium, Chicago, Ill. (October 1976).

14. Statement by John J. Wise, Vice President, Mobil Research and Development Corporation, before the Senate Appropriations Committee, Washington, D.C., January 31, 1978.

15. S. E. Voltz and J. J. Wise, "Development Studies on Conversion of Methanol and Related Oxygenates to Gasoline," Final Report, Mobil R&D Corp., U.S. ERDA Contract No. E(49-18)-1773, November 1976.

16. W. Lee, N. Y. Chen, and R. H. Perry, Jr., "Conversion of Alcohols to High Octane Gasoline," presented at 1st Petroleum Conference, Rio de Janeiro, Brazil, November 5-10, 1978.

17. A. Y. Kam, S. Yurchak, and W. Lee, "Fluid Fed Process Scale-up and Development Studies on Selective Conversion of Methanol to High Octane Gasoline," presented at AIChE 71st Annual Meeting, Miami, Fla., Nov. 15, 1978.

18. W. Lee, J. Maziuk, and W. K. Thiemann, "A New Process for Conversion of Coal to Gasoline," presented at DGMK Coal and Petroleum Conference, Berlin, October 4-6, 1978.

19. B. M. Harney, G. Alex Mills, and L. M. Joseph, "High Quality Transportation Fuels from CO-H_2 — A Competitive Option," presented at American Chemical Society Division of Petroleum Chemistry meeting, Anaheim, Calif., March 12-17, 1978.

20. M. Schreiner, "Research Guidance Studies to Assess Gasoline from Coal by Methanol-to-Gasoline and Sasol-type Fischer-Tropsch Technologies, Final Report," FE-2447-13, August 1978.

21. B. T. Fant and W. J. Barton, "Refining Coal Liquids," presented at the API Refining Dept. 43rd Midyear Meeting, Toronto, May 10, 1978.

22. "Exxon Donor Solvent Coal Liquefaction Commercial Plant Design Study," Report FE-2353-13, prepared for U.S. ERDA, submitted January 1978.

23. L. E. Swabb, Jr., "Synthetic Liquid Fuels from Coal," presented at National Academy of Engineering Annual Meeting, Washington, D.C., November 2, 1978.

24. G. R. DeVaux and B. Dutkiewicz, "H-Coal Commercialization," presented at AIChE 71st Annual Meeting, Miami, Fla., November 12-16, 1978.

25. Badger Plants, Inc., Report FE-2416-24, Conceptual Design of a Coal to Methanol Commercial Plant, February 1978.

26. Oil and Gas Journal, January 1, 1979.

27. Energy User News, July 10, 1978.

28. A. Krasts and T. Henkel, "Effect of Inflation on Discounted Cash Flow Rates of Return," Managerial Planning, November/December 1977, p. 21.

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Fig. 1

CLASSIFICATION OF COAL LIQUEFACTION PROCESSES

1. DIRECT LIQUEFACTION
    - SRC-I
    - SRC-II
    - H-COAL
    - EXXON DONOR SOLVENT (EDS)
2. TWO-STAGE LIQUEFACTION
    - CONOCO CSF
3. PYROLYSIS AND HYDROPYROLYSIS
    - CITIES SERVICE
    - ROCKETDYNE
    - COED
4. INDIRECT LIQUEFACTION
    - FISCHER-TROPSCH
    - METHANOL AND MOBIL-M

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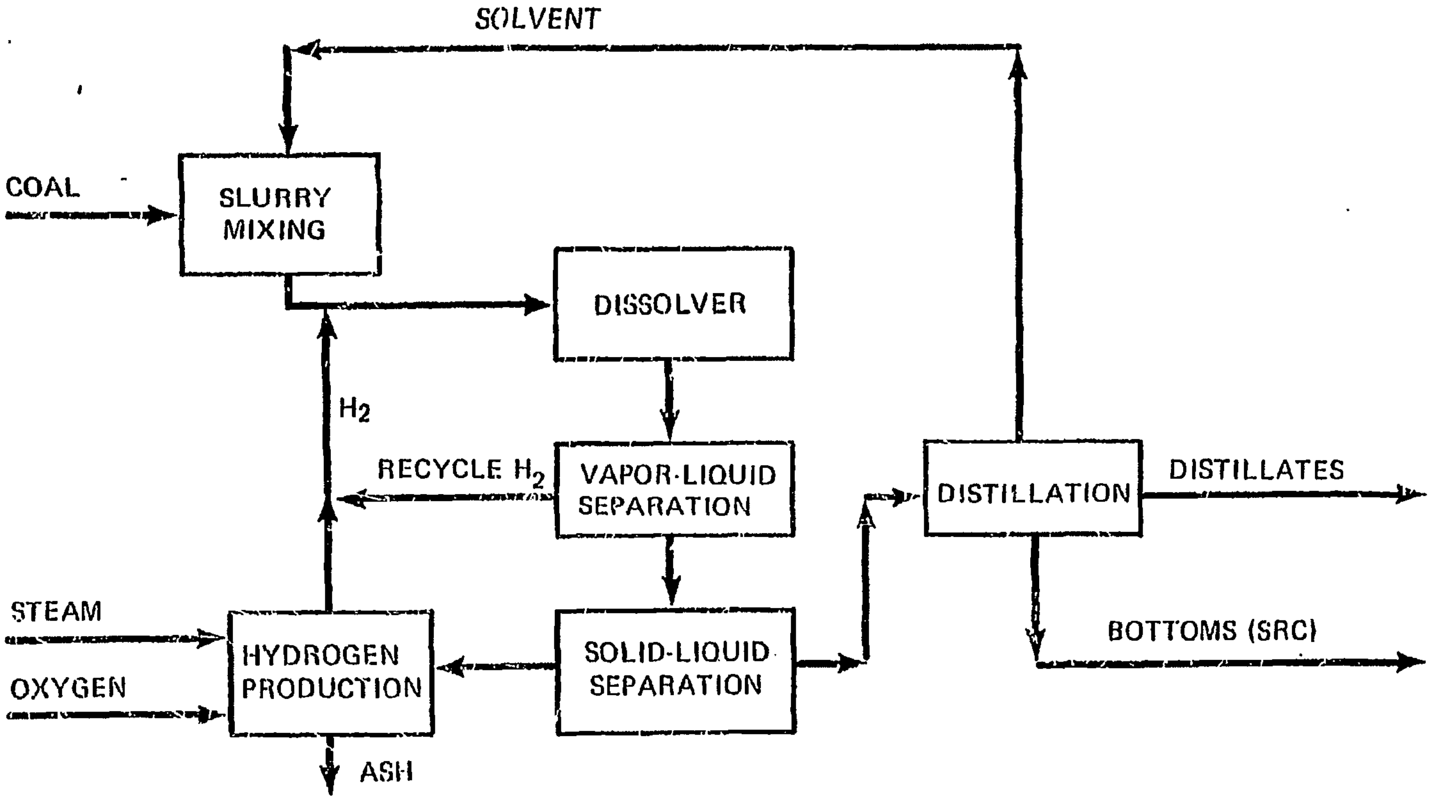

SRC-I PROCESS

Fig. 2

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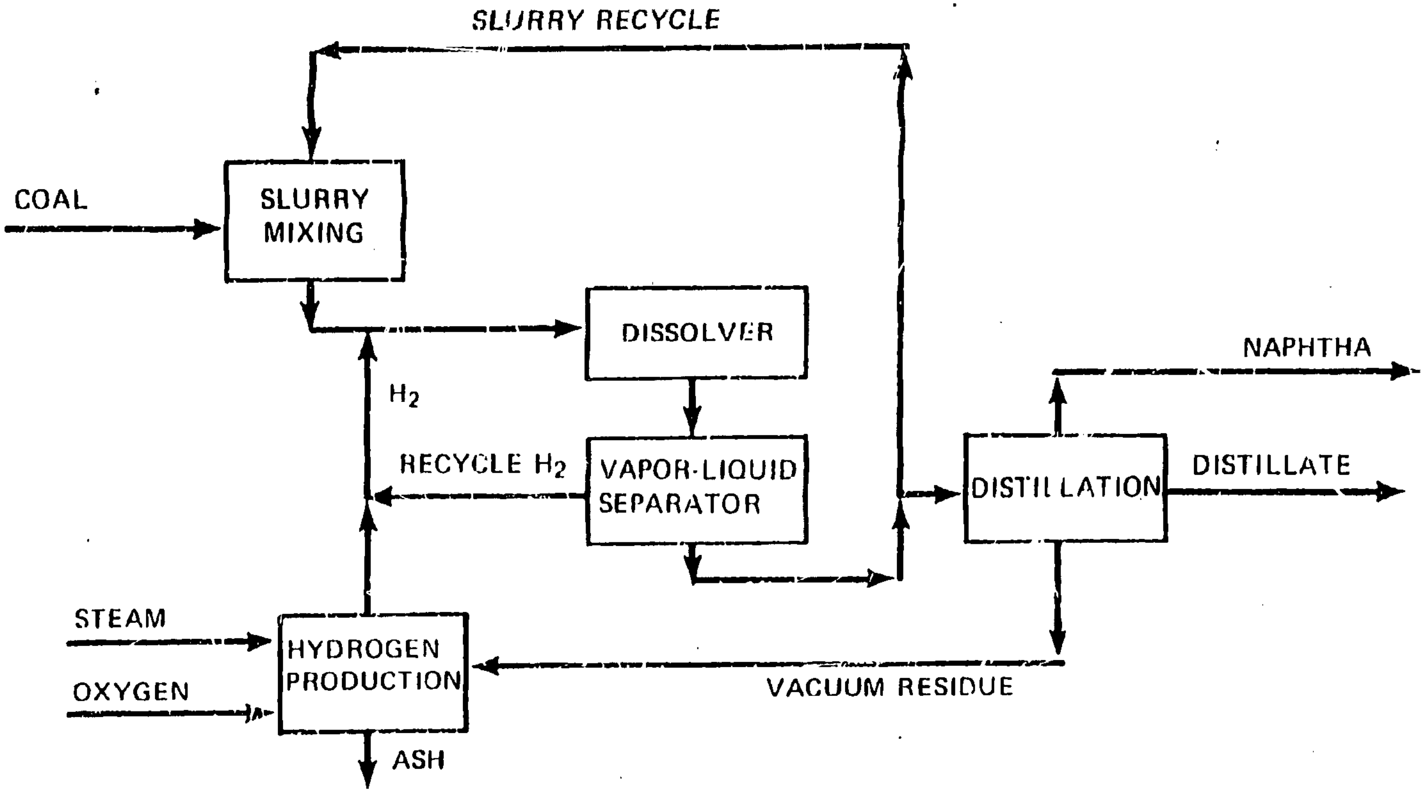

SRC-II PROCESS

Fig. 3

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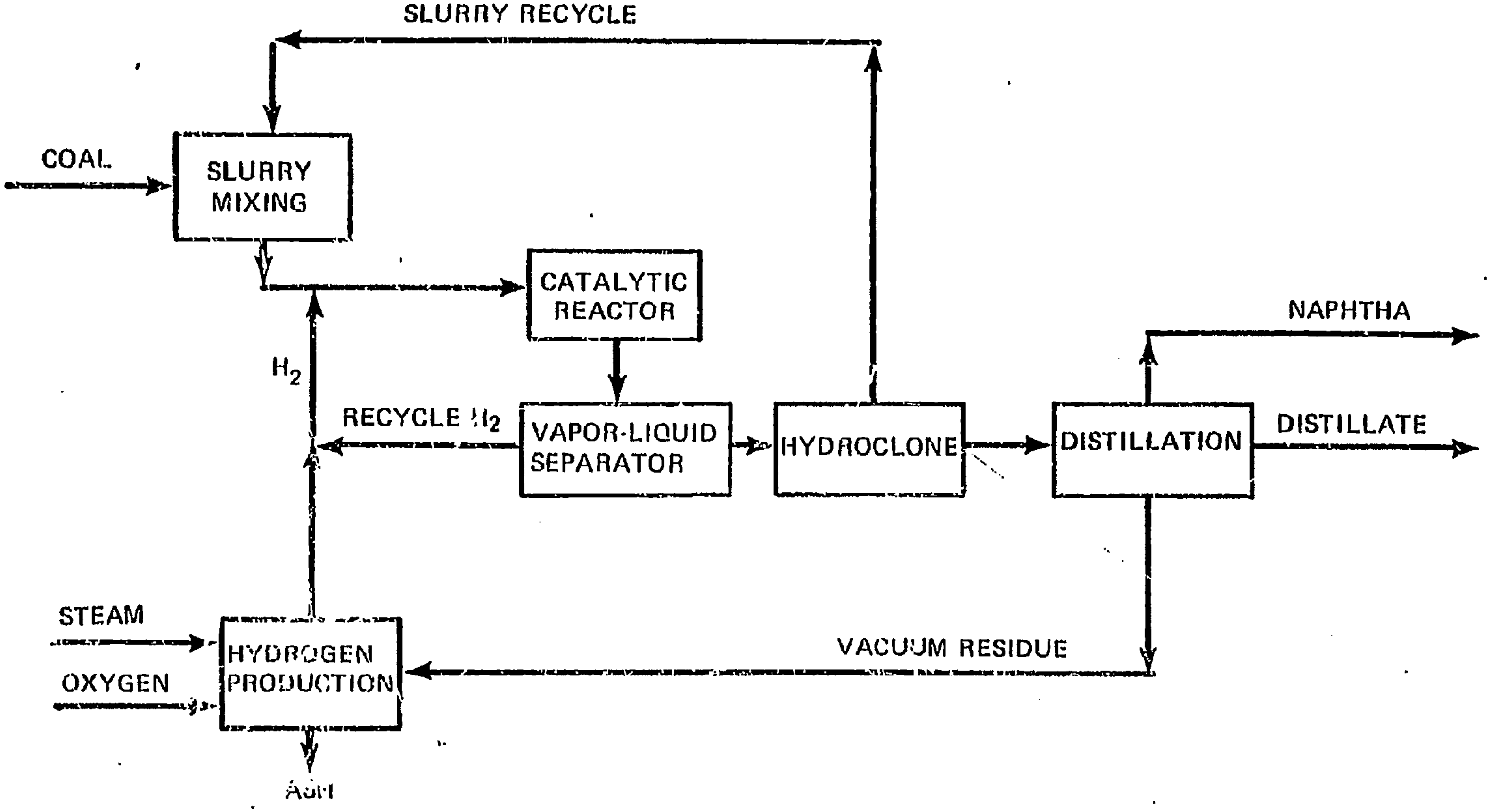

H-COAL PROCESS

Fig. 4

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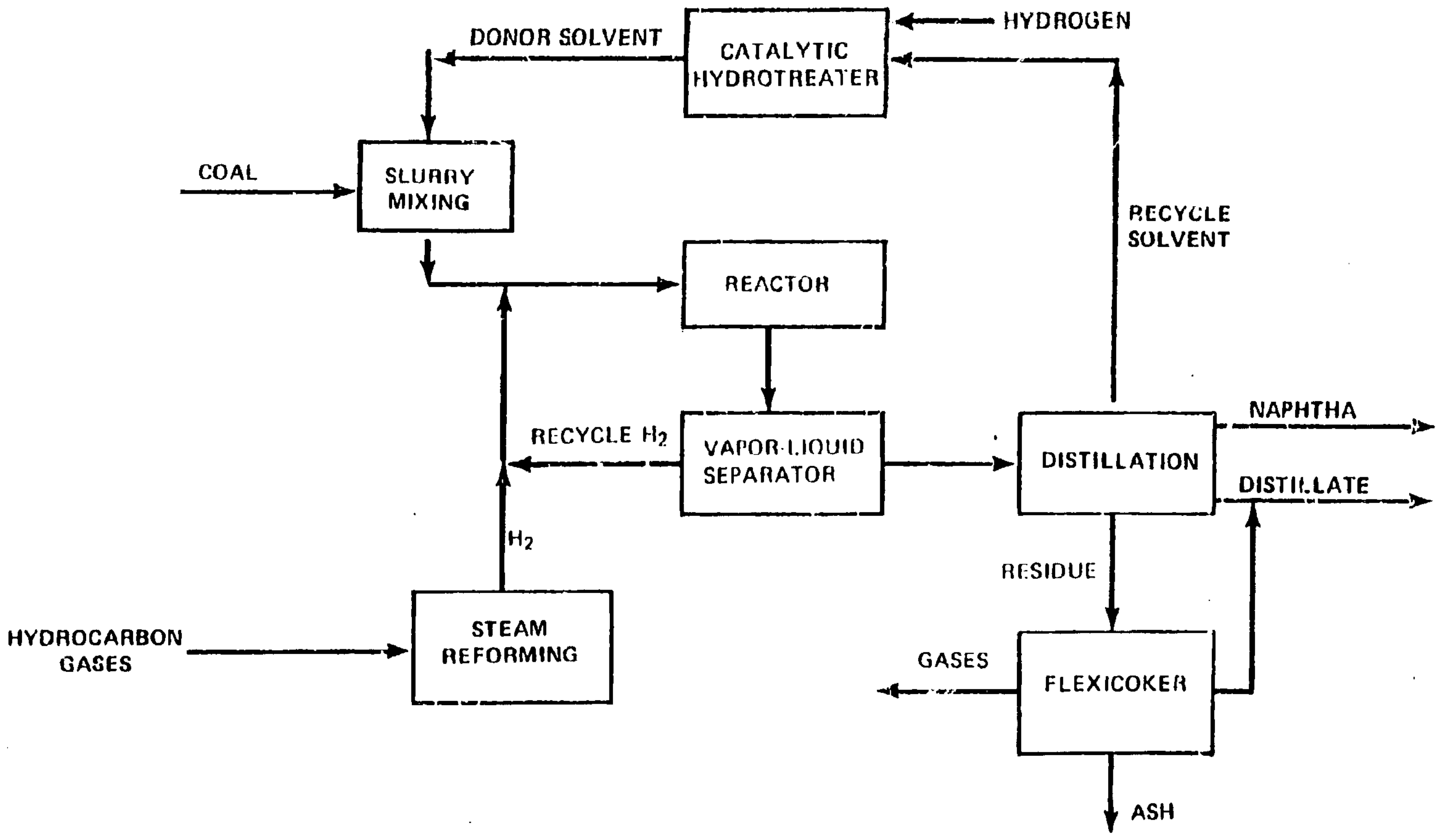

EDS PROCESS

Fig. 5

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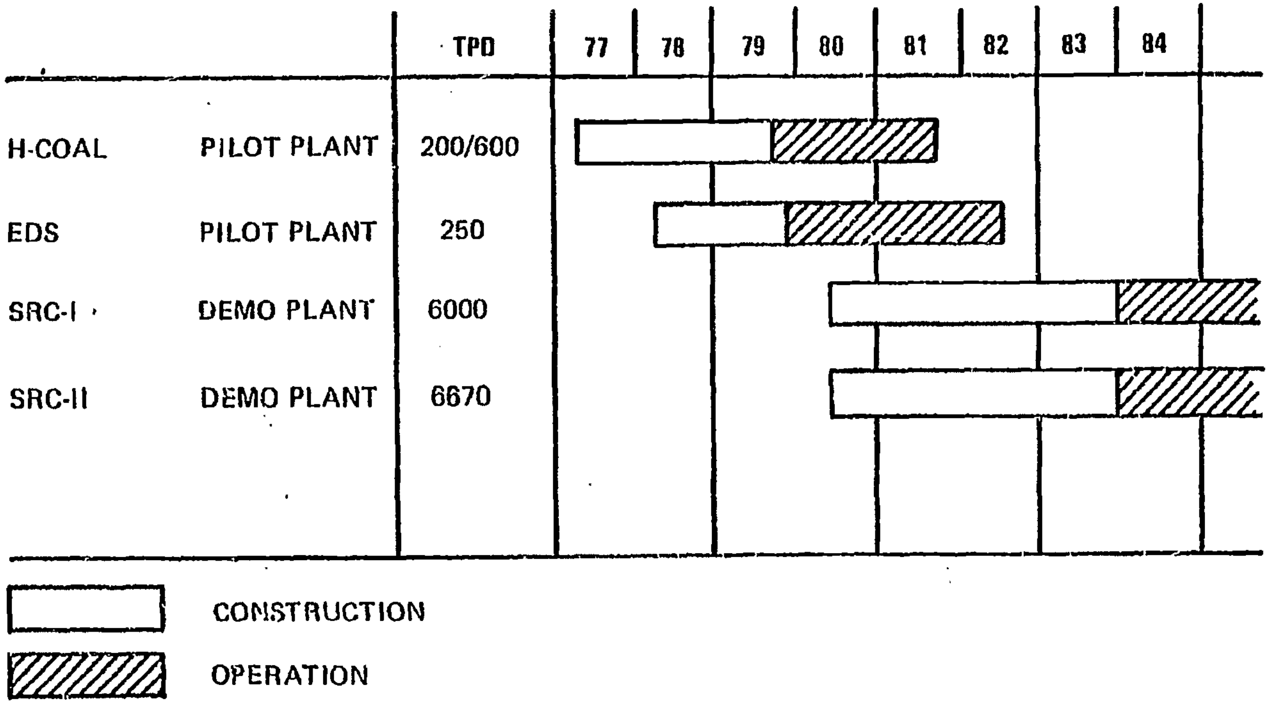

DIRECT LIQUEFACTION PILOT PLANT – DEMO PLANT SCHEDULE

Fig. 6

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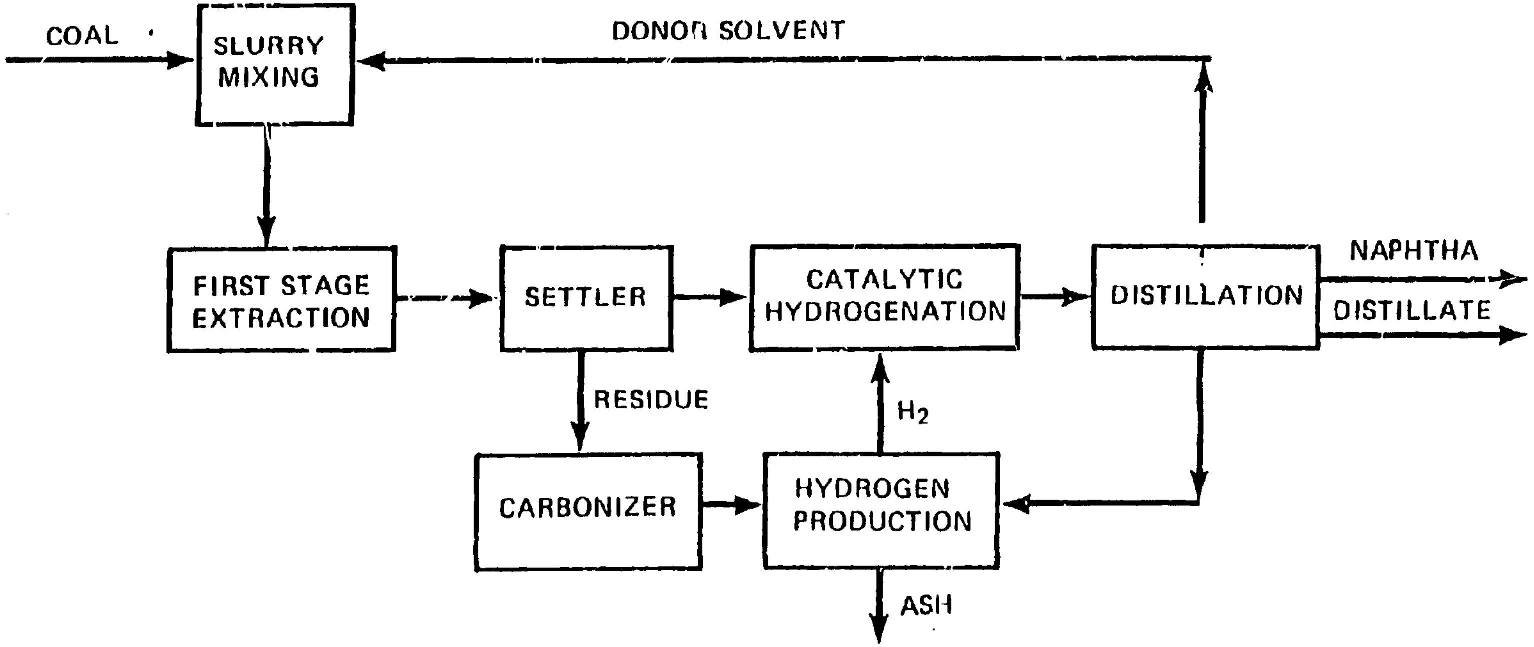

TWO-STAGE LIQUEFACTION (CSF)

Fig. 7

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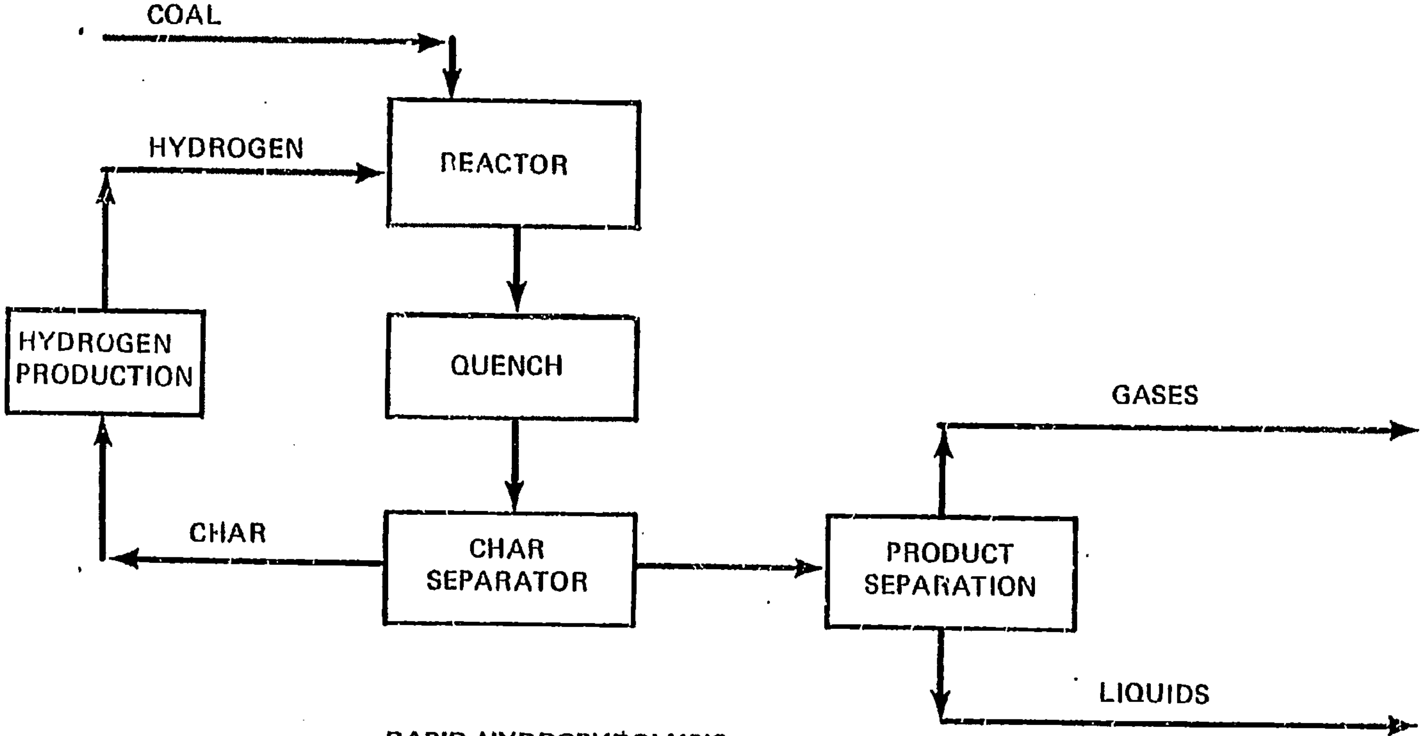

RAPID HYDROPYROLYSIS

Fig. 8

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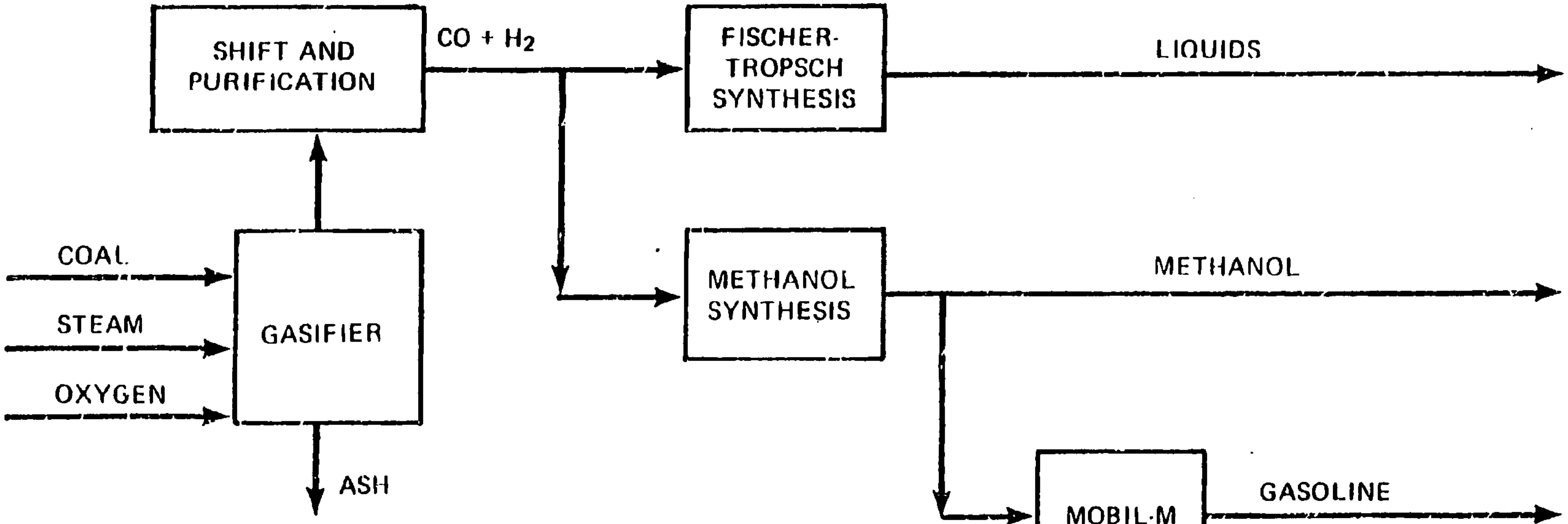

INDIRECT LIQUEFACTION

Fig. 9

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Fig. 10

GENERIC PROBLEM AREAS IN COAL LIQUEFACTION

- INSTRUMENTATION AND CONTROL
- ESTIMATES AND CORRELATIONS OF STREAM PROPERTIES
- MATERIALS AND COMPONENTS
- GASIFICATION
- GAS CLEANUP AND RECYCLE
- HEAT RECOVERY
- HEALTH AND SAFETY CONSIDERATIONS
- WASTE TREATMENT

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Fig. 11

PROBLEM AREAS IN COAL LIQUEFACTION

DIRECT AND TWO-STAGE PROCESSES

- SLURRY PUMP
- SLURRY PREHEATER
- REACTOR FLOW DISTRIBUTION
- HIGH PRESSURE SLURRY LETDOWN VALVE
- SOLID-LIQUID SEPARATION
- VACUUM COLUMN
- GASIFIER
- LOW-TEMPERATURE CARBONIZER
- HEAT RECOVERY

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Fig. 12

PROBLEM AREAS – PYROLYSIS AND HYDROPYROLSIS

- PRESSURIZED DRY COAL FEED SYSTEM
- FEEDING CAKING COALS TO REACTORS
- PROCESS HEAT SUPPLY TO REACTORS
- HEAT RECOVERY AT HIGH TEMPERATURES
- REMOVAL OF SOLIDS FROM GASES

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Fig. 13

PROBLEM AREAS – INDIRECT LIQUEFACTION

- GASIFIER AND GAS CLEANUP
- FLUID BED REACTOR SCALEUP

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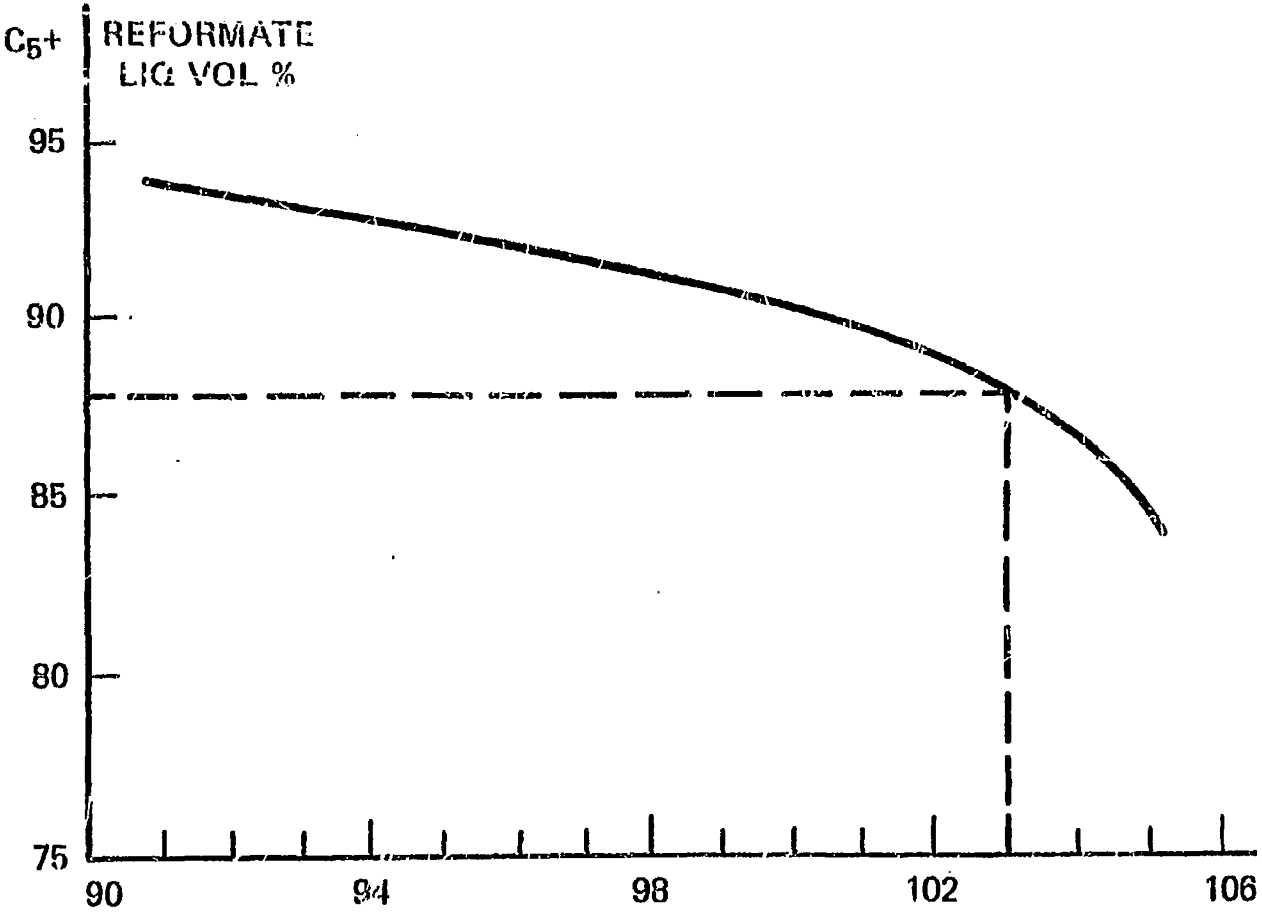

RESEARCH OCTANE NUMBER (clear)

Fig. 14

CATALYTIC REFORMING OF EDS NAPHTHA
SOURCE: B. T. FANT AND W. J. BARTON,
MAY 1978 (REF. 21)

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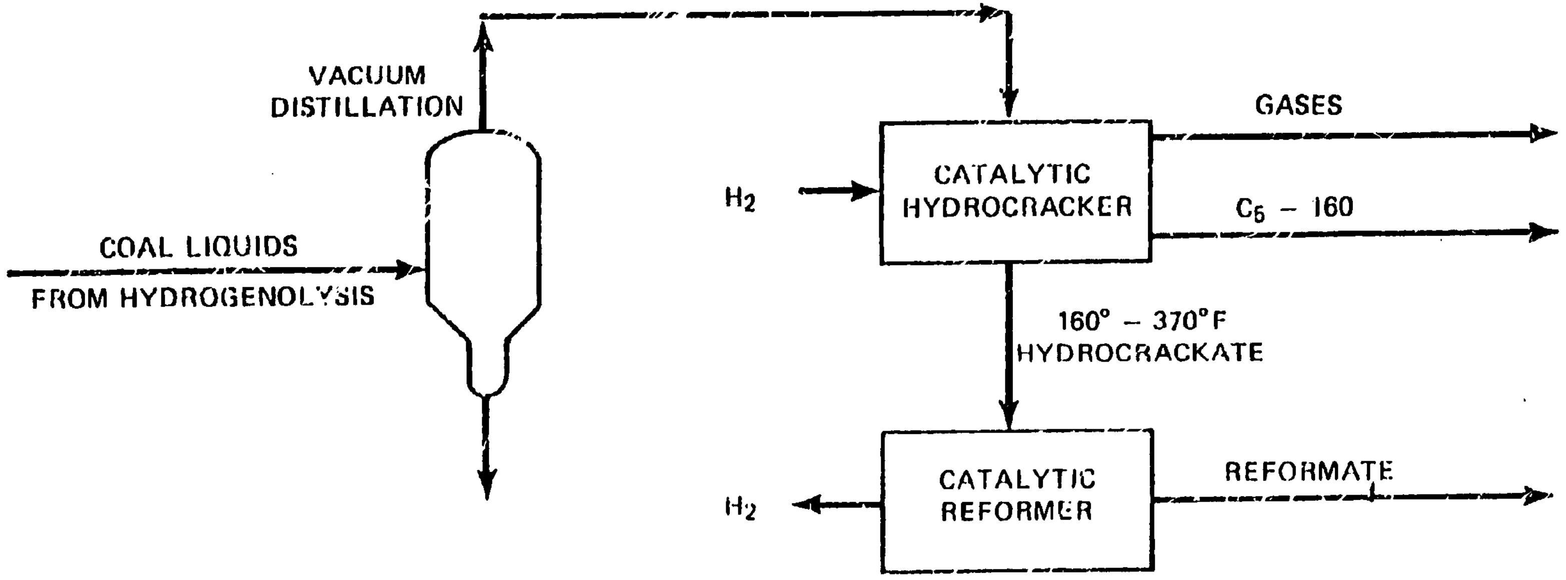

UPGRADING BY CATALYTIC HYDROCRACKING AND CATALYTIC REFORMING

Fig. 15

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Fig. 16

EXXON DONOR SOLVENT COMMERCIAL PLANT STUDY DESIGN[a]

COAL TYPE	ILLINOIS NO. 6
COAL FEED RATE, TPD	24,000
YIELDS, B/SD	
$C_3 - C_4$ LPG	8,000
C_5 – 400°F NAPHTHA	22,000
FUEL OIL (0.5 wt % S)	29,800
TOTAL LIQUIDS	59,800
CAPITAL INVESTMENT, $ BILLION (1978)	1.6
INITIAL SELLING PRICE, $/bbl (1978)[b]	29
OVERALL THERMAL EFFICIENCY	63%

[a] SOURCE: REFS. 22, 23

[b] BASIS: 100% EQUITY AT 15% DCF RETURN, 5% COST INFLATION, 6% PRODUCT PRICE INFLATION.

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Fig. 17

ESTIMATED H-COAL COSTS[a]

CAPITAL COST, $/DAILY BARREL (1977)	14,800
LIQUID PRODUCT COSTS	$/bbl
COAL	5.84
OPERATING	7.54
MAINTENANCE, TAXES, INSURANCE	1.31
BY-PRODUCT CREDIT	(0.46)
TOTAL	$16.83

BASIS: COAL AT $15/ton WITH 10% MOISTURE
55% DEBT AT 8%
45% EQUITY AT 10%
20-YEAR LIFE

[a] SOURCE: REF. 24.

Fig. 18

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COMPARISON OF H-COAL AND MOBIL-M (ALL COSTS IN 1977 DOLLARS)[a]

	H-COAL	MOBIL-M
GASOLINE, \$/gal		
D/E = 0/100	1.23	1.27
D/E = 25/75	1.10	1.14
D/E = 50/50	0.99	1.02
D/E = 75/25	0.89	0.92
TOTAL CAPITAL, BILLION \$	1.64	1.76
ECONOMIC PARAMETERS:		
COAL COST	\$1.00/million Btu	
INTEREST RATE ON DEBT	9%	
RATE OF RETURN ON EQUITY	12%	

[a] SOURCE: REF. 19.

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Fig. 19

ECONOMIC COMPARISON OF MOBIL-M AND FISCHER-TROPSCH BASED ON WYOMING SUBBITUMINOUS COAL AND LURGI GASIFIERS[a]

	MOBIL-M (FLUID BED)	FISCHER-TROPSCH
COAL FEED RATE, TPD	27,300	27,800
PRODUCTS, B/SD		
GASOLINE	23,065	13,580
SNG	152	173
C_3 LPG	1,790	1,107
C_4		146
DIESEL FUEL		2,307
FUEL OIL		622
ALCOHOL		610
TOTAL FUEL OIL EQUIVALENT, B/SD	45,560	44,950
OVERALL EFFICIENCY, %	63	58
CAPITAL INVESTMENT, $ BILLION (1977)	1.68	1.89
PRODUCT COST, $/million Btu[b]	6.80	7.78
GASOLINE COST, $/gal[c]	0.83	0.93

[a] SOURCE: REF. 20.

[b] ALL PRODUCTS VALUED EQUIVALENTLY ON Btu BASIS.

[c] 100% EQUITY FINANCING, 12% RETURN ON INVESTMENT. ALL COSTS IN 1977 DOLLARS.

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Fig. 20

ECONOMIC EVALUATION OF COAL TO METHANOL CONCEPTUAL COMMERCIAL PLANT[a]

COAL FEED RATE, TPD	74,000
PRODUCTS	
METHYL FUEL, B/SD	386,000
METHANOL, B/SD	28,700
THERMAL EFFICIENCY, %	59.2
CAPTIAL INVESTMENT (1977) $ BILLION	3.1
PRODUCT COST, c/gal[b]	
WITH 6% ESCALATION, 1977 BASIS[c]	18.8
WITHOUT ESCALATION, 1977 BASIS	24.5

[a] SOURCE: REF. 25.

[b] 65% DEBT AT 9%, 35% EQUITY AT 12%. COAL COST $25/ton. PLANT LIFE 20 YEARS.

[c] INITIAL COST IN FIRST YEAR OF PRODUCTION (1987) IS 33.6c/gal; DEFLATING THIS TO 1977 GIVES 18.8c/gal.

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Fig. 21

ECONOMIC STUDY OF CONOCO CSF PROCESS WITH PRODUCT UPGRADING[a]

COAL FEED RATE, TPD	30,000
PRODUCTS	
SNG, MILLION scf/day	78
LPG, bbl/day	15,000
GASOLINE, bbl/day	66,000
PLANT CAPITAL INVESTMENT, $ BILLION[b]	1.7
$/DAILY BARREL	21,000
GASOLINE PRICE, $/bbl[c]	24
$/gal[c]	0.57
$/million Btu[c]	4.70

[a] SOURCE: REF. 6.

[b] EXCLUDING COAL MINE. ALL COSTS IN 1977 DOLLARS.

[c] COAL PRICE APPROXIMATELY $25/ton; 65% DEBT AT 9%, 35% EQUITY AT 14% *BEFORE* TAXES; SNG VALUED AT $3/MILLION Btu; LPG VALUED AT $4/MILLION Btu.

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