

4--SYNTHETIC LIQUID FUELS: THE TECHNOLOGY,
RESOURCE REQUIREMENTS, AND
POLLUTANT EMISSIONS

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A. Introduction and Overview

To assess the impacts of large-scale production and use of synthetic fuels it is necessary to set forth the technological systems or networks through which these fuels proceed from resource extraction to end use. We have attempted to do this by examining the technologies that are likely to be utilized for synthetic fuels production, as well as associated mining, transportation, refining, and distribution technologies. We have attempted to quantify flows of energy, materials, and dollars through the systems and to identify specific areas where impacts may be expected.

The level of detail with which the various technological system elements have been discussed is sufficient to understand flows of materials, labor, dollars, and energy through the system, and to identify flows of residuals into the environment. We have not undertaken detailed engineering and economic analyses of these technologies since this work has been performed elsewhere, often by several sources.*

*Specifically, two previous studies on the feasibility of alternative fuels for automotive transportation^{1,2} are pointed out as sources of more detailed engineering and economic analysis.

The basic elements that make up the alternative fuels network are shown in Figure 4-1. This block flow diagram is sufficiently general that the particular energy conversion technologies and the transportation and distribution steps need not be specified. These will be discussed in detail later. The important thing to notice about the diagram is the way the alternative fuels are introduced into the conventional fuel production and distribution system. It is our judgment that methanol, because of its special properties, would have its own distribution network parallel to, but distinct from, the conventional gasoline and distillate fuel networks. On the other hand, for gasoline and distillate fuels derived from coal and oil shale, we expect that once the syncrude has been produced and introduced into the conventional pipeline/refinery system, its fate will be essentially indistinguishable from the natural crudes that are processed in the same system. The block flow diagram reflects these judgments and also allows for the additional alternative of introducing a methanol/gasoline blend at the last stage of fuel distribution, i.e., at the pump.

It becomes apparent from the above discussion that most of the social, economic and environmental impacts resulting from the development of alternative fuels, with the possible exception of methanol, will be in the extraction and conversion stages. For this reason, most of the subsequent discussion, as well as the identification of impacts, will center around these two stages. Since the production of methanol from coal and of synthetic crude oil (syncrude) from coal and oil shale are new technologies, they may have impacts that are qualitatively different from current types of energy conversion activities. In addition, new types of impacts from the distribution and end use of methanol are likely to occur. The extraction of coal for liquid fuels production is not likely to pose any new problems in addition to those already encountered with conventional coal mining methods. However, the scale of

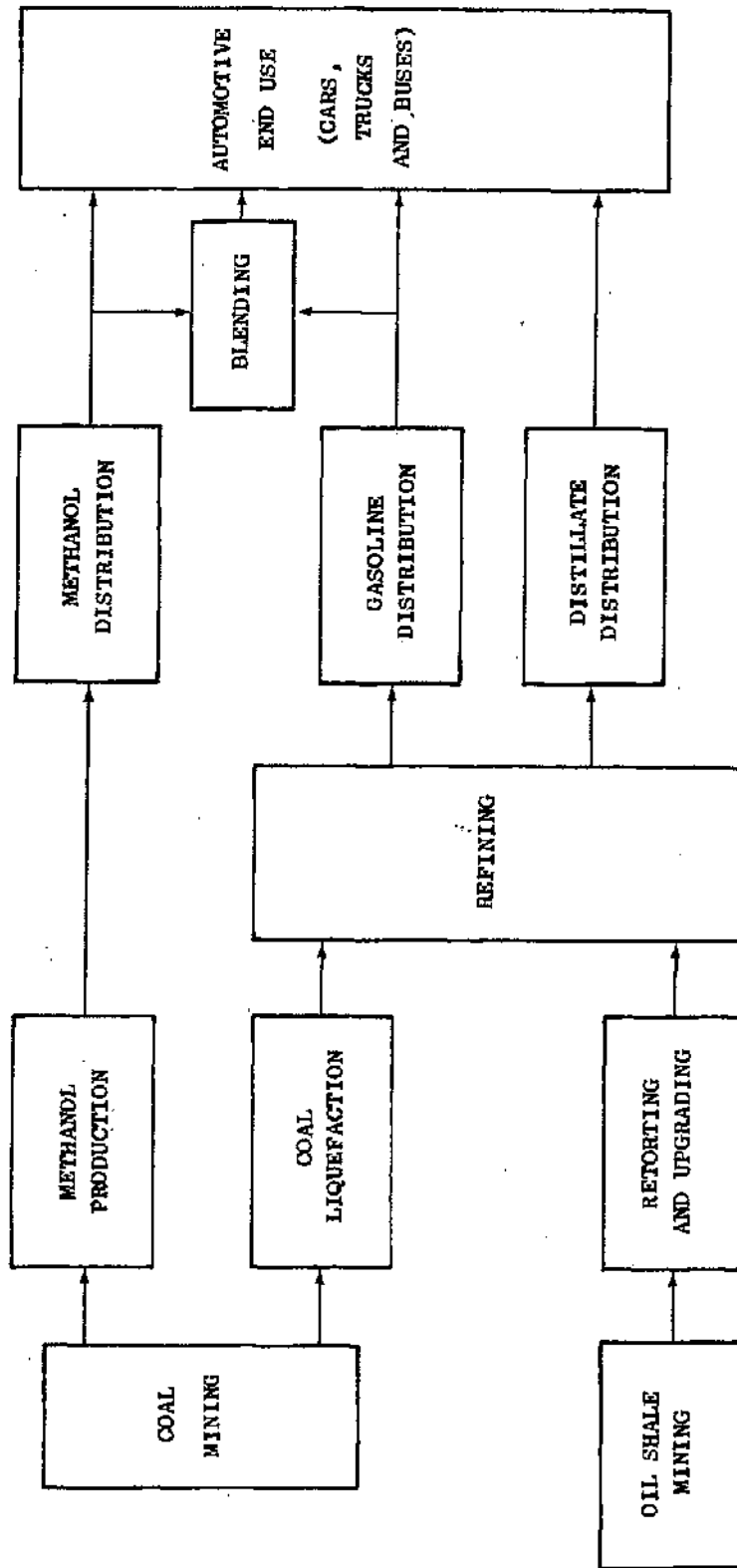


FIGURE 4-1. SYNTHETIC FUELS NETWORK

impacts is likely to increase in certain areas. The extraction and processing of oil shale will have significant new impacts in shale-bearing regions due to the very large amount of material that must be mined and disposed of.

Two important considerations in the development of a synthetic fuels industry are the cost and availability of the resource required for input into the conversion processes. In coal conversion processes, large quantities of coal are required by a single large plant (10 to 20 million tons per year), and this requirement contributes significantly to the cost of producing the final product. Since it is important to ensure a continuous supply of coal over the 20-year life of the plant, the companies that operate the plants will attempt to "block up" (i.e., acquire leases) at least a 20-year supply of coal for each plant. The large reserves required are more readily obtained in the western states than in the eastern states. In addition, the costs of western coal extraction are appreciably lower (\$3-5/ton) than those for eastern coal (\$8-10/ton) due the thick seams and low stripping ratios typical of western coal deposits.

A large part of the expansion of the coal industry can be expected to take place in the West. For this reason a large energy conversion industry may also be centered in the western United States, in which case many of the impacts due to synthetic fuels development would be specific to this region. Thus, the use of western coal to produce synthetic petroleum and methanol is emphasized in the following discussion. This emphasis does not rule out the use of midwestern and eastern coals for conversion to synthetic liquid fuels; in fact, there are strong reasons for utilizing these high sulfur coals to produce clean liquid fuels, and a major expansion of eastern coal production can be expected. However, the judgment that the greater part of the projected expansion of the coal and energy conversion industries is likely to take

place in the West and that problems associated with this expansion are more likely to be serious in the western states than in the eastern states is reflected in this emphasis.

The technologies for converting coal and oil shale into liquid fuels can best be described as emerging technologies in the sense that bench scale, pilot plant, and, in some cases, demonstration plant, operation of the various processes have been carried out, but none of the technologies has yet been utilized in a commercial-sized plant. Of the three technologies considered--crude oil from oil shale, crude oil from coal and methanol from coal--it is widely accepted that the technology for extracting crude oil from shale is the most advanced and the one closest to commercial application. We judge the second most advanced of the technologies to be the conversion of coal to methanol, even though no pilot or demonstration plants have been built. The reason for this judgment is that the two steps for converting coal to methanol--production of synthesis gas and catalytic conversion of synthesis gas to methanol--are both well understood and developed sufficiently so that the combination of the two into a coal-to-methanol operation does not present serious technical difficulty. Coal liquefaction is the least advanced technology. Even though several processes have been tested through the pilot plant stage, serious difficulties remain in the large scale application of this technology, and the first commercial plants are not expected for at least ten years.

Synthetic liquids derived from coal and oil shale are expected to be expensive. Estimates of the market price range from \$12 to \$17 per oil-equivalent barrel³ (two barrels of methanol have approximately the same energy content as one barrel of oil). Some estimates go even higher. A large fraction of the price of synthetic fuels is due to the high initial capital investment required for a synthetic fuel plant. This investment is of the order of \$1 billion (1973) for a 100,000-B/D

(16,000 m³/D) plant. Since construction costs have escalated at a rate significantly higher than the overall rate of inflation, the capital investment may be much higher (in constant dollars) over the next ten years. Ultimately technological improvements as well as standardization of some process components can be expected to reduce both capital investment and operating costs. The problems associated with generating the large amounts of capital required to build up the synthetic fuels industry constitute a significant economic and institutional impact, and are discussed in detail in Chapter 8.

Brief mention should be made of the kinds of products to be expected from synthetic fuels plants. In the conversion of coal and oil shale to liquid fuels, a variety of products can be produced, ranging from light oils and naphtha to fuel oil and synthetic crude oil. Some of these products may be used as fuel for power plants, heating oil, etc. However, since this study is directed toward the use of synthetic fuels in automotive transportation, we assume that the major end product of a coal liquefaction or oil shale plant is synthetic crude oil, which is suitable as a refinery feedstock, and which is ultimately converted to gasoline and distillate fuel as well as to other refined products consistent with the composition of the syncrude.

B. Discussion of Technologies

1. Liquid Fuels from Coal

a. Extraction

The various techniques for surface mining coal are discussed in detail in Chapter 13, and only brief mention is made here on the extraction stage of coal conversion. The techniques of area strip mining utilizing large "walking" draglines to remove overburden and electric shovels and heavy duty trucks to scoop out and remove the coal from

the exposed seam are both well developed and well adapted to mining the large western coal deposits lying near the surface. These mines can be made rather large, in the 5- to 10-million ton per year (4.5×10^8 to 9×10^8 kg/Y) range, and thus it will be feasible to dedicate two or three large mines to a single large (100,000 B/D or 16,000 m³/D) synthetic fuel plant, which will require 10 to 20 million tons per year (9×10^8 kg/Y to 18×10^8 kg/Y) of coal.

Although there are some large underground and surface mines in Illinois (up to 5 million tons per year or 4.5×10^8 kg/Y), most eastern mines are much smaller,⁴ and many more of these mines will have to be dedicated to a single synthetic fuel plant operating in the East. It may be difficult to ensure a continuous source of supply from many small mines unless they are all controlled by the same company that operates the synthetic fuel plant.

Eventually western coal deposits lying near the surface will be depleted and technology will have to be developed to extract the much larger deep-lying coal resource. The presently used techniques such as room-and-pillar and longwall mining, which are used in the relatively narrow underground seams in the East, will have to be replaced by newer methods suitable for the much thicker deposits in the West. The long-term future of the western coal industry as well as the synthetic fuels industry may hinge on the successful development of such techniques.

b. Conversion

Coal is an organic material consisting primarily of carbon and hydrogen and secondarily of oxygen, nitrogen, sulfur and other inorganic constituents. The molecular constituents of coal are complex aromatic (ring) compounds in which the atomic ratio of carbon to hydrogen is about one. Typical carbon-to-hydrogen weight ratios are 11 to 15. Under the appropriate conditions, these large molecules can be broken

down into smaller ones, with carbon-to-hydrogen weight ratios of the order of 6 to 8, and a liquid hydrocarbon fuel can be obtained. There are three distinct routes for carrying out the conversion of coal to liquid fuels, of which two are of interest for this study.

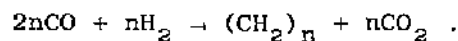
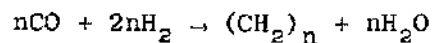
(1) Fischer-Tropsch Synthesis/Methanol Synthesis--

Fischer-Tropsch synthesis was used extensively by the Germans during World War II to produce synthetic petroleum from coal when natural petroleum was in short supply. Through 1943, large quantities of gasoline were produced in this fashion. Even though this method of coal liquefaction is expensive and inefficient, it is the only coal liquefaction process currently being used in a commercial plant (South African Gas and Oil Company [SASOL]--operating at 6600 tons (6×10^5 kg) of coal input per day). The main product of this plant is synthetic gasoline, but significant amounts of diesel oil, liquefied petroleum gas (LPG), waxes and alcohols are also produced.⁵ SASOL has recently announced plans to expand the plant to three times its present size.

Fischer-Tropsch synthesis is actually the second step of a two-step process for converting coal to liquid fuels. In the first step, the coal is gasified to produce a synthesis gas consisting mainly of carbon monoxide (CO) and hydrogen (H_2). There are several processes by which gasification can be accomplished. As an example, we will use the Lurgi process, which is both well developed and widely used. In the Lurgi process, coal is crushed and fed to a pressurized lock hopper from which it is admitted to the gasification vessel. Inside the vessel the coal moves from top to bottom by the force of gravity and is reacted with a counterflowing stream of oxygen and steam at 1100-1400°F (590-760°C) and 350-450 psi ($2.4-3.1 \times 10^6$ N/m²). Ash is removed via another lock hopper at the bottom of the vessel. The gas produced by the reaction is

bled off at the top of the vessel. It consists primarily of CO and H₂ along with carbon dioxide (CO₂), water vapor (H₂O), methane (CH₄), and contaminants such as hydrogen sulfide (H₂S). After leaving the gasifier, the hot gas is quenched with water to remove tars and oils, which are formed during gasification, and then purified to remove the acid gases CO₂ and H₂S.

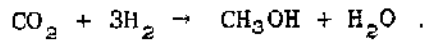
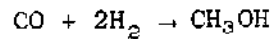
The resulting synthesis gas containing H₂ and CO in the approximate molecular ratio of 2/1 is suitable for conversion to hydrocarbons via Fischer-Tropsch synthesis. This synthesis is carried out in a fluidized bed catalytic reactor at 430-490°F (220-250°C) and 360 psi (2.5 × 10⁵ N/m²). The two major reactions on which the synthesis is based are as follows, where (CH₂)_n is the symbolic representation of a hydrocarbon containing n carbon atoms with n larger than about 4 or 5:



The resulting liquid product is fractionated (distilled) to separate the various components described earlier. Depending on the conditions and catalysts employed, different product mixes can be obtained.

Although it is unlikely that this inefficient and obsolete process will be used to produce liquid hydrocarbon fuels from coal in the United States, a variation of this process will be of primary importance for the production of methanol. The synthesis of methanol from coal is similar in almost all respects to the Fischer-Tropsch synthesis of gasoline. The major difference is in the final synthesis step where the nature of the catalyst and the operating conditions determine the final product.

In methanol synthesis, a copper-zinc catalyst is used to convert purified synthesis gas to methanol at 500°F (260°C) and 1500 psi (1×10^7 N/m²). The principal reactions involved are:



To achieve the maximum yield of methanol (CH₃OH) it is important to have the correct H₂/(CO + CO₂) molecular ratio in the synthesis gas. This is accomplished by allowing some of the gas to undergo CO shift conversion, whereby steam and CO are reacted to form CO₂ and H₂. This step constitutes another difference between methanol synthesis and the Fischer-Tropsch process.

Figure 4-2 shows a block flow diagram for the conversion of coal to methanol. Nearly a third of the coal input to the plant is converted to low-Btu fuel gas in a gasifier operating with air instead of oxygen. This gas is burned on-site to provide steam and electricity to run the various plant processes.⁶ This method of producing plant fuel is not as efficient as burning coal directly but does result in significantly lower emissions to the air.

Most of the processes associated with methanol production have been discussed previously. Other processes shown in Figure 4-2 are: methane reforming, wherein methane produced in the gasifier (methane is not suitable as a feed to methanol synthesis) is reacted with steam to produce additional CO and H₂; compression of the 300-400-psi ($2.1\text{-}2.8 \times 10^6$ N/m²) synthesis gas to the 1500 psi (1.0×10^6 N/m²) necessary for methanol synthesis--since less than 7 percent of the synthesis gas is converted to methanol during a single pass through the synthesis stage, the remainder is recycled to the compression stage; sulfur recovery, in

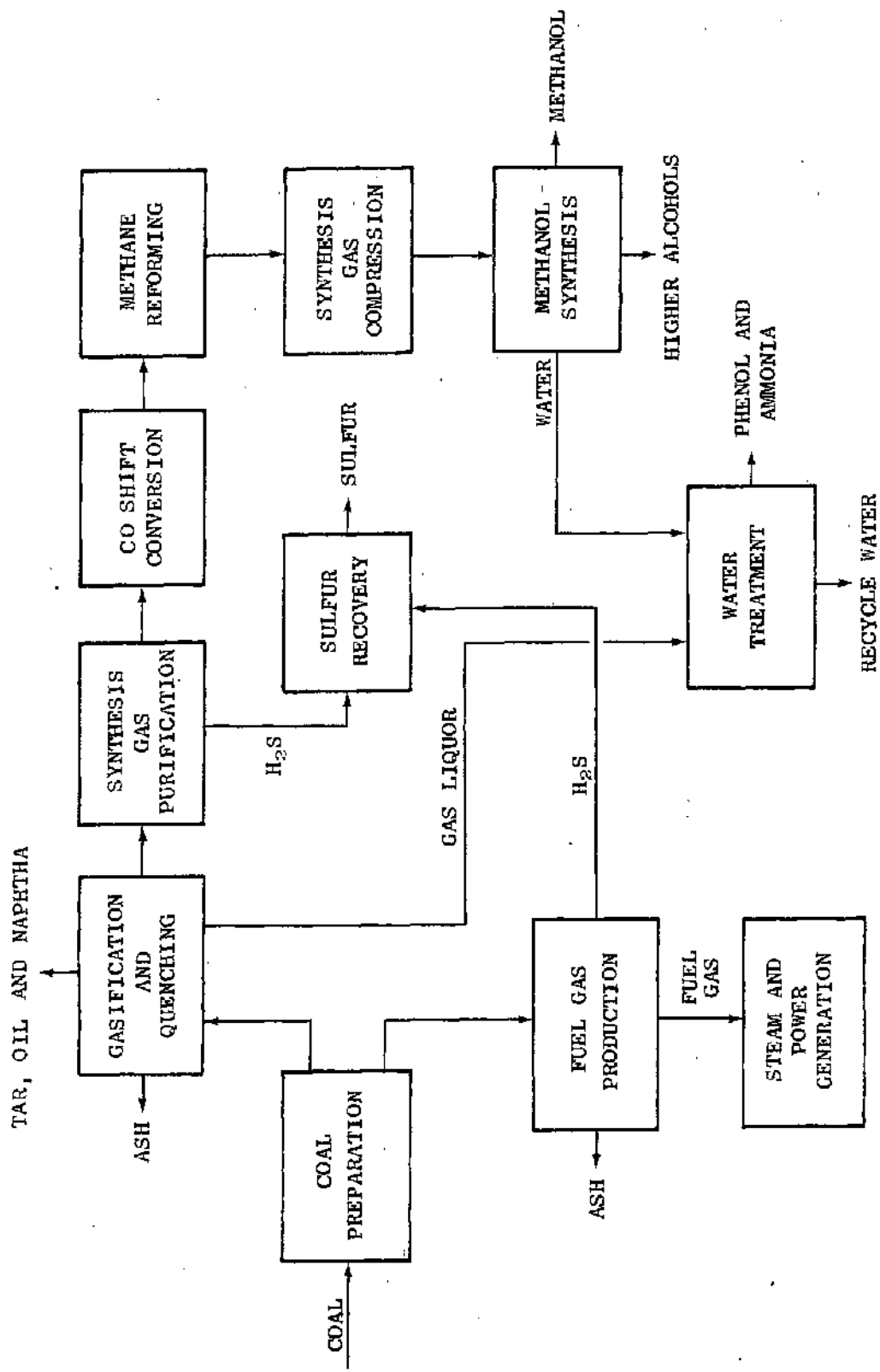


FIGURE 4-2. PRODUCTION OF METHANOL FROM COAL

which H_2S is a concentrated stream from the gas purification stage is reduced to elemental sulfur, which can be sold as a byproduct.

For the process shown in Figure 4-2, the thermal efficiency is rather low--56.6 percent if the heating value of all the byproducts is counted; 40 percent if only methanol is counted.⁶ Certain changes in process components could result in a higher overall efficiency. Burning coal directly instead of converting it to low-Btu fuel gas has been discussed previously. This procedure increases efficiency but results in a higher environmental cost. Another process change would be to utilize a high-temperature gasifier, which would produce a negligible methane yield in the synthesis gas. This would eliminate the energy consumptive methane reforming step, and high temperature operation would produce far fewer byproduct tars and oils.

There are two commercially available gasifiers that have low direct methane yields--the Winkler and the Koppers-Totzek. These gasifiers also have the advantage of producing practically no tars and oils, thus eliminating an additional separation step. However, both gasifiers have the disadvantage of operating at atmospheric pressure, thus requiring a large degree of compression of the gas before methanol synthesis. In the Koppers-Totzek process, the additional energy savings brought about by low tar and methane yield is offset by the large compression energy requirement, resulting in an overall coal to methanol efficiency of about 40 percent,² the same as when the Lurgi gasifier is used.

A number of advanced gasifiers suitable for producing synthesis gas have been tested. These include the Bureau of Mines Synthane process, the CO_2 Acceptor process of Consolidation Coal Company, the Westinghouse fluidized bed process and various in situ gasification processes, developed by the Bureau of Mines, Lawrence Livermore Laboratory, and others. All of these processes incorporate design features

which promote increased synthesis gas yields and other process improvements that will eventually render the Lurgi and Koppers-Totzek processes obsolete. However, none of these processes are commercially available at present. First generation methanol plants will undoubtedly be designed around current technology, while second and third generation plants will incorporate the more advanced gasification technologies mentioned above, as they become available.

(2) Pyrolysis--Pyrolysis is a technique for extracting the volatile material in coal by heating it to high temperatures (about 1600°F) in successive stages. The volatile material driven off contains most of the hydrogen in the coal, and consists of medium-Btu gas and a high-density synthetic crude oil. A portion of the gas can be reformed to produce hydrogen, which can then be used to hydrotreat the liquid product, thus upgrading it to a crude oil suitable as a refinery feedstock. The material left behind after pyrolysis is called char; it consists mostly of carbon and ash. This material may be usable as fuel if the sulfur content is low enough.

Pilot plant tests made by FMC Corporation on its COED (Char Oil Energy Development) coal pyrolysis process indicate that just slightly over one barrel (0.16 m³) of synthetic crude oil is obtained per ton (910 kg) of coal input.⁵ Thus, the coal-to-oil thermal efficiency is only about 25 percent. The remainder of the product energy is in the form of char or gases. Since this study is directed toward the production of liquid fuels from coal, and other processes are capable of liquid fuel yields of three barrels per ton (0.53 m³ of oil per 1000 kg of coal) or more, we do not consider that coal pyrolysis is of sufficient interest to warrant further analysis.

(3) Coal Dissolution--The process by which coal is dissolved in a solvent, hydrogenated, and converted into a liquid hydrocarbon

fuel is known as coal dissolution. It is also referred to as solvent hydrogenation or solvent extraction. This appears to be the most promising technology for converting coal into synthetic crude oil (syncrude). It has the advantage of achieving a high liquid product yield (approximately three barrels per ton or 0.53 m^3 per 1000 kg of bituminous coal) with relatively high thermal efficiency (up to 75 percent). In addition, most of the sulfur in the coal is removed during the process. Although several variations of this process have been developed, there are some steps common to all processes including the dissolution of the organic matter in the coal in a process-derived solvent and hydrogenation of the resulting product to yield synthetic crude oil. These are shown in the block flow diagram of Figure 4-3. The dotted lines indicate the different stages at which hydrogenation can take place, depending on the process.

The three variants of the coal dissolution technique that have been the most extensively evaluated are the Solvent Refined Coal (SRC) process of Pittsburgh and Midway Coal Company, the Consol Synthetic Fuel (CSF) process of Consolidation Coal Company and the H-Coal process of Hydrocarbon Research, Inc. (HRI).

In the SRC process, the crushed coal is first slurried with the solvent and then reacted with hydrogen at 815°F (435°C) and 1000 psi ($6.9 \times 10^5 \text{ N/m}^2$), causing complete dissolution of the organic matter. After separating unreacted solids and solvent, a low-sulfur, ash free product, which is a solid at room temperature, is obtained. It must be further upgraded by hydrotreating to yield synthetic crude oil. Two pilot plants have been constructed to test the SRC process. A six ton per day (5400 kg/D) plant producing a clean boiler fuel recently completed a 75-day test run at Wilsonville, Alabama. Sponsors are the Electric Power Research Institute (EPRI) and the Southern Services

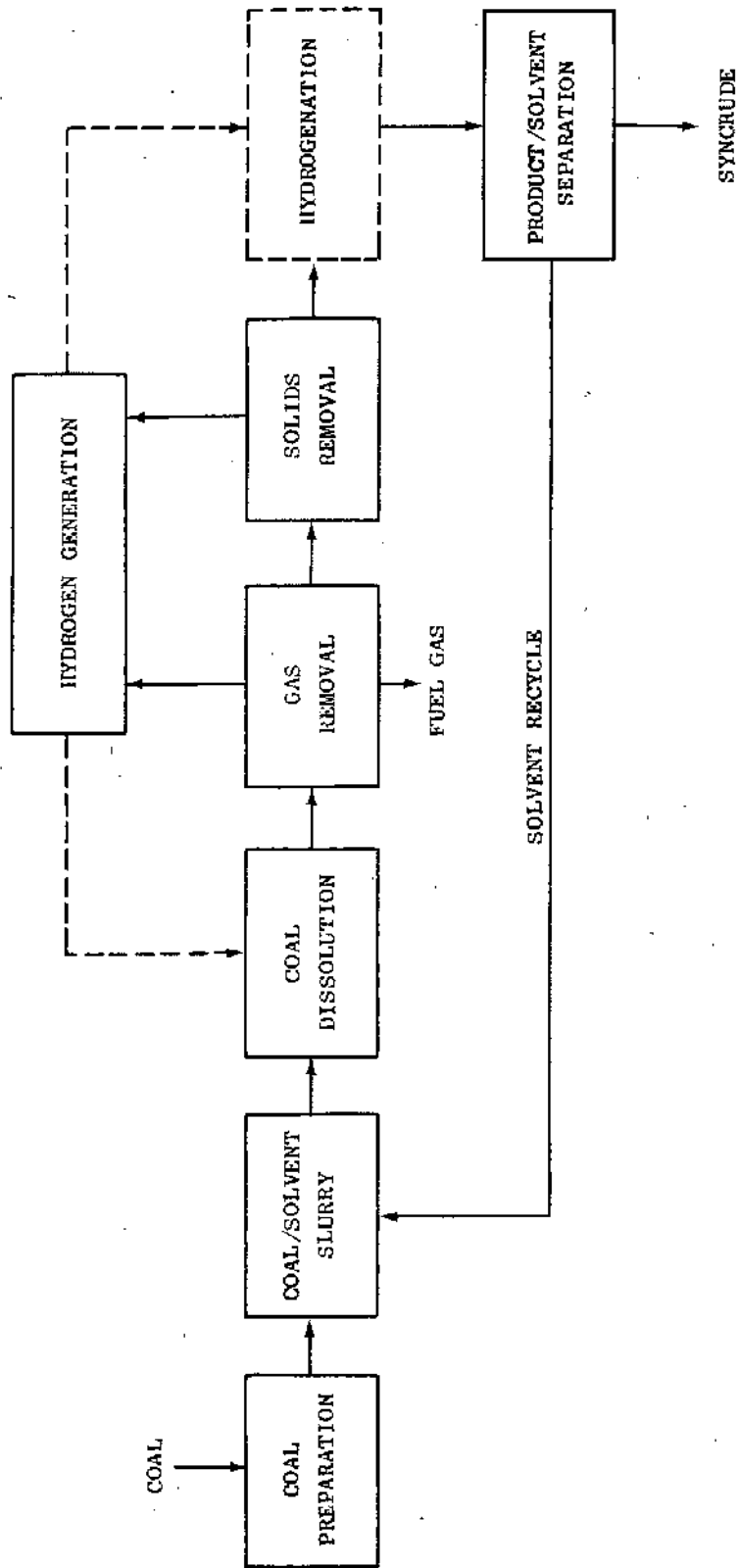


FIGURE 4-3. COAL LIQUEFACTION VIA DISSOLUTION AND HYDROGENATION (FROM REFERENCE 7)

Company. In Tacoma, Washington, a 75 ton per day (68,000 kg/D) pilot plant has been built for Pittsburgh and Midway under ERDA sponsorship.

The CSF process separates the dissolution and hydrogenation steps. The crushed, dried, and preheated coal is first slurried with a hydrogen donor solvent. Then it is passed through a tubular furnace at 150 psi (1.0×10^6 N/m²) and 765°F (410°C) to an extraction vessel where dissolution of the organic matter is completed. After unreacted solids are separated, the resulting liquid is fractionated. The low-boiling fraction is recovered as solvent, and the heavy bottom product is further hydrogenated at 800°F (430°C) and 3000 psi (2.1×10^7 N/m²) to yield synthetic crude oil.

A 70 ton per day (6.4×10^4 kg/D) pilot plant based on the CSF process was operated at Cresap, West Virginia, for 40 months, ending in 1970. Because of recurring equipment failures, the plant was shut down for a detailed study of problem areas. However, it was concluded that the process, as designed, is technically feasible. This plant is scheduled to be reactivated by the Fluor Corporation; several coal-to-liquid-fuels processes will be tested.

A third variant of the solvent refining method, the H-Coal process, carries out dissolution and hydrogenation in the same step in the presence of a catalyst. The slurried coal is reacted with hydrogen in an ebullating bed reactor at 850°F (450°C) and 2700 psi (1.9×10^7 N/m²). Cobalt-molybdenum catalyst is continuously added to the reactor as spent catalyst is removed. After separating gases and unreacted solids, synthetic crude oil is recovered from fractionation of the resulting liquid.

Initial testing of the H-Coal process has been carried out in a three ton per day (2700 kg/D) pilot plant at the HRI facilities at Trenton, New Jersey, under the sponsorship of Ashland, ARCO,

Standard of Indiana, and Exxon. In addition, ERDA and HRI are planning a 600 ton per day (5.4×10^5 kg/D) pilot plant at Catlettsburg, Kentucky, to test the commercial feasibility of the H-Coal process. Industrial sponsors include the ones mentioned above (except Exxon), EPRI and Sun Oil.

Several additional variants of the coal dissolution method are being tested. Gulf Research and Development recently began testing a catalytic process in a one ton per day pilot plant. The Bureau of Mines has contracted Foster-Wheeler Corporation to design an eight ton per day pilot plant to test its Synthoil process, which is similar to the H-Coal process, and has been tested through the one-half ton per day (450 kg/D) pilot plant stage.

In all the above processes, large amounts of hydrogen (15,000-20,000 cubic ft per ton of coal or 470-620 m³/1000 kg of coal) are consumed. In most cases, sufficient hydrogen can be produced by a combination of gasification of unreacted coal solids (char) and heavy distillation products, and steam reforming of high-Btu byproduct gases. If necessary, some of the feed coal itself can be gasified to provide additional hydrogen.

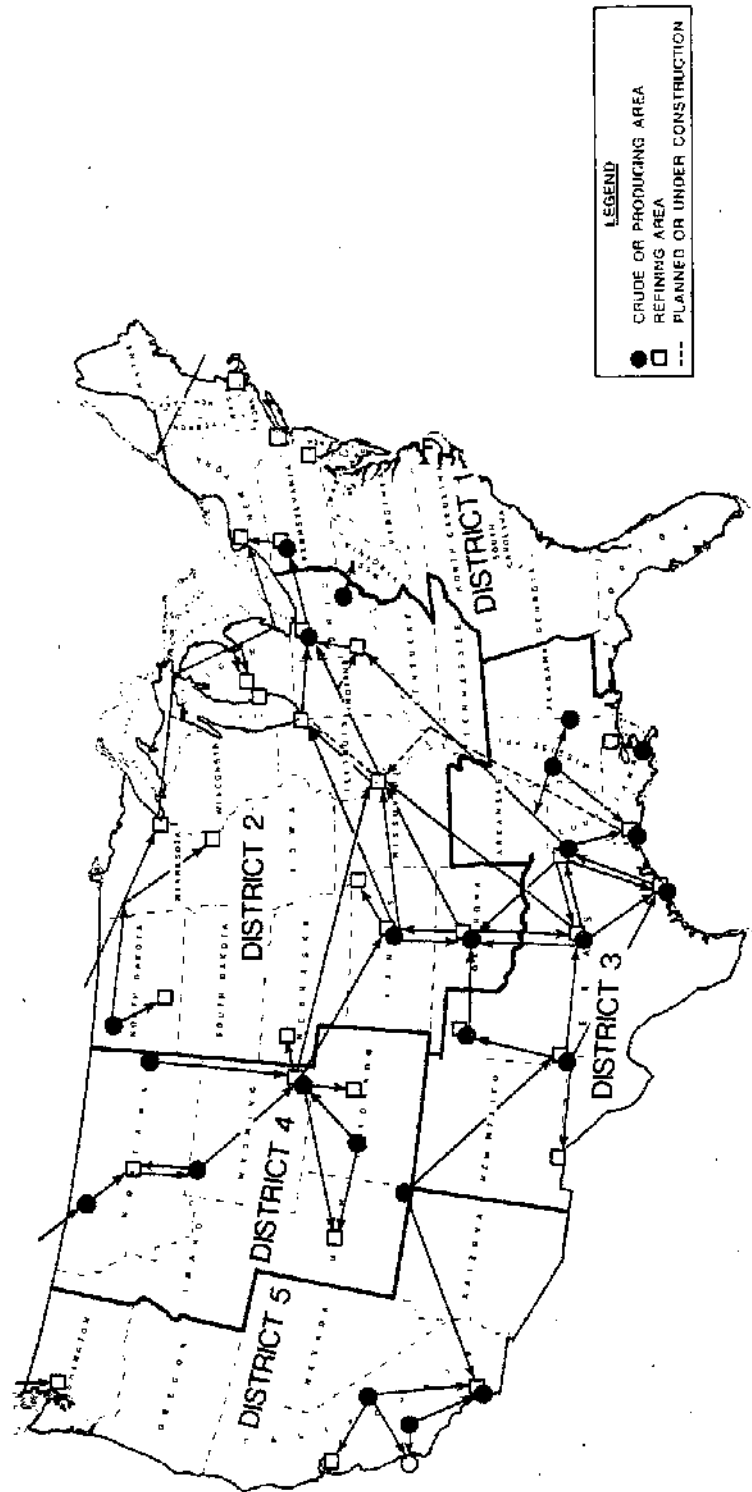
At present no coal liquefaction processes are suitable for incorporation into a commercial-size plant. Several processes have been tested at the pilot-plant level as indicated above. However, considerable research and development remains before the first commercial coal liquefaction plants can be built and operated successfully. In particular, areas in which further R&D are required are coal slurring and pressurization, durability of reactor materials under severe operating conditions, separation of unreacted solids from liquid products, and maintenance of the activity of hydrogenation catalysts.

It is widely believed that a single-step catalytic hydrogenation process, such as the H-Coal process, is the one most likely to achieve rapid commercialization for the production of synthetic crude oil from coal.^{1,7,8} While other processes, such as the SRC process, may be utilized to provide clean boiler fuels for power plants, it appears that the H-Coal or a similar process is the most suitable for providing refinery grade crude oil in terms of cost, efficiency, and technological readiness. Other promising processes are currently undergoing development, including the Union Carbide process, which has been chosen by the Office of Coal Research to be used in a 2600 ton per day (2.4×10^6 kg/D) demonstration plant. However, details of this process are largely proprietary, and furthermore half of the product output of the plant (on a Btu basis) will be in the form of high-Btu gas--the liquid yield is only 1.5 barrels per ton ($0.26 \text{ m}^3/1000 \text{ kg}$) of coal.

Due to the substantial amount of analysis that has been carried out on the H-Coal process,^{1,8} its suitability for producing syncrude, and its advanced stage of technological development, we have chosen it as the basis for scaling the impacts from coal liquefaction.

c. Distribution

Due to the similarity between coal-derived syncrude and natural crude oil, the most likely mode of distribution is through the presently existing crude oil pipeline system shown in Figure 4-4. Depending on the location of the syncrude plants, some new pipeline additions or extensions will undoubtedly be built. However, it is likely that the location of crude oil pipelines, as well as the availability of coal, water, etc., will be taken into account in siting the plants. Once the syncrude has entered the pipeline distribution system, it will probably be treated as another source of "sweet" (low sulfur) crude, as



SOURCE: NATIONAL PETROLEUM COUNCIL

FIGURE 4-4. CRUDE OIL PIPELINE NETWORK

is presently done with syncrude from Canadian tar sands, and distributed to refineries as a supplement to natural crude supplies.

Once the syncrude has entered the refinery and is blended with natural crudes, its fate will become indistinguishable from that of other crudes, and products derived from refining the blended syncrude will enter the product distribution network along with other refined products. Due to the high aromatic content of H-Coal syncrude, it is relatively more suitable for the production of gasoline than distillate fuel or other products.⁸ Thus, refineries that process significant fractions of syncrude will undoubtedly produce an even larger proportion of gasoline, relative to distillate fuel, than the 2 to 1 ratio that characterizes the present average refinery product slate.

The distribution of methanol derived from coal presents a different problem. There is no pipeline network suitable for transporting methanol. Presumably such a pipeline system could be built, but in the early days of the industry there would not be the financial incentive to do so. Thus, it is likely that methanol will be transported to major distribution centers in the same manner as other liquid chemicals, via railroad tank car. If the industry grows to a large size and firm markets are established, both volume requirements and economic incentives would probably induce the construction of product pipelines to the regions of highest consumption.

The distribution of methanol to final consumption (cars, trucks, and buses) poses additional problems of handling and storage. Since methanol is compatible with gasoline as a blend, it is likely to be consumed initially as a 10-15 volume percent methanol/gasoline blend.⁸ However, small amounts of water in the methanol tend to cause phase separation in the gasoline/methanol mixture. To mitigate this problem, the methanol should be stored and handled with special equipment designed to

keep moisture out of the system, and blended with gasoline at the last stage of distribution when the fuel is pumped into the vehicle. Thus, methanol is likely to be distributed through the same network as gasoline, but with separate storage and handling facilities.

Ultimately, assuming new engines are designed to operate with pure methanol, some distribution facilities may be built solely to handle methanol sales, but most of the methanol would probably continue to be sold through gasoline distribution facilities (service stations) either in the pure form or as a blend.

An alternative to locating a coal liquefaction or methanol plant near the mine and shipping the product to refining or distribution centers is to locate the plant near these centers and ship the coal to the plant. In coal liquefaction, this is undoubtedly a more expensive alternative than shipping syncrude via pipeline. However, the tendency of some western states, such as Montana, to encourage resource extraction, while discouraging energy conversion activities within the state, will cause increased attention to be directed toward this alternative.

To transport the large quantities of coal required by synthetic fuel plants, either unit trains or coal slurry pipelines will be utilized. A single coal slurry pipeline could supply one or two 100,000-B/D (16,000 m³/D) plants. Four to five unit trains per day of 100-car length would be required to supply a single plant of the same size. Assuming a two-day transit time between the mine and the plant, about 20 to 25 unit trains would be required to be dedicated full time to a single plant. Assuming several plants will be located in a particular area, say northern Illinois, an enormous supply problem can be envisioned. Coal slurry pipelines will undoubtedly help relieve these problems. However, at least one limiting factor will be the large

amounts of water that are required for slurring the coal--about 750 acre-ft per million tons ($100 \text{ m}^3/1000 \text{ kg}$) of coal.¹⁰ Many western states are reluctant to have scarce water supplies leave the state in this fashion.

Further discussion of coal slurry pipelines and railroads and problems involved in the large scale transport of coal can be found in Chapter 19.

2. Oil Shale

a. Extraction

The production of synthetic crude oil from oil shale involves mining and processing an enormous amount of material--1.4 tons of shale per barrel of oil recovered, on the average. This means that an oil shale retorting and upgrading plant producing 100,000 barrels ($16,000 \text{ m}^3$) of syncrude per day must process about 50 million tons ($4.5 \times 10^{10} \text{ kg}$) of shale per year. The mining operation for this plant would be ten times larger than the largest underground coal mines now in operation.

It is anticipated that most of the oil shale lying in underground deposits will be mined via the room-and-pillar technique.¹¹ This is a conventional, well-established mining technology whereby large underground "rooms" (about 60 ft \times 60 ft or 18 m \times 18 m) are blasted and dug from the resource bed, and large "pillars" are left standing between the "rooms" to support the roof of the mine. With this method, about 60 percent of the resource in-place can be extracted and 40 percent is left in the form of "pillars."¹²

When oil shale lies in deposits near the surface, open pit mining can be carried out. The overburden is first stripped away and stored, then the shale is recovered, crushed, and retorted. After

all the resource is removed from the mine area, the overburden is replaced, contoured, and revegetated. The feasibility of surface mining oil shale is determined by the overburden-to-resource ratio and the availability of an area for overburden storage.

A more complete discussion of oil shale mining and spent shale disposal and reclamation can be found in Chapter 14.

b. Conversion

Conceptually, the technology of obtaining liquid hydrocarbons from oil shale is simple. The crushed shale is heated in a closed vessel (retort) to a temperature of 900°F (480°C) or greater, at which point the kerogen (the organic portion of the oil shale) vaporizes and is separated from the solid inorganic portion of the rock. After retorting, the shale oil is upgraded by means of hydrotreating (chemically reacting with hydrogen) to yield a synthetic crude oil, which is suitable for transport via pipeline and can be used as a refinery feedstock.

The various methods for retorting oil shale differ in the manner in which heat is generated and transferred to the shale. The simplest method is the Fischer assay technique in which heat from an external source is transferred to the shale through the wall of the retort. Any fuel may be used to supply the heat. Due to large capital and operating costs, this method is unsuitable for commercial development. However, it is commonly used on a laboratory scale to measure the kerogen content of the shale.

There are four additional methods for retorting oil shale, which are in various stages of development and which have the potential for commercial application. These are discussed in the following paragraphs.

(1) Hot Solids or Solids-to-Solids Heating Method--

The TOSCO II process is the most advanced version of this technique. In this process ceramic balls are heated by the combustion of byproduct gases and liquids and transferred to the retort where they are mixed with crushed, preheated shale. Shale oil vapor is driven off and recovered. The ceramic balls are separated from the spent shale (on the basis of size) and subsequently reheated. A high efficiency of energy recovery is achieved; however, capital and operating costs are high.

In the Lurgi-Ruhr gas version of this technique which has been tested in a 12 ton per day pilot plant in West Germany, spent shale is used as the heat carrier. The spent shale is heated by combusting the carbon residue which remains after retorting, together with additional fuel as needed.

The TOSCO II process is essentially ready for commercial application. Colony Development Operation (a joint venture of ARCO, Ashland, Shell, and The Oil Shale Corporation) has successfully completed tests on a 25 ton per day test unit and an 1100 ton per day semi-works plant at Parachute Creek, Colorado. Colony had announced plans to begin construction in April 1975, of a 50,000-B/D commercial plant based on the TOSCO II process. These plans were later postponed, with Colony citing rapidly inflating construction costs and uncertainties in U.S. energy policy as the basis for its decision.¹³

There are several other planned commercial operations in which the TOSCO II retort will be used. These include the following: a 50,000-B/D (8000 m³/D) plant planned to begin operation in 1982 by ARCO, TOSCO, Ashland, and Shell as a joint venture on Colorado Tract C-b; the Rio Blanco Oil Shale Project, a joint venture on Colorado Tract C-a by Gulf Oil and Standard of Indiana with 50,000-B/D (8000 m³/D) initial production planned for 1980; the 75,000-B/D (12,000 m³/D)

Sand Wash Project in Utah planned by TOSCO with start-up expected in 1981-83.

(2) Gas-to-Solids Heating/Internal Gas Combustion

Method--Crushed shale is fed to the top of a vertical retort and low-Btu byproduct gas is injected at the bottom. The gas is combusted in the retort along with residual carbon on the spent shale, and the hot combustion gases heat the shale, driving off the oil vapors that are condensed at the top of the retort. The noncondensable gases are recycled for combustion. Due to the lack of external heating equipment, this method is less costly than other types of retorts. Energy recovery efficiency is somewhat lower, however.

The Bureau of Mines tested a version of this technique, called the Gas Combustion process, in 1966-67. No tests have been carried out on this process since then.

The Union Oil Company version of the process utilizes a unique "rock pump" which injects shale at the bottom of the retort while combustion gases are drawn down from the top by blowers, and retorted shale oil is collected at the bottom. A 1000 ton per day (9×10^5 kg/D) pilot plant was successfully demonstrated in 1957-58. A more advanced version of this retort, called the steam gas recirculation (SGR) process, was recently announced and a 1500 ton per day (1.4×10^6 kg/D) demonstration plant based on this process will be built on private land in Colorado. (The SGR retort is actually an example of the gas-to-solids, external heat generation method discussed in the next section.) Union reportedly plans to have a 50,000-B/D ($8000 \text{ m}^3/\text{D}$) commercial plant operating by 1980.

A third variation on the process has been constructed by Development Engineering, Inc. (DEI), the operating arm of Paraho Development Corporation (a consortium of 17 firms). This process, usually

referred to as the Paraho retort, utilizes patented shale-feed and spent shale-discharge grates, which provide a uniform flow of shale through the retort. Multilevel gas injectors are also used to carefully control the level of incoming gases. DEI recently completed a successful 30-day run on its 500 ton per day (4.5×10^5 kg/D) test plant near Rifle, Colorado, as part of a 30-month R&D program. Paraho has also proposed to construct and test a commercial size retort on the Naval Oil Shale Reserve in Colorado.

Both of the planned commercial operations on federally leased tracts in Utah have proposed to use primarily the Paraho retort. However, since the Paraho retort can operate only on coarse shale, the TOSCO II process will also be used to deal with the 10 to 20 percent of the crushed shale that is too fine for the Paraho process. Sun Oil and Phillips Petroleum have leased the U-a tract and propose to have a 50,000-B/D ($8000 \text{ m}^3/\text{D}$) plant operating by 1978. The White River Shale Corporation (a joint venture of Sun, Phillips, and Standard of Ohio) has leased the other Utah tract (U-b) and is also planning a 50,000-B/D ($8000 \text{ m}^3/\text{D}$) operation. Due to the contiguous nature of the two tracts, and overlapping ownership in the two ventures, it is likely that these operations will be carried out jointly by all the participants.

(3) Gas-to-Solids Heating/External Heat Generation

Method--Recirculated byproduct gas is used as the medium of heat transfer; however, heating of the gas is carried out in the external furnace, rather than by combusting the gas and spent shale within the retort. Some of the byproduct gas, carbon residue on the spent shale, or any other suitable fuel may be combusted to supply heat to the furnace. During 1975, Paraho will begin testing a version of its retort which operates with externally heated gases.

The Brazilian national oil company (Petrobras) has tested a 2200 ton per day (2.0×10^6 kg/D) version of the external gas heating retort called the Petrosix process. The tests were successful; however, there are no plans for commercial application in the United States.

(4) In-Situ Retorting--Shale rock is fractured in place by explosives to form an underground retorting chamber. Air is injected to combust part of the shale, and retorting is carried out via heat transfer from the hot combustion gases. Shale oil is collected from a hollow mined at the bottom of the shale column.

Numerous tests of this method have been made by various companies. Commercial feasibility has not yet been demonstrated, although recent tests by Garrett Research and Development, a subsidiary of Occidental Petroleum, appear promising. A $30 \times 30 \times 70$ -ft ($9 \times 9 \times 21$ -m) shale column was successfully retorted, resulting in a shale oil yield of about 60 percent. Further tests are planned on a $100 \times 100 \times 250$ -ft ($30 \times 30 \times 76$ -m) column, with yields in excess of 70 percent expected. If the Garrett or other tests demonstrate the commercial feasibility of in-situ retorting, the use of this method could considerably reduce water consumption, spent shale disposal, and other problems presently associated with aboveground retorting. However, new problems, such as surface subsidence and the release of large quantities of combustion gases, would be created, and these would need to be carefully managed. This method is expected to be less costly than any aboveground retorting technique.

The TOSCO II process is the most advanced retorting method for which a sufficient amount of information is available to provide the scaling factors required for analysis. In addition, it has been incorporated into the plans of a majority of the companies which will be actively developing oil shale. Thus, we have chosen to use it in our

analysis of oil shale conversion. A block flow diagram showing the steps in oil shale processing, from crushing through upgrading is shown in Figure 4-5.

Subsequent to retorting, described previously, the shale-derived gases and liquids must be processed to remove sulfur and nitrogen, and produce a syncrude that is suitable as a refinery feedstock. The raw shale oil is separated into naphtha, gas oil, and residual fractions. The naphtha and gas oil are sent to separate hydrotreaters where they are upgraded and desulfurized. The residual oil is sent to the coker unit, where coke is produced along with additional naphtha and oil, which are sent to the hydrotreaters. During hydrogenation of the naphtha and gas oil sulfur and nitrogen compounds are converted to H_2S and ammonia, which are separated in the sour water waste stream and subsequently recovered as ammonia solution and elemental sulfur.

The hydrogenated naphtha and gas oil are recombined and leave the plant as synthetic crude oil. The high-Btu byproduct gases from the retort are purified to remove H_2S and ammonia impurities, and to remove uncondensed liquids (naphtha). All of these gases are then consumed on site, either as plant fuel to provide steam and heat, or as feed to the steam reforming furnaces, where they are reacted to form hydrogen for the hydrotreaters.

Although it is conceivable that the raw shale oil upgrading could be carried out elsewhere, transporting it via pipeline would pose severe problems due to its high viscosity. The viscosity is reduced in the process of upgrading and the syncrude product is suitable for shipment via pipeline.

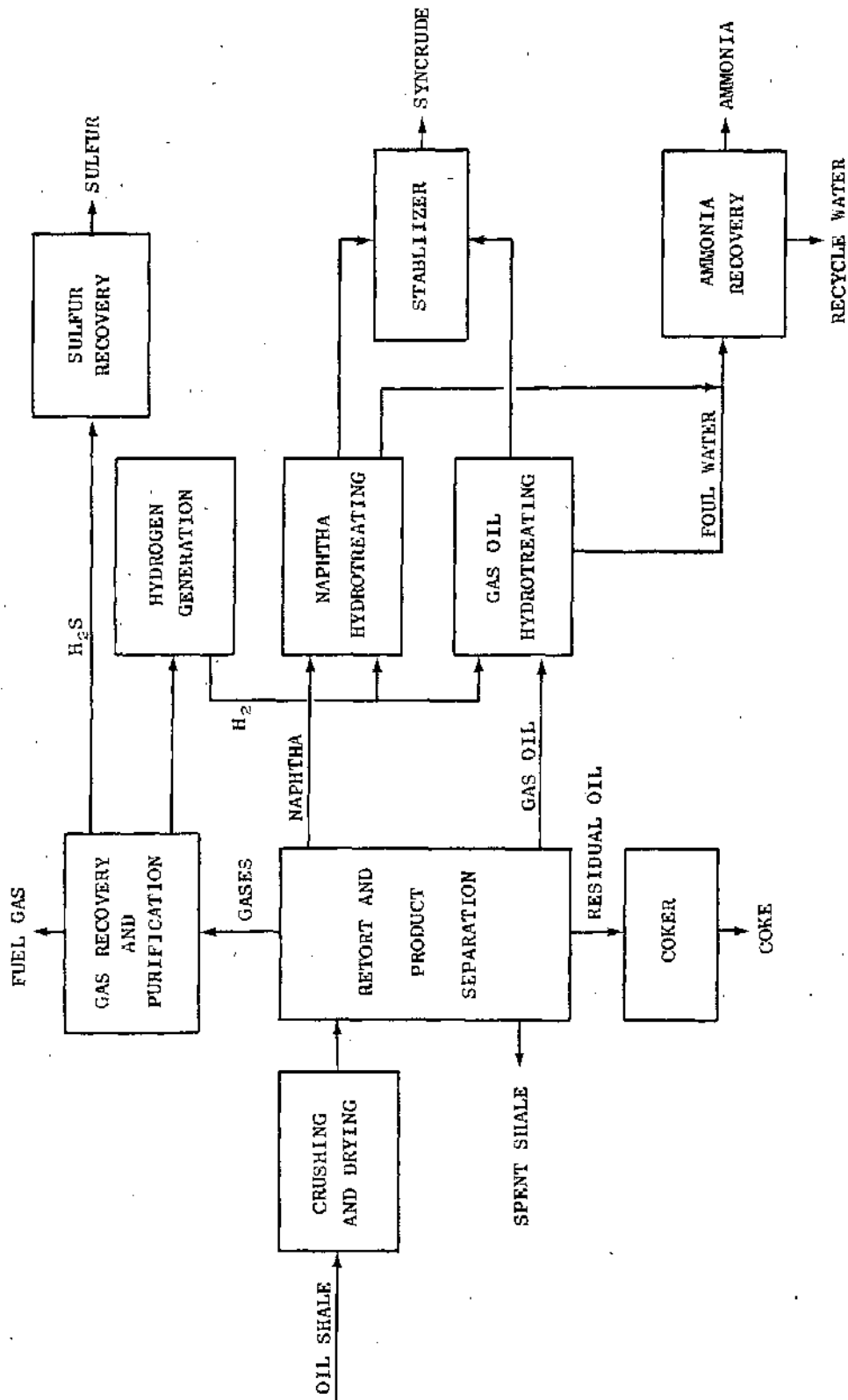


FIGURE 4-5 OIL SHALE RETORTING AND UPGRADING

c. Distribution

As in coal-derived syncrude, the distribution of upgraded shale oil will undoubtedly be done via the present crude oil pipeline network. Colony Development Operation has proposed a pipeline system that would originate in the Piceance Basin of Colorado and connect with existing crude pipelines to carry shale syncrude to refinery centers. Other pipeline connectors will undoubtedly be built as the oil shale industry develops. Figure 4-6 shows the location of the existing crude oil pipeline network in relation to the oil shale-bearing regions of Utah, Wyoming, and Colorado.

3. Building Block Sizes

The sizes of building blocks which will make up the production and transportation systems for synthetic liquid fuels from coal and oil shale will be determined by many interacting factors. Among these are the limiting physical size of the components of each building block, the capacity at which economies of scale are achieved, and the level of production or throughput that best fits into the regional energy supply/demand picture. For the first generation of synthetic liquid fuel plants there is another constraint on size--the amount of capital that private companies are willing to risk in a venture based on technology that has not been previously tested on a commercial scale.

An inspection of the literature on current energy industry practices and future plans for synthetic fuel plants quickly reveals that there is a range of sizes that characterizes building blocks in the synthetic fuels system. Table 4-1 shows the higher and lower sizes in the range typical of each building block. These figures are not meant to indicate absolute limits on sizes; rather they are meant to indicate what "large" and "small" building blocks look like in the

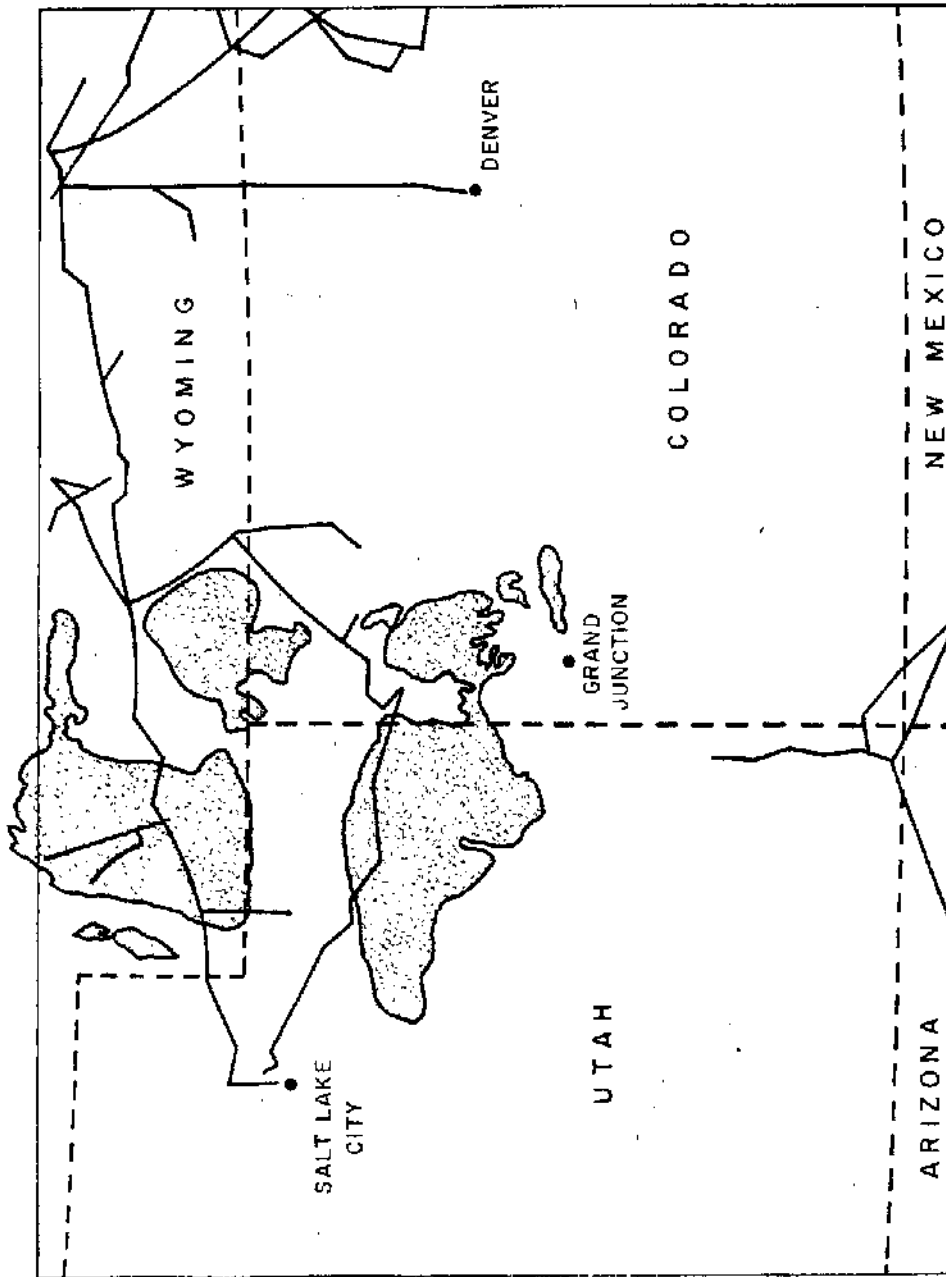


FIGURE 4-6. EXISTING CRUDE OIL PIPELINES IN RELATION TO OIL SHALE AREAS

context of a synthetic fuel supply system. For example, there are many Appalachian coal mines that produce less than 100,000 tons (9×10^7 kg) per year. However, these are not considered to be viable building blocks in the synthetic fuel system.

Table 4-1

BUILDING BLOCK SIZES IN THE SYNTHETIC LIQUID
FUELS PRODUCTION SYSTEM

Building Block	Units*	Building Block Size	
		Small	Large
Western surface coal mine	tons/yr	1 million	10 million
Eastern underground coal mine	tons/yr	0.1 million	5 million
Unit train (coal)	tons of capacity	--	10,000
Coal liquefaction plant	B/D	25,000	100,000
Methanol plant	B/D	35,000	200,000+
Oil shale mine	tons/yr	25 million	75 million
Oil shale retort and upgrading complex	B/D	50,000	150,000
Crude oil pipeline	B/D of capacity	25,000 (8 in.)	1.5 million (48 in.)
Refinery	B/D	50,000	400,000

*1 ton/yr = 910 kg/yr

1 B/D = 0.6 m³/D

1 in. = 2.54 cm.

In spite of the range of sizes possible for the different building blocks, there tend to be certain nominal or "typical" sizes

that characterize industry plans for synthetic fuels. For coal liquefaction, the earliest commercial plants will probably be in the range of 25,000 to 40,000 B/D (4000-6400 m³/D). As the industry matures, the plant sizes will probably increase to about 100,000 B/D (16,000 m³/D). There are few indications that plants larger than this will be built.

The first planned commercial oil shale complexes are of the order of 50,000 B/D (8000 m³/D). Later complexes of 100,000 B/D (16,000 m³/D) or larger are contemplated. Plants larger than 100,000 B/D (16,000 m³/D) will probably be combinations of smaller units.

Consideration of methanol plant size is usually made by analogy with substitute natural gas (SNG) plants. A plant using Lurgi gasifiers, which processes the same amount of coal as a 250 million cubic ft per day (7.1×10^5 m³/D) SNG plant (typical size) can produce about 81,200 B/D of methanol. This is the approximate energy equivalent of a 40,000-B/D (6400 m³/D) syncrude plant. Although conceptual designs have been carried out for much smaller coal-to-methanol plants, it appears that economy of scale will favor the larger plant sizes. Plants with capacities in excess of 200,000 B/D (32,000 m³/D) are conceivable.

Recent trends in construction of the other building blocks in Table 4-1 have been toward the higher end of the scale. However, to a large extent synthetic fuel plants will have to interface with existing facilities, which tend to be at the lower end of the scale. The country abounds with 8-in. (20 cm) pipelines and refineries with capacities well under 100,000 B/D (16,000 m³/D).

C. Material and Energy Flows

In this section the quantities of raw materials, resource energy, labor and capital required to produce a given quantity of synthetic fuel are given and flows of these quantities are traced both through the

extraction-conversion-distribution systems and to areas external to the systems. Tracing the flows of these quantities is important to the assessment of the social, economic, and environmental impacts of synthetic fuels development.

1. Energy Efficiency

Since the processes for converting solid resources into synthetic liquid fuels are themselves energy intensive activities, it is important to identify both the sources of energy loss during conversion and the requirements for external sources of energy to operate the conversion plants. Additional energy will be consumed in the extraction, transportation, refining, and distribution stages as well. By dividing the energy available for end use by the initial resource energy plus all the external energy inputs into the system, we can obtain an overall efficiency for the production of each alternative fuel.

We are concerned here only with the efficiency with which resource energy can be converted into product energy. We do not address the larger question of net energy, in which the energy required to manufacture and deliver the materials that go into the plant along with secondary energy inputs are considered. Net energy calculations are carried out and discussed in Chapter 5.

a. Methanol from Coal

Figure 4-7 shows the energy balance for converting 39,000 tons per day ($3.5 \times 10^7 \text{ m}^3/\text{D}$) of 8870 Btu/lb ($2.1 \times 10^6 \text{ J/kg}$) Navajo coal into 100,000 barrels ($16,000 \text{ m}^3$) of methanol.¹⁴ All energy consumed in the plant is derived from the initial coal input--no external energy source is required. Of the 692 billion Btu per day ($7.3 \times 10^{14} \text{ J/D}$) entering the plant as the heating value of the coal, 272 billion Btu ($2.9 \times 10^{14} \text{ J}$) exit the plant as methanol, 120 billion Btu

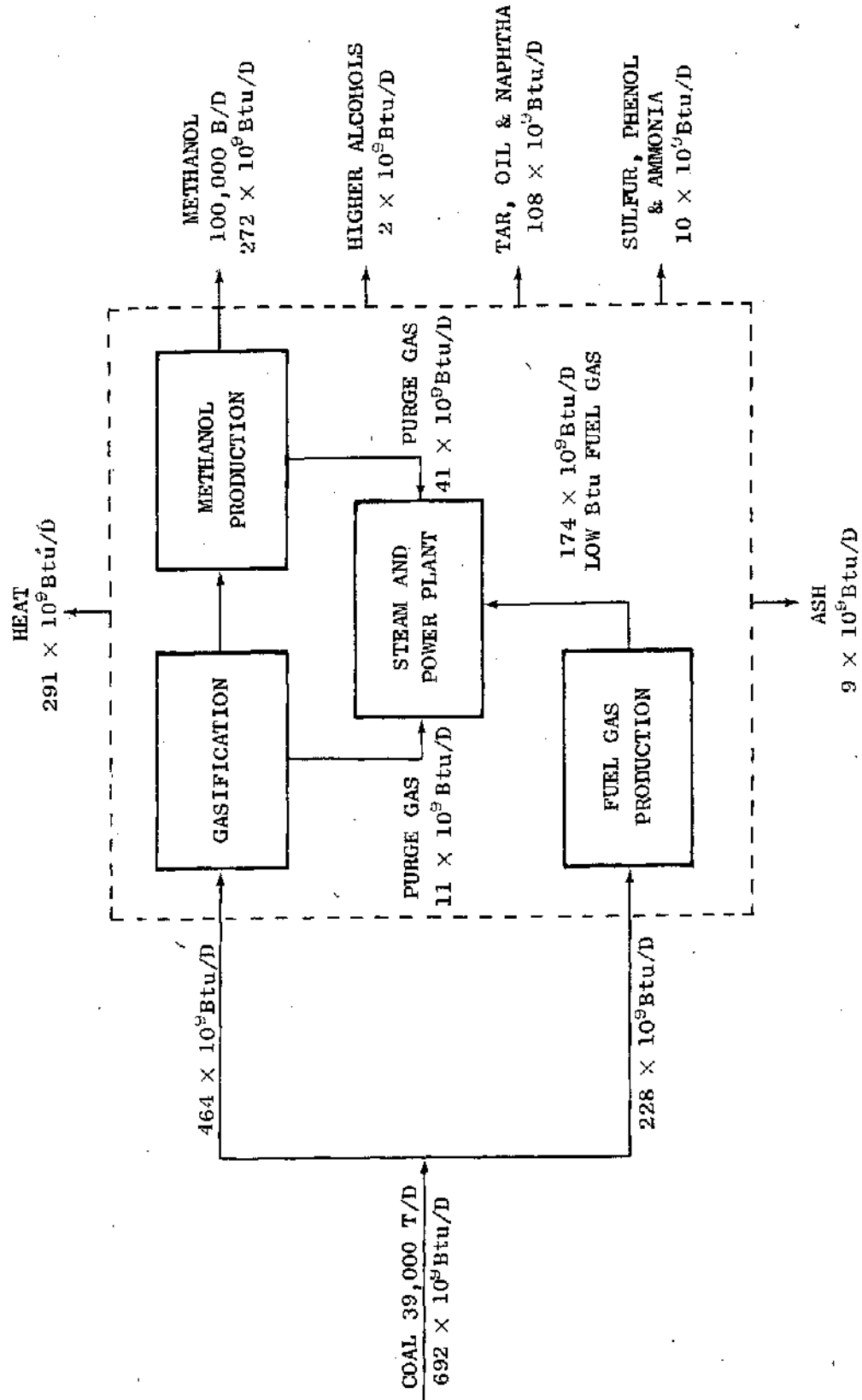


FIGURE 4-7. METHANOL FROM COAL ENERGY BALANCE

$(1.3 \times 10^{14} \text{ J})$ are in the form of byproducts, and 300 billion Btu $(3.2 \times 10^{14} \text{ J})$ end up as waste heat, endothermic reaction heat or in the ash.¹⁴

There are several ways to define thermal efficiency, all of which are useful in different contexts. For this study we wish to know the efficiency with which the energy in the initial resource (coal in this case) can be converted into energy in the form of the alternative fuel of interest. With this definition, we simply divide the heating value of the methanol by the heating value of the coal to obtain:

$$\text{Efficiency (coal-to-methanol)} = \frac{272 \times 10^9}{692 \times 10^9} = 39.3 \text{ percent.}$$

(If the byproduct higher alcohols (ethanol, propanol, etc.) are not separated but remain blended with the methanol, the product is called "methyl fuel." The coal-to-"methyl fuel" efficiency is only slightly greater, however, 39.6 percent.)

It is important to note that in this case significant quantities of combustible byproducts are produced along with the methanol--about 110 billion Btu per day $(1.2 \times 10^4 \text{ J/D})$. If these byproducts are counted as part of the total useful product energy we have

$$\text{Efficiency (coal-to-products)} = \frac{272 + 110}{692} = 55.2 \text{ percent.}$$

One final accounting method that is useful in comparing one alternative fuel with another and in computing net energy is the primary resource energy/ancillary energy method. Primary resource energy is defined as the initial energy content (heating value) of the

resource that is actually processed into the final product. The ancillary resource energy is the energy content of the resource which is required to provide the electricity, steam, or general fuel to run the process. This concept is especially useful when the resource from which the ancillary energy is derived is different from the primary resource.

In the coal-to-methanol conversion, 228 billion Btu (2.4×10^{14} J) of ancillary resource energy are required to convert 464 billion Btu (4.9×10^{14} J) of primary resource into 272 billion Btu (2.9×10^{14} J) of methanol. The 52 billion Btu (5.5×10^{14} J) of off-gas from methanol production are not counted in the ancillary energy requirement since they are generated internally and do not place any demand on external resources.

The primary and ancillary resource energy requirements for producing 10^{12} Btu (1.1×10^{15} J) of methanol are tabulated in Table 4-2 below.

Table 4-2

COAL-TO-METHANOL ENERGY REQUIREMENT

	<u>10^{12} Btu</u>	<u>10^{15} J</u>
Methanol energy	1.00	1.06
Primary resource energy	1.71	1.80
Ancillary resource energy	0.84	0.89

b. Syncrude from Coal

The energy balance for converting 55,200 tons per day (5.0×10^7 kg) of 7800 Btu per lb (18×10^6 J/kg) Powder River coal into 100,000 barrels ($16,000 \text{ m}^3$) of synthetic crude oil via the H-Coal

process is shown in Figure 4-8.¹⁵ This process has been designed to produce only plant steam and heat on-site. An additional 144,000 kW of purchased electricity is required to operate the plant. The 35 billion Btu per day (3.7×10^{13} J/D) of ancillary resource energy required to produce this quantity of electricity (assuming 33 percent conversion efficiency) must be taken into account in the energy balance.

Unlike the coal-to-methanol process, this plant has been designed to utilize all byproducts within the plant. The coal char and vacuum bottoms (derived from fractionation of the coal hydrogenation product) are gasified to produce hydrogen, and part of the high-Btu byproduct gas is steam reformed to produce hydrogen. The remaining gas is burned to provide process steam and heat (93 billion Btu per day or 9.8×10^{13} J/D).⁸ All the usable product energy is in the form of syncrude.

The efficiency for converting the initial coal resource into synthetic crude oil is:

$$\text{Efficiency (coal-to-syncrude)} = \frac{567}{861 + 35} = 63.3 \text{ percent.}$$

We have assumed that the 35 billion Btu per day (3.7×10^{13} J/D) of resource input into electric power generation are in the form of coal.

The primary and ancillary resource energy required to produce 10^{12} Btu of syncrude are shown in Table 4-3.

c. Syncrude from Oil Shale

The energy balance for oil shale mining, TOSCO II re-torting and upgrading is shown in Figure 4-9.¹⁶ Mining is included in this balance since it is considered to be an integral part of the oil shale operation. All the process energy requirements are generated

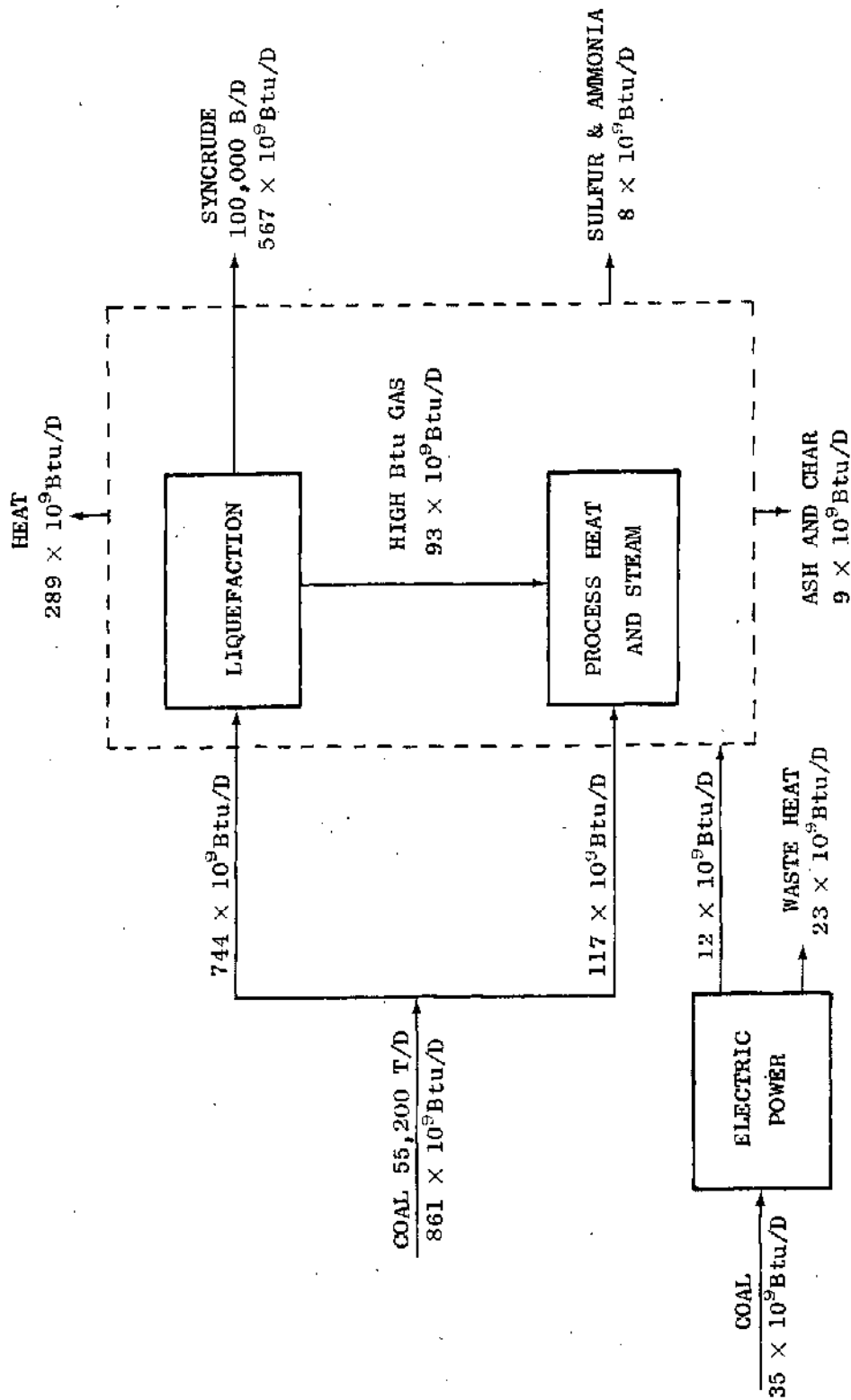


FIGURE 4-8. H-COAL LIQUEFACTION PROCESS ENERGY BALANCE

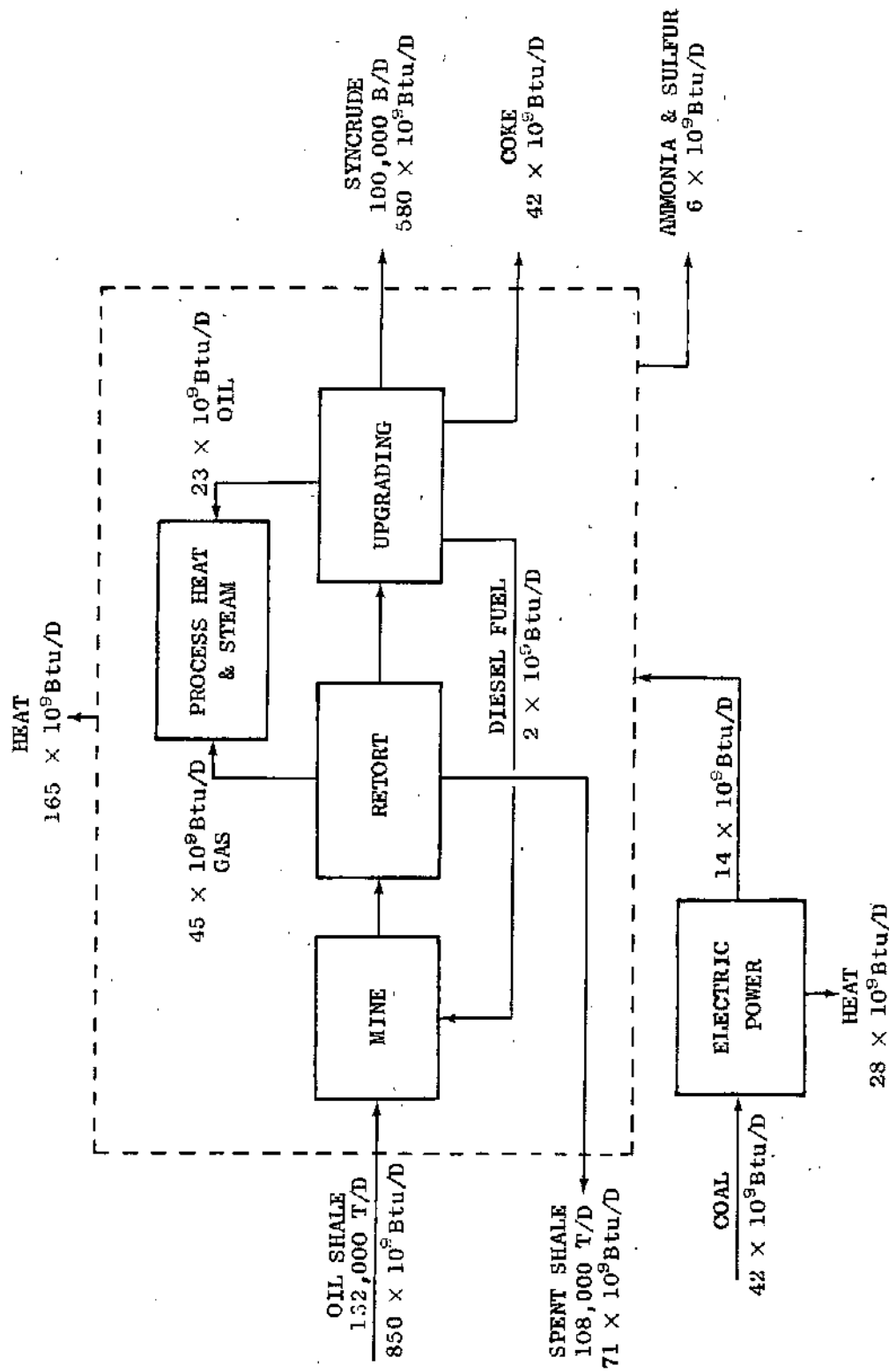


FIGURE 4-9. TOSCO II OIL SHALE RETORTING AND UPGRADING ENERGY BALANCE

on-site by the combustion of byproduct gases and fuel oil except for 170,000 kw of purchased electricity.¹²

Table 4-3

COAL-TO-SYNCRUDE ENERGY REQUIREMENT

	<u>10¹² Btu</u>	<u>10¹⁵ J</u>
Syncrude energy	1.00	1.06
Primary resource energy	1.31	1.38
Ancillary resource energy	0.27	0.28

The thermal efficiency for converting oil shale to syncrude is:

$$\text{Efficiency (oil-shale-to-syncrude)} = \frac{580}{858} = 67.6 \text{ percent.}$$

Strictly speaking, the resource (probably coal) required to produce the electric power for the plant should be included, so that the resource-to-syncrude efficiency is:

$$\text{Efficiency (resource-to-syncrude)} = \frac{580}{858 + 42} = 64.4 \text{ percent.}$$

The efficiency for conversion of resource to useful product energy, including byproduct coke, is:

$$\text{Efficiency (resource-to-products)} = \frac{580 + 42}{858 + 42} = 69.1 \text{ percent.}$$