VII

ECONOMICS

A. INTRODUCTION

Estimates of the capital investment and operating cost requirements for various coal liquefaction processes utilizing preliminary conceptual designs have been made by a diversity of organizations.[1-18] Extreme caution must be used when comparing economic data generated from such different bases since all of the processes being presently considered, with the exception of Fischer-Tropsch and methanol, have not been utilized commercially. Advanced liquefaction processes must demonstrate that they can operate reliably and produce the predicted product yields in pilot plants of sufficient size to provide the data required for scale-up and for a detailed economic evaluation. Furthermore, it should be recognized that the calculated costs can vary widely, even for a particular process, depending on factors such as plant size and location, specifications of feed coal, product mix,* method of financing, estimates of operating costs, and coal costs.

For these reasons, it is emphasized that the specific economic figures presented in this section are merely indicative of the general level of cost on the basis of certain assumptions. Selected studies from published material have been used in presenting specific costs associated with the liquefaction process considered representative of one possible configuration of each process. No attempt has been made to adjust the costs for variations in design other than to provide a common time basis (January 1977).

While this method of estimation and application of the data now available appears to be the best procedure the Panel can adopt, it is recognized that variations of substantial magnitude may still be encountered. Some of the factors responsible have been noted earlier, but others, such as long negotiations on siting and the many years required for construction, are additional important considerations. Experience in such economic estimates by the Panel as well as by many other study groups has shown that capital cost estimates for complex processes

*It is particularly important to note differences in costs for heavy fuel oil and for synthetic crude oil.

not yet commercialized may be low by a significant percentage. Estimates for the cost of the product are, of course, greatly influenced by the capital costs, but the range of variations is less, since much of the product cost depends on the cost of coal, and this is treated as a variable in the estimates. Finally, it should be clearly noted that the product costs are in terms of fuel oil equivalent (FOE) and not in terms of synthetic crude oil. Both capital and operating costs would be expected to be higher on the basis of producing synthetic crude oil.

Cost estimates for the following generic types of process are presented, including two cases of indirect liquefaction:

1. Pyrolysis (with catalytic hydrogenation of primary product)
2. Solvent extraction (with catalytic hydrogenation of primary product)
3. Catalytic liquefaction
4. Indirect liquefaction
    a. Fischer-Tropsch
    b. Methanol

Since most variations may be expected because of the various alternative processing factors mentioned above, brief definitions of the processing arrangement employed, the products produced, and the coal used are presented with the applicable costs. Each process produces clean liquid fuels with the exception of pyrolysis, in which about one-half of the product energy is in the form of gas. Depending on circumstances of location and demand, it is likely that simultaneous production of co-products such as oil and gas may be economically attractive, compared with oil production alone. Even in the case of liquid products there is a considerable variation, ranging from heavy boiler fuel to gasoline. In order to put the various product qualities on a somewhat comparable basis (including methanol), all have been converted to a FOE basis of 6 million Btu per barrel.

The cost of producing liquids will vary considerably with the price of coal, which has been assumed to range from \$0.40 to \$1.40 per million Btu. The cost of product (FOE) in dollars per barrel is related to coal cost in dollars per million Btu for the various coal liquefaction routes as shown in Figure 25. The estimates are based on a discounted cash flow method incorporating a 20-year project life, 12 percent return rate, and 100 percent equity capital.

As can be seen, the estimated costs for each process vary over a considerable range at a given coal price and over a wide range with coal costs. The lower line of the band for each type of process is based on a reported estimated cost for the particular system considered with the corresponding

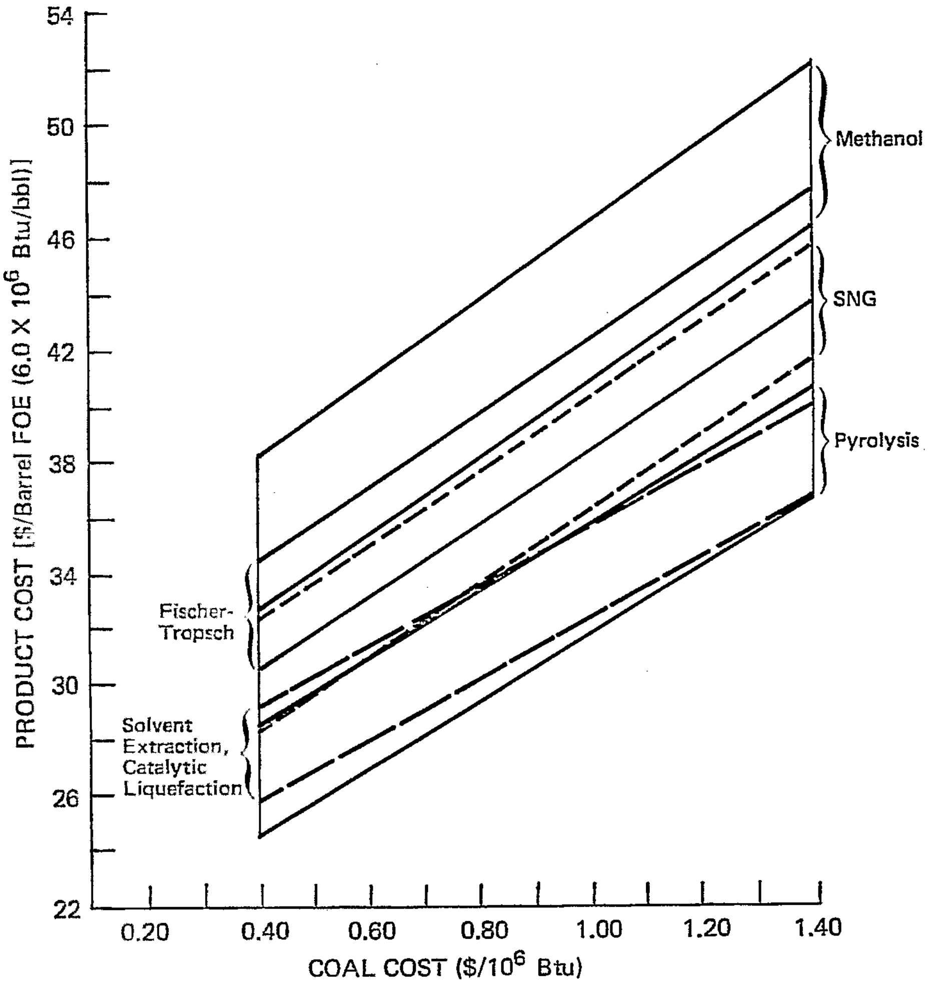


Figure 25 Product cost for different liquefaction processes as a function of coal costs.

yield and quality of products. The portion above includes a safety factor of 30 percent on the base investment estimate to take into account contingencies such as different product ranges, construction conditions, and possible increased costs for environmental considerations. Also shown for comparison is a range of costs for substitute natural gas (SNG) from coal on a FOE basis, which has been derived from a 1975 ERDA report among other sources.

Figure 25 indicates that a significant cost difference remains between the present (January 1977) cost of petroleum products and coal-derived substitutes. Closing the gap by optimization of the technologies would be the preferred path toward removing the economic roadblocks remaining in their commercial development. Continued price increases in worldwide petroleum products in the order of 100 percent or more also may bring coal liquefaction economics into a more competitive situation. A combination of technical improvements and increased costs for imported oil may be the avenue that ultimately permits coal liquefaction to play a part in the commercial production of oil in the United States.

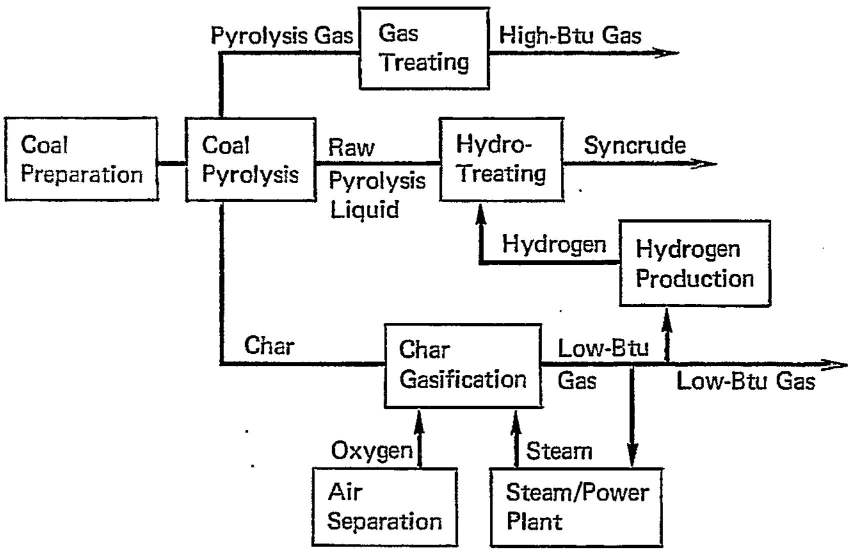
The magnitude of capital requirements would appear beyond the limits available to most corporations in conventional financial markets. In addition, associated technical risks are still high. It probably will require governmental encouragement to ensure that a company undertaking coal liquefaction operations will not be at a competitive disadvantage with respect to conventional products from petroleum.

B. PYROLYSIS PROCESS

The block flow diagram in Figure 26 represents a possible route for producing clean liquid fuel by pyrolysis. Raw pyrolysis liquid is upgraded to a low-sulfur syncrude product by hydrotreating. High-Btu gas also is produced as a product from the pyrolysis. Residual char from pyrolysis is gasified with steam and oxygen to produce low-Btu gas. After desulfurization, portions of the low-Btu gas are used for production of hydrogen and for generating steam and power needed for the process. The remainder of the low-Btu gas is another product. Capital and operating costs are given in Table 18.

Although all pyrolysis solid residue is utilized in this system, about half of the product energy is in the form of gas, with a considerable portion as low-Btu gas. This poses a problem as to how to value these products compared with liquids. Conversion of the gaseous products to liquids is possible (e.g., by Fischer-Tropsch synthesis), but the efficiency of the total conversion would necessarily be decreased and conversion costs increased. The gas also might be utilized as fuel for electric power generation, in which case its value is still difficult to establish.

For purposes of this presentation, it has been assumed that high-Btu gas has the same value as the syncrude on an equivalent-Btu basis. Low-Btu



Products Produced, Coal Used, and Energy Recovery

	10^6 Btu/hr
Syncrude, 28,000 bbl/day, 25 °API, 0.1% S at 6×10^6 Btu/bbl	7,005
High-Btu Gas, 80 x 10^6 SCF/day, 5-10 gr/100 SCF S, at 890 Btu/SCF	2,948
Low-Btu Gas, 411 x 10^6 SCF/day, 1 ppm S, at 250 Btu/SCF	4,279
Sulfur, 858 ST/day at 3,983 Btu/lb	254
Total Products—57,944 bbl/day (FOE) at 6×10^6 Btu/bbl	14,486
Coal, 274,00 tons/day Eastern Bituminous at 11,140 Btu/lb	25,433
Thermal Efficiency = 57.0%	

Figure 26 Pyrolysis process: a possible route for producing clean liquid fuel.

Table 18 Pyrolysis Costs

TOTAL CAPITAL REQUIRED - $1,000-$1,300 MILLION

	%
Coal preparation	4
Pyrolysis and gasification	16
Oil recovery and filtration	6
Gas treating	5
Hydrogen plant	3
Oil hydrotreating	8
Flue gas clean-up, by-product recovery	2
Oxygen plant	12
Plant steam and power	11
Plant utilities	6
Plant facilities	4
Total Construction	77
Other Costs[a]	23
Total Capital Required	100

TOTAL CAPITAL REQUIRED PER BBL/DAY (FOE) - $17,000-$22,000[b]
$20,000-$26,000[c]

Operating Costs[d]	$\$10^6$/yr
Operating labor, gen. and admin.	5.2
Maintenance labor, materials, gen. and admin.	36.7
Water supply	1.8
Catalyst and chemicals	7.9
Operating supplies	3.6
Local taxes and insurance	15.8
Total Annual Operating Cost	71.0

[a]Initial catalyst and chemicals, interest during construction, start-up costs, and working capital.
[b]Low-Btu gas at 6 X 10^6 Btu/bbl, FOE.
[c]Low-Btu gas at 12 X 10^6 Btu/bbl, FOE.
[d]Not including coal or capital-related cost.

gas must have some lower value, and for purposes of cost evaluation, it has been assumed that it may be valued anywhere between equal to and one-half the value of oil on an equivalent-Btu basis.

C. SOLVENT EXTRACTION PROCESS

A version of the solvent extraction process that produces low-sulfur heavy and light fuel oils as principal products is outlined in the block flow diagram in Figure 27. Coal is liquefied by reaction with synthesis gas ($CO + H_2$) in a recycle liquid medium that is not separately hydrogenated. Unreacted coal from the dissolver is separated from product liquids by filtration and then gasified with steam and oxygen. Part of the syngas produced is utilized to furnish hydrogen for the coal-dissolving step. The remainder of the syngas is shifted and scrubbed to produce hydrogen that is used to hydrotreat light oil products from the process. Capital and operating costs are given in Table 19.

D. CATALYTIC LIQUEFACTION PROCESS

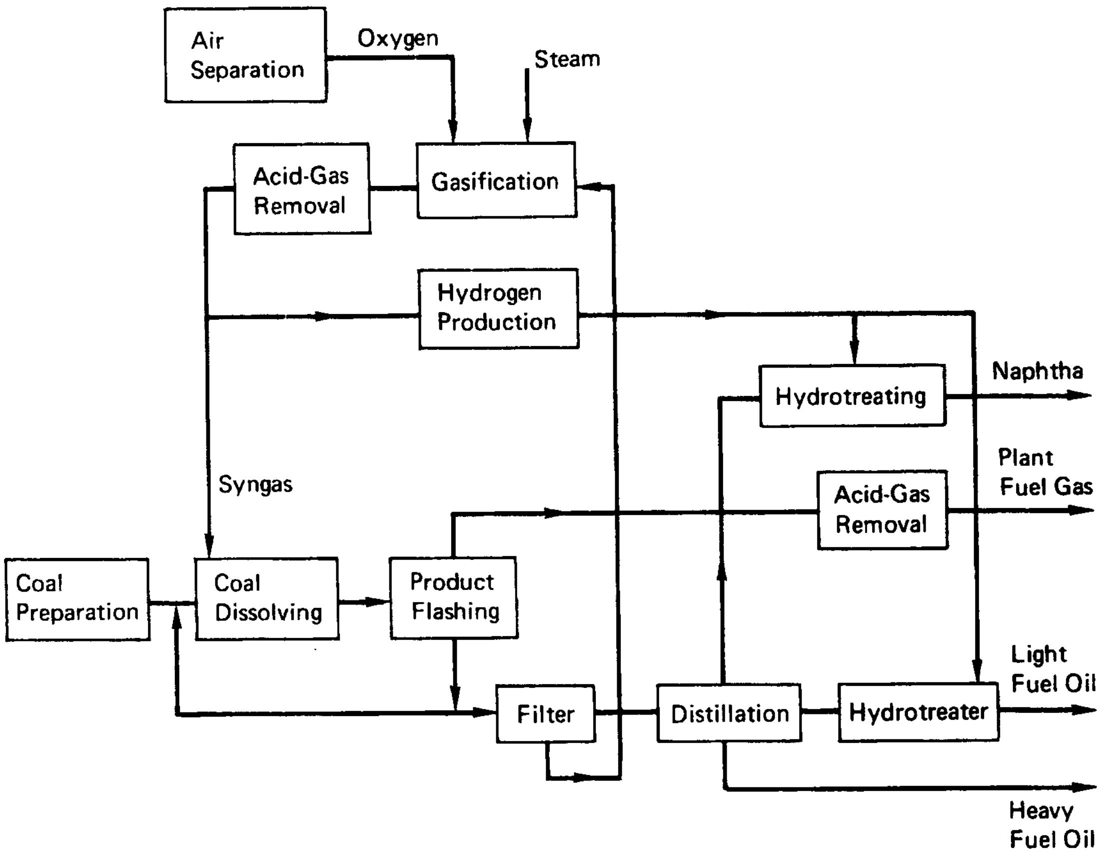
A version of catalytic liquefaction depicted in the block flow diagram in Figure 28 produces boiler fuel and naphtha. Conversion of coal to low-sulfur liquids takes place directly by reaction with hydrogen in a light oil medium in the presence of a solid catalyst. Residual char is separated from liquid products by precipitation accomplished by the addition of an anti-solvent. Residual char is then gasified and converted to hydrogen for utilization in the liquefier. Capital and operating costs are given in Table 20.

E. FISCHER-TROPSCH PROCESS

Gasoline of 86 octane (Research) is produced by the Fischer-Tropsch process with major steps as shown in the block diagram presented in Figure 29. In the case considered here (where Lurgi gasification is employed), considerable tar, oil, and naphtha also are produced during the initial processing step of coal gasification. Other gasification systems may produce practically no such by-products. There are also small quantities of oil and liquefied petroleum gas produced as by-products in the synthesis step. As shown, no gas is produced as product in this particular configuration. It may be desirable in certain situations to produce high-Btu gas from the gasifier as a coproduct to liquids, in which case overall investment and operating costs can be reduced and thermal efficiency will be increased. Capital and operating costs are given in Table 21.

F. METHANOL PROCESS

Methanol can be produced from coal by gasification of the coal followed by conversion of the synthesis gas produced. The process shown in the flow diagram in Figure 30 utilizes steam and oxygen in a Lurgi pressure gasifier to produce synthesis gas. All tars and oils produced are recycled to the gasifier. Methane produced in the gasifier is converted to additional



<u>Products Produced, Coal Used, and Energy Recovery</u>

	10^6 Btu/hr
Heavy Boiler Fuel, 30,652 bbl/day, 9.7 °API, 0.5% S at 6.77 x 10^6 Btu/bbl	8,648
Light Boiler Fuel, 15,326 bbl/day, 13.9 °API, 0.2% S at 6.2 x 10^6 Btu/bbl	3,985
Naphtha, 4,022 bbl/day, 52 °API, 1 ppm S, at 5.4 x 10^6 Btu/bbl	904
Sulfur, 634 ST/day at 3,983 Btu/lb	210
Total Products--54,988 bbl/day (FOE) at 6 x 10^6 Btu/bbl	13,747
Coal, 20,456 tons/day, Illinois No. 6 at 12,861 Btu/lb	21,924
Thermal Efficiency = 63.7%	

Figure 27 Solvent extraction process: a version that produces low-sulfur and light fuel oils as principal products.

Table 19 Solvent Extraction Costs

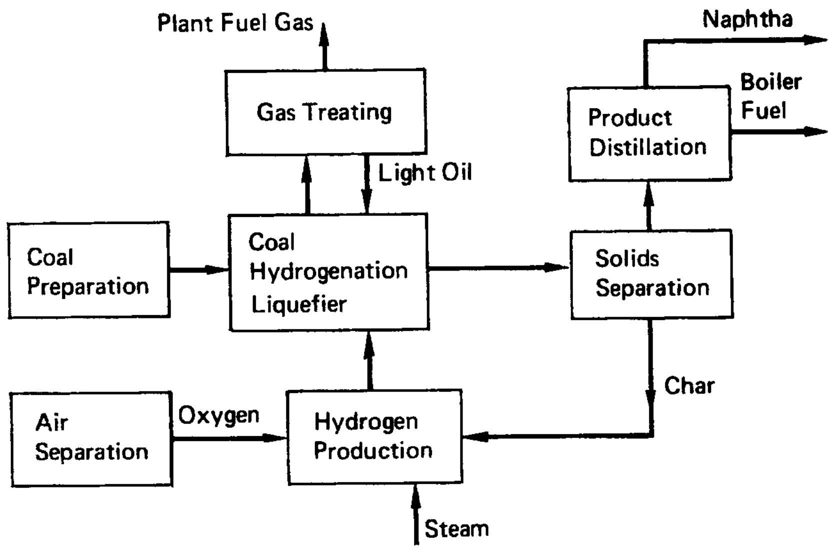
TOTAL CAPITAL REQUIRED - $900-$1,150 MILLION

	%
Coal preparation	2
Liquefaction and solids separation	21
Gas clean-up, recycle hydrogen recovery	8
Product hydrotreating	11
Hydrogen production	9
Oxygen plant	3
By-product recovery, product storage	3
Steam and power plant	7
Plant utilities	7
Plant facilities	5
Total Construction	76
Other Costs[a]	24
Total Capital Required	100

TOTAL CAPITAL REQUIRED PER BBL/DAY (FOE) - $16,500-$21,500

Operating Costs[b]	$\$10^6$/yr
Operating Labor, Gen. and Admin.	4.4
Maintenance Labor, Materials, Gen. and Admin.	53.6
Water Supply	1.3
Catalyst and Chemicals	6.4
Operating Supplies	6.6
Taxes and Insurance	13.2
TOTAL ANNUAL OPERATING COST	85.5

[a]Initial catalyst and chemicals, interest during construction, start-up costs, and working capital.
[b]Not including coal or capital-related costs.



Products Produced, Coal Used, and Energy Recovery	10^6 Btu/hr
Boiler Fuel, 38,118 bbl/day, 3.1 °API, 0.5% S at 6.3×10^6 Btu/bbl	10,006
Naphtha, 11,882 bbl/day, at 5.0×10^6 Btu/bbl	2,475
Sulfur, 711 ST/day at 3,983 Btu/lb	236
Ammonia, 120 ST/day at 9,675 Btu/lb	97
Total Products--51,256 bbl/day (FOE) at 6×10^6 Btu/bbl	12,814
Coal, 22,231 tons/day, Illinois at 11,000 Btu/lb	20,378
Thermal Efficiency = 62.9%	

Figure 28 Catalytic liquefaction process producing boiler fuel and naphtha.

Table 20 Catalytic Liquefaction Costs

TOTAL CAPITAL REQUIRED - $800-$1,050 MILLION

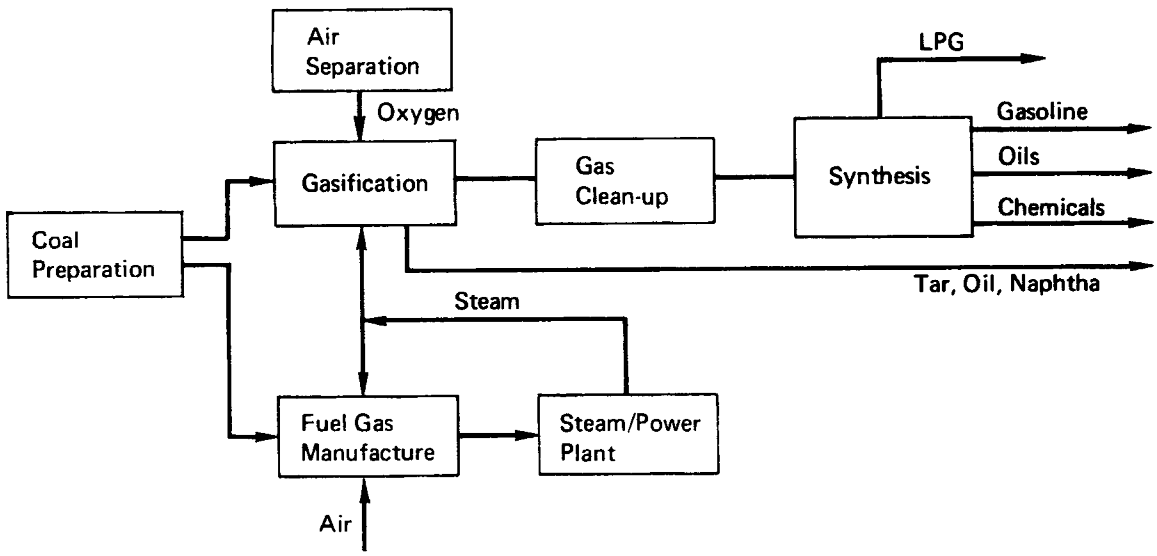
	%
Coal preparation	4
Hydrogenation and solids separation	31
Fuel gas clean-up	1
Hydrogen production and compression	12
Oxygen plant	5
By-product recovery, product storage	4
Steam and power plant	6
Plant utilities	7
Plant facilities	5
Total Construction	75
Other costs*	25
Total Capital Required	100

TOTAL CAPITAL REQUIRED PER BBL/DAY (FOE) - $15,500-$20,000

Operating Costs†	$\$10^6$/yr
Operating Labor, Gen. and Admin.	5.3
Maintenance Labor, Materials, Gen. and Admin.	51.1
Water Supply	0.9
Catalyst and Chemicals	16.5
Operating Supplies	6.2
Taxes and Insurance	12.4
Total Annual Operating Cost	92.4

*Initial catalyst and chemicals, interest during construction, start-up costs, and working capital.

†Not including coal or capital-related costs.



<u>Products Produced, Coal Used, and Energy Recovery</u>

	10^6 Btu/hr
Gasoline, 25,500 bbl/day, 86 octane (Research)	5,265
Tar, Oil, Naphtha, 13,230 bbl/day	3,880
Synthesis Oils, 2,158 bbl/day	509
LPG, 2,000 bbl/day	341
Phenol and Chemicals	179
Sulfur	55
Ammonia	276
Total Products--42,020 bbl/day (FOE) at 6 x 10^6 Btu/bbl	10,505
Coal, 34,249 tons/day, New Mexico Subbituminous at 8,872 Btu/lb	25,321

Thermal Efficiency = 41.5%

Figure 29 Fischer-Tropsch process producing gasoline of 86 octane (Research).

Table 21 Fischer-Tropsch Costs

TOTAL CAPITAL REQUIRED - $900-$1,150 MILLION

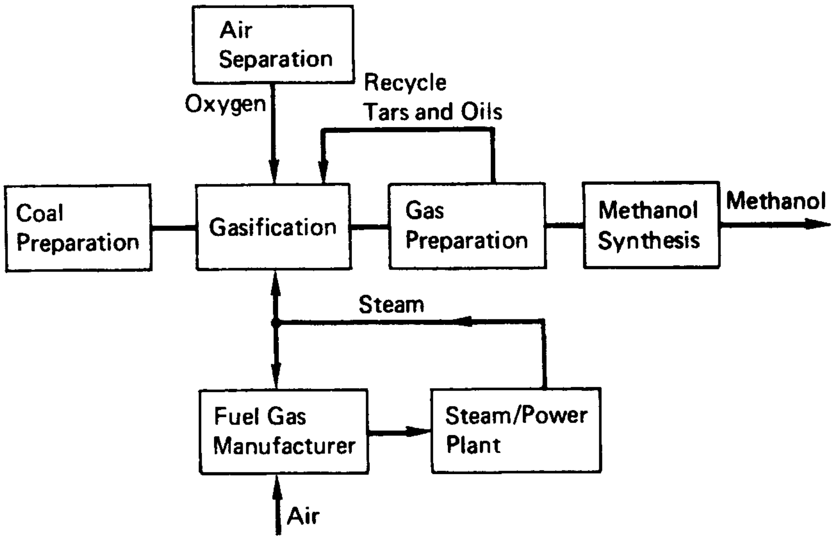
	%
Coal Preparation	6
Coal Gasification	7
Gas Clean-up and Methane Reforming	8
Synthesis	8
Product and Chemical Recovery	5
Hydrogen and Catalyts Manufacture	1
Oxygen Production	11
Fuel Gas Production	9
Steam and Power Plant	6
Waste Disposal, By-Product Recovery	5
Raw Water Treating	1
Cooling Water	2
Offsite and General	6
Total Construction	75
Other Costs*	25
Total Capital Required	100

TOTAL CAPITAL REQUIRED PER BBL/DAY (FOE) - $21,500-$28,000

Operating Costs†	$\$10^6$/yr
Operating Labor, Gen. and Admin.	19.9
Maintenance Labor, Materials, Gen. and Admin.	32.3
Water Supply	0.6
Catalyst and Chemicals	9.6
Operating Supplies	6.0
Taxes and Insurance	13.2
TOTAL ANNUAL OPERATING COST	81.6

*Initial catalyst and chemicals, interest during construction, start-up costs, and working capital.

†Not including coal or capital-related costs.



<u>Products Produced, Coal Used, and Energy Recovery</u>

	10^6 Btu/hr
Methanol, 11,338 tons/day at 9,860 Btu/lb	9,314
Sulfur, 136 ST/day at 3,983 Btu/lb	45
Ammonia, 329 ST/day at 9,630 Btu/lb	264
Total Products--38,492 bbl/day (FOE) at 6.0 x 10^6 Btu/lb	9,623
Coal, 28,130 tons/day, New Mexico at 8,872 Btu/lb	20,797
Thermal Efficiency = 46.3%	

Figure 30 Methanol process: methanol production from coal by gasification of coal followed by conversion of the synthesis gas produced.

synthesis gas by reforming with steam. Capital and operating costs are given in Table 22.

Numbers presented are for a plant to produce about 11,000 tons per day of methanol. This is a rate of about 80,000 barrels per day, but since methanol has a heating value of only 2.7 million Btu per barrel, the fuel oil equivalent (6 million Btu per barrel) is only 37,000 barrels per day.

G. TIME, CAPITAL, AND MATERIAL REQUIREMENTS FOR A SYNTHETIC CRUDE OIL INDUSTRY

A major objective of the current study on coal liquefaction processes has been to estimate the time, capital, and materials required to produce enough synthetic crude to significantly reduce imports. Accordingly, estimates have been made for the most promising coal liquefaction processes, and a schedule has been established for construction of 37 plants during the period between 1980 and 1994 when synthetic crude production could reach 3.35 million barrels per calendar day.

Although extensive efforts have been made to accurately determine capital costs for the most promising and most highly developed liquefaction processes, the results have shown great variations, depending not only on the processes selected but also on the many economic and engineering judgments involved in the estimates. Furthermore, estimating has been made much more difficult by the inflation that has occurred during the past 5 years, and it is necessary to talk in terms of ranges rather than specific figures.

Estimates indicate that the capital cost for the most promising of the coal liquefaction processes to produce a synthetic crude from a plant of 25,000 to 50,000 bbls of oil per day will fall in the range of $20,000 to $30,000 per barrel per operating day (pbd).* While the cost of the product will depend mainly on the capital and operating costs of the plant, an additional important factor is the cost of the coal. With coals priced from $0.40 to $1.40 per million Btu (about $10 to $35 per ton), the corresponding cost of synthetic crude is $20 to $30 per barrel ($3.35 to $5.00 per million Btu). These cost ranges are for the pyrolysis, solvent extraction, and catalytic coal liquefaction processes under development in the United States, which appear more favorable than the Fischer-Tropsch or methanol processes.

At the present time no process for coal liquefaction is sufficiently well developed to permit the detailed engineering required for the 50,000- or 100,000-bpd plants necessary for a large-scale industry, and it is improbable that the necessary data will be available before 1980. If 4 years are required to design, construct, and start up a plant, a possible schedule for synthetic fuel plants of 100,000 bpd each is given in Table 23. Since the schedule is based on the assumption that each plant would

*Similar estimates on the basis of heavy fuel oil are $18,000 to $22,000 pbd.

Table 22 Methanol Costs

TOTAL CAPITAL REQUIRED - $850-$1,200 MILLION

	%
Coal preparation	5
Coal gasification	7
Gas clean-up shift and methane reforming	12
Methanol synthesis and recovery	19
Waste disposal and by-product recovery	2
Oxygen production	6
Fuel gas production	8
Steam and power plant	5
Plant utilities	6
Off site and general	5
Total Construction	75
Other Costs[a]	25
Total Capital Required	100

TOTAL CAPITAL REQUIRED PER BBL/DAY (FOE) - $23,000-$30,000

Operating Costs[b]	$\$10^6$/yr
Operating Labor, Gen. and Admin.	23.9
Maintenance Labor, Materials, Gen. and Admin.	33.0
Water Supply	0.5
Catalyst and Chemicals	7.2
Operating Supplies	6.0
Taxes and Insurance	13.6
TOTAL ANNUAL OPERATING COST	84.2

[a]Initial catalyst and chemicals, interest during construction, start-up costs, and working capital.
[b]Not including coal or capital-related costs.

Table 23 Estimated Construction Schedule and Synthetic Crude Oil Production From Coal Liquefaction Plants

Year	Plants Started	Plants Finished	Capital[a] Required (billions/yr.)	Accumulated Capital (billions)	Steel[b] Required (million tons)	Coal (million tons/yr.)	Oil Produced (million barrels) Operating Day[c]	Calendar Day[d]
1980	1	--	0.62	0.62	0.15	--		
1981	2	--	1.87	2.50	0.45	--		
1982	3	--	3.75	6.25	0.90	--		
1983	3	--	5.62	11.87	1.35	--		
1984	4	1	7.50	19.37	1.80	16.5	0.1	0.09
1985	4	3	8.75	28.12	2.10	49.5	0.3	0.27
1986	4	6	9.37	37.50	2.25	99.0	0.6	0.54
1987	4	9	10.00	47.50	2.40	148.5	0.9	0.81
1988	4	13	10.00	57.50	2.40	214.5	1.3	1.18
1989	4	17	10.00	67.50	2.40	280.5	1.7	1.54
1990	4	21	10.00	77.50	2.40	346.5	2.1	1.90
1991	0	25	7.50	85.00	1.80	412.5	2.5	2.26
1992	0	29	5.00	90.00	1.20	478.5	2.9	2.62
1993	0	33	2.50	92.50	0.60	544.5	3.3	2.98
1994	0	37	0.00	--	0.00	610.5	3.7	3.35
TOTAL	37	37	92.50	92.50[e]	22.20	610.5	3.7	3.35

[a]Capital cost of $25,000 per barrel per day for synthetic crude oil.
[b]6 tons of steel per barrel per day.
[c]2 barrels oil per ton of coal (20 million Btu/T-60% eff.).
[d]330 operating days per year.
[e]If product is heavy fuel oil, the total would be $74 billion.

be finished in 4 years, 16 plants would be under construction simultaneously during the 1984-1990 period. This represents approximately the maximum rate of plant construction that is believed possible, even with considerable expansion of activity in the many industrial areas that would be involved.

By 1990 the plants could be supplying about 1.9 million barrels per calendar day of synthetic crude (approximately the capacity of the Alaska pipeline) at an accumulated capital expenditure of $77.5 billion. Assuming that construction was completed and the plants in operation by 1994 (no additional plants started between 1990-1994), oil output would be 3.35 million bpd (1.2 billion bbl per year) and total capital cost would be $92.5 billion. Coal requirements would then be 610 million tons per year, which represents an additional output approximately equal to the country's present coal production.

It is not foreseen that the products from these plants (assumed to be a sweet synthetic crude) could be produced for less than $20 to $30 per barrel. These prices may not be competitive with domestic or imported petroleum by 1990 and possibly not during the entire construction program. In that case, special provisions would be required to supply most of the capital for the plants or to support the selling price for the product.

The last column in Table 23 shows that the 14-year construction program would increase the country's daily oil production by 3.35 million barrels, an amount that probably would not be sufficient to make up for the loss in domestic production during the 1976-1994 period, and just to maintain present oil production would require a much larger program than that envisioned in the table.

In the previous discussion it has been noted that in addition to the large capital requirement for liquefaction plants, the daily output of oil would have to be supported, probably to the extent of about $10 per barrel over and above the 1976 cost for importing oil from abroad. For a production of 3.35 million barrels per day, this would amount to an annual expenditure of $12.2 billion per year. This subsidy would be for approximately 15 percent of the total oil demand expected by 1990.

H. RECOMMENDED DEVELOPMENT PROCEDURES AND REQUIREMENTS FOR LOWER COST LIQUEFACTION PROCESSES

To provide a basis for establishing a synthetic fuels industry, the Panel believes that two of the most promising coal liquefaction processes should be developed through 250- to 600-ton-per-day units as soon as possible. Successful development then could be followed by the construction of at least one commercial unit to gain the necessary experience for a full-fledged effort. Consideration also should be given to construction of a Fischer-Tropsch plant, employing the latest technical developments, in view of the successful operation of this process in South Africa.

Because of the very large capital expenditures estimated for a synthetic fuel industry, the Panel believes that ERDA should place much more emphasis on the investigation of second- and third-generation processes that might reduce these costs. General experience in process development, verified in recent coal programs, has shown that pilot plants as large as those built by ERDA and its predecessors are not required. Smaller equipment not only saves money but also time--less time for initial fabrication, for making changes, and for establishing optimum operating procedures.

As much work as possible should be carried out on the bench scale. Pilot plants should not be larger than 1 to 5 tons per day. Process demonstration should be carried out on units not larger than 250 to 600 tons per day. Such equipment should be constructed and operated to provide all the essential information needed for design of "pioneer" commercial plants. Thus, vigorous efforts should be made to scale down the size of experimental equipment and the magnitude of future programs.

Economic developments since the oil embargo of 1973 have significantly changed the commercial incentives for coal liquefaction plants. Costs for plant construction have escalated to an alarming extent, and the price of crude oil produced in the United States has been placed under control, with the result that the incentive for commercialization by industry has been pushed into the future. In addition, for the past three years the price of imported oil has held reasonably steady and the foreign exchange costs have been balanced to an unexpected extent by increased sales of plants and equipment to the OPEC nations and by large sales of agricultural products worldwide. At this time, therefore, it would appear that the only hope for early commercialization of coal conversion by private industry is the development of a new process that is considerably cheaper than those developed to date. Such a process should:

1. Provide a full range of distillate petroleum products from coal

2. Convert essentially all the coal to liquid and gaseous products readily transportable and refinable by existing means

3. Reduce equipment requirements considerably and thereby reduce capital costs

4. Operate at an overall thermal efficiency of not less than 70 percent, based on the ratio of heat in the products to heat in the coal

The chances that these requirements can be met by presently developed hydrogenation processes are not high. Similar processes have been under investigation for over 50 years and are still too complex to promise technical and economic solutions that approach the needs listed.

One promising area for improved liquefaction technology is the direct catalytic conversion of the coal particle to a liquid in an atmosphere of hydrogen gas. This would eliminate the use of recycle oil and accompanying preheaters, since the coal may be heated by hot hydrogen-containing gases. This process of direct conversion would also eliminate the separation of solids from heavy oil if it is possible to hydrogenate the heavy oil within the cycle to volatile products. A further major advantage is that the time required for hydrogenation is reduced to seconds instead of many minutes, which greatly reduces the size of the required high-pressure reactor system. Reduction in hydrogen recycle generation and recycle costs is also possible.

Other second-generation processes that offer potential promise are the direct catalytic conversion of synthesis gas to high-octane gasoline and also the direct conversion of coal to aromatic and isoparaffin distillates in molten halide catalysts.

REFERENCES

1. U.S. Department of the Interior, Bureau of Mines, *Estimated Cost of Producing Heavy Fuel Oil by Hydrogenation of Coal*, R.I. 4413 (Washington, D.C.: U.S. Department of the Interior, 1948).

2. U.S. Department of the Interior, *Estimated Plant and Operating Costs for Producing Gasoline by Coal Hydrogenation*, R.I. 4564 (Washington, D.C.: U.S. Department of the Interior, 1949).

3. FMC Corporation, *Commercial Complex, Conceptual Design/Economic Analysis, Oil and Power by COED-Based Coal Conversion*, R&D Report No. 114 (Washington, D.C.: U.S. Energy Research and Development Administration, 1975).

4. FMC Corporation, *Char Oil Energy Development Process--Development Unit Results and Commercial Analysis*, prepared under OCR Contract No. 14-01-0001-498 (Washington, D.C.: U.S. Department of Interior, Office of Coal Research, 1970).

5. Ralph M. Parsons Company, *1969 Feasibility Report on Consol Synthetic Fuel Process Synthetic Crude Production*, OCR R&D Report No. 45 (Washington, D.C.: U.S. Department of the Interior, Office of Coal Research, 1969).

6. Chem Systems, Inc., *COG Refinery Economic Evaluation*, Vol. I, Part 3, Phase 2, U.S. Department of Interior, Office of Coal Research R&D Report No. 53 (Washington, D.C.: U.S. Government Printing Office, 1971).

7. Foster-Wheeler, *Engineering Evaluation and Review of Consol Synthetic Fuel Process*, OCR R&D Report No. 70 (Washington, D.C.: U.S. Department of the Interior, Office of Coal Research, 1972).

8. American Oil Company, *Economic Evaluation of COED Process Plus Char Gasification*, OCR R&D Report No. 72 (Washington, D.C.: U.S. Department of Interior, Office of Coal Research, 1972).

9. Ralph M. Parsons Company, *Demonstration Plant Clean Boiler Fuels from Coal Preliminary Design/Economic Analysis*, OCR R&D Report No. 82 (Washington, D.C.: U.S. Department of the Interior, Office of Coal Research, 1974).

10. U.S. Bureau of Mines, Process Evaluation Group--MMRD, *50,000 Barrels per Day Liquid Fuels Plant, H-Coal Process--Illinois Coal: An Economic Analysis*, Report No. 76-1 (Morgantown, West Virginia: U.S. Bureau of Mines, 1975).

11. U.S. Bureau of Mines, Process Evaluation Group--MMRD, *Methanol From Synthesis Gas by Lurgi Gasification of New Mexico Coal, 5,000 Ton-per-Day Plant: An Economic Analysis*, Report No. 75-18a (Morgantown, West Virginia: U.S. Bureau of Mines, 1975).

12. K. C. Vyas and W. W. Bodle, "Coal and Oil Shale Conversion Looks Better," *Oil and Gas Journal* (March 24, 1975):45.

13. Hydrocarbon Research, Inc., *Project H-Coal Report on Process Development*, OCR R&D Report No. 26 (Washington, D.C.: U.S. Department of Interior, Office of Coal Research, 1967).

14. American Oil Company, *Evaluation of "Project H-Coal,"* prepared under OCR Contract No. 14-01-0001-1188 (Washington, D.C.: U.S. Department of Interior, Office of Coal Research, 1967).

15. P. Wellman, "The Economics of Coal Conversion Processes," paper presented at the Fourth Energy Resource Conference, University of Kentucky, January 7-8, 1976.

16. M. W. Kellogg Company, *A SASOL-Type Process for Gasoline, Methanol, SNG, and Low-Btu Gas from Coal*, prepared under EPA Contract No. 650/2-74-072 (Washington, D.C.: U.S. Environmental Protection Agency, 1974).

17. Dravo Corporation, Chemical Plants Division, *Conceptual Commercial Design and Commercial Feasibility Evaluation for Clean Boiler Fuel Facility*, Final Report, Vol. 3, prepared under ERDA Contract No. E(49-18)1772 (Washington, D.C.: U.S. Energy Research and Development Administration, 1976).

18. Bonner and Moore Associates, Inc., *Economics Evaluation of Coal-Based Synthetic Crude*, prepared under ERDA Contract No. E(49-18)1506, TID-26810 (Washington, D.C.: U.S. Energy Research and Development Administration, 1975).