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ENVIRONMENTAL AND ECONOMIC ASPECTS OF INDIRECT COAL LIQUEFACTION PROCESSES:

A Report Emphasizing the Relationship Between Product Mix and Efficiency

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16. ABSTRACT

This report covers environmental and economic aspects of three indirect liquefaction processes. Specifically, the following are addressed: U. S. coal resources; the Lurgi/Methanol, Lurgi/Methanol/Mobil M, and the Lurgi/Fischer-Tropsch indirect coal liquefaction processes; and environmental and economic aspects associated with the considered processes.

Even though our coal resources are considered very large, the life expectancy of currently defined reserves would be quite limited if we were to derive an appreciable part of our fossil-fuel-derived energy from coal. The conservation of coal resources would be affected by conversion efficiencies, which vary with process and product mix. For the processes considered, for similar liquid-to-gas ratio values (product mix), the coal-to-methanol is the most efficient while the Fischer-Tropsch is the least efficient. For these processes, the cost per Btu of product at reasonable equivalent liquid/gas ratios is greatest for Fischer-Tropsch and the least for the coal-to-methanol process.

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FOREWORD

In September of 1980 the U. S. Environmental Protection Agency (EPA) published a report that described selected fuel utilization and conversion technologies in a form suitable for general distribution:

Environmental, Operational, and Economic Aspects
of Thirteen Selected Energy Technologies
EPA-600/7-80-173

Because the amounts of gaseous and liquid products are dependent on process conditions and because these conditions can be altered to produce more or less of a specific product it was determined that it would be useful if an analysis were attempted to relate product mix to a synthetic fuel process efficiency. This analysis of efficiency would be based on process capability to (1) produce the maximum amount of liquid fuel, (2) recover a useful product based on recovering the maximum input energy, and (3) maximize its efficiency to produce a preselected standard (i.e., another process within the same technology area).

Environmentally speaking, it should be obvious to everyone that a resultant reduction in pollutant emissions and effluences will occur per unit output if the efficiency of a given process is maximized. The national importance of this concept in preserving a quality environment and in conserving our nation's natural energy resources is highlighted by the following newsbriefs released just prior to this publication:

In a guest editorial for Fossil Energy I & C Briefs, U. S. Department of Energy, vol. 2, no. 3, May 1981, Dr. Robert E. Roberts, Acting Director, Office of Advanced Research and Technology, states

> "The 1981 estimate of our national demonstrated coal reserve is 475,000,000,000 tons. While this is not 100% recoverable with known technology, it is still a vast national resource. Our future and that of many generations to come will depend to a large extent upon our steward-ship of this vast energy resource.
>
> We are all aware that processes for turning coal into other forms of energy are not new. Such processes have been used for more than 200 years. It is frequently asked why we

> continue to develop new processes when the old ones appear to have been successful. The World War II German technology is often cited as an example.
>
> The answer to this question lies in a close examination of the old processes as well as those that represent the latest developments in the emerging technology. Good steward-ship requires that we maximize the efficiency with which we use our resources. The key to this lies in the implementation of a carefully considered and executed broad program of research to upgrade and refine our techniques".

The California Energy Commission told the U. S. Synthetic Fuels Corporation, as reported in SynFuels, May 29, 1981, (McGraw Hill) that one factor "curiously absent" from the proposed synfuel project selection criteria guidelines is

> "the consideration of efficiency of feedstocks being turned into synthetic fuels. The minimum efficiency standard, below which a project should be considered less favorably, should be 50%"

This publication is a follow-up to that initial EPA survey/analysis, but for just one of the 13 technologies, namely, indirect liquefaction. The Office of Environmental Engineering and Technology trusts that this report will prove useful and would consider it to be so if the importance of efficiency as it relates to the environment and conservation is henceforth appreciated or if this report initiates in the mind of the reader efficiency-oriented thinking.

Robert M. Statnick, PhD.
Acting Director,
Energy Processes Division

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The authors of this report gratefully acknowledge the technical support, consultations, and review provided by Mr. Morris H. Altschuler and Mr. William N. McCarthy, Jr., of the U. S. Environmental Protection Agency, Office of Environmental Engineering and Technology, Washington, D. C., in the preparation of this study.

1.0 INTRODUCTION

Currently, considerable activities are being pursued in addressing the United States' intermediate and longer range energy supply requirements. In this regard, even though the reserves of petroleum and to a lesser extent of natural gas are quite limited, the nation is quite fortunate in coal resources. Even so, our society and supporting infrastructure is very dependent on substantial amounts of liquid and gaseous fuels. Currently we are forced to import approximately 40 percent of the oil consumed in this country. This being the situation, considerable efforts have and are being directed at developing technically sound and environmentally acceptable technologies for converting coal to gaseous and liquid fuels. In pursuing this effort there are many underlying facets that must be considered. These cover the attainment of viable, economically acceptable technologies that could convert coal into more desirable forms and are commensurate with environmental acceptability and resource conservation.

In this regard, this study addresses some indirect conversion technologies that are currently being investigated for converting coal to gaseous and/or liquid fuel forms. The included material covers indirect coal conversion technologies, associated efficiencies, environmental aspects and relative economics. The intent of this paper is to provide insight into the impact of product mixes on process efficiency for a variety of energy production scenarios incorporating indirect coal liquefaction technologies. It is hoped that efficiency and its positive impact on the environment and energy resources will be incorporated into the decision making process regarding the selection and promotion of energy technologies.

2.0 U. S. COAL RESOURCES

Essentially, the reserve base refers to the total inplace coal that is technically and economically minable at this time (as based on specific depths and thickness criteria). It is not a fixed quantity, but one that will increase with discovery and additional development, decrease with mining and change if the criteria for its calculation are modified. No consideration was given to marketability in calculating the reserve base for this report. Nevertheless, the criteria used for bed thickness and depth correspond generally with those of the coals currently being mined commercially in the United States (1).

The proportion of coal that can be recovered from the reserve base is termed the reserve. Recoverability varies in the range from approximate 40 to over 90 percent according to the characteristics of the coal bed, the mining method, legal restraints and the restrictions placed upon mining a deposit because of natural and manmade features. Generally surface mining recovers a greater percentage of the inplace coal than does underground mining. In fact, western surface mining generally recovers over 90% of available coal while recovery from underground coal deposits can be less than 40%. Mining experience in the United States has indicated that, on a national basis, at least one-half of the inplace coals can be recovered (1).

The demonstrated coal reserve base of the United States on January 1, 1974 was estimated to total 475 billion tons. This quantity is widely distributed geographically, with 45 percent occurring in the states east of the Mississippi River and 55 percent occurring in western states and Alaska. However, quantities of different ranks as well as the amounts amenable to production by underground and surface mining methods differ markedly in different areas (1).

The sulfur content of United States coals also varies. While 46 percent of the total reserve base can be identified as low-sulfur coal, which is generally acknowledged as coal with less than one percent sulfur, 21 percent contains more than three percent sulfur. The sulfur content of 12 percent of the coal reserve base is unknown, largely because many coalbeds have not yet been mined (1).

Eighty-four (84) percent of the coal reserve base with less than 1 percent sulfur occurs in States west of the Mississippi River. The bulk of the western coals are of a lower rank than the eastern coals, however, and, on a calorific basis, it is estimated that at least one-fifth of the Nation's reserve of low-sulfur coal is in the East (1).

In 1980, 835 million tons of coal, mined in the U. S., supplied 18.9 quads of energy. Out of this total, coal supplied 15.7 quads toward the domestic consumption of 76.3 quads. Thus, in 1980, coal supplied 20.5% of our domestic needs. By comparison, in 1950 coal supplied 38.3%; in 1960, 23.0%; and in 1970, 18.9% of the energy consumed in the U. S. As can be seen coal, our largest fuel resource, has been satisfying less of our domestic needs since 1950 and now appears to be making a comeback (2).

As is generally recognized, our substantial coal resources can be used in two specific fashions: 1) directly as coal, and 2) as a feedstock for conversion into an alternate fuel form (e.g. oil). Whenever possible, from an energy conservation consideration, it is best to use coal directly. For in any conversion process some of the total energy is lost. However, there are numerous fuel use applications that cannot utilize coal (e.g. motor vehicle combustion engines) and if coal is to be a primary energy source, then it must be converted to a usable energy form(s).

At the current rate of production our currently defined reserves will suffice for approximately 240 years. If coal were to be required to supply 50 percent (as compared to a current 20.5 percent value) of our energy needs with synthetic fuels from coal supplying half of the total coal-derived energy, the life of our reserves would be greatly diminished. The coal reserve life, as based on our current energy-consumption level, if coal were to supply half our energy would be dependent on the synthetic conversion efficiency and is equal to:

79 years for a 70% synthetic conversion efficiency
72 years for a 60% synthetic conversion efficiency
64 years for a 50% synthetic conversion efficiency

As can be seen from the above, the conversion efficiency is very important when considering the conservation of our limited fossil fuel resources.

The tons of coal per year required to provide 100,000 barrels per day of crude oil equivalent* can be estimated as indicated by the following example:

---

* Includes all gaseous and liquid fuels

Coal: Subbituminous - 17 MM Btu/ton
Btu equivalent of product - 6 MM Btu/bbl
Conversion efficiency - 60 percent (assumed value)

$$\text{Tons of coal per day} = \frac{100{,}000 \text{ bbl/day} \times 6 \text{ MM Btu/bbl}}{17 \text{ MM Btu/ton} \times 0.6 \text{ Conv. Eff.}} =$$

58,823 tons/day

Tons of coal per year = 58,823 X 365 = 21.5 million tons/year

This is the approximate amount required to supply approximately 0.6% of our current yearly petroleum requirement.

When coal is used directly, obviously the greatest overall efficiency results. As a further example, obtainable boiler efficiency (i.e. the ratio of heat absorbed by water and steam to the heat in the fuel fired) for an appropriately designed boiler is essentially independent of whether oil, gas, or coal is fired. In converting coal to a medium-Btu gas, a reasonable conversion efficiency is 80 percent (Reference 3). When converting coal to liquid fuels, a reasonable conversion efficiency is 55 percent (Reference 3). An industrial fossil fuel-fired boiler typically could achieve an 85% boiler efficiency value. The obtainable efficiencies by direct coal firing or firing by oil or gas derived from coal as based on a boiler with an 85% efficiency are typically as follow:

Coal-fired boiler	- 85 %
Medium-Btu gas derived from coal to fire boiler	- 68% (i.e. 0.85 X 0.80 X 100)
Oil derived from coal to fire boiler	- 47% (i.e. 0.85 X 0.55 X 100)

Therefore, when viewing the conservation of energy resources, it is obvious that whenever feasible, coal should be used directly. However, there are, as previously indicated, many fuel uses that are dependent on a specific fuel form. These include steam plants designed for gas, automobiles, diesel locomotives, etc. In the past, coal was substantially used as a residential heating fuel, but it is now impractical to consider the direct use of coal as a future significant residential fuel. Existing gas and oil-fueled furnaces will not accept coal, the infrastructure to supply coal to a significant number of homes has been lost, and the environmental implications associated with particulate, NO_x, and SO_x emissions from low stacks over large metropolitan areas are staggering.

3.0 INDIRECT COAL LIQUEFACTION

3.1 General

Coal liquefaction processes can be classified into two principal classes -- direct liquefaction and indirect liquefaction. In indirect liquefaction, the coal is first gasified to make a synthesis gas and then passed over a catalyst to produce alcohols (methanol) or parafinic hydrocarbons (3).

A particular advantage of indirect liquefaction is that essentially all of the sulfur and nitrogen present in the coal can be separated in the gaseous phase and thus eliminated from the liquid products. These materials are difficult and expensive to remove to a very low concentration with direct processes (3).

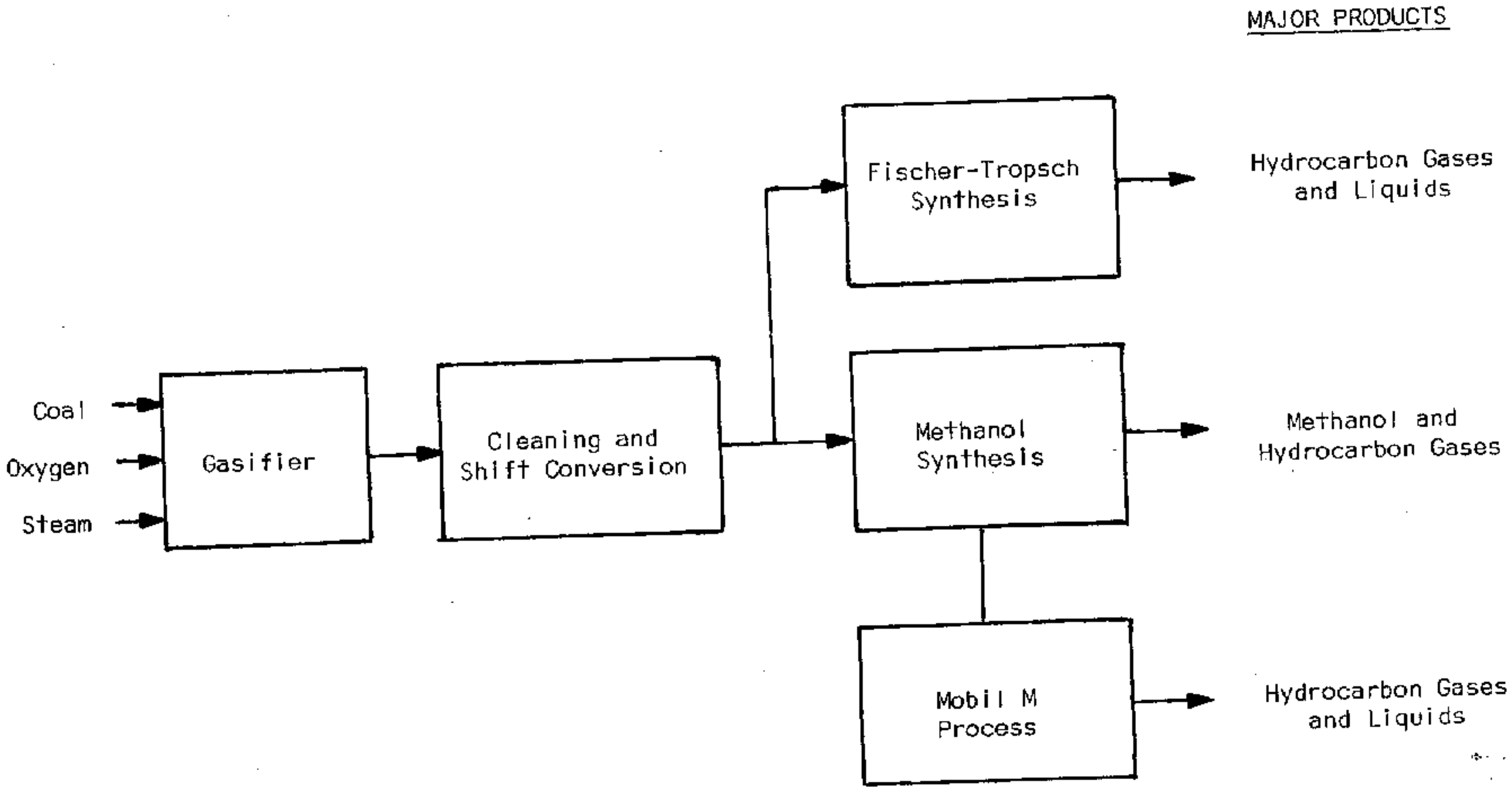
The indirect liquefaction processes receiving significant attention are the Coal-to-Methanol, Fischer-Tropsch and the Mobil M. A modification of the Fischer-Tropsch process is in commercial use in South Africa. A range of hydrocarbon products are obtainable with this process. The Mobil process is in the demonstration stage. The principal product of this process is gasoline. The basic flows for the indirect liquefaction processes are provided by Figure 1.

Environmental problems common to fossil energy facilities will also apply to coal liquefaction facilities. Liquefaction facilities do, however, present some unique problems due to incomplete combustion resulting in a wide variety of organic compounds, reducing conditions resulting in H_2S and other reduced sulfur compounds and catalytic processes producing spent catalyst with associated environmental concerns. These problems are generally common to all liquefaction processes. Since no large scale plants are in operation in the U. S., the only available data on emissions and effluents are estimates based on bench scale, pilot and demonstration synfuel plants and related industries. Because of the lack of domestic commercial plants there are no readily transferable hard data.

3.2 Specific Processes

Lurgi/Methanol

In the Lurgi/Methanol indirect liquefaction process medium Btu synthetic gas is produced by Lurgi gasifier(s). The synthesis gas is shift converted to the proper carbon-to-hydrogen ratio and the resulting gas is converted to methanol by any one of a number of proven processes. In addition to methanol, other reaction products are also produced. The yield of methanol is maximized by a combination of optimum reaction conditions, catalyst and the recycle of



Source: Reference 4

Figure 1
Basic Flows for Indirect Liquefaction

unreacted gases. High catalyst selectivity limits the production of ethers, ketones, and higher alcohols. Figure 2 is a simplified diagram of the basic process flow (3).

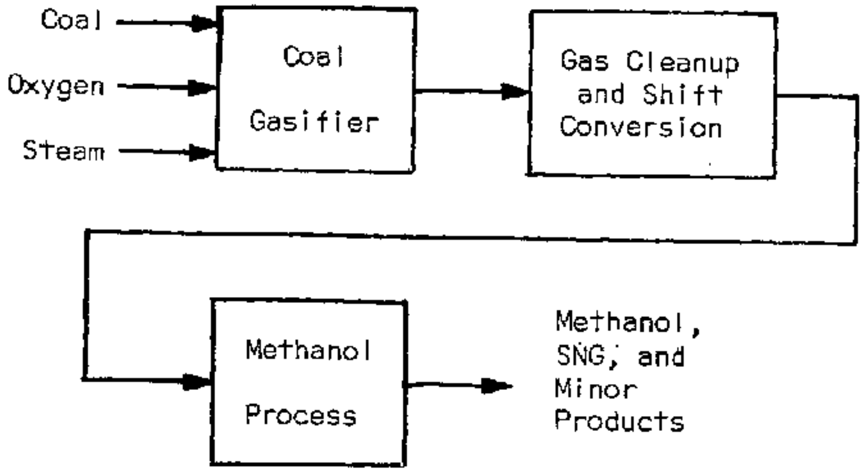


Figure 2
Lurgi/Methanol Flow

Lurgi/Methanol/Mobil M

In the Lurgi/Methanol/Mobil M indirect liquefaction process medium Btu synthetic gas is produced by Lurgi gasifier(s). The synthesis gas is shift converted to the proper carbon-to-hydrogen ratio and the resulting gas is converted to methanol by any one of a number of proven processes. The Mobil process converts methanol into a high-octane gasoline by dehydration over a shape-selective catalyst. In addition, other hydrocarbon and minor products are produced. The secret of the process is the catalyst, a unique zeolite identified a few years ago. Figure 3 is a simplified diagram of the basic process flow (3).

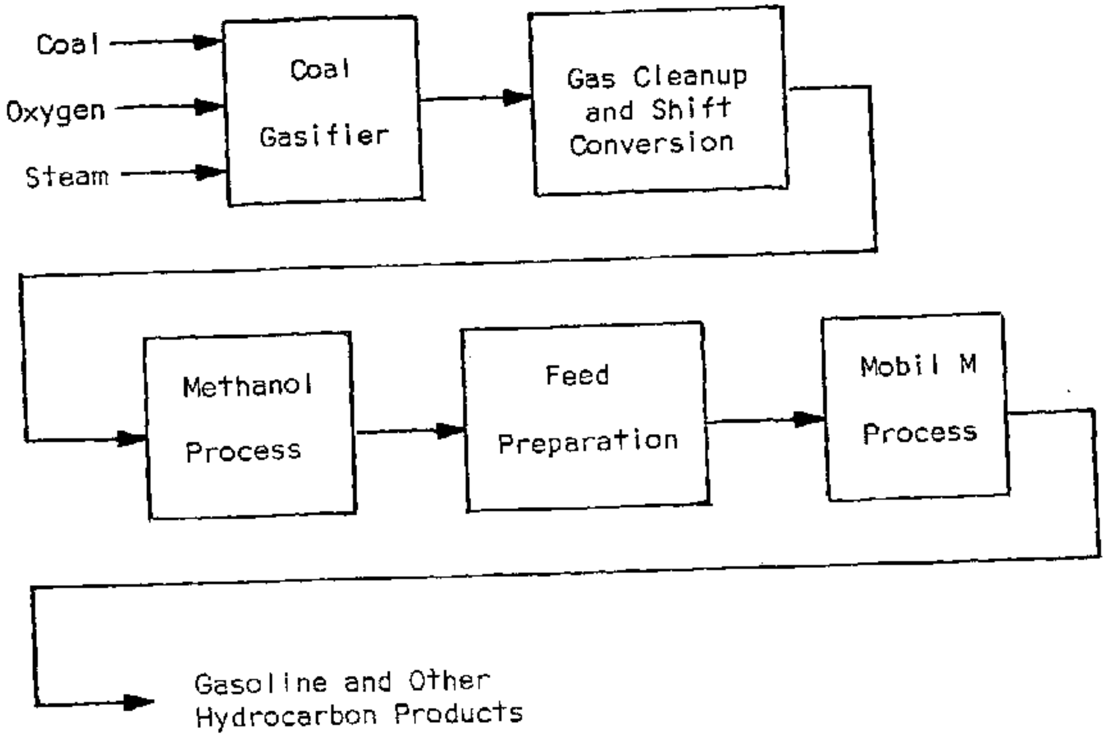


Figure 3
Lurgi/Methanol/Mobil M Flow

Lurgi/Fischer-Tropsch

The Fischer-Tropsch (F-T) indirect liquefaction process is based on the F-T catalytic reactions that were discovered in 1923. The F-T reactions can cover a range of combinations using different metallic oxide catalysts to react hydrogen and carbon monoxide to form a mixture of olefins, paraffins, and alcohols. The reactions are exothermic and are not specific to the formation of any single compound. The range of products from the F-T process depends on the reaction and temperature conditions as well as the type of catalyst and the composition of (input) reactants. In the overall process coal is initially gasified, cleaned of H_2S, CO_2, and impurities and shift converted to the proper carbon to hydrogen ratio before being fed to the F-T reactor(s). The product output covers a range of hydrocarbon fuels plus various chemical products. Figure 4 is a simplified diagram of the basic flow (3).

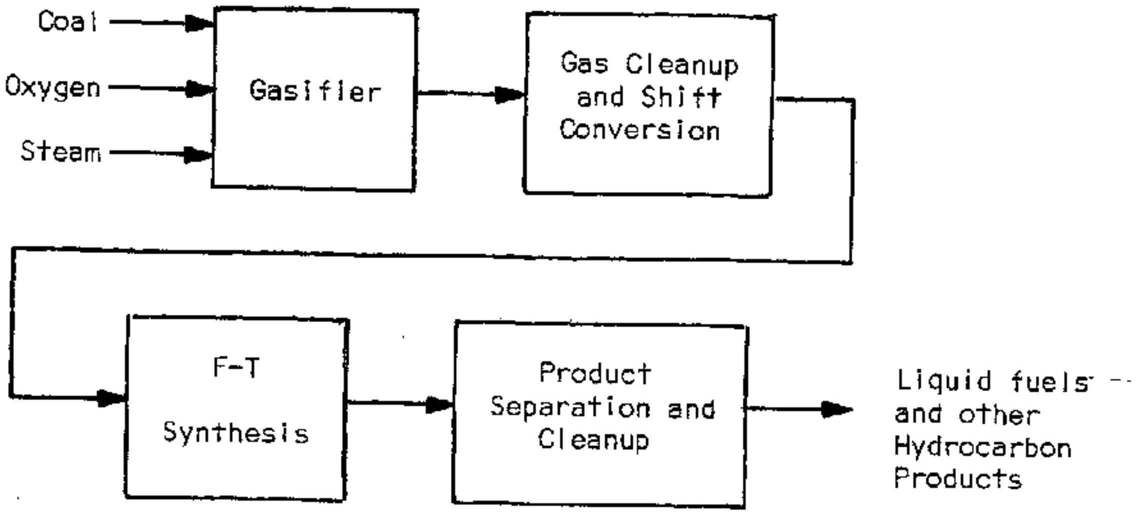


Figure 4
Lurgi/Fischer-Tropsch Flow

3.3 Process Efficiencies

There have been a number of estimates and assessments of the obtainable efficiencies from indirect liquefaction processes. Some estimates have been based on energy balance approaches and/or the performance of process elements comprising the overall conversion system. It must be recognized that since there are no commercial liquefaction plants in the United States, available efficiency values are estimates and assessments.

As previously indicated, obtainable conversion efficiencies are a function of process, output product mix, input fuel characteristics, and plant operating factors. The following material is based on high heating values. Process efficiencies for indirect liquefaction processes were obtained from a number of sources.

Reference 5 contains estimated efficiency values for several indirect liquefaction processes. The assessments are based on using a Wyoming high volatile subbituminous strip coal with an as-received heating value of 8500 Btu per pound. For the presented material, coal is gasified using a Lurgi dry-ash, moving-bed pressure gasifier. For the assessments, sufficient process steps are included so as to provide liquid products meeting U. S. market specifications and to produce SNG that would be interchangeable with natural gas.

Provided thermal efficiencies as based on Reference 5 are as follows:

> Table 1 is the estimated thermal efficiency for the co-production of methanol and SNG. Coal is gasified and methanol is produced from the coal derived synthesis gas. This is essentially the same as given by Table 2 except the Mobil methanol-to-gasoline technology is eliminated. The SNG can be converted to additional methanol. The efficiency of "reasonable" maximum production to methanol can readily be estimated from the efficiency provided in Table 3 by considering that the Mobil M process is approximately 92 percent efficient.
>
> Table 2 indicates the estimated thermal efficiency for the co-production of gasoline and SNG using the Mobil methanol-to-gasoline technology. As previously indicated, coal is gasified, methanol is produced from the coal derived synthesis gas; and the methanol is then processed by the Mobil process. This case provides the "practical" expected efficiency (i.e. methane is not reformed) for process products when gasoline is desired.
>
> Table 3 is the estimated thermal efficiency for coal to gasoline production with elimination of SNG. The same technology and synthesis gas production as in Table 2 except SNG is eliminated. A reforming unit converts methane into synthesis gas which is recycled to produce additional methanol and, ultimately, additional gasoline. Table 3 indicates the estimated efficiency with "practical" production of gasoline.
>
> Table 4 is the estimated thermal efficiency for the co-production of gasoline and SNG using state-of-the-art Sasol-type Fischer-Tropsch technology. Coal is gasified by a Lurgi dry-ash pressure gasifier, cleaned of H_2S, CO_2, and impurities, shift converted, and fed to the Fischer-Tropsch (F-T) reactors. The F-T products undergo extensive upgrading to become marketable under U. S. specifications. Table 4 can be assumed to indicate a reasonable "practical" output (i.e. methane is not reformed) using the Fischer-Tropsch technology when gasoline is desired with the output products meeting U. S. specifications.

Information based on Reference 6 is also provided on Tables 1 through 4. Values contained in this reference were modified to reflect estimate efficiencies as based on high heating values. It should be noted that there is general agreement between the values based on References 5 and 6.

Table 1
Estimated Thermal Efficiency For Co-production of Methanol & SNG(5)[a]

(Subbituminous Coal, Lurgi Gasifier
followed by Methanol Process)

Input	10^6 Btu/Hr	Percent of Input (Btu Basis)
Coal	19,383	
Coal Fines (Excess)	(1,125)	
Required Power[b]	22[c]	
Net Input	18,280	
Output[d]		
SNG	5,948	32.5
Methanol	5,737	31.4
Naphtha	285	1.5
Total	11,970	65.4[e]

---

[a] Based on subbituminous coal with as-received heating value of 8500 Btu/lb.

[b] Boiler is sized for optimum efficiency (i.e. balanced steam demand) which results in the need for a small amount of externally supplied power.

[c] Direct Thermal Equivalent Value.

[d] In addition, there are small outputs of sulfur & ammonia with economic value.

[e] Reference 6 indicates an overall efficiency value of 66%, with a 53% value for primarily a methanol product.

Table 2
Estimated Thermal Efficiency For Co-production of Gasoline & SNG With the Mobil M Process[a]

(Subbituminous Coal, Lurgi Gasifier, Methanol Process, Mobil M Process)

Input	10^6 Btu/Hr	Percent of Input (Btu Basis)
Coal	19,383	
Coal Fines (Excess)	(872)	
Net Input	18,511	
Output[b]		
SNG	6,067	32.8
C_3 LPG	247	1.3
C_4 LPG	385	2.1
10 RVP Gasoline	4,689	25.3
Power (Process Excess)	18[c]	0.1
Total	11,406	61.6[d]

---

[a] Based on subbituminous coal with as-received heating value of 8500 Btu/lb.

[b] In addition, there are small amounts of sulfur & ammonia with economic value.

[c] Direct Thermal Equivalent Value

[d] Reference 6 indicates an efficiency of 61% with gasoline containing 24% of the input Btu's.

Table 3
Estimated Thermal Efficiency For Production of Gasoline With the Mobil M Process(5)[a]

(Subbituminous Coal, Lurgi Gasifier, Methanol Process, Mobil M Process with Elimination of SNG)

Input	10^6 Btu/Hr	Percent of Input (Btu Basis)
Coal	19,458	
Output[b]		
C_3 LPG	424	2.2
C_4 LPG	664	3.4
10 RVP Gasoline	7,962	40.9
Power (Process Excess)	5[c]	-
Total	9,055	46.5[d]

---

[a] Based on subbituminous coal with as-received heating value of 8500 Btu/lb.

[b] In addition, there are small outputs of sulfur & ammonia with economic value.

[c] Direct Thermal Equivalent Value

[d] Reference 6 indicates an overall efficiency value of 49% for primarily a gasoline product.

Table 4
Estimated Thermal Efficiency For Co-production of Motor Fuels & SNG With F-T Technology(5)[a]

(Subbituminous Coal, Lurgi Gasifier, Sasol-Type Fischer-Tropsch Technology. Products Extensively upgraded for U. S. Market)

Input	10^6 Btu/Hr	Percent of Input (Btu Basis)
Coal	19,708	
Methanol	3	
Total Input	19,711	
Principal Output[b]		
SNG	7,243	36.8
C_3 LPG	176	0.9
C_4 LPG	26	0.1
10 RVP Gasoline	2,842	14.4
Diesel Fuel	514	2.6
Heavy Fuel Oil	147	0.7
Power (Process Excess)	11[c]	0.1
Total	10,959	55.6[d]

---

[a] Based on subbituminous coal with as-received heating value of 8500 Btu/lb.

[b] In addition, there are outputs of alcohols (1.5% of input Btu value), and small amounts of sulfur & ammonia, with economic value.

[c] Direct Thermal Equivalent Value

[d] Reference 6 indicates a 53% efficiency value with 24% liquids (vs 18.8% for this case).

As we tend away from a gaseous product to gas/liquid co-products to all liquids the efficiencies decrease. This is what would be expected as based on Reference 3. Basically, as we tend to increase the yields of gasoline and hydrocarbon liquids we pay an increasing price in lost energy. It should also be noted that the Mobil process is inherently more efficient than the Fischer-Tropsch process. As an example, the Mobil-process estimates indicate that when 24% of the input energy is contained in the gasoline product the overall system efficiency is 61% (see footnote (d), Table 2). For the Fischer-Tropsch with the 24% of the input energy contained in liquid hydrocarbons, the estimated overall system efficiency is 53% (see footnote (d), Table 4). That is, the Mobil process is indicated to be 15% more efficient than the Fischer-Tropsch process at this product mix. However, the Fischer-Tropsch is a proven process being in commercial use in South Africa.

Because incremental portions of the process streams can be treated differently, it is possible to estimate how the overall efficiency would vary as the liquid-gaseous product ratios are changed. The basis of the provided estimates, as indicated, is because of the nature of indirect processes and the ability to process and further process (e.g. reform methane to CO + H_2) incremental portions of process streams in different fashions. Thus intermediate components can be provided by combining lesser processed and greater processed product outputs to provide products associated with intermediate efficiencies. The following estimates derived by using values shown in Tables 1 through 4 are based on subbituminous coal, used with a Lurgi gasifier to produce a synthesis gas for indirect liquefaction processes.

Table 5 indicates the liquid/gaseous Btu product mixes as percentage of input energy for the three addressed indirect liquefaction approaches based on Lurgi gasification as derived from Figures 5, 6, and 7. Where Figure 5 is an estimate of thermal efficiency versus liquid/gas product mix for the Mobil M process; Figure 6 is for the Methanol process; and Figure 7 is for the Sasol-type Fischer-Tropsch process. The Table 5 values are indicated on Figures 5, 6, and 7. Interpolation of the figures will allow one to make a reasonable approximation of the efficiency associated with a selected liquid/gas product mix by process.

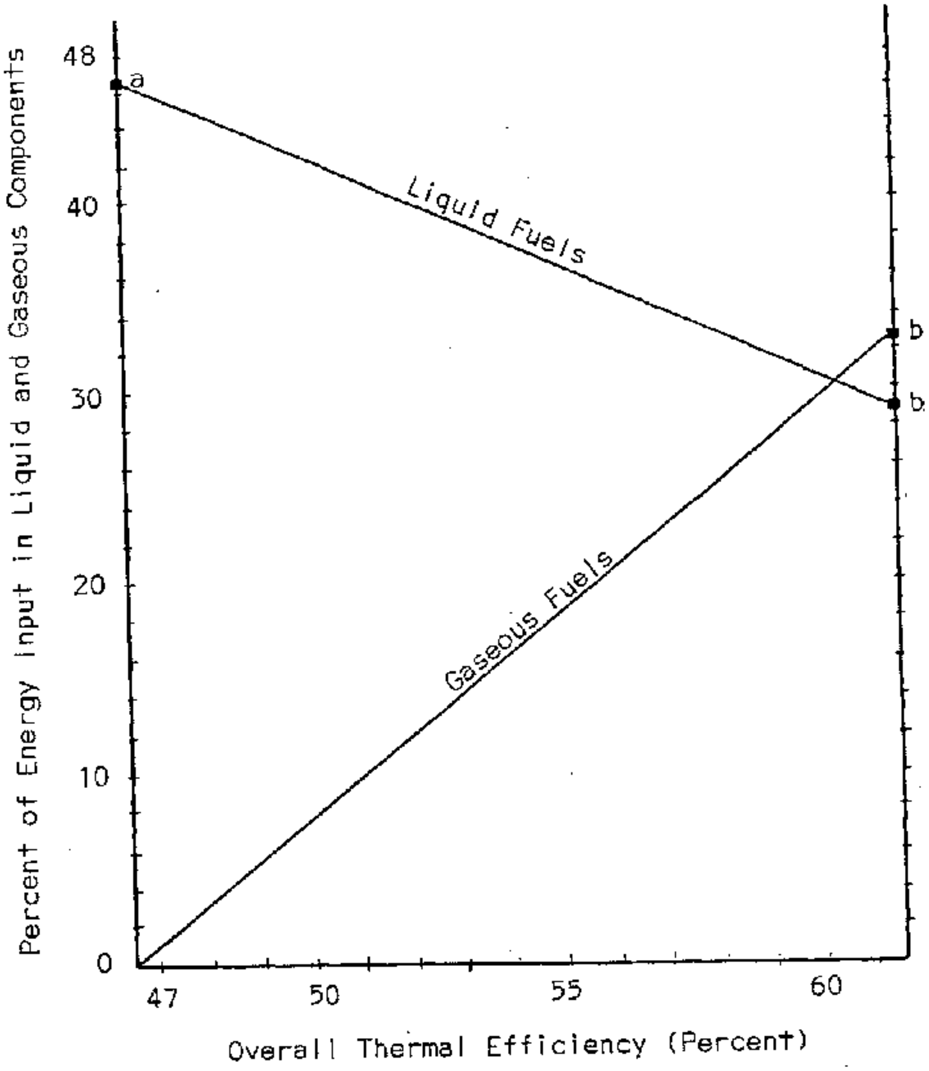


Figure 5
Estimate of Obtainable Efficiency with Product Mix
for Mobil M Process
(using Subbituminous Coal, Lurgi Gasifier & Methanol Process)

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a) Value from Table 3. Also presented in Table 5 as Mobil M max. liquid value.

b) Values from Table 2. Also provided in Table 5 as Mobil M max Btu values and Mobil M mix ratio values.

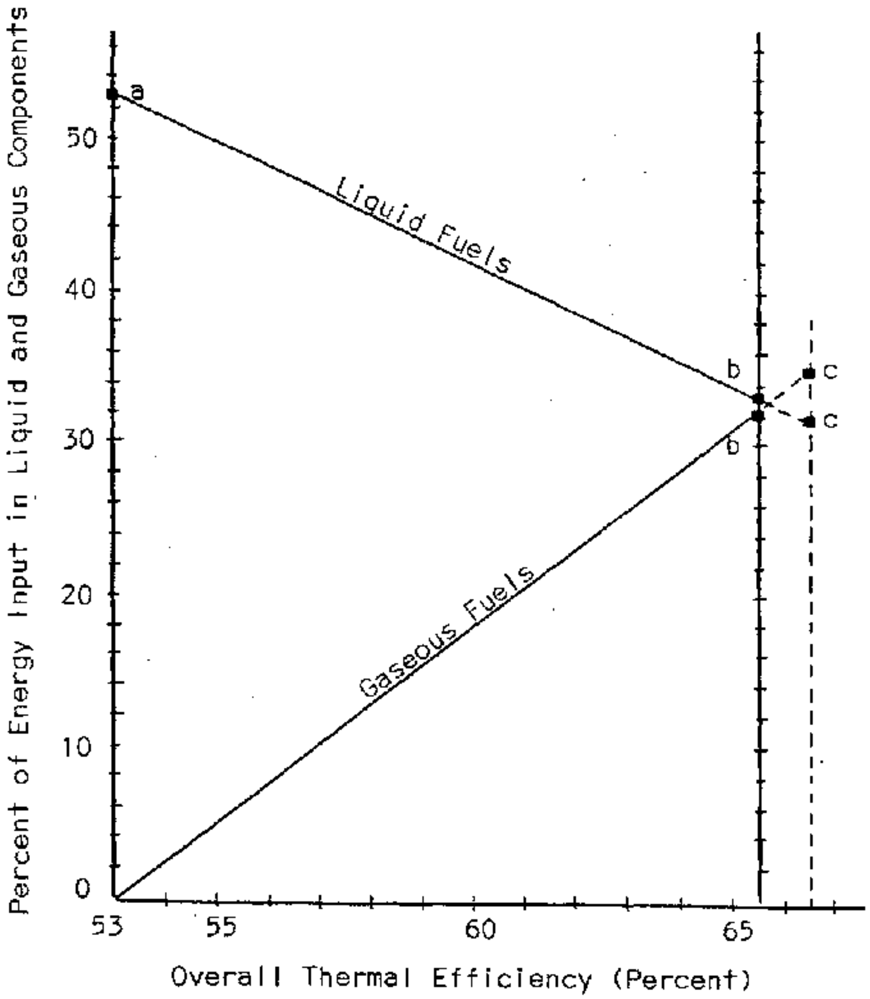

Figure 6
Estimate of Obtainable Efficiency with Product Mix
for Methanol Process (using Subbituminous Coal and Lurgi Gasifier)

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[a] Value based on Reference 6 (see footnote d, Table 3) and a 92% conversion efficiency for the Mobil M methanol to gasoline process (i.e. 49%/0.92). Also provided in Table 5 as Methanol maximum liquid value.

[b] Values from Table 1. Also provided in Table 5 as Methanol maximum Btu value (i.e. without methane reforming).

[c] Values based on Mobil M liquid/gas ratio, i.e. reduced synthesis gas to methanol conversion as compared to "b" values. Values provided in Table 5.

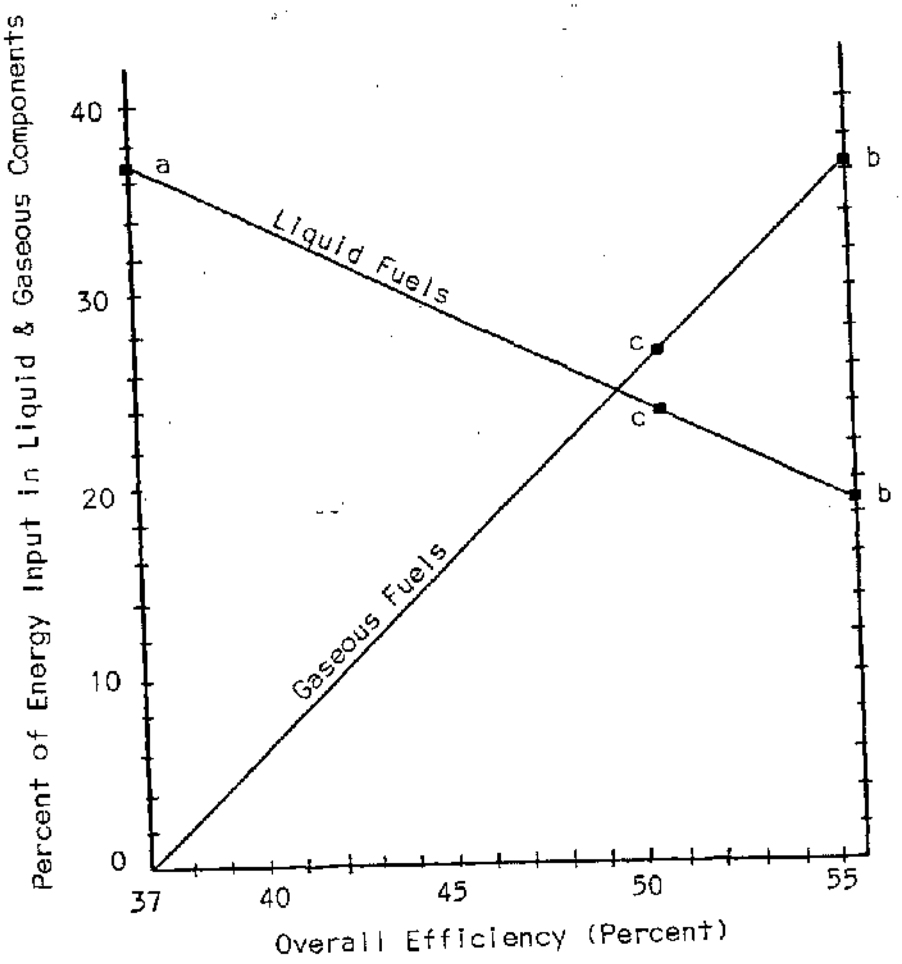

Figure 7
Estimate of Obtainable Efficiency with Product Mix for Sasol Type Fischer-Tropsch Technology (using Subbituminous Coal and Lurgi Gasifier)

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a) Value based on Reference 6 for the production of gasoline and diesel fuel. Also provided in Table 5 as F-T maximum liquid value.

b) Values from Table 4. Also provided in Table 5 as F-T maximum Btu values.

c) Values based on Mobil M liquid/gas ratio with methane reforming as required to provide desired liquid/gas ratio. Values provided in Table 5.

Table 5
Comparison of Indirect Technologies' Products As Based On Btu Input

Product Basis	Conversion Technologies (With Component Stream Processing as Required) Fischer-Tropsch	 Mobil M	 Methanol
Max. liquids	Liquids-37%	Liquids-46.5%	Liquids-53%
Mobil M mix ratio[a]	Liquids-23.5% Gas-26.9%	Liquids-28.7% Gas-32.8%	Liquids-31.3%[b] Gas-35.5%
Max. Btu when methane is not reformed	Liquids-18.7% Gas-36.8%	Liquids-28.7% Gas-32.8%	Liquids-32.9% Gas-32.5%

Source of Values - See footnotes of Figures 5, 6, and 7.

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[a] Mobil M Mix Ratio = $\frac{\text{Btu liquid}}{\text{Btu gas}} \approx 0.87$

[b] For this product mix not all of the available synthesis gas is directed toward the methanol product. Therefore the overall efficiency is greater than the conventional methanol case (Table 1).

4.0 ENVIRONMENTAL ASPECTS

4.1 Coal Mining (7)

In the West, wind erosion, and hence, particulates, generate air pollution from surface mining at a far higher rate than in any other coal mining region in the country. For example, air pollution, measured in tons of particulates per 10^{12} Btu, was, under controlled conditions, 0.83 in the Northwest and 2.40 in the Southwest compared to an average of 0.05 in the Appalachian and Central Regions. Because most of the coal surface-mining equipment in the West is electrically powered, diesel emissions are relatively low. Air pollution indirectly generated by western surface mining occurs at the electric power station site rather than at the mine site.

Air pollution from underground mines arises from several sources. Blasting and other production operations generate some pollutants. Fires from coal refuse banks emit not only smoke and minute particulate materials, but also noxious and lethal gases. In the past, fires have occurred in abandoned deep mines and in unmined underground areas.

Surface coal mining normally generates a lesser solid waste problem than underground mining because surface mining generally levels most of the overburden after the mining operation has been completed. Data reported by Hittman Associates indicate that the solid wastes generated by surface coal mining in southwestern states averaged 414 tons per 10^{12} Btu compared with 730 tons per 10^{12} Btu in the northwestern states.

Underground mining produces large quantities of solid wastes where preparation plants are associated with the underground mines in order to upgrade the coal. On the average, approximately 25 percent of the extracted coal is rejected as waste by a coal preparation plant. Some waste is produced from the sinking of shafts and the driving of entryways and tunnels.

It should be noted that coal conversion facilities are envisioned to be essentially mine-month operations. Therefore pollution and energy usage arising from coal transportation would be of minimal concern.

4.2 Liquefaction

4.2.1 General (8,9)

The products of coal liquefaction span a broad range of chemical compounds, depending on the specific liquefaction processes and feedstocks employed. Many by-products of coal liquefaction and associated discharges have been identified, but the full range of chemicals created and their potential environmental effects have not been completely characterized. Since a boiler will be associated with a coal liquefaction facility, the site will also be impacted by emissions/effluents emitted by that source, such as boiler flue gases, boiler ash and flue gas desulfurization sludges.

The environmental and health hazards posed by these not fully characterized compounds are uncertain. The chemical structure of many species appears to indicate a potential carcinogenic risk which is higher than that of conventional petroleum products. Whether the hazard would be restricted to the occupational health area rather than the public at large is unknown.

4.2.2 Wastewater & Gaseous Effluents (8)

Coal liquefaction processes, like coal gasification processes, produce water effluent streams which include cooling tower blowdown and "sour" process water. While the specific point of generation of individual compounds and their local concentrations within the liquefaction train will vary from process to process, all will eventually appear as an effluent requiring separation and treatment.

"Sour" process water contains ammonia, hydrogen sulfide, and dissolved hydrocarbons such as phenols and cresols. For the major identified pollutants commercial control technology is available, including the following:

- Physical separation of oil and water streams
- Steam stripping to remove volatiles
- Phenol recovery by non-proprietary oil extraction or by Lurgi's proprietary Phenosolvan process
- Sulfur recovery through a number of processes for removal, conversion to elemental sulfur, and cleanup of tail-gas streams
- Biological oxidation to remove residual amounts of dissolved salts, phenol, ammonia, etc.
- "Polishing" operations, such as activated carbon adsorption, if required, to remove residual amounts of refractory organics which are not biodegradable

Substantial quantities of sulfur and nitrogen compounds may remain in the liquefied product and, especially in the case of synthetic crude production, will require additional refining. This will increase the number of individual cleanup processes required and, hence, plant emissions.

4.2.3. Solid Waste

The principal solid effluent from coal liquefaction will consist of the mineral matter present in the coal feedstock. Indirect liquefaction processes will discharge an ash with properties which depend on the process specifics. Landfill disposal is an alternative, but leaching characteristics of the solid wastes must be considered in selecting landfill procedures.

Other solid wastes will include spent catalysts, organic sludge from biological wastewater facilities, inorganic sludges from flue-gas desulfurization or evaporation ponds, and byproduct sulfur if not recovered. These wastes may require specialized treatment to avoid transmission of soluble components, including trace elements (e.g. arsenic, chromium, mercury, molybdenum, and selenium) to local water supplies.

Coal storage and preparation will also require pollution control techniques for dust and rainwater runoff.

4.2.4 Water Requirements (8)

A commercial-size coal liquefaction facility producing 100,000 barrels of synthetic crude per day will require an estimated 5 to 25 million gallons of water daily. While many liquefaction processes consume water as a chemical feedstock to produce hydrogen, the primary use of water in all processes is cooling-related. Direct air coolers and dry cooling towers are commercial technologies which could be employed to reduce water consumption. They would be used only in areas where additional competition for available water supplies would be unacceptable because they increase energy consumption, land requirements, and total capital cost by as much as 7 to 10 percent.

4.2.5 Process Waste Streams & Residuals

The potential pollutants and amounts are dependent on both process specifics and plant size. Even so, it is possible to partially categorize the typical waste streams associated with functional liquefaction areas. Table 6 indicates key process waste streams (prior to controls). Table 7 indicates air, water, and solid waste environmental residuals. The estimated range of residual emission

Table 6
Key Process Waste Streams(9)

Gaseous Wastes

- Boiler Flue Gases
- Rectisol Acid Gases
- Transient & Intermittent Waste Gases

Aqueous Wastes

- Raw Gas Liquor/Rectisol Condensates
- Synthesis Condensates

Solid Wastes

- Gasifier Ash, Boiler Ash, FGD Sludge
- By-product Sulfur
- Biotreatment Sludge

Table 7
General Environmental Residuals From Indirect Liquefaction(9)

Air Pollutants

Pollutants of concern in the boiler flue gases include SO_2, particulates and NO_x. In the Rectisol acid gases, pollutants of concern are reduced sulfur compounds, reactive hydrocarbons and CO, ammonia and HCN. Of concern in all transient and intermittent waste gases are reduced sulfur compounds, POM, HCN, ammonia, particulates, reactive hydrocarbons and CO.

Water Pollutants

Key pollutant species and wastewater parameters in the combined stream include: pH, ammonia, total phenol, cyanide, thiocyanate, TOC, COD, BOD, inorganic dissolved solids (including trace elements), priority organic pollutants, sulfide, oil and grease.

Solid Wastes

Available data indicate that the unquenched gasifier ash, when subjected to the RCRA leach/extraction procedure, is nonhazardous. It is believed that residual organics present in unincinerated process wastewaters may render the ash hazardous if mixed in a co-disposal alternative. The same arguments apply to the FGD sludge if mixed with unincinerated process wastewaters. It is believed that biological sludges will be hazardous because of their organics and trace metal contents, although no confirming data are available.

levels after control, by process type, per 100,000 equivalent barrels of product output, is provided by Table 8. The exact outputs are dependent on effectiveness of the utilized controls.

It should be noted, that when viewed from a mass balance basis, the residues for disposal generally increase with decreasing thermal conversion efficiency. What does not appear on a mass basis as output products, must be disposed of in some manner. However, it should be noted that since the production of environmentally undesirable waste components will vary between processes and since the efficiency of environmental control measures will differ, we cannot accurately quantify the relationship between efficiency and environmental impact. Even so, it must be noted that many components of indirect systems are common. As an example, coal handling, gasifiers and ancillaries, raw gas cleaning and shift conversion, etc. elements are common to various liquefaction concepts and the associated material losses from such elements should be comparable. Therefore, the environmental concern associated with such units would increase with a decrease in overall conversion efficiency. That is, with decreasing efficiency, more coal input and consequently more effluents are generated for a given product output. This output (i.e. pollutant discharges) would be inversely proportional to the efficiency value. It is not unreasonable to assume that over a limited range a linear relationship exists between conversion efficiency and air emissions per given amount of feedstock. Table 5 indicates a liquid-conversion efficiency of 46.5 percent for Mobil M and 53 percent for methanol. Therefore going from a Mobil M to a methanol liquid product, the reduction in air emissions could be on the order of (1-46.5/53) or 12 percent. In a similar fashion, for the Methanol process, comparing a maximum liquid output option to the maximum Btu output option (Reference Table 5) we have, as based on the same rationale, a potential air emissions reduction of (1-53/65.4) or 19 percent. Considering the substantial estimated air emission levels per 100,000 equivalent barrels of product (Table 8), this reduction if applied to a commercial operation could be very significant.

It should be emphasized, that even though many by-products of coal liquefaction have been identified, the full range of chemicals created, and their potential environmental effects (after control) have not been fully characterized.

Table 8
Estimated Residual-Emission Levels* (After Control)(4,10)

AIR EMISSIONS

Process	Particulates	SO_2	NO_x
	(Tons Per 10^5 Equiv. Bbl. of Liquid Output)		
Fischer-Tropsch	2-12	18-28	10-47
Mobil M (Coal-Methanol-Gasoline)	1-15	12-28	10-31
Methanol (Coal-Methanol)	1-15	12-28	10-31

SOLID WASTE

Category	Total Quantity (pounds per 10^6 Btu of produced energy product)
Boiler ash	
Linestone sludge	
Gasifier ash	
Wastewater treatment sludge	
Spent catalyst	
Spent catalyst tailings	12-14 (Total)

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* Only for pollutants cited.

5.0 COST OF SYNTHETIC PRODUCTS

It is difficult to provide confident projections of the cost of synthetic fuels from indirect liquefaction processes. Even so, using the same plant-costing concepts, plant-duty parameters, the same value of capital concept for all considered plants, the relative cost of conversion in terms of cost per million Btu of product output can be estimated. Table 9 provides an assessment of relative costs.

Table 9
Synfuels-from-coal Projected Efficiencies & Relative Cost*

Product(s) of Interest (With Btu percentages of input)	Efficiency	Relative Cost per Btu of Product
Methanol		
Liquids-34%, Gas-32%	66%	1.0 (Reference)
Liquids-53%	53%	1.3
Methanol-Mobil M		
Liquids-31%, Gas-30%	61%	1.1
Liquids-49%	49%	1.5
Fischer-Tropsch		
Liquids-24%, Gas-29%	53%	1.3
Liquids-37%	37%	2.0

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* Based on Reference 6

6.0 CONCLUSIONS

1. There is a significant difference in the thermal efficiencies of the coal-to-methanol, Mobil M, and the Fischer-Tropsch processes when compared on a similar basis. In general, the thermal efficiencies are highest for coal-to-methanol and lowest for Fischer-Tropsch. When the liquid fuel component contains approximately 25 percent of the Btu output, the Mobil M process is estimated to be approximately 15 percent more efficient than the Fischer-Tropsch process.

2. The thermal efficiency for each of the above processes decreases as we increase the percent of the liquid products. Since thermal efficiencies are higher with greater percentages of gaseous outputs and are reduced with additional reforming of methane, it would be desirable from resource conservation and environmental standpoints to increase the utilization of gaseous fuels and minimize the demand for liquid fuels.

3. The cost per Btu of product at reasonable equivalent liquid/gas ratios is greatest for Fischer-Tropsch and least for the coal-to-methanol process.

4. The reduction in environmental impacts resulting from increased efficiencies resulting from modifying the product mix (i.e. by process and/or output mix selection), although not completely quantifiable, appears to present a significant opportunity for reducing pollution.

5. In the national interest of maximizing conservation of energy resources and minimizing environmental impacts, energy planners should consider applications that will maximize the use of synthetic gaseous-fuels.

References

1. Demonstrated Coal Reserve Base of the United States, by Sulfur Category, on January 1, 1974. Mineral Industry Surveys, U. S. Department of the Interior, Bureau of Mines, Washington, D. C., May 1975 (with Department of Energy January 1, 1979 update - DOE/EIA-0280(79)).

2. 1980 Annual Report to Congress. Energy Information Administration, DOE/EIA-0173(80)/2, Volume 2 of 3.

3. Environmental, Operational, and Economic Aspects of Thirteen Selected Energy Technologies, EPA-600/7-80-173. U. S. Environmental Protection Agency, September 1980.

4. Chartock, M. A., et al. Draft Background Report, Environmental Issues of Synthetic Transportation Fuels from Coal. Report to Energy Office of Technology Assessment, U. S. Congress. University of Oklahoma, March 5, 1981.

5. Schreiner, M., et al. Research Guidance Studies to Assess Gasoline from Coal by Methanol-to-Gasoline and Fischer-Tropsch Technologies, FE-2447-13. Prepared for U. S. Department of Energy. Mobil Research and Development Corporation, August 1978.

6. Rudolph, P. F. H., Synfuels from Coal - How and at what cost. Lurgi Corporation. Presented at Seventh Energy Technology Conference, Washington, D. C., March 24-26, 1980.

7. Criteria for Evaluating the Feasibility of Mining Technologies on Federal Lands. Prepared for Office of Technology Assessment, U. S. Congress. Hoffman-Muntner Corporation, April 1978.

8. International Coal Technology Summary Document, HCP/P-3885. U. S. Department of Energy, December 1978.

9. Based on personal communications with the U. S. Environmental Protection Agency, Office of Environmental Engineering and Technology, May 1981.

10. Hoffman-Holt, Incorporated, estimates as based on relatable data.