INTRODUCTION

This report forms a part of a larger study investigating the resource costs of a number of sources of liquid fuels. Previous reports have examined North Sea oil production(1), production of synthetic crude oil from Colorado oil shales(2) and Athabasca tar sands(3). Although all these reports have been largely concerned with energy requirements, material and capital inputs have been documented. It is planned to extend the study to include labour requirements and to examine likely production costs of these possible sources of liquid fuels in the future.

Because of its large and fairly widely distributed resource base, coal is an attractive raw material for conversion to both oil and gas as world production of crude oil and natural gas declines. Ion(4) gives a figure for the estimated recoverable reserves of coals of the world as 551×10^9 tonnes (of a total resource base of $10{,}755 \times 10^9$ tonnes). Of this total 34% is in the United States and 31% is in Russia and China. At present levels of consumption, recoverable coal reserves would provide supplies for several centuries, and, although demand for coal can be expected to increase as oil and gas is depleted, recoverable reserves of coal clearly represents a very large source of hydrocarbons.

In addition to its large and widely distributed supplies throughout the world, coal as a raw material for the production of oil/gas has another advantage over oil shales and tar sands. As seen in previous reports(2,3), the exploitation of both oil shales and tar sands by methods at present feasible (viz. conventional mining and above-ground processing rather than by in-situ methods) implies large material handling operations since the hydrocarbon content of either resource only account for 10-20% by weight. Thus, in adddition to overburden, large quantities of inert materials (shale or sand) have to be mined, transported, processed and disposed of in an environmentally satisfactory way in order to recover the hydrocarbons from either oil shales or tar sands. By comparison, coals have much lower contents of inert mineral matter - ash contents are commonly of the order of 10% by weight and may be as high as 30% for some coals. So although strip mining of coal is an environmentally unpopular issue, problems are not exacerbated by the need to dispose of large quantities of process wastes.

Most available data on coal liquefaction relates to research in U.S.A. where there have been a number of different projects. Although there is a commercial plant operating in South Africa (SASOL) it is unlikely that a large synthetic fuel industry would use the SASOL process because of its low thermal efficiency (~40%) and thus expensive products. The SASOL plant is based on technology developed in Germany during World War II and has been operating for over 20 years processing some 7000 tonnes of coal/day and a much larger plant is being built. However the success of the SASOL plant depends largely on the availability of cheap supplies of coal and the desire of South Africa to have some security in its supplies of motor spirit. Most current research on coal liquefaction is directed at processes thought capable of achieving a thermal efficiency of 60-70%. However, none of these processes has yet advanced beyond the pilot plant stage and much of this study is necessarily based on conceptual designs of commercial scale plants derived from small-scale experiments. One is also in the position of not having access to unpublished &/or proprietary data which may or may not alter the overall picture.

The scope of this study has been restricted to a detailed examination of coal conversion processes using data from other sources of the energy requirement of coal mining by various techniques(7,8). So that the results of this study are comparable with those of previous reports, the system boundary has been chosen (where possible) at the refinery gate, that is with synthetic crude as the major product. However, because of the nature of the SASOL process it is not sensible to consider synthetic crude as a product and care must be taken in comparing the efficiency of this process with others considered. Also the production of methanol from coal has been considered. It also seemed most sensible to consider cases where the liquefaction plant was sited at or near the mine mouth since oil is much easier and cheaper (per unit of energy) to transport than coal. A final stipulation was made that the whole complex (mine and liquefaction plant) be self-sufficient in energy with on-site steam raising, electricity generation and other plant fuel production. This avoids giving the process subsidies from sources of energy which may be cheaper in the short term, and effectively considers the situation when oil and gas from conventional sources are not available.

Finally, it should be stressed that coals are heterogenous materials containing a number of different components and that the coal resources of the U.S. for instance represent a very diverse set of substances. Although it seems that most coals <u>can</u> be converted to satisfactory liquid fuels, the costs, yields and optimum process conditions are likely to vary considerably. Some work has been done on the dependence of liquefaction behaviour on coal characteristics(15,16) and preliminary results indicated that coals of low rank* (lignites and subbituminous coals) and high rank (medium volatile bituminous and higher) behaved less satisfactorily in liquefaction experiments than coals of intermediate rank (highly volatile bituminous coals). It was also found in a number of cases that the mineral constituents of coals may act as additonal catalysts for the liquefaction process. Also hydrogen requirements for liquefaction will vary according to hydrogen content of the parent coal, and the amounts of nitrogen, oxygen and sulphur, all of which are removed by hydrogenation.

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*Coals originated from the accumulation and burial of partially decomposed vegetation in previous geologic ages. Biological changes and the subsequent effects of temperature and pressure convert the plant debris progressively with time to lignite (brown coal), then to subbituminous coals, bituminous coals and ultimately to anthracite. The rank of a coal is a measure of its degree of coalification and increases with increasing pure-coal carbon content. That is, the rank of a coal indicates how far along the sequence of fuels it has been taken by natural processes.

1. PROCESSES FOR CONVERTING COAL TO LIQUID FUELS.

Basically the conversion of coal into oil requires the addition of hydrogen to the coal (the ratio of H atoms to C atoms in coal is of the order of 0.8 : 1 whereas in crude oil it is about 1.75 : 1). Ash, moisutre, oxygen, nitrogen and sulphur must also be removed from the coal, the last three of these consuming additonal hydrogen. In all the schemes considered here the source of hydrogen will be assumed to be water (steam) and the energy for hydrogen production will be assumed to be from the combustion of some part of the coal or products of liquefaction (yielding CO_2 and representing a loss of carbon).

There are four basic routes currently being investigated by which liquid fuels can be obtained from coal. These are the gasification/synthesis (Fischer-Tropsch), liquefaction by direct hydrogenation or by solvent refining and pyrolysis (carbonization) routes.

1.1. Gasification/Synthesis (Fischer-Tropsch)

In this process coal is first gasified in a high pressure Lurgi gasifier via the following reactions :

$$C + CO_2 \longrightarrow 2CO \qquad (1)$$

$$CO + H_2O \longrightarrow CO_2 + H_2 \qquad (2)$$

where CO_2 is supplied by burning some of the coal, and the heat generated in the combustion is used to sustain reactions (1) and (2) which are endothermic. Following purification to remove H_2S and NH_3, the synthesis gas $\left[CO + H_2\right]$ is passed over a catalyst yielding liquid products ranging from methanol to hydrocarbons of high molecular weight. The most important reactions which take place in the synthesis reactor are the following:

$$CO + 3H_2 \longrightarrow CH_4 + H_2O \qquad (3)$$

$$nCO + 2nH_2 \longrightarrow C_nH_{2n} + nH_2O \qquad (4)$$

$$nCO + (2n+1)\ H_2 \longrightarrow C_nH_{2n+2} + nH_2O \qquad (5)$$

$$CO_2 + H_2 \longrightarrow CO + H_2O \qquad (6)$$

Since methane is an unwanted product it is fed together with unconverted hydrogen and carbon monoxide to a steam/oxygen reformer where it is reformed to yield mainly hydrogen and carbon monoxide and then returned to the synthesis reactor. An example of this process is the SASOL plant in South Africa which has been producing waxes, oils, motor fuel and a range of chemicals since about 1955. Typical yields from 1 tonne of coal would be from 1-2 bbls of liquid products and 8000-10000 scf of gaseous products(5).

1.2. Direct Hydrogenation involves the reaction of coal [in a slurry with recycled solvent] with hydrogen at high pressure and usually in the presence of a catalyst. These processes require a temperature ~450°C and pressures from 2000-4000 psi. A lower pressure and a shorter reaction time limit the reaction between coal and hydrogen and favour the formation of a heavy fuel oil while a high pressure and longer reaction time favour the production of lighter fractions. Hydrogen can be supplied by steam reforming the solid or gaseous products of the hydrogenation reactions. Typical yields are 2.5 - 3.5 bbls oil and 2000-3000 scf gas/tonne coal(5). Examples of this process are the H-Coal process devised by Hydrocarbon Research Inc. (USA) and the Synthoil process being developed by the U.S. Bureau of Mines. At present, both of these processes have only been demonstrated on a small scale.

1.3 Extractive Hydrogenation (Solvent Refining) involves the partial or complete solution of the coal. Two systems are being investigated commercially and they differ in the method of bringing hydrogen to the coal. In the solvent refined coal (SRC) system, coal is dissolved in an organic liquid in the presence of hydrogen gas under pressure (~2500 psi). Most of the coal is dissolved and the slurry is subsequently filtered, the filtrate is distilled to recover the solvent and coal is reformed by cooling. Solvent refining was initiated by the Pittsburg and Midway Coal Mining Co. (Pamco) to produce a clean low-sulphur boiler fuel. The product is a semi-solid (with a softening point ~150°C), low-ash, low-sulphur fuel suitable for steam boilers but not as a refinery feedstock. Considerably more processing would be required to upgrade the SRC product to syncrude. In the hydrogen-donor process coal is dissolved by being mixed with solvent at low pressure (~300 psi). The hydrogen-donor solvent is a coal-derived extract containing compounds such as tetralin and, being rich in hydrogen it transfers hydrogen to the coal during extraction. The solvent is regenerated and recycled within the process. The Consol Synthetic Fuel (CSF) Process developed during the 1960's by Consolidation Coal Co., uses the hydrogen-donor principle. Briefly the CSF process first dissolves coal in the donor solvent at pressure ~300 psi and temperature ~400°C. The slurry is then filtered to remove unreacted coal and ash, and the liquid extract is water-washed and then further upgraded by catalytic hydrocracking to produce a medium quality syncrude. Typical yields would be 2-3 bbls oil and 3500-4500 gas/tonne coal(5).

1.4. Pyrolysis (Carbonisation)

The basic idea in this method is to increase the H/C ratio, firstly by removal of carbon and then by the addition of hydrogen. Pyrolysis or carbonisation is the destructive distillation of coal and involves heating coal in the absence of air until it decomposes. The best known of the pyrolysis processes is the COED (for Char-Oil Energy Development) process being developed by the FMC Corporation (U.S.A.). The heat required for pyrolysis is obtained by burning some of the coal feed with oxygen in a system of four fluidised beds. The coal is rapidly heated and pyrolysis of unburned coal takes place. Char is removed from the pyrolysis stage and gas and oil are recovered as products. The oil is filtered to remove solids and then further hydrotreated to produce syncrude. Hydrogen may be derived either from the gaseous products or by gasifying some of the char. The process is characterised by low production of syncrude and high production of char and gas, and as such is of dubious usefulness as a large supplier of liquid fuels. Typically, the process may produce 1 bbl of syncrude/tonne coal whereas the production of char may be 50-60% by weight of the coal feed(6).

2. CALCULATION OF ENERGY REQUIREMENTS.

As described in the previous section, there are a number of methods of converting coal to liquid hydrocarbons, all of which require the ratio of hydrogen atoms to carbon atoms to be increased. This is usually achieved by the addition of hydrogen, except in the case of pyrolysis methods where carbon is removed. Here, an example of each of the four main methods will be considered in detail.

The terminology used to describe energy requirements in this report follows the conventions suggested by the IFIAS workshop(9) where the following definitions were agreed:

(1) The Process Energy Requirement (PER) is the sum of the fuel energy supplied to drive all the process stages within the system boundary.

(2) The Gross Energy Requirement (GER) is the PER plus the gross heat of combustion of inputs that have alternative uses as fuels.

(3) The Net Energy Requirement (NER) is the GER less the gross heats of combustion of the products of the process.

In all the cases the liquefaction plant is assumed to be situated at the mouth or near vicinity of a coal mine so that coal transportation is not a significant factor. The complex will be assumed to meet all its energy needs from coal so that electricity, fuel gas, steam,hydrogen and oxygen are all generated on-site if required. Because none of the coal conversion processes produces a single product, the energy inputs to the plant must be partitioned between a number of products. For fuels this has been done on the basis of calorific values and for non-fuel products replacement energy requirements (i.e. the energy required to make a material by the usual method) have been used.

Since almost all of the available process data refers to American coals, it seemed appropriate to consider the production of liquid fuels in U.S.A. It should be mentioned that the calculated energy requirements will be specific to each particular coal (and the method of mining) since such factors as calorific values, ash and moisture contents and levels of impurities will determine quantities of coal to be mined, requirements for coal drying and ash removal and hydrogen requirements.

American coals are commonly divided into two broad categories - subbituminous western coals (e.g. Wyoming Powder River coal) and bituminous eastern coals (e.g. Illinois No.6 coal). In general westerncoals, as received have a higher moisture content than eastern bituminous coals so that more western coal must be mined and additional water removed before the coal enters the process. Western coal also generally consumes more hydrogen during liquefaction than eastern coal; although the western coal contains less sulphur and nitrogen (which consume hydrogen producing hydrogen sulphide and ammonia), that effect is more than offset by the higher oxygen content in the western coal which is removed by reaction with hydrogen to form water. The amount of ash is generally lower in western coals and, following the liquefaction process, it could be returned to the worked out surface mine. On the other hand, most eastern coal is recovered by underground mining and the problems of handling and disposal of the larger amounts of ash are not as easily solved(10).

If one wanted to estimate the energy requirements of producing liquids from other coals using the data given here, one would have to take account of the properties of the specific coal (moisture, ash, sulphur, nitrogen and oxygen contents, calorific value etc.) and the method of mining used and the nature of the coal seams.

2.1. Liquids from coal by direct hydrogenation.

The energy requirements for converting coal to synthetic crude oil using the H-Coal process are given in Appendix 2. Calculations were based on a conceptual design presented by Goen et al(10). Two cases were examined -

processing a typical Eastern American coal (Illinois No.6) and a Western American coal (Wyoming Powder River coal). It will be assumed that the former is recovered by underground mining and the latter by strip mining. In each case all requirements for electricity, steam, gas, hydrogen and oxygen are assumed to be met from on-site facilities fueled by coal. Calculated energy requirements are summarised below.

CASE I. Illinois No.6 bituminous coal.

Calorific value of coal (as received) = 25,530 MJ(th)/tonne

Moisture content of coal (as received) = 10%

Inputs	Energy Requirement ($\times 10^6$ MJ(th)/stream day)	
Calorific value of coal feed (36,182 tonnes)	923.74	(97.7%)
Coal mining (cs Appendix 1)	6.87	(0.7%)
Plant and capital equipment	8.25	(0.9%)
Catalyst and chemicals	6.28	(0.7%)
TOTAL	945.14×10^6 MJ(th)/stream day	

In Appendix 2.1.1.2 it was calculated that 94.9% of the plant energy requirements should be apportioned to the production of the synthetic crude oil (100,000 bbls or 14,452 tonnes/stream day). Thus, GER of this syncrude (calorific value of 42,700 MJ(th)/tonne) produced from Illinois No.6 bituminous coal by the H-Coal process is given by

$$GER_{syn} = \frac{1}{14,452} \times 0.949 \times 945.14 \times 10^6 = 62,060 \text{ MJ(th)/tonne}$$

and NER_{syn} = 19,360 MJ(th)/tonne.

CASE II. Wyoming Powder River subbituminous coal.

Calorific value of coal = 18,100 MJ(th)/tonne(as received)

Moisture content = 33%.

Inputs	Energy Requirement ($\times 10^6$ MJ(th)/stream day)	
Calorific value of coal feed(52,439 tonnes as received)	949.14	(96.2%)
Coal mining (cf Appendix 1)	22.81	(2.3%)
Plant and capital equipment	8.16	(0.8%)
Catalyst and chemicals	7.17	(0.7%)
TOTAL	987.28x10^6 MJ(th)/stream day	

In Appendix 2.1.2. it was calculated that 96.0% of the plant energy requirement should be apportioned to the production of the synthetic crude oil (13,538 tonnes/stream day). Thus,GER of this syncrude (calorific value of 42,700 MJ(th)/tonne) produced from Wyoming Powder River subbituminous coal by the H-Coal process is given by

$$GER_{syn} = \frac{1}{13538} \times 0.960 \times 987.14\times10^{6} = 70,000 \text{ MJ(th)/tonne}$$

and NER_{syn} = 27,300 MJ(th)/tonne.

It can be seen from the results of these calculations for an eastern and a western coal, that coal properties and mining methods have quite a considerable effect on calculated energy requirements. For the particular coals considered the higher NER of syncrude from the western coal - 27,300 MJ(th)/tonne compared with 19,400 MJ(th)/tonne for the eastern coal, reflects the higher requirements for hydrogen, plant fuel (drying etc), the greater tonnage of coal that must be mined per unit of output and the more energy intensive mining method (it has been assumed that strip mining costs will include the replacement and revegetation of overburden). It is also seen that energy requirements attributed to coal mining, capital equipment and chemicals are small compared with the calorific value of the coal feed.

2.2. Motor spirit from coal by the CSF process (extraction hydrogenation).

The energy requirements for converting coal to motor spirit using the CSF process are given in Appendix 3. Calculations were based on a conceptual design presented in the summary report of 'Project Gasoline'(11). Two cases were examined - processing a typical Eastern American coal (Illinois No.6) and a Western American coal (Montana). It will be assumed that the Eastern coal is obtained by underground mining and the Western coal by strip mining. All energy requirements are assumed to be met from on-site facilities fueled by coal. Calculated energy requirements are summarised below.

CASE I. Illinois No.6 bituminous coal.

Calorific value of dry coal = 27170 MJ(th)/tonne.
Moisture content of coal = 14.4%.
(as received)

Inputs	Energy Requirement ($\times 10^6$ MJ(th)/stream day)	
Calorific value of coal feed (25,723 tonnes as received)	610.93	(97.3%)
Coal mining (underground -cf Appendix 1)	4.89	(0.8%)
Plant and capital equipment	4.86	(0.8%)
Catalyst and chemicals	6.70	(1.1%)
TOTAL	627.43x10^6MJ(th)/stream day	

In Appendix 3.1.1.2. it was calculated that 96.8% of the plant energy requirements should be apportioned to the 7667.3 tonnes of motor spirit produced per stream day. Thus GER of motor spirit (calorific value 46830 MJ(th)/tonne) produced from Illinois No.6 coal by the CSF process is given by

$$\mathrm{GER}_{M.S.} = \frac{1}{7667.3} \times 0.968 \times 627.43 \times 10^{6}$$

$$= 79210 \text{ MJ(th)/tonne}$$

and $\mathrm{NER}_{M.S.} = 32{,}380$ MJ(th)/tonne

CASE II - Montana Coal.

Calorific value of coal (dry) = 27360 MJ(th)/tonne

Moisture content of coal (as received) = 24%.

Inputs	Energy Requirement ($\times 10^6$ MJ(th)/stream day)	
Calorific value of coal feed(27581 tonnes as received)	608.57	(96.4%)
Coal mining (strip-cf.Appendix 1)	12.00	(1.9%)
Plant and capital equipment	5.24	(0.8%)
Catalyst and chemicals	5.67	(0.9%)
TOTAL	631.48x10^{6} MJ(th)/stream day	

In Appendix 3.1.2. it was estimated that 97.4% of the energy requirements of the plant should be apportioned to the production of 7607 tonnes of motor spirit/stream day. Thus, GER of motor spirit produced from Montana coal by the CSF process is given by

$$GER_{M.S.} = \frac{1}{7607} \times 0.974 \times 631.48 \times 10^{6}$$

$$= 80,850 \text{ MJ(th)/tonne}$$

and $NER_{M.S.} = 34,020$ MJ(th)/tonne.

2.3. Liquids from coal by pyrolysis.

The energy requirements for converting coal to synthetic crude oil using the COED process are given in Appendix 4. Because this process typically produces about 60% by weight of low value char and only about 20% by weight of oil it was decided to consider first a scheme where char was converted to a more saleable product viz. pipeline gas. Shearer(12) has produced a conceptual design and economic study for such a plant, combining the COED pyrolysis process with a low pressure version of the Kellogg molten salt process to gasify char and his scheme has been used as the basis of this analysis. The plant would use Illinois No.6 coal and produce crude oil, pipeline gas and small quantities of light hydrocarbons, phenols and sulphur. The energy requirement of the plant are summarised below.

Calorific value of coal = 26,040 MJ(th)/tonne (as received)
Moisture content = 10%.

Inputs	Energy Requirement ($\times10^6$MJ(th)/stream day)	
Calorific value of coal feed(28,455 tonnes as received)	740.97	(96.8%)
Coal mining (underground-cf.Appendix 1)	5.41	(0.7%)
Plant and capital equipment	7.81	(1.0%)
Catalyst and chemicals	11.66	(1.5%)
TOTAL	765.85x10^6MJ(th)/stream day	

In Appendix 4.2 it was estimated that 39.74% of the plant energy requirements should be apportioned to the production of 27,275 bbls (3896.4 tonnes) of synthetic crude oil per stream day using Shearer's scheme. Thus, GER of synthetic crude (calorific value = 42,800 MJ(th)/tonne) produced by the COED process with char gasification is given by

$$\mathrm{GER}_{syn} = \frac{1}{3896.4} \times 0.3974 \times 765.85 \times 10^{6}$$

$$= 78{,}100 \mathrm{MJ(th)/tonne}$$

and NER_{syn} = 35,300MJ(th)/tonne

For comparison, a scheme whereby char would not be further treated was also considered. Calculations were based on a study by Eddinger et al(13) which examined the conceptual design of a plant processing Utah A-seam coal. Details are given in Appendix 4.3 and summarised below.

Calorific value of coal(dry) = 31400 MJ(th)/tonne

Moisture content = 6%.

Inputs	Energy Requirement ($\times 10^6$ MJ(th)/stream day)
Calorific value of coal feed(10,039 tonnes as received)	297.38
Coal mining(strip-cf.Appendix 1)	4.37
Plant and capital equipment	0.64
TOTAL	302.39x10^6MJ(th)/stream day

In Appendix 4.2.2. it was calculated that 34.6% of the plant energy requirements should be apportioned to the 41,200 bbls (≡2028.6 tonnes) of synthetic crude oil produced each stream day. Thus, GER of this synthetic crude oil (calorific value 43,000 MJ(th)/tonne) produced from Utah A-seam coal is given by

$$GER_{syn} = \frac{1}{2028.6} \times 0.346 \times 302.39 \times 10^{6} = 51600 MJ(th)/tonne$$

and $NER_{syn} = 8600 MJ(th)/tonne$

At the other extreme, if no value is attributed to product char, from Eddinger's scheme one can calculate the NER of synthetic crude as 74,320MJ(th)/tonne.

2.4. Motor spirit from coal by Fischer-Tropsch Processes.

The energy requirements for converting coal to liquid products using a Fischer-Tropsch process are given in Appendix 5. Data was taken from a conceptual design of Chan's (14) based on the commercial scale plant at Sasolburg, South Africa. The plant would use Western U.S. coal and would primarily produce motor spirit, but a wide range of chemicals would also be produced. Again, electricity, steam, plant fuel are generated on-site from coal. The energy requirements of the plant are summarised below.

Calorific value of coal = 20,600 MJ(th)/tonne(as received)

Inputs	Energy Requirement ($\times 10^{6}$MJ(th)/stream day)	
Calorific value of coal feed (31,135 tonnes as received)	641.00	(96.3%)
Coal mining(strip-cf.Appendix 1)	13.54	(2.0%)
Plant and capital equipment	7.25	(1.1%)
Catalyst and chemicals	3.92	(0.6%)
TOTAL	665.71x10^{6}MJ(th)/stream day	

In Appendix 5.2.2. it was estimated that 46.91% of the plant energy requirements should be apportioned to the production of 2862.08 tonnes/stream day of motor spirit by Chan's scheme. Thus, GER of motor spirit (calorific value of 47000 MJ(th)/tonne) produced by a Fischer-Tropsch reaction is given by

$$GER_{M.S.} = \frac{1}{2862.03} \times 0.4691 \times 665.71 \times 10^6$$

$$= 109{,}100 MJ(th)/tonne$$

and $NER_{M.S.}$ = 62,100MJ(th)/tonne.

2.5. Methanol from coal by Fischer-Tropsch process.

Methanol can be produced from coal by gasification followed by direct methanol synthesis from carbon monoxide and hydrogen. The energy requirements for methanol production using a Fischer-Tropsch process are given in Appendix 6. Figures are again based on a conceptual design by Chan(14) using Sasol technology and Western U.S. coal. Calculated energy requirements are summarised below.

Calorific value of coal = 26,600MJ(th)/tonne (as received)

Inputs	Energy Requirement ($\times 10^6$ MJ(th)/stream day)
Calorific value of coal feed(28,904 tonnes)	594.68
Coal mining (strip-cf.Appendix 1)	12.57
Plant and capital equipment	6.42
Catalyst and chemicals	2.94
TOTAL	616.61 x 10^6 MJ(th)/stream day

In Appendix 6.2. it was estimated that 65.97% of plant energy requirements should be attributed to the production of the 10,120.9 tonnes per stream day of methanol which would be synthesised in the plant. Thus GER of methanol (calorific value of 23,100 MJ(th)/tonne) produced by a Sasol-type process is given by

$$GER_{MeOH} = \frac{1}{10,120.9} \times 0.6597 \times 616.61 \times 10^6$$

$$= 40200 \text{ MJ(th)/tonne}$$

and $NER_{MeOH} =$ 17100 MJ(th)/tonne.

3. SUMMARY AND DISCUSSION OF RESULTS

The results of calculations of the energy requirements of converting coal to liquid fuels are given in Tables 1A and 1B. It is difficult to make generalisations from these results because of the variety of products obtained from different processes according to the particular aims of the development projects. However, it can be seen that for both the H-Coal and CSF processes that coal properties do have a significant effect on energy requirements with western US coals requiring more energy than eastern US coals for conversion to liquids. The reasons for this include the higher moisture content of western US coals (and hence more drying is required and more coal must be mined to give the same dry weight of coal), the method of mining (strip) is more energy intensive than deep mining when replacement and revegetation of overburden is included, and, because western coals contain much higher quantities of oxygen which must be removed by hydrogenation, hydrogen requirements are considerably higher.

It can also be seen in Table 1A that energy requirements vary considerably between processes. If one assumes a total loss of 10% in refining of synthetic crude oil to motor spirit and other products, then the processes examined can be listed in order of increasing energy requirements for motor spirit as follows: COED without char gasification < H-Coal < CSF < COED with char gasification < Fischer-Tropsch. However, in addition to energy requirements, other factors must be considered. So, although the COED process without char gasification has the lowest energy requirements, high sulphur char comprises the main product (~60% by weight) and synthetic crude represents only about 20% by weight of the products. The low NER of this scheme partly reflects the fact that no hydrogen is required in the process, whereas in other processes, hydrogen is a major component in cost and energy calculations (see for example Appendix 2.1.1.1.1). The large quantities of char produced by this process would be of uncertain value in an environmentally conscious society, but when a scheme is considered where char is gasified, NER of synthetic crude is increased by a factor of 3-4 (depending on the efficiency of gasification). It is also interesting to note from Table 1A, that the only process considered where the NER exceeds the calorific value of the fuel product (i.e. more energy is consumed than is produced, reflecting a thermal efficiency $<$ 50%) is the Fischer-Tropsch process for motor spirit and this is the process used at Sasolburg in the only commercially operating plant in the world today. Clearly the advantages of very cheap coal, a known and well-tried technology and the desire for some security of fuel supply are thought to outweigh the inherent inefficiency in coal conversion of the Fischer-Tropsch reaction where a polymer (coal) is broken down to very small units ($CO + H_2$) which are then recombined to give motor spirit and a wide range of chemicals.

In Table 1B it can be seen that in most cases 30-40% of the coal fed to the plant is consumed in the conversion process (except for COED and Fischer-Tropsch processes which are discussed above). In all cases, indirect energy requirements represent less than 10% of NER. As would be expected, mining energy requirements for western strip-mined coal are higher than for eastern deep-mined coal as a fraction of net plant energy requirements.

Comparing the results in Table 1A with results of previous analyses (1, 2, 3) it would seem that, except for the special case of pyrolysis without char gasification, coal liquefaction is a more energy intensive method of producing liquid fuels than processing of all but the leanest grades of tar sands or oil shales. However, coal liquefaction does have the advantage of a widely distributed and very large resource base and does not produce the same quantities of waste material for disposal. If energy savings are to be made in coal conversion, the production and utilisation of hydrogen in liquefaction would seem to be the most likely area to offer the greatest rewards.

TABLE 1A. ENERGY REQUIREMENTS OF PRODUCING LIQUIDS FROM COAL BY VARIOUS PROCESSES.

PROCESS	COAL PROPERTIES			PRIMARY PRODUCT	CALORIFIC VALUE (MJ(th)/tonne)	CALCULATED NER (MJ(th)/tonne)
	TYPE	MINING METHOD	CALORIFIC VALUE (MJ(th)/tonne)			
H-COAL	Illinois No.6	Underground	25,530 (as rec.)	Synthetic Crude	42700	19,360
	Wyoming Powder River	Strip	18,100 (as rec.)	Synthetic Crude	42700	27,300
COED with char gasification	Illinois No.6	Underground	26,040 (as rec.)	Synthetic Crude	42800	35,300
COED without char gasification	Utah A-seam	Strip	29,600 (as rec.)	Synthetic Crude	43000	8,600
COED without char gasification but with no value attributed to char	Utah A-seam	Strip	29,600 (as rec.)	Synthetic Crude	43000	74,320
CSF	Illinois No.6	Underground	23,750 (as rec.)	Motor Spirit	46830	32,380
CSF	Montana	Strip	22,060 (as rec.)	Motor Spirit	46830	34,020
Fischer-Tropsch(Sasol-type)	Western	Strip	20,600 (as rec.)	Motor Spirit	47000	62,100
Fischer-Tropsch(Sasol-type)	Western	Strip	20,600 (as rec.)	Methanol	23100	17,100

TABLE 1B. BREAKDOWN OF ENERGY REQUIREMENTS FOR PROCESSES PRODUCING LIQUIDS FROM COAL.

PROCESS	% COAL FEED USED TO FUEL PLANT*	ENERGY FOR COAL MINING AS % of NER	TOTAL INDIRECT ENERGY AS % OF NER
H-Coal (Eastern coal)	30.0	2.3	7.2
H-Coal (Western coal)	37.4	5.8	9.7
COED with char gasification	42.4	1.2	5.5
COED without char gasification	16.9	8.6	9.9
CSF (Eastern coal)	39.7	1.9	6.3
CSF (Western coal)	40.7	4.4	8.5
Fischer-Tropsch (motor spirit)	58.3	3.4	6.2
Fischer-Tropsch (methanol)	43.4	4.5	7.8

*The amount of coal used as fuel in the plant is calculated as the difference between the calorific value of the coal input and the total calorific value of the products.