COAL-BASED FUEL FOR MARINE PROPULSION

BY

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Introduction

Of the two basic lines of development—coal-based hydrocarbon fuels and direct burning of coal in fluidized beds—the former offers the more immediate prospects. The technology exists but the price of oil would need to double to make it competitive.

During the 1950s and 60s world energy consumption increased by about 5 per cent. per annum. The period of growth in demand was accompanied by an increasing dependence on oil and natural gas, so that about two thirds of the world's energy needs are now satisfied by these fuels. It is expected that before the turn of the century there will be a shortfall in the supply of both: the only alternative fossil fuel of real significance is coal.

Fortunately the U.K.'s coal reserves are large enough to last for about 300 years at the present rate of consumption. The problems with coal are not therefore concerned with the availability of reserves, but are rather those of mining and utilizing the quantities required to supplement the dwindling supplies of oil and natural gas. In particular, it will be essential to increase the efficiency of the direct use of coal and to develop processes to convert coal to clean liquid and gaseous fuels and chemical feedstocks.

The convenience of liquid hydrocarbon fuels and the abundance of coal reserves leads naturally to the idea of synthetic liquids derived from coal as the most desirable transport fuel for the future. The technical feasibility of coal liquefaction is not in doubt: its economic viability will improve as the cost of petroleum products increases.

One result of the oil shortage already manifest is the decline in the quality of marine diesel fuel oil. Improved methods of refining to meet the still growing demand for premium fuels for aircraft and road vehicles leave only residual fuel oils for firing marine diesel engines. The supply will inevitably deteriorate further as the output of crude oil decreases and its price increases.

It is therefore desirable to consider alternative means of ship propulsion based on the abundant reserves of coal. A number of proposals are being studied and this article considers some of the options available for utilizing coal in marine propulsion.

Possible Alternative Strategies

The slow-running diesel engine is currently the most common means of merchant ship propulsion, mainly because of its reliability and high thermal efficiency (40 per cent.) over a wide power turn-down range. These engines can digest a remarkable range of fuels, though the highly-rated engines suitable for naval use are much more selective. It is only in large units ($>$20 MW) that the economics of scale allow the steam turbine to approach a thermal efficiency of 40 per cent. Simple-cycle gas turbine plant is limited to efficiencies of 30–35 per cent.

The characteristics of warships which govern their choice of fuel are different from those of large merchant vessels, but are similar to those of small, versatile merchant ships such as ferries and trawlers[1]. The petroleum product most commonly used by warships is a medium distillate (Dieso), burned in gas turbines, diesel engines and highly-rated steam boilers. A few of the older steam ships use R.F.O.

In considering alternative strategies, it must be borne in mind that internal combustion cycles are much more sensitive to fuel quality than those in which the fuel is burned externally. The options for future development appear to be:

(*a*) to use nuclear propulsion systems. This option is not considered here but it appears that nuclear propulsion may be limited to very large or specialized vessels (e.g. ice-breaker) and some classes of warship;

(*b*) to replace the diesel fuels now derived from crude oil with fuel oils refined from coal;

(*c*) to use methanol derived from coal or from biomass. The cost of producing methanol from coal is likely to be higher in energy terms than that of producing oil from coal;

(*d*) to develop slow-running diesel engines which can operate directly on powdered coal or coal/oil slurries, although at the moment there is no proven means of reducing the wear rate on the moving parts to within tolerable limits. (It is interesting that Dr. Diesel originally intended that his engine should be coal-fired);

(*e*) to raise steam to drive turbines using fluidized bed boilers, which offer great flexibility in the fuel which can be fired. Coal could be used directly or as a slurry when mixed with oil;

(*f*) to develop highly integrated combined gas and steam plant in which an external fluidized bed combustor would serve both the gas and the steam cycles.

The research and development work currently carried out by the fuel industries is of course linked to the overall energy situation. Industrial fluidized bed boilers and furnaces are already being used successfully at a number of land-based trial sites in the U.K.

The coal conversion processes under investigation can produce a wide range of liquid fuels but are aimed chiefly at the high-value fuels for air and land transport. However, these developments are clearly relevant to the options listed above and might be adapted to the future needs of the shipping industry. In 1978. marine requirements accounted for five per cent. of the total U.K. oil consumption.

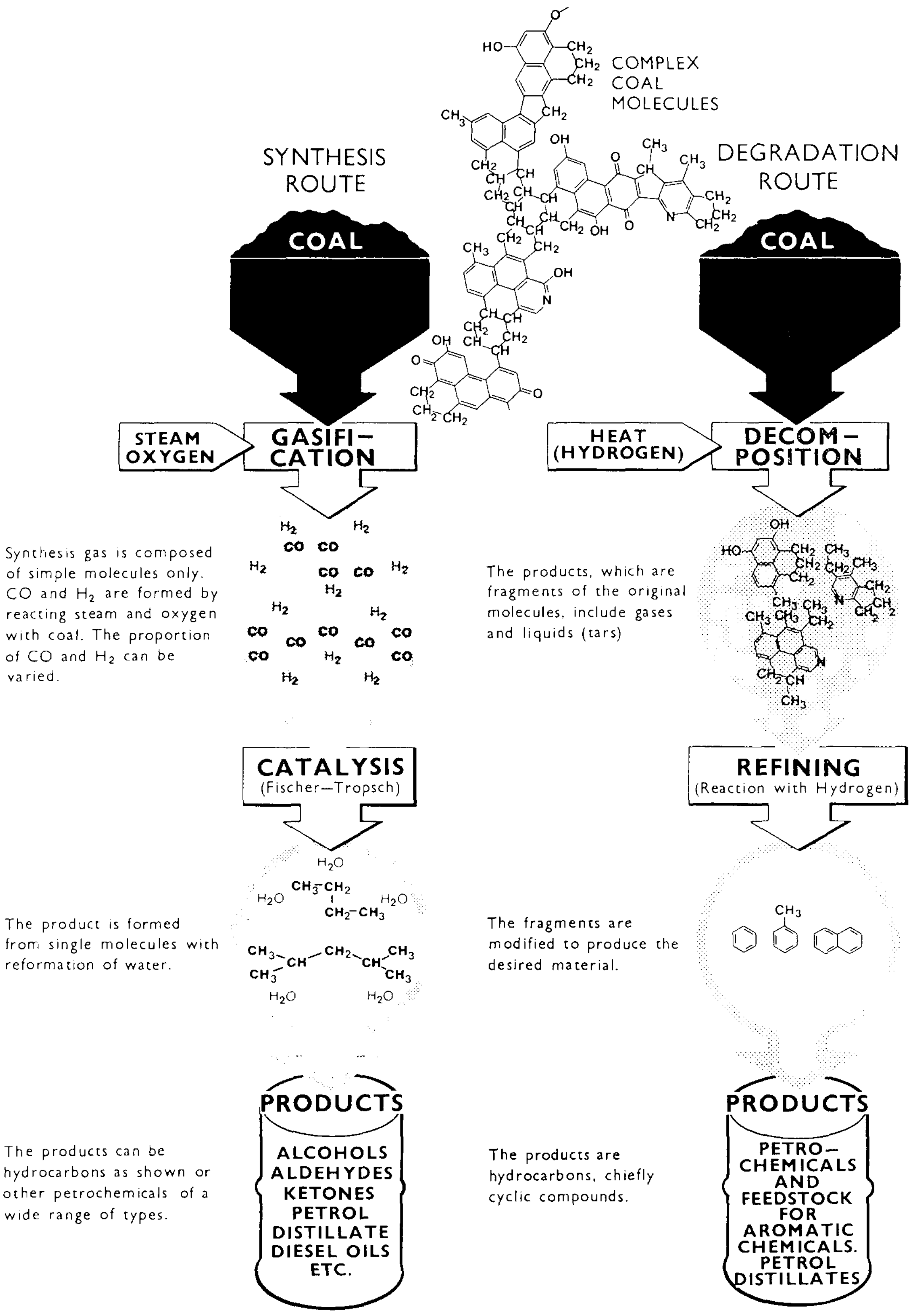
Coal Liquefaction

The principal component of coal is carbon, together with some hydrogen, oxygen, nitrogen and sulphur. It is composed mainly of large aromatic molecules and is fundamentally different from liquid fuels in that it contains a much lower proportion of hydrogen. Basically, therefore, the liquefaction of coal is concerned with increasing the hydrogen content and all conversion processes must involve a hydrogenation stage. This can be done via either a degradation of a synthesis route: the different steps in these processes are shown schematically in FIG. 1.

In degradation processes, the large coal molecules are broken down to give mixtures of hydrogen-rich tars, benzole, and gas, leaving a solid residue. Degradation is commonly achieved by pyrolysis (i.e. the decomposition of coal heated in the absence of oxygen). and can be promoted by the use of solvents and/or catalysts.

On the other hand, in synthesis the large coal molecules are initially broken down into very much simpler substances (see FIG. 1) which are then combined to form liquid fuels.

In practice, hydrogenation can be achieved either in the initial stage, where the coal itself reacts with hydrogen, or in the refining of the crude intermediate



Synthesis gas is composed of simple molecules only. CO and H_2 are formed by reacting steam and oxygen with coal. The proportion of CO and H_2 can be varied.

The products, which are fragments of the original molecules, include gases and liquids (tars)

The product is formed from single molecules with reformation of water.

The fragments are modified to produce the desired material.

The products can be hydrocarbons as shown or other petrochemicals of a wide range of types.

The products are hydrocarbons, chiefly cyclic compounds.

FIG. 1—SYNTHESIS AND DEGRADATION ROUTES. THE DIFFERENCE IS THAT SYNTHESIS LEADS TO HYDROGEN RICH HYDROCARBON PRODUCTS AND DEGRADATION PRODUCES AROMATIC HYDROCARBONS

products. Liquid fuels are already produced from coal in a number of pilot-scale plants, particularly in the U.S.A., and in a large commercial plant in South Africa.

The Fischer-Tropsch Process

The world's largest coal liquefaction plant is operated by the South African Coal, Oil and Gas Corporation at Sasolburg.

Coal is first gasified to produce raw synthesis gas (a mixture of carbon monoxide and hydrogen) which is liquefied using the processes illustrated in FIG. 2. Two process options are available; the Synthol process uses iron entrained in the flow as the catalyst and the Arge process has the catalyst in a fixed bed of iron-oxide-cobalt. The Synthol route yields highly-branched paraffins and is intended mainly for the production of gasoline. Arge conditions produce mainly diesel fuel, gasoline and waxes as well as some alcohols.

The original plant at Sasolburg has been in large-scale production for some years and consumes about 3 M tonnes of coal per year. A larger plant is now under construction at Secunda where it is planned to increase the total coal consumption to 15 M t/year.

South Africa has been forced to develop processes to the commercial scale primarily because of political pressures rather than the economic forces which may soon affect many other nations. However, the SASOL plant clearly demonstrates the technical feasibility of the large-scale production of liquid fuels from coal.

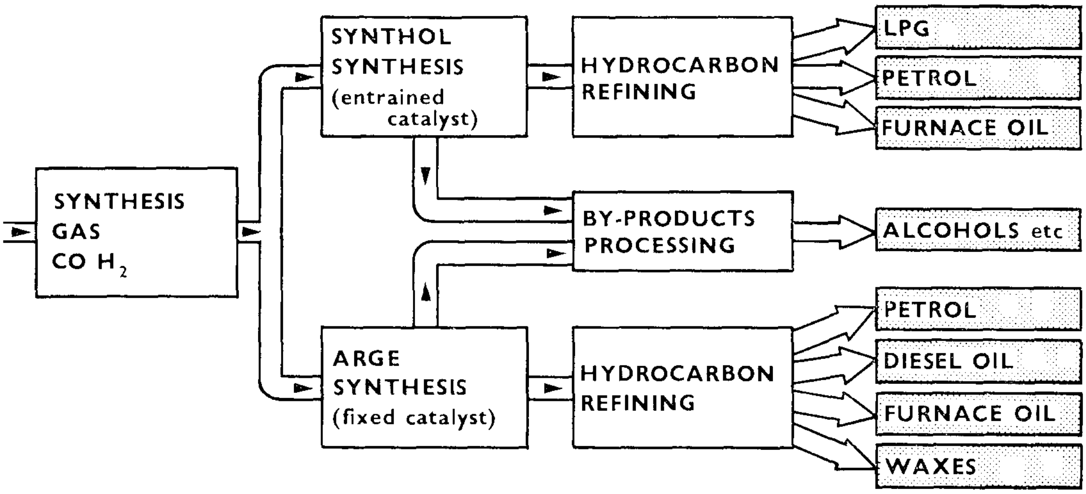


FIG. 2—TWO FISCHER-TROPSCH METHODS FOR CONVERTING GAS INTO LIQUID FUELS. THE ARGE PROCESS LEADS TO PARAFFINIC PRODUCTS AND SYNTHOL LEADS TO LIGHTER PRODUCTS

The Synthoil Process

The principal aim in the development of the Synthoil process has been the introduction of low-sulphur fuel oil through limited hydrogenation. A pilot-scale plant consuming 10 tonnes per day has been operated at the Pittsburgh Research Centre of the U.S. Department of Energy. The stages involved in the conversion are shown in FIG. 3. A fixed-bed catalyst is used and this is protected by maintaining a rapid turbulent flow of coal/solvent slurry. Pyrolysis of the unconverted coal residue gives an increased oil yield.

Exxon have examined the processing of different samples of the liquids produced in the Synthoil plant. Though there may be some doubt about their suitability for use as aviation fuels, they could clearly be used in diesel engines.

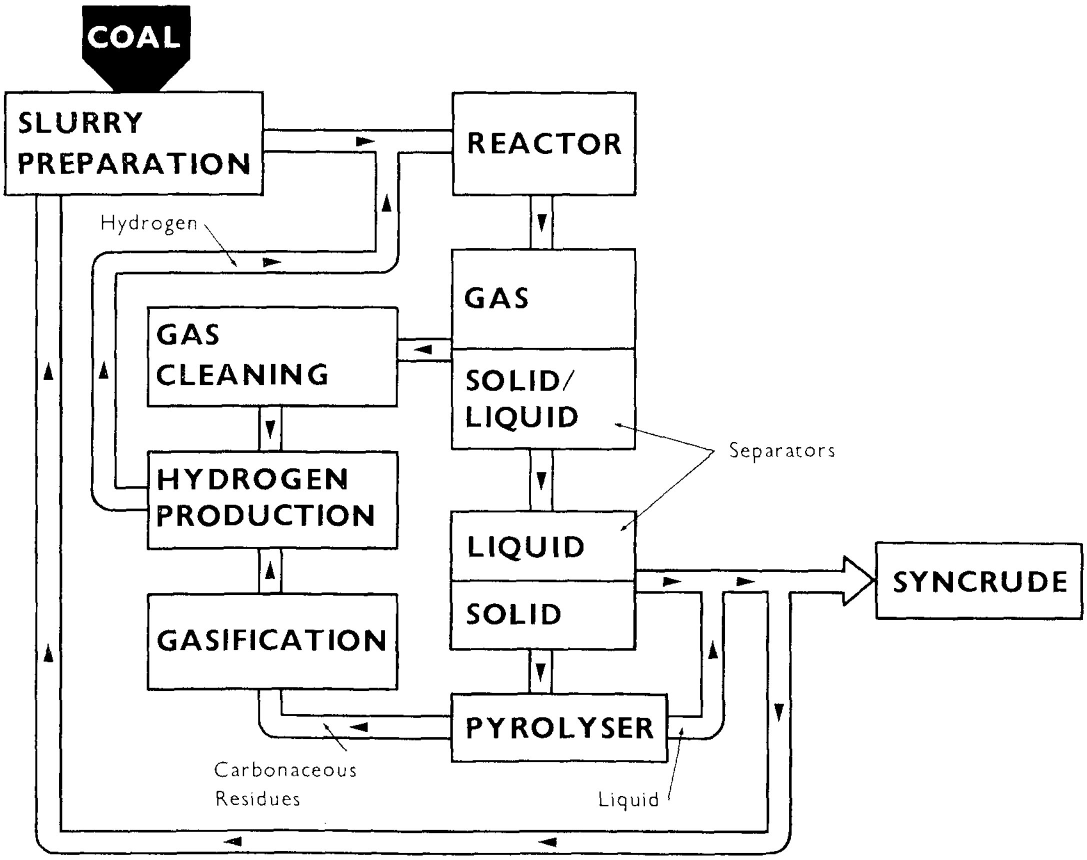


FIG. 3—SCHEMATIC OF THE SYNTHOIL PROCESS

H-coal

Hydrocarbon Research Inc. are developing a liquefaction process known as H-coal. A coal/solvent oil slurry is introduced into a reactor fitted with a mixing paddle. Hydrogen is bubbled through the stirred suspension of coal and catalyst. This system has been found to reduce the deactivation of the catalyst which can result from the deposition of coal residues. A range of liquid fuels, including a low-sulphur oil, is produced in the process. A plant which will consume 600 tonnes of coal per day is being constructed in Kentucky to evaluate this technique on a large scale.

The U.K. Programme

Two approaches to coal liquefaction are being developed by the National Coal Board at the Coal Research Establishment, near Cheltenham and design studies have been initiated for two proposed pilot plants with capacities of about 25 tonnes of coal per day. In essence, both processes involve two stages; the first produces a coal extract free from coal residue and the second subjects the extract to hydrocracking and secondary refining operations. One extraction process employs a supercritical gas as the solvent; the other a heavy, process-derived liquid solvent.

The enhanced solvent power of a gas at and above its critical temperature is exploited in the former process. A slurry of crushed coal in a light aromatic solvent, for instance toluene, is pumped into a vessel maintained at a temperature above the critical temperature of the solvent (FIG. 4). The solvent is transformed smoothly from liquid to the gaseous state.

By suitable combinations of temperature, pressure, solvent, and contact time, 40 per cent. of the coal substance becomes dissolved in the gas phase and the

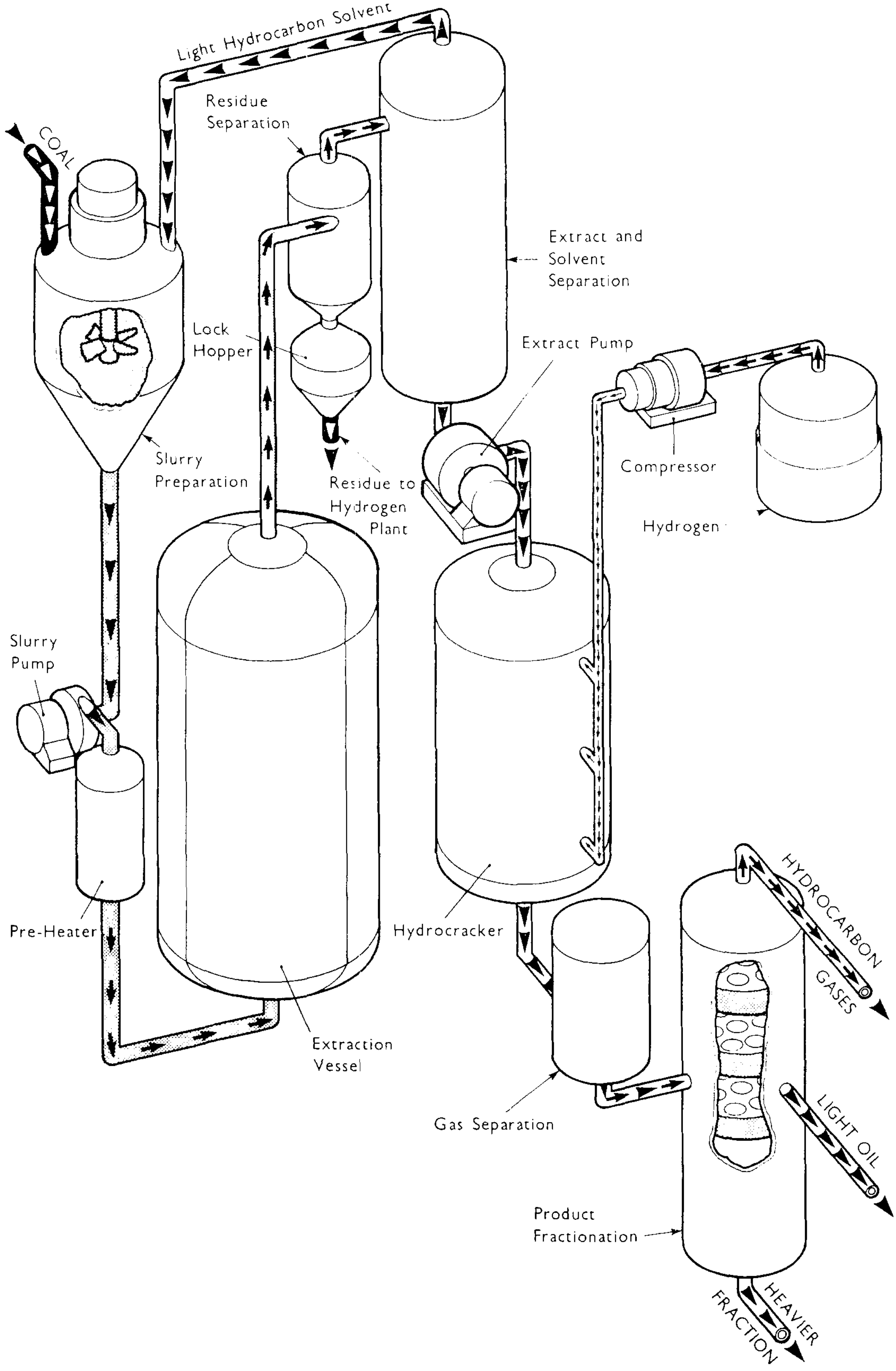


FIG. 4—THE N.C.B. SUPERCRITICAL GAS SOLVENT EXTRACTION PROCESS USES SPECIAL SOLVENT POWERS OF GASES AT PRESSURES AND TEMPERATURES ABOVE THE CRITICAL POINT WHERE THE DISTINCTION BETWEEN GASES AND LIQUIDS DISAPPEARS

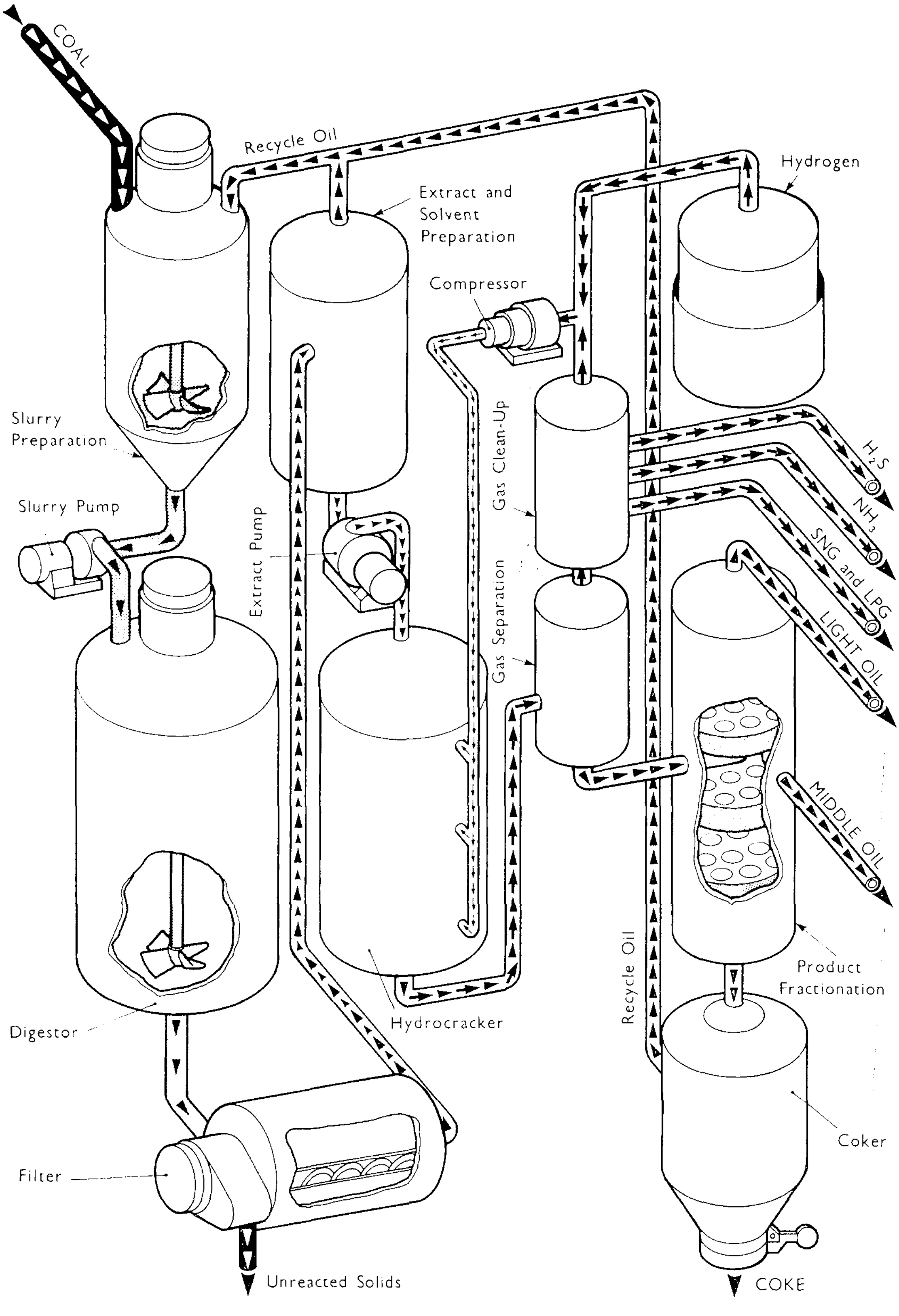


FIG. 5—THE N.C.B. LIQUID SOLVENT EXTRACTION PROCESS. THE SEPARATION OF RESIDUES FROM THE COAL DIGEST IS EFFECTED BY FILTRATION AND THE EXTRACT IS UPGRADED BY HYDROGENATION

solution is readily separated from the coal residue. On transfer to another vessel where the pressure is reduced, the solvent effect is destroyed and the extract separates cleanly from the light solvent.

The extract can be hydrocracked to produce naphtha, middle distillate and a heavier distillate oil (boiling point greater than, say, 300°C) which can be used as a fuel oil or further hydrocracked. The extraction stage has been operated on a scale of 10 kg of coal per hour and the hydrocracking of the extract is on a laboratory scale.

Liquid solvent extraction, illustrated in FIG. 5, involves digestion of crushed coal in recycled process-derived solvent oil at about 420°C when about 85 per cent. of the coal dissolves. The solution is separated from residual material by filtration and hydrocracked. The main liquid products are a naphtha, motor spirit middle distillates (i.e. a potential source of aviation and diesel fuels) and a heavy oil which is recycled to the digestion stage. The extraction equipment has a capacity of 0·75 tonnes of coal per day, while the continuous hydrocracker treats 25 kg/day.

Potential for Marine Fuels

An important advantage of the coal liquefaction option is that it would allow technical continuity in marine propulsion practice. Neither the ship-borne machinery nor the fuel bunkering and feeding systems would need to undergo any revolutionary changes. Coal-derived fuels could be introduced in parallel with petroleum fuels in response to changing economics.

Even at this comparatively early stage in the development of coal liquefaction processes the use of coal-based motor spirit has been successfully demonstrated. In 1977, an AA motor van was run on motor spirit produced at the Coal Research Establishment. Two fractions in the Dieso range (as used by naval vessels) produced at C.R.E. have been analysed and subjected to I.P. and A.S.T.M. tests and the results were encouraging. However, coal-based distillates have low cetane numbers, because of their high aromatic content. The less demanding criteria for fuels used in slow-running marine diesel engines could be met by simplifying the processes to optimize the production of heavy fuel oils. The barriers to the production of marine fuels are therefore economic rather than technical.

Though much work remains to be done on the optimization of the conversion techniques and on proving them on a commercial scale, the success to date justifies the further investment necessary. The market price of crude oil is artificial, in that it is far in excess of the cost of production, and an effective upper limit is that of the alternative—oil derived from coal.

In late 1978 conversion costs were estimated to be about the same as the price of crude oil (i.e. £45 to £63 per tonne), so at that time the difference in the cost of liquid fuel derived from coal and crude oil was roughly the cost of the coal itself. However, the Energy Technology Support Unit predicts that the price of crude oil will double in real terms by the year 2000; recent developments tend to suggest that this price level may be achieved significantly before that date.

Coal in Fluidized Beds

An economic case can be argued for the direct use of coal in large merchant ships, particularly if fluidized beds can be used in either compact packaged boilers to drive steam turbines or, in pressurized form, as fuel gas generators for firing gas turbines.[1, 2]

An important requirement for a marine boiler is the ability to operate satisfactorily with fuels of widely differing quality: there must be little or no limitation because of the grade of coal bunkered, if world-wide operation is to be ensured. Fluidized-bed boilers can be designed which are capable of burning almost any grade of fuel. However, the direct use of coal would necessitate major changes in the bunkering infrastructure both on board and at the dock.

In fluidized-bed combustion, the fuel which can be solid, liquid, or gaseous is injected into a bed of inert particles suspended in an evenly distributed rising air

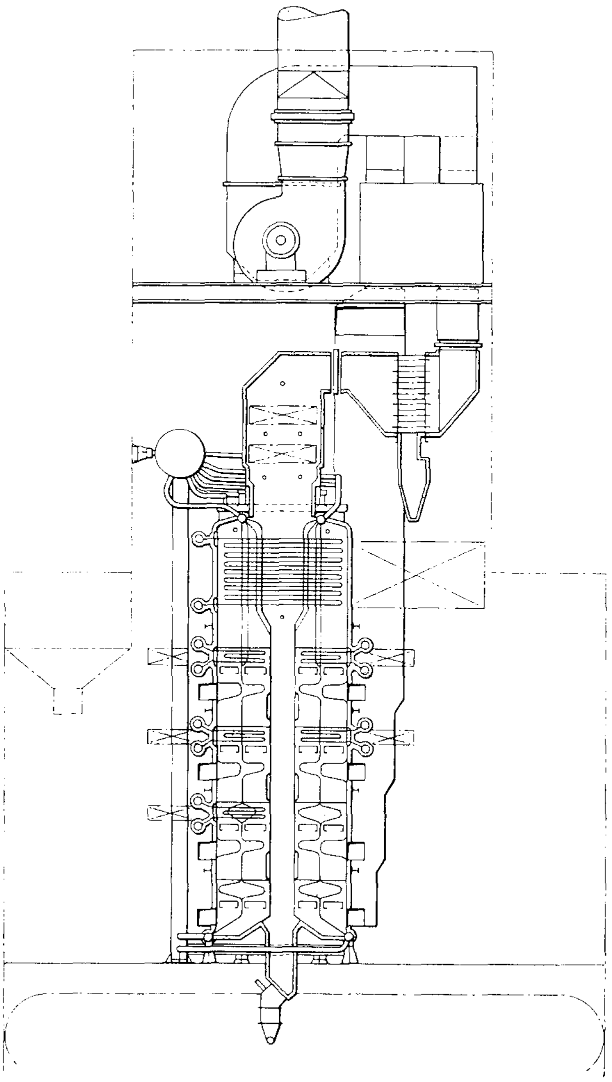


Fig. 6—Babcock & Wilcox proposed coal-burning fluidized-bed boiler

stream. In such a boiler, a much higher heat transfer coefficient is obtained than with conventional boilers, offering the possibility of a reduction in boiler size for a given thermal output. Coal in a size range of, say, 25 mm to zero can be used and the disadvantages associated with the use of pulverized fuel (i.e. the explosion hazard when it is bunkered and the need for expensive and bulky on-board milling equipment) are avoided.

The land-based technology is well advanced. After ten years research and development, fluidized combustion is now at a position where demonstration prototype units have been, or are about to be, built for several applications, ranging from industrial water-tube and shell-type boilers (up to, say, 30 MW output) to furnaces for producing hot gas for industrial and agricultural drying. The experience gained from these units and research and development plants should enable a marine boiler to be designed with a reasonable degree of confidence.

A preliminary proposal for a marine coal-fired fluidized-bed boiler has been made by Babcock and Wilcox.[2] The boiler, shown in Fig. 6, has four tiers of beds stacked vertically in order to minimize floor area. Air is fed to the outer casing of the boiler and, after passing through the fluidized bed, exhausts into a central duct which leads to an economizer, feed heaters, cyclone dust collectors, air heaters, and induced draught fan. Ash from the fluidized beds is bled off and collected below the boiler.

Concern over the suitability of a fluidized-bed boiler for operation in a ship in heavy seas has been countered by the proposal that the beds could be subdivided in order to control the movement of the bed contents in a seaway. Recent advances in materials handling suggest that the problems of moving the fuel from shore-based storage into bunkers in the ship and then to the boilers, and also the problem of ash disposal, will be capable of solution without undue development problems and cost.

Steam plant is relatively easy to convert to alternative fuels, and a fluidized-bed coal-fired boiler with immersed tubes could be comparable in size with a highly-rated oil-fired boiler of the same output.

However, a serious objection to the direct use of coal has been raised by the shipping companies who believe that the loss of ship space for coal storage would be too great. Furthermore, there are greater constraints on the shape of coal storage bunkers than on liquid fuel stores. From this point of view, the use of a fluidized-bed boiler burning a liquid fuel/coal mixture (or slurry) would have the advantage that it would require little more fuel storage space than that for a conventional oil-fired boiler.

Pressurized fluidized beds can be used to raise steam and as gas generators for gas turbines. Highly-integrated gas turbine/steam cycles are being considered in the U.S.A. for use in naval vessels[3]. Such cycles are thermodynamically attractive and could lead to improved efficiency, possibly offsetting the coal storage problem to some extent. Mathematical models have been used to study the control problems which would be encountered if this type of plant were used for marine propulsion.

However, the time scale for such developments would be much longer than for atmospheric fluidized beds and, in addition, combined cycles are likely to be too bulky and complex for mercantile marine use. In the context of naval vessels, it has been argued that compound cycles are likely to result in larger ships with greater manpower requirements[1].

It seems likely that any attempt to operate a modern diesel engine of high specific output on pulverized coal would fail because of rapid wear caused by the presence of ash in the cylinders. It might be possible to reduce the wear problem by the use of special materials and lubricants but as yet such a system has not been successfully demonstrated. To add to the ash and coal storage problems, grinding costs in the preparation of pulverized fuel on board ship are high, making this route unattractive in comparison with other options.

Recently there has been some interest in the use of coal/oil slurries in low-speed marine diesel engines. This kind of fuel could be prepared on shore, and then handled and stored in a conventional manner. It is claimed that such a system could reduce the size of ash particles to a point where wear was tolerable but an economic milling and mixing system has still to be demonstrated.

Conclusions

It is now clear that alternative sources of marine fuels will need to be developed to augment energy supplies as decreasing petroleum resources are directed to premium uses. Fortunately, the U.K. is well-endowed with coal reserves, which make coal a prime contender as a future marine fuel.

Of the possible ways in which coal could be used for marine propulsion, the most promising appears to be after conversion to liquid fuels suitable for use in marine diesel engines. A number of promising process options have already been identified and much of the necessary technology now exists or is under development. Successful trials with coal-derived motor spirit make us hopeful that it will not be difficult to produce diesel fuels of the required quality for marine use, where requirements are less stringent.

Although a case has been argued[2] for the direct use of coal in fluidized-bed boilers, this option would introduce storage problems on board and necessitate changes in the bunkering infra-structure at the dock. It would be feasible to burn a coal/oil slurry in a fluidized-bed boiler without using any more fuel storage space than for a conventional oil-fired boiler but an economic means of producing a stable oil/coal slurry has not yet been demonstrated. Combined cycles are considered too complex for marine use.

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