A New Route to Liquid Fuels from Coal [and Discussion]

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A new route to liquid fuels from coal

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For many decades to come, the transformation of coal to high-grade liquid fuels and chemicals will be a continuing challenge. Chemically speaking, this conversion requires a gradual rearrangement of the carbon and hydrogen atoms and the addition of hydrogen, or the complete transformation of coal into building blocks containing a single carbon atom, and putting them together selectively with hydrogen to form the desired molecules. A catalyst discovered at Mobil will convert methanol, made from such building blocks, into high-octane gasoline. A simple process based on this catalyst produces the final link in a new route from coal to gasoline. A fluidized-bed version of this methanol-to-gasoline process will be tested in a 100 barrels (*ca.* 16 m^3) per day pilot plant in Germany.

A fixed-bed, commercial-size version has been selected by the New Zealand government for the conversion of methanol made from natural gas. This unit will produce 13000 barrels (*ca.* 2100 m^3) of gasoline per day.

If the catalyst is modified, we can command it to construct basic chemical components such as light olefins, including ethylene, or BTX aromatics (benzene, toluene, xylenes) as the major product. The emergence of these new conversion processes exemplifies industrial R. and D., which spans the technology spectrum from basic and exploratory research by a few scientists to process development and commercialization involving industries and governments.

INTRODUCTION

The Mobil Methanol-to-Gasoline (MTG) process efficiently converts crude methanol to high-quality gasoline. When coupled with proven coal-to-methanol technology, MTG offers a new route to premium transportation fuel from coal. The process has undergone significant development since it was first announced (Meisel *et al.* 1976).

MTG has been successfully demonstrated in a fixed-bed and a fluid-bed 4 barrels/day† pilot unit operating under commercial conditions. The product from these units was shown to give better in-vehicle performance than commercial regular unleaded gasoline. Economic estimates based on the pilot plant results show the process to be less expensive than Sasol's Fischer–Tropsch process, the only coal liquefaction process in commercial operation today.

This paper reviews the fundamentals of coal liquefaction in general and of MTG in particular. The current status and opportunities for future development of the process are discussed.

COAL LIQUEFACTION: THREE BASIC TASKS

A principal objective in coal liquefaction is the production of high quality, clean-burning transportation fuel. In the production of gasoline from coal, three major chemical tasks need to be accomplished: generate hydrogen and combine it with the very carbonaceous chargestock;

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† 1 barrel ≈ 0.159 m^3.

Remove sizable amounts of sulphur and other heteroatoms; and Rearrange the coal structure into a mixture of small molecular units that will have the proper combustion characteristics.

For the first task, we need a large amount of hydrogen. A good gasoline fuel has the approximate composition C_8H_{16}: two hydrogen atoms for each carbon atom. On the other hand, coal has a meagre amount of elemental hydrogen: less than one hydrogen atom for each carbon atom.

A typical high-volatile bituminous coal has an elemental distribution of

$$C_{100}H_{82}O_{10}N_2S_{0.6}.$$

This suggests that 82 hydrogen atoms are available for each 100 carbon atoms. However, the actual hydrogen available for constructing fuels is significantly less than this, since the oxygen, nitrogen and sulphur are generally removed in combination with hydrogen. For liquefaction, the atomic distribution might more properly be represented as

$$C_{100}H_{55}+10H_2O+2NH_3+0.6H_2S.$$

If we wish to convert this $C_{100}H_{55}$ material into a conventional gasoline (C_8H_{16}), we will need to add 145 hydrogen atoms for each 100 carbons. The only source available is water, by the reaction

$$C+2H_2O \longrightarrow CO_2+2H_2.$$

To produce those 145 hydrogen atoms, we must sacrifice 36 carbon atoms in our gasifier by the above reaction. In addition, since the whole process of producing gasoline from coal is endothermic, an additional ten carbon atoms must be burned to provide the heat of reaction.

We see then that for an ideal process, 46 carbon atoms must be sacrificed for each 100 carbon atoms in the final liquid. Since practical processes are always inherently less efficient, they consume more than this theoretical minimum. Therefore, a major portion of the coal and of the process investment is dedicated to the production of hydrogen from water and to the generation of heat from combustion of the coal, regardless of the technology employed in meeting the overall objective.

Transforming the structure

The third basic task – transforming the chemical structure of the carbon skeleton – demands extensive and specific changes. For gasoline, each molecule must contain 4–10 carbon atoms in a mixture light enough for proper volatility yet heavy enough to minimize vaporization in the fuel supply system. The mixture should include not too many olefins and nearly no diolefins, as they can cause product instability. And, there must be enough aromatics and branched aliphatics to ensure anti-knock quality.

Direct and indirect liquefaction compared

Two approaches to coal liquefaction are being pursued. The first has often been termed direct liquefaction. The term 'direct' seems to imply a simple, straightforward procedure; one of progressively adding hydrogen to coal until it is liquefied.

As the block diagram in figure 1 indicates, however, some 30–50 % of the coal must actually be gasified (with water and oxygen) to produce synthesis gas. This is a mixture of carbon monoxide and hydrogen, which is then shifted further to create the hydrogen needed for the 'direct' hydroprocessing operation in the remaining part of the scheme. The initial products of direct liquefaction are large polycyclic molecules (Farcasiu *et al.* 1977) which, as figure 2 indicates, must undergo extensive refining to produce gasoline.

Figure 3 shows the historical Fischer–Tropsch route. This route is termed 'indirect' since all the coal is gasified to synthesis gas, which is then processed into a mixture of hydrocarbons and oxy-hydrocarbons. This mixture is then separated into fractions suitable for further processing into motor fuels and other products.

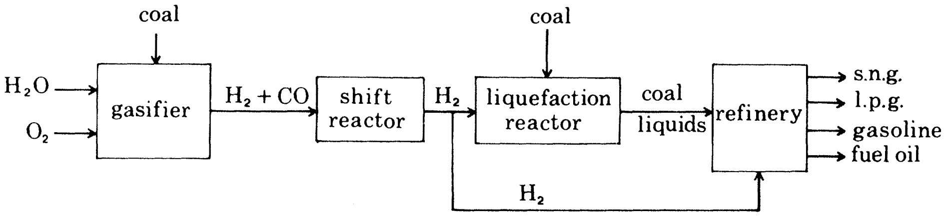
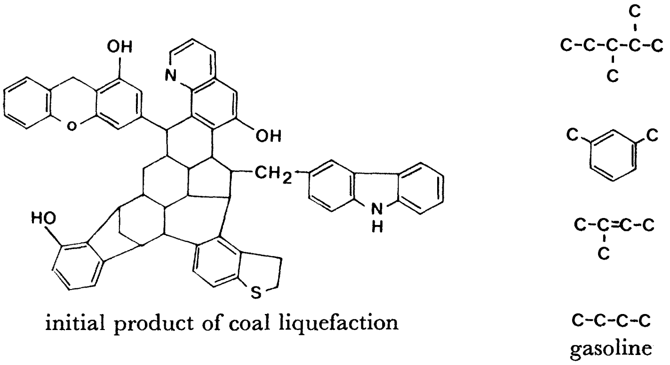


FIGURE 1. Direct liquefaction.



initial product of coal liquefaction

gasoline

FIGURE 2. Representative structures.

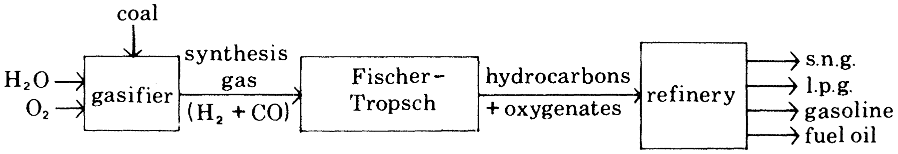


FIGURE 3. Indirect liquefaction by the Fischer–Tropsch process.

We observe that *both* of these routes require an extensive refinery complex to turn the raw liquids produced into finished products.

In the direct method, sulphur is progressively eliminated at every processing step in the sequence, and hydrogen must be used not only in the liquefaction but also in the subsequent refining steps for producing the 'syncrude' liquid.

The Fischer–Tropsch method requires a larger gasification effort. However, it benefits from a single step of sulphur elimination before any liquid product is produced. It also avoids the need to handle heavy, solids-containing residual streams.

THE METHANOL ROUTE

The Mobil Methanol-to-Gasoline (MTG) process provides a new indirect liquefaction route (figure 4) which is significantly different from the Fischer–Tropsch route. The first step in this route is gasification of the coal, a step common to the first two processes as well. The second step is the conversion of synthesis gas to crude methanol, with the use of well known commercial technology (Engineering Foundation Conference 1974).

The third step is the MTG process. This is a relatively simple process using ZSM-5, a very rugged synthetic zeolite catalyst developed by Mobil.

Methanol is converted stoichiometrically into water and hydrocarbons. A high yield of high-octane gasoline is obtained without the need for complex refining of the primary liquefaction products.

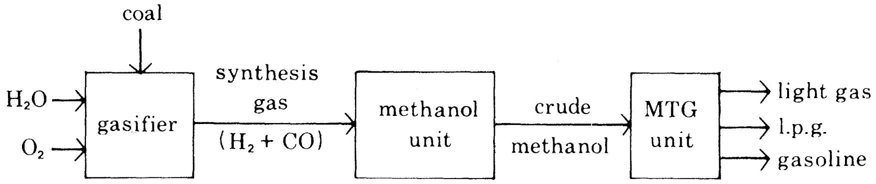


FIGURE 4. The MTG route.

TABLE 1. FIXED-BED MTG YIELDS

(All percentages are by mass.)

temperature		hydrocarbon product (%)	
inlet	360 °C	light gas	1.4
outlet	415 °C	propane	5.5
pressure	2170 kPa	propene	0.2
recycle ratio (mol)	9.0	isobutane	8.6
space velocity (m.h.s.v.)†	2.0	*n*-butane	3.3
		butenes	1.1
yields (% of charge)		$\geqslant C_5$ gasoline	79.9
methanol + ether	0.0		100.0
hydrocarbons	43.4		
water	56.0	gasoline (including alkylate)	85.0
CO, CO_2	0.4	l.p.g.	13.6
coke, other	0.2	fuel gas	1.4
	100.0		100.0

† M.h.s.v. is mass hourly space velocity, the mass of feedstock that comes into contact each hour with a unit mass of catalyst.

TABLE 2. PROPERTIES OF FINISHED GASOLINE

components (% by mass)		research octane	
butanes	2.7	clear	93
alkylate	3.2	leaded, 3 cm^3 TEL/U.S. gal (*ca.* 3.6 l)	100
$\geqslant C_5$ synthesized gasoline	94.1	Reid vapour pressure	62 kPa
	100.0	relative density	0.730
		sulphur	nil
		nitrogen	nil
		corrosion, copper strip	1A
composition (% by volume)			
paraffins	51	A.S.T.M. distillation	
olefins	13	10%	46 °C
naphthenes	8	30%	63 °C
aromatics	28	50%	92 °C
	100	90%	166 °C

Table 1 shows the typical product yields from our fixed-bed MTG pilot unit. Nearly 80% of the raw product is already high-octane gasoline, but the propene, butenes and isobutane can be alkylated by a conventional petroleum process to additional, premium alkylate gasoline components. Thus with alkylation included, methanol, minus its chemical water constituents, is converted to 85 % sulphur-free 93 research octane number gasoline. Most of the remainder of the product is propane and butanes which can be further processed into l.p.g. (liquefied petroleum gas).

Table 2 gives the composition and properties of the finished gasoline. The product meets or exceeds existing gasoline specifications.

Chemistry of MTG conversion

The heart of the MTG process is a novel catalyst, ZSM-5, a highly siliceous zeolite composition (Argauer & Landoldt 1972). It contains no precious metals and is capable of continuous operation for 3–5 weeks. Then it is regenerable, using air for oxidative removal of residual hydrocarbons. The ultimate life of the catalyst is longer than a year, during which time each kilogram of catalyst will have processed more than 13 t of methanol.

The catalytic conversion of methanol relies on the action of protonic (Brønsted) acid sites of the zeolitic silica–alumina structure. As a first reaction step, they induce dehydration of oxygen-containing compounds. Methanol is dehydrated to dimethyl ether and progresses to a reactive hydrocarbon fragment (Chang & Silvestri 1977). Our scientists have examined the nature of the early steps (Chen & Reagan 1979), and others (Derouane *et al.* 1978) have entered into active investigation of the detailed kinetics.

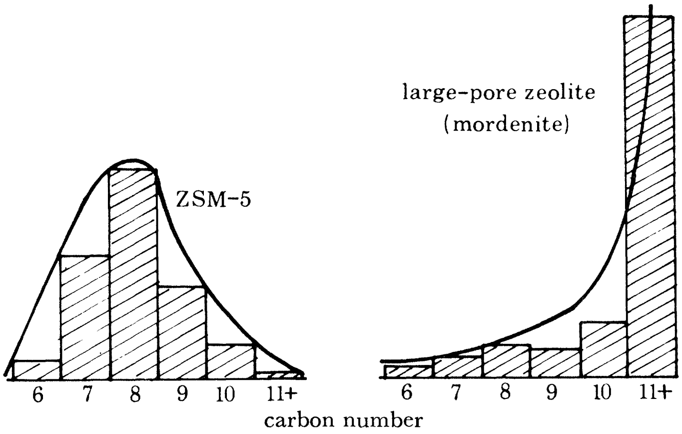


Figure 5. Aromatics distribution from methanol.

Dealuminized mordenite, a larger-pore zeolite, can also catalyse the conversion of methanol to hydrocarbons. However, this conversion gives a significantly different product distribution. Figure 5 compares the aromatic product distribution from ZSM-5 and dealuminized mordenite. With ZSM-5, the principal aromatic product has eight carbon atoms with almost no aromatics having greater than ten carbon atoms. However, with the mordenite catalyst most of the aromatics have eleven or more carbon atoms. The data in figure 5 were taken at 1 h on-stream. At 2 weeks on-stream, the ZSM-5 gives almost the same results. The mordenite catalyst, however, is almost completely inactive after only a few hours on-stream.

On acid catalysts, condensation of unsaturated molecules to polycyclic structures takes place, including formation of 'coke' precursors and ultimately of pore-filling solids ('coke') which deactivate the catalyst. Such condensation is geometrically restricted in ZSM-5.

As a result of these several factors, the new catalyst and its operating conditions will selectively generate hydrocarbons only in the gasoline range, which ends at about C_{10} in carbon number. Longer aliphatic chains, if formed, are aromatized, transalkylated and dealkylated until their molecular dimensions are, again, not greater than those of tetramethylbenzene, and they diffuse out. The catalyst remains active for these reactions because condensation to 'coke' is greatly suppressed.

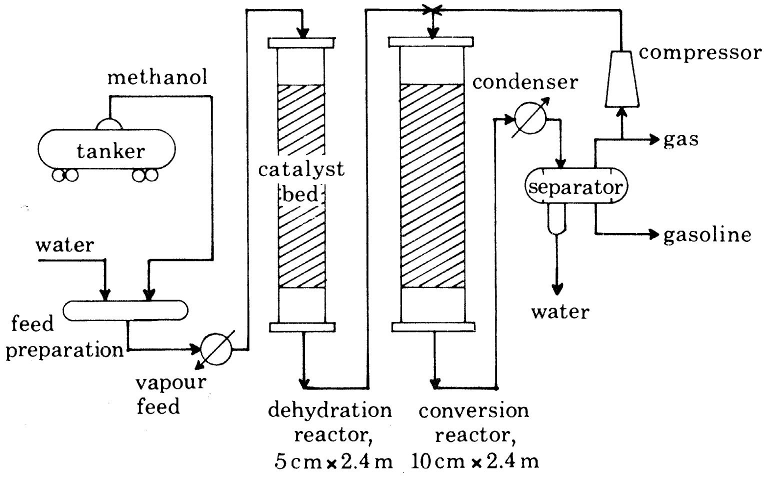


FIGURE 6. The 4 barrels/day fixed-bed pilot plant.

FIXED-BED AND FLUID-BED REACTORS DEVELOPED

The methanol-to-hydrocarbon reaction is highly exothermic with a heat of reaction of 1500–1740 J/g. This results in an adiabatic temperature rise of almost 600 K. Both fixed-bed and fluid-bed reactors were investigated in our pilot units.

Fixed-bed reactor

The fixed-bed scheme was demonstrated in a 4 barrels/day unit with two adiabatic fixed catalyst beds (figure 6). In the first reactor the methanol is dehydrated to an equilibrium mixture of methanol, dimethyl ether and water. About 20 % of the overall reaction heat is liberated in this step. The products from this reactor are diluted with recycle gas and converted to hydrocarbons in the second reactor. The zeolite catalyst is periodically regenerated by burning off the coke. Average cycle time (between regenerations) is about 22 days. In a long-term ageing test the catalyst was regenerated ten times over 8 months; the catalyst was still active. The fixed-bed process can be easily scaled up to commercial size from existing pilot plant results.

MTG selected by New Zealand

The government of New Zealand, a country with an abundance of natural gas but a shortage of crude oil, has decided to use MTG to produce gasoline from its Maui gas. Although in this case the raw material will be natural gas instead of coal, the process steps are the same, after the conversion of the natural gas to synthesis gas. The fixed-bed MTG plant will produce 13 000 barrels of gasoline per day. On the basis of studies conducted by a number of engineering contractors, the Liquid Fuels Trust Board of New Zealand has reported that gasoline made by the Mobil MTG route will cost 30 cents per gallon (*ca.* 6½ cents per litre) less than gasoline made by the Fischer–Tropsch process.

The U.S. Department of Energy has also announced that it will provide M$12–16 for initial design of a full-size coal-to-gasoline plant proposed by W. R. Grace and Company. The plant would produce 50000 barrels of high-octane gasoline per day by the fixed-bed MTG process.

Fluid-bed pilot plant to be built

MTG has also been demonstrated in a 4 barrels/day fluid-bed pilot unit (figure 7). Fluid-bed technology offers several potential advantages. Heat can be removed by exchange coils in the bed and good temperature control can be achieved. Catalyst activity can be maintained at an optimal level by continuously regenerating a slip-stream of catalyst in another small vessel. These advantages can lead to higher gasoline yields.

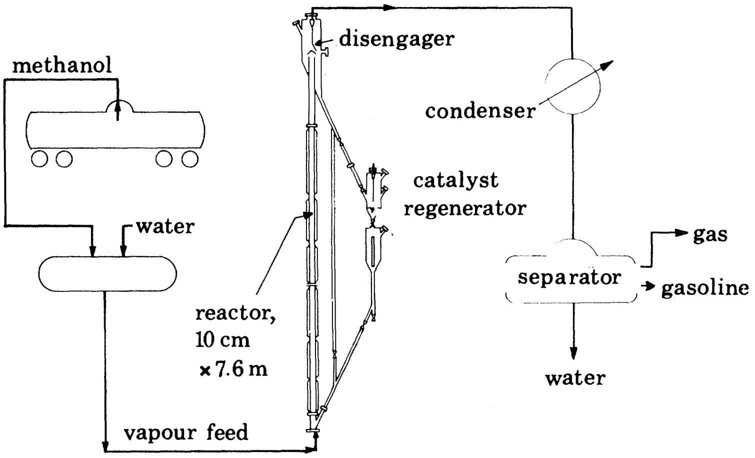


FIGURE 7. The 4 barrels/day fluid-bed pilot plant.

The fluid-bed test culminated in a successful, continuous operation of 109 days. The next step is the scale-up to a larger pilot plant. An agreement has been completed for a $4\frac{1}{2}$ year programme to build and operate a 100 barrels/day fluid-bed demonstration unit in Germany. This will be a joint undertaking by three private companies and two government agencies: Uhde G.m.b.H. of Dortmund, Union Rheinische Braunkohlen Kraftstoff A.G. of Wesseling, Mobil Research and Development Corporation, the Federal Ministry for Research and Development of the Federal Republic of Germany, and the United States Department of Energy (D.o.E.).

FUTURE DEVELOPMENTS

Using efficient gasifiers

The relative investment costs of the MTG route to gasoline from coal are illustrated graphically in figure 8. The processes upstream of the methanol synthesis account for 78 % of the total capital investment. A reduction in the gasification-related costs would offer a significant reduction in overall costs (Kuo & Schreiner 1978).

New gasification techniques that require less oxygen and have higher thermal efficiencies are under development. The slagging moving-bed gasifier is one such scheme (E.P.R.I. 1977). The gas from these new gasifiers typically has a H_2:CO ratio of one or less. However, processes such as Fischer–Tropsch or methanol synthesis require a H_2:CO ratio of about 2. The extensive shifting of this gas to increase the H_2:CO ratio results in decreased efficiency and increased cost.

There are processes that can operate on synthesis gas with H_2:CO ratios around unity. An example is the experimental work carried out by Kölbel in Germany on a slurry-type modification of the Fischer–Tropsch process (Kölbel & Ackerman 1956). This system makes use of internal shift reactions on an iron catalyst and can be run on synthesis gas with H_2:CO ratios of 0.6–1.0.

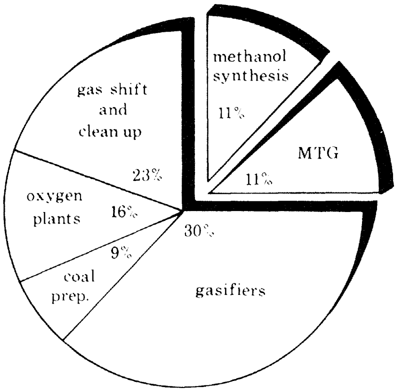


FIGURE 8. Investment distribution.

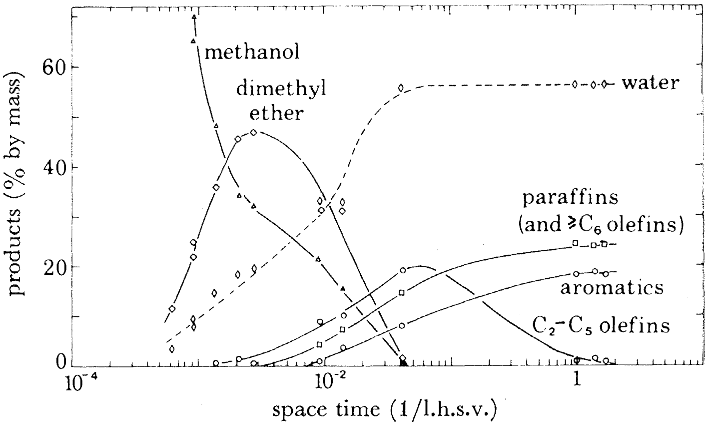


FIGURE 9. Reaction path. L.h.s.v. is liquid hourly space velocity, the volume of feedstock that comes into contact each hour with a unit volume of catalyst.

We have explored the use of a slurry-type Fischer–Tropsch reactor for the synthesis of hydrocarbons and oxygenates. We find that the products of this reaction can be converted over ZSM-5 catalyst to a high yield of high-octane gasoline, which is much like that produced in the MTG process. Although it is in the early stages of development, we feel this route offers the potential for significant cost reductions in the production of gasoline from coal. A recent D.o.E. report provides a favourable assessment of the potential of this advanced indirect liquefaction scheme (Poutsma 1980).

Making chemicals from coal

As the name petrochemicals implies, petroleum is the raw material for many of our industrially important chemicals. The demand for most of these petroleum-derived chemicals is expected to grow rapidly. With the increasing demands on our limited petroleum resources, it seems appropriate to look to coal as a source of chemicals in the future.

The high-octane gasoline produced in the MTG process is, of course, a mixture of chemicals, including several important intermediates. As figure 9 shows, two products of MTG conversion are light olefins and aromatics. By modifying the catalyst and varying the operating conditions, we can maximize light olefins (C_2–C_5) or aromatic products. Mobil investigators have been able to obtain light olefin yields as high as 70% of the hydrocarbon products (Kaeding & Butter 1980). Conditions can be chosen so that ethylene is a major constituent of the olefin fraction and xylenes a major portion of the aromatics.

The path of research and discovery

Since the methanol-to-gasoline technology provides the first new and practical route to gasoline production from coal in more than 40 years, examining its early roots in the research laboratory may be pertinent. Some key achievements are listed in table 3.

A major step dates back to the 1950s when our scientists upset the widely held, traditional belief that solids – particularly acidic oxides – had to be amorphous to offer sufficient surface area per volume element to produce useful catalytic cracking activity. They demonstrated highly active catalysis on crystalline aluminosilicates (Weisz & Frilette 1960) and showed that the active sites are not located on classical surfaces. Rather, they are atomic sites within an exact crystalline solid. The chemical modification of such sites within zeolites of the faujasite structure (X and Y zeolites) led to a new generation of petroleum-cracking catalysts, now used around the world (Plank *et al.* 1964).

Table 3. From basic research to technology

crystalline solids (zeolites) shown to be active catalysts
and
intra-crystalline sites are available for catalysts
↓
molecular shape selectivity is demonstrated
↓
organic cations are used to create new zeolite structures
↓
ZSM-5 is synthesized
↓
monomethyl paraffins shown to enter ZSM-5 in contrast to dimethyl paraffins
↓
olefins converted to aromatics
↓
oxy-compounds shown to be converted to hydrocarbons
↓
methanol converted to typical gasoline
↓
methanol-to-gasoline seen to complete the technology path from coal to gasoline

The concept arose of a precise and controllable catalytic selectivity based on molecular shape and the very exact dimensional restrictions of the structures of crystalline zeolites. Such selectivities were soon demonstrated in selective dehydration of linear alcohols (Weisz & Frilette 1960), the sharply selective combustion (Chen & Weisz 1967) or hydrogenation (Weisz *et al.* 1962) of only linear aliphatics, and the cracking of exclusively normal paraffins from isomeric mixtures (Miale *et al.* 1966).

The choice of dimensions for creating molecular selectivities was greatly limited by the few crystalline zeolite structures available: they were either materials, like X or Y zeolites, with pore openings of about 0.9 nm, too large to offer much selectivity; or they had intracrystalline dimensions of about 0.5 nm. This would admit linear chain structures, but not much else.

New classes of zeolites discussed

One shape-selective process that used a 0.5 nm category catalyst was developed and commercially used (Chen *et al.* 1968). It cracked only *n*-paraffins from all the components of a gasoline, and thereby raised the octane number. However, when our scientists tried to extend this capability to waxes of high molecular mass, they found that the existence of a single methyl group on an otherwise linear wax molecule restricted its conversion over a 0.5 nm zeolite, making the catalyst ineffective for 'dewaxing'. This spawned a growing interest and effort in producing and testing new zeolite structures.

A crucial step toward this goal resulted from the concept of using bulky organic cations in traditionally inorganic recipes, to act as templates during zeolite synthesis (Kerr 1966). This led to the creation and discovery of new classes of zeolites.

It was in an examination of some of these that the new zeolite that we called ZSM-5 (Argauer & Landolt 1972) was identified as one that would allow monomethyl paraffin to penetrate, while not admitting bulkier paraffins (Chen & Garwood 1978). This was a long-awaited event, and the beginning of the now-commercialized catalytic dewaxing technology.

Structure of ZSM-5 determined

In a tedious effort involving complex X-ray crystallography and adsorption measurements, the structure of ZSM-5 was determined (Kokotailo *et al.* 1978). It contains a two-dimensional channel system, the entrance to which is formed by rings that are composed of ten oxygen atoms linked either entirely to silicon atoms or to some combination of silicon atoms and other atoms such as aluminium that can substitute for silicon. The degree of substitution can cover a wide range and for aluminium (expressed in terms of $SiO_2:Al_2O_3$) will vary from about 5 to infinity. This creates the characteristic molecular size and shape-dependent constraints on intramolecular motion.

The new selectivities offered by the ZSM-5 family also were explored. Thus its ability to transform oxy-hydrocarbons, including one-carbon compounds like methanol or formaldehyde into higher hydrocarbons was discovered (Chang & Silvestri 1977); moreover, under proper conditions a synthetic gasoline mix could be produced. Along with this sequence of events, a unique practical application was recognized: this reaction step could be the last and missing link to a full commercializable 'bridge' from coal (or natural gas) to gasoline via synthesis gas and methanol.

CONCLUSION

The MTG process is a key step in a new route to gasoline from coal or natural gas. The heart of the process is a novel new zeolite catalyst, ZSM-5. The product meets or exceeds existing gasoline specifications. The process has been successfully demonstrated in two 4 barrels/day pilot units operating under commercial conditions. An evaluation based on pilot plant results shows this process to be more economical than the Sasol process presently used in South Africa.

The fixed-bed version of the MTG process is ready for commercialization. It has been selected by the New Zealand government as a key unit in a complex that will process natural gas into 13000 barrels of gasoline per day.

The fluid-bed version of the process, which has potential advantages over the fixed-bed version, is scheduled for an additional scale-up before commercialization. A 100 barrels/day pilot plant will be built in Germany as a joint project among two German companies, Mobil, and the German and U.S. governments.

Current research efforts are being directed toward process developments that could use new gasification techniques that have the potential for significant cost improvements. MTG may also provide a new route to chemicals – olefins and aromatics – from coal. Process and catalyst modifications can yield as much as 70 % light olefin products from methanol.

The United States and other countries are looking for new sources for transportation fuels and petrochemicals in the future. We expect the MTG process to help fill this need.

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Discussion

G. D. SHORT (*I.C.I. Agricultural Division, Billingham, U.K.*). Are the reaction conditions for gasoline production from methanol over ZSM-5 limited in any way by formation of durene (1,2,4,5-tetramethylbenzene)? If they are, what would be the optimum temperature and pressure of the MTG process if durene could be disregarded?

S. L. MEISEL. Since the formation of durene is a strong function of such operating conditions as temperature and pressure, disregarding the durene yield would provide some added design and operating flexibility. The durene content of the gasoline could then be reduced by removing the fractions of higher boiling point. Durene yield could also be relaxed if the gasoline were blended with conventional gasoline. Since MTG gasoline is 93 r.o.n. clear, it is likely to be blended in many instances.

To date, however, we have considered only a 'stand alone' product with a durene content of below 4 % by mass. This will avoid any possible cold-startup problems without blending or durene removal.

A. Stratton (*Imperial Chemical Industries Ltd, Millbank, London, U.K.*). Questions were raised after Dr Hoogendoorn's paper on the relative economics of the Sasol Fischer–Tropsch synthesis and the Mobil process. Figure 10 (from Stratton 1980) shows a comparison between the two processes for coal and gas feedstock based on published data (Hoogendoorn 1977; N.Z.L.F.T.B. 1979; Schreiner 1978). A simple standard costing based on 10 % d.c.f. return in constant pounds sterling (1979 value) has been used. Some assumptions have been made on interpreting Hoogendoorn (1977), the capital cost of the mine being subtracted and an equivalent pit-head price for South African coal being substituted; no allowance has been made for lower South African labour rates.

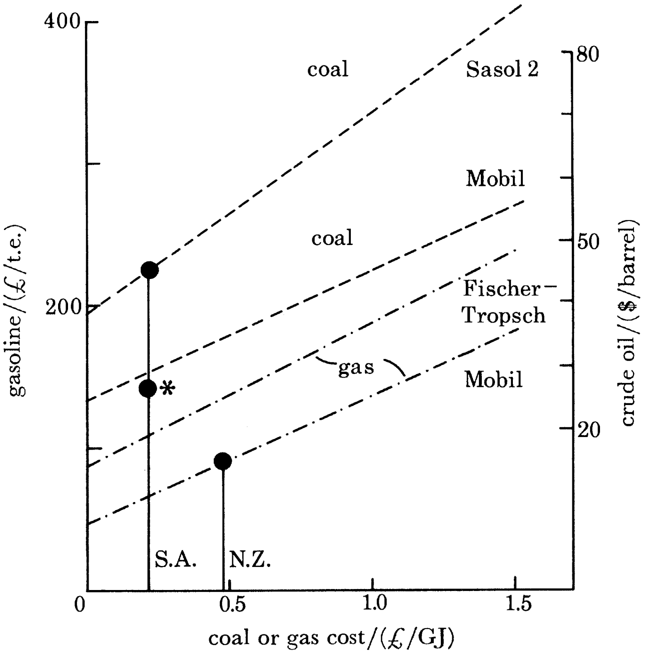

Figure 10. Liquid fuels from coal and gas via gasification, with 10 % d.c.f. The point asterisked is with 5 % d.c.f. and tax rebate.

Allowance has been made for the different product values from Fischer–Tropsch relative to gasoline. The cost of gasoline by Fischer–Tropsch from Schreiner (1978) (not shown) agrees closely with the Sasol line on the figure. An independent costing of methanol from natural gas converted to gasoline at the conversion cost of Schreiner (1978) (not shown) agrees closely with the natural gas – Mobil gasoline line on the figure, from N.Z.L.F.T.B. (1979).

While greater confidence can be placed in the relative costs than the absolute, it is clear that both Sasol 2 and the Mobil process are economic at coal prices obtaining in South Africa (also Australia and U.S.A.) and that when cheap gas is available, as in New Zealand, a substantial margin exists above the standard 10 % d.c.f. used in the costing.

It is also evident that where gasoline is the desired product the Mobil process has the advantage.

References

Hoogendoorn, J. I. 1977 Presented at American Gas Association Ninth Synthesis Pipeline Gas Symposium, Chicago, November.

N.Z.L.F.T.B. 1979 *New Zealand Liquid Fuels Trust Board Report* no. LF 5502.

Schreiner, M. 1978 Mobil Research and Development Corporate New Jersey, Report to the U.S. Department of Energy no. NTIS FE-2447-13.

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S. L. MEISEL. I am pleased to have Dr Stratton's independent appraisal of relative costs. I should like only to emphasize his statement that 'greater confidence can be placed in the relative costs than the absolute'.