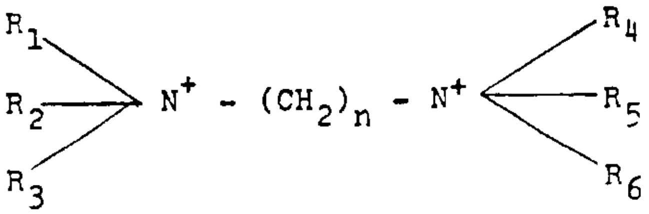
4. ICI Zeolites

a) Zeolite EU-1

Zeolite EU-1 is a recent development of Imperial Chemical Industries described in the European patent application 0042226.[133] EU-1 has a molar composition expressed by 0.5 to 1.5 $R_2O:Y_2O_3$: at least 10 XO_2: 0 to 100 H_2O. Where R is a monovalent cation, X is silicon and/or germanium, and Y is 1 or more of the elements; aluminum, iron, gallium or boron. The x-ray powder diffraction data for EU-1 as synthesized is shown in Table 13 and that for EU-1 after calcination is shown in Table 14.[133] Zeolite EU-1 is thought to be similar to the ZSM-23 family of zeolites described in U.S. patent 4076842.[133] The sorption capacity of EU-1 for molecules of various sizes is shown in Table 15.[133] The pore system of EU-1 is thought to have 6 angstrom diameter pores which are hydrophobic in nature. The rapid sorption of paraxylene and the slow sorption of metaxylene indicates that this zeolite might be useful in separating the xylene isomers. EU-1 is synthesized using at least one alkalated derivative of polymethylene, α ω diamine having the formula:



where n is the range from 3 to 12 and R_1 to R_6 may be the same or different can be alkyl or hydroxyalkyl groups

d (A)	I/Io
11.03	Very Strong
10.10	Strong
9.72	Weak
6.84	Weak
5.86	Very Weak
4.66	Very Strong
4.31	Very Strong
4.00	Very Strong
3.82	Strong
3.71	Strong
3.44	Medium
3.38	Medium
3.26	Strong
3.16	Very Weak
3.11	Very Weak
2.96	Very Weak
2.71	Very Weak
2.55	Weak
2.48	Very Weak
2.42	Very Weak
2.33	Very Weak
2.30	Very Weak
2.13	Very Weak

Table 13. Zeolite EU-1 as Freshly Prepared.[133]

d (A)	I/Io
11.11	Very strong
10.03	Very strong
9.78	Weak
7.62	Weak
6.84	Medium
6.21	Very weak
5.73	Weak
4.87	Very weak
4.60	Very strong
4.30	Very strong
3.97	Very strong
3.77	Strong
3.71	Weak
3.63	Very weak
3.42	Medium
3.33	Medium
3.27	Strong
3.23	Medium
3.15	Weak
3.07	Weak
2.93	Weak
2.69	Weak
2.63	Very weak
2.57	Very weak
2.51	Weak
2.45	Very weak
2.41	Very weak
2.32	Very weak
2.29	Very weak
2.11	Very weak

Table 14. Zeolite EU-1 in Calcined Na-H Form.[133]

Adsorbate	Kinetic* Diameter oA	Pressure mm Hg	Time Hours	Wt sorbed g/100 g	Voidage available cc/100 g
Water	2.7	4.5	2	6.9	6.9
	2.7	4.5	16	11.0	11.0
n-hexane	4.3	45.8	2	9.5	14.[illegible]
p-xylene	5.8	1.6	2	10.5	12.1
	5.8	1.6	18.5	10.6	12.2
m-xylene	5.9	1.6	2	2.3	2.6
			18.5	5.5	6.3
cyclohexane	6.0	2.7	2	1.1	1.4
			18.5	1.1	1.4

Table 15. The Sorption Capacity of EU-1 For Molecules of Various Sizes.[133]

containing from 1 to 8 carbon atoms and up to 5 of these groups R_1 to R_6 can be hydrogen atoms. Zeolite EU-1 is synthesized under autogenous pressure at a temperature from 85 to 250 C and the synthesis time can range from 1 hour to many months depending on reactant composition. Following synthesis, EU-1 is washed, calcined, and ion-exchanged to its hydrogen form, followed by ion-exchange or impregnation with cations or oxides of the following metals, Cu, Ag, Mg, Ca, Sr, Zn, Cd, B, Ar, Sn, Pb, V, P, Sb, Cr, Mo, W, M, N, Re, Fe, CO, Ni or the noble metals. Zeolite EU-1 is thought to be applicable for catalysis in the following processes. Catalytic cracking, hydrodesulfurization, hydrodenitirfication, catalytic dewaxing, alkylation of alkanes or aromatics, dealkylation, disproportionation, isomerization of alkanes and alkyl benzenes, dehydration reactions, oxidation, and polymerization.[134]

Zeolite EU-1 has been found to be especially useful for catalytic xylene isomerization. The batch composition described by example 1 of this patent application is the following:

$$7.5\ Na_2O \cdot 7.5\ H_xBr_2 \cdot 1\ Al_2O_3 \cdot 43\ SiO_2 \cdot 2220\ H_2O$$

Where H_xBr_2 is hexamethonium bromide $(CH_4)_3$ n $(CH_2)_6$ n $(CH_4)_3^{2+}$ (Br^-). The range of batch compositions from which EU-1 can be synthesized is described on page 8 of the patent application.

b) Zeolite EU-2

Zeolite EU-2 is described in the U.K. patent application #GB207709A which was submitted by Imperial Chemical Industries, Ltd. The molar composition of EU-2 is expressed by the formula:

$$0.5\text{-}1.5\ R_2O:Y_2O_4:\text{ at least } 70\ XO_2:\ 0\text{-}100\ H_2O.$$

Wherein R is a monovalent cation, X is silicon or germanium and Y is 1 or more of the elements; aluminum, iron, gallium or boron.

The x-ray diffraction lines evidenced in the EU-2 family of zeolites is shown in Table 16.[135] The typical sorption results which demonstrate the characteristic molecular sieve properties of this zeolite are shown in Table 17.[135] EU-2 is extremely hydrophobic and exhibits a pore diameter near 6 angstroms which is characteristic of a 10-ring window. The organic cations used in its synthesis are the same used in the synthesis of zeolite EU-1. The range of batch compositions which can be used in the synthesis of EU-2 are expressed by the following mole ratios:

XO_2/Y_2O_3 at least 70, preferably at least 150, OH^-/XO_2 0.1 to 6.0, preferably 0.1 to 1.0, $(M^+ + Q)/Y_2\ O_3$ 0.5 to 100, $Q/(M^+ + Q)$ 0.1 to 1.0, H_2O/XO_2 1 to 100.

Q denotes the organic salt having a cationic form Q^{2+}. M^+ is a univalent metal cation and X and Y were previously defined. Zeolite EU-2 is thought to possess catalytic behavior which make it applicable to the following processes: hydrodesulfurization, hydrodenitrification, catalytic dewaxing, selective alkylation, dehydration, and oxidation reactions. The dehydration of methanol on EU-2 has been found to yield a wide range of aromatic and aliphatic hydrocarbons.[136] The product distribution obtained from the dehydration of methanol described in Example 7 of this patent, is shown in Tables 17 and 18.[137]

Zeolite EU-2	
Interplanar Spacings d(A)	Relative Intensity 100 %
11 74	17
10 13	14
6.33	7
5.85	7
4 33	5
4.18	86
3.89	100
3 69	7
3 27	7
3 08	5
2 85	18
2 09	5

Table 16.

X-ray Diffraction Lines in EU-2 Family of Zeolites.[135]

Table 17.

Typical Sorption Results which Demonstrate characteristic Molecular Sieve Properties of EU-2.[135]

C_1-C_4 hydrocarbon analysis % v/v	
Methane	1 7
Ethane	0 5
Ethene	8 8
Propane	7 5
Propene	17 8
2-methyl propane	30 4
Butane	0 7
Butene-1	1 9
2-methyl propene	0
trans-butene-2	2 9
cis-butene-2	27 8

	Aromatics analysis (% v/v)			
	A	B	C	D
Benzene	7.5	7 0	6 8	4 6
Toluene	26 8	26 3	27 9	28 9
Ethylbenzene + m,p-xylene	35.1	34 7	32 7	35.3
o-xylene	6 7	6 9	8 1	6 5
C_9 aromatics	9 6	9 8	10 5	10.8
C_{10+} aromatics	14 0	15 3	13 9	13 8

Table 18.

Product Distribution Obtained From the Dehydration of Methanol.[137]

C. The Synthesis of Gasoline

1. Fischer-Tropsch Synthesis

Fischer-Tropsch synthesis which was named after two German scientists, Franz Fischer and Hanz Tropsch, who first investigated the reaction, is a process by which hydrocarbons are polymerized during the catalytic hydrogenation of carbon monoxide. The general reactions involved in the hydrogenation of carbon monoxide are given by Shah et al.[138]

1) $(2n+1)\ H_2+nCO = C_n\ H_{2n+2} + nH_2O$
2) $(n+1)\ H_2+2nCO = Cn\ H_{2n+2} + nCO_2$
3) $2nH_2+nCO = Cn\ H_{2n} + nH_2O$
4) $nH_2 + 2nCO = C_n\ H_{2n} + nCO_2$
5) $2nH_2 + nCO = Cn\ H_{2n+1}\ OH + (n-1)\ H_2O$
6) $(n+1)\ H_2+(2n-1)\ CO = Cn\ H_{2n+1}\ OH + (n-1)\ CO_2$. 138

Although other reactions had been previously observed in the catalytic regimen for carbon monoxide hydrogenation, such as methanol synthesis:

$$CO + 2H_2 \rightarrow CH_3OH$$

and the methanation reaction:

$$CO + 3H_2 \longrightarrow CH_4 + H_2O$$

It was Fischer and Tropsch who first observed measurable quantities of higher hydrocarbons when in 1923 they passed hydrogen and carbon monoxide over alkyzed iron filings. The synthesis reaction which can be expressed as:

$$CO \xrightarrow{H_2} C_aH_b + C_cH_d(OH)_e + C_fH_gCHO + C_nH_i\ COOH$$

The virtually unlimited array of saturated hydrocarbons, olefins, aromatic hydrocarbons, and oxygenated derivatives are formed through a myriad of competing reactions which are collectively called Fischer-Tropsch synthesis. Five processes are involved in Fischer-Tropsch synthesis which were reviewed by Muetterties and Stein.[139] They include:

1) Hydrogen atom transfer from metal surface atoms or from surface intermediates to carbon whereby a carbon hydrogen bond is formed.
2) Net hydrogen atom transfer to oxygen resulting in oxygen - hydrogen bond formation.
3) Carbon - carbon bond formation.
4) Carbon - oxygen bond scission.
5) Carbon - oxygen bond formation.[139]

Only steps 1 and 2 are operative in methanol synthesis and steps 1, 2, and 4 in methanation. The chemistry involved in each of these five steps has been extensively reviewed.[139] Indirect coal liquefaction by Fischer-Tropsch synthesis involves two steps. In the first coal is reacted with water to produce synthesis of gas having a H_2/CO ratio of 2 or less:

$$3C+4H_2O(g) \rightleftharpoons 2CO+4H_2+CO_2$$

$$\Delta H^0_{1500} = +374.9kJ;\ K_{1500} = 7.7 \times 10^7$$

With the rejection of steam and with gases recycled to extinction, the synthesis gas is reacted over a potassium promoted iron catalyst:

$$CO+2H_2 \longrightarrow (-CH_2-)(g) + H_2O\ (g)$$

$$\Delta H^0_{700} = -149.7kJ$$

The Schulz-Flory distribution function has been used to model the formation of hydrocarbons via Fischer-Tropsch synthesis. Three assumptions are involved in the derivation of the Schulz-Flory distribution function. First, that Fischer-Tropsch synthesis involves a polymerization process wherein all monomer units are equivalent in weight. Second, that hydrocarbon chains grow by the successive addition of monomer units each containing a single carbon atom and third, that the polymerization process takes place on the catalyst surface and that all hydrocarbon species and intermediates adsorbed on this surface have an equal probability of adding a monomer unit to form the next higher monolog in the hydrocarbon series. If we defined P as the probability that a monomer unit has polymerized then the probability of forming a surface hydrocarbon of carbon number n can be obtained. The probability of forming a surface species wherein one monomer unit has polymerized with a surface carbon (carbitic carbon) is defined as P. The probability of forming a surface species wherein two monomer units have polymerized with the surface carbon is therefore, P2. The probability of forming a surface species containing n carbon atoms is therefore, P^{n-1}. The probability that a surface species will terminate (desorb from the surface) before adding one more monomer unit is given by 1-P. For an oligomer C_n to be synthesized it must first polymerize and then terminate. The overall probability for the formation of an oligomer with carbon number is, therefore,

$$M_n = P^{n-1} (1-P).$$

Since the sum of the fractions of product at each carbon number must total 1, M_n is equivalent to the mole fraction of product having carbon number n. Since by definition, the average degree of polymerization is 1/(1-P) and by assumption one, all monomer units are of equivalent weight, we can convert the mole fraction equation to a weight fraction equation by multiplying by n and dividing by the average degree of polymerization $1/(1-P)$. The resulting weight fraction equation is:

$$W_n = (1-P)^2 \cdot P^{n-1}$$

This distribution function can be linearized by taking the logarithm of both sides:

$$\log W_{n/n} = n \log P + \log((1-P)^2/P).$$[140]

Plotting reaction data with $\log W_{n/n}$ on the ordinate against carbon number n on the abscissa, the polymerization probability can be determined from the intercept:

$\log ((1-P)^2/P$ or from the slope $\log P$.

This Schulz-Flory distribution function predicts with considerable accuracy the product distribution in Fischer-Tropsch synthesis over a wide variety of reaction conditions and a wide variety of Fischer Tropsch catalysts. The inherent non-selective nature of Fischer-Tropsch synthesis causes economic difficulties which have prevented the utilization of this process in all free economies. The only plants in operation today utilizing the Fischer-Tropsch method for the indirect liquefaction of coal are the Sasol plants in South Africa. Inspection of the distribution function shows the only hydrocarbon which can be produced with this technology in 100% yield is methane. With the appropriate selection of operating conditions and catalyst type, the polymerization probability can approach 0 and the reaction selectivity driven toward methane. The most useful and valuable product of the indirect liquefaction of coal is gasoline range hydrocarbons which have carbon numbers ranging from C_6 to C_{12}. The Schulz Flory polymerization mechanism in Fischer Tropsch synthesis is capable of producing only a fraction of the product yield in this hydrocarbon range. The product fraction outside of this range must undergo secondary treatments such as cracking or reforming to generate a useful product. It is the cost of these secondary treatments which prohibit utilization of this technology. Recently, technologies have emerged which provide substantially improved control of the product distribution and product quality. The following sections will review these emerging technologies.

2. Methanol to Gasoline

Mobil's methanol to gasoline process represents the first major breakthrough in indirect coal liquefaction technology since the pioneering work by German scientists prior to World War II. Mobil Research and Development Corporation found that methanol could be converted to gasoline of high octane number over a shape selective zeolite catalyst, ZSM-5, in excellent yields with long catalyst life. The process of indirect coal liquefaction, involving the Mobil M conversion is shown in Figure 30.[141] The three steps involved in this conversion were reviwed by Probstein and Hicks.[141] First, the coal is gasified into 2:1 synthesis gas:

$$3C + 4H_2O(g) \rightleftharpoons 2CO_2 + 4H_2 + CO_2$$
$$\Delta H^0_{1500} = +374.9\text{kJ};\ K_{1500} = 7.7 \times 10^7$$

Methanol is synthesized from the synthesis gas over a zinc oxide catalyst:

$$CO + 2H_2 \rightleftharpoons CH_3OH$$
$$\Delta H^0_{700} = -101.9\text{kJ}$$

In the final step methanol is converted to high octane gasoline over zeolite ZSM-5 with the rejection of steam.

$$CH_3OH(g) \longrightarrow (-CH_2-)(g) + H_2O(g)$$
$$\Delta H^0_{700} = -47.3\text{kJ}$$

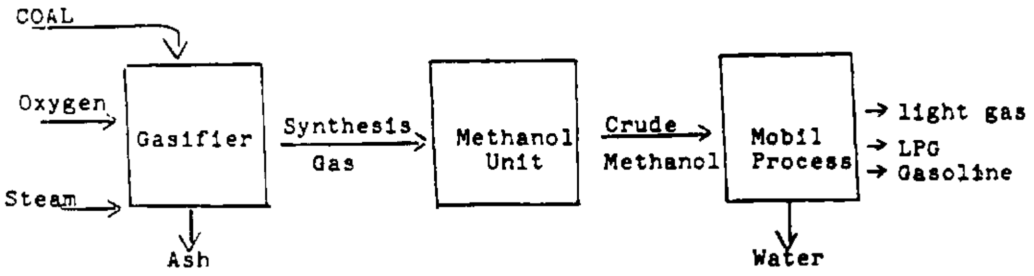


Figure 30. The Process of Indirect Coal Liquefaction Involving Mobil M Conversion.[141]

The ZSM-5 catalyst dehydrates the methanol and rearranges the remaining hydrogen and carbon atoms into a concentrated high energy fuel known as gasoline. Although, methanol itself has been used in motor fuels both as an octane booster to conventional gasoline and in its pure form, each gallon of gasoline has twice the energy content of a gallon of methanol. The toxicity and corrosive properties of methanol combined with its low energy to weight ratio make its conversion to gasoline economically attractive. For methanol to be used instead of gasoline the transportation capacity, storage and distribution capacity for motor fuels would have to double. In addition to the cost incurred in doubling the fuel capacity of automotive fuel tanks, an efficiency loss would be introduced because the water weight contained in methanol would increase the inertia of the motor vehicles. The first public disclosure of the Mobil M technology was presented in the article, "Gasoline from Methanol in One Step" in February, 1976.[142]

An excellent review manuscript was published by Clarence D. Chang in 1983.[143] Similar reactions of methanol over other highly siliceous zeolites have been reported.[144]

A reaction path diagram for the conversion of methanol to hydrocarbons is shown in Figure 31.

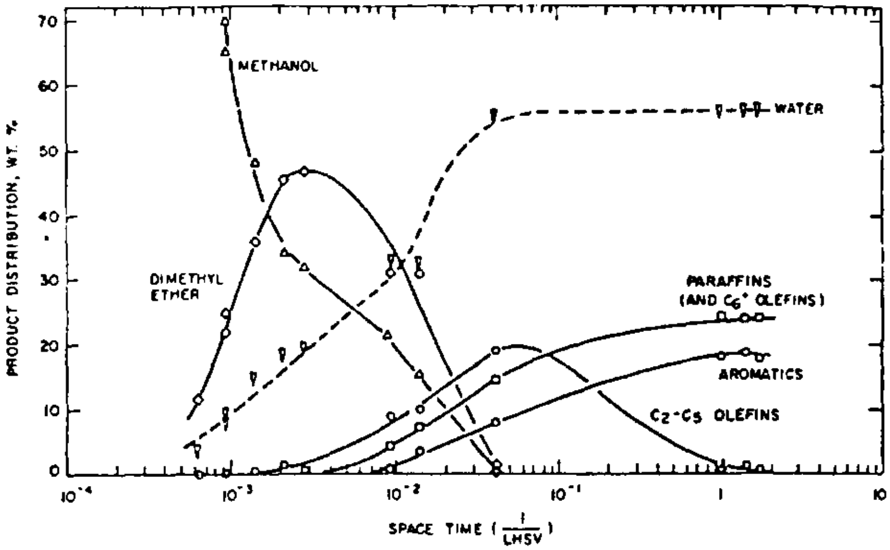


Figure 31. Reaction Path Diagram For the Conversion of Methanol to Hydrocarbons.[145]

In this figure variation of the product distribution with space time is shown for a reaction temperature of 371 C. A similar reaction path diagram is shown in Figure 32 [145] for the conversion of dimethylether into hydrocarbons over ZSM-5. Methanol, dimethylether or an equilibrium mixture of methanol, dimethylether and water appears to be first converted to C_2 to C_5 range olefins which are subsequently converted to parafins, aromatics, cycloparafins, and C_6^+ olefins.[145] The reaction path appears consistent with the

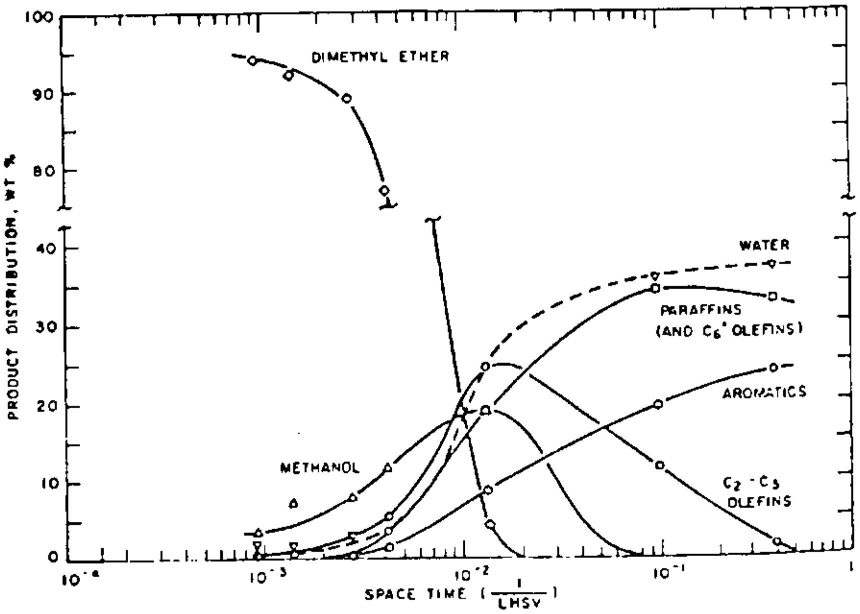


Figure 32. Reaction Path for dimethyl ether Conversion to Hydrocarbons.[145]

following reaction scheme:

$$2CH_3OH \underset{+H_2O}{\overset{-H_2O}{\rightleftarrows}} CH_3OCH_3 \xrightarrow{-H_2O} C_2\text{-}C_5 \text{ olefins} \longrightarrow$$

parafins, aromatics, cycloparafins, and C_6 olefins.[145]

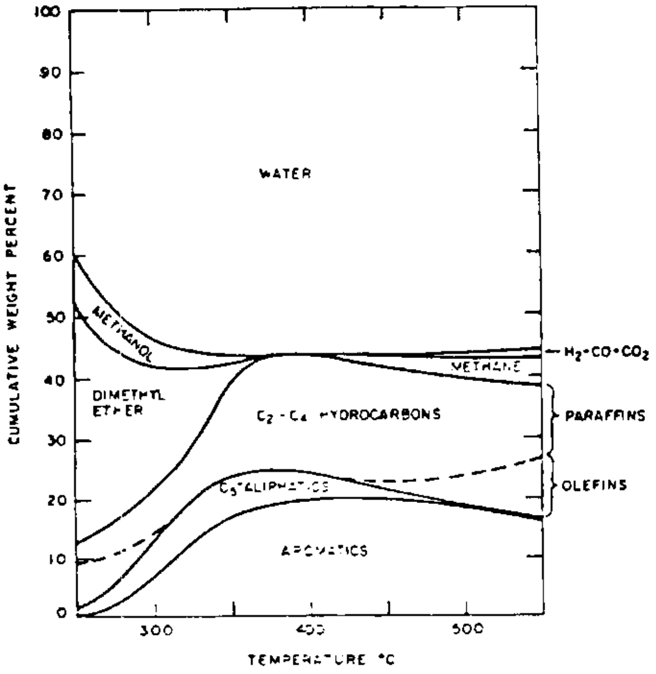


Figure 33. Zeolite-catalyzed Methanol Conversion; Yield Structure vs Temperature (0.6-0.7 LHSV, 101.3 kPa).[145]

The effect of temperature on the product distribution at relatively low space velocity (LHSV = 0.6-0.7) and 101.3kPa is shown in Figure 33 for the temperature span 260-538 C.[145] At the lowest temperatures the main reaction occurring is the dehydration of methanol to dimethyl ether. At a temperature between 340 C and 375 C the conversion of methanol to dimethyl ether approaches completion and substantial amounts of the dimethyl ether appear to be polymerized into aromatics. As the temperature increases, secondary cracking reactions increase the amount of methane and light olefins being formed. The distribution of aromatics formed in the conversion of

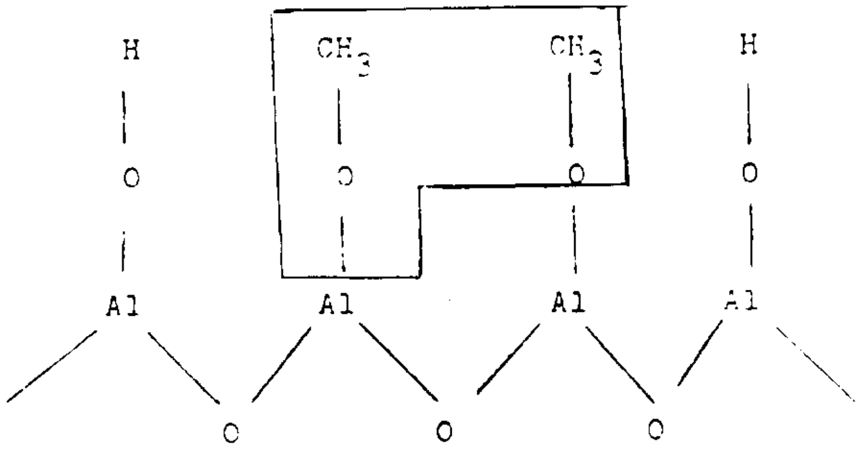
Reactant:	Methanol	*t*-Butanol	1-Heptanol	Methanethiol	Propanal	Meth
Reaction conditions						
T (°C)	371	371	371	482	371	371
LHSV (hr^{-1})	1.0	1.0	0.7	1.0	1.0	1.0
Conversion (%)	100.0	100.0	99.9	99.9[a]	99.9	100.0[b]
Hydrocarbon distribution (wt%)						
Methane	1.0	0.1	0.0	6.6	0.8	1.2
Ethane	0.6	0.7	0.3	8.3	0.4	0.7
Ethylene	0.5	0.5	<0.1	6.7	0.4	0.1
Propane	16.2	18.8	16.4	15.3	7.3	16.4
Propylene	1.0	1.1	0.2	1.3	0.6	0.9
i-Butane	18.7	18.4	19.3	9.0	4.6	15.1
n-Butane	5.6	8.6	11.0	3.1	3.0	5.8
Butenes	1.3	0.7	<0.1	0.2	0.3	0.3
i-Pentane	7.8	6.2	8.7	1.2	1.8	[illegible]
n-Pentane	1.3	1.4	1.5	<0.1	0.6	1.9
Pentenes	0.5	0.2	0.1	<0.1	0.2	0.5
C_6^+ aliphatics	4.3	7.6	3.0	0.1	1.3	3.2
Benzene	1.7	3.3	3.4	0.2	4.1	1.1
Toluene	10.5	11.6	14.3	1.3	23.7	7.9
Ethylbenzene	0.8	1.3	1.2	<0.1	2.6	0.7
Xylenes	17.2	12.4	11.6	8.9	26.4	20.5
C_9 Aromatics	7.5	6.1	5.3	27.0	18.6	12.4
C_{10} Aromatics	3.3	0.4	2.9	9.5	3.7	5.4
C_{11}^+ Aromatics	0.2	0.6	0.6	1.3	0.6	0.2

[a] 27.2% C converted to $(CH_3)_2S$.
[b] 11.0% C converted to $CO + CO_2$.

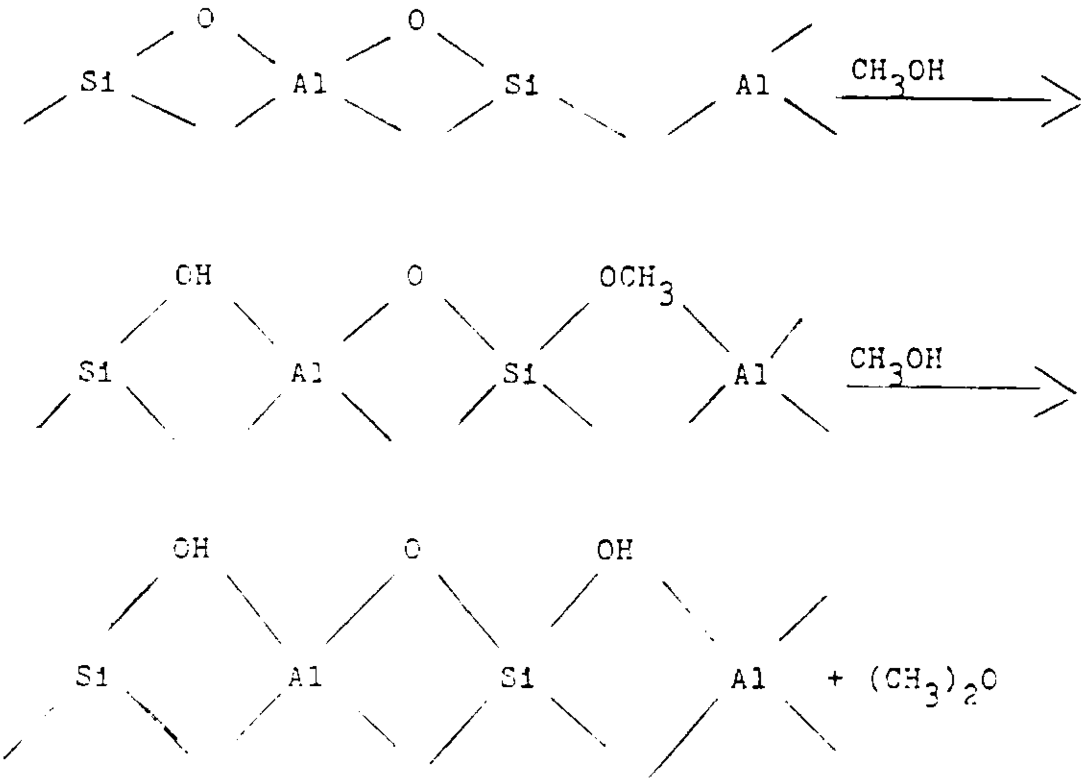
Table 19. Distribution of Aromatics Formed in The Conversion of Methanol to Gasoline.[145]

methanol to gasoline is shown in Table 19.[145] Toluene, ortho-, meta-, and paraxylenes, and 1,2,4 trimethylbenzene account for the majority of the product.

The reaction mechanism involved in this conversion is composed of three key steps; ether formation, initial C-C bond formation, and aromatization with hydrogen transfer.[146] The mechanisms involved in the formation of ether from alcohols on oxide catalysts has been thoroughly investigated and comprehensively reviwed.[147,148,149] From the evidence collected, Perera et al.[150] concluded that the synthesis of methanol over oxide catalysts, such as alumina, involves surface methoxy groups as shown below:



The formation of dimethyl ether from methanol by dehydration on the zeolite, clinoptilolite, was investigated by Detrekoy and Kallo.[151] Proposing the following mechanism, they attribute the formation of dimethyl ether to the creation of Bronsted sites from Lewis sites via hydration during reaction with methanol.



The second of the three key steps in the acid catalyzed conversion of methanol to hydrocarbons i.e., initial C-C bond formation, occurs by a mechanism which is currently subject to much speculation. Numerous mechanistic schemes have been proposed including surface alkoxyls, carbenes, carbenium ions, oxonium ions, free radicals, penta coordinate carbon, and successive carbeene insertion into surface alkoxy species. The proposed mechanisms were reviewed by Chang and Chu[152] and by Chang.[146] Kormerias et al.[153,154] proposed that hydrocarbon chain growth occurs by the successive insertion of carbene into surface alkoxy species via a rake type mechanism. The mechanism proposed is shown in Figure 34.[155]

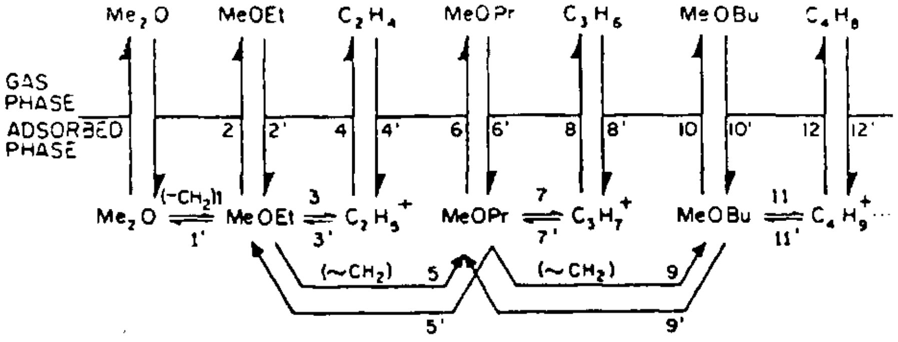


Figure 34. "Rake" Mechanism for Dimethyl Ether conversion to Hydrocarbons.[155]

The final step in this conversion i.e., aromatization with hydrogen transfer has been comprehensively reviewed in a number of publications. Olefin condensation, cyclization, and H-transfer over acid catalysts is well known to zeolite literature.[156,157].

The two versions of Mobil's MTG process are based on fixed bed and fluidized bed reactors which were installed in New Zealand and West Germany, respectively. The fixed-bed process is shown in Figure 35,[158] the two reactors in which, operate under the conditions shown in Table 20.[158] A schematic diagram of the fluidized bed pilot plant is shown in Figure 36,[159] and the composition of hydrocarbon products from the fluid bed pilot plant is shown in Table 21.[160]

A natural progression from the MTG technology which requires two reactors, one for methanol synthesis and one for carbon polymerization is to attempt to carry out both

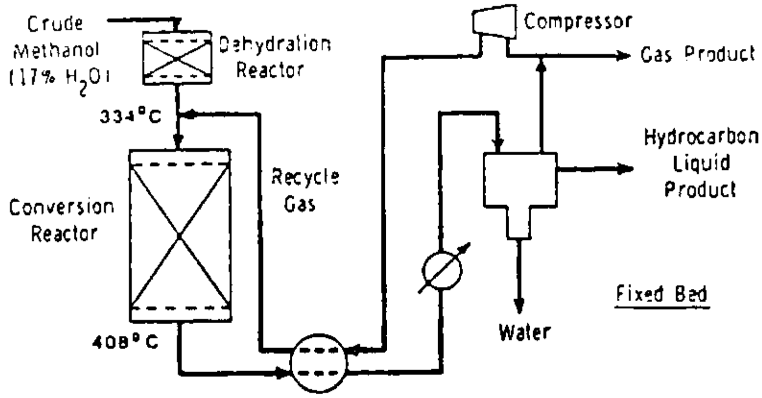


Figure 35. Mobil Methanol-to-Gasoline Process.[158]

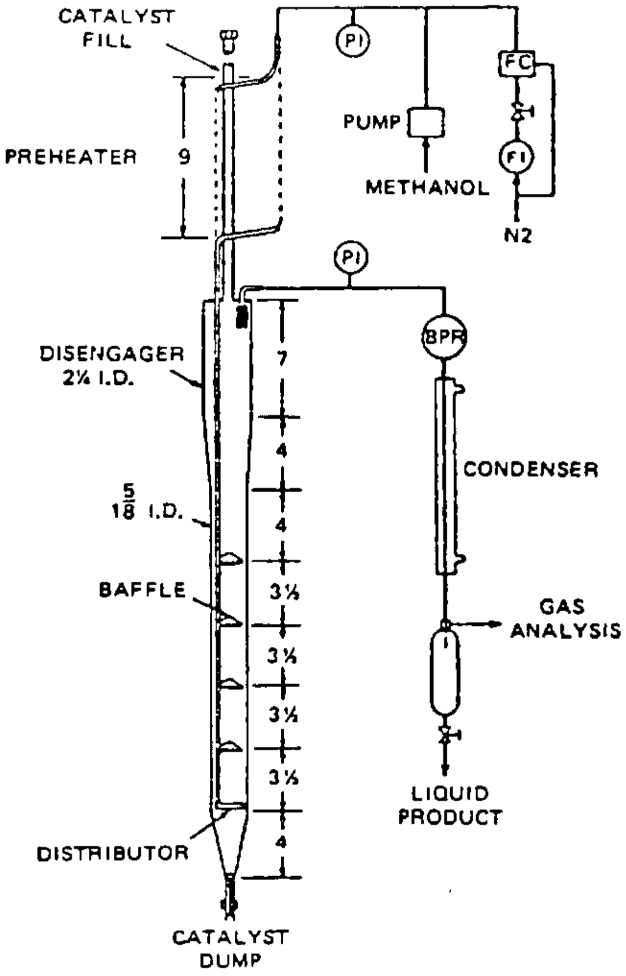


Figure 36. Schematic of Fluidized Dense Bed Pilot Plant.[159]

First Reactor	
Temperature, inlet	316°C
Temperature, outlet	∿399°C
Pressure, inlet	13.6-23.8 atm
Space velocity	20 h^{-1}, WHSV
Second Reactor	
Temperature, inlet	343°C
Temperature, outlet	∿454°C
Pressure, inlet	13.6-23.1 atm
Space velocity	1.5-5.0 h^{-1}, WHSV
Molar recycle ratio	3-4 (based on total fresh feed)
Separator	
Temperature	37.8°C

Table 20. Operating Conditions for Dual Reactor Fixed-Bed Process.[158]

Material balance no.	26-01	25-04	25-07	25-10
MeOH charged (lb of MeOH/ lb of cat.)	6	71	135	203
Isopentane	12.36	11.45	11.06	10.07
n-Pentane	0.49	0.43	0.42	0.33
Pentenes	2.19	2.60	3.04	3.12
Cyclopentane	0.44	0.05	0.10	0.07
Methylcyclopentane	0.71	0.67	0.63	0.58
n-Hexane	4.06	5.02	5.14	5.42
Methylpentanes	5.46	6.04	6.03	5.40
Dimethylbutanes	0.99	1.17	1.18	1.00
Hexenes	0.26	0.39	0.43	0.47
Cyclohexane	0.03	0.23	0.09	0.25
C_7-PON	3.31	3.87	4.00	4.29
C_8-PON	2.89	3.62	3.46	3.91
C_9-PON	1.64	2.43	2.15	2.20
C_{10}-PON	0.11	0.22	0.43	0.27
Benzene	0.00	0.00	0.00	0.00
Toluene	1.38	2.12	2.38	4.03
Ethylbenzene	0.16	0.18	0.17	0.17
Xylenes	6.05	6.30	5.80	5.50
Trimethylbenzenes	8.39	8.30	7.30	7.20
Methylethylbenzenes	1.34	1.44	1.30	1.31
Propylbenzenes	0.02	0.03	0.02	0.03
1,2,4,5-Tetramethylbenzene	1.94	3.38	2.87	3.93
1,2,3,5-Tetramethylbenzene	1.52	1.80	1.74	1.02
1,2,3,4-Tetramethylbenzene	0.56	0.50	0.41	0.45
Other C_{10}-benzenes	1.36	1.23	0.97	1.07
C_{11}-Benzenes	1.72	0.48	0.43	0.33
Naphthalenes	1.14	0.02	0.00	0.01
Other aromatics	2.58	0.67	1.71	1.86

[a] 700°F, 0 psig, 1 WHSV: concentrations are wt% of total hydrocarbons.

Table 21. Composition of Hydrocarbon Products From Fluid-Bed Pilot Plant.[160]

processes in a single reactor over a dual function catalyst. The following section considers this approach which we will call STG standing for the direct conversion of synthesis gas to gasoline.