EXECUTIVE SUMMARY

SASOL, operated commercially in South Africa, represents the state-of-the-art in Fischer-Tropsch technology. The SASOL process employs dry ash Lurgi gasifiers and fast fluid bed Synthol Fischer-Tropsch synthesis reactors. SASOL technology has a number of limitations which adversely affect process efficiency and product cost. Potential improvements in SASOL technology were highlighted in prior MITRE reports* based on the use of advanced gasifiers and an advanced slurry phase Fischer-Tropsch configuration (Koelbel).

Mobil Oil has investigated a modified slurry phase Fischer-Tropsch concept in a continuous bench-scale unit with DOE support. The Mobil two stage Fischer-Tropsch process incorporates a slurry-phase Fischer-Tropsch unit closely coupled to a fixed bed zeolite (ZSM-5) reactor. This was designed to exploit the capabilities of ZSM-5 to isomerize, alkylate, and aromatize the raw Fischer-Tropsch distillate and eliminate oxygenated compounds by conversion to hydrocarbons. The objective was to produce finished high-octane gasoline with minimal additional downstream refining.

DOE requested that MITRE carry out an assessment of the Mobil two stage Fischer-Tropsch program. This would include a review of bench scale studies to date. The original slurry phase Fischer-Tropsch development by Koelbel in Germany claimed low methane-ethane production, high selectivity to gasoline boiling-range hydrocarbons, and negligible wax make. Subsequently, a number of investigators

*Reference 1, Section 1.0.

have attempted to duplicate Koelbel's original results without complete success. Mobil, as part of their study, reexamined this question.

Fischer-Tropsch catalysts were produced by Mobil. These are proprietary, precipitated-iron catalysts promoted with copper and potassium.* The slurry-phase Fischer-Tropsch unit was closely coupled to a fixed bed ZSM-5 unit to produce a high octane gasoline.

Mobil completed five bench scale runs which ranged in duration from 13 to 86 days on-stream. Three Fischer-Tropsch catalysts were evaluated. The key process variables were explored. These include, in addition to catalyst composition, pressure, temperature, superficial gas velocity, gas space velocity, and catalyst loading. Stable operation over extended periods was demonstrated, with high conversion of synthesis gas.

The product distribution claimed in the slurry-phase Koelbel pilot plant, i.e., very low methane and ethane production with low wax make, was not duplicated. Two modes of operation were demonstrated with runs of reasonable duration and steady-state operation. A low wax case produced C_1 and C_2 yields of 12 percent, C_3/C_4 yields of 32 percent, gasoline yields of 48 percent, and wax yields of 8 percent. A high wax case was also demonstrated, resulti[illegible] in a product analyzing 6.8-percent C_1-C_2, C_3/C_4 yiel[illegible] 9 percent, gasoline yields of 40 percent, and 4[illegible] percent wax. Utilization of wax required hydrocracking to diesel fuel. It

*See reference Section 1, Reference 4, Koelbel and Ralek.

is estimated that the resulting gasoline-diesel fuel product contained 37 percent diesel. This provides additional marketing flexibility.

Following the detailed assessment of the bench-scale runs, MITRE carried out economic analyses of commercial-size plants, using the experimental test run data from the Mobil two-stage SFT/ZSM-5 benchscale unit. These data were scaled to provide a conceptual design for commercial-size plants with a total coal input of 27,800 tons of as-received Wyoming coal per day. These commercial plants utilized the British Gas Corporation Slagging Lurgi (BGC) gasifier for the production of synthesis gas. Predicted thermal efficiency, product slate, capital cost, operating cost, annual revenue requirement, and unit product cost of such commercial facilities are compared to the corresponding figures for the reference cases.

Six cases are examined in this report. Three of these cases involve various versions of Mobil's two stage SFT/ZSM-5 process. The other three cases are provided for comparison purposes and include a SASOL-like or SASOL(U.S.) case which uses a dry ash Lurgi gasifier and Synthol synthesis units, a BGC/Synthol case, and a slurry-phase Fischer-Tropsch case identified as the BGC/Koelbel case. The latter three reference cases have already been examined in MITRE's report MTR-80W326. The three cases all include refining of raw Fischer-Tropsch gasoline to market grade, high octane gasoline and alkylation of C_3-C_4 olefins to additional gasoline. Marketable diesel fuel and fuel oil are produced. To maintain a common basis of comparison, the cost data for all these cases are adjusted to 1983 dollar value and their thermal output is calculated on the lower heating value basis.

The three versions of the Mobil conceptual two stage SFT/ZSM-5 design examined in this report include a Mobil low wax case, a MITRE version of the Mobil low wax case, and a MITRE conceptual design of a Mobil high wax case.

In the Mobil low wax case, the zeolite reactor produces high octane gasoline supplemented by additional alkylation of C_3-C_4 olefins. The small quantity of wax is marketed. In the MITRE version, a more conservative process efficiency was obtained and a product distribution, more consistent with the bench-scale data, was utilized. In the high wax case, hydrocracking of wax to a maximum diesel fuel make was included. Hydrocracking product distribution was based on published data by Dry of SASOL.

The results of the economic analyses are summarized in Tables 1 and 2. The product cost is based on 100 percent equity financing with a DCF of 12 percent. Plant and product output in terms of amounts and thermal efficiency are highlighted. In these tables, each case is evaluated for two modes of operation: the mixed output mode (Table 1), in which both SNG and liquid fuels are produced, and the all-liquid output mode (Table 2), where the SNG is reformed back to synthesis gas and recycled to the F-T reactor.

In addition, the unit product cost is expressed in Tables 1 and 2 on two bases: the thermal basis and the market basis. In the thermal basis, all products are assumed to have equal thermal unit value. On

TABLE 1

COMPARATIVE SUMMARY OF PREDICTED PERFORMANCE FOR MOBIL SFT/ZSM-5 CONCEPTUAL PLANT DESIGN (MIXED-OUTPUT MODE)

Case / Comparative Items	SASOL(U.S.)*	BGC/Synthol	BGC/Koelbel	MITRE BGC/Mobil Low-Wax	BGC/Mobil Low-Wax	BGC/Mobil High-Wax
Plant Costs and Revenue, MM $, 1983						
Total Construction Cost	1,910	1,778	1,719	1,678	1,701	1,718
Total Capital Cost	3,037	2,827	2,733	2,668	2,705	2,732
Annual Capital Charge	805	745	724	707	717	724
Coal Cost	73	73	73	73	73	73
Operating Cost	279	260	251	237	241	251
ZSM-5 Catalyst Cost	—	—	—	5	5	5
Hydrotreatment Catalyst Cost	—	—	—	—	—	2
By-Product Revenue	(10)	(10)	(10)	(10)	(10)	(10)
Annual Revenue Requirement	1,147	1,072	1,038	1,012	1,026	1,045
Plant Output and Thermal Efficiency						
Annual Thermal Output, (MMBTU/yr, LHV)	81,163,000	85,973,580	86,935,530	84,276,720	87,199,200	88,292,140
Gasoline Equivalent (Bbls/yr)	11,584,000	13,342,439	15,345,634	13,927,741	14,710,177	14,796,452
Thermal Efficiency, % (LHV)	54	57	58	56	58	59
Product Slate						
SNG (MMSCFD)	173.3	147.9	94.2	114	118.7	112.5
Gasoline (Bbl/day)**	13,580	19,137	30,766	25,283	28,607	20,940
C_3 (Bbl/day)	1,107	1,604	3,084	4,515	3,026	1,127
C_4 (Bbl/day)	146	212	—	1,285	885	625
Diesel Oil (Bbl/day)	2,307	3,343	3,821	—	—	12,264
Heavy Fuel Oil (Bbl/day)	622	901	398	—	—	—
Alcohol (Bbl/day)	1,829	2,650	618	—	—	—
Wax (Bbl/day)	—	—	—	2,246	2,400	—
Unit Product Cost						
Thermal Basis, $/gal ($MMBtu)	1.57 (14.1)	1.38 (12.4)	1.32 (11.9)	1.33(12.0)	1.31 (11.77)	1.31 (11.83)
Market Basis, $/gallon Gasoline equivalent	2.36	1.91	1.61	1.73	1.66	1.68

*Combines a dry bottom Lurgi gasifier with a Synthol fast-fluid bed F-T unit.
**Including 1,630 BPSD of gasifier naphtha and 55% of $n\text{-}C_4H_{10}$ to adjust RVP.

TABLE 2

COMPARATIVE SUMMARY OF PREDICTED PERFORMANCE FOR MOBIL SFT/ZSM-5 CONCEPTUAL PLANT DESIGN (ALL-LIQUID OUTPUT MODE)

Comparative Items / Case	SASOL(U.S.)	BGC/Synthol	BGC Koelbel	MITRE BGC/Mobil Low-Wax	BGC/Mobil Low-Wax	BGC/Mobil High-Wax
Plant Costs and Revenue, MM $, 1983						
Total Construction Cost	2,226	2,076	1,900	1,873	1,902	1,936
Total Capital Cost	3,540	3,301	3,021	2,918	3,024	3,079
Annual Capital Charge	940	876	801	789	801	816
Coal Cost	73	73	73	73	73	73
Operating Cost	326	304	278	265	269	283
ZSM-5 Catalyst Cost	--	--	—	5	5	5
Hydrotreatment Catalyst Cost	--	--	—	—	—	2
By-Product Revenue	(10)	(10)	(10)	(10)	(10)	(10)
Annual Revenue Requirement	1,329	1,243	1,142	1,122	1,138	1,169
Plant Output and Thermal Efficiency						
Annual Thermal Output, (MMBTU/yr, LHV)	62,008,000	69,599,000	76,546,140	71,010,720	73,378,800	75,200,4[illegible]0
Gasoline Equivalent (Bbls/yr)	12,[illegible]9,000	14,319,507	16,053,733	14,542,147	14,994,341	15,408,620
Thermal Efficiency, % (LHV)	41	46	51	47	49	50
Product Slate						
Gasoline (Bbl/day)*	28,090	31,514	39,945	35,569	40,449	28,525
C_3 (Bbl/day)	2,436	2,738	4,055	6,478	4,351	1,571
C_4 (Bbl/day)	321	361	—	1,844	1,275	670
Diesel Oil (Bbl/day)	5,078	5,706	5,025	—	—	17,082
Heavy Fuel Oil (Bbl/day)	1,369	1,538	523	—	—	—
Alcohol (Bbl/day)	4,026	4,524	813	--	—	—
Wax (Bbl/day)	—	—	—	3,223	3,453	—
Unit Product Cost						
Thermal Basis, $/gal ($MMBtu)	2.38 (21.43)	1.98 (17.86)	1.66 (14.92)	1.75 (15.8)	1.72 (15.51)	1.73 (15.5)
Market Basis, $/gallon	2.48	2.07	1.70	1.83	1.81	1.80

*Including 1,630 BPSD of gasifier naphtha.

the market basis, however, all products other than gasoline are priced according to their relative thermal gasoline equivalent indicated in Table 3.

The thermal efficiency improvement over the conventional dry ash Lurgi/Synthol system (SASOL U.S.) in both versions is apparent. In the mixed output cases, over 40 percent of the output energy is SNG. The improvement in gasoline output and gasoline plus diesel fuel output over SASOL(U.S.) and BGC/Synthol is apparent in both mixed and all-liquid versions.

Product costs for the various cases highlight the improvement made possible by the Mobil two stage results. When the BGC/Mobil in the low and high wax versions is compared to SASOL(U.S.) a 27 to 30 percent reduction in product cost is observed in the mixed output mode. A reduction of 13 percent in product cost is calculated when compared to the reference BGC/Synthol configuration in the mixed output mode. Comparing product costs in the all-liquid output cases, BGC Mobil shows a reduction of 26 to 27 percent compared to SASOL(U.S.) and 13 percent over BGC/Synthol.

The conceptual commercial plant, using Mobil experimental data, from the high-wax mode, approaches the Koelbel product cost results within 6 percent. The cost of gasoline from the high wax Mobil plant configuration is shown in Table 2 to be slightly lower than from the low wax plant configuration. This cost of gasoline from the high wax plant is sensitive to the relative value of diesel and gasoline which

TABLE 3

GASOLINE EQUIVALENT FACTOR*

Product	Barrels of Gasoline Value Equivalent	Btu Equivalent
SNG (MMSCF)	96.5	.5
Gasoline	1.0	1.0
C_3	0.758	1.0
C_4	0.861	1.0
Diesel Oil	0.95	.89
Heavy Fuel Oil	0.57	.50
Alcohol	0.73	1.0
Wax	0.62	.50

*In order to calculate product costs, the volumes of each fuel are adjusted based on their value versus gasoline, using factors listed in Column 1. The SNG conversion is based on MMSCF. The total number of adjusted barrels of all fuels in gallons is divided into the required revenue to calculate dollars/gallon of equivalent gasoline in Tables 1 and 2 for the market basis values.

is assumed. The data presented in Table 2 for the market basis cost analysis assume that diesel is valued at 95 percent of the value of gasoline on a cost-per-barrel basis. Any escalation of the cost of diesel relative to gasoline will preferentially reduce the gasoline cost from the high-wax Mobil configuration. If diesel and gasoline are assumed to be equivalent on a \$/Btu basis, the computed cost of gasoline from the Mobil high wax plant would be \$1.64/gallon--slightly lower than the cost of gasoline from the BGC/Koelbel reference plant. Pricing diesel and gasoline at equivalent values on a Btu basis is consistent with future pricing projections. This is particularly true for the high cetane diesel produced from hydrocracking of wax.

In the high wax BGC-Mobil case, the product distribution from the Fischer-Tropsch-zeolite two stage unit used in this study was calculated by extrapolation of experimental data. The results were confirmed in a later experimental run of limited duration. Hydrocracking of the wax in the overall refining process with its high selectivity to diesel fuel (80%) and gasoline (15%) was not demonstrated to date by Mobil on the actual wax fraction but predicated on published data by M. Dry for an Arge wax produced at SASOL. This aspect must be confirmed experimentally. Inherent in the process analyses contained in this report are the following additional assumptions for the BGC/Mobil two stage process:

- Sustainable single-pass conversion of synthesis gas of 85 percent

- Recycle of Fischer-Tropsch catalyst from a wax separator system with acceptable activity

- Catalyst removal from product wax to a level acceptable for fixed bed hydrocracking

Experimental verification of the above items is required in addition to the scaleup of the slurry phase Fischer-Tropsch reactor with the projected throughput and conversion.

In any analysis of relative product costs arising from a comparison of SASOL with advanced gasifier-synthesis, we must remember that the selection of the gasifier is important. If an all-liquid product slate is desired, it is very important to minimize the formation of methane in the gasification process. In the all-liquid mode, the use of a Shell gasifier in place of the BGC slagging Lurgi would result in all-liquid product cost reductions of about 10 percent over those shown for both the Mobil two stage and the BGC-Koelbel plant.