to the gasoline pool. Typically, the Alkymax process may not be used to alkylate an almost pure benzene stream. This benzene would be sold for its chemical value. Because the objective of the current program is to maximize the production of transportation fuels, the Alkymax unit was included to lower the benzene content of the gasoline pool. The reformulated gasoline specified in the future Clean Air Bill may limit benzene content in gasoline to a maximum of 0.8 vol-%.

- **Naphtha Hydrotreater Process.** The naphtha hydrotreater (NHT) processes the F-T C_5-C_{11} stream as well as the C_5-C_{11} naphtha stream from the hydrocracker. The primary purpose of the NHT unit is to saturate olefins and to convert small quantities of oxygenates and organic acids that may otherwise affect performance of the downstream Platforming unit. The C_5-C_6 product is charged to the Penex* isomerization unit, and the C_7-C_{11} product from the NHT is fed to a CCR Platforming unit.
- **Penex-Molex* Units.** The highly paraffinic C_5-C_6 product from the NHT is charged to the Penex isomerization unit. The octane of the fraction is improved as low-octane normal paraffins are isomerized to higher octane isoparaffins. The conversion of normal paraffins to isoparaffins is limited by thermodynamic equilibrium. The Molex unit separates and directs higher octane isoparaffins to the gasoline pool and lower octane normal paraffins back to the Penex unit for isomerization.
- **CCR Platforming Unit.** The C_7-C_{11} naphtha from the NHT product is fed to the UOP CCR Platforming or reforming unit. The unit is used to convert F-T naphtha to high-octane gasoline. The details of the process are given in Tasks 5 and 6 of the Topical Report. [9] The resulting product is blended into the gasoline pool.
- **Hydrocracker.** The hydrocracker (HC) provides a means of upgrading heavy material, primarily F-T wax, into transportation fuel. The yields and product properties were derived from past work done under the PETC-sponsored contract on F-T wax hydrocracking.

The gasoline and diesel pool properties for the Arge case are shown in Table 4.3. The gasoline blend from the complex has a research octane (RONC) of 98, RVP of 6.9 psia, aromatics level of 48.2 vol-%, and benzene content of 0.4 vol-%. The diesel pool has an extremely high cetane of 73.1 and meets all diesel specifications. The capital cost and operations summary is shown in Table 4.4. The complex before-tax IRR is 36.7% based on market feed and product prices (Table 4.5).

4.2 Synthol Products Upgrading

A similar complex flow scheme was developed for the Synthol case (Figure 4.2). The differences in the Synthol product upgrading complex are:

- The highly olefinic F-T LPG feed to the Cyclar unit is saturated using the Huels CSP process to prevent excessive catalyst coking in the Cyclar unit. The Huels CSP process hydrogenates olefins contained in the C_3-C_5 LPG stream to their respective paraffins.
- The F-T C_{12}-C_{18} stream is processed in a distillate hydrotreater before sending it to the diesel pool. The purpose of this distillate-finishing step is to saturate the olefins and remove any oxygenates or organic acids. The cetane number of the distillate stream improves with hydrotreating.
- No hydrocracker is specified for the F-T C_{19}+ wax stream. The quantity of wax from a Synthol reactor is extremely small, and the wax is used as fuel in the complex.

The overall material balance for the Synthol case is shown in Table 4.6. The gasoline and diesel pool properties are shown in Table 4.7. The gasoline blend from the complex has a research octane (RONC) of 99.7, RVP of 7.1 psia, aromatics level of 48.8 vol-%, and benzene content of 0.5 vol-%. The capital cost and operations summary is shown in Table 4.8. The complex before-tax IRR of 19.7% is based on market feed and product prices (Table 4.9).

4.3 Sensitivity Analysis

The sensitivity of the F-T complex economics was studied over a range of product prices, feedstock costs, and plant capital investment. The results are summarized in Figure 4.3.

First, the prices of the gasoline and diesel products were increased by a factor of 1.5 over the base case. The high-end case more closely represents the market prices prevalent since the onset of the Middle East crisis. Next, the feedstock costs were increased by a factor of 1.2. The feedstock costs make up more than 70% of the net cost of production. The rate of return is extremely sensitive to both the product price and the cost of feed to the upgrading complex. In reality, the feedstock costs should represent the costs of indirect liquefaction of coal. For the base case, market values were assigned to feedstock costs because the economics of synthesis gas production and the F-T reactor section was beyond the scope of the current work. Finally, the plant capital investment was increased by a factor of 1.5 over the base case. The plant capital investment does not have as much of an impact on the F-T upgrading complex economics as the product prices and the feedstock costs.

4.4 Summary

When the economics of the Arge and the Synthol complexes is compared, middle distillate production via Arge is seen as less complex and cheaper than gasoline production via Synthol. This conclusion assumes that the costs of products derived from the Arge and the Synthol reactors are the same. Apart from the economics, if F-T products are considered as liquid fuels, Arge should be used to produce middle distillate (jet fuel plus diesel) for two good reasons:

- The chain-growth mechanism inherent in F-T technology is not selective to a particular boiling range, and the probability of high chain growth maximizes the formation of reactor wax, which can be hydrocracked easily to distillates.
- The F-T diesel and jet fuel have unique property attributes, such as no sulfur, no nitrogen, and no aromatics.

Table 4.1

Price and Cost Basis for the Economic Analysis of an F-T Complex

	Costs and Product Values	
Feedstock:		
Gasoline	$242 $/MT	28.4 $/bbl
Diesel	193 $/MT	26.0 $/bbl
Fuel Gas	3.00 $/MM Btu	2.84 $/GJ
LPG	140 $/MT	1132 S/bbl
Hydrogen (95 vol-%)	694 $/MT	2.25 $/M SCF
Naphtha, FBR	160 $/MT	16.9 $/bbl
Diesel	193 $/MT	26.0 $/bbl
Wax	125 $/MT	
Utilities:		
Power	0.06 $/kWh	
Steam, 600 psig (HP)	4.50 $/M lb	
Steam, 350 psig (MP)	4.00 $/M lb	
Steam, 50 psig (LP)	3.00 $/M lb	
Boiler Feed Water	0.40 $/M lb	
Condensate	0.40 $/M lb	
Cooling Water	0.10 $/M gal	
Fuel Fired	3.00 $/MM Btu	
Labor:		
Operators	36,000 $/year	
Supervision	25%	
Labor Overhead	35%	

Table 4.2

Overall Material Balance of the F-T Complex Arge Case

Feed from Arge	MT/d
C_1-C_2 Fuel Gas	221.3
C_3-C_4 LPG to Cyclar	423.5
C_3-C_4 LPG to Alkymax	110.0
C_5-C_{11} Naphtha to NHT	1015.9
C_{12}-C_{18} to Diesel	788.9
C_{19}+ to Wax to Hydrocracking	2934.2
	5493.8
Misc. Chemicals	181.6
	5675.4

Product	MT/d
Hydrogen	39.1
C_1-C_4 Fuel Gas	532.4
Gasoline:	
Alkylate	166.0
C_7+ from Cyclar	280.0
Isomerate	648.0
Reformate	1025.9
Diesel:	
C_{12}-C_{18} from Arge	788.9
C_{12}-C_{18} from Hydrocracking	2013.6
	5493.9
Misc. Chemicals	181.6
	5675.5

Table 4.3

Product Properties for the F-T Complex-Arge Case

GASOLINE POOL:

	Alkymax	Cyclar	Penex-Molex	CCR Reforming	Blend	U.S. Unleaded Pool Comp.	Possible Reform. Gasoline Specs.
Flow Rate, MT/d	166.0	280.0	648.0	1025.9	2119.9	--	--
Specific Gravity	0.8666	0.893	0.641	0.8022	0.7585	--	--
API	31.8	26.95	89.2	44.9	55.1	--	--
RVP, psia	0.1	0.7	14.4	3.3	6.92	8-12	8 max.
Molecular Weight	130	101.4	78.4	103.5	95.4	--	--
RONC	118	113.2	89	100	98.7	87-88	(R+M)/2
MONC	108	102.5	87.3	88.6	91.0	--	--
ASTM D-86, °F							
IBP	198	223	75	107	--	--	--
50% over	268	268	105	282	--	--	--
90% over	354	354	132	340	279	300-350	300 max.
EP	441	441	150	411	--	--	--
Aromatics, vol-%	100.0	100.0	0.0	65.9	48.2	30-35	20-25 max.
Benzene, vol-%	0.0	0.0	0.0	0.9	0.4	1-2	0.8 max.
Olefins, vol-%	0.0	0.0	0.0	1.0	0.5	10-12	5 max.

DIESEL POOL:

	Arge	Hydrocracking	Blend	Specs.
Flow, MT/d	788.9	2013.6	2802.4	--
Specific Gravity	0.7752	0.7891	0.7851	--
API	51.0	47.8	48.7	--
ASTM 50% Pt., °F	501	583	560	--
Cetane Index	73.3	73.0	73.1	40 min.
Flash Point, °F	191.7	210.5	203.8	125 min.
Pour Point, °F	40.9	-13.3	17.1	20 max.
Freeze Point, °F	N/A	N/A	N/A	--
Viscosity, cSt @ 100°F	2.91	4.61	3.99	1.9-4.1

Table 4.4

Capital Cost and Utilities Summary for the F-T Complex Arge Case

	Cyclar	Splitter+ Alkymax	NHT+ Splitter	CCR Reforming	Penex-Molex	HC Unibon
Feed Rate, MT/d	614.6	211.5	1881.3	1231.6	651.3	2934.2
ISBL, $MM	28.55	6.89	8.80	13.02	10.20	29.15
Utility Consumptions:						
Power, kW	3533	100	705	2183	353	2148
HPS, M lb/h	-6.6	9.0	0.0	-6.9	0.0	16.8
MPS, M lb/h	0.0	0.0	0.0	0.0	9.2	7.5
LPS, M lb/h	2.2	0.0	0.0	0.1	20.3	0.0
BFW, M lb/h	9.7	0.0	0.0	11.6	0.0	0.0
Cool Water, M gal/h	241.6	14.6	9.9	159.4	0.2	67.2
Fuel, MM Btu/h	53.5	5.0	65.6	88.8	0.0	121.4
Labor: Operators/Shift	3	2	1	2	2	3

Table 4.5

Economic Evaluation (Base Case) for the F-T Complex Arge Case

Capital Items	$ MM
Plant Investment (ISBL)	96.61
OSBL (50% ISBL)	48.31
Interest	29.16
Total Fixed Investment	174.08
Royalties & Fees	12.24
Inventory	8.91
Working Capital	44.75
Total Capital Investment	239.98

Economic Analysis:	$ MM
Gasoline Sales	171.01
Diesel Sales	180.29
By-Products Credits	30.3
Feedstock Costs	260.5
Gross Margin	121.1
Variable Costs	14.91
Fixed Costs	17.99
Cash Flow	88.2
Internal Rate of Return (before tax), %	36.68

Table 4.6

Overall Material Balance of F-T Complex Synthol Case

Feed from Synthol	MT/d
C_1-C_2 Fuel Gas	1021.6
C_3-C_4 LPG to Cyclar Unit	1218.9
C_3-C_4 LPG to Alkymax Unit	200.0
C_5-C_{11} Naphtha to NHT	2270.2
C_{12}-C_{18} Diesel	397.3
C_{19}+ Wax to Fuel	227.0
	5335.0
Misc. Chemicals	340.5
	5675.5

Product	MT/d
Hydrogen	32.9
C_1-C_4 Fuel Gas	1573.5
C_{19}+ Wax to Fuel	227.0
Gasoline	
Alkylate	413.5
C_7+ from Cyclar	607.8
Isomerate	1025.5
Reformate	980.7
Diesel	
C_{12}-C_{18} from Distillate Finishing	397.3
	5258.2
Misc. Chemicals	417.3
	5675.5

Table 4.7

Products Properties of the F-T Complex Synthol Case

GASOLINE POOL:

	Alkymax	Cyclar	Penex-Molex	CCR Reforming	Blend	U.S. Unleaded Pool Comp.	Possible Reform. Gasoline Specs.
Flow Rate, MT/d	413.5	607.8	1025.5	980.7	3027.5	--	--
Specific Gravity	0.8665	0.893	0.6424	0.8054	0.7622	--	--
API	31.8	26.95	88.76	44.2	54.1	--	--
RVP, psia	0.1	0.7	14.4	3.39	7.09	8-12	8 max.
Molecular Weight	127	99.9	78.4	106.6	95.7	--	--
RONC	118	113.2	88.3	100	99.7	87-88	(R+M)/2
MONC	108	102.5	87.3	88.6	92.8	--	--
ASTM D-86, °F							
IBP	198	223	89	114	--	--	--
50% over	268	268	109	271	--	--	--
90% over	354	354	130	341	274	300-350	300 max.
EP	441	441	150	401	--	--	--
Aromatics, vol-%	100.0	100.0	0.0	64.1	48.8	30-35	20-25 max.
Benzene, vol-%	0.0	0.0	0.0	1.7	0.5	1-2	0.8 max.
Olefins, vol-%	0.0	0.0	0.0	1.0	0.3	10-12	5 max.

DIESEL POOL:

	Distillate Finishing	Blend	Specs.
Flow, MT/d	397.3	397.3	--
Specific Gravity	0.79	0.79	--
API	47.6	47.6	--
ASTM 50% Pt., °F	475	475	--
Cetane Index	66	66	40 min.
Flash Point, °F	160	160	125 min.
Pour Point, °F	15.0	15.0	20 max.
Freeze Point, °F	N/A	N/A	--
Viscosity, cSt @ 100°F	3.00	3.00	1.9-4.1

Table 4.8

Capital Cost and Utilities Summary of the F-T Complex Synthol Case

	Huels CSP +Cyclar	Splitter Alkymax	NHT+ Splitter	CCR Reforming	Penex-Molex	Distillate Finishing
Feed Rate, MT/d	1371.4	461.7	2270.2	1177.3	1043.8	397.3
ISBL, $MM	52.48	11.01	9.85	12.67	13.53	6.94
Utility Consumptions:						
Power, kw	7678	218	851	2087	566	310
HPS, M lb/h	-47.6	19.6	0.0	-6.6	0.0	0.0
MPS, M lb/h	0.0	0.0	0.0	0.0	14.8	0.0
LPS, M lb/h	8.3	0.0	0.0	0.1	32.6	0.0
BFW, M lb/h	55.6	0.0	0.0	11.1	0.0	0.0
Cool. Water, M gal/h	879.7	31.9	11.9	152.4	0.4	5.2
Fuel, MM Btu/h	306.0	10.0	79.1	84.9	0.0	11.1
Labor: Operators/Shift	3	2	1	2	2	2

Table 4.9

Economic Evaluation (Base Case) of the F-T Complex Synthol Case

Capital Items	$ MM
Plant Investment (ISBL)	106.48
OSBL (50% ISBL)	53.24
Interest	32.14
Total Fixed Investment	191.86
Royalties & Fees	13.9
Inventory	17.27
Working Capital	38.14
Total Capital Investment	261.17

Economic Analysis:	$ MM/y
Gasoline Sales	244.22
Diesel Sales	25.56
By-Products Credits	63.38
Feedstock Costs	242.83
Gross Margin	90.33
Variable Costs	19.84
Fixed Costs	17.7
Cash Flow	52.79
Internal Rate of Return (before tax), %	19.66

Figure 4.1

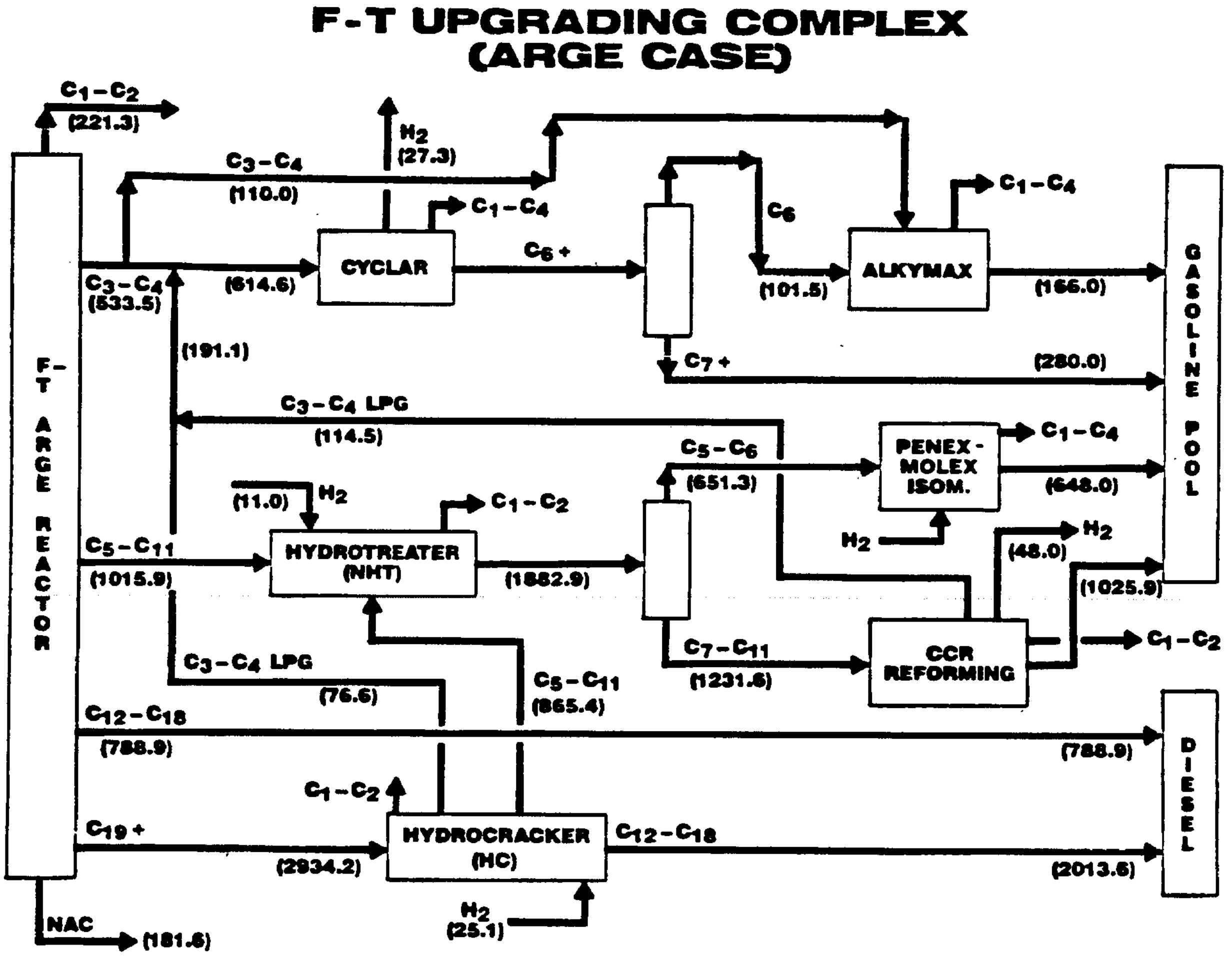

F-T UPGRADING COMPLEX
(ARGE CASE)
C1-C2
(221.3)
H2
(27.3)
C3-C4
(110.0)
C1-C4
C6
C1-C4
CYCLAR
C6+
ALKYMAX
C3-C4
(533.5)
(614.6)
(101.5)
(166.0)
(191.1)
C7+
(280.0)
F-T ARGE REACTOR
GASOLINE POOL
C3-C4 LPG
(114.5)
C5-C6
PENEX-MOLEX ISOM.
C1-C4
(651.3)
(648.0)
(11.0)
H2
C1-C2
H2
H2
(48.0)
C5-C11
(1015.9)
HYDROTREATER (NHT)
(1882.9)
(1025.9)
C1-C2
C3-C4 LPG
(76.6)
C5-C11
(865.4)
C7-C11
(1231.6)
CCR REFORMING
C12-C18
(788.9)
(788.9)
DIESEL
C1-C2
C19+
(2934.2)
HYDROCRACKER (HC)
C12-C18
(2013.6)
H2
(25.1)
NAC
(181.6)

Figure 4.2

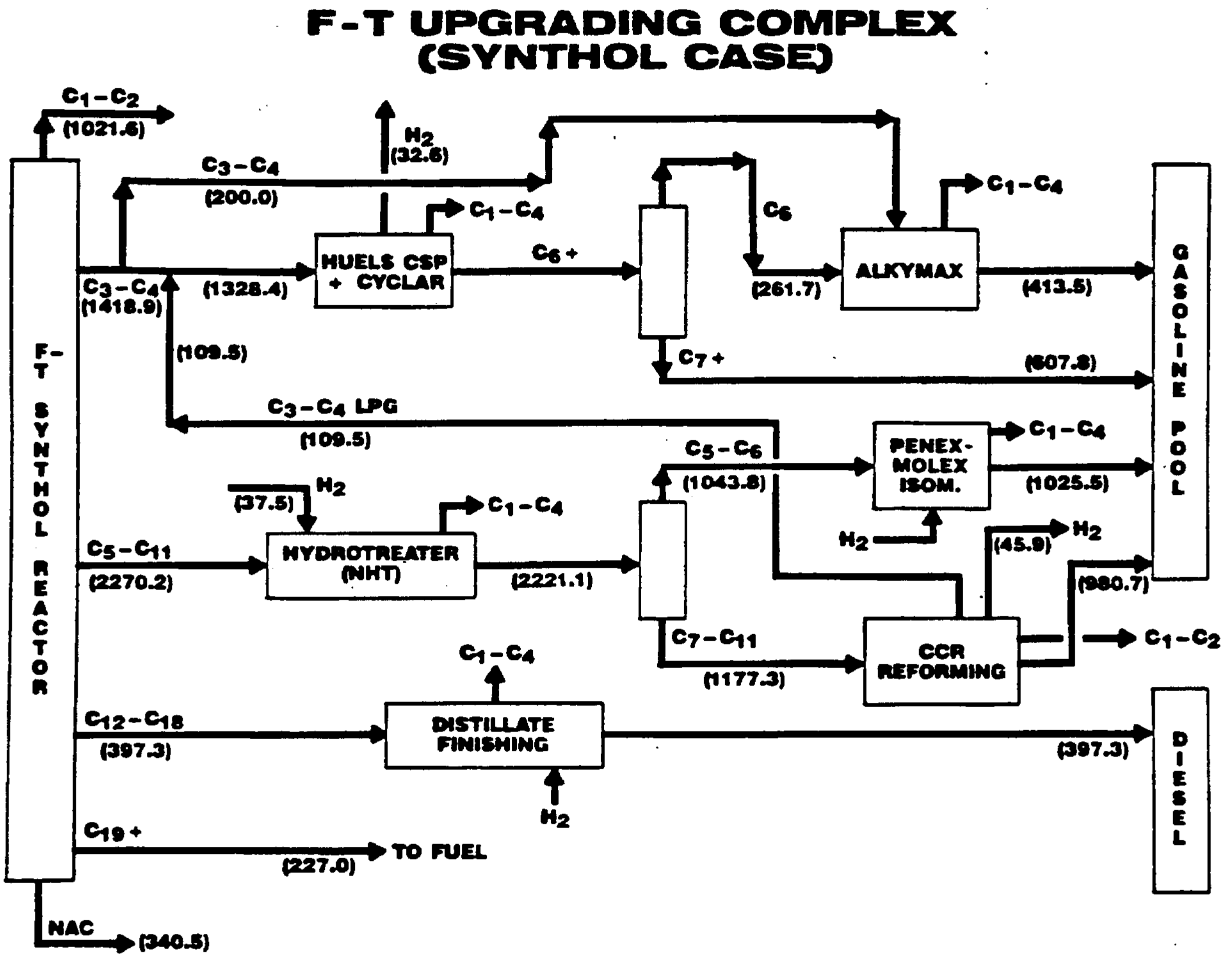
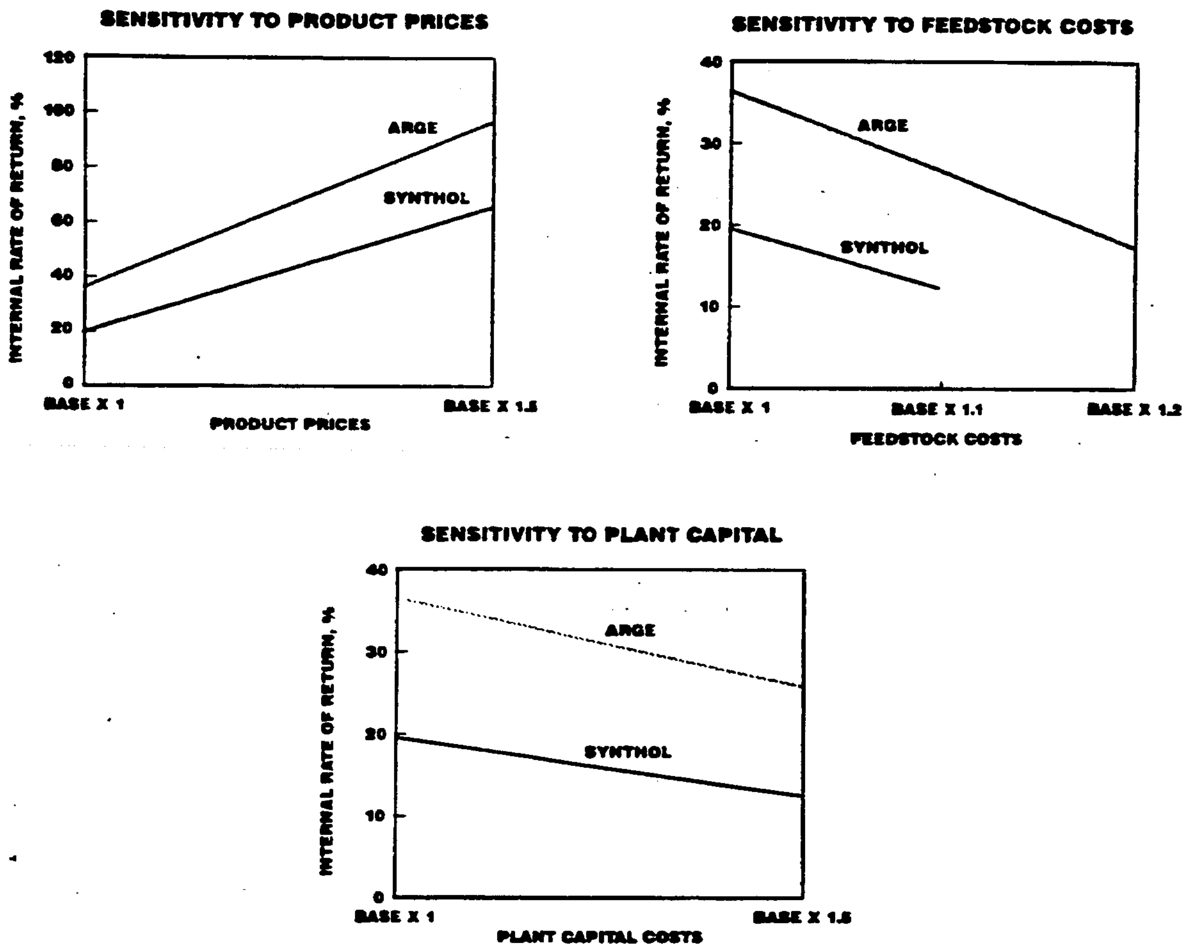

F-T UPGRADING COMPLEX
(SYNTHOL CASE)
C1-C2
(1021.6)
H2
(32.6)
C3-C4
(200.0)
C1-C4
HUELS CSP + CYCLAR
C3-C4
(1418.9)
(1328.4)
C6+
C6
(261.7)
ALKYMAX
C1-C4
(413.5)
(109.5)
C7+
(607.8)
GASOLINE POOL
C3-C4 LPG
(109.5)
C5-C6
(1043.8)
PENEX-MOLEX ISOM.
C1-C4
(1025.5)
H2
(37.5)
C1-C4
C5-C11
(2270.2)
HYDROTREATER (NHT)
(2221.1)
H2
(45.9)
H2
(980.7)
C7-C11
(1177.3)
CCR REFORMING
C1-C2
C1-C4
C12-C18
(397.3)
DISTILLATE FINISHING
(397.3)
DIESEL
H2
C19+
(227.0)
TO FUEL
NAC
(340.5)
F-T SYNTHOL REACTOR

Figure 4.3

FISCHER-TROPSH COMPLEX SENSITIVITY ANALYSIS



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Acknowledgments

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* UOP, Cyclar, CCR Platforming, Platforming, Alkymax, Penex, and Molex are tradenames and/or service marks of UOP.

GLOSSARY OF ABBREVIATIONS

GLOSSARY OF ABBREVIATIONS

Abbreviation	Meaning
API	American Petroleum Institute
ASTM	American Society for Testing and Materials
BFW	Boiler Feed Water
BP	British Petroleum
bbl	Barrel
Btu	British Thermal Unit
BTX	Benzene, Toluene, Xylene
°C	Degrees Centigrade (Celsius)
$C_{\#}$	Carbon Number (e.g., C_1 = Methane)
CF	Cash Flow
CSP	Huels Complete Saturation Process
cSt	Centistokes
DCF	Discounted Cash Flow
DOE	United States Department of Energy
EP	Endpoint
°F	Degrees Fahrenheit
F-T	Fischer-Tropsch
gal	U.S. Gallon
GJ	Giga Joule
h	Hour
HC	Hydrocracking
HP	High Pressure
IBP	Initial Boiling Point
IRR	Internal Rate of Return
ISBL	Inside Battery Limits
kW	Kilowatt
kWh	Kilowatt Hour
LPG	Liquefied Petroleum Gas
lb	Pound (Mass)
LHSV	Liquid Hourly Space Velocity
LP	Low Pressure
M	Thousands
MM	Millions

Abbreviation	Meaning
MONC	Motor Octane Number
MP	Medium Pressure
MT	Metric Ton (1,000 kg)
MTA	Metric Tons per Annum
MT/d	Metric Tons per Day
NHT	Naphtha Hydrotreater
OSBL	Outside Battery Limits
ROI	Return on Investment
PETC	Pittsburgh Energy Technology Center
ppm	Parts per Million
psia	Pounds per Square Inch Absolute
psig	Pounds per Square Inch Gauge
RONC	Research Octane Number
RVP	Reid Vapor Pressure
SCFD	Standard Cubic Feet per Day
Wt-%	Weight (Mass) Percent
Vol-%	Volume Percent
(R+M)/2	Average of Research + Motor Octane

APPENDIX A

DEFINITION OF INSIDE BATTERY LIMIT (ISBL) COSTS