5.0 INDIRECT LIQUEFACTION USING ENTRAINED GASIFICATION OF ILLINOIS #6 COAL

5.1 Introduction

Two entrained gasifiers were considered in this report, as was the procedure in Reference 1 where the Texaco and Shell-Koppers systems were used. Illinois #6 was the plant feedstock. Entrained systems are able to process all coal feedstock types and no specific modifications to the gasifiers were necessary to process this weakly-caking bituminous coal. In the Texaco system, where a coal-water slurry is used to introduce the coal to the pressurized gasifier, high carbon concentrations in the slurry can be readily obtained with Illinois #6 coal without the necessity of prior coal drying.

5.2 Data Sources Used for Process Evaluation

5.2.1 Texaco

Gasification data for the Texaco system were obtained from a study prepared by Fluor Engineers and Constructors and sponsored by EPRI.[12] The Fluor analysis employed an Illinois #6 coal feedstock having a substantially lower moisture content than the coal considered in this report. To compensate for this difference, gasifier inputs and corresponding outputs were scaled to the DAF coal input of 1,869,000 pounds per hour used for total plant coal in this report. Total water content entering the gasifier was then adjusted to be the same as in the Fluor case by slurrying the coal with less water. The result of this was that the slurry concentration obtained was 74 to 26 as-received coal-to-water.

5.2.2 Shell-Koppers

Gasification data for the Shell-Koppers system were obtained from a publication by Shell International Petroleum.[13] Data were given for several coals, one of which was an Illinois #6 bituminous. Again, the coal analysis was not exactly the same as the Illinois #6 analysis used in this report, but the comparison was performed on the same weight of DAF coal. In the Shell paper, the coal was dried to 2 percent moisture before feeding to the gasifier. To obtain comparable output from the Shell data, their output was scaled to the DAF coal input of 1,869,000 pounds per hour. Adjustments were then made to compensate for the extra moisture contained in the Illinois coal used in this report. The decision was made that as-received coal could and should be fed directly to the gasifier without drying.

5.3 Systems Descriptions and Analyses

5.3.1 Texaco

The indirect liquefaction plant using Texaco gasifiers is designed to process 27,800 tons per stream day of as-received Illinois #6 coal. All the coal entering the plant is sent to the gasifier, since sensible heat recovery from the product gases leaving the gasifier is considered sufficient to produce all steam requirements.

Data from Reference 12 were scaled to total DAF coal plant input, and the resulting coal-to-water slurry concentration of 74 to 26 was then adjusted to a more reasonably obtainable slurry concentration of 65 to 35 coal-to-water. This corresponds to the coal being slurried as-received. Appendix C shows the computation of resulting gasifier output for this adjustment in slurry concentration.

Table 5-1 shows the material and energy flux at each stage of the production of clean synthesis gas for the Texaco Synthol system. The raw gasifier output contains a small amount of methane but no C_2 or other heavy hydrocarbon species. Other gas impurities include H_2S, COS, NH_3, etc. For raw gas production the efficiency is 74.4 percent. This efficiency is the same as the net efficiency since all plant coal is sent to gasification. As in the Wyoming coal feedstock case, we have concluded that the Texaco system can produce sufficient waste heat to eliminate the need for a coal- burning steam plant. This capability, however, is marginal and probably requires a sophisticated use of waste heat in the plant.

The plant configuration in the Texaco case is the same as for the Texaco case using Wyoming coal in Reference 1 (see (1), Figure 5-6) except that no coal drying facilities are required. For Synthol synthesis, the total raw gas stream passes to the shift conversion unit for adjustment of the hydrogen-to-carbon monoxide mole ratio to

TABLE 5-1

MATERIAL AND ENERGY FLUX IN SYNTHESIS GAS PREPARATION UNITS
FOR TEXACO/SYNTHOL SYSTEM
(ILLINOIS #6 COAL)

COMPONENT	INPUTS		RAW GASIFIER OUTPUT			SHIFTED RAW GAS			CLEAN GAS TO SYNTHESIS		
	Mlb/hr	MMBtu/hr	MlbMoles/hr	Mlbs/hr	MMBtu/hr	MlbMoles/hr	Mlbs/hr	MMBtu/hr	MlbMoles/hr	Mlbs/hr	MMBtu/hr
CO			91.86	2574	11187	45.2	1266	5503	4502	1261	5481
H_2			66.12	137	7089	114.8	231	11947	114.3	230	11899
CH_4			0.188	3	65	0.188	[illegible]	65	0.182	2.9	63
C_2			0	0	0	0	0	0	0	0	0
CO_2			28.05	123[illegible]	0	74.73	3288	0	[illegible]	0	0
H_2O			66.[illegible]	1195	0	26.62	479	0			
H_2S			2.3[illegible]	8[illegible]	525	2.37	81	525			
NH_3			0.46	[illegible]	63	0.46	8	63			
INERTS	37.728		2.04	57	0	2.04	57	0			
TOTAL GASES			259.5	5298	18924	266.4	5506	18103			
TARS											
OILS											
PHENOLS											
NAPHTHA											
TOTAL			259.5	5288	18924	266.4	5506	18103	164.3	1707	17443
COAL/ASH	[illegible]	25443		[illegible]							
STEAM WATER	[illegible]					6.689	120				
OXYGEN	[illegible]										
FLUX											
TOTAL	5505.9										
EFFICIENCY [illegible]					.744			.712			.686

2.54. For Kolbel synthesis, the raw gas hydrogen-to-carbon monoxide ratio of 0.74 can be directly utilized in the synthesis unit without external shift.

Texaco can produce clean synthesis gas with a net LHV efficiency of 68.6 percent. Syngas is produced at the rate of 159.3 M pound moles per hour. This is equivalent to 60 x 10^6 SCFH of clean synthesis gas.

Refined products from Synthol are shown in Table 5-2 derived from two process configurations, mixed output and all-liquid cases. In the all-liquid case, 2.29 barrels of refined C_4^+ liquids are produced per ton of dry coal at an overall HHV efficiency of 47.2 percent. This can be compared to the Texaco case using a Wyoming coal where 2.21 barrels of liquids were produced at an efficiency of 48.6 percent. Table 5-3 shows the outputs of refined products obtained with Kolbel synthesis. The difference in efficiency between the mixed and all-liquid cases is only 2.0 absolute percent since little efficiency penalty is incurred in reforming the small quantity of C_1 and C_2 gases produced when using the Texaco-Kolbel combination. In the all-liquid case, 2.43 barrels of C_4^+ liquids are produced at an HHV efficiency of 52 percent. Approximately 12,000 extra barrels per day of gasoline are produced with this Kolbel system.

TABLE 5-2

PRODUCT SLATE FOR TEXACO/SYNTHOL SYSTEM
(ILLINOIS #6 COAL)

	Mixed			All-Liquid		
	MMBtu/hr Syngas	MMBtu/hr Total	B/SD MMSCF/SD*	MMBtu/hr Syngas	MMBtu/hr Total	B/SD
Gasoline		6,152	29,394		8,494	40,584
C_3		428	2,694		591	3,720
C_4		63	351		87	485
Diesel		1,251	5,616		1,727	7,754
Fuel Oil		358	1,511		494	2,086
Alcohol		706	4,458		974	6,155
Total Liquids		8,958	44,025		12,368	60,785
SNG		5,591	133.8*			
Totals		14,548			12,368	
FOE			58,192			49,472
Efficiency (HHV %)		55.6			47.2	
B C^+/Ton Dry Coal			1.66			2.29

Syngas = 159.36 1000 # moles

Gasifier Naphtha = 0 Btu

Gasifier Methane = 68.[illegible] Btu

TABLE 5-3

PRODUCT SLATE FOR TEXACO/KOLBEL SYSTEM
(ILLINOIS #6 COAL)

	Mixed			All-Liquid		
	MMBtu/hr Syngas	MMBtu/hr Total	B/SD MMSCF/SD*	MMBtu/hr Syngas	MMBtu/hr Total	B/SD
Gasoline		10,107	48,293		10,888	52,022
C_3		813	5,112		875	5,506
C_4		0	0		0	0
Diesel		1,410	6,332		1,519	6,821
Fuel Oil		156	660		168	721
Alcohol		162	1,024		175	1,103
Total Liquids		12,648	61,420		13,625	66,162
SNG		1,601	38.3*			
Totals		14,249			13,625	
FOE			56,996			54,[illegible]
Efficiency (HHV %)		54.4			52.0	
B C_4^+/Ton Dry Coal			2.26			2.43

Syngas = 159.36 1000 # moles

Gasifier Naphtha = 0 Btu/hr

Gasifier Methane = 68.9 Btu/hr

5.3.2 Plant Construction Costs

Table 5-4 shows the elements of plant construction costs for the Texaco gasification systems coupled with Synthol and Kolbel systems.

Coal handling costs have increased over the dry-ash Lurgi case slightly because of equipment necessary for coal-water slurry preparation. For the Synthol case, in the preparation of synthesis gas, the total raw gas stream is sent to shift and the cost of the two-stage shift reactor is scaled from a vendor estimate. Since the shifted gas cooler in this case is such a large unit, as it handles the total stream, its cost was scaled from the base case raw gas cooling unit which is a larger unit than the base case shift unit. The gasifier cost was the same as for the Wyoming coal case as in Reference 1, with scale adjustments for total gas flow applied to the waste heat recovery section. Byproduct recovery is less expensive than the fixed-bed system, since no phenol recovery or gas liquor facilities are necessary when handling Texaco gas. Synthesis and upgrading are more costly with Texaco than with the fixed-bed units because of the greater volume of synthesis gas with a correspondingly larger quantity of raw Fischer-Tropsch products to be refined. The very costly oxygen plant is required with Texaco because of the high oxygen requirements in the gasifier. The oxygen-to-DAF coal ratio for Texaco is 1.02, compared to 0.62 for the BGC Lurgi and 0.56 for the dry-ash Lurgi. This high oxygen requirement is needed to vapor-

TABLE 5-4

CONSTRUCTION COST FOR TEXACO SYSTEMS
(ILLINOIS #6 COAL)
(MM 1977 $)
(27.8 M Tons/Day As-Received Coal)

System / Unit Description	Texaco/Synthol Illinois #6 Coal		Texaco/Kolbel Illinois #6 Coal	
	Mixed	All-Liquid	Mixed	All-Liquid
Coal & Ash Handling	72.2	72.2	72.2	72.2
Synthesis Gas Preparation	361.6	361.6	300.1	300.1
Gasifiers	53.0		53.0	
Gas Cooling	106.0		106.0	
Shift	38.2		0	
Gas Cleaning	164.4		141.1	
By-Product Recovery	108.8	108.8	66.2	66.2
Gasifier Naphtha Treatment	0	0	0 0	0
Synthesis	194.4	243.6	223.2	235.7
SNG Preparation or Reforming	20.3	33.9	8.4	14.1
F-T Liquid Recovery & Upgrading	171.6	215.1	208.7	219.6
Oxygen Plant	298.5	318.7	298.5	304.4
Steam Plant*	57.9	61.2	57.9	58.9
Waste Water Treatment	8.5	13.0	6.0	6.0
Miscellaneous	108.0	108.0	108.0	108.0
TOTALS	1,401.8	1,536.1	1,349.2	1,385.2

*BFW preparation/LP + MP superheater + CW towers only.

ize the slurry water used to transport the coal into the pressurized reactor, as well as to provide the necessary reaction heat for the high temperature operation and the endothermicity of the steam-carbon system. Since waste heat recovery for the gasifier is expected to provide steam balance for the plant, no separate coal-fired steam plant is required. However, associated units like boiler feed water treatment, low pressure and medium pressure superheaters, cooling water towers and cooling water makeup are still necessary.

For the Texaco-Kolbel system, synthesis gas preparation is less expensive since no external shift is required. Eliminating the gas shift results in a smaller Rectisol system as no extra carbon dioxide is produced in the gas stream. A savings of $103 million in synthesis gas preparation and byproduct recovery is realized by eradicating the need for shift. Less waste-water treatment is required with the Kolbel system as the predominant byproduct of synthesis is carbon dioxide and not water.

5.3.3 Product Costs

Table 5-5 shows the cost data for the Texaco indirect liquefaction plant for mixed and all-liquid outputs using Synthol and Kolbel synthesis. On a market basis for all-liquid output, use of Kolbel reflects a potential savings in product costs for gasoline of 22¢/gallon (i.e., 21 percent). For all-liquid products, plant coal costs represent approximately 19 percent of the total product costs.

TABLE 5-5

COST DATA FOR TEXACO SYSTEMS WITH ILLINOIS #6 COAL
(27.8 M Tons/Day As-Received Coal)

System	Mode	Construction Cost (MM $)	HHV Output (MMBtu/hr)	Capital Derived Cost ($/MMBtu)	Total Cost ($/MMBtu)	Gasoline Cost ($/Gallon)	
						Thermal	Market
Texaco-Synthol	M	1,401.8	14,548	6.45	8.07	0.97	1.13
	AL	1,536.1	12,368	8.31	10.22	1.22	1.27
Texaco-Kolbel	M	1,349.2	14,249	6.35	8.02	0.96	1.01
	AL	1,385.2	13,625	6.82	8.55	1.02	1.05

M = Mixed Output
AL = All Liquid Output

Comparison of gasoline cost on a market basis obtained with Illinois #6 coal to that obtained using Wyoming coal as feedstock (Reference 1) shows that in spite of the considerably lower cost of the Wyoming coal, the gasoline cost is very similar for both coal feedstocks. The gasoline cost for Texaco-Kolbel all-liquids using Wyoming coal is $1.01/gallon. For Illinois coal, it is $1.05/gallon. Gasoline costs for Texaco-Synthol with Wyoming coal are $1.23/gallon, and for Illinois coal, $1.27/gallon.

5.3.4 Shell-Koppers

The computation of raw gas output from the Shell-Koppers gasifier is shown in Appendix C. This analysis computes the raw gas produced from an Illinois #6 coal dried to 2 weight percent moisture from data given in Reference 13. In the present plant analysis using Shell-Koppers it is desirable to feed as-received Illinois #6 coal with its 10 percent moisture content. Appendix C therefore also computes the adjustments in raw gas output obtained when gasifying the as-received coal.

Table 5-6 shows the material and energy fluxes at each stage in the production of clean synthesis gas for the Shell-Koppers Synthol system. The raw gas contains essentially only synthesis gas with a little carbon dioxide, steam and impurities. For raw gas production, the net efficiency is 81.8 percent. Again, sensible heat recovered in the waste heat boilers of the gasifiers is assumed to be suffic-

TABLE 5-6

MATERIAL AND ENERGY FLUX IN SYNTHESIS GAS PREPARATION UNITS
FOR SHELL-KOPPERS/SYNTHOL SYSTEM
(ILLINOIS #6 COAL)

COMPONENT	INPUTS		RAW GASIFIER OUTPUT			SHIFTED RAW GAS			CLEAN GAS TO SYNTHESIS		
	Mlb/hr	MMBtu/hr	MlbMoles/hr	Mlbs/hr	MMBtu/hr	MlbMoles/hr	Mlbs/hr	MMBtu/hr	MlbMoles/hr	Mlbs/hr	MMBtu/hr
CO			115.746	3242	14092	49.359	1383	6010	49.162	1377	5986
H_2			58.985	119	6138	125.372	253	13047	124.87	252	12994
CH_4			0	0	0	0	0	0		-	
C_2			0	0	0	0	0	0			
CO_2			5.211	229	0	71.598	3150	0	4.65	205	0
H_2O			13.609	245	0	27.780	500	0			
H_2S			2.61	89	579	2.61	89	579			
NH_3			-	0	0	-	0	0			
INERTS	16.9		1.33	37	0	1.329	372	0			
TOTAL GASES			197.49	3961	20809	278.048	5412	19636	178.686	1833	18980
TARS			-	-	-						
OILS			-	-	-						
PHENOLS			-	-	-						
NAPHTHA			-	-	-						
TOTAL			197.49	3961	20809	278.048	5412	19636	178.686	1833	18980
COAL/ASH	(1859 DAF) 2317	25443									
STEAM	144.077										
OXYGEN	168.3					80.3	1445				
FLUX	0										
TOTAL	4165.1			4122							
EFFICIENCY (%)					.820			.772			.744

ient to produce all steam requirements for oxygen production, gasifier steam and other downstream plant units and no separate coal-fired steam plant is included.

For this Illinois coal feedstock the oxygen-to-DAF coal ratio is 0.902 and the steam-to-DAF coal ratio is only .077. This can be compared to the parameters used when gasifying Wyoming coal[1] of .828 for the oxygen-to-MAF coal ratio and .03 for the steam-to-coal ratio.

Downstream plant configuration using the Shell-Koppers gasifier is identical to that when using the Texaco system. Because of the low hydrogen-to-carbon monoxide mole ratio in the off-gas, considerable shift is required for Synthol synthesis. Thus, the total raw gas stream is passed to shift, including the addition of 80 M pound moles of extra shift steam that is required because of the dry nature of the Shell-Koppers gas. When the Shell-Koppers system is coupled to Kolbel, only a portion of the gas needs to be shifted to bring the hydrogen-to-carbon monoxide ratio up to the 0.67 requirement. Shell-Koppers can produce clean synthesis gas with a net LHV efficiency of 74.6 percent at a rate of 174 M moles per hour.

Table 5-7 shows the quantities of refined products produced with the Shell-Koppers Synthol combination for as-received Illinois #6 coal. In the mixed output case, although no methane is produced in the gasifier, SNG production is still 144 MMSCF per day. For the all-liquids case, 2.49 barrels of C_4^+ liquids are produced per

TABLE 5-7

PRODUCT SLATE FOR SHELL-KOPPERS/SYNTHOL SYSTEM
(ILLINOIS #6 COAL)

	Mixed			All-Liquid		
	Btu Syngas	Btu Total	B/SD MMSFC/SD*	Btu Syngas	Btu Total	B/SD
Gasoline		6,718	32,101		9,245	44,170
C_3		468	2,943		644	4,049
C_4		69	384		95	528
Diesel		1,366	6,133		1,880	8,439
Fuel Oil		391	1,650		528	2,271
Alcohol		771	4,869		1,060	6,699
Total Liquids		9,783	48,079		13,461	66,156
SNG		6,030	144.3*			
Totals		15,813			13,461	
FOE			63,252			53,844
Efficiency (HHV %)		60.4			51.4	
B C_4^+/Ton Dry Coal			1.81			2.49

Syngas = 174.033 1000 # moles

Gasifier Naphtha = 0 Btu

Gasifier Methane = 0 Btu

ton of dry coal at a HHV efficiency of 51.4 percent. This is a large plant producing over 66,000 BPSD of total liquids.

For the Shell-Koppers Kolbel combination, the refined outputs are shown in Table 5-8. Only 40 MMSCF of SNG are produced in the mixed output when this combination is used. For the all-liquids production there is very little reforming of methane to be done, hence, 2.05 barrels of C_4^+ liquids per ton of dry coal can be produced at an HHV efficiency approaching 57 percent. For an all-liquids output indirect liquefaction plant, this represents the highest performance of the combinations studied in this report.

5.3.5 <u>Plant Construction Costs</u>

Table 5-9 shows the elements of construction costs for the Shell-Koppers gasification system coupled with Synthol and Kolbel units.

Costs of the Shell-Koppers gasifier were assumed equal to the Texaco, as was assumed in the Wyoming coal cases analyzed in Reference 1. For Synthol synthesis the large cost for shift reflects the need to pass all raw gas through this unit for correct adjustment of the hydrogen-to-carbon monoxide mole ratio. In the Kolbel case, only approximately 12 mole percent of the raw gas is sent to shift; thus the shift conversion unit is much smaller. This smaller shift requirement means less acid gas has to be removed and sent to the sulfur recovery unit. Byproducts recovery costs are therefore con-

TABLE 5-8

PRODUCT SLATE FOR SHELL-KOPPERS/KOLBEL SYSTEM
(ILLINOIS #6 COAL)

	Mixed			All-Liquid		
	MMBtu/hr Syngas	MMBtu/hr Total	B/SD MMSCF/SD*	MMBtu/hr Syngas	MMBtu/hr Total	B/SD
Gasoline		11,038	52,740		11,854	56,637
C_3		887	5,592		953	5,995
C_4		0	0		0	0
Diesel		1,540	6,915		1,654	7,426
Fuel Oil		171	720		183	774
Alcohol		177	1,118		190	1,200
Total Liquids		13,813	67,075		14,834	72,031
SNG		1,673	40.0*			
Totals		15,486			14834	
FOE			61,944			59,336
Efficiency (HHV %)		59.1			56.6	
B C_4^+/Ton Dry Coal			2.46			2.65

Syngas = 174.033 1000 # moles

Gasifier Naphtha = 0 Btu

Gasifier Methane = 0 Btu

TABLE 5-9

CONSTRUCTION COST FOR SHELL-KOPPERS SYSTEMS
(ILLINOIS #6 COAL)
(MM 1977 $)

Unit Description \ System	Shell-Koppers/Synthol Illinois #6 Coal		Shell-Koppers/Kolbel Illinois #6 Coal	
	Mixed	All-Liquid	Mixed	All-Liquid
Coal & Ash Handling	71.4	71.4	71.4	71.4
Synthesis Gas Preparation	350.7	350.7	290.6	290.6
Gasifiers	53.0		53.0	
Gas Cooling	89.7		86.7	
Shift	40.3		9.4	
Gas Cleaning	167.7		141.5	
By-Product Recovery	105.9	105.9	41.2	41.2
Gasifier Naphtha Treatment	0	0	0	0
Synthesis	206.7	258.5	238.5	251.6
SNG Preparation or Reforming	21.4	35.5	8.7	14.6
F-T Liquid Recovery & Upgrading	182.5	228.2	222.0	233.4
Oxygen Plant	274.3	296.9	274.3	280.6
Steam Plant*	55.4	59.1	55.4	56.4
Waste Water Treatment	23.6	27.2	8.4	7.9
Miscellaneous	108.0	108.0	108.0	108.0
TOTALS	1,400.0	1,541.4	1,318.5	1,355.7

*BFW preparation/LP + MP superheater + CW towers only.

siderably reduced. Savings of approximately 120 million dollars can be realized in the synthesis gas preparation and byproducts recovery sections of this plant because of the use of Kolbel synthesis. The cost of oxygen plants for these systems are again high because of the relatively high oxygen-to-coal ratio required with entrained gasifiers. The low cost of steam plants is because no coal burning plant is necessary. Only the accompanying boiler-feed water and cooling water tower accessories are needed. The lower cost of waste water treatment with the Kolbel system is the result of carbon monoxide being the major byproduct of synthesis in this unit.

5.3.6 Product Costs

Table 5-10 shows the cost data for the Shell-Koppers indirect liquefaction plants for mixed and all-liquid outputs using Synthol and Kolbel units. For the all-liquid outputs, both Synthol and Kolbel show reduced costs over the Texaco cases. Kolbel represents a potential savings of 23 percent for gasoline cost over the Synthol system when using Illinois #6 coal.

It is interesting to note that for the cases considered here, where the same quantity of as-received coal is processed for both Illinois #6 and Wyoming coal, the gasoline costs for both coal feedstocks are identical when using Shell-Koppers gasification. This means that the advantage of scale for the larger Illinois plant exactly compensates for the increased cost of the Illinois #6 coal feedstock.

TABLE 5-10

COST DATA FOR SHELL-KOPPERS SYSTEMS WITH ILLINOIS #6 COAL

System	Mode	Construction Cost (MM $)	HHV Output (MMBtu/hr)	Capital Derived Cost ($/MMBtu)	Total Cost ($/MMBtu)	Gasoline Cost ($/Gallon)	
						Thermal	Market
S-K/Synthol	M	1,400.0	15,813	5.92	7.42	0.89	0.99
	AL	1,541.4	13,461	7.66	9.41	1.13	1.16
S-K/Kolbel	M	1,318.5	15,486	5.69	7.22	0.86	0.90
	AL	1,355.7	14,834	6.11	7.71	0.92	0.94

M = Mixed Output
AL = All-Liquid Output