3.0 INDIRECT LIQUEFACTION USING WESTINGHOUSE FLUID BED GASIFICATION

3.1 Introduction

The technical and economic advantages of substituting a Westinghouse gasifier for the dry-bottom Lurgi gasifier in a U.S. plant otherwise employing SASOL technology has been evaluated. There is not sufficient data available from SASOL to permit the actual SASOL plants to be used as a basis of comparison. The base case employed is a recent Mobil Research and Development Corporation (MRDC) Lurgi assessment of Fischer-Tropsch, involving a SASOL-type plant at a U.S. location.[3] Analysis methods used herein are identical to those used in Reference 1 to evaluate the substitution of Texaco, Shell-Koppers and BGC gasifiers into this baseline plant. Specifically, the alternative gasifier system is substituted and minimum other system changes are made to accommodate it in a practical system design. The scope of the effort has not permitted the plant system to be fully optimized to take advantage of each gasifier. However, system changes required to permit a fair and equitable analysis of each gasifier have been made and opportunities for further systems improvement through system optimization are noted.

After the plant has been modified to accept the new gasifier, heat and mass balances and process unit capacities are calculated. Costs of individual process units are scaled from the costs of similar units in the base case where possible. Vendor estimates or alternative sources are used for process units not present in the base case. This methodology permits the effect of gasifier substitution on cost, efficiency and output to be determined.

The prior MITRE effort also evaluated the effect of using Kolbel slurry phase synthesis in lieu of the Synthol fast fluid bed synthesis units employed at SASOL. The performance of Westinghouse gasifiers combined with the advanced synthesis system is evaluated herein.

The prior study considered only a Wyoming subbituminous coal feedstock. The performance of the gasifiers previously considered has been reevaluated when Illinois #6 coal is used as a feedstock. These results are presented in Section 4.0 of this report. For the Westinghouse gasifier, performance with both Wyoming subbituminous and Illinois #6 coal is presented in this section.

3.2 Plant Configuration

Figure 3-1 shows a schematic of an indirect liquefaction plant employing Westinghouse gasification. The only changes from the SASOL-U.S. base case which are evident at this level of detail is the elimination of the coal fired steam plant. All steam requirements are met from waste heat from the Westinghouse gasifier and other exothermal processes in the design shown. Other changes from the base case are in the gas cooling, cleaning and shift section and are discussed in Section 3.4, Gas Preparation.

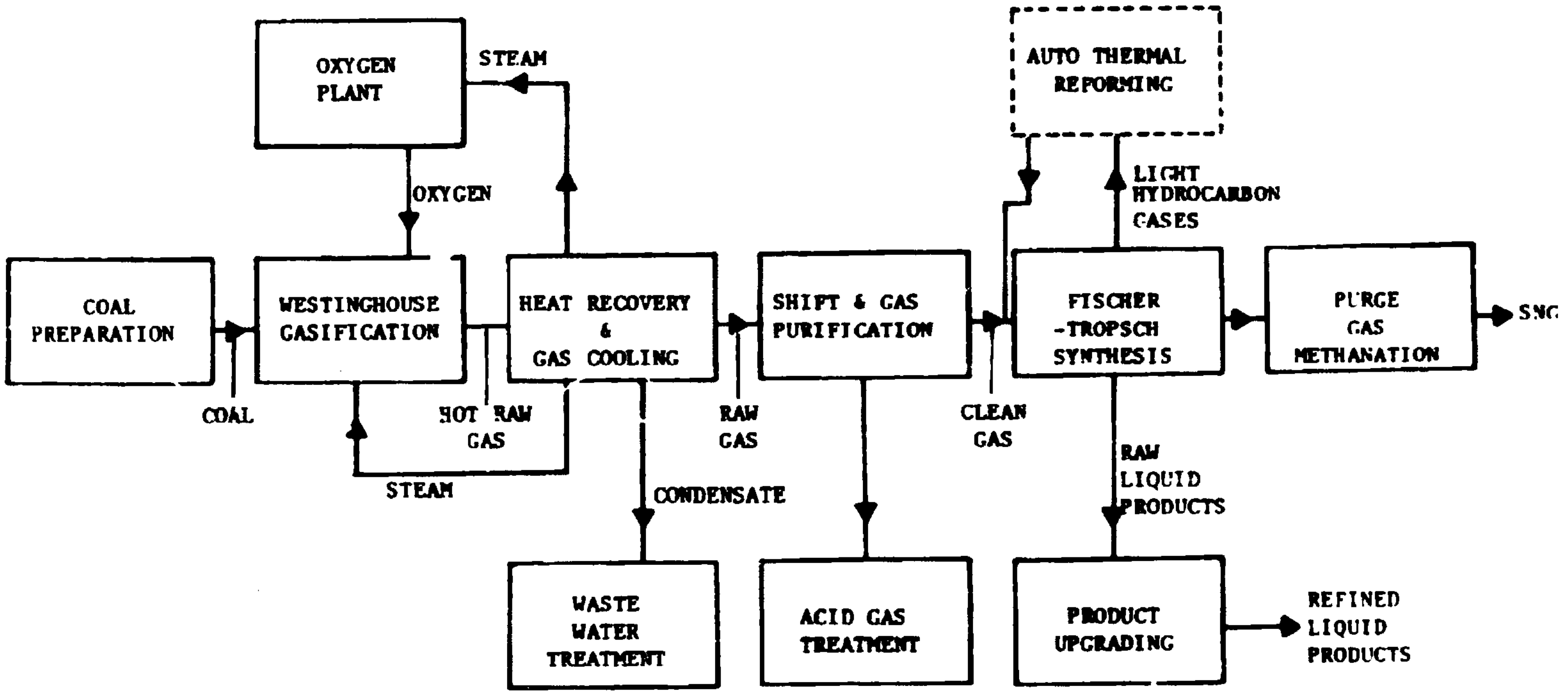


FIGURE 3-1
SCHEMATIC OF INDIRECT LIQUEFACTION PLANT EMPLOYING WESTINGHOUSE GASIFICATION

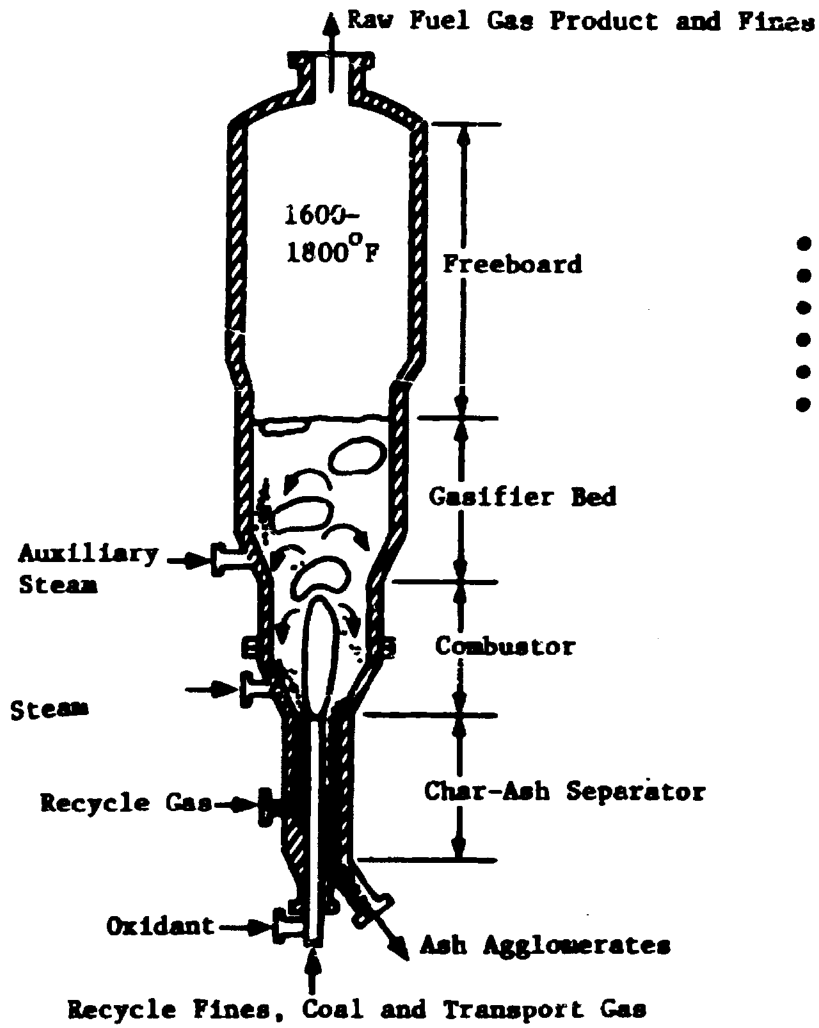
Note that Figure 3-1 shows two alternative modes of operation. In the mixed product mode, when both liquids and SNG are produced, purge gas from the Synthol unit is methanated to produce SNG. If an all-liquid product is desired the purge gases, which contain methane produced in the gasifier and synthesis units, as well as unconverted H_2 and CO, are autothermally reformed (i.e., partially oxidized) in the purge gas reforming unit shown in broken lines and returned to the synthesis unit. Operation in the all-liquid mode is substantially less efficient than the mixed product mode since about 39 percent of the energy in the SNG product is lost in its ultimate conversion to a liquid product.

3.3 Westinghouse Gasification

3.3.1 Gasifier Operation

The Westinghouse agglomerating ash fluid bed gasifier(4) is illustrated in Figure 3-2. Coal is pneumatically transported from lock hoppers into the gasifier where it is combined with input streams of steam and oxygen using recycle gas. The combustion of a portion of the incoming coal produces the heat necessary to devolatilize the remainder of the incoming coal to form a char and to react the char with steam to form hydrogen and carbon monoxide.

As the bed of char circulates through the jet formed at the end of the central feed tube, the carbon in the char is consumed by combustion and gasification, leaving particles that are rich in ash.



- CARBON STEEL VESSEL
- REFRACTORY LINING
- PNEUMATIC COAL FEED
- AIR/OXYGEN CONFIGURED
- DRY ASH WITHDRAWAL
- FINES RECYCLE

FIGURE 3-2
WESTINGHOUSE PRESSURIZED FLUIDIZED BED GASIFIER

The unique fluid dynamic design of the gasifier allows the ash-rich particles to agglomerate and form large, dense particles, which defluidize from the bed and collect in the ash annulus. These agglomerates are cooled and removed through a lock hopper system. A large inventory of unreacted carbon is always present in the bed. This inventory dilutes the incoming coal feed and permits agglomerating coals to be fed without pretreatment.

Raw product gas from the gasifier passes through cyclones to recover entrained particles, which are recycled to the gasifier. The gas next passes through heat exchangers and then is water quenched in a Venturi scrubber. A third of the quenched gas is recompressed for use as a transport gas and bed fluidization medium.

The Westinghouse unit is the outgrowth of nine years of development under OCR/ERDA/DOE sponsorship. The development has closely paralleled the development of the IGT U-Gas gasification system. Both were initially two-stage systems accomplishing devolatilization and char gasification in separate chambers. Both efforts have recently concentrated on development of a reliable agglomerating ash single-chamber unit. An indication of the advanced state of the Westinghouse gasifier development is provided by the recent announcement that SASOL plans to install a 1200 T/D unit at the liquefaction facility in Secunda, South Africa.

Several unique advantages can be obtained in a fluid bed unit having a reaction temperature intermediate between the fixed-bed and entrained-flow system. The intermediate temperature (usually about 1800 to 1900°F) is high enough to react tar, oil, phenol and naphtha, which are present in the output of fixed bed units, but low enough to be contained in vessels protected by conventional refractory material. Unlike entrained flow systems, the output of the fluid bed unit is cool enough to employ conventional heat recovery systems without fear of molten slag impingement problems.

The major limitation of fluid-bed systems is the carry over of fines with the exit gas. In an agglomerating ash system such as Westinghouse, there is the further problem of carbon trapped in the ash globule. Through a combination of cyclone separation and recycle of fines and well controlled slag agglomeration by use of recycled gas as a fluidization medium, Westinghouse has achieved 97 percent carbon utilization in test runs. A more conservative figure of about 96 percent carbon utilization is assumed in the data supplied by Westinghouse for use in this study.(5)

3.3.2 Gasifier Performance

Table 3-1 shows gasifier input and output for both Wyoming sub-bituminous and Illinois #6 coals.(5) The quantity of coal gasified in both cases is 2,317 M lb/hr. The gasifiers are identical 14.5 foot diameter units. Thirteen gasifiers are required in the Wyoming

TABLE 3-1

SUMMARY DATA FOR WESTINGHOUSE COAL GASIFICATION FOR ILLINOIS #6 AND WYOMING SUBBITUMINOUS C COALS(5)

	Illinois #6	Wyoming Sub-C
Input		
Coal to Gasifiers, M lb/hr		
(as-received)	2,317	2,317
(MAF)	1,869	1,550
Steam to Gasifiers,		
M lb/hr	1158.4	579.15
Steam lb/lb MAF Coal	0.620	0.374
Oxygen to Gasifiers,		
M lb/hr	1343.2	1232.53
Oxygen lb/lb MAF Coal	0.720	0.795
Output		
Net Gas Output, SCFH	80.30×10^6	65.75×10^6
Product Gas Composition,		
Volume %		
CO	34.98	32.70
H_2	27.5	24.95
CH_4	4.88	4.25
CO_2	12.54	16.63
H_2S/COS	1.32	0.12
NH_3	0.12	.07
N_2	0.54	.48
H_2O	18.12	20.80
Carbon Utilization	96%	97%
Operating Parameters		
Freeboard Temperature, °F	1900	1800
System Pressure, psig	400	400
Reactor Size, Diam. ft.	14.50	14.50
Number of Reactors	16	13
Gas Exit Temperature from		
Heat Recovery, °F	425	425

coal case and 16 are required if Illinois #6 coal is used. Throughput of coal per gasifier, measured on a DAF basis, is similar for the two coals.

When measured on a DAF basis, steam requirements for the Illinois #6 coal are higher than for the Wyoming coal, while oxygen requirements are lower. This occurs because the major source of steam in the Wyoming coal case is the moisture in the coal. Producing steam from this source requires a slightly higher sensible heat release in the gasifier and, hence, more oxygen than is required in the Illinois #6 case.

Gas compositions are almost identical for both the Wyoming and Illinois coals used. In both cases fluidization is achieved by recycle of cooled synthesis gas. The recycle-to-plant feed ratio is 1:2. The quantity of hot gas which passes through the waste heat recovery system is thus 1.5 times greater than the net gas output. Heat recovered when these gases are cooled is adequate to meet steam requirements in the mixed product plant analyzed herein, thus obviating the need for a separate steam plant. Overall steam balances were somewhat less critical than in the case of the Texaco and Shell-Koppers entrained-flow systems which were also judged to be capable of operation without coal burning steam plants.

3.4 Synthesis Gas Preparation

Synthesis gas preparation consists of cleaning, cooling and shifting 425°F gas which exits the waste heat recovery system of the Westinghouse gasifier. These operations are shown schematically in Figure 3-3. After passing through the quench scrubber, one-third of the gas is compressed and returned to the gasifier as the fluidization media. The balance represents the net product of the gasification process.

The raw gas is shifted to obtain the H_2/CO ratio required for the downstream synthesis process. When Synthol Fischer-Tropsch reactors are used, an H_2/CO ratio of 2.54 is required. The gasifier H_2/CO ratio in the western coal illustrated in Figure 3-3 is 0.76.

The shift reactor employed is a two stage design. In the first stage moisture in the raw gas is used as a source of shift steam. The shift process proceeds until the moisture in the shifted stream is reduced to 10 percent by volume. The gas stream, which has been heated by the exothermal shift reaction, is then cooled by the injection of low quality, unsaturated steam. It is then passed through a second shift reactor. The shift steam is produced from heat recovered from the shift gas coolers.

After shift, the gas is passed through a Rectisol unit for removal of CO_2, H_2S and COS. The remaining moisture in the stream is also removed in this unit. Note that there is no requirement for

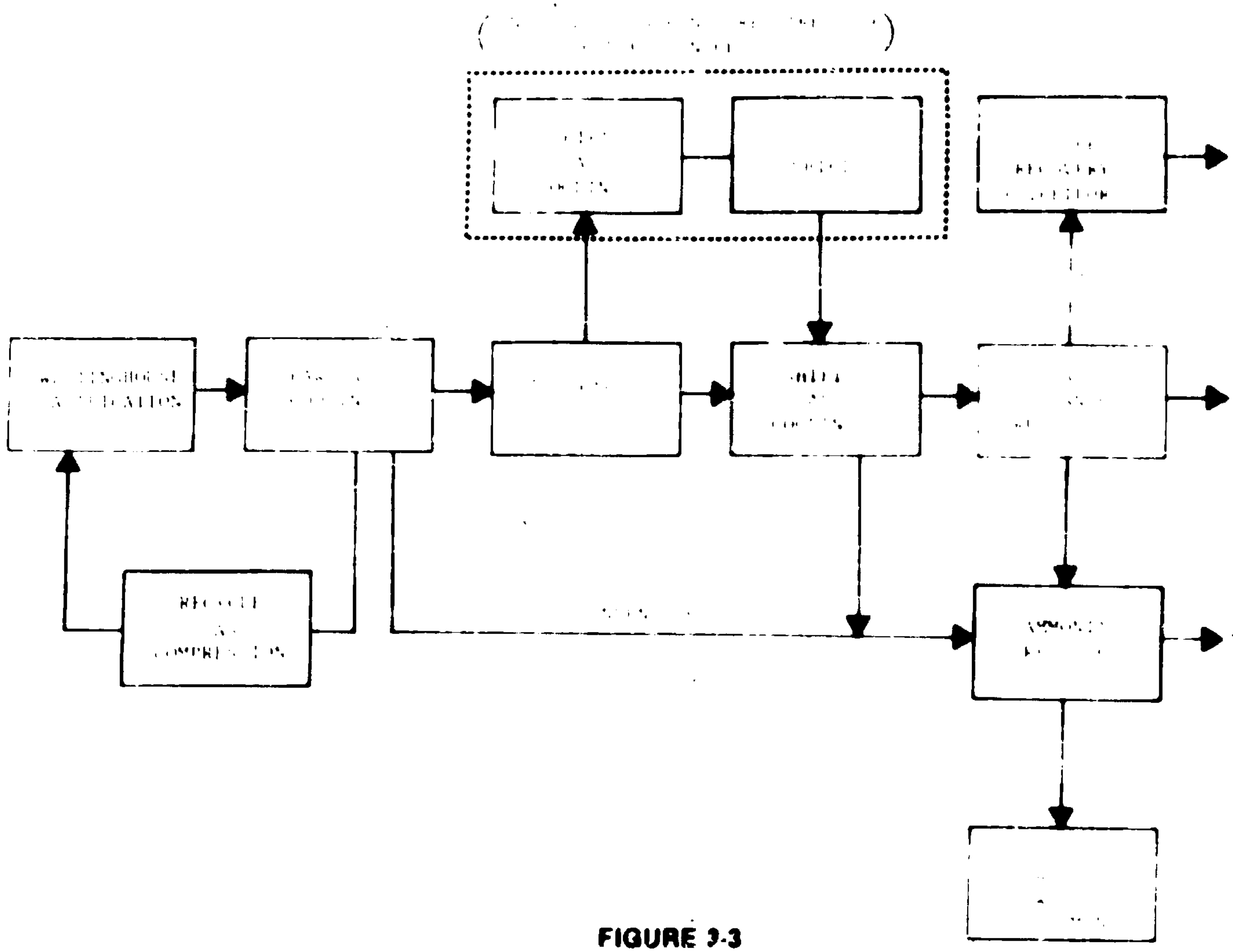


FIGURE 3-3
SYNTHESIS GAS PREPARATION USING WESTINGHOUSE GASIFICATION

a gas/liquor separation unit since there are no hydrocarbon species in the gas heavier than methane.

Tables 3-2 and 3-3 show the composition and LHV of the net raw gasifier output, shifted gas and clean gas for Wyoming and Illinois #6 coals, respectively.

3.5 Product Synthesis and Upgrading

3.5.1 Introduction

The Westinghouse gasification system has been evaluated with two types of Fischer-Tropsch synthesis systems—the fast fluid bed Synthol system used at SASOL and a slurry phase system based on Kolbel technology. The two systems are described and compared in Reference 1. The primary technical advantage of the Kolbel based system is its superior temperature control which permits better selectivity of the hydrocarbon species which are synthesized. This advantage is illustrated in Table 3-4, which compares the output of Synthol and Kolbel synthesis systems. Note that the weight percent of products in the gasoline and diesel boiling range (C_5-320°C) is much higher for the Kolbel system and that the production of methane and C_2 is much lower. A secondary advantage of the Kolbel system is its ability to accept synthesis gas with an H_2/CO ratio of .6 to .8 versus 2.54 for Synthol. The output of many advanced gasifiers, including Westinghouse, can be synthesized with no shift requirement.

[illegible]

COMPONENT	INPUTS [illegible]	INPUTS [illegible]	RAW GASIFIER OUTPUT [illegible]	RAW GASIFIER OUTPUT [illegible]	RAW GASIFIER OUTPUT [illegible]	SHIFTED RAW GAS [illegible]	SHIFTED RAW GAS [illegible]	SHIFTED RAW GAS [illegible]	CLEAN GAS [illegible]	CLEAN GAS [illegible]	CLEAN GAS [illegible]
CO			[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
H_2			[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		
CH_4			[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		
C_2											
CO_2			[illegible]	[illegible]		[illegible]	[illegible]			[illegible]	
H_2O			[illegible]	[illegible]		[illegible]	[illegible]				
H_2S			[illegible]		[illegible]	[illegible]		[illegible]			
NH_3											
INERTS			[illegible]			[illegible]					
TOTAL GASES			[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]		[illegible]
TARS											
OILS											
PHENOLS											
NAPHTHA											
TOTAL			[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]			
COAL/ASH	[illegible]	[illegible]									
STEAM	[illegible]			[illegible]	[illegible]						
OXYGEN	1,[illegible]										
FLUX CARBON				[illegible]							
TOTAL	[illegible]	[illegible]		[illegible]							

EFFICIENCY

[illegible]

TABLE [illegible]

MATERIAL AND ENERGY FLOW IN SYNTHESIS GAS PREPARATION UNITS
FOR WESTINGHOUSE SYSTEM
(ILLINOIS #6 COAL)

COMPONENT	INPUTS Mlb/hr	INPUTS MMBtu/hr	RAW GASIFIER OUTPUT Mlb-moles/hr	RAW GASIFIER OUTPUT Mlbs/hr	RAW GASIFIER OUTPUT MMBtu/hr	SHIFTED RAW GAS Mlb-moles/hr	SHIFTED RAW GAS Mlbs/hr	SHIFTED RAW GAS MMBtu/hr	CLEAN GAS TO SYNTHESIS Mlb-moles/hr	CLEAN GAS TO SYNTHESIS Mlbs/hr	CLEAN GAS TO SYNTHESIS MMBtu/hr
CO			[illegible],118	2,076	9,025	37,476	1,050	4,561	[illegible]	[illegible]	[illegible]
H_2			58,561	118	6,092	95,105	193	9,905	96,004	191	1,836
CH_4			10,366	166	1,567	10,366	166	1,56[illegible]	10,036	161	1,600
C_2			0	0	0	0	0	0			
CO_2			26,5[illegible]	1,169	0	61,216	2,701	0	4,167	180.8	0
H_2O			38,395	691	0	23,552	470	0			
H_2S			2,804	96	622	2,804	96	622			
NH_3			356	6	35	356	6	35			
INERTS			1,168	32	0	1,168	32	0			
TOTAL GASES			212,176	6,152	19,360	235,515	6,[illegible]	18,692	166,271	1,570	17,871
TARS											
OILS											
PHENOLS											
NAPHTHA											
TOTAL			212,176	6,352	19,360	235,215	6,722	18,692	166,271	1,570	17,871
COAL/ASH	2,317	25,443		255							
STEAM/H_2O	1,150.4			191		23,339					
OXYGEN	1,163.2										
FLUX/CARBON				25							
TOTAL	4,818.6	25,443		6,821							
EFFICIENCY					.760			.735			.702

(Efficiency shown is output HHV divided by HHV of as-received coal input.)

TABLE 3-4

PRODUCT SELECTIVITY FOR SYNTHOL AND KOLBEL FISCHER-TROPSCH SYNTHESIS REACTORS[1]

Product Wt % of Total Hydrocarbons	Kolbel	Synthol
$C_1 + C_2$	6.8	22.8
C_3	22.6	15.3
C_4	5.1	10.6
C_5 - 320°C	63.6	46.6
>320°C	1.9	4.6

The Westinghouse gasification system has been evaluated for plants producing a mixed output of SNG and liquid products and for plants producing an all-liquid output slate. It is in the all-liquid case that the advantages of Kolbel synthesis are most pronounced, since all light gases produced must be reformed at substantial thermal loss to [illegible]duce the required all-liquid output.

Liquid product upgrading is accomplished in a refinery complex designed to maximize the production of specification RVP-10 gasoline. The refinery design is adapted from MRDC.[3] Table 3-5 lists the upgrading units and briefly describes their function.

3.5.2 Performance of Plant Employing Synthol Synthesis

Products from Synthol synthesis and upgrading of clean synthesis gas produced from Westinghouse gasification of Wyoming sub-bituminous coal and Illinois #6 coal, respectively, are shown in Tables 3-6 and 3-7. With the Wyoming coal (Table 3-6) the mixed product output consists of 27,558 barrels of liquid fuel and 148.3 MMSCF per day of SNG. 1.29 barrels of C_4^+ liquids are produced per ton of dry coal processed. The overall efficiency, measured as the HHV of all output fuels divided by the HHV of the input coal, is 59.9 percent.

In the all-liquids case, 46,138 barrels per day of liquids, representing 2.16 barrels of C_4^+ per ton of dry coal, are produced. Efficiency is substantially lower (47.6 percent) as a result of losses incurred in reforming and resynthesizing the C_1 and C_2 products to extinction.

TABLE 3-5

PRODUCT UPGRADING UNITS FOLLOWING F-T SYNTHESIS[1]

No.	Unit	Process	Purpose
210	Hydrocarbon Recovery	Low Temp. Heptane Wash (prevents freezing out of CO_2)	Remove and recover heavy hydrocarbons from F-T synthesis purge gas to meet methanation feedstock specifications
211	Hydrogen Recovery	Pressure Swing Process (Union Carbide)	Recover hydrogen for use in the refinery
212	Methanation	Lurgi Process	SNG production (CO < 0.1%)
213	Carbon Dioxide Removal	Amine Guard Process (uses monoethanol amine MEA)	Lowers CO_2 content in SNG to 0.5%
214	SNG Drying/Compression	TEG Wash Process (Triethylene Glycol)	Dry SNG to 4 lb. moisture/MM SCF
251	Naphtha Hydrotreating	-	To produce clean stable naphtha for gasoline blending from raw gasifier naphtha
252	F-T Product Fractionation	4-Tower Dry System	Separates F-T products into light gases, feed for polymerization and hydrogenation and 850° residue for boiler fuel
253	F-T Product Hydrotreating	-	Saturates olefins and destroys remaining [illegible] and acids
254	Hydrotreater Product Fractionation	Conventional 3-Tower System	Separates hydrotreated products into pentane hexane stream for isomerization, [illegible] 380° for reforming, diesel and heavy fuel oil products
255	Catalytic Reforming	Platformer	To increase anti-knock quality of [illegible] 380° naphtha
256	C_5/C_6 Isomerization	Pt. Cat. Promoted with Organic Chlorides	Increase anti-knock of pentanes and hexanes
257	Catalytic Polymerization	Catalysed by Acids 85% Conversion Exothermic Phosphoric on Kieselguhr (UOP)	Polymerize propene/butene to gasoline (dimers with butene/trimers with propene)
258	HF Alkylation	HF or H_2SO_4 Catalysed Highly Exothermic (Phillips/UOP/Stretford)	Increase gasoline yield by catalytic alkylation of iso-butane and unpolymerized C_3 and C_4 olefins also n-butane and propane LPG produced.
259	Poly-gasoline Hydrogenation	-	Saturates olefins in heavy cat poly gasoline
260	Light Ends Recovery	-	Separates light gasoline and iso-butane from [illegible] rich off gases
261	Hydrogen Purification	Commercial Cryogenic Technology (Linde)	Obtain hydrogen of 90% purity from hydrogen [illegible] gases
262	Alcohol Recovery	-	Prepare marketable alcohol mixture and [illegible] for Rectisol

TABLE 3-6

PLANT OUTPUT--WESTINGHOUSE/SYNTHOL
(WYOMING COAL)

	Mixed			All-Liquid		
	MMBtu/hr Syngas	MMBtu/hr Total	B/SD MMSCF/SD*	MMBtu/hr Syngas	MMBtu/hr Total	B/SD
Gasoline		3,851	18,399		6,447	30,805
C_3		268	1,687		449	2,824
C_4		40	220		66	368
Diesel		783	3,515		1,311	5,886
Fuel Oil		224	946		375	1,584
Alcohol		442	2,791		740	4,672
Total Liquids		5,607	27,558		9,388	46,138
SNG		6,198	148.3*		---	---
Totals		11,805			9,388	46,138
FOE			47,220			37,552
Efficiency (HHV %)		59.9			47.6	
B C_4^+/Ton Dry Coal			1.29			2.16

Syngas = 99.751 1000# moles

Gasifier Naphtha = 0 Btu/hr

Gasifier Methane = 2.742 Btu/hr (HHV)

TABLE 3-7

PLANT OUTPUT--WESTINGHOUSE/SYNTHOL
(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		5,101	24,371		8,627	41,222
C_3		355	2,234		601	3,779
C_4		52	291		89	493
Diesel		1,037	4,657		1,754	7,376
Fuel Oil		297	1,253		502	2,119
Alcohol		585	3,696		990	6,252
Total Liquids		7,427	36,502		12,562	51,740
SNG		8,419	201.5*		--	--
Totals		15,846			12,562	61,740
FOE			63,384			50,249
Efficiency (HHV %)		60.5			48.0	
B C_4^+/Ton Dry Coal			1.37			2.32

Syngas = i›2.128 1000# moles

Gasifier Naphtha = 0 Btu/hr

Gasifier Methane = 3,841 Btu/hr (HHV)

With Illinois #6 coal (Table 3-7) outputs are higher because of the higher energy content of the coal. In the mixed product case, 36,502 barrels per day of liquids and 201.5 MMSCF per day of SNG are produced. C_4^+ liquids per ton of dry coal are 1.37. The HHV efficiency, at 60.5 percent, is slightly higher than with the Wyoming coal. For the all-liquids case, 2.3 barrels of C_4^+ liquids per day of dry coal are produced with an HHV efficiency of 48 percent which is the same as for the Wyoming coal case.

3.5.3 Performance of Plants Employing Kolbel Synthesis

The results of Kolbel synthesis and upgrading for Wyoming and Illinois #6 coals are shown in Tables 3-8 and 3-9, respectively. With the Wyoming coal (Table 3-8) the Kolbel system produced substantially more liquids than were produced with Synthol synthesis (38,445 versus 27,558 barrels per day) and substantially less SNG (89.6 versus 148.3 MMSCF per day). The overall efficiency, however, is slightly lower (59 percent versus 59.9 percent).

In the all-liquid case, the Kolbel output is 49,407 barrels per day versus 46,138 for Synthol. The overall HHV efficiency is 51.6 versus 47.6 for Synthol. The efficiency advantage is slightly higher percentage wise than the barrels of output advantage because the Kolbel output contains less alcohol. Note that the gasoline make, at 38,848 barrels per day, is over 25 percent higher than the 30,805 barrels per day produced with Synthol synthesis.

TABLE 3-8

PLANT OUTPUT—WESTINGHOUSE/KOLBEL
(WYOMING COAL)

	Mixed			All-Liquid		
	MMBtu/hr Syngas	MMBtu/hr Total	B/SD MMSCF/SD*	MMBtu/hr Syngas	MMBtu/hr Total	B/SD
Gasoline		6,327	30,229		8,131	38,848
C_3		509	3,200		654	4,112
C_4		0	0		0	0
Diesel		883	3,963		1,134	5,093
Fuel Oil		98	413		126	531
Alcohol		101	641		130	823
Total Liquids		7,917	38,445		10,175	49,407
SNG		3,701	89.6*		--	--
Totals		11,618			10,175	49,407
FOE			46,472			40,700
Efficiency (HHV %)		59.0			51.6	
B C_4^+/Ton Dry Coal			1.76			2.26

Syngas = 99.751 1000# moles

Gasifier Naphtha = 0 Btu/hr

Gasifier Methane = 2,742 Btu/hr (HHV)

TABLE 3-9

PLANT OUTPUT--WESTINGHOUSE/KOLBEL
(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		8,380	40,040		10,871	51,944
C_3		674	4,238		874	5,498
C_4		0	0		0	0
Diesel		1,169	5,250		1,517	6,810
Fuel Oil		129	547		168	710
Alcohol		134	849		174	1,101
Total Liquids		10,487	50,924		13,605	66,063
SNG		5,111	122.3*		--	—
Totals		15,598			13,605	66,063
FOE			62,392			54,420
Efficiency (HHV %)		59.6			52.0	
B C_4^+/Ton Dry Coal			1.87			2.43

Syngas = 132.128 1000# moles

Gasifier Naphtha = 0 Btu/hr

Gasifier Methane = 3,841 Btu/hr (HHV)

With the Illinois #6 coal and Kolbel synthesis, trends in output relative to the Synthol case are similar to those described above for the Western coal case; namely, a more favorable output in the mixed product case and a substantially higher output and efficiency in the all-liquid case. In the all-liquid case, liquid output is 2.43 barrels of C_4^+ liquids per ton of dry coal. This figure compares favorably with projected outputs of direct liquefaction plants.

3.6 Economic Comparisons

3.6.1 Plant Construction Costs

Table 3-10 shows plant construction costs for plants employing Westinghouse gasification and Wyoming subbituminous coal. The costing methodology is identical to that described in Appendix C of Reference 1. Table 3-11 compares the construction costs of plants employing Westinghouse gasification and Wyoming coal with plants using other gasifiers considered in the earlier study. For similar synthesis assumptions, all plant costs fall within a rather narrow range of about plus or minus 5 percent with Westinghouse being near the center of the range.

Table 3-12 shows plant construction cost breakdowns for plants employing Westinghouse gasification and Illinois #6 coal. As in the Wyoming coal case, plants are designed to process 27.8 M tons per day of as-received coal. Plant costs are higher with Illinois #6 coal because virtually all process units of the plant are larger than with

TABLE 3-10

CONSTRUCTION COSTS OF PLANTS EMPLOYING
WESTINGHOUSE GASIFICATION (1)
(WYOMING COAL)
(MM 1977 $)

Unit Description \ System	Westinghouse/Synthol		Westinghouse/Kolbel	
	Mixed	All-Liquid	Mixed	All-Liquid
Coal & Ash Handling	71.4	71.4	71.4	71.4
Synthesis Gas Preparation	320.8	320.8	275.3	275.3
Gasifiers	149.3	149.3	149.3	149.3
Gas Cooling	15.0(2)	15.0	14.4	14.4
Shift	29.3	29.3	--	--
Gas Cleaning	127.2	127.2	116.6	116.6
By-Product Recovery	83.9	83.9	62.0	62.0
Gasifier Naphtha Treatment	--	--	--	--
Synthesis	139.8	200.5	159.1	189.6
SNG Preparation or Reforming	21.8	36.5	15.3	25.6
F-T Liquid Recovery & Upgrading	123.6	117.4	150.4	179.3
Oxygen Plant	220.2	245.6	220.2	235.7
Steam Plant	51.5	55.1	51.5	53.9
Waste Water Treatment	16.7	20.8	12.2	11.6
Miscellaneous	108.0	108.0	108.0	108.0
TOTALS	1,163.1	1,325.4	1,125.4	1,212.4

(1) Plants sized for 27.8 M tons/day as-received coal throughput.

(2) Raw gas coolers are included in gasifier estimate.

TABLE 3-11

CONSTRUCTION COST DATA FOR INDIRECT LIQUEFACTION PLANTS USING SYNTHOL SYNTHESIS AND WYOMING COAL

Gasification System Used	Mode	Construction Cost (MM 1977 $)
Lurgi Dry Ash	M	1186.1
Lurgi Dry Ash	AL	1382.7
BGC Lurgi	M	1104.3
BGC Lurgi	AL	1289.4
Texaco	M	1167.1
Texaco	AL	1189.0
Shell-Koppers	M	1231.4
Shell-Koppers	AL	1347.2
Westinghouse	M	1163.1
Westinghouse	AL	1325.4

M = Mixed Output
AL = All-Liquid Output

Source: Reference (1)

TABLE 3-12

CONSTRUCTION COST OF PLANTS EMPLOYING WESTINGHOUSE GASIFICATION(1) (ILLINOIS #6 COAL) (MM 1977 $)

Unit Description \ System	Westinghouse/Synthol		Westinghouse/Kolbel	
	Mixed	All-Liquid	Mixed	All-Liquid
Coal & Ash Handling	71.4	71.4	71.4	71.4
Synthesis Gas Preparation	381.6	381.6	327.0	327.0
Gasifiers	179.3	179.3	179.3	179.3
Gas Cooling	17.7	17.7	16.5	16.5
Shift	33.6	33.6	--	--
Gas Cleaning	151.0	151.0	131.2	131.2
By-Product Recovery	96.5	96.5	58.6	58.6
Gasifier Naphtha Treatment	--	--	--	--
Synthesis	170.5	245.3	193.7	232.4
SNG Preparation or Reforming	27.0	45.2	19.0	31.5
F-T Liquid Recovery & Upgrading	150.5	217.5	183.1	219.7
Oxygen Plant	223.8	267.2	233.8	254.3
Steam Plant	59.5	64.5	59.5	62.6
Waste Water Treatment	20.8	25.4	13.0	12.2
Miscellaneous	108.0	108.0	108.0	108.0
TOTALS	1,319.6	1,523.6	1,267.1	1,377.7

(1) 27.8 M tons/day as-received coal.

the Wyoming coal as a result of the higher carbon content of the Illinois #6 coal on an as-received basis. Table 3-13 compares the costs of plants using Westinghouse gasification and Illinois #6 coal with plants using the gasifiers considered in Section 4.0 of this study. As with the Wyoming coal, plant costs for plants employing advanced gasifiers fall within a fairly narrow range. In the Illinois #6 coal case, however, Westinghouse is at the lower end of the range.

3.6.2 Product Costs

Product costs have been computed using methods similar to the previous study (Reference 1). Costs are based on a 12 percent discounted cash flow. Total depreciable capital is 1.59 times the estimated plant construction cost. Gasoline prices are computed on two bases. Thermal base costs are computed from the assumption that all products are valued at the same value per million Btu's. The product cost basis assumes the relationship between product cost shown in Table 3-14. The SNG price of $6.17 per MM Btu (1977 $) was computed by MRDC as the SNG cost from a grass roots SNG plant employing Lurgi dry-ash gasifiers and Lurgi methanation technology.

Computed gasoline costs are given in Table 3-15. Costs for the cases employing the other gasification systems evaluated in Reference 1 are shown for comparison. Gasoline costs for all-liquid product plants are shown in the upper section of Table 3-15. With the

TABLE 3-13

CONSTRUCTION COST DATA FOR INDIRECT LIQUEFACTION PLANTS USING SYNTHOL SYNTHESIS AND ILLINOIS #6 COAL

Gasification System Used	Mode	Construction Cost (MM 1977 $)
Lurgi Dry Ash	M	1464.5
Lurgi Dry Ash	AL	1670.5
BGC Lurgi	M	1335.2
BGC Lurgi	AL	1542.2
Texaco	M	1401.8
Texaco	AL	1536.1
Shell-Koppers	M	1[illegible]00.0
Shell-Koppers	AL	1541.4
Westinghouse	M	1319.6
Westinghouse	AL	1523.6

M = Mixed Output
AL = All-Liquid Output

TABLE 3-14

PRICE OF FUELS OTHER THAN GASOLINE
(October 1977 $)

Product	Price
SNG & C_3 LPG	$6.17/MMBtu
C_4 LPG*	Gasoline - $.30/MMBtu
Diesel*	Gasoline - $1.70/B
Fuel Oil*	Gasoline - $3.50/B
Alcohols	$.15/lb

*Shown relative to gasoline price

Source: Reference (3)

TABLE 3-15

COMPARISON OF GASOLINE COSTS FROM INDIRECT LIQUEFACTION PLANTS[1]
(27.8 M Tons/Hour Coal Throughput)

	ALL-LIQUID OUTPUT				
	SASOL-U.S. Base Case	BGC Lurgi	Westinghouse Fluid Bed	Texaco	Shell-Koppers
<u>Synthol Synthesis</u>					
Western Coal	1.51 (2.00)	1.24 (1.65)	1.28 (1.70)	1.23 (1.64)	1.16 (1.55)
Illinois #6 Coal	2.32 (3.01)	1.39 (1.81)	1.24 (1.61)	1.27 (1.66)	1.16 (1.55)
<u>Kolbel Synthesis</u>					
Western Coal	(2)	1.03 (1.36)	1.08 (1.44)	1.01 (1.34)	.94 (1.25)
Illinois #6 Coal	(2)	1.16 (1.55)	1.05 (1.40)	1.05 (1.40)	.94 (1.25)
	MIXED OUTPUT				
<u>Synthol Synthesis</u>					
Western Coal	1.33 (1.76)	.92 (1.22)	1.03 (1.37)	1.05 (1.39)	.98 (1.30)
Illinois #6 Coal	2.14 (2.78)	1.20 (1.56)	.97 (1.26)	1.13 (1.47)	.99 (1.29)
<u>Kolbel Synthesis</u>					
Western Coal	(2)	.84 (1.12)	.93 (1.24)	.95 (1.26)	.89 (1.18)
Illinois #6 Coal	(2)	1.05 (1.40)	.89 (1.19)	1.01 (1.35)	.90 (1.20)

(1) Costs shown bold face are 1977 \$, \$/Gal, Product basis 1980 \$ are shown in parentheses.

(2) Not analyzed.

western coal and Synthol synthesis, Westinghouse gasification offers cost savings on the order of 20 percent relative to the base case employing dry-ash Lurgi gasification. Further savings are possible by use of the Westinghouse/Kolbel plant, which produces gasoline at a cost of $1.44 (1980 $) versus $2.00 for the base case SASOL U.S. plant using dry-ash Lurgi-Synthol technology--a savings of 28 percent.

The other advanced gasifiers considered in Reference 1 are shown to provide gasoline costs slightly less than Westinghouse when western coals are used. However, we have noted our belief that Westinghouse has been more conservative in their projections of gasifier performance than have the data sources for the other gasifiers. On balance, we believe that BGC/Lurgi, Texaco and Westinghouse offer quite comparable performance levels with Shell-Koppers offering a slight advantage if the problems associated with dry coal feeding and refractory integrity can be solved.

With the Illinois #6 coal the cost of gasoline produced from plants employing Westinghouse gasification becomes lower than for plants employing Texaco or BGC/Lurgi gasification. However, results for Texaco, Shell-Koppers and Westinghouse are quite similar and distinctly better than results obtained when the BGC/Lurgi gasifier is used. This result reflects the deficiencies of fixed bed gasifiers when used with moderately caking coals of lower reactivity.

These deficiencies are addressed in detail in Section 4.0 of this report.

The gasoline prices computed for plants producing a mixed output of liquid fuels and SNG are shown on the lower portion of Table 3-15. The value assumed for the coproduct SNG is $6.17 per million Btu's (1977 $). This value was determined by MRDC as the required selling price for SNG produced by a grass roots plant employing the dry-ash Lurgi technology. Escalated to 1980 dollars, the SNG price assumed is approximately $8.12 per million Btu's.

When this relatively high value is assigned to SNG all plants considered in our study are able to reduce the cost of gasoline by selling SNG rather than reforming it to produce an all-liquid output. The plants which offer the greatest cost reduction in the mixed-output mode are predictably those which employ lower temperature gasification systems, such as Westinghouse, BGC and dry-bottom Lurgi, and thus have substantial quantities of methane in their raw gas output.

The position of the Westinghouse unit is changed relative to the other gasifiers if mixed output plants are considered. The relative position of the Westinghouse unit is improved slightly relative to the two entrained flow gasification systems, but not sufficiently to alter our prior conclusion that the three systems are comparable with either feedstock.

Plants employing BGC/Lurgi gasification enjoy the greatest advantage from SNG sales and, with a Western coal feedstock, produce the lowest cost gasoline of any of the gasifiers studied. However, the advantages gained from SNG coproduction are not sufficient to make the BGC/Lurgi competitive with the other advanced gasifiers if Illinois #6 coal is used.

The earlier MITRE study presented a sensitivity analysis which investigated the impact of SNG price assumptions other than the $6.17 per million Btu's (1977 $). The results of this analysis indicated that the sale of SNG, as an alternative to reforming, would result in little or no reduction in gasoline cost unless the value of SNG, on a dollar per Btu basis, were more than half that of finished gasoline. We concluded that price relationships this favorable to SNG were unlikely and that the all-liquid plants provided the most reasonable basis for comparison of gasification and synthesis systems.

Table 3-15 shows that gasoline costs for plants using Illinois #6 coal are comparable to the Wyoming coal cases for both Westinghouse and entrained-flow systems. This result was initially surprising since costs for the Illinois #6 coal are much higher than for the Wyoming coal. For example, detailed cost computations presented in Appendix D shows for all-liquid output with Westinghouse gasification and Synthol synthesis a Wyoming coal cost of $.86 per MM Btu of output versus $1.88 per MMBtu for the Illinois #6 coal. Coal represents only 8.3 percent of product costs for the Wyoming coal versus 18.8 percent when Illinois #6 coal is used. It was subsequently determined that the larger size of the plants using Illinois #6 coal provided the plant with a benefit of scale which compensated for the higher coal costs. A sensitivity analysis, discussed in Section 2.0, was undertaken to determine how product costs for plants employing the two kinds of coal would compare if the plants were scaled to require the same capital investment, rather than the same quantity of as-received coal input. The results are shown in Table 2-7. When compared on a fixed investment basis, gasoline costs for plants employing Illinois #6 coal are higher and thus reflect the higher coal cost.

3.7 Environmental Considerations

The Westinghouse gasifier offers many of the same advantages relative to the base case SASOL technology plant, as were shown for BGC/Lurgi, Texaco and Shell-Koppers gasifiers evaluated in Reference 1; specifically:

- Reduced water requirements
- Less waste-water requiring treatment
- Lower levels of CO_2 generation
- Less mining required per unit of output as a result of higher overall efficiency

The Westinghouse gasifier and the entrained-flow gasification system evaluated enjoy two important advantages over the BGC/Lurgi:

(1) They are able to operate without a coal-fired steam generation unit and associated stack gas cleanup systems.

(2) They produce no tars, oils or phenols requiring separation and handling.

The Westinghouse gasifier has a disadvantage relative to the other advanced systems in that it does not produce a nonleachable slag.