APPENDIX A

INDIRECT COAL LIQUEFACTION

The purpose of this Appendix is to present process descriptions and cost data estimates for some indirect liquefaction processes. Coal to methanol systems are the first topic. The Mobil-M process which first converts coal to methanol and then converts methanol to gasoline is the second process studied herein. Finally, the process by which natural gas is converted to methanol is considered. The three process discussions each have two subdivisions: Process description and Raw cost data estimate.

As the reader will see, the estimates by the Badger Company for both methanol and Mobil-M are adjusted in two important respects by ICF for use in the market analysis. First, costs for two smaller plants are estimated. Second, the original estimates were based on a low sulfur bituminous coal in Appalachia, ICF adjusted the costs to reflect the use of a high sulfur bituminous coal in Illinois and some different equipment sizes.

METHANOL FROM COAL

Process Description

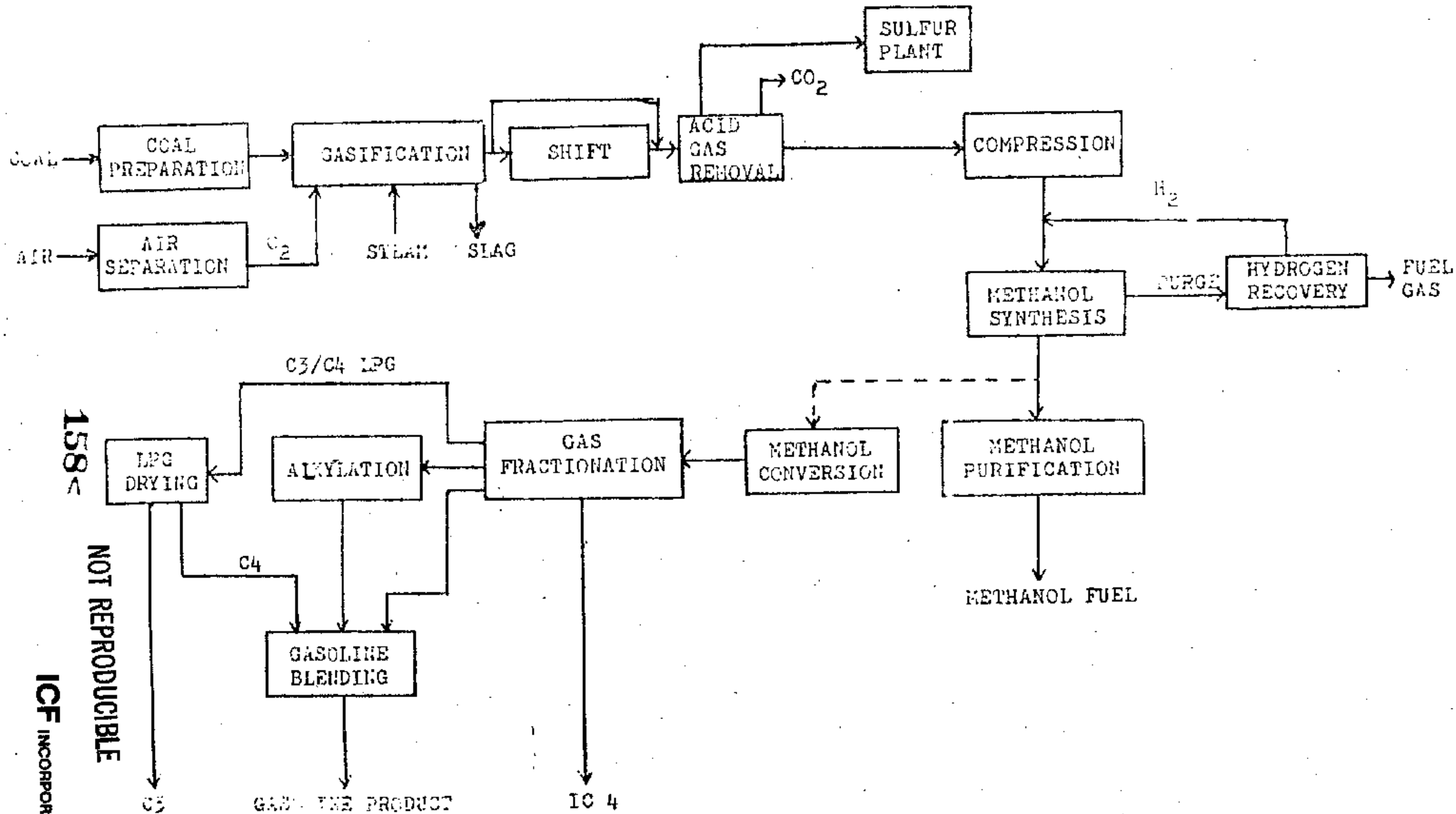
A diagram illustrating the major steps in the production of methanol from coal is provided as Figure A-1. Also shown are the steps necessary to then produce gasoline from methanol with the Mobil technology. The actual processing sequence will vary somewhat depending upon the type of coal utilized and the particular gasification and methanol synthesis technologies employed. The following process description is drawn from the Badger study for DOE, which assumes an entrained bed type of gasifier and Lurgi methanol synthesis.

Washed, sized coal received from the mine is dried and pulverized in the coal preparation area and then transported to the gasifier where it is injected under pressure. With the introduction of oxygen and superheated steam the temperature reaches 3000° F inside the reaction zone. The product gases, which are primarily carbon monoxide, hydrogen, and carbon dioxide, are cooled with water before leaving the gasifier overhead. Molten ash slag is removed at the bottom of the gasifier where it is cooled and broken into manageable pieces

The gases leaving the gasifier overhead are scrubbed and cooled to remove all particulate matter and then are further cooled before entering the Shift Unit where sufficient hydrogen is produced so as to prepare the gas for methanol synthesis. That is, the shift unit assures that the hydrogen to carbon content is set for methanol production in the Lurgi methanol synthesis equipment.

Figure A-1

BLOCK FLOW DIAGRAM - PRODUCTION OF
METHANOL AND GASOLINE FROM COAL



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NOT REPRODUCIBLE

The gases from the Shift Unit are treated in the Acid Gas Removal Unit for removal of sulfur compounds and excess carbon dioxide. Molten sulfur and carbon dioxide are removed as by-products. This purified synthesis gas is then compressed from 380 psig to 750 psig before entering the methanol synthesis reactors. In this stage, the carbon, hydrogen, and oxygen is combined to form methanol (whose chemical formula is CH_3OH). Hydrogen in the gas purged from the synthesis system is recovered and recycled. The offgas from hydrogen recovery is used as fuel elsewhere. The product from the methanol synthesizer is dried from 6.5% to 3.5% water before entering storage.

Raw Cost Estimate

The most detailed capital cost estimate found for the production of methanol from coal was that produced by Badger for DOE. The base case estimate prepared by Badger was for what we believe was an unreasonably large plant processing 74,000 T/SD of Southern Appalachian Coal. Cost estimates for this and two smaller plant sizes using Illinois No. 6 coal are shown in Table A-1. These estimates have been modified somewhat from those presented by Badger to reflect a different type of coal, the impact of reductions in unit size for some of the key units to more conventional or obtainable sizes, and escalation of costs to a $ 1980 basis. The assumed changes in unit size were as follows:

Unit	Badger T/SD	ICF T/SD
Gasifier[1/]	10,500	1,500
Methanol Synthesis	3,157	2,367
O_2	5,000	2,500

1/ The original Badger design assumed six operating gasifiers with three spares. With the reduction in size assumed from 10,500 T/D to 1,500 T/D of coal feed, the number of spares assumed was reduced from three for six to one spare for each six gasifiers required.

These changes are important since they change the cost estimates by eliminating some of the economies of scale built-in by Badger. For example, there are about seven smaller gasifiers now for each large unit assumed by Badger.

TABLE A-1

ESTIMATED CAPITAL COSTS FOR PRODUCTION OF METHANOL
FROM ILLINOIS NO. 6 COAL
MID-1980 DOLLARS (000's)

Plant Size - T/SD Coal	12,950	25,900	77,700
Plant Section			
Coal Preparation	17,200	32,090	86,270
Gasification	121,000	255,790	606,880
Shift Conversion	30,840	57,550	154,690
Acid Gas Removal	128,820	209,270	451,540
Sulfur Removal	27,140	42,130	90,930
Syn Gas Compression	14,990	27,970	75,190
Methanol Synthesis	100,060	186,710	501,860
Cryogenic Recovery	10,580	17,190	37,090
Methanol Fuel Drying	8,720	16,270	43,730
Oxygen Production	179,940	335,770	902,520
Steam and Power Generation	59,920	97,340	210,030
Environmental	20,570	33,420	72,110
Storage & Shipping	10,140	16,480	35,550
General Facilities	139,200	226,130	487,910
Sub Total	869,120	1,524,110	3,756,300
Indirect Field Costs	44,510	72,300	156,000
Home Office Charges	113,090	183,730	396,400
Prepaid Royalties	3,100	5,800	14,900
Spare Parts	7,170	12,900	31,700
Catalysts & Chemical Inventory	3,090	6,190	18,550
Project Contingency	156,012	270,755	656,078
Process Contingency	18,150	33,869	91,032
TOTAL	1,214,242	2,109,654	5,120,960

Comparative capital cost estimates also are presented in Table A-2 for the production of methanol from Illinois No. 6 coal using three different gasification processes. These data are of interest as they afford a relatively consistent basis for comparison among the three gasification processes, as the estimates were developed by Parsons in a single study for EPRI. These estimates were developed in less detail than those by Badger and assume the Chem Systems methanol synthesis technology rather than the Lurgi system assumed by Badger. While the Chem systems methanol process is not commercially proven, estimated costs for it are not likely to be substantially less than those for other processes.

TABLE A-2

ESTIMATED CAPITAL COSTS FOR PRODUCTION OF METHANOL FROM ILLINOIS NO. 6 COAL FOR THREE GASIFICATION TECHNOLOGIES MID-1980 DOLLARS (000's)

Gasifier Type	BGC/LURGI	KOPPERS-TOTZEK	TEXACO
Plant Size-Coal, T/SD	22,918	24,574	22,100
Plant Section			
Coal Preparation	36,500	78,100	65,100
Gasification	131,500	507,800	345,100
Tar and Phenol Recovery	89,800	-	-
Acid Gas Removal	27,300	70,300	91,100
Shift Conversion	50,800	45,600	45,600
CO_2 Removal	191,400	168,000	162,000
Sulfur Recovery	26,000	26,000	26,000
Syn Gas Compression	69,000	112,000	-
Fuel Gas Separation	27,300	-	-
Methanol Synthesis	171,800	171,800	171,800
Oxygen Production	238,300	355,900	385,400
Steam & Power Generation	72,900	177,100	95,000
Sub Total	1,131,400	1,946,400	1,387,900
Offsites	169,700	253,900	208,300
Prepaid Royalties	5,300	8,800	6,500
Project Contingency	195,960	331,365	240,405
Process Contingency	19,725	-	51,765
TOTAL	1,522,085	2,540,465	1,894,870

The first generation Lurgi system produces significant quantities of methane. This is an advantage when SNG is the goal since methane is the desired end product. It is not a particularly propitious starting point for maximum production of methanol, however, as methanol is produced from synthesis gas. While it would be possible to reform methanol into synthesis gas this would add additional expense. One solution to this potential incompatibility problem is to take advantage of the methane yield and design a plant to coproduce SNG and methanol. The estimated capital costs for such a plant are shown in Table A-3.

Estimated operating costs and product yields for each of the methanol production processes considered are presented in Tables A-4, A-5, and A-6, respectively.

TABLE A-3

ESTIMATED CAPITAL COSTS FOR THE COPRODUCTION OF SNG AND METHANOL FROM WYOMING SUB-BITUMINOUS COAL MID-1980 DOLLARS (000's)

Plant Size - Coal, T/SD	27,334
Plant Section	
Coal Preparation	78,400
Gasification	248,400
Gas Cooling	23,900
Process Condensate Treating	63,600
Shift	15,800
Acid Gas Removal	97,200
Sulfur Recovery	73,000
Methanol Synthesis	67,300
Hydrogen Recovery	3,200
Methanation	22,300
SNG Drying	600
Methanol Distillation	8,200
Naphtha Hydrotreated	4,000
Oxygen	136,300
General Facilities	396,100
Sub-Total	1,238,300

TABLE A-3 (Continued)

ESTIMATED CAPITAL COSTS FOR THE
COPRODUCTION OF SNG AND METHANOL FROM
WYOMING SUB-BITUMINOUS COAL
MID-1980 DOLLARS (000's)

Sales Tax	19,800
Catalysts Chemical Inventory	7,400
Construction Camp	83,800
Labor Premium	153,100
Paid Up Royalties	6,200
Project Management	35,400
Engineering and Design	158,400
Other	11,100
Project Contingency	257,025
Process Contingency	-
TOTAL	1,970,525

Note: Gillette Wyoming Location Assumed.

TABLE A-4

ESTIMATED YIELDS AND OPERATING REQUIREMENTS FOR THE PRODUCTION OF METHANOL FROM ILLINOIS NO. 6 COAL
MID-1980 DOLLARS

VARIABLE COSTS			
Coal, T/SD	12,450	25,900	77,700
Catalyst and Chemical, $/SD	12,150	24,300	72,900
Water, $/SD	4,600	9,200	27,600
Power, MWH/SD	1,130	2,260	6,782
Slag Disposal, $/SD	2,650	5,300	15,900
Sub-Total	-	-	-
FIXED COSTS, $/CD			
Operating Labor	21,920	26,030	34,250
Overhead	49,830	77,790	170,900
Maintenance	83,620	151,100	389,000
Sub-Total	155,370	254,920	594,150
PRODUCT YIELDS			
Methanol Fuel, MMBtu/SD	183,300	366,700	1,100,000
Sulfur, T/SD	386	772	2,313

TABLE A-5

ESTIMATED YIELDS AND OPERATING REQUIREMENTS
FOR THE PRODUCTION OF METHANOL FROM ILLINOIS NO. 6 COAL
FOR THREE GASIFICATION TECHNOLOGIES
MID-1980 DOLLARS

Gasifier Type	BGC/LURGI	KOPPERS-TOTZEK	TEXACO
VARIABLE COSTS			
Coal, T/SD	22,918	24,574	22,100
Catalyst, Chemicals, & Water, $/SD	26,600	26,600	26,600
Ash Disposal Cost, $/SD	3,370	3,540	3,180
Sub Total	-	-	-
FIXED COSTS, $/CD			
Operating Labor	25,070	26,038	25,070
Overhead	67,800	98,800	82,600
Maintenance	125,670	209,370	166,760
Sub Total	218,540	338,200	274,430
PRODUCT YIELDS			
Methanol, MMBtu/SD	315,000	315,000	315,000
Fuel Gas, MMBtu/SD	4,500	-	-
Sulfur, T/SD	848	766	750

TABLE A-6

ESTIMATED YIELDS AND OPERATING REQUIREMENTS FOR THE COPRODUCTION OF SNG AND METHANOL FROM WYOMING SUBBITUMINOUS COAL
MID-1980 DOLLARS

VARIABLE COSTS	
Coal, T/SD	27,334
Catalyst & Chemicals, $/SD	14,000
Power, KWH/SD	157,200
Water, $/SD	3,570
Slag Disposal, $/SD	-
Sub-Total	-
FIXED COSTS, $/CD	
Operating Labor	19,500
Overhead	61,500
Maintenance	122,100
Sub-Total	203,100

Product Yields	MMBtu/SD	Unit/SD
SNG	142,740	
Methanol	137,690	
Hydrotreated Naphtha	6,840	1,315 B
Sulfur		61 T
Ammonia		103 T
Excess Coal Fines		1,586 T

Notes:

1. The product naphtha from this design is hydrotreated and suitable for direct gasoline blending. It has an R+M/2 of 88.7.

2. Slag Disposal costs not included for western cases.

3. As water was priced at some cost as in eastern cases, water costs may be relatively understated.

MOBIL GASOLINE (M-GAS) FROM COAL

Process Description

The production of gasoline from coal by the Mobil process via methanol was also shown in Figure A-1. Crude methanol is used as feed to the methanol conversion unit which dehydrates methanol into a gasoline like material. The hydrocarbons produced are predominately in the gasoline boiling range and the gasoline is chemically conventional.[1/]

The hydrocarbons are separated in the Gas Fractionation Unit to produce fuel gas, propane LPG, high purity isobutane, alkylation feed, and stabilized gasoline. An LPG Drying Unit is included as a backup system in case of an upset in the operation of the Gas Fractionation Unit.

Fuel gas from the Methanol Conversion Unit and Gas Fractionation Unit are discharged into the fuel gas system. Alkylate and butane from the Alkylation Unit, stabilized gasoline, and a portion of the isobutane are combined to make product gasoline. The estimated clear road octane of the gasoline is 87.7, similar to that for regular unleaded gasoline.[2/]

Cost Estimate

Capital cost estimates for the production of gasoline from coal via methanol are shown in Table A-7. These estimates are based on a study by Badger for DOE and were modified as described before. Estimated product yields and operating requirements corresponding to the indicated capital cost estimates are shown in Table A-8.

1/ That gasoline consists of highly branched paraffins (51%), highly branched olefins (13%), napthenes (8%), and aromatics (28%). Essentially no hydrocarbons larger than C_{10} and no oxygenates are produced.

2/ Road octane is the average of motor and research octanes.

TABLE A-7

ESTIMATED CAPITAL COSTS FOR PRODUCTION OF GASOLINE
FROM ILLINOIS NO. 6 COAL VIA METHANOL
MID-1980 DOLLARS (000's)

Plant Size - T/SD Coal	12,950	25,900	77,700
Plant Section			
Raw Methanol Production	630,140	1,169,200	2,981,960
Methanol Conversion	75,790	141,140	378,340
Gas Fractionation	17,390	28,240	60,940
Alkylation	2,750	4,460	9,640
LPG Drying	310	500	1,070
Gasoline Blending	120	200	430
Steam & Power Generation	72,280	117,420	253,360
Environmental	37,410	60,780	131,140
Storage & Shipping	6,380	10,360	22,360
General Facilities	154,070	250,280	540,030
Sub Total	996,640	1,782,580	4,379,270
Indirect Field Costs	51,810	84,160	181,590
Home Office Charges	146,660	238,250	514,070
Prepaid Royalties	3,550	6,600	16,900
Spare Parts	14,850	26,620	65,500
Catalyst & Chem. Inventory	3,530	7,070	21,200
Project Contingencies	182,556	321,792	776,780
Process Contingencies	25,729	31,627	128,866
TOTAL	1,425,325	2,498,699	6,084,176

TABLE A-8

ESTIMATED YIELDS AND OPERATING REQUIREMENTS FOR THE PRODUCTION OF GASOLINE FROM ILLINOIS NO. 6 COAL VIA METHANOL MID-1980 DOLLARS

VARIABLE COSTS			
Coal, T/SD	12,950	25,900	77,700
Catalyst and Chemical, $/SD	32,170	79,340	238,080
Water, $/SD	4,840	9,680	29,040
Power, MWH/SD	1,185	2,370	7,105
Slag Disposal, $/SD	2,650	5,300	15,900
Sub-Total	-	-	-
FIXED COSTS, $/CD			
Operating Labor	23,290	27,530	36,300
Overhead	55,510	87,000	186,500
Maintenance	95,980	172,840	427,290
Sub-Total	174,780	287,370	650,090
PRODUCT YIELDS			
Gasoline, B/SD	27,922	55,843	167,530
LPG, B/SD	1,523	3,047	9,140
I-C4, B/SD	2,448	4,897	14,690
Sulfur, T/SD	386	772	2,313

METHANOL FROM NATURAL GAS

Process Description

At present, production of methanol in the U.S. is almost entirely from natural gas. If methanol from coal is to be competitive in chemical markets, coal conversion technology must be able to offer economics equal to or better than those available for production from natural gas. A diagram illustrating the major steps involved in methanol production via steam reforming of natural gas is provided in Figure A-2.

Natural gas is desulfurized prior to reforming. The desulfurized gas is countercurrently contacted with hot water which heats the feedstock and saturates it with water vapor. The feedstock is then preheated to the reformer inlet conditions, and the balance of the process steam is added. The steam/natural gas mixture is then passed to the reformer where the former components are reorganized (reformed) to synthesis gas with the help of a nickel catalyst.

The synthesis gas produced from the steam reforming of natural gas (primarily methane, CH_4) has an excess of hydrogen for the methanol synthesis, reacton, and purchased CO_2 is normally added to utilize the surplus hydrogen, resulting in two primary methanol synthesis reactions. (Carbon monoxide reacts with hydrogen to yield methanol (CH_3OH) and simultaneously carbon dioxide reacts with hydrogen to yield even more methanol.

Subsequent to synthesis gas manufacture and heat recovery. The process sequence for production of methanol from natural gas is similar to that for a coal based route, namely raw gas compression, snythesis, and purfication.

Cost Estimate

A capital cost estimate for a 2,000 T/SD plant is presented in Table A-9. This size is comparable with the synthesis train sizes assumed in the methanol from coal designs considered. The plant design upon which this estimate is based assumes the availability of CO_2 for purchase; this reflects current practice. The cost estimate shown in based on data provided by Chem Systems, Incorporated. The ICI methanol synthesis technology is assumed while lurgi and Chem Systems processes were used earlier. Estimated process yields and operating requirements are shown in Table A-10.

Figure A-2

BLOCK FLOW DIAGRAM - PRODUCTION OF METHANOL FROM NATURAL GAS

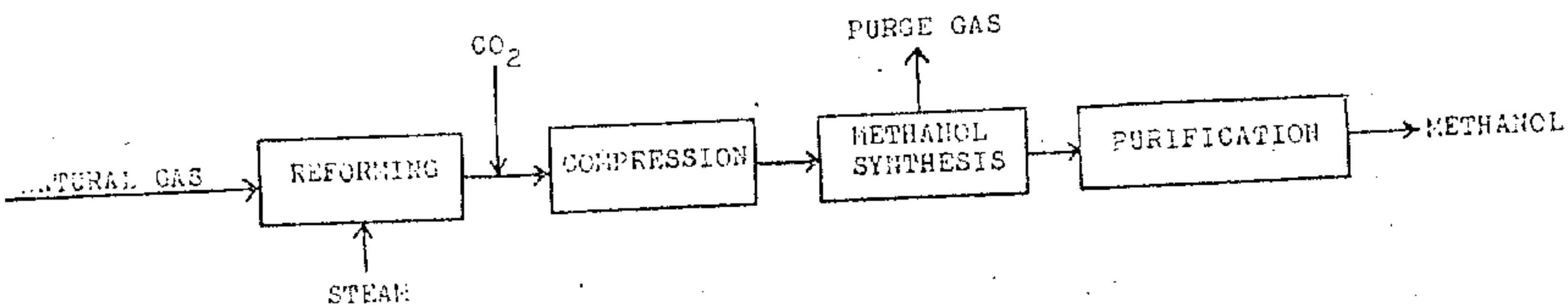

TABLE A-9

ESTIMATED CAPITAL COSTS FOR PRODUCTION OF METHANOL
BY STEAM REFORMING NATURAL GAS
MID-1980 DOLLARS (000's)

Plant Size - Methanol T/SD	2,000
Plant Section	
Reforming	38,000
Syn Gas Compression	21,000
Methanol Synthesis	13,000
Methanol Purification	12,000
Sub Total	84,000
Offsites	29,000
Prepaid Royalties	400
Contingency	17,010
TOTAL	130,410

1. Plant location assumed is for the Gulf Coast.

2. Costs are for the production of chemical grade methanol. Estimated higher heating value is 9,755 Btu/lb.

TABLE A-10

ESTIMATED YIELDS AND OPERATING REQUIREMENTS FOR PRODUCTION OF METHANOL BY STEAM REFORMING NATURAL GAS MID-1980 DOLLARS

VARIABLE COSTS	
Natural Gas, MMBtu/SD	60,000
CO_2 Addition, MSCF/SD	12,600
Catalyst & Chemicals, $/SD	3,500
Water, $/SD	7,590
Power, KWH/SD	100,000
Sub Total	-
FIXED COSTS, $/CD	
Operating Labor	2,800
Overhead	6,580
Maintenance	9,450
Sub Total	18,830
PRODUCT YIELDS	
Methanol, T/SD	2,000

Water priced at 15¢/m gal rather than the 40¢/m gal cost used in coal conversion processes.

PRIMARY REFERENCES FOR APPENDIX A

INDIRECT LIQUEFACTION

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METHANOL FROM NATURAL GAS

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3. A. Pinto and P.L. Rogerson, "Optimizing the ICI Low-Pressure Methanol Process", Chemical Engineering, July 4, 1977.