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Technical Report

Exxon Donor Solvent Coal Liquefaction Process

by

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Standards Development and Support Branch
Emission Control Technology Division
Office of Mobile Source Air Pollution Control
Office of Air, Noise and Radiation
U.S. Environmental Protection Agency

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I. Introduction

This report presents the technical and economic aspects of the Exxon Donor Solvent (EDS) coal liquefaction process. First, background information is provided by discussing the EDS process history, project status, and commercialization outlook. Next, a process description is provided along with a description of the EDS flexibility in liquefying coals of different rank. Then, the product yields and overall efficiency are discussed. Lastly, the economics of the EDS process are presented. A discussion of feeding different coals to the EDS plant will also be presented in the section on economics.

II. Background

A. History of Process

The EDS process was developed by Exxon as a private venture from 1966 until 1976. During this time Exxon developed and demonstrated the process in laboratory scale reactors up to 1 ton per day (TPD) of coal. In July 1977, ERDA (now DOE) agreed to fund 50 percent of a project to design and construct a $268 million 250-TPD pilot plant. Construction of this pilot plant in Baytown, Texas, was completed in March, 1980, and is to be followed by a thirty month operational program.[1][2]

B. Project Status[3][3a]

Engineering design and technology studies, bench scale research and small pilot unit operation are being integrated to support operation of the 250 TPD coal liquefaction pilot plant. On June 2, 1981 an eleven month first test operation on Illinois bituminous coal without liquefaction bottoms recycling was completed. During September, 1981 the pilot plant was restarted for a five month operation to evaluate the suitability of Wyoming sub-bituminous coal and to incorporate liquefaction bottoms recycling into the EDS process. The bottoms recycling is expected to boost the output of higher-value naptha and middle distillates while decreasing the amount of heavier lower-value products.

After this period of operation, a decision will be made whether to run with lignite or to rerun Illinois No. 6 with bottoms recycling, for a period of six months, until June, 1982. At this time DOE's participation in the pilot plant venture will terminate unless government funding is approved for ancillary programs such as partial oxidation and a hybrid boiler which are under consideration for bottoms processing. This additional funding is not expected to be approved. Another bottoms process, a planned 70 TPD FLEXICOKING prototype program has been cancelled due to budget constraints. After June, 1982 the remaining partners of the project will decide whether they will build a commercial plant.

C. Operation of the 250 TPD EDS Pilot Plant

Sixteen process goals were established for the first four months of operation of which eleven were reached. The goals reached included operation on 8 mesh coal, demonstration of the ability to dry coal to 4 percent moisture, achievement of a 50 percent on-stream factor, and several fractionation section objectives. The five goals not reached include steady operations at conditions near the design coal feed rate and a 1/2:1 solvent-to-coal ratio, operation of the reactor solids withdrawal system, and operation of the slurry drier.

During the first four months of operation the plant problems experienced were mechanical rather than process oriented. The mechanical problems included erosion of the vacuum tower transfer line, breakdown of the solids-handling systems and plugging of the slurry heat exchangers. The key to successful operation was avoiding solidification of heavy materials and solids plugging. The service factor was strongly dependent upon the time required to unplug the equipment after a coal outage due to solidification-based plugging.

A preliminary observation indicated a lower plant efficiency than expected. The reason for this has not been determined.

D. Remaining Steps to Commercialization

According to Exxon's commercialization estimates, after operation of the 250 TPD EDS pilot plant in the 1980-1982 time frame, a design basis for an EDS demonstration plant could be available in 1982.[4] With a three year design and construction period, construction of the demonstration plant could begin in 1985 and be completed in 1988 or 1989. The 13,000 TPD demonstration plant would be equivalent to one train of a 25,000 TPD commercial plant. Each train includes two identical liquefaction lines. Therefore, the commercial plant would have four liquefaction lines processing 6,250 tons of coal per line. As a result, the overall scale-up factor from the 250 TPD pilot plant to the demonstration plant equals twenty-five. Design of a commercial plant could begin after the demonstration plant operates one year. This would mean beginning the design in 1989 and construction in 1992. Therefore Exxon projects start-up of its first commercial plant in 1997.[4] The commercial plant start-up date is dependent upon successful completion of all previous steps.

III. Process Description[5]

Block diagrams for two different EDS coal liquefaction commercial designs are shown in Figures 1 and 2.[5] These two processing schemes differ in the methods used to produce the hydrogen and fuel gas required by the plant. These differences affect plant economics and efficiency.

Figure 1

EDS COMMERCIAL PLANT STUDY DESIGN UPDATE
ILLINOIS COAL BASE CASE
SIMPLIFIED BLOCK DIAGRAM

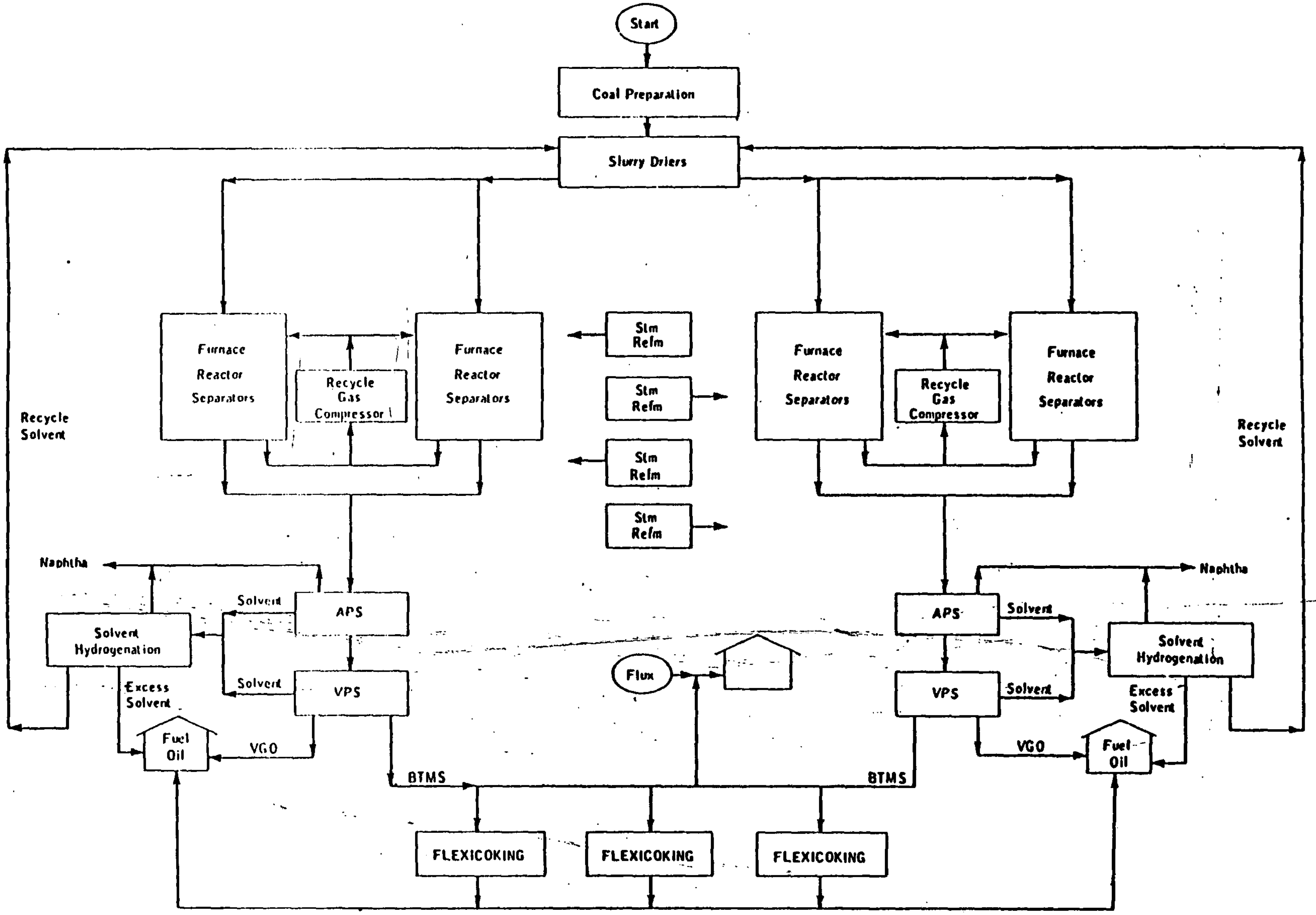
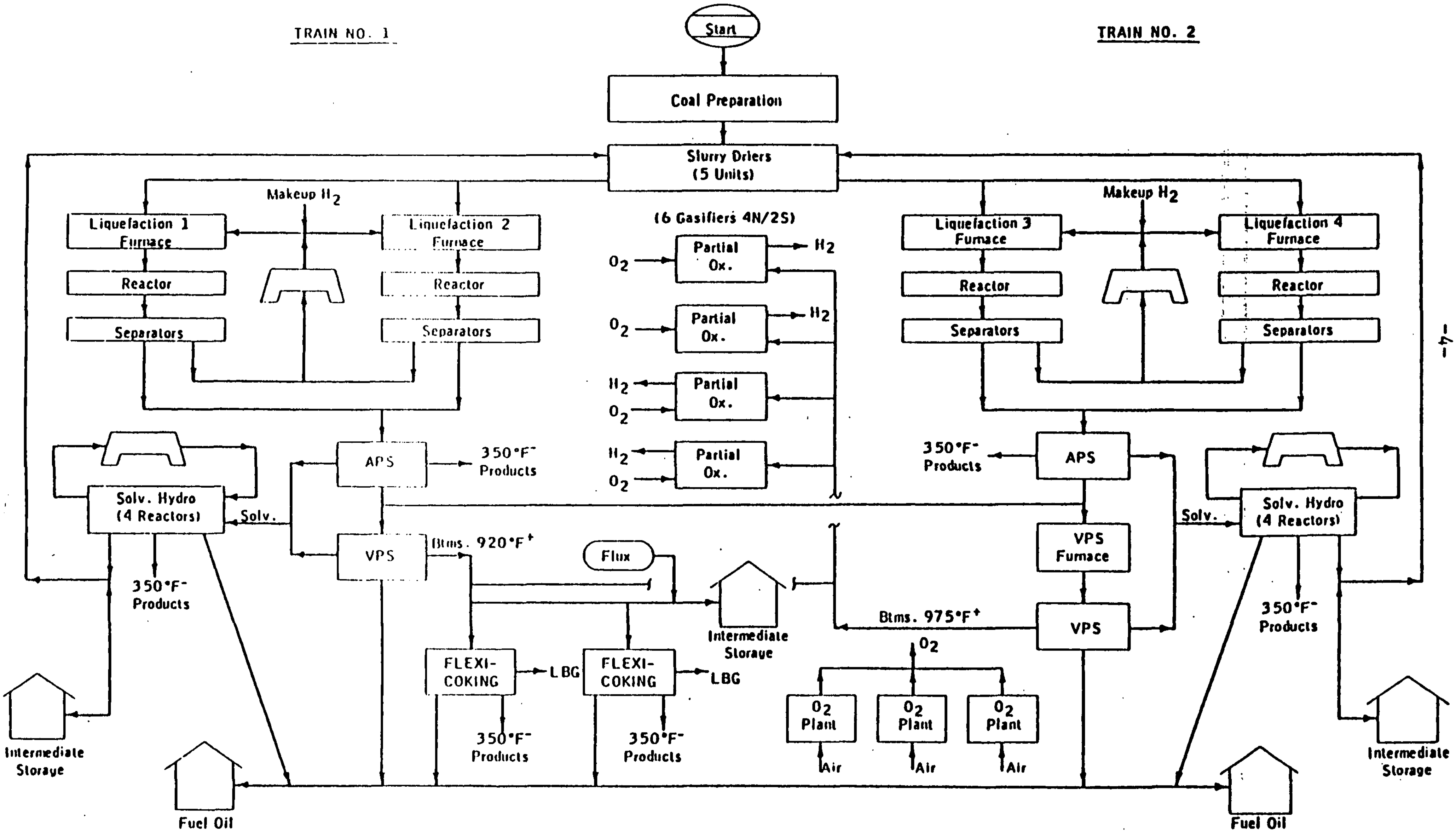


FIGURE 2

EDS COMMERCIAL PLANT STUDY DESIGN UPDATE
ILLINOIS COAL MARKET FLEXIBILITY SENSITIVITY CASE
SIMPLIFIED BLOCK DIAGRAM



In either scheme, the coal conversion plant receives coal from three mines via conveyor belts. After cleaning the coal, the coal is crushed and fed via enclosed belt conveyors to the corresponding slurry drier. Coal to be used in the offsite boilers is conveyed to the boiler crusher/pulverizers. In the slurry driers the crushed coal is first dried to less than 4 weight percent moisture (dry coal basis) and then slurried with the hydrogen donor recycle solvent. The slurry is then pumped to reaction pressure, treated with hydrogen and heated in the liquefaction slurry furnace before entering the liquefaction reactors which operate at 840°F and 2000 psig. There the coal is liquefied in the presence of molecular hydrogen and hydrogenated donor solvent.

Products from the liquefaction reactor are separated into a gas stream and a liquid/solid stream. The gas is cooled to separate vaporized naptha, scrubbed to remove NH_3, H_2, and CO , treated with makeup hydrogen, and then compressed for recycle to the liquefaction reactors.

The liquid/solids stream and the condensate recovered from the gas stream are sent to atmospheric and vacuum fractionators where naptha, a spent solvent stream, and vacuum gas oil (VGO) are separated. The naptha is sent to light ends processing for stabilization, the spent solvent stream is sent to solvent hydrogenation prior to recycling, and the vacuum gas oil is removed as the bottom sidestream of the vacuum fractionator and sent to product tankage. Vacuum bottoms are sent to FLEXICOKING and/or partial oxidation.

In the light end recovery section, naptha from: 1) liquefaction, 2) solvent hydrogenation, and 3) FLEXICOKING are fed to a conventional light end system. C_1/C_2 hydrocarbons are stripped out as high-BTU gas (HBG) product, C_3 and C_4 hydrocarbons are separated as LPG product, and the remaining C_5/350°F naptha stream is sent to product tankage.

Solvent hydrogenation restores donatable hydrogen to the spent solvent stream before it is recycled to the slurry drier in the liquefaction section.

Two different methods may be used to generate hydrogen. One method, designated as the Base Case by Exxon, uses steam reforming of C_1-C_3 hydrocarbons from the light ends recovery section of the plant and C_1-C_3 hydrocarbons from the hydrogen recovery unit to produce hydrogen. Under this route 100 percent of the vacuum bottoms would go to FLEXICOKING. The other method, designated the Market Flexibility Sensitivity case by Exxon, uses a partial oxidation (POX) process to generate H_2 from the vacuum bottoms. This eliminates the need for steam reforming, which in turn allows the sale of C_1/C_2 hydrocarbons as HBG and C_3 hydrocarbons as LPG. About one-half of the vacuum bottoms would be fed to the POX process with the rest being fed to the FLEXICOKER. The POX unit gasifies all carbonaceous material fed to it. Oxygen is supplied to the POX by three oxygen plants (33-1/3 percent capacity/train).

The Market Flexibility Sensitivity case has been shown to have both an economic and thermal efficiency advantage over the Base Case. These advantages will be discussed in the efficiency and economic section of this report.

IV. Coal Feed Flexibility[6][6a]

Lab-scale work by Exxon has shown that the EDS process is suitable for coals of different rank. Figure 3 shows that bituminous, sub-bituminous, and lignite rank coals can all be liquefied using the EDS process. This figure also shows that the C_3-1000°F yields for the various coals correlate with coal rank.

One way to increase C_3-1000°F liquid yields is to recycle the 1000°F+ vacuum bottoms stream to the liquefaction reactor. Using once-through liquefaction, bituminous coals yielded 39-46 percent liquids, sub-bituminous coals yielded 38 percent liquids and lignite yielded about 36 percent liquids (see Figure 3). With vacuum bottoms recycle, liquefaction of various coals resulted in liquid yields of 55-60 percent for bituminous coals, 44-50 percent for sub-bituminous coals, and 47 percent for lignite. The effect of FLEXICOKING the vacuum bottoms is not included in the above liquid yields.

The economics of feeding sub-bituminous Wyodak Coal as well as Illinois No. 6 coal to the EDS process will be discussed in the economics section. No economics are available for a lignite feed. In this report all costs are based on once-through liquefaction as these were the only detailed costs that were available at this time.

V. Product Yields

For the average annual operation of the plant, the feedstock (bituminous coal), product, and byproduct rates for both the Base Case and the MFS case are summarized in Table 1.[5] The C_3 LPG and C_4 LPG are produced as finished products. In addition C_1/C_2 high Btu gas (HBG) is a finished product from the MFS case. To produce transportation fuels and distillate as major products, the naptha and fuel oil would require further downstream processing in an upgrading facility (refinery).

The greatest difference between the product yields from the Base Case and MFS Case is the higher yield of C_3/C_4 LPG and HBG in the MFS case. This higher yield is the result of replacing the steam reforming of C_1-C_3 light hydrocarbons for hydrogen

INCREASED LIQUID YIELDS OBTAINED WITH BOTTOMS RECYCLE COMPARED TO ONCE THRU OPERATION

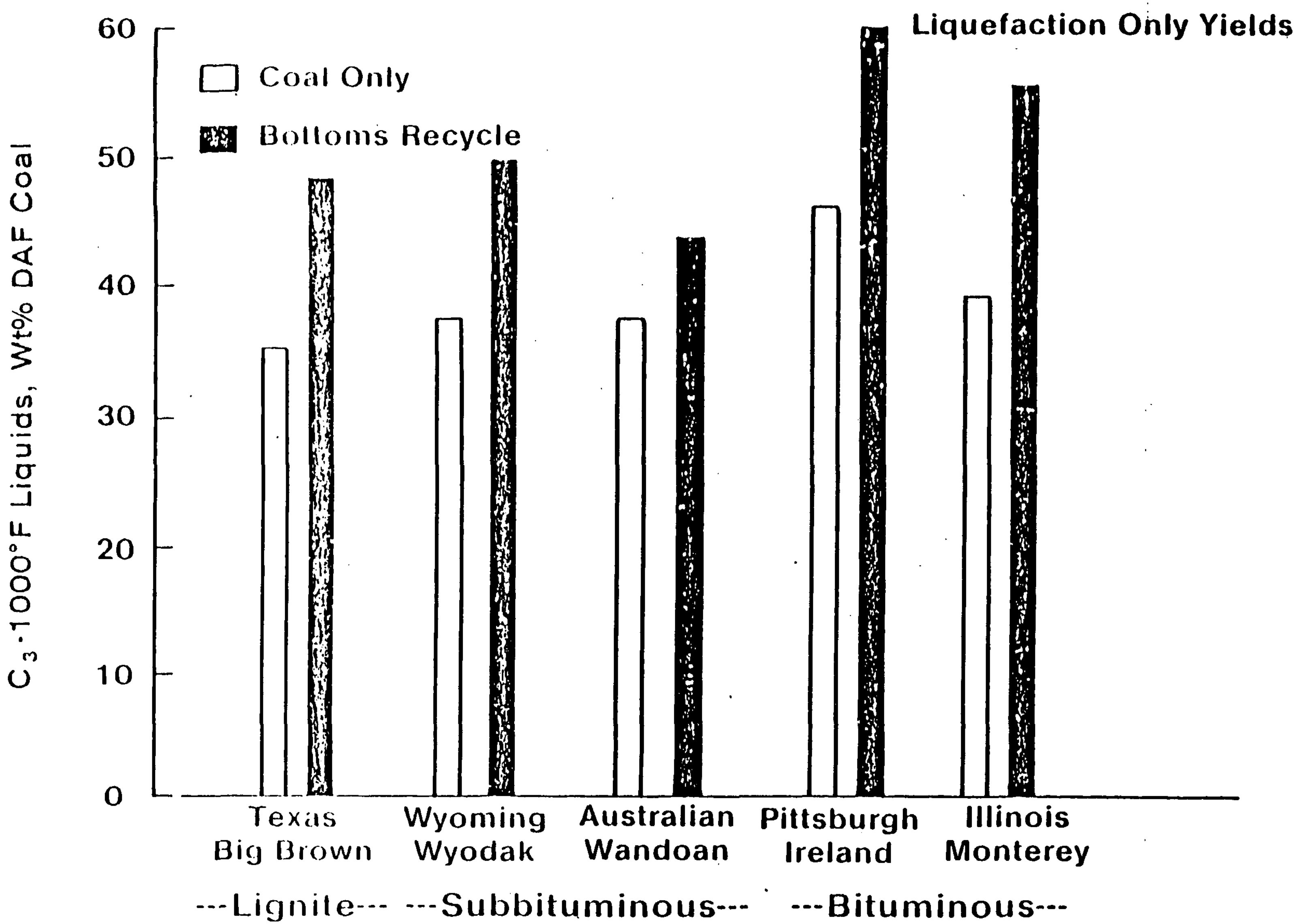


Figure 3

Table 1

Feedstocks and Product Yields

	HHV Btu/lb	Base Case ST/CD	Base Case FOEB/CD*	MFS Case ST/CD	MFS Case FOEB/CD*
Feedstock					
Process Coal (Dry)	12,562	19,577	83,364	16,256	69,224
Offsite Coal (Dry)	12,562	684	2,915	1,204	5,129
Total Coal (Dry)	12,562	20,261	86,279	17,460	74,352
Purchased Power (Energy Equiv.)	-	-	6,937	-	6,732
Total			93,215		81,082

	HHV MBtu/B	B/CD	FOEB/CD*	B/CD	FOEB/CD*
Product					
High Btu Gas	-	-	-	8,177**	8,177
C_3 LPG	3.85	81	53	2,731	1,782
C_4 LPG	4.34	1,948	1,433	1,649	1,213
Naptha	5.41	18,418	16,889	14,995	13,750
Fuel Oil (350-650°F)	6.36	14,611	15,750	12,052	12,992
Residual Oil (650°F+)	6.41	14,611	15,874	11,125	12,086
Total		49,669	50,000	50,729	50,000
By-products					
Sulfur (ST/CD)		890		934	
Ammonia (ST/CD)		179		110	
Phenol (B/CD)		294		298	

* One FOEB = 5.9 mBtu

** FOEB.

production, with the partial oxidation of about one-half of the liquefaction bottoms to produce hydrogen.

Much of the 650-1000°F residual product yield can be eliminated by utilizing bottoms recycle liquefaction. This serves to lighten the product slate. Table 2 shows the yield distribution improvements which can be obtained by using bottoms recycle liquefaction along with FLEXICOKING and coal partial oxidation instead of just once-through liquefaction and bottoms FLEXICOKING as in the Base Case.[7] This table shows that the residual oil can be eliminated and the naptha yield increased to 45 percent of the total product. It has been roughly estimated that about a 20 percent reduction in product cost (with respect to the Base Case) may be obtained by utilizing bottoms recycle liquefaction.[7]

VI. Overall Energy Efficiency

An analysis of the EDS process indicated that the thermal efficiency is 53.64 percent for the Base Case and 61.66 percent for the MFS case; these efficiencies do not include by-product heating values.[5] The efficiencies are listed in Table 1. In the Base Case 100 percent of the vacuum bottoms are sent to FLEXICOKING, and hydrogen is generated by steam reforming of the light hydrocarbon gases (C_2- and LPG) produced in the plant. In the MFS case, about one half of the vacuum bottoms stream is sent to FLEXICOKING with the remainder sent to a partial oxidation unit for hydrogen generation. In the Base Case the steam reforming furnaces were the largest onsite consumer of fuel gas (low Btu gas), whereas no fuel gas is required for the partial oxidation unit of the MFS case. The differences between these hydrogen production processes allows for the recovery of product C_2- gas and LPG in the MFS case. However, the MFS case requires more offsite coal than the Base Case since more steam must be generated to offset the steam generated by the steam reforming units of the Base Case.[5]

Overall the increase in product heat due to recovery of the C_2- gas in the MFS case more than offsets the increased input heat due to its higher electric power and offsite coal requirements.[5] The result is a higher efficiency in the MFS case relative to the Base Case.

VII. Economics

A. Illinois Coal

There have been a number of reports and papers presented in the literature which discuss the economics of the EDS direct liquefaction process or simply present the cost of the EDS products.[8][9][10][11] These reports include the ICF and ESCOE studies. All of these reports were based on the 1975/1976 study design prepared by Exxon Research and Engineering (ER&E).[12] All

Table 2

EDS Liquefaction Product Yields[7]
(% of Total Yield)

Liquid	Once Through Liquefaction/ Flexicoking	Bottom Recycle Liquefaction/ Flexicoking/ Partial Oxidation
C_1-C_2	-	20.8
C_3-C_4	5.3	9.0
Naptha	35.1	45.6
Distillate	35.0	24.3
Resid	24.6	-

of the economic figures presented here are based on the most recent study design published by ER&E in March, 1981.[5] This recent study design covered the conceptual design of an EDS coal liquefaction commercial plant receiving Illinois No. 6 bituminous coal. This design depicts the state of EDS technology in 1978 as this technology might be applied in a commercial facility.[5] About 20 man-years of effort were required for this work.[5]

This recent design is a complete update of the earlier, less extensive 1975/1976 design.[5] It represents a "detailed study design" for the onsite facilities, and a high-quality screening type of study design for the offsites. The current capital cost as reported by ER&E was estimated to be about twice that of their 1975/76 estimate.[5] Reasons for this increased capital cost include:

1. An 11 percent increase due to new estimating methods for large-job field-labor overheads.

2. A 51 percent increase due to scope changes in the study design. The most significant scope change was a 25 percent increase in coal feedrate to liquefaction, which required larger process units and added 19 percent to the plant cost.

3. A 43 percent increase due to design and estimating developments.

For the purposes of this report the total instantaneous plant investment as estimated by Exxon was used and then placed on a consistent economic basis with other liquefaction technologies that have been analyzed in other reports. This included resizing the plant to produce 50,000 FOEB/CD* of liquid products. The economic assumptions, including the plant size scaling factor, construction schedule, and coal cost, have been presented in a previous report.[13] The costs presented for the Base Case and MFS Case are based on once-through liquefaction since no detailed costs were available for bottoms recycling.

Table 3 presents an economic summary of the capital and product costs for the EDS direct liquefaction process. Costs based on two different capital charge rates (CCR) (11.5 and 30 percent) are shown for both the Base Case and the MFS Case. With a capital charge rate of 11.5 percent, the Base Case product cost is $50.09/FOEB and the MFS Case cost is $42.16/FOEB. With a 30 percent capital charge rate the Base Case product cost is $87.22/FOEB and the MFS cost is $71.83/FOEB. As can be seen, the MFS Case also has a lower capital investment than the Base Case. Since the MFS Case is both more efficient (61.8 percent vs. 53.6 percent)

* One FOEB = one fuel oil equivalent barrel = 5.9 MBtu

Table 3

Economic Summary of EDS Costs

	CCR = 11.5%		CCR = 30%	
	Base Case	MFS Case	Base Case	MFS Case
(Million of Dollars)				
Total Instantaneous Investment	3315	2649	3315	2649
Total Adjusted Capital Investment	3759	3004	3700	2956
Annual Capital Charge	432	345	1110	887
Annual Operating Cost	482	424	482	424
Total Annual Charge	914	769	1592	1311
Product Cost				
$/FOEB of Product*	50.09	42.16	87.22	71.83
$/Million Btu of Product	8.49	7.15	14.78	12.18

* One FOEB = 5.9 million Btu.

and more economical than the Base Case, it follows that the MFS Case has been selected in this report for comparison with other liquefaction technology costs.

Table 4 presents a breakdown of the investment and operating costs for the MFS Case. The total instantaneous investment in first quarter (1Q) 1981 dollars is $2.65 billion. The real 1990 total erected cost has been estimated at $3.0 billion in 1Q 1981 dollars. The total annual operating cost per year is $452 million before taking a by-product credit of $28 million. Coal represents about 50 percent of the operating cost while repair materials account for 21 percent and utilities 14 percent.

Table 5 presents the annual capital charge and the various operating costs as a percentage of product cost. With a CCR of 11.5 percent the annual capital charge accounts for 42 percent of the product cost while coal accounts for 29 percent. With a CCR of 30 percent the annual capital charge accounts for 65 percent of the product cost with coal accounting for 17 percent.

In addition to the Base Case and MFS Case there are three additional cases being investigated by Exxon Research and Engineering, for convenience called Cases 1, 2, and 3.[7] The differences amongst these cases involve the method used for bottoms processing. The main feature common to these three cases and different from the Base and MFS Cases is the recycling of the bottoms stream to the liquefaction reactor. In addition to the recycle stream, Case 1 includes coal partial oxidiation to produce hydrogen and bottoms FLEXICOKING for plant fuel. Case 2 is identical to Case 1 except bottoms partial oxidation is used to produce the plant fuel instead of FLEXICOKING. Case 3 employs coal partial oxidation for hydrogen production and utilizes a hybrid boiler which burns liquefaction bottoms to provide process heat.

These alternate bottoms processing routes can significantly affect product cost. Relative to the Base Case, product cost reductions for Cases 1-3 were roughly estimated as follows:

Case	% Cost Reduction[7]
1	20
2	22
3	28

B. Wyoming Coal Case

To determine the effect of coal type on the EDS liquefaction process, ER&E performed a study design for sub-bituminous Wyodak coal.[12][14][15] This design was patterned after the 1975/76 Illinois design, but done in less detail.[12] Although both of these designs are now outdated, their comparison should give a rough indication of the relative yields, investments, and product

Table 4

MFS Case, Investment and Operating Cost,
(1st Q 1981 Dollars)

MFS Case	50,000 FOEB/CD 1 Q 1981 $
Investment Cost (Millions of Dollars)	
Onplot Investment	1281
Offplot Investment	780
ER&E Charges	60
Subtotal	2121
Contingency	309
Total Instantaneous Investment	2430
Working Capital and Startup Costs	219
Total Instantaneous Capital Investment	2649
Operating Cost (Millions of Dollars Per Year)	
Capital Related	
Interest on Working Capital	7.1
Repair Materials	114
Raw Materials	
Coal	210
Catalyst & Chemicals	8.6
Salaried and Related Costs	
Wage Earners	34.7
Salaried	9.1
Overhead, Supplies, etc.	8.8
Utilities, Power	59.7
Gross Annual Operating Cost	452
By-product Credits	
Sulfur	12.8
Ammonia	5.4
Phenol	10.0
Net Annual Operating Cost	424

Table 5

Product Cost Breakdown, % of Cost

	MFS Case	
	CCR=11.5%	CCR=30%
Annual Capital Charge	42	65
Coal	28.9	17.4
Repair Materials	12.4	7.5
Utilities	8.2	4.9
Labor	5.3	3.2
Catalyst & Chemicals	1.2	0.7
Overhead	1.1	0.6
Other	4.8	2.9
Byproduct Credit	(3.9)	(2.3)

costs. The design includes a FLEXICOKER to handle vacuum bottoms and a steam reformer to produce hydrogen. Both designs are based on feeding the same quantity of dry coal. Yields for both cases are shown in Table 6. The Wyoming coal case has an overall 13 percent lower product yield with the greatest difference lying in the 400°F+ fuel oil yield. The lower product yield is expected since Wyoming coal has a lower feed carbon content than Illinois coal.

From a material balance Exxon performed on the Wyoming coal case, it was expected that the major process blocks for both cases would be approximately the same size and hence, the total investment for either an Illinois or a Wyoming EDS plant should be about the same.[15] The total expected cost for the Wyoming coal plant was calculated to be about 96 percent of that for the Illinois coal plant with respect to the 1975/76 study design.[14] The product costs for both cases were estimated to be about the same.[14]

VIII. Summary

The EDS product costs based on the MFS case will be used for comparison with costs from other liquefaction technologies. The real 1990 total erected cost for this case has been estimated at about $3.0 billion (1Q 1981 dollars). The total instantaneous capital cost has been estimated to be $2.65 billion. Total annual operating cost before taking by-product credits is $452 million in real 1990 dollars. Based on a CCR of 11.5 percent the product cost is $42.16/FOEB ($7.15/MBtu); based on a CCR of 30 percent the product cost is $71.83/FOEB ($12.18/MBtu).

Table 6

Product Yields for the Wyoming and Illinois Coal EDS Plants[14] (lb/100 lb. Process Coal Feed)

	Wyoming Case	Illinois Case
Products		
C_3 LPG	1.8	1.8
C_4 LPG	1.8	2.0
C_5/400°F Naptha	14.5	15.6
400°F$^+$ Fuel Oil	2.6	27.3
Total	40.7	46.7
Byproducts		
Sulfur	0.7	3.9
Ammonia	0.4	0.4

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