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**Scoping Study
on
Two Flash Hydropyrolysis Processes**

Suman P. N. Singh

MASTER

OAK RIDGE NATIONAL LABORATORY
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CHEMICAL TECHNOLOGY DIVISION

SCOPING STUDY
ON
TWO FLASH HYDROLYSIS PROCESSES

Suman P. N. Singh

Prepared for the
Department of Energy/Fossil Energy
Division of Coal Conversion

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DEPARTMENT OF ENERGY

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SCOPING STUDY ON TWO FLASH HYDROLYSIS PROCESSES

Suman P. N. Singh

ABSTRACT

A scoping study was performed on two conceptual flash hydrolysis processes. The two processes selected were the Cities Service and the Schroeder-Spencer Chemical Company (SCC) processes because they represent two aspects of the flash hydrolysis technology. The Cities Service process was designed primarily to produce substitute natural gas from North Dakota lignite, while the Schroeder-SCC process was designed primarily to produce a crude aromatic distillate-type oil from Pittsburgh No. 8 bituminous coal.

Preliminary mass and energy balances were developed for conceptual plants designed to produce 250 MMscfd of substitute natural gas by the Cities Service process and 50,000 bbl/day of distillate oil by the Schroeder-SCC process. Preliminary economic evaluations were also made on the two processes based on cost data reported by the two process developers.

The usable fuel energy efficiency of the Cities Service process was calculated to be 62%, while that for the Schroeder-SCC process was calculated to be 76%. The preliminary evaluations indicate that a more detailed engineering evaluation of the flash hydrolysis process is justified after a firm data base for the process is established.

1. INTRODUCTION

Flash hydrolysis (FHP) of coal is an emerging technology in which the coal is rapidly hydrogenated (coal residence times are on the order of fractions of a second) at a high temperature and pressure and then quenched to yield after further processing a slate of products consisting of substitute natural gas (SNG), an aromatic distillate oil consisting mainly of benzene, toluene, and xylene (BTX), a fuel oil, sulfur, ammonia,

and a usable char. The process is essentially self-sufficient in hydrogen; hydrogen requirements can be met either by gasifying the spent char or by reforming a portion of the SNG.

The development of the FHP process is still at the small pilot plant scale level. However, the FHP process has attracted considerable attention because it offers a comparatively simple method of converting coal to commercially valuable products such as SNG, BTX liquids, fuel oil, sulfur, and ammonia. For example, the SNG produced may be used as a source of fuel to augment the nation's rapidly dwindling supplies of natural gas, and the fuel oil and the BTX liquids may be used either as gasoline blending stock or as a chemical feedstock.

Several investigators are currently studying the FHP process.

Following is a list of some of them:

1. Brookhaven National Laboratory
2. Cities Service R&D Company, Inc.
3. Clean Fuels Institute, City College of New York
4. Institute of Gas Technology
5. Rocketdyne Division, Rockwell International
6. W. C. Schroeder

1.1 Objective

The objective of the present work is to perform a scoping study of two FHP processes to determine if a more detailed engineering evaluation of the FHP process is justified at this time. The two conceptual processes selected to be evaluated are:

1. Cities Service's Short Residence Time (SRT) Hydropyrolysis Process.

2. Schroeder modified Spencer Chemical Company (SCC) Process, hereafter referred to as the Schroeder-SCC FHP Process.

1.2 Scope

The scoping study was envisaged to consist of performing the following tasks for each of the above listed processes:

1. Review the information available on the process. This task was necessary because much of the information available on the two processes is considered to be proprietary in nature by the two process developers.
2. Firm up the process flowsheet for a conceptual plant based on the process.
3. Make an overall material and energy balance for the conceptual plant.
4. Make a preliminary estimate of the capital and annual operating cost for the conceptual plant, if possible.
5. Appraise the available data base on the process for its adequacy for a process design.
6. Derive conclusions regarding the process both from a technical and an economics viewpoint.

Based on the results of the above scoping study, recommendations were to be made regarding the justification for a more detailed engineering evaluation of the flash hydrolysis process.

1.3 Preamble for Economic Evaluations

Preliminary economic evaluations were performed for conceptual plants based on the two processes using the ORNL computer program PRP.¹ Briefly

stated, the PRP computer program calculates the product price of the product from a processing plant for a given set of input economic parameters using the discounted cash flow method.

In the present study, the price of the primary product of the processes was calculated for several feed coal costs and annual after-tax rates of return on equity capital using the discounted cash flow method. The following financing schemes were used to provide the capital for the conceptual plants: (1) 100% equity capital and (2) 75% debt and 25% equity capital. The costs developed were adjusted to reflect costs in the first quarter of 1977. No cost was included for a captive coal mine. Instead, the cost of the feed coal to the plants was varied between \$10/ton and \$50/ton in \$10/ton increments. The economic evaluations for the two processes were performed for 10, 12, and 15% annual after-tax rates of return on the equity capital, and 9% annual interest rate on the debt capital.

Basic cost information required for the development of the economic evaluations performed in this study were derived from cost information developed by the proponents of the two processes evaluated, namely, Cities Service Research and Development Company and Professor W. C. Schroeder. In line with the preliminary nature of the present study, no attempt was made to develop more detailed costing (i.e., by sizing and cost estimating the process equipment). Consequently, the costs developed in the present study should be regarded as order-of-magnitude-type costs.

Further details regarding the basis of the economic information for each conceptual process are presented in later sections of this report.

2. CITIES SERVICE SRT HYDROLYSIS PROCESS

2.1 Introduction

Cities Service has conducted several bench-scale experiments to develop their version of the FHP process at their R&D facilities in Cranbury, New Jersey, using corporate funds. The primary intent of Cities Service in developing their process was to maximize the production of SNG from coal. In addition to their process developmental efforts, they have retained Foster-Wheeler to conduct a detailed engineering evaluation of their conceptual process.

The information presented in the following sections is based on the data provided by Cities Service² and represents evaluations that they conducted using North Dakota lignite. Cities Service indicated that this information was synthesized from their own and Foster-Wheeler's evaluation of the process. It is pointed out that the information presented should be regarded as tentative since the evaluation by Cities Service is still continuing.

2.2 Process Description

In the Cities Service FHP process, pulverized coal (70% through 200 mesh) is mixed with preheated hydrogen and fed to the FHP reactor at pressures ranging between 600 and 3000 psig (4.2 and 20.8 MPa) and at temperatures ranging between 1100 and 1800°F (593 and 982°C). Coal-particle residence time in the reactor is typically between 0.1 and 2 sec. Figure 1 shows a block diagram of the conceptual process in which the hydrogen required by the process is produced via char gasification.

• • •

Following the short duration reaction between the pulverized coal and the preheated hydrogen, the products are rapidly quenched. In the bench-scale unit, hydrogen gas that had been cryogenically cooled was used as the quenching medium. However, in the commercial version of the process, other quenching means (such as water sprays) are proposed to be used.

The quenched reaction products are taken to a char separator where the char is separated from the product gas stream. The char-free gas stream is then cooled by exchanging heat with the feed hydrogen stream. The BTX liquids, oil, ammonia liquor, and water that condense out of the gas stream are separated from the gas stream in the gas-liquid separators. Acid gases (such as H_2S and CO_2) are then removed from the gas stream using commercially available processes prior to the product gases being taken to the methanation step. In the methanator, CO and hydrocarbon product gases (such as C_2H_4 , C_2H_6 , etc.) are converted to methane and hydrogen. The CO_2 and water formed in the methanation reaction are separated from the product gas, which is then taken to the hydrogen recovery section. In the hydrogen recovery step, hydrogen is separated cryogenically from the SNG. The recovered hydrogen is recycled to the FHP reactor, while the SNG produced is taken to product storage. The SNG is designed to consist essentially of methane and hydrogen and is designed to have a gross heating value of 983 Btu/scf ($36.6 \times 10^6 \text{ J/m}^3$).

The liquid stream that is separated in the gas-liquid separator is further separated into two fractions--one consisting mainly of the BTX liquids and fuel oil, and the other, ammonia and water. The aromatic oil fraction is distilled further to produce the BTX liquids and the oil; the ammoniacal liquor is distilled to produce anhydrous ammonia.

The char produced in the FHP reactor is gasified with oxygen and steam to produce synthesis gas. The synthesis gas is then taken through shift conversion and acid-gas removal steps to yield make-up H_2 which is mixed with the recycle H_2 stream and ultimately fed as a reactant to the FHP reactor.

The H_2S streams that are separated from the two acid-gas removal steps are combined and taken to a Claus sulfur plant where the H_2S is converted to sulfur.

Excess steam generated in the plant is used to generate power to help meet the plant power requirements.

A small amount of oxygen is used to burn a small fraction of the feed hydrogen to the FHP reactor to generate the high inlet-gas temperature required by the process.

It is emphasized that what is described above is the conceptual process based on Cities Service's FHP technology. No actual plants have been built to date, and some of the process steps indicated may be modified as the process undergoes further development.

2.3 Material and Energy Balances

Material and energy flows around the Cities Service FHP reactor and typical reactor operating conditions are given in Fig. 2. Material and energy flows for the conceptual overall FHP plant are presented in Fig. 3 for a plant designed to primarily produce 250 MMscfd ($7.1 \times 10^6 \text{ m}^3/\text{day}$) of substitute natural gas having a gross heating value of 983 Btu/scf ($36.6 \times 10^6 \text{ J/m}^3$). The plant also produces $\sim 6400 \text{ bbl/day}$ ($1 \times 10^3 \text{ m}^3/\text{day}$) of BTX liquids. The material and energy balances were developed from

ORNL DWG 77-2026R

NOTE: BBtu/DAY = BILLION Btu/DAY

REACTOR OPERATING CONDITIONS:

TEMPERATURE = 1600°F (871°C)
 PRESSURE = 1500 psig (10.4 mPa)
 RESIDENCE TIME < 2 SEC.

MATERIAL BALANCE:

INPUT = 14,124 + 838 = 14,962 TPD

OUTPUT = 3030 + 840 + 982 + 1463 + 129 + 103 + 78 + 2265 + 6092 = 14,962 TPD.

Fig. 2. Material and energy flows for the Cities Service FHP reactor.

ORNL DWG 77-1523R

- NOTES: 1. BBtu/D = BILLION BTU/DAY
 2. ASSUMING 99.5% CONVERSION
 3. SNG CONSISTS MAINLY OF METHANE AND HYDROGEN

ENERGY EFFICIENCY:

$$\text{OVERALL} = \frac{(246 + 35 + 2 + 1) \times 10^9}{454 \times 10^9} = 63\%$$

$$\left. \begin{array}{l} \text{USABLE FUEL} \\ \text{ENERGY EFFICIENCY} \end{array} \right\} = \frac{(246 + 35) \times 10^9}{454 \times 10^9} = 62\%$$

Fig. 3. Material and energy flows for the Cities Service FHP process.

information supplied by Cities Service² for a conceptual plant processing $\sim 22,000$ TPD (20×10^6 kg/day) of moisture-free North Dakota lignite. The ultimate analysis of the lignite feed was indicated by Cities Service² to be as follows:

<u>Component</u>	<u>Analysis (wt %)</u>
C	63.61
H	4.29
N	1.40
O	21.51
S	1.00
Ash	8.19
<u>Moisture</u>	<u>---</u>
Total	100.00

Cities Service³ reported the heating value of the lignite to be 11,206 Btu/lb (26.04×10^6 J/kg) on a moisture- and ash-free basis.

From Fig. 3 it can be noted that the overall energy efficiency of the FHP process was calculated to be $\sim 63\%$; the usable fuel energy efficiency was calculated to be $\sim 62\%$.

As used in this report, the overall energy efficiency of a process is defined as the energy content of the total products of the process divided by the energy content of the feed materials; the usable fuel energy efficiency is defined as the energy content of the usable fuel products of the process (in this case, SNG and BTX liquids) divided by the energy content of the feed materials. Since the conceptual plants evaluated in the present study were treated as grassroots-type facilities, no utilities were

assumed to be supplied to the processing plants. All process utility requirements were premised to be developed onsite.

Figure 4 is a block flow diagram of another version of the conceptual Cities Service FHP process in which the feed hydrogen is generated by methane reforming rather than char gasification. According to Pelofsky, Greene, and La Delfa⁴ this should result in a lower capital investment for the plant. However, they indicate that the energy efficiency and the SNG production from the plant are also lower.

2.4 Economic Evaluation

As indicated earlier, an economic evaluation of the conceptual plant based on the Cities Service FHP process was performed. The price of the primary product of the process (SNG in this case) was computed using the discounted cash flow method for several coal costs, annual rates of return on equity capital, and for two different financing schemes.

2.4.1 Basis for economic evaluation

The economic evaluation of the conceptual plant was performed based on information obtained from a paper presented recently by La Delfa and Greene⁵ of Cities Service. They reported on the economics of a conceptual plant designed to produce 255 MMscfd of SNG from lignite using the Cities Service flash hydrolysis process. Pertinent information extracted from the above paper is presented in Tables 1 to 3.

2.4.2 Economic evaluation procedure

The information reported in Tables 1 to 3 was used to develop the economic evaluation of the conceptual Cities Service FHP plant developed

Table 1. Summary of information regarding the
Cities Service FHP process^a

Design plant capacity = 255 MMscfd of SNG as primary product

Plant type = grassroots facility

Basis of cost estimate = first quarter 1977 dollars

Installed cost of FHP plant = \$680.7 x 10⁶
(see Table 2 for details)

Installed cost of support facilities for FHP plant = \$238.7 x 10⁶
(see Table 3 for details)

Total installed cost of grassroots facility = \$919.4 x 10⁶

Plant raw water requirements = 19,862 gpm

Cost of raw water = \$0.4/1000 gal

Number of process operators/shift^b = 44

^aData obtained from La Delfa and Greene in ref. 5.

^bInformation obtained by telephone conversation with
Marvin Greene of Cities Service R&D.

Table 2. Summary of the installed equipment cost
for the Cities Service FHP plant^a

Component	Cost (\$10 ⁶)
Coal handling system	51.7
Coal feed system	39.9
Flash hydrolysis reactors	47.1
Gas/liquor separation	23.3
Gas purification	24.2
Methanation	23.2
Hydrogen recovery	41.2
Sour water stripper/ammonia recovery	16.3
Aromatics recovery	1.2
Char gasification	82.1
Make-up hydrogen production	172.3
Sulfur recovery	6.5
Waste water treatment	10.9
Oxygen plant	<u>140.8</u>
Installed cost of FHP plant	680.7

^aData obtained from ref. 5.

Table 3. Summary of the installed cost of support facilities for the Cities Service FHP plant^a

Component	Cost (\$10 ⁶)
Raw water treating	19.0
Boiler feedwater treating	11.2
Cooling water system	30.2
Glycol cooling system	0.8
Flare	3.1
Tankage	5.4
Loading/unloading facilities	2.4
Fire water and underground systems	8.6
Plant air/instrument nitrogen	0.8
Power generation	19.7
Steam generation	108.0
Ash handling system	3.5
Interconnecting piping	16.0
Buildings	3.9
Railroads, roads and fences	1.0
Area lighting, power distribution and communication system	4.9
Site preparation	<u>0.2</u>
Installed cost of support facilities	238.7

^aData obtained from ref. 5.

in the present study. Details of the economic evaluation procedure are presented in Appendix A, and the results of the economic analyses are summarized in the following section.

2.4.3 Economic evaluation results

The estimated total capital investment, the working capital, and the gross annual operating cost (for 90% plant service factor) were calculated to be about \$1207 million, \$57 million, and \$88 million respectively. Details of these costs are presented in Tables 4 to 6. The gross annual operating cost indicated above does not include the feedstock cost, depreciation, and taxes since these costs are accounted for separately in computer program PRP.

Results of the economic evaluation are summarized in Table 7 for the two financing schemes. As indicated earlier, the heating value of the SNG produced by the process was assumed to be 983 Btu/scf ($36.6 \times 10^6 \text{ J/m}^3$). The calculated price of the SNG produced from the conceptual plant is also shown graphically in Fig. 5 for the 100% equity financing scheme.

Table 4. Capital investment estimate for conceptual Cities Service
FHP plant producing primarily 250 MMscfd SNG

Components	Cost (\$10 ⁶)
Direct installed cost of FHP plant (from Table 1)	680.7
Direct installed cost of support facilities for FHP plant (from Table 1)	<u>238.7</u>
Total direct installed cost of plant, TDIC	919.4
Engineering & contractor's fees, 8% TDIC	73.6
Project contingency, 15% TDIC	137.9
Startup plant modifications, 2% TDIC	18.4
Land costs, 200 acres @ \$2000/acre	0.4
Working capital (see Table 5)	<u>57.0</u>
Total capital investment	1206.7

Table 5. Working capital estimate for conceptual Cities Service
FHP plant producing primarily 250 MMscfd SNG

Component	Cost (\$10 ⁶)
20 days of feedstock cost @ \$20 per ton of coal	14.01
30 days of product SNG @ \$4.0 per Mscf of SNG	30.00
30 days of product BTX liquids @ \$30 per bbl of liquids	5.77
30 days of gross operating costs (from Table 6)	<u>7.26</u>
Total working capital	57.04

Table 6. Annual operating cost^a estimate for conceptual Cities Service FHP plant producing primarily 250 MMscfd of SNG

Component	Cost (\$10 ⁶)
Labor costs	
a. Process operating labor	3.78
b. Supervisory personnel cost	0.76
Labor burden	1.59
Plant maintenance cost ^b	45.97
Operating supplies*	1.13
General administrative overhead costs	20.35
Utilities*	
a. Electric power - generated in the plant	0.0
b. Water	4.20
Catalyst and chemicals*	0.50
Waste disposal cost*	0.66
Property insurance cost	<u>9.38</u>
Gross annual operating cost	88.32

^aThe above costs are reported for a 100% plant service factor. For other plant service factors, multiply the cost for the items marked with an asterisk (*) by the desired plant service factor to obtain the appropriate annual operating cost. The above costs do not include the feedstock cost, depreciation, and taxes. These costs are accounted for separately in the computer program PRP. (Details regarding the derivation of the above costs are given in Appendix 6.2.2.)

^bIncludes maintenance materials, labor, supervision and maintenance labor burden.

Table 7. Calculated product price of SNG produced by the conceptual Cities Service FHP plant

Run-of-mine coal ^a cost (\$/ton)	Calculated SNG product price ^{b,c} (\$/MMBtu)					
	Debt/equity = 0/100			Debt/equity = 75/25 ^d		
	Rate of return on equity			Rate of return on equity		
	10%	12%	15%	10%	12%	15%
5	4.11	4.79	5.95	2.96	3.09	3.29
10	4.82	5.50	6.66	3.67	3.80	4.00
20	6.25	6.93	8.09	5.10	5.23	5.42
30	7.67	8.35	9.51	6.53	6.65	6.85
40	9.10	9.78	10.95	7.96	8.08	8.27
50	10.53	11.20	12.37	9.39	9.50	9.69

^aCoal used in the analysis is North Dakota lignite.

^bThe product SNG price is calculated (using ORNL computer program PRP) based on costs presented in Tables 4 to 6. These costs were developed from costs reported by La Delfa and Greene in ref. 5.

^cThe heating value of the SNG was taken to be 983 Btu/scf ($36.6 \times 10^6 \text{ J/m}^3$).

^dInterest rate on the debt fraction was computed at 9%/annum.

Fig. 5. Product price variation of SNG produced by the Cities Service FHP process with variation in feed coal cost.

The salable by-products from the conceptual plant are sulfur, ammonia, and BTX liquids. The premised selling prices of the by-products are given in the table below. The sensitivity of the product price of the SNG to a \$10/unit change in the selling price of the by-products was determined to be as follows:

By-product	By-product unit	Premised selling price (\$/unit)	Sensitivity of the SNG product price (\$/Mscf)
Sulfur	long ton	60	-0.0067
Ammonia	ton	140	-0.0052
BTX liquids	barrel	30	-0.2565

The negative signs in the above table indicate that a decrease in the selling price of the by-product results in an increase in the product price of the SNG produced and vice versa.

2.4.4 Discussion of results

Based on the economic analysis conducted in this study, the price of producing SNG from coal by the Cities Service FHP process was calculated to be \$4.79/MMBtu for \$5/ton coal (lignite in this case), 100% equity financing, and a 12% annual after-tax rate of return on equity capital. The cost of producing SNG from coal by the IGT steam-oxygen HYGAS process (on a comparable basis) was estimated to be \$4.18/MMBtu based on the cost reported by Detman⁶ of C. F. Braun & Co. Comparing the above two SNG gas costs, it can be seen that the SNG cost from the Cities Service FHP process (although higher) is comparable to the SNG cost from the HYGAS process.

Based on the following values--75% debt, 25% equity financing, with return on equity at 12% after taxes, interest rate on debt at 9%, and with lignite at \$5/ton--the calculated price for the SNG was \$3.09/MMBtu.

La Delfa and Greene⁵ compared the cost of converting coal to SNG gas by the Cities Service and the Lurgi process on a common and consistent basis. They developed their economic analysis based on the ERDA/AGA⁶ guidelines. They report⁵ the average gas cost from the Cities Service process as \$2.66/MMBtu as compared to \$3.49/MMBtu by the Lurgi process. This indicates that an economic incentive exists for developing the Cities Service FHP process.

The cost of \$2.66/MMBtu reported by La Delfa and Greene should not be compared with the \$3.09/MMBtu indicated here, since the ERDA/AGA average gas price method is known to give lower costs than the discounted cash flow method used here.

It is reiterated that the analysis reported here for the Cities Service plant should be regarded as a preliminary-type analysis. Judgments regarding the economic viability of the process should await a more detailed engineering evaluation of the process. La Delfa and Greene report⁵ that efforts are currently underway at Cities Service to develop optimized process designs for the process. Such designs may result in lowering the cost of producing SNG from coal via the Cities Service FHP process.

3. SCHROEDER - SCC FHP PROCESS

3.1 Introduction

In the late 50's, the Process Development Department of Spencer Chemical Company operated a pilot plant to investigate the technical and the economic feasibility of the rapid hydrogenation of coal process suggested by Dr. W. C. Schroeder who at the time was a consulting chemical engineer to the company. The Process Development Department presented the results of their evaluation in a final report⁷ dated March 1, 1960, and stated the following conclusions:

1. The process is technically feasible.
2. Further development effort would be required to solve certain problems in the process such as high-pressure feeding of coal.
3. The process appeared to be economically unattractive at that time because of the low selling prices for the products of the process.

In January 1976, Schroeder⁸ published an article in Hydrocarbon Processing describing a modified version of the Spencer Chemical Company rapid hydrogenation process. In the article, Schroeder indicated that the process could competitively produce a desulfurized crude-like oil from high-sulfur bituminous coal.

In the present study, the updated Schroeder version of the process was examined. Information for the process was obtained primarily from refs. 7 and 8 and from telephone conversations with Professor Schroeder, who is presently at the University of Maryland. In the telephone conversations, Professor Schroeder indicated that the process was proprietary in nature and expressed his inability to divulge much more information than that

given in the Hydrocarbon Processing article mentioned earlier. Hence, the present scoping study is based on several assumptions which will be elaborated upon in the subsequent sections.

3.2 Process Description

The Schroeder-SCC FHP process is a catalytic process. A 1% deposit of ammonium molybdate on the pulverized coal is used as a catalyst to accelerate the reaction. In the Schroeder-SCC FHP process, the pulverized coal is rapidly hydrogenated at temperatures ranging between 900 and 1000°F (483 to 538°C) and pressures ranging between 1500 and 2000 psi (10 to 14 MPa) in a residence time of < 1 min. The process yields a crude aromatic-type oil, H_2 , CO, CH_4 , other higher hydrocarbon gases, H_2S , and crude NH_3 . The crude aromatic-type oil can be further refined in a conventional refinery to produce aromatic liquids such as benzene, toluene, etc. The H_2 , CO, CH_4 , and other higher hydrocarbon gases are reformed (using steam and oxygen) to meet the hydrogen requirements of the flash hydrolysis reactor. According to ref. 8, sufficient gases are produced to meet the process hydrogen requirements. The H_2S produced is converted to sulfur in a Claus plant, while the crude NH_3 is rectified. Sulfur and ammonia are recovered as salable by-products of the FHP process.

Figure 6 is a schematic flowsheet for the conceptual Schroeder-SCC FHP process. A brief description of the process follows.

Pulverized coal (containing the catalyst) and preheated hydrogen are reacted rapidly in the flash hydrolysis reactor at high temperature and pressure. The products of the reaction are cooled rapidly and then separated in the tar separator. The tars produced from the FHP reactor are further hydrogenated in the tar hydrogenator (using recycle gas rich in

Fig. 6. Schematic flow diagram for the Schroeder-SCC FHP process.

hydrogen) to produce aromatic-type oils and hydrocarbon gases. The temperature in the hydrogenator is kept high enough so that the products remain in the vapor state. The product stream from the tar hydrogenator is combined with the vapor stream from the tar separator and is taken to the cyclone separator where the entrained solids are separated from the gas stream. The solid-free gas stream is then cooled through a series of indirect heat exchangers to condense the aromatic oils. The aromatic oils are then separated from the uncondensed gas stream in the oil-gas separator. The aromatic distillate (the main product of the process) is then taken to a conventional refinery for further processing. A small fraction ($\sim 4\%$) of the distillate is used in the plant to meet the process energy requirements.

The gas stream from the oil-gas separator is purified in the recycle gas purification step using commercially available processes to remove the CO_2 , H_2S , and NH_3 . The H_2S removed from the gas is fed to a Claus plant to produce sulfur, while the ammoniacal solution recovered is distilled to yield anhydrous ammonia. Both sulfur and anhydrous ammonia are by-products of the process.

The cleaned gas from the recycle gas purification step is taken to a reformer where it is converted to hydrogen using steam and oxygen. The hot hydrogen from the reformer is used to preheat the feed gas to the reformer and is then recycled to the FHP reactor to treat fresh coal. As mentioned earlier, a small fraction of the cleaned recycle gas is used in the tar hydrogenator to hydrogenate the tars produced by the FHP reaction.

The solids recovered from the product gas stream in the cyclone separator are taken to a catalyst recovery step where the catalyst is

recovered from the ash and char. The catalyst is recycled, and the ash and spent char are disposed of as waste products of the process.

3.3 Material and Energy Balance

Material and energy flows for a conceptual plant based on the Schroeder-SCC process were developed. The flow rates were developed for a plant capable of nominally producing 50,000 barrels per day ($7950 \text{ m}^3/\text{day}$) of the aromatic distillate oil based on yields reported in ref. 8. The specific gravity of the aromatic distillate oil was reported⁸ to be 0.92. The heating value of the aromatic distillate oil was assumed to be 5.5×10^6 Btu/bbl. Coal feed to the above plant was 14,840 TPD (13.5×10^6 kg/day) of as-received Pittsburgh No. 8 bituminous coal. The analysis of the feed coal, as indicated by Schroeder⁹ is as follows:

<u>Component</u>	<u>Analysis (wt %)</u>
C	67.51
H	4.74
N	1.16
O	6.17
S	4.17
Ash	10.59
<u>Moisture</u>	<u>5.66</u>
Total	100.00

The feed coal was estimated to have a higher heating value of 14,500 Btu/lb (33.7×10^6 J/kg) on an MAF basis.

Material and energy flows around the FHP reactor and the tar hydrogenator are presented in Fig. 7 as well as the operating conditions (for the

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- NOTES: 1. HEATING VALUE OF GAS = 780 Btu/scf
 2. BBtu / DAY = BILLION Btu / DAY.
 3. AMOUNT DETERMINED BY DIFFERENCE
 4. ASSUMING MAF COAL HEATING VALUE = 14,500 Btu/lb.
 5. ASSUMING ASH + CHAR HEATING VALUE = 2040 Btu/lb.

REACTOR OPERATING CONDITIONS:

TEMPERATURE = 832 ° F (500°C)
 PRESSURE = 1500 psig (10.4 mPa)
 RESIDENCE TIME = <1 minute

MATERIAL BALANCE:

INPUT = 14840 + 325 = 15,165 TPD
 OUTPUT = 1610 + 2483 + 8383 + 205
 + 644 + 1840 = 15,165 TPD

Fig. 7. Material and energy flows for the FHP reactor and tar hydrogenator used in the Schroeder-SCC conceptual FHP process.

FHP reactor) for the above balances. These operating conditions were obtained from ref. 8. The information has been presented for the FHP reactor and tar hydrogenator because insufficient information was available regarding the process to enable a material and energy balance to be completed around the FHP reactor alone. The other assumptions used to develop the material and energy balances are also listed as notes in Fig. 7.

Figure 8 presents the material and energy flows for the overall Schroeder-SCC FHP conceptual plant. From Fig. 8 it can be noted that the overall energy efficiency of the process is estimated to be $\sim 81\%$, while the usable fuel efficiency is $\sim 76\%$.

Comparing the overall estimated energy efficiencies of the Cities Service and the Schroeder-SCC FHP process (see Figs. 3 and 8), it should be noted that the estimated efficiency of the Schroeder-SCC process is higher than that of the Cities Service process. Some of the reasons that may account for this difference are the following:

1. The estimated overall energy efficiency for the Cities Service process (63%) is the efficiency calculated for converting the coal to primarily SNG gas and BTX liquids, whereas the estimated overall energy efficiency for the Schroeder-SCC process (81%) is the efficiency calculated for converting the coal to primarily a crude aromatic oil. Since the two processes produce different primary end products, the efficiency figures of the two estimated processes reported cannot be compared directly. However, if the efficiency for converting the crude aromatic oil produced by the Schroeder-SCC process into SNG gas and BTX liquids (similar to the end products from the Cities Service

ORNL DWG 77-1522

- NOTES:
1. BBtu/D = BILLION Btu/DAY
 2. ASSUMING 99.5 % CONVERSION
 3. ASSUMING ASH + CHAR HEATING VALUE = 2040 Btu/lb
 4. ASSUMING MAF COAL HEATING VALUE = 14,500 Btu/lb

ENERGY EFFICIENCY:

$$\text{OVERALL} = \frac{(274 + 4 + 5 + 8) \times 10^9}{360 \times 10^9} = 81\%$$

$$\left. \begin{array}{l} \text{USABLE FUEL} \\ \text{ENERGY EFFICIENCY} \end{array} \right\} = \frac{274 \times 10^9}{360 \times 10^9} = 76\%$$

Fig. 8. Material and energy flows for the Schroeder-SCC conceptual FHP process.

process) is considered, then the energy efficiencies of the two processes may be much closer than indicated in this report.

2. The Schroeder-SCC process operates at a lower temperature than the Cities Service process (932°F compared to 1600°F).

3.4 Economic Evaluation

A preliminary economic analysis of a conceptual 50,000-bbl/day plant based on the Schroeder-SCC process was also made. The price of the primary product of the process (an aromatic distillate oil in this case) was computed using the discounted cash flow method for several coal costs, annual rates of return on equity capital, and for two different financing schemes.

3.4.1 Basis for cost estimate

The basis for the cost estimate for the 50,000-bbl/day plant was the cost information presented by Schroeder⁸ for a conceptual plant designed to produce 47,300 bbl/day (7520 m³/day) of the aromatic distillate oil. The costs reported in the article were based on 1975 dollars. Details of the information taken from ref. 8 are summarized in Tables 8 to 10.

3.4.2 Economic evaluation procedure

The economic evaluation of the 50,000-bbl/day conceptual grassroots plant developed in the present study was conducted according to the guidelines presented in Appendix A. The costs obtained from ref. 8 (and summarized in Tables 8 to 10) were scaled-up for the 50,000-bbl/day plant by using the six-tenths factor rule. These costs were then escalated to reflect first-quarter 1977 costs by using the M&S Indexes reported in Chemical Engineering.¹⁰ The results of the economic evaluation are summarized in the following section.

Table 8. Summary of information regarding the
Schroeder-SCC FHP process^a

Design plant capacity = 47,300 bbl per day of product oil
Coal feed rate = 13,755 TPD of as-received Pittsburgh No. 8 seam coal
Plant type = grassroots facility
Basis of cost evaluation = 1975 U.S. dollars
Plant power requirements = 1.6×10^6 kWhr/day
Plant process water requirements = 470 gpm
Plant cooling water requirements = 2030 gpm
Operating labor requirements = 26 men/shift
Operating labor wage rate = \$8/man-hr
Installed cost of plant + support facilities = $\$116.2 \times 10^6$ (see Tables 9 and 10 for details)
Cost of catalyst/day = $\$23.63 \times 10^3$

^aData taken from ref. 8.

Table 9. Summary of the installed capital cost for the Schroeder-SCC FHP plant and support facilities based on 1975 U.S. dollars^a

Component	Cost (\$10 ⁶)
Coal receiving, storage and pulverizing facilities	14.0
Coal hydrogenation facilities (see Table 10 for details)	34.0
Oxygen plant & compressor	19.4
Product purification (including NH ₃ recovery)	12.0
Claus sulfur plant	4.0
Catalyst recycle	2.0
Preheaters & steam generation (1500 psi)	2.0
Two boilers (500,000 lb steam/hr each)	9.2
Power generation and distribution	4.6
Water system (supply, cooling towers and treatment)	3.5
Product oil storage	4.0
Ash disposal	1.5
Support facilities:	
a. Railroads & roads	0.5
b. Warehouse & shops	2.5
c. Buildings	<u>3.0</u>
Subtotal, support facilities	6.0
Total installed cost of FHP plant	<u>116.2</u>

^a Data taken from ref. 8.

Table 10. Summary of the installed cost for the coal hydrogenation facilities in the Schroeder-SCC FHP plant based on 1975 U.S. dollars^a

Component	Cost (\$10 ⁶)
Coal feeder vessels, compressor, and coal feeder	7.10
FHP reactor	1.49
Tar cooler	0.21
Tar-gas separator vessel	0.20
Tar hydrogenation vessel & pump	0.54
Cyclone separator and solids discharge	0.26
Heat exchangers:	
a. Recycle gas	0.90
b. Tar hydrogenation gas	0.18
Waste heat boiler & water cooler	1.27
Gas-oil separator & oil cooler	1.02
Oil-CH ₄ separator	0.15
Recycle compressor & driver (for tar hydrogenation)	0.38
Recycle gas compressor and driver	0.92
Preheater + reformer	2.35
Subtotal installed cost	16.97
Allowance for piping, instrumentation, foundations, etc.	16.97
Total installed cost for coal hydrogenation section	33.94

^aData taken from ref. 8.

3.4.3 Economic evaluation results

The estimated total capital investment, working capital, and gross annual operating cost (for 90% plant service factor) for the conceptual 50,000-bbl/day plant were calculated to be about \$205 million, \$38 million, and \$26 million respectively. Details of these costs are summarized in Tables 11 to 13. The gross annual operating cost indicated above does not include the feedstock cost, depreciation, and taxes, since these costs are accounted for separately in computer program PRP.

Results of the economic evaluation are summarized in Table 14 for the two financing schemes used in the present economic analysis. The product price of the aromatic distillate oil was calculated as \$/bbl by computer program PRP. The \$/MMBtu product price reported in Table 14 was determined by dividing the calculated \$/bbl price by the heating value of the oil, namely, 5.5 MMBtu/bbl ($36.47 \times 10^9 \text{ J/m}^3$).

The results of the economic analysis are also shown graphically in Figs. 9 and 10 for the 100% equity financing case. In Fig. 9, the product oil price has been plotted as \$/bbl; in Fig. 10, the oil price has been plotted as \$/MMBtu.

The salable by-products from the conceptual plant are sulfur and ammonia. The premised selling prices of the by-products are given in the table below. The sensitivity of the product price of the distillate oil to a \$10/unit change in the selling price of the by-products was determined to be as follows:

By-product	By-product unit	Premised selling price (\$/unit)	Sensitivity of the distillate oil product (\$/bbl) price
Sulfur	long ton	60	-0.1077
Ammonia	ton	140	-0.0408

Table 11. Capital investment estimate for conceptual Schroeder-SCC FHP plant producing 50,000 bbl per day of aromatic distillate

Component	Cost (\$10 ⁶)
Total direct installed cost of plant and offsites, TDIC (from Appendix 6.2)	132.92
Engineering and contractor's fees, 8% TDIC	10.63
Project contingency, 15% TDIC	19.94
Start-up modifications, 2% TDIC	2.66
Land costs, 200 acres @ \$2000/acre	0.40
Working capital (see Table 12)	38.16
Total capital investment	204.71

Table 12. Working capital estimate for conceptual Schroeder-SCC FHP plant producing 50,000 bbl per day of aromatic distillate oil

Component	Cost (\$10 ⁶)
1. 20 days of feedstock cost @ \$20 per ton of coal	5.94
2. 30 days of product distillate @ \$20 per bbl of product	30.00
3. 30 days of gross operating costs (from Table 13)	<u>2.22</u>
Total working capital	<u>38.16</u>

Table 13. Annual operating cost estimate^a for conceptual Schroeder-SCC FHP plant producing 50,000 bbl per day of aromatic distillate oil

Component	Cost (\$10 ⁶)
1. Labor costs	
a. Process operating labor	2.55
b. Supervisory personnel cost	0.51
2. Labor burden	1.07
3. Plant maintenance cost ^b	6.65
4. Operating supplies*	0.76
5. General administrative overhead costs	3.98
6. Utilities*	
a. Electric power - generated in the plant	0.0
b. Process water	0.13
c. Cooling water	0.06
7. Catalyst and chemicals*	8.92
8. Waste disposal cost*	0.67
9. Property insurance cost	1.66
Gross annual operating cost	26.96

^aThe above costs are reported for a 100% plant service factor. For other plant service factors, multiply the cost for the items marked with an asterisk (*) by the desired plant service factor to obtain the appropriate annual operating cost. The above cost does not include the feedstock cost, depreciation, and taxes. These costs are accounted for separately in the computer program PRP. (Details regarding the derivation of the above costs are given in Appendix 6.2.2.)

^bIncludes maintenance materials, labor, supervision, and maintenance labor burden.

Table 14. Calculated product price of aromatic distillate oil produced by the conceptual Schroeder-SCC FHP process

Run-of-mine coal ^a cost (\$/ton)	Calculated aromatic distillate oil price ^{b,c} (\$/MMBtu)					
	Debt/equity = 0/100			Debt/equity = 75/25 ^d		
	Rate of return on equity			Rate of return on equity		
	10%	12%	15%	10%	12%	15%
10	1.09	1.19	1.36	0.91	0.93	0.96
20	1.63	1.73	1.90	1.45	1.47	1.50
30	2.17	2.27	2.44	1.99	2.01	2.04
40	2.71	2.81	2.98	2.53	2.55	2.58
50	3.25	3.35	3.52	3.07	3.09	3.12

^aCoal used in the analysis is Pittsburgh No. 8 seam bituminous coal.

^bThe product aromatic distillate oil price is calculated (using ORNL computer program PRP) based on costs presented in Tables 11 to 13. These costs were developed from costs reported by Schroeder in ref. 8.

^cThe heating value of the aromatic distillate oil produced was assumed to be 5.5 MMBtu/lbl ($36.47 \times 10^9 \text{ J/m}^3$).

^dInterest rate on the debt fraction was computed at 9%/annum.

Fig. 9. Product price (\$/bbl) variation for the distillate oil produced by the Schroeder-SCC process with variation in feed coal cost.

Fig. 10. Product price (\$/MMBtu) variation for the distillate oil produced by the Schroeder-SCC FHP process variation in feed coal cost.

As before, the negative sign is intended to indicate that the distillate oil product price moves in the opposite direction of the change in the by-product selling price.

3.4.4 Discussion of results

The product price calculated for the aromatic distillate oil appears to be attractively low. However, any interpretation of the significance of the results should be coupled with the following caveats:

1. The product price was calculated based on information developed from cost data reported by Schroeder.⁸
2. The costs developed in this study should be regarded as preliminary-type costs. These costs are only as reliable as the basic cost information from which they were developed.

The Schroeder-SCC FHP process could prove to be an attractive means of converting coal to oil if the above numbers could be substantiated by a more detailed engineering evaluation of the process.

4. CONCLUSIONS

The prime objective of the present study was to determine if a more detailed engineering evaluation of the FHP technology would be justified. To meet this objective, the Cities Service and the Schroeder-Spencer Chemical Company FHP processes were evaluated. These two processes were chosen for the evaluation because they represent two distinct aspects of the FHP technology: The Cities Service process (evaluated in the present study) is a noncatalytic version of the FHP technology designed to primarily produce SNG from lignite. The Schroeder-SCC process, on the other hand, is a catalytic version of the FHP technology designed to primarily produce an aromatic distillate-type oil from bituminous coal.

Information necessary to conduct the evaluation was obtained from open literature sources and from the two process developers. Considering the scope of the study and the general reticence of the process developers to provide more substantive information regarding their FHP processes, more accurate cost information was not developed. It is pointed out that, between the two process developers, Cities Service was more forthcoming in providing information regarding their FHP process. Intercomparisons between the two processes is strongly discouraged, since this may lead to erroneous conclusions. Some of the reasons for the aforementioned caveat are:

1. The process technologies for the two processes are different.
2. The feed coals are different.
3. The primary end-products are different.
4. The sources of the basic cost data used to develop the economics in the present study are different.

Based upon the information gathered during the course of this study, the following conclusions can be made regarding the FHP process in general and the two specific FHP conceptual processes evaluated in the present study:

1. The FHP process is relatively simple compared to other coal liquefaction and gasification processes being developed and has the potential of yielding an attractive slate of products from coal (namely, SNG, BTX liquids, and fuel oil).
2. Preliminary economics conducted on the two FHP processes tend to indicate that the FHP technology is economically competitive with other coal conversion technologies currently being evaluated. In Table 15, information regarding the two selected processes is compared with information culled from three other more detailed process evaluations, which were performed on three different coal conversion technologies. Although the cost information presented in Table 15 cannot be strictly compared because of the widely different sources of the estimates, the cost information presented does indicate that the cost of the FHP technology is at least comparable with, if not better than, the cost of the other coal conversion technologies reported.
3. According to a Mechanics Research Institute (MRI) report,¹¹ which evaluated the FHP process based on experimental information obtained from the Brookhaven National Laboratory FHP project, the FHP process appears to be economically superior to the Hygas, Lurgi, and the Fischer-Tropsch coal conversion processes. The MRI report cited above consisted of (1) a techno-economic

Table 15. Reported costs and operating characteristics of various coal conversion processes

Process name	Coal Type processed	Coal feed rates, TPD to process to reactor		Reactor conditions Temp Pressure °F psig		Estimated Plant Production Rates					Plant energy efficiency ^a (%)	Total capital investment ^b (\$10 ⁶)	Gross annual plant operating costs ^b (\$10 ⁶)
						SNG gas MMscfd	BTX liquids BPD	Fuel oil BPD	Other products Name Production rate				
1. Cities Service SRT hydrolysis ^c	N. Dakota lignite	22,044 (MF coal)	14,124 (MF coal)	1600	1500	250	6412 ^d	-	Sulfur Ammonia	188 TPD 129 TPD	57	1207	88
2. Schroeder-SCC hydrolysis ^e	Pitt. No. 8 bituminous	14,840 (as received)	14,840 (as received)	932	1500	-	50,000 ^f (aromatic oil)		Sulfur Ammonia	603 TPD 204 TPD	76	205	27
3. Oil/gas study ^g -- based on SRC-II	Ill. No. 6 bituminous	36,000 (MF coal)	30,000 (MF coal)	850	2025	165	-	56,000	LPG Naphtha Sulfur Ammonia	10,000 BPD 10,000 BPD 1,300 TPD 90 TPD	76	1273	98
4. Hydrocarbonization study ^h --based on J.S. Steel clean coke process	Ill. No. 6 bituminous	40,665 (MF coal)	27,474 (MF coal)	1380	105	63	-	20,756	Naphtha Char Sulfur Ammonia Phenols	2,174 BPD 13,178 TPD 519 TPD 193 TPD 53 TPD	70	1090	370
5. Synthoil study ⁱ -- based on USBM process	W. Ky. Coal bituminous	50,133 (as received)	32,069 (as received)	860	4000	-	-	97,216	Sulfur Ammonia	1,696 TPD 180 TPD	60	2030	138

^a Calculated as usable fuel plant products - does not include sulfur and ammonia.

^b Costs for processes 3, 4, and 5 have been increased by 7% annual inflation rate (capital investment and costs expressed in first-quarter 1977 dollars).

^c Costs for the Cities Service process are based on costs reported by La Delfa and Greene in ref. 5.

^d Includes 10 TPD of fuel oil produced.

^e Costs for the Schroeder-SCC process are based on costs reported by Schroeder in ref. 8.

^f Specific gravity of aromatic oil - 0.92.

^g Data obtained from ref. 12.

^h Data obtained from ref. 13.

ⁱ Data obtained from ref. 14.

analysis of a conceptual FHP process and (2) an economic comparison (on a comparable basis) of the FHP process with the three coal conversion processes mentioned above. The conceptual plant was designed by MRI to yield a product slate (similar to the product mix obtained from the Cities Service FHP process) with a product energy output equivalent to 250 billion Btu/day.

4. The technical feasibility of the FHP process has been established experimentally by several investigators using equipment up to a small pilot-plant-scale level (coal throughput rates of up to 1/4 TPH, as noted in ref. 15. However, before the process can be considered commercially viable, much developmental effort will have to be expended in larger scale pilot plants to ferret out and resolve possible processing problems. Following is a list of some of the problems that may require further study:

- (a) The rapid intimate mixing of the pulverized coal and the hot hydrogen to bring the reactants to processing conditions rapidly.
- (b) The mechanical design of the FHP reactor such that the FHP reaction is permitted to occur for a very short period of time (generally, of the order of fractions of a second) and the products of the reaction are quenched rapidly thereafter.
- (c) The recovery of the heat released in the quenching process (preferably as high-temperature heat) so that it can be used in the process, thereby decreasing the heat requirements of the overall process.

5. An adequate data base for a firm process design does not exist up to the present time. The data base that was used as a basis for the present scoping study must be considered sketchy in nature. However, the data base for the Cities Service process appears to be much more extensive than that of the Schroeder-SCC process. Much of the data on the two processes is considered proprietary and is not available in the public domain.

Some of the process areas where additional development effort is required are the following:

- (a) The development of complete material balances for all the components fed to and produced by the process.
- (b) The establishing of the reactor pressure and temperature conditions for the optimum production of either SNG or BTX liquids or fuel oil.
- (c) The determination of the residence time of the reactants at process conditions. (This is an important parameter because experimental runs have demonstrated that the residence time is a critical parameter in the FHP process to produce a desirable product slate such as maximum SNG or maximum BTX liquids production. Cities Service³ feels that the residence time over the range of interest is not as critical as indicated above. However, several other investigators tend to disagree with the Cities Service viewpoint.)
- (d) Evaluation of the thermochemistry of the FHP reaction. (The thermochemistry of the FHP reaction is rather

complex. Initial bench-scale experiments conducted at Rocketdyne¹⁵ tend to suggest that the reaction is either thermally neutral or endothermic in nature. The Cities Service conceptual design tends to support the Rocketdyne findings since they also propose to burn a small fraction of the feed hydrogen to the reactor to generate the high reaction temperature required to provide the heat of the reaction.

It is important that the thermal characteristics of the reaction be known before proceeding with the process design. Cities Service³ indicated that they have proprietary correlations for predicting heats of reaction.

- (e) The FHP process needs to be evaluated using coals other than noncaking lignite to determine the yields and more importantly, from a process design viewpoint, the possible problems that may arise when processing caking bituminous coals.

6. Taking into account the economic incentives for producing SNG and/or crude oil from coal by the flash hydrolysis process and the preliminary nature of the present analyses, a more detailed engineering evaluation of the process would be required to firm up the process design and the economics of the process. Such an evaluation should be conducted as soon as a more firm process data base is developed.

5. RECOMMENDATIONS

The flash hydropyrolysis process offers the potential of a relatively simple process for the conversion of coal to valuable BTX liquids, fuel oil, and substitute natural gas. BTX liquids are important chemical feedstocks, while fuel oil and SNG are valuable as fuel. According to the Oil and Gas Journal Newsletter,¹⁶ benzene demand in the U.S. is forecasted to grow between 5.5 and 6.5% annually between 1977 and 1981. Most of the nation's benzene is presently made from petroleum; however, with the nation's oil supplies dwindling, the flash hydropyrolysis process offers the potential of a relatively simple and possible economical process to convert the nation's coal to meet the demand for benzene, fuel oil, and SNG.

Hence the following recommendations are made for future work on the development of the flash hydropyrolysis of coal process:

1. Experimental studies should be continued to establish the necessary and sufficient data base required for a firm process design of a plant based on the process.
2. A detailed engineering evaluation of the process should be undertaken as soon as the data base is established to determine the commercial viability of the process and to indicate areas of the process where additional developmental effort is required.

Process design information regarding the flash hydropyrolysis process is currently being developed by several investigators, and it appears very likely that a sufficient data base should exist by some time in late 1978 to facilitate a more detailed engineering evaluation of the process.

6. APPENDIX A: BASIS AND DETAILS OF THE ECONOMIC EVALUATION OF THE FHP PROCESSES

6.1 Introduction

Preliminary economic analyses were performed on the two FHP processes using ORNL-developed economics analysis computer program PRP.¹ For each process the price of the primary product was determined using the discounted cash flow (DCF) rate of return method. The primary product for the Cities Service conceptual plant was taken to be 250 MMscfd of 983 Btu/scf SNG while the primary product for the Schroeder-SCC conceptual plant was taken to be 50,000 bbl/day of aromatic distillable oil with a specific gravity of 0.92. The heating value of the oil was assumed to be 5.5×10^6 Btu/bbl.

The following guidelines were used in the economic analysis of both processes:

1. The conceptual plants were designed to be grassroots facilities.
2. The plant service factor was taken to be 90% from the first year of startup and throughout the life of the plant which was assumed to be 20 years.
3. The construction period for the plant was assumed to be 4 years.
4. All costs were developed based on first quarter 1977 dollars. No forward escalation beyond first-quarter 1977 was included in the cost estimates. Cost escalations up to the first quarter of 1977 were made using the M&S Indexes reported in Chemical Engineering.¹⁰
5. Two financing schemes were used to finance the projected plants:
 - (a) 100% equity capital and
 - (b) 75% debt and 25% equity capital.

6. Feed coal costs were varied from \$10/ton to \$50/ton in \$10/ton increments.
7. Values of 10, 12, and 15% annual after-tax rates of return on equity capital were used in the analyses.
8. Interest rate on the debt fraction of the plant capital was computed at 9% per annum.

Results of the economic analyses are presented in the text as tables of the calculated product price (in \$/MMBtu) for various feed coal costs and rates of return on equity capital. Plots of the calculated product price are also presented in the text of the report for the 100% equity capital financing case.

Information for developing the costs for the Cities Service FHP plant was obtained from the paper by La Delfa and Greene.⁵ Cost information for the Schroeder-SCC conceptual plant was developed based on information given by Schroeder.⁸

Due to the lack of sufficient information regarding the two FHP processes, additional premises had to be made to permit the economic evaluation of the processes. These additional premises and the procedure for the determination of the various costs are presented in the following sections.

6.2 Additional Premises for the Economic Analyses

The additional premises used in the economic analyses will be presented in three sections as follow:

- 6.2.1 Capital investment related items.
- 6.2.2 Operating costs related items.
- 6.2.3 Economic evaluation procedure related items.

6.2.1 Capital investment related items

1. Direct plant cost: The direct plant cost for the installed Cities Service FHP conceptual plant was taken to be \$919.4 million. This cost was obtained from ref. 5 where it is reported as the direct installed cost (in first-quarter 1977 dollars) for a grassroots complex designed to primarily produce 255 MMscfd of SNG from lignite using the Cities Service FHP process.

The direct installed cost for the conceptual Schroeder-SCC plant was determined from data obtained from ref. 8. Based on the ref. 8 data, the direct plant cost for a grassroots complex was estimated to be \$132.92 million.

2. Engineering and contractor's fee: This was estimated to be 8% of the direct plant cost.
3. Contingency: Contingency costs were estimated to be 15% of the direct plant cost.
4. Startup plant modifications: Plant modifications that may be necessitated during the startup phase were estimated to be 2% of the direct plant cost.
5. Working capital requirements: Working capital requirements were estimated to be the sum of the following items:

(a) 20 days of feedstock costs at \$20 per ton of feed coal.

(b) For the Cities Service plant:

+ 30 days of SNG product at \$4/Mscf

+ 30 days of BTX liquids product at \$30/bbl

For the Schroeder-SCC plant:

+ 30 days of distillate oil product at \$20/bbl.

- (c) 30 days of gross operating costs for the conceptual plant.

More information regarding the working capital is presented in Sect. 6.2.3.

6. Land: The proposed facilities were estimated to require 200 acres of land and the land costs were estimated at \$2000 per acre.

6.2.2 Operating costs related items

1. Labor costs: These costs were subdivided into the following two groups: (1) process operating labor cost and (2) supervisory personnel cost.

Process operating labor cost: The process operating labor cost for each process was estimated separately because of different manpower requirements and wage rates. The operating manpower requirements for the Cities Service plant was determined (by telephone conversation) to be 44 men per shift. The operating labor wage rate was assumed to be \$7/man-hr since the plant was assumed to be located in the western U.S.

The operating labor requirements for the Schroeder-SCC plant was determined from ref. 8 to be 26 men per shift. The operating labor wage rate was taken to be \$8/man-hr since the plant was premised to be located in the eastern U.S. The 4,2 manning shifts/day were used for both facilities to permit 24-hr coverage of the plant and to account for operator vacations, holidays, etc.

Supervisory personnel cost: These costs were estimated to be 20% of the process operating labor cost for each plant.

2. Labor burden: The labor burden was estimated to be 35% of the labor costs.
3. Plant maintenance cost: The plant maintenance cost was estimated to be 5% of the direct plant cost for the grassroots facility. This cost included the cost of maintenance materials, labor, labor supervision, and the labor burden for the maintenance crew.
4. Operating supplies: The cost of operating supplies was estimated to be 30% of the process operating labor cost.
5. General administrative overhead costs: These costs were estimated to be 40% of the sum of the process operating labor, plant maintenance and operating supplies cost indicated above.
6. Utilities: Since the plants were premised to be grassroots facilities, the only utility premised to be available to the plants was water. All other plant utilities were assumed to be generated onsite.

For the Cities Service plant, the cost of the water requirements were estimated at \$0.4/kgal. This is the cost reported by La Delfa and Greene.⁵

For the Schroeder-SCC plant, the cost of the water requirements were estimated based on the process and cooling water requirements indicated in ref. 8. Process water was estimated to cost \$0.5/kgal while cooling water was estimated to cost \$0.05/kgal. The cost of water estimated was intended to reflect the cost of procuring, storing and treating the water used in each process.

7. Catalyst and chemicals: The cost of the catalyst and chemicals

used was determined for each process individually based on the costs reported in refs. 5 and 8.

8. Waste disposal cost: Waste disposal cost was estimated at \$1 per ton of waste material to be disposed.
9. Property insurance cost: This cost was estimated to be 1% of the total depreciable capital annually including the cost of the startup modifications related capital equipment.
10. By-product credits: Credits for salable by-products from the two conceptual plants were estimated according to the following schedule:
 1. Sulfur was credited at \$60/long ton.
 2. Anhydrous ammonia was credited at \$140/ton.
 3. The BTX liquids produced in the Cities Service process were credited at \$30/bbl.

The above prices were estimated from the Chemical Marketing Reporter issues for the first quarter of 1977.

11. Other costs: Other operating costs nominally include taxes, depreciation and interest on invested capital during the construction phase of the plant. These costs are accounted for as part of the cash flow analysis performed by the computer program and will be discussed in the next section.

6.2.3 Economic evaluation procedure related items

1. Project life: The project life was assumed to consist of a construction period of 4 years followed by a plant operating period of 20 years. The following capital spending schedule was assumed to occur for the two facilities:

<u>Year</u>	<u>Spending schedule % of depreciable capital investment/year</u>
1	5.0
2	20.0
3	45.0
4	30.0
<hr/>	<hr/>
Total	100.0

2. Interest on capital during construction: The capital invested during the construction phase of the project was assumed to earn interest at the same rate as during the years following the start-up of the facilities. Since there is no income generated by the plant prior to startup, the interest that accrued on the capital was accumulated and added to the outstanding capital that was to be recovered during the plant operating years. For tax purposes, the interest on the debt was treated as a deductible expense in the year in which it was paid. The above procedure is accounted for internally in the computer program FRP.
3. Depreciation: Depreciation was not included as an operating cost because the recovery of the capital is accounted for by the DCF analysis procedure. For tax purposes, depreciation was calculated by the sum-of-the-years' digits method using a depreciable life of 16 years for the process and offsites facilities. Depreciation life was assumed to commence at the end of the construction period.

4. Taxes: Taxes were accounted for in the computer program as part of the cash flow analysis. The following tax rates were assumed:

Federal income tax	48%
State income tax	3%
State revenue tax	0%
Local property tax	2%

An investment tax credit of 10% of the depreciable capital was also assumed in the economic analysis.

5. Working capital: The working capital was assumed to remain invested throughout the project and was assumed to be recovered intact at the end of the project life.
6. Salvage value: The salvage value of the plant was assumed to be zero at the end of the project life.

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