H-Coal® Integrated Pilot Plant

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Prepared by
Hydrocarbon Research, Inc.
Trenton, New Jersey

ELECTRIC POWER RESEARCH INSTITUTE

H-Coal® Integrated Pilot Plant

AF-681, Volume 1
Research Project 238-1

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FOREWORD

The H-Coal® project is being conducted in three phases:

Phase I - Laboratory and Design
Phase II - Construction
Phase III - Operations

This contract, EX-76-C-01-1544, had two objectives:

- laboratory confirmation of key design features
- detailed engineering design of the Pilot Plant to operate in both the syncrude and boiler fuel modes.

This report covers the laboratory program: Volume I is a summary and Volume II presents more extensive detail. A separate report will cover the engineering design of the H-Coal Pilot Plant.

The H-Coal® project is the responsibility of the Assistant Director for Synthetic Fuels Development, Dr. Martin B. Neuworth, and the Chief, Liquid Fuels Project Management Branch, Dr. James D. Batchelor. Mr. John L. Morris is the Program Manager.

The current funding sponsors of the H-Coal program are:

Energy Research and Development Administration
Commonwealth of Kentucky
Electric Power Research Institute
Ashland Synthetic Fuels, Inc.
Standard Oil Company (Indiana)
Conoco Coal Development Company
Mobil Oil Corporation

ABSTRACT

Phase I of the H-Coal Program consists of the design of a 200/600 ton per day coal liquifaction pilot plant and a laboratory program to support this design. This final report covers the laboratory effort. The work was carried out by Hydrocarbon Research, Inc., at their Trenton, New Jersey, labs and Morristown, New Jersey, engineering offices.

The H-Coal process catalytically converts coal to oil in an ebullated bed reactor. Advantages of this process include flexibility of operation, constant catalyst activity level through on line addition and withdrawal of catalyst and reactor back mixing which allows low temperatures of the reactor feed streams.

The 3 ton per day PDU was operated to demonstrate: a) heavy boiler fuel oil mode operation, b) operation at commercial reactor gas velocities, and c) operation with high residum concentration in the reactor. Solid liquid separation was demonstrated by antisolvent precipitation, high vacuum distillation and hydrocloning. This lab program provided improved vapor-liquid K values and improved on the H-Coal reactor internals design.

Finally, the Technical Management Plan for Phase III - Operations of the large pilot plant - was developed.

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Section 1

INTRODUCTION

FUNDING

Funding for the efforts of Hydrocarbon Research, Inc. on the H-Coal program was and is being provided by:

- ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
- COMMONWEALTH OF KENTUCKY
- ELECTRIC POWER RESEARCH INSTITUTE
- STANDARD OIL COMPANY (INDIANA)
- ASHLAND SYNTHETIC FUELS, INC.
- CONOCO COAL DEVELOPMENT COMPANY
- MOBIL OIL COMPANY
- ATLANTIC RICHFIELD OIL COMPANY
- SUN OIL COMPANY
- SHELL OIL COMPANY

OBJECTIVES

The ultimate objective of the project is to construct and operate a nominally 600 ton-per-day Pilot Plant to provide data for design of larger demonstration or commercial plants. The objectives of the laboratory program were to demonstrate reliable operation and to resolve any problems revealed in the laboratory or engineering programs.

MAJOR PROGRAM ACCOMPLISHMENTS

The experimental program resulted in several major accomplishments:

- PDU Run No. 1 - operability demonstration in the boiler fuel mode by an uninterrupted run to a catalyst life of 3000 lb coal/lb catalyst.
- PDU Run No. 2 - demonstrated the use of high gas velocities required for commercial operation with negligible catalyst attrition or loss.
- PDU Run No. 3 - demonstration of fuel oil mode with high residuum concentration in the reactor.
- PDU Run No. 4 - demonstration of syncrude mode with high residuum concentration in the reactor.
- Utilization of an on-line, continuous hydroclone system, similar to the pilot plant design, to achieve a high residuum concentration in the reactor. This system was used in all PDU operations.
- Demonstration in the syncrude mode of solid-liquid separation by vacuum distillation to a flowable material containing up to 55% solids.
- Demonstration in both the syncrude mode and boiler fuel mode of an on-line antisolvent precipitation and settling system for solid-liquid separation.
- Demonstration of improved reactor intervals.
- Improved definition of the physical data base (vapor-liquid K values) for Pilot Plant design and operation.
- Demonstration of the vapor-liquid separator design to be used in the Pilot Plant; a direct result of this vapor-liquid separator design is substantial increase in slurry letdown valve life.
- Application of improved seals and packing for pumps and valves.

In addition, several other results were obtained which promise improvements to the H-Coal Process. These results included:

- Low pressure operation to achieve a specification fuel oil.
- Catalyst regeneration to reduce catalyst use.
- Testing a high density catalyst which would permit higher residuum concentrations in the reactor.

In addition to the technical accomplishments, the program has demonstrated that industry and government can work together to help alleviate the country's energy problems. Creative input by industry as well as flexibility by the Government when necessary resulted in technical and managerial success of the program. As a consequence, funding for the construction and operation of the Pilot Plant has been committed by the industry and government sponsors. The construction and operation commitments total $188-million, and support is being provided by the Energy Research and Development Administration, the Electric Power Research Institute, Standard Oil Company (Indiana), Ashland Synthetic Fuels, Inc., Conoco Coal Development Company, Mobil Oil Corporation, and the Commonwealth of Kentucky.

The H-Coal Process catalytically converts coal to oil. At more severe conditions, a net product slate consisting of all distillate material is produced. At lower severity, a low-sulfur, liquid boiler fuel is the product. This flexibility is achieved by varying the rate of coal throughput to the H-Coal reactor.

A key feature of the process is the ebullated bed reactor. In the reactor, coal, recycled oil and hydrogen are reacted in the presence of an expanded catalyst bed. The catalyst expansion is controlled by the rate at which internal recycle oil is circulated by the ebullating pump. In the upper part of the reactor the relatively large catalyst particles are disengaged from the liquid and relatively small ash and unconverted coal particles. The liquids, gases and small solid particles are then removed, while the catalyst remains behind.

The ebullating bed reactor has many features of a fluidized bed. The temperature gradient across the reactor bed is minimal. This permits the incoming hydrogen and slurry feed to enter the reactor at a temperature lower than the catalyst bed temperature. The exothermic heat of reaction is used to heat the incoming streams to reaction temperature. Because the catalyst is in motion, a portion of the aged catalyst can be removed and fresh catalyst can be added without a unit shutdown. The ability to add and withdraw catalyst permits operation at a constant equilibrium catalyst activity level.

Prior to the program covered in this report, Hydrocarbon Research, Inc. had extensive operating experience on the H-Coal Process at its Research and Development Center. The bench-scale unit (25 pounds per day) had been operated for about 1600 days. Four bituminous coals, four subbituminous coals and three lignites had been tested. Illinois No. 6 and Wyodak coals were the main coals used. The Process Development Unit (three tons per day of coal) had been operated for 174 days using Illinois No. 6 and Wyodak coals in the syncrude mode. A more extensive discussion of the process, reactor concept, process advantages, and the history of the development are discussed in the Appendix.

This extensive experimental background provided the basis for proceeding with the design of a 200-600 ton per day Pilot Plant. Simultaneously, supportive experimental work was carried out at the Research and Development Center to demonstrate reliable operations on the PDU scale and to obtain supportive design information for the Pilot Plant. This work is the subject of this report and will be discussed in the following order:

- Process Development Unit - 3 tons of coal per day
- Bench Scale Unit - 25 pounds of coal per day
- Reactor Hydrodynamics - Cold Model
- Solid-Liquid Separation
- Technical Management Plan for the Pilot Plant

Section 2

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

The objectives of the Process Development Unit program were successfully attained. The operability of the H-Coal Process was clearly demonstrated and it has been concluded that the process is feasible for scale up to Pilot Plant size. This conclusion is supported by execution of participation agreements for the construction and operation of the Pilot Plant between Hydrocarbon Research, Inc. and

- Standard Oil Company (Indiana)
- Ashland Synthetic Fuels
- Conoco Coal Development Company
- Mobil Oil Corporation
- Commonwealth of Kentucky
- Electric Power Research Institute

The expected yields and product compositions of the various projected Pilot Plant cases (which were obtained from PDU operations) are included in Appendix B. The planned space velocities will range from 31-78 pounds of coal per hour per cubic foot of reactor. This translates to a coal throughput for the Pilot Plant between 211 and 531 tons per day on a moisture-free basis. The projected sulfur content in the 400°F+ fuel oil will range from 0.2 W % to 0.58 W %.

Also as a result of PDU operations during this contract, HRI concluded that hydroclone systems can be operated to increase the residuum concentration in the reactor, and that the higher concentration will permit obtaining a lower sulfur level in the fuel oil product. Residuum concentration in the reactor at levels of 42 W % have been demonstrated.

HRI also concluded that a ratio of 1.75 pounds of slurry oil per pound of solids is operable. Lower levels may be possible.

Two methods of solid-liquid separation were demonstrated. Distillation is suitable for those modes of operation in which the yield of residuum is low. Antisolvent precipitation and settling were also successfully operated in a continuous unit using a process derived antisolvent. A boiler fuel product containing less than 0.1 W % ash was produced. Therefore, HRI concluded that the H-Coal Process can produce a boiler fuel product which will meet current EPA standards for sulfur and particulate material without stack gas scrubbing, or stack gas solids removal.

Hydrocarbon Research, Inc. has also concluded that the design basis originally proposed for the Pilot Plant is adequate and that no modifications to the design basis are required because of this experimental program.

RECOMMENDATIONS

Because the construction and operation of the H-Coal Pilot Plant will involve up to $188-million, several recommendations to assure successful operations of the Pilot Plant with a minimum of down time were made and accepted. These operations will be undertaken in 1977 and 1978.

Process Development Unit

The objectives of the recommended PDU program were:

- to simulate the Pilot Plant design as closely as possible
  - -- test the hot slurry feed system
  - -- demonstrate catalyst addition and withdrawal
  - -- test the two stage pressure reduction system
  - -- install a naphtha stabilizer
  - -- test a PDU-size antisolvent precipitation and settling system
  - -- test for possible antisolvent degradation
- duplicate in the PDU, as closely as possible, the operating conditions for the Pilot Plant as stated in the Technical Management Plan.
- develop Pilot Plant emergency operating procedures by exploring potential failure modes and responses on the PDU
- provide training for Pilot Plant personnel

To achieve these objectives, the following PDU runs were recommended:

PDU 5 - A thirty-day run in the syncrude mode with Illinois coal with continuous catalyst addition and withdrawal.

PDU 6 - A fifteen-day syncrude mode operation with Kentucky coal and the "start-up" oil to be used in the Pilot Plant.

PDU 7 - A thirty-day syncrude mode operation with Wyodak coal.

PDU 8 - Sixty days of PDU time devoted to exploring emergency conditions including:

- -- Response to step increases in slurry feed temperatures
- -- Re-ebullating a slumped catalyst bed
- -- Emergency shutdown procedures for the reactor

PDU 9 - A fifteen-day boiler fuel mode operation with Illinois No. 6 coal to study denitrogenation of the 400°F+ fuel oil produced and/or an improved H-Coal catalyst. The catalyst used will depend on bench-scale work discussed below.

PDU 10 - A twenty-day run with Illinois No. 6 coal at an intermediate space velocity between 31 and 78.

Bench Scale

It was recommended that catalysts with higher density and higher activity be tested for possible use in the H-Coal Pilot Plant.

Higher density catalyst permits higher residuum concentration in the reactor and therefore a better yield pattern. Hydrocarbon Research, Inc. recommends that two catalysts with densities higher than the American Cyanamid catalyst HDS-1442A used under this contract be tested.

The relatively high nitrogen content of the 400°F+ fuel oil has caused concern that the product use will be limited by EPA regulations on NO_x. Therefore, Hydrocarbon Research, Inc. recommended that two runs be made to test two commercially available catalysts which have shown high activity for nitrogen removal from petroleum liquids.

Hydrocarbon Research, Inc. recommended that a run be made at a low pressure to produce a 400°F+ fuel oil. The pressure level will be recommended after engineering studies of fuel oil modes.

Cold Flow Model

It was recommended that scale-up of the improved recycle suction cup be tested in a full size (five-foot diameter) ambient temperature model.

Section 3

PROCESS DEVELOPMENT UNIT PROGRAMS

The Process Development Unit (PDU) has a nominal capacity of 3 tons per day. It is suited for testing process parameters, operability, and certain equipment designs. Under this contract, the PDU program provided a clear demonstration of the operability of the H-Coal Process.

Four runs were completed on the PDU. The use of hydroclones to increase the reactor residuum concentration was demonstrated. The improved yield patterns expected from the higher residuum concentration were obtained. Operability with high gas velocity was demonstrated. Several design features of the Pilot Plant were proven feasible and desirable. Maintenance requirements for the PDU slurry feed pumps and pressure reduction valves were substantially reduced.

PDU 1-FUEL OIL MODE DEMONSTRATION OPERATION

The purposes of PDU 1 were to:

- demonstrate the reliable, uninterrupted operability of the H-Coal Process, while
- feeding coal having more than 3% sulfur, and
- producing 70% of the liquid product as fuel oil (400°F+ oil),
- desulfurized to less than 0.7 W % sulfur,
- using less than 4,000 SCF of hydrogen per bbl,
- with economically tolerable catalyst attrition and loss,
- to a catalyst age of 3,000 pounds of coal per pound of catalyst.

ALL OF THESE OBJECTIVES WERE ACHIEVED IN PDU 1 (RUN 130-73).

This operation was performed at a space velocity of 70 lbs coal/hr/ft^3, a reactor temperature of 850°F, and an outlet hydrogen partial pressure of about 1500 psi. The hydroclones were in operation from the third day until the end of the run.

- The unit operated continuously for 23 days to a catalyst age of 3060 lbs of coal per pound of catalyst.

- The catalyst was removed as free-flowing extrudates in good mechanical condition. The recovery was 97% of the catalyst charged. This is equivalent to a loss of 0.02 pound of catalyst per ton of coal processed and is far below the catalyst replacement rate of 1.0 pound of catalyst per ton of coal planned for the Pilot Plant.

- Burning Star Mine Illinois No. 6 coal with a total sulfur content of 3.51 W % was used throughout the operation.

- The product yields and sulfur contents are shown in Column 1 of Table 3-2.

- During Period 9, the yield of C_4-400°F naphtha was 14.7 pounds per 100 pounds of dry coal feed. The weight yield of fuel oil was 78.9% of the total liquid product.

- During Period 9, which corresponds to an economically attractive catalyst usage rate of about 0.78 pounds of catalyst per ton of coal, the 400°F+ fuel oil product had a sulfur content of 0.69 W %.

- The hydrogen consumption was 3,550 SCF/Bbl of liquid produced during Period 9.

Table 3-2 compares the actual results of PDU 1 with correlation predictions. Estimates of the impact of catalyst replacement rate on product yields, on product sulfur content and on hydrogen consumption are also shown in Table 3-2. Column 2 is based on achieving a 400°F+ fuel oil content of 0.70 W % using a catalyst replacement rate of 0.75 pound of catalyst per ton of coal. Column 3 is a batch catalyst system which corresponds to the catalyst replacement rate in Column 2. Column 4 is based on a catalyst replacement rate of 1.0 pound of catalyst per ton of coal. Column 5 is the corresponding batch catalyst system. As can be seen from Table 3-2, a 25% reduction in catalyst replacement results in a 3% reduction in hydrogen usage and a 10% increase in product sulfur content.

PDU 2-HIGH GAS VELOCITY OPERATION

The purposes of this operation were to demonstrate that high gas velocity was operationally feasible and that the high gas velocity would not cause excessive catalyst loss by attrition or carryover.

Factors such as cost per unit volume, the ability to roll heavy plate, and shipping restrictions dictate that commercial reactors should be designed to the highest operable L/D ratio. The Pilot Plant reactor was designed in this manner. Because the PDU reactor has a much lower L/D, the hydrogen ratio that results in a velocity of 0.11 ft/sec in the PDU results in a superficial gas velocity on the order of 0.16 ft/sec in the Pilot Plant. Therefore, in order to demonstrate operability of the Pilot Plant at this gas velocity, it was necessary to operate the PDU at an artificially high circulation.

Several modifications were made to the PDU prior to the run. To accomodate the higher gas flows, the design of the distributor, which introduces the feed, was changed. Another significant change involved product withdrawal. In previous PDU operations, the effluent vapor and liquid were separated in the reactor. In order to improve the separation an external separator was installed. The external separator was designed to the same principles as the external separator design for the Pilot Plant. This resulted in decreased heavy oil entrainment into the vapor lines and longer liquid product letdown valve life due to the fact that the net slurry no longer contained entrained vapors which caused excessive velocities.

Previous PDU operations had indicated a limitation on gas velocity of about 0.06 to 0.08 ft/sec. Above this level, excessive amounts of gas were entrained into the suction of the recycle ebullating pump which caused erratic pumping and loss of control. Therefore, it was necessary to develop an improved suction cup design. This program was undertaken in a six-inch-diameter glass tube. The improved design was installed in the PDU.

The PDU 2 was operated at a space velocity of 78 lbs coal/hr/ft^3 reactor liquid, with American Cyanamid HDS-1442A catalyst and with recycle coal slurry oil rates and composition such that the slurry composition in the reactor closely approached that used in PDU 1. Operations at reactor outlet gas velocities of 0.16 to 0.17 ft/sec were demonstrated for the planned seven days of operations.

Loss of catalyst was minimal, corresponding to a catalyst loss of 0.03 pound catalyst per ton of coal processed. This is far below the catalyst replacement rate of one pound per ton planned for the Pilot Plant.

A 0.67 W % sulfur fuel oil product was produced at the catalyst age corresponding to an equilibrium age in a continuous catalyst replacement system.

A scaled-up version of theimproved suction cup design was developed for the Pilot Plant. Because the scale-up geometry is extremely complex, it was recommended that a full size model of the cup be tested in a loop similar to the 6-inch diameter test unit used to develop the cup.

PDU 3-PILOT PLANT DUPLICATION - FUEL OIL MODE

The purpose of PDU 3 was to demonstrate operations at conditions corresponding to the Fuel Oil Mode for the Pilot Plant. Particularly close attention was paid to :

- space velocity
- ratio of slurry oil to solids
- ratio of hydrogen to coal
- slurry oil composition

The run successfully met its targets and substantially bettered the fuel oil sulfur specification by producing a 400°F+ fuel oil with a sulfur content of 0.49 W %.

Table 3-3 presents a comparison of the Fuel Oil Mode operating parameters for PDU 3, PDU 1, and a planned Pilot Plant case. PDU 3 duplicated the planned Pilot Plant case space velocity, slurry ratio, and hydrogen ratio. PDU 3 achieved a much higher residuum and solids content in the reactor. These higher concentrations make operation more difficult, but produce a lower sulfur content in the product.

PDU 3 operated at a space velocity of 78 lbs coal/hr/ft^3 of reactor, an average reactor temperature of 848°F, and a slurry oil ratio of 1.76. The run was terminated as planned at 1500 pounds of coal per pound of catalyst. Catalyst loss during the run was minimal at about 1% of the expected catalyst replacement rate.

Table 3-4 compares the operating parameters, yields, and sulfur content of PDU 3 and PDU 1. PDU 3 had a higher space velocity, 78 vs. 70, but this was more than offset by a higher hydrogen partial pressure, 1760 vs. 1480 psig, and a higher residuum content. The 400°F+ fuel oil sulfur content was substantially lower for PDU 3, 0.49 W % vs. 0.71 W %. This was accompanied by a higher hydrogen consumption, 3.8 W % for PDU 3 vs. 3.5 W % for PDU 1. The gas make was higher for PDU 3, 7.7 vs. 5.0 W %.

Residuum concentration is important to the yields obtained in the reactor. The concentration has a significant impact on the liquid properties in the reactor such as viscosity, density, and possibly surface tension; and on the control of the catalyst level. Therefore, it is recommended that on-line instruments capable of measuring these properties at the reactor conditions of 3000 psig and 850°F be developed, installed on the PDU, and tested.

During PDU 3, the equipment performed with much less maintenance than previously. The feed pump operated throughout the run and was in excellent condition at the end of the run.

One high pressure letdown valve was in service for the entire run of 274 hours. Medium wear occurred on the stem and seat. This improved performance is attributed to better separation of gas from the liquid in the new external separator. Therefore, this improved valve performance is expected to be duplicated in the Pilot Plant.

The ceramic Doxie hydroclone was operated for the entire run. There was some wear, but this did not have any significant impact on the separation efficiency. Ceramic hydroclones were recommended for use in the Pilot Plant.

PDU 4-PILOT PLANT DUPLICATION - SYNCRUDE MODE

The purpose of PDU 4 was to demonstrate operations at conditions corresponding to the Syncrude Mode of the Pilot Plant. Particularly close attention was paid to:

- space velocity
- ratio of slurry oil to solids
- ratio of hydrogen to coal
- slurry oil composition
- use of hydroclones

Table 3-5 presents a comparison of the Syncrude Mode operating parameters for PDU 4 and the planned Pilot Plant case. Important operating parameters closely matched the planned levels of the Pilot Plant. The run was terminated as planned at 1500 pounds of coal per pound of catalyst. This corresponds to 603 hours of operation. At the end of the run, 99% of the catalyst was recovered and it was in a free flowing condition.

Table 4-1 compares the yields used for the design basis of the Syncrude Mode from the Pilot Plant and PDU 4. In addition, a calculated set of yields is included. The basis of the calculation is a yield of residuum equal to the design basis, and the dependent variable is the reactor residuum construction.

The yield of C_1-C_3 gases in PDU-4 was approximately 1.5 lbs/100 lbs coal higher than the design yields. The yield of total distillate (C_4-975°F) was slightly lower: 45.5 versus 52.2 lbs/100 lbs. coal. The characteristically higher proportion of naphtha in the distillate product, which has been observed in the other PDU runs in the fuel oil mode when compared to bench-scale results, was observed. As shown in Table 4-7 the yield of naphtha in PDU-4 was about 23.5 lbs/100 lbs coal as compared to the bench-scale run yield of 17.4 lbs/100 lbs coal. The PDU-4 yield of 975°F+ residuum was approximately 6 pounds higher per 100 pounds coal.

Table 3-1

SUMMARY OF PREDICTED AND EXPERIMENTAL DATA

Objective	Exp. PDU Operation 130-73 Period 9 Actual	Catalyst Replacement Rate Lb Cat/Ton Coal 0.70% Sulfur	Corresponding Avg. Batch Catalyst Age Lb Coal/Lb Cat 0.70% Sulfur	Catalyst Replacement Rate Lb Cat/Ton Coal 1.0 Lb Cat/Ton Coal	Corresponding Avg. Batch Catalyst Age Lb Coal/Lb Cat 0.64% Sulfur
Space Velocity, Lb/Hr/Ft^3	69.9	70.8	70.8	70.8	70.8
Catalyst Replacement Rate Lb Cat/Ton Coal	--	0.75	--	1.00	--
Avg. Batch Cat. Age, Lb Coal/Lb Cat.	1021	--	1040	--	888
Reactor Temperature, ^{o}F	850	850	850	850	850
Outlet H_2 Partial Pressure,psig	1480	1530	1530	1530	1530
Yields, W % of Dry Coal Fed					
C_1-C_3 Hydrocarbons	4.60	4.75	4.86	4.83	4.94
C_4-400^{o}F Naphtha	14.72	14.60	14.81	14.76	14.95
400-975^{o}F Distillate	21.32	18.32	20.35	19.87	21.78
Residuum	33.80	35.96	33.92	35.25	32.22
Unreacted Coal	7.45	7.90	7.42	7.70	7.37
Ash	11.46	11.10	11.10	11.10	11.10
H_2O	6.26	7.09	7.34	7.28	7.52
CO and CO_2	0.83	0.81	0.82	0.81	0.82
NH_3	0.66	0.61	0.66	0.65	0.68
H_2S	2.44	2.33	2.34	2.37	2.38
Total	103.50	103.47	103.62	103.62	103.76
400^{o}F+ Fuel Oil	55.12	54.28	54.27	54.12	54.00
400-975^{o}F Distillate	21.32	18.32	20.35	19.87	21.78
Sulfur Contents					
400^{o}F+ Fuel Oil	0.69	0.70	0.70	0.64	0.64
H_2Consumption, SCF/Bbl C_4+	3,550	3,504	3,613	3,614	3,721

Table 3-2

OPERATING PARAMETERS - FUEL OIL MODE

	PDU 3 130-78-8	Planned For Pilot Plant Case 5	PDU 1 130-73-23
Space Velocity, Lbs/Hr/Ft^3			
Reactor Liquid	77.9	78.0	70.0
Reactor Temperature, ^oF	847	850	848
Excess Hydrogen Circulated, MSCF/Ton Coal	27.5	28.8	16.2
<u>Feed Slurry Oil</u>			
Pounds/Pound Coal	2.10	2.25	2.24
Composition			
Solids	6.6	8.1	4.2
Residuum	29.3	30.0	16.8
Distillate	64.1	61.9	79.0
Pounds Oil/Pound Solids	1.72	1.75	1.96
Hydrogen Partial Pressure, Reactor Outlet, psig	1760	1800	1480
Outlet Superficial Gas Velocity, Ft/Sec	0.11	0.16	0.06

Table 3-3

OPERATING PARAMETERS, YIELDS AND SULFUR CONTENTS

PDU 3 VS. PDU 1

	PDU 3 Run 130-78	PDU 1 Run 130-73
Run Hours - Beginning	124	126
- End	244	247
Catalyst Age - Beginning	646	679
- End	1330	1375
Coal Feed Rate, Lbs/Hr/Ft^3	77.9	70.2
Reactor Temperature, ^oF	847	848
Hydrogen Partial Pressure, psig	1760	1480
Product Distribution, W % of Dry Coal		
C_1-C_3	7.71	4.98
C_4-400^oF	16.90	15.30
400-975^oF	18.28	19.44
975^oF+ Residual Oil	32.45	33.62
Unconverted Coal	6.75	7.81
Ash	10.95	11.93
H_2O (Net)	6.67	6.00
NH_3	0.53	0.66
H_2S	2.55	2.40
CO, CO_2	1.01	0.83
Hydrogen Consumed, W % of Dry Coal	3.80	3.50
Sulfur Content, W %		
400^oF+ Fuel Oil	0.49	0.71
975^oF+ Residuum	0.68	0.96
Distillates in Vacuum Bottoms	0.23	0.58
Atmospheric Still Bottoms	0.03	0.03

Table 3-4

OPERATING PARAMETERS - SYNCRUDE MODE

	PDU 4 Run 130-79	Pilot Plant Syncrude Mode Case 3
Coal Feed Rate, $Lbs/Hr/Ft^3$	33.2	31.2
Average Reactor Temperature, ^oF	848	850
Excess Hydrogen, MSCF/Ton Coal	37.9	35.1
Recycled Slurry Oils		
Pounds/Pound Coal	2.12	2.35
Composition - Solids, W %	8.95	9.28
- Residuum, W %	23.29	34.60
- Distillate, W %	67.76	56.12
Pounds Oil/Pound Solids	1.62	1.75
Outlet Lineal Velocity in Reactor, F/S	0.058	0.082
Hydrogen Partial Pressure, Reactor Outlet, psig	1835	1800

Table 3-5

COMPARISON OF YIELDS - SYNCRUDE MODE

	Pilot Plant Design Basis Syncrude Mode	PDU 4		Concentration To Meet Residuum Yield
Catalyst Replacement, Lbs/Ton Coal				1.0
Coal Rate, Lbs/Hr/Ft^3	31.2	33.5	33.8	31.2
Catalyst Age, Lbs Coal/Lb Catalyst		850	1370	
Yields: W % Dry Coal				
C_1-C_3	8.26	9.97	9.68	10.54
C_4-400°F	17.37	23.66	23.56	24.96
400-975°F	34.87	23.21	20.51	27.31
975°F+ Residuum	14.86	19.25	22.31	14.86
Unconverted Coal	3.88	5.68	5.79	5.10
Ash	10.46	11.67	11.59	10.46
H_2O	9.51	7.37	8.05	8.25
CO_2	0.42	0.95	0.57	0.84
NH_3	0.82	0.84	0.70	1.04
H_2S	4.01	2.65	2.39	2.53
Total Products	104.46	105.25	105.15	105.88
H_2 Consumption	4.46	5.25	5.15	5.88

Section 4

BENCH SCALE UNIT PROGRAMS

Both bench scale units have reactor volumes of about 1000 cc. These units are suited for process parametric and yield studies.

COMPARISON RUNS

The purpose of these runs was to attempt to achieve the same yields by duplicating in the bench scale unit process conditions which had previously been used on the PDU.

On the first run, process conditions identical to the PDU were established resulting in yields of distillate oils which were very nearly the same. The bench scale unit achieved higher coal conversions by 2 to 5 W % and higher residuum yields by 6 to 8 W %.

A second run was undertaken to duplicate the startup oil preconditioning used in the PDU. The bench scale continued to achieve better coal conversion, but the difference was reduced to 0 to 3 W %. The residuum yield of the bench scale remained 6 to 8% higher than the PDU. It was concluded that for the same process parameters, the bench scale operation adequately predicts PDU yields.

LOW PRESSURE RUNS

The objectives of these runs were to study the effects of lower pressure and of lower hydrogen partial pressure on yields and product sulfur content. Lower design pressure will result in lower capital and operating cost.

In the fuel oil mode (space velocity 78 $lbs/hr/ft^3$), three levels of hydrogen circulation were tested: 100%, 60%, and 47% of the standard rate. Correlation of the results showed that a 22.2 percent reduction in process pressure will increase the sulfur content of the 400°F+ fuel oil product by 0.1 W %, from 0.5 W % to 0.6 W %.

The reduced hydrogen partial pressure can be compensated for by lowering the space velocity or by increasing the catalyst replacement rate. Calculations indicated a reduction in space velocity of 26% would be required to offset the pressure reduction. An increase in catalyst consumption from 1.0 to 2.5 lbs. of catalyst per ton of coal would be required to achieve the same effect.

In the Syncrude mode (space velocity 31 lbs of coal/hr/ft^3 of reactor), a hydrogen circulation rate equal to 33% of the standard rate was tested. Correlation of the results showed that a 22.2 percent reduction in total pressure results in an increase in residual oil yield of from about 15 W % to about 18 W % of coal fed. This additional residual oil can be used to bring the Syncrude mode into hydrogen balance by partial oxidation of the residual oil only, as opposed to using some distillate for hydrogen manufacture. Alternatively a 25% decrease in space velocity will compensate for the reduction in pressure. A third method of compensation is to increase the catalyst replacement rate from 1.0 to 2.25 pounds of catalyst per ton of coal.

Table 3-1 compares key parameters and predicted yields for the Syncrude and Fuel Oil modes for low pressure operation.

DISTILLATE OIL RECYCLE MODEL OF THE PDU

The purpose of the run was to predict the space velocity and slurry oil composition required to achieve a sulfur content of 0.7 W % in the 400°F+ fuel oil product during PDU 1.

As a result of this run it was concluded that residuum recycle was required and that a space velocity of 70 lbs coal/hr/ft^3 was appropriate. To achieve the residuum recycle, it was recommended that a hydroclone be installed on the PDU.

HIGH GAS VELOCITY MODEL OF THE PDU

The objective of this run was to develop a set of process parameters which would permit operating PDU Run 2 at high gas velocities.

Because the PDU reactor has a lower L/D than the Pilot Plant reactor, the PDU requires about twice as much excess gas to provide the same linear velocity. There was concern that the extra gas would strip too much liquid from the reactor slurry leaving an extremely viscous material in the reactor. Three strategies were considered:

- lowering reactor temperature
- recycling more light oil to compensate for the stripping
- using a heavier recycle stream

Lowering the reactor temperature to 800°F proved successful. Later, in PDU 2, a heavier recycle stream was utilized because of the proven performance of the hydroclones

CATALYST TESTING RUNS

Regenerated Catalyst

One run was made using a catalyst which had been regenerated by combustion of the carbon deposits. The catalyst activity was about half the original activity. It is recommended that a method of segregation and regeneration be developed to improve the catalyst usage and to permit the use of more active catalysts which may be subject to higher rates of deactivation.

High Density Catalyst

The purpose of this run was to test a catalyst of high density. A higher density catalyst permits a high residuum concentration in the reactor which results in a greater distillate yield.

A catalyst with a particle density of 1.7 grams per cc was used. This compares to the normal density of 1.1 to 1.3 grams/cc.

Results confirmed the projected hydrodynamic benefits. Lower coal conversion by 1 to 7 W % was obtained and the yield of distillate oils was about 10 W % lower.

It is recommended that higher density catalyst continue to be examined to find one with high density and reasonable activity.

Catalyst for the PDU

American Cyanamid HDS-1441 catalyst has a relatively high activity for desulfurizing petroleum products. A 1/16" diameter extrudate was tested but the catalyst agglomerated in the reactor. Therefore, this catalyst was not recommended for use on the PDU.

Nalcomo 471 catalyst had previously given superior results for desulfurization in H-Coal operations. During the run about 20% of the catalyst degraded into undersized particles and the bed plugged. Therefore, this catalyst was not recommended for the PDU.

American Cyanamid HDS-1442A catalyst was recommended for use in the PDU program.

Table 4-1

EFFECT OF HYDROGEN PARTIAL PRESSURE ON H-COAL RESULTS

Monterey Mine Coal Operations

	Low Sulfur Fuel Oil - Correlated Equilibrium Catalyst - Reduced Pressure				Syncrude - Correlated Equilibrium Catalyst - Reduced Pressure				
	Standard Rates	Standard Rates	Reduced Turnover Adjusted to Obtain Yields	Recycle Rates Adjusted for Sulfur, Conc.	Standard Rates	Standard Rates	Reduced Turnover Adjusted to Obtain Yields	Rates Adjusted for Yields, Conc.	Rates Adjusted for Design Yields, Conc.
System Pressure, psig	2250	1750	1750	1750	2250	1750	1750	1750	1750
Hydrogen Partial Pressure, psig	1800	1400	1400	1400	1800	1400	1400	1400	1400
Catalyst Turnover, Lbs/Ton Coal	1	1	2.5	1	1*	1*	2.25	1*	1*
Coal Rate, Lbs/Hr/Ft^3	78	78	78	58	31.2*	31.2*	31.2*	23.4	25.9
Distillate Recycle, Lbs/Lb Coal	0.16	0.16	0.16	0.185	0.1*	0.1*	0.1*	0.17	0.136
Filtered Liquid Recycle, Lbs/Lb Coal	0.72	0.72	0.72	0.695	0.9*	0.9*	0.9*	0.82	0.854
Yields, W % Dry Coal									
C_1-C_3	5.02	5.69	5.80	6.68	9.42	10.09	10.19	12.47	11.55
C_4-400°F	10.35	9.70	10.99	11.17	17.36	16.50	19.20	19.66	18.48
400-975°F	31.15	26.14	28.60	28.15	36.12	31.98	32.38	29.95	30.99
Residuum	27.97	31.64	27.95	27.61	13.19	16.22	13.01 *	13.23 *	14.07 *
Unreacted Coal	4.38	5.51	5.06	4.96	3.87	4.33	4.15	4.10	4.17
Ash	11.49	11.49	11.49	11.49	10.46	10.46	10.46	10.46	10.46
Sulfur in 400°F+ Product	0.50	0.61	0.50	0.50					

*Items Fixed for Calculation

Section 5

REACTOR HYDRODYNAMICS - COLD MODEL

In order to meet the program objectives, several modifications to the internals of the PDU reactor were required. These modifications and their impact on the reactor hydrodynamics were first tested in a cold model operated at room temperature.

The model consisted of a 6-inch diameter glass tube, ten feet long. Nitrogen and Number 2 fuel oil were used as the feeds. The unit tested :

- bubble cap design changes
- product withdrawal configurations
- various recycle pump suction cup designs

The results from the model were extremely useful in modifying the PDU. It was recommended that a full size model of the Pilot Plant be constructed.

Section 6

SOLID-LIQUID SEPARATION PROGRAM

A portion of coals (4 to 8 W %) will not convert to liquids. This portion and the ash must be removed from the liquid product. The H-Coal Process can be operated at a sufficiently high severity to convert most of the coal to distillable liquids. In this mode the non-distillable liquids, unconverted coal and ash can be used in a partial oxidation process to supply hydrogen to the process. At lower severities, substantial amounts of non-distillable liquids are produced. To obtain a low solids content product, the solids must be separated from the liquid.

Five methods of solid-liquid separation were investigated:

- distillation
- antisolvent precipitation and settling
- filtration
- centrifugation
- magnetic

The magnetic method did not achieve an acceptable ash level. Centrifugation was effective but expensive, so it was not recommended for the Pilot Plant. Filtration was effective but expensive, and was not recommended for use in the Pilot Plant. Filtration may be desirable as a guard to a primary separation method. Antisolvent precipitation and settling was effective. It has been recommended for use in the Pilot Plant. Distillation was effective and it is included in the Pilot Plant.

SPECIFICATIONS

To permit burning the fuel oil product without stack gas cleaning devices, the product specifications were established as follows:

sulfur	0.7 W %
ash	0.1 W %

The sulfur content meets the current EPA standards for petroleum-derived fuels. The current EPA standards for particulates equates to 0.17 W %. A reduced specification of 0.1 W % was used:

- because the opacity of stack gas from burning the fuel is uncertain
- because the carbon contribution to particulate matter is uncertain
- because the process of liquid solid separation is subject to minor upsets.

ANTISOLVENT PRECIPITATION AND SETTLING

In this method of solid–liquid separation, a light distillate is mixed with the stream containing heavy liquid, unconverted coal, and ash. The antisolvent property of the distillate causes asphaltenes to precipitate on the solid particles. The particles grow in size by both precipitation and agglomeration. The settling of the particles is enhanced because of:

- the larger particle size.
- the greater density differential between the liquid and the particles.
- the lower viscosity of the liquid.

The results of the program were very promising. A thirty pound per hour unit was continuously operated to produce a clean product of less than 0.1 W % ash. The unit operated on high ash feed, up to 18 W % ash (27 W % total solids). A highly concentrated underflow was achieved, up to 30 W % ash (45 W % total solids). In the 975^{o}F+ fraction, the process resulted in the preferential rejection of the benzene insoluble components. The insoluble component has a sulfur content of about 1 W % versus 0.6 W % for the soluble component. Therefore, a slight decrease in the product sulfur component will result.

The antisolvent used was a 350^{o}F to 500^{o}F distillate fraction produced by the H-Coal process. The rate of use of the antisolvent was about ten times the production rate. Therefore, redistillation and recycling of the antisolvent will be necessary. Because the purge rate of the antisolvent used by HRI will be about 10%, it seems unlikely that trace contaminants will build up to reduce the antisolvent property.

The antisolvent precipitation and settling method appears to be technically and economically promising. Therefore, it is recommended that:

- antisolvent precipitation and settling be included in the Pilot Plant.
- the Process Development Unit in Trenton be equipped with a full flow (300 lbs. per hr.) unit.
- the planned solvents for the Pilot Plant be tested.
- the sulfur reduction capabilities of the method be investigated.
- the comparative economics of distillation and antisolvent precipitation be developed.

DISTILLATION

In this method of solid-liquid separation, the stream containing distillable oil, vacuum resid, unconverted coal and ash is distilled in a vacuum tower with steam stripping. This method has the following advantages:

- process simplicity
- thermal efficiency (no recycle liquid)
- adiabatic flashing (no preheater)

One disadvantage of this method is that the benzene soluble 975^{o}F+ material (sulfur content of about 0.6 W %) is rejected with the ash and unconverted coal. Therefore, the process conditions must be controlled so that this fraction is not a substantial portion of the product.

During PDU operations, the solids content of the vacuum flash overhead was monitored. The clean product ash content of 0.1 W % was achieved. In addition, a bottoms product of 40 W % solids was achieved.

Two 50-ton lots of vacuum still bottoms produced prior to the program under this contract, were supplied to Texaco. Under contract to the Electric Power Research Institute, Texaco demonstrated that this material is a suitable feedstock to produce the hydrogen required for the H-Coal process.

The upper limit at which vacuum distillation could reduce the solid contaminated stream to an amount that would just meet plant hydrogen requirements and still be pumpable was estimated to be at a space velocity between 45 and 60 lbs of coal/hr/ft^3 of reactor volume. Therefore, it was recommended that:

- the yield patterns at 45 and 60 lbs. of coal/hr/ft^3 be determined.
- these intermediate space velocities be included in the Pilot Plant operations.
- an economic comparison of the all-distillate fuel oil modes (space velocity 45 to 60 lbs/hr/ft^3) and the boiler fuel modes (space velocity 78 lbs/hr/ft^3) be developed.

FILTRATION

Filtration is effective in meeting the product ash specification. A number of drawbacks exist, including:

- mechanical and process complexities.
- low filtration rate (i.e., high capital cost).
- high filter aid consumption.

Therefore, it was recommended that filtration not be used for solid-liquid separation at the Pilot Plant.

A filter might be desirable as a "guard" on the clean outlet of an antisolvent precipitation system. This "clean" stream is characterized by a low solid content, high distillate content, low residuum content, and a low viscosity. Therefore, a much higher filtration rate is anticipated, much lower filter aid consumption will be obtained, filter cake drying probably can be eliminated, and filter cake washing probably can be eliminated. These changes would mean a simpler process and a less complex filter. The lower viscosity liquid would permit lower operating temperature of the filter. This would result in simpler designs for seals and bearings. A much lower cost might be obtained for a "guard" filter.

Therefore, it is recommended that filtration rate data be obtained on the clean product from the PDU antisolvent precipitation and settling system.

Section 7

TECHNICAL MANAGEMENT PLAN

The Technical Management Plan was prepared for the two-year operating program of the Pilot Plant.

A six-month shakedown period is provided using Kentucky coal.

Initial operations will be in the syncrude mode. The next period of operations will be concerned with boiler fuel operations. This will be followed by operations at intermediate severities. Planned operations are summarized in the following table:

Months	Mode	Space Velocity Lbs Coal/Hr/Ft^3	Coal
0-6	Shakedown	Various	Kentucky No. 11
7-9	Syncrude	31	Illinois No. 6
10-12	Syncrude	31	Wyodak
13-15	Boiler Fuel	78	Kentucky No. 11
16-18	Boiler Fuel	78	Illinois No. 6
19-21	Intermediate	60	Illinois No. 6
22-24	Intermediate	45	Illinois No. 6

Appendix A

THE H-COAL PROCESS

PROCESS HISTORY

In the late 1950's HRI invented the ebullated bed reactor. The basic concept is to use an upflowing mixture of vapor and liquid to maintain an expanded state catalyst bed in random motion. The application first envisioned was the processing of heavy oil extract containing some sand from the Alberta Tar Sands because the expanded state and random motion of the catalyst bed permit processing a feed containing fine solids. It soon became obvious that the ebullated bed had certain advantages for the catalytic processing of any exothermic, two phase mixture:

- Because the catalyst bed is in motion and totally mixed, catalyst can be added and withdrawn from a single point to maintain constant activity.
- The totally mixed bed is essentially isothermal thus eliminating the need for quench points.
- The ebullating action within the bed prevents formation of dead spots and channels and eliminates the need for vapor-liquid redistribution devices.

Thus, the H-Oil® Process was commercialized in the late 1960's for the hydroconversion of petroleum derived vacuum residuum. The largest plant is currently in operation in Kuwait processing over 55,000 barrels per day of vacuum bottoms.

Experiments which explored the possibilities of a continuous flow catalytic system which could handle fine solids soon led to feeding a slurry of finely ground coal. Preliminary results were sufficiently encouraging that in February of 1965 the Office of Coal Research awarded HRI a three year development contract. Work was done on two scales. The initial experiments were carried out in 25-pound-per-day (coal feed rate) "bench units". These units have the advantage of low inventory, quick start-up, rapid achievement of equilibrium following a change of conditions, and reasonably low operating labor cost. The flows, however, are too small to sustain the continuous operation of product separation facilities which produce the slurry oil recycle streams envisioned for a commercial-scale unit. In addition, it is very difficult to control bed expansion on this scale and an internal screen is required in the reactor. Therefore, a larger Process

Development Unit (PDU) capable of feeding up to three tons of coal per day was also employed. All operations were in the syncrude mode.

The bench unit OCR program achieved slightly over 8000 hours of operation roughly broken down as follows:

- Illinois No. 6 Coal - 6000 hours
  - Studies employing non-H-Coal derived feed slurrying oils-2800 hours. Catalytic cracker decant oil and anthracene oil. The most significant result was improvement in conversion when hydrogenated anthracene oil was employed. The increase in conversion was attributed to a donor solvent effect.
  - Process variable studies - 1200 hours. Temperatures of 830°-860°F, pressures of 1500-3000 psi, space velocities of 15-45 Lbs/Hr/Ft^3 and other process conditions were studied.
  - Residuum content of feed slurrying oil - 1000 hours. Use of a vacuum column to vary the proportion of distillate vs. residuum in the slurry confirmed the significant effect this had on the yields.
  - Alternate catalyst - 1000 hours. Ni-Mo was found to be no better than the standard Co-Mo.
- Wyodak Coal - 1550 hours. Yields were determined to compare with the Illinois No. 6 Coal.
- North Dakota Lignite - 550 hours. A yield comparison run.
- Utah-D - A short run to determine the yields from this coal.
- Two Stage Processing - A short run employing PDU vacuum tower bottoms in place of coal feed to determine if a two stage operation significantly enhances coal and residuum conversion.

The PDU had several short runs during which mechanical problems due primarily to the erosive nature of the coal-oil slurry were resolved. A 473-hour continuous run on Illinois No. 6 coal was then made and the results provided a basis for relating Bench Unit and PDU yields. The program was terminated prematurely in September of 1967, when the Office of Coal Research budget was cut.

From 1967 to 1969 the program was funded by HRI and ARCO. More process variable studies were run in the bench units and more coals were tested. At constant temperature and pressure, space velocity and slurry composition were varied to determine conversion and yields for the following coals:

Pittsburgh Seam	-	1400 hours operation
Texas Lignite	-	1200 hours operation
Black Mesa	-	1000 hours operation
Colorado	-	1400 hours operation

All of these operations were in the syncrude mode.

In 1970 a 400-hour run was made on Australian Gelliondale Brown Coal. This proved to be a very reactive coal. At a space velocity of 93 $Lbs/Hr/Ft^3$ (as opposed to the normal 30) conversions of over 80 percent were achieved with less than 20 percent of the yield being 975^oF+ residuum.

In early 1971 the "Boiler Fuel" mode of operation was demonstrated in a 716-hour bench unit run on Illinois No. 6 coal. This run was jointly sponsored by HRI and ARCO and explored space velocities from 43.7 to 187.2 $Lbs/Hr/Ft^3$, pressures of 1250 to 2250 psi and temperatures between 850 and 875^oF. The results were then correlated to predict those conditions which would produce a product with acceptable residuum and sulfur contents. Additional operations were then carried out for almost 2000 hours on Illinois No. 6 coal to confirm the projections and test additional process improvements such as the use of hydroclones to produce a high residuum-low solids recycle slurry oil and to test the effect of more coarsely ground coal feed.

Work continued through 1972 and 1973 under industrial sponsorship. Almost 3000 hours of bench unit operations were carried out with Wyodak coal to verify yields and test such additional process features as coal dried with flue gas and the behavior of regenerated catalyst. In addition, a run of over 500 hours was made on Big Horn coal to verify its similarity to Wyodak.

During this period of time the Process Development Unit also operated for almost 2400 hours, all in the syncrude mode. Recycle slurry oil was provided by a combination of continuous product fractionation and the batchwise use of hydroclones on the reactor product slurry. There were 1350 hours of operation on Illinois No. 6 coal and 1050 hours on Wyodak.

H-COAL REACTOR

Figure A-1 is a sketch of the H-Coal reactor. For purposes of clarity, an external separator is shown. Normally, an internal recycle separator is used.

The reactor feed, consisting of coal, slurry oil and hydrogen, is introduced into the bottom of the reactor. The controlled reactor recycle stream is also pumped into the bottom of the reactor. The cross-hatched area in the diagram indicates the catalyst bed prior to expansion. The amount of bed expansion is controlled by the physical properties of the feed and recycle and by the upward flow rate. The dotted area on the diagram indicates the amount of expansion. Catalyst particles within the expanded bed are in constant, random motion. There is a gradient of catalyst particles from the bottom to the top of the bed, with the heavier, less buoyant particles tending to collect near the bottom. A very sharp interface between the top of the ebullating catalyst bed and the oil-coal slurry is obtained.

The effluent is separated into vapor and liquid streams. Recycle liquid is pumped back into the reactor to control the rate of liquid upflow in the reactor and the amount of catalyst bed expansion. Because the catalyst is constantly in motion a portion of the catalyst can be withdrawn and replaced with fresh catalyst. Additionally, because the catalyst is totally mixed, the average age (or activity) is controllable by the amount of addition and withdrawal. Normally, this withdrawal and addition is done on a daily or less frequent basis with the amount of catalyst changed being about 1 to 3% of the inventory. A further consequence of the catalyst being in motion is that the reactor is nearly isothermal. Therefore, the optimum temperature is selected by the operator. The feed is below the reactor temperature and is heated by the exothermic hydrogenation reaction. Thus, the reactor also serves as an efficient heat exchanger, thereby minimizing the capital cost for heating and cooling equipment and eliminating a portion of the thermal inefficiencies caused by heating the feed and cooling the reactor effluent.

The reactor diameters used in the H-Coal and H-Oil programs are shown in the following table.

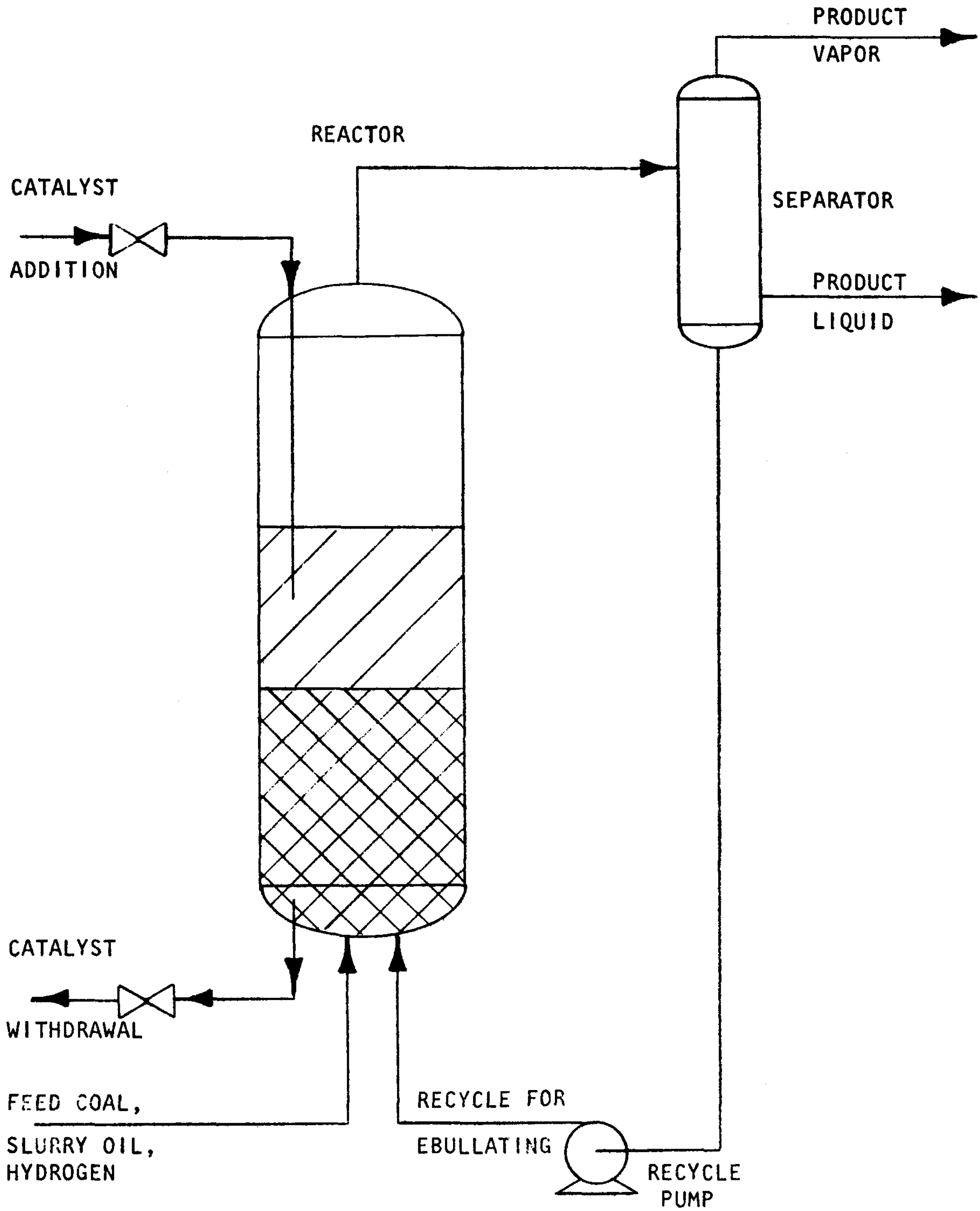
	H-Oil Reactor Internal Diameter	H-Coal Reactor Internal Diameter
Bench Scale (Approximate)	3/4"	3/4"
Process Development Unit	8.5"	6" and 8.5"
Pilot Plant	4'-6"	5'-0" *
Commercial	10' to 12'-6"	12' (Probable)

* Under Construction

The bench-scale reactors at the Research and Development Center of Hydrocarbon Research, Inc. are used without reactor modifications to test H-Oil, H-Coal and solvent refined coal processes. Because of the background in scaling up the H-Oil reactor from four feet, six inches to twelve feet, six inches, HRI anticipates that scaling up the H-Coal Process from the five-foot Pilot Plant to commercial diameters will be straightforward.

Figure A-1

H-COAL REACTOR



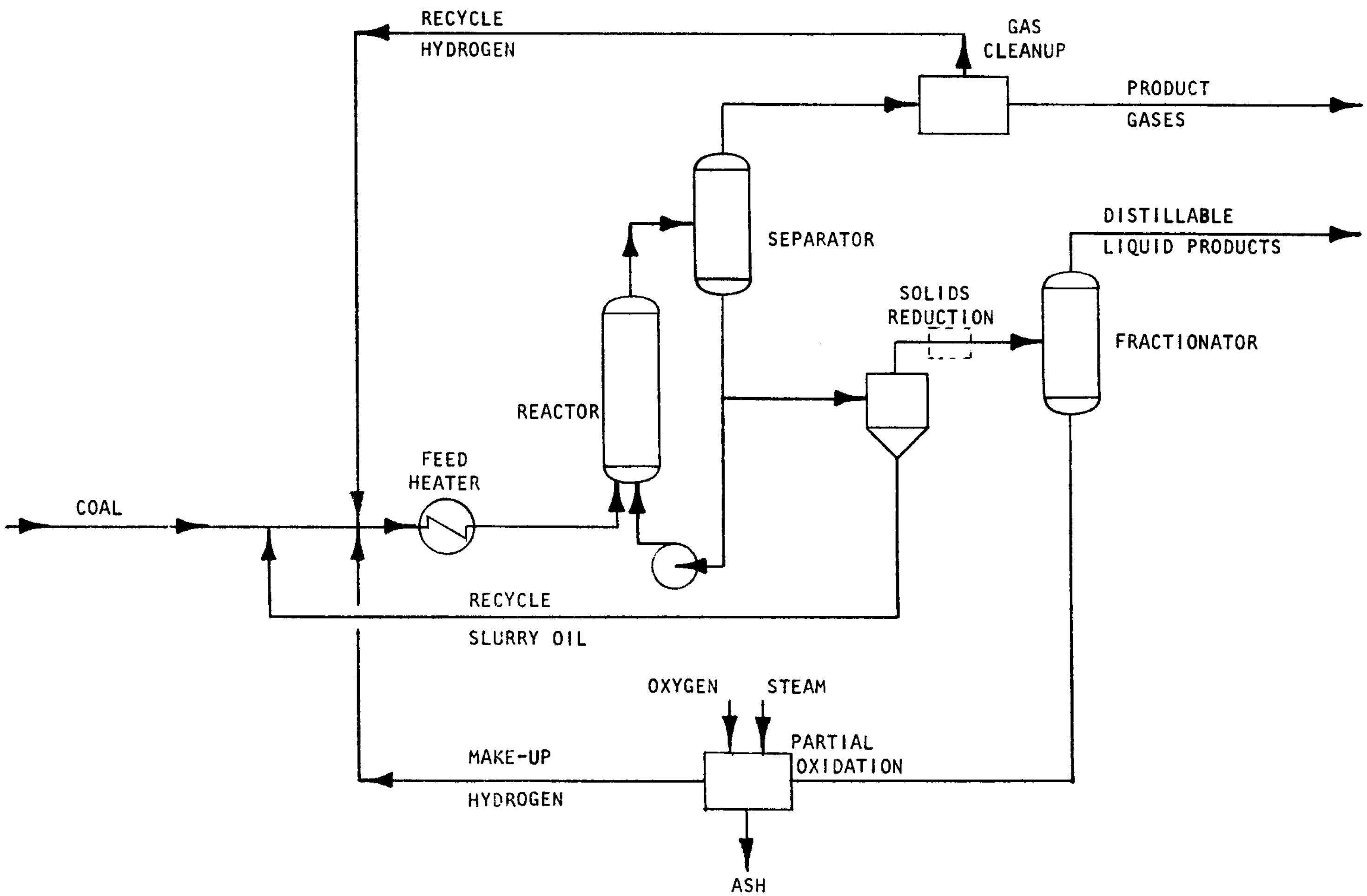
H-COAL PROCESS DESCRIPTION

Figure A-2 is a simplified sketch of the H-Coal Process. Coal is prepared by crushing and drying. A process-derived recycle oil is used to slurry the coal. The mixture is pumped to reactor pressure and mixed with hydrogen. This stream is heated and enters the reactor. Contact with the contents of the reactor and with the recycle ebullating flow heats the feed to reaction temperature. The reaction takes place in the presence of a commercially-available catalyst. Products are withdrawn from the reactor and separated into vapor and liquid streams. The vapor stream is cooled and cleaned to recover light net products and unreacted hydrogen, which is recycled. The remaining gases are treated and used or exported. A portion of the liquid stream is recycled to the reactor to control catalyst expansion. The remaining liquid is depressured and separated into a high-solids-content stream and a low-solids-content stream. Flash vapors are condensed and the solids-free liquid sent to fractionation. The low-solids-content stream is recycled to become part of the slurry oil. To obtain a desired yield slate, other fractions may be recycled to adjust the composition of the slurry oil. The net liquid enters a distillation train and the distillable liquids are exported as products. The vacuum tower bottoms, which contain the 975°F+ material, unconverted coal and ash, enters a partial oxidation section. Oxygen and steam are reacted with the hydrocarbonaceous material to form the hydrogen for the plant. Ash is separated from the gas and the ash is discharged. In this manner, essentially all of the hydrocarbonaceous material is efficiently used in the process.

If lower severities are desirable, the non-distillable hydrocarbonaceous material exceeds the hydrogen requirements of the process and the ash must be separated from the non-distillable liquid. This is known as the boiler fuel mode of operation. Settling, promoted by an antisolvent, promises to be the most economic and most reliable method. The dotted box in Figure A-2 represents this method.

Figure A-2

H-COAL PROCESS SCHEMATIC



ADVANTAGES OF H-COAL TECHNOLOGY

H-Coal technology offers several advantages which make the process the leading candidate for early commercialization.

- BASIC PROCESS FEATURES
  - Almost 14 years of continuous development
  - Outgrowth of proven commercial technology
  - Direct catalytic hydrogenation of coal offers potential for improvement by better catalyst (e.g.,denitrogenation)
  - Can vary operation to meet product slate requirements
  - Simple and proven scale-up of unique process features

- UNIQUE EBULLATED BED REACTOR SYSTEM
  - Products produced from coal in one reactor - no external solvent hydrogenation
  - Not dependent on coal ash having catalytic properties
  - Coal slurry can be handled in catalyst bed directly
  - Expanded bed permits continuous catalyst addition and withdrawal to control activity
  - Catalyst addition and withdrawal capability permits recovery from upset and/or poisoning without shutdown
  - Catalyst addition and withdrawal capability permits continuous catalyst regeneration
  - Reactor is isothermal - better process control
  - Use of mixed reactor as means of transferring hydrogenation exotherm to feed reduces capital cost and problems associated with high temperature heat transfer equipment

- COAL FEED ADVANTAGES
  - Work to date has shown that any rank coal can be processed
  - No pretreatment of the feed coal to eliminate caking
  - Exact sizing of feed coal is not required
  - Coal fines may be fed

- PRODUCT ADVANTAGES
  - Product slate can be varied from all distillate to predominately heavy fuel oil
  - Low sulfur fuels are produced directly
  - Products are compatible with existing refinery process units
  - Commercial residue gasification processes may be used to convert any unconverted coal and heavy residue
  - Most of the liquid products can be produced by simple distillation

- SCALABILITY
  - The ebullated bed technology has been applied to petroleum residuum hydrogenation and has been in operation nine years at throughputs up to 55,000 barrels per day

- FLEXIBILITY
  - Product slate can be varied to meet demand
  - Changing catalyst addition-withdrawal rate allows product slate/quality to be varied and/or upset recovery

Appendix B

PREDICTED YIELD PATTERNS

The following tables contain predicted yield patterns for the various modes of operation currently planned for the Pilot Plant.

Table B-1

PROJECTED PILOT PLANT YIELDS - SYNCRUDE MODE

Space Velocity, Lbs Coal/Hr/Ft^3 Reactor	31
Coal Throughput, T/D MF	211
Hydrogen Partial Pressure, psi	1650
Catalyst Replacement Rate, Lb Catalyst/Ton Coal	1.0

Reactor Yields	Lb/100 Lb MF Coal	^{o}API	B/D	% S
C_1-C_3	10.49			
C_4	2.16	113.0	44.3	
C_5-400^{o}F	22.93	47.0	350.3	0.05
400-650^{o}F	16.52	23.6	219.4	0.06
650-975^{o}F	9.82	0.6	109.7	0.20
975^{o}F+	16.32	-20.0	156.1	0.33
Unconverted Coal	4.73			
Ash	10.00			
H_2O	8.26			
$CO + CO_2$	0.85			
NH_3	1.05			
H_2S	2.70			
Total	105.84		879.8	
W % Sulfur in 400^{o}F+ Oil				0.20

Table B-2

PROJECTED PILOT PLANT YIELDS - INTERMEDIATE MODE

Space Velocity, Lbs Coal/Hr/Ft^3 Reactor	45
Coal Throughput, T/D MF	306
Hydrogen Partial Pressure, psi	1650
Catalyst Replacement Rate, Lb Catalyst/Ton Coal	1.0

Reactor Yields	Lb/100 Lb MF Coal	^{o}API	B/D	% S
C_1-C_3	8.55			
C_4	1.67	113.0	49.0	
C_5-400^{o}F	17.73	47.0	394.7	0.06
400-650^{o}F	16.09	23.1	309.1	0.08
650-975^{o}F	11.05	0.3	180.5	0.24
975^{o}F+	22.31	-20.0	309.1	0.47
Unconverted Coal	5.39			
Ash	10.00			
H_2O	7.81			
$CO + CO_2$	0.85			
NH_3	0.92			
H_2S	2.62			
Total	104.99		1242.4	
W % Sulfur in 400^{o}F+ Oil				0.29

Table B-3

PROJECTED PILOT PLANT YIELDS - INTERMEDIATE MODE

Space Velocity, Lbs Coal/Hr/Ft^3 Reactor	60
Coal Throughput, T/D MF	408
Hydrogen Partial Pressure, psi	1650
Catalyst Replacement Rate, Lb Catalyst/Ton Coal	1.0

Reactor Yields	Lb/100 Lb MF Coal	°API	B/D	% S
C_1-C_3	7.34			
C_4	1.49	113.0	57.1	
C_5-400°F	15.79	47.0	469.2	0.06
400-650°F	12.81	22.5	326.4	0.08
650-975°F	10.32	0.0	224.4	0.24
975°F+	29.00	-20.0	534.5	0.70
Unconverted Coal	6.15			
Ash	10.00			
H_2O	7.31			
NH_3	0.84			
H_2S	0.80			
Total	104.35		1611.6	

W % Sulfur in 400°F+ Oil: 0.45

Table B-4

PROJECTED PILOT PLANT YIELDS - BOILER FUEL MODE

Space Velocity, Lbs Coal/Hr/Ft^3 Reactor	78
Coal Throughput, T/D MF	531
Hydrogen Partial Pressure, psi	1650
Catalyst Replacement Rate, Lb Catalyst/Ton Coal	1.0

Reactor Yields	Lb/100 Lb MF Coal	°API	B/D	% S
C_1-C_3	6.36			
C_4	1.26	113.0	63.7	
C_5-400°F	13.37	47.0	515.1	0.07
400-650°F	11.44	21.7	377.0	0.09
650-975°F	11.27	-0.1	318.6	0.27
975°F+	32.09	-20.0	770.0	0.86
Unconverted Coal	7.14			
Ash	10.00			
H_2O	7.01			
$CO + CO_2$	0.83			
NH_3	0.72			
H_2S	2.39			
Total	103.88		2044.4	
W % Sulfur in 400°F+ Oil				0.58