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TECHNOLOGY AND DEVELOPMENT

REQUIREMENTS FOR

ADVANCED COAL CONVERSION SYSTEMS

FINAL REPORT

AUGUST, 1981

SRS

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SRS/SE-TR81-102

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Prepared for:

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

Under Contract Number NAS8-34264

FOREWORD

This final report is submitted to the National Aeronautics and Space Administration (NASA), George C. Marshall Space Flight Center (MSFC) by Spectra Research Systems, Southeastern Operations, 555 Sparkman Drive, Suite 608, Huntsville, Alabama, 35805, as fulfillment of the final report requirement of Contract Number NAS8-34264, entitled "Technology and Development Requirements for Advanced Coal Conversion Systems."

The work reported in this document was performed under the technical guidance of Mr. Robert L. Middleton and Dr. Shelba J. Proffitt, MSFC-Coal Gasification Task Team as part of the NASA Headquarters Energy Systems Division's Energy Technology Program. The thrust of the study was the analysis of technology and development requirements for advanced coal conversion processes with major emphasis on third generation gasification and liquefaction processes. The study was accomplished by Spectra Research Systems (SRS), with the Mittelhauser Corporation (MC) acting as a subcontractor.

Mr. John D. Hyde was the project leader and was supported by the SRS technical and management staff which included Mr. Rodney Bradford, Dr. D. David Marshall, Mr. C. Wendell Mead, Mr. Edward E. Montgomery, Mr. David E. Marty, and Mr. James Morrison.

The MC technical staff included Mr. M. Dale Dowden, project leader, Mr. Henry Ho, and Mr. Carl J. Kelly.

The key administrative support staff for the effort was Mrs. Kathryn Henson and Ms. Sherry Clark.

SUMMARY

This report contains a compendium of coal conversion process descriptions and the results of a detailed investigation of five third generation and two second generation coal conversion processes. The extent of the investigation of each process varied depending on factors such as availability of information and development status. The thrust of this effort was to analyze the development status, the design characteristics, and plant operating experience to determine the development requirements for the process and related systems and equipment and to compare these requirements with those for other first or second generation processes.

The SRS and MC data bases were utilized to provide information particularly in the areas of existing process designs and process evaluations. Additional information requirements were established and arrangements were made to visit process developers, pilot plants, and process development units to obtain information that was not otherwise available. Plant designs, process descriptions and operating conditions, and performance characteristics were analyzed and requirements for further development identified and evaluated to determine the impact of these requirements on the process commercialization potential from the standpoint of economics and technical feasibility. A preliminary methodology was established for the comparative technical and economic assessment of advanced processes.

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1.0 INTRODUCTION

Petroleum fuels and petroleum products have become a vital part of the way of life in the United States. The economic vitality of the nation is greatly affected by the supply of petroleum. Although conservation measures have resulted in an approximate ten percent reduction in the consumption of petroleum products, the level of consumption remains at near thirteen million barrels per day. Almost half of the nation's petroleum is supplied by foreign sources and U.S. production has been decreasing since 1970. The U.S. reserves have been estimated as low as ten years supply and world supplies are projected to be significantly depleted by the end of the century.

A major candidate for supplementing diminishing oil supplies is synthetic fuels manufactured from the nations coal reserves which are currently estimated at over 450 billion tons. There is proven technology available on a commercial scale in foreign countries and there are many other processes being demonstrated in the U.S. and other countries. There are several advanced processes being tested in the U.S. that appear to have major advantages over the older more proven (first and certain second generation) technologies. These advantages include process efficiency, improved reliability, lower cost, and reduced complexity. However, these processes are not well demonstrated on a scale large enough for commercial operation and therefore uncertainty is associated with them. This report addresses many of the uncertainties associated with advanced processes and weighs the impact on the technical feasibility and the cost of scale-up. Data is included on the process configurations, process designs, and run histories which served as input for the assessment of process characteristics and their technical and economic status.

Coal conversion processes are classified as liquefaction or gasification and some processes contain elements of both. Liquefaction processes are identified as either direct or indirect and gasification processes may be categorized several ways. The advanced processes addressed in this study include direct liquefaction, entrained flow gasification (including hydro-gasification), molten salt gasification, and a fluid wall reactor system. A compendium which describes the major processes is presented in Section 10.0 of this report.

The following is a list of the processes that received particular emphasis:

- Bell High Mass Flux
- Bigas
- CS/R Hydropyrolysis
- Mountain Fuel
- Rockwell Molten Salt
- Texaco
- Thagard

Many sources of information were utilized such as published literature, data from previous SRS and MC studies, personal contacts, plant visits, and the analysis of plant test run results.

This report does not reflect a comparison of processes to establish recommendations on relative performance but does identify characteristics that influence the technology development requirements and the technical and economic feasibility of the processes. Detailed descriptions of each of the above processes, their designs, and operational histories and the results of the analyses are presented. This report is a synopsis of the work that was performed during the contract period and summarizes information that was delivered at various times throughout the execution of the effort.

2.0 PROCESS AND SYSTEMS DESCRIPTIONS

The advanced processes are in various stages of development and the Pilot Plant/PDUs contain varying amounts of ancillary systems and equipment and degree of integration. The critical unit of each process is the reactor which is of major concern in development. The process and systems descriptions that follow include information concerning the development and programmatic status and physical characteristics. Detailed descriptive information on the following processes is provided:

- Bell High Mass Flux
- Bigas
- CS/R Hydropyrolysis
- Rockwell Molten Salt
- Thagard
- Mountain Fuel

The Texaco and Westinghouse processes are included but were analyzed less extensively.

A process and pilot/subscale demonstration reference compendium, Section 10.0, was assembled from the information obtained during the performance of this study and from the SRS in-house data base. The compendium describes the major advanced coal gasification and coal liquefaction processes and contains information on their current status, development history, and flow schematics where available. The processes described in the compendium, Figure 2.1, are those that have been tested or are currently undergoing testing.

2.1 DEVELOPMENT STATUS SUMMARY

Much of the development of coal conversion processes has been funded at least in part by the Department of Energy (DOE). All the processes studied in detail had received prior funding from DOE except for Thagard and its developers were, during the course of this study, attempting to obtain DOE funding. The status of development, except for Thagard, appeared to be related to the level of funding that the developers had obtained. All of the processes studied had progressed to at least the PDU stage and all were (according to the developers) ready for scale-up to the next phase of development. Figure 2.2 provides a listing of the Pilot Plant/PDUs and information related to the development status of the processes. The following subsections provide more detailed development information for each process.

Bell High Mass Flux
Bigas
British Gas Slagging Lurgi
CO_2 Acceptor
Combustion Engineering (Atmospheric Entrained-Bed)
Cogas
GFETC Slagging Fixed Bed
HRI Fast Fluid Bed
Hygas
Molten Salt
METC Stirred Fixed Bed
Mountain Fuel (High-Rate Entrained Flow)
CS/R Short Residence Time Hydrogasification (Flash Hydropyrolysis)
Synthane
Texaco
Thagard
Tri-Gas (BCR Fluid Bed)
U-Gas
Westinghouse
Battelle (Coal Catalyzation Process)
Bergius
Clean Coke Process (USS)
Clean Fuel From Coal (CFFC)
Consol (CFS)(CRESAP)
CO-Steam (Grand Forks Liquefaction Process)
Disposable Catalyst Hydrogenation
Dow Catalytic Liquefaction
Exxon Donor Solvent (EDS)
Fischer Tropsch
H-Coal
Mobil-M-Gasoline
Occidental (Flash Pyrolysis)
Riser Cracking (IGT)
Short Residence Time Hydropyrolysis (Flash Liquefaction)
SRC I
SRC II
Two Stage Liquefaction
Zinc Halide

FIGURE 2.1 COAL CONVERSION PROCESSES

SRS

PROJECT			STATUS *		PLANT			DOE FUNDING	
NAME	LOCATION	DEVELOPER/ CONTRACTOR	PLANT SCALE	DEVELOPMENT PHASE	GASIFICATION PROCESS	COAL CONSUMPTION (TONS/DAY)	PRODUCTS	YES	NO
BELL HIGH MASS FLUX	BUFFALO, NEW YORK	BELL AEROSPACE	PDU	O	HIGH MASS FLUX ENTRAINED FLOW	12	MED-BTU	X	
BIGAS	HOMER CITY, PENNSYLVANIA	BCR, INC./ STERNS ROGER	P	O	BIGAS ENTRAINED FLOW	120	HIGH-BTU	X	
CS/R HYDRO-PYROLYSIS	SANTA SUSANA, CALIFORNIA	CITIES SERVICE, ROCKWELL INT.	PDU	O	ROCKWELL HYDROPYROLYSIS	6	GAS & LIQUIDS	X	
"	"	"	P	C	"	18	"	X	
"	PITTSBURGH, PENNSYLVANIA	ROCKWELL, U.S. STEEL	P	P	"	300	"		X
ROCKWELL MOLTEN SALT	SANTA SUSANA, CA.	ROCKWELL INT.	P	O	MOLTEN SALT	24	LOW-BTU	X	
MOUNTAIN FUEL	PROVO, UTAH	EYRING RESEARCH/ MOUNTAIN FUEL RESOURCES	PDU	TESTING COMPLETE	ENTRAINED FLOW	0.5	MED-BTU	X	
"	SALT LAKE CITY, UTAH	MOUNTAIN FUEL	PDU	D/C	"	30	"	X	
THAGARD FLUID WALL REACTOR	SOUTH GATE, CALIFORNIA	THAGARD OIL	PDU	O	FLUID WALL RADIANT HEAT	5.0	GASES		X
THAGARD CARBON BLACK PLANT	TEXAS	THAGARD	P	D/C/O	"	50	CARBON BLACK/GAS		X

* PLANT SCALE: PDU-PROCESS DEVELOPMENT UNIT; P-PILOT PLANT
DEVELOPMENT PHASE: P-PLANNED; D-DESIGN; C-CONSTRUCTION: O-OPERATIONAL

FIGURE 2.2 MAJOR COAL CONVERSION PILOT PLANTS AND PDUs

2.1.1 BELL HIGH MASS FLUX

The development of this process has been intermittently funded by DOE (or ERDA) since 1976. It utilizes a rocket-type combustion reactor to achieve high carbon conversions with a high mass flux (HMF) through the reactor to produce a low-Btu gas. Funding from DOE has been provided to operate the PDU except for periods in which Bell continued operation of the process on Bell funds. Figure 2.3 shows the development history of the process and additional project data is given in Figure 2.4.

2.1.2 BIGAS

The 120 tons/day (TPD) fully integrated pilot plant has been operating since 1976. Stearns Roger is the plant operator. The plant test facilities were the most extensive and the largest scale of any of the operating plants that were studied. Many of the problems associated with larger scale continuous operation have been identified and resolved and the capability for continuous operation demonstrated. These problems are identified in subsequent sections of this report. Development status and project overview information is shown in Figure 2.5.

2.1.3 CS/R HYDROPYROLYSIS

The CS/R Hydropyrolysis Process was initially conceived and developed under private funding. Development and process optimization is continuing under DOE funding and is being pursued by the Rockwell International Energy Systems Group with Cities Service Research and Development as a major subcontractor.

The process has advanced to the point where reactor performance and preliminary process economics have been established. Recent engineering scale reactor test data, at a 3/4 ton/hour (TPH) throughput, have demonstrated the carbon conversion capabilities to synthetic natural gas (SNG), the capability of coproducing significant amounts of benzene as a byproduct, and the reproducibility of reactor performance data. An Integrated Process Development Unit (IPDU) is under construction. This operation should provide the necessary bridge to process commercialization by demonstrating long duration operability under reactor conditions characteristic of commercial reactor operations. The test program schedule is shown in Figure 2.6 and project overview information

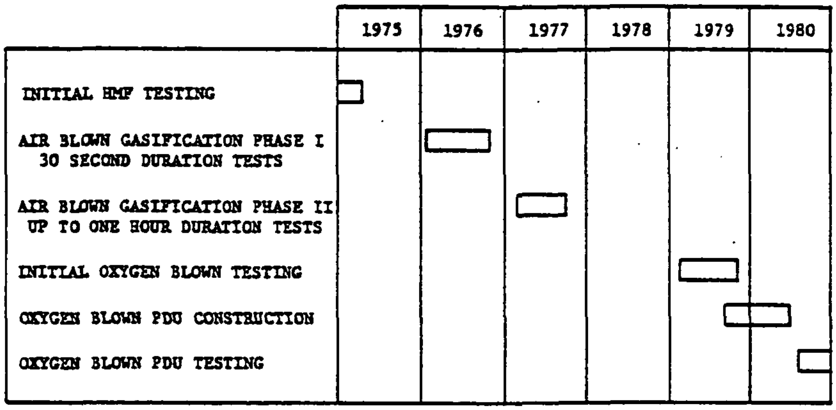

FIGURE 2.3 BELL HMF PROCESS DEVELOPMENT HISTORY

Process Developer:	Bell Aerospace Textron
Scale:	0.5 TPH Process Development Unit
Location:	Buffalo, New York
Funding:	\$1.2M 1976-1978, \$1.5M 1979-1980
Sponsor:	DOE, Gas Research Institute
DOE Program Manager:	Louis Jablansky, DOE Headquarters Germantown, Maryland Phone: (301)353-3792
Concept:	High efficiency mixing techniques are achieved using rocket engine technology. A high mass flux entrained flow gasifier reactor with rocket combustor-like feed system will decrease the required size of the reactor vessel. The process produces low-Btu gas in an air-blown system. An oxygen-blown system is used to produce medium-Btu gas.
Description:	Coal, oxygen and steam are fed to the single-stage slagging reactor to produce slag and raw gas. The effluent is quenched to 1900°F with water. The slag is separated from the raw product gas and sent to disposal. The gas stream is then sent to a cyclone for char separation and then to simultaneous cooling and water scrubbing for final removal of the solid fines.
Operating Conditions:	Temperature: 2500°F Pressure: 220 psia
Reactants:	Coal, oxygen, and steam.
Products:	Low and Medium-Btu gas.
Status:	Process development is continuing under DOE support.

FIGURE 2.4 BELL HMF PROJECT

Process Developer:	Bituminous Coal Research
Scale:	120 TPD Pilot Plant
Location:	Homer City, Pennsylvania
Funding:	FY80 ~ $10,000,000 FY81 ~ $10,000,000
Sponsor:	DOE
DOE Program Manager:	Louis Jablansky, DOE Headquarters Germantown, Maryland Phone: (301)353-3792
Concept:	Utilizes a two stage entrained gasifier operating at high temperature (2800°F) and pressure (1500 psig) in an oxygen-blown, ash slagging process to produce medium-Btu gas which is methanated to yield high-Btu gas.
Description:	The feed coal is slurried, pulverized, and passed through a spray dryer, then to two eductors. The coal then enters stage two of the gasifier through injector nozzles. Steam is injected through a separate annulus in the injector. Two streams combine at the injector tip and join the hot synthesis gas from the bottom stage. The coal is converted to methane, synthesis gas and char. The raw gas rises through the gasifier, quenched by atomized water and sent to a cyclone separator where it leaves for further processing to yield a high-Btu gas. The char is recycled to stage one of the gasifier where it is gasified under slagging conditions to provide heat and synthesis gas for stage two reactions.
Operating Conditions:	Temperature: 1500 - 3000°F Pressure: 500 - 1500 psig
Reactants:	Coal, oxygen, and steam
Products:	High-Btu gas
Status:	The Pilot Plant at Homer City, Pennsylvania has been operating since 1976 - operation of plant to continue at least through FY81.

FIGURE 2.5 BIGAS PROJECT DATA

SRS

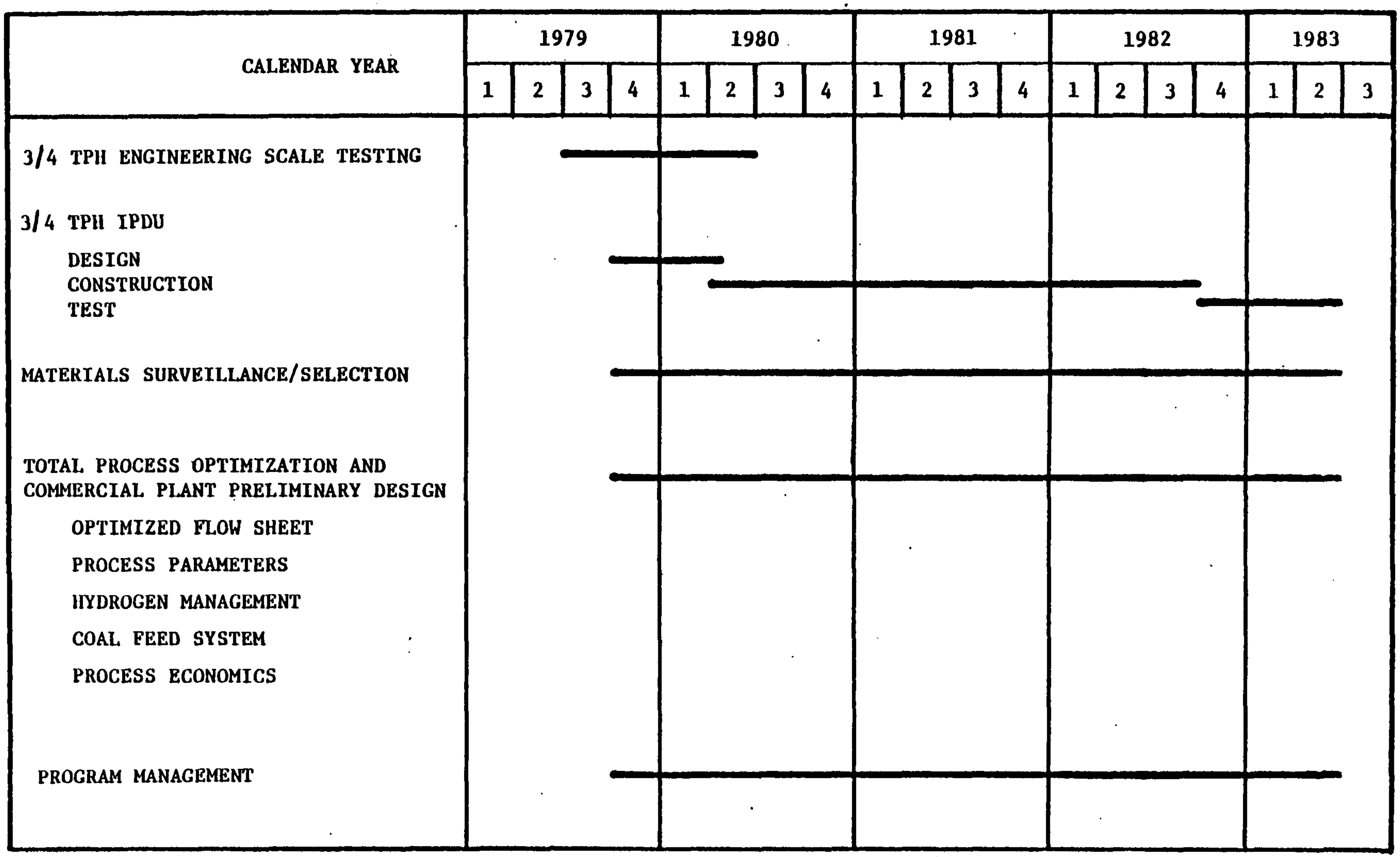

FIGURE 2.6 SCHEDULE FOR ROCKWELL INTERNATIONAL's 3/4 TPH INTEGRATED PROCESS DEVELOPMENT PROGRAM

in Figure 2.7. C. E. Lummus is currently performing an independent commercial design study on this process.

2.1.4 ROCKWELL MOLTEN SALT

The Molten Salt Gasification Process has been under development by Rockwell International since the early 1970's. Current work is being conducted by Rockwell's Energy Systems Group at a 24 TPD PDU in Santa Susana, California. The design and construction was funded by DOE and the operation is being funded by DOE. In the process, coal is gasified in a highly turbulent pool of sodium carbonate-based melt by reaction with air or oxygen and steam. The testing to date in the PDU has been done with air feed to produce low-Btu gas, however, future funding will support operation of the PDU with oxygen feed to produce medium-Btu gas. Figure 2.8 provides additional programmatic and project data.

2.1.5 THAGARD

Thagard Research Corporation has been performing research and testing on its high temperature fluid wall reactor for several years. Thagard Research was established for the purpose of developing the reactor and applying the technology to industrial applications. The process was developed on Thagard funds although Southern California Edison has funded some testing of the reactor and is considering the process for a 1000 TPD installation to replace natural gas with medium to low-Btu gas derived from coal. The present test facilities are a bench scale reactor in Irvine, California and a 5.0 TPD PDU in South Gate, California. The PDU runs have been mostly on the order of less than eight hours and a variety of feedstocks have been processed. Thagard is currently seeking DOE funding for further testing of the reactor specifically aimed at DOE goals. Additional project data is shown in Figure 2.9.

2.1.6 MOUNTAIN FUEL

Mountain Fuel Resources and Ford, Bacon & Davis Utah, Inc. are currently providing management and engineering for the Mountain Fuel High Rate Entrained Flow gasification process development in a cost-sharing effort with DOE. Design of a 30 TPD PDU was initiated in late 1977 and is essentially complete and construction is scheduled to start in 1981. The site will be at the Interstate Brick Company 20 miles south of Salt Lake City, Utah.

Process Developer:	Rockwell International
Scale:	18 TPD PDU
Location:	Santa Susana, California
Funding:	FY80-$6,700,000 FY81-$5,300,000
Sponsor:	DOE
DOE Program Manager:	Louis Jablansky, DOE Headquarters Germantown, Maryland Phone: (301)353-3792
Concept:	This process employs a rapid non-catalytic coal hydrogenation technique, termed flash hydropyrolysis, in an entrained flow reactor to accomplish the coal/hydrogen reaction.
Description:	Pulverized coal and oxygen are fed to the reactor and entrained rapidly with 2000°F hydrogen using a rocket engine injector element. The reactants react for about 10-100 milliseconds. The reactor effluent is quenched, utilizing a set of water spray nozzles or a heat exchanger, or both and the liquids are condensed.
Operating Conditions:	Temperature: 1800°F Pressure: 1000 psi
Reactants:	Coal, hydrogen, oxygen
Products:	SNG/Benzene
Status:	The process has been tested in a 3/4 TPH short run PDU to develop the reactor. An 18 TPD continuous unit is underway to optimize the process. Startup may occur in 1982.

FIGURE 2.7 CS/R HYDROPYROLYSIS PROJECT DATA

SRS

Process Developer:	Energy Systems Group, Rockwell International
Scale:	PDU
Location:	Santa Susana, California
Funding:	FY80 ~ $1,800,000 FY81 ~ $3,900,000
Sponsor:	DOE
DOE Program Manager:	Ray Hsia; DOE Headquarters Germantown, Maryland Phone: (301)353-4119
Concept:	Low or Medium Btu gas is produced from reaction of air or oxygen plus steam with coal in a molten bath of sodium salts which results in high reaction rates in the pressurized gasifier with ash and sulfur being trapped in the ash melt.
Description:	Crushed coal, sodium carbonate and air or oxygen are fed to the reactor where product gas is produced and sent to a cooling and particulate removal step. Ash and sulfur are retained in the molten bath and must be continuously withdrawn and treated to regenerate the salt for return to the gasifier. The ash is removed and the sulfur is recovered in a Claus plant. After particulate removal the gas from the gasifier can be used as low or medium Btu fuel or upgraded to methanol or SNG.
Operating Conditions:	Temperature: $1800^{o}F$ Pressure: Atmospheric to 400 psi
Reactants:	Coal, Sodium Carbonate, air (or oxygen plus steam)
Products:	Low or medium Btu gas, sulfur
Status:	During 1980 and 1981 the 24 TPD PDU was operated successfully with air blown operation. Plans for the process includes operating the PDU in 1982 using oxygen to produce a medium Btu fuel/synthesis gas. Evaluation of the process for commercialization should come in 1982.

FIGURE 2.8 MOLTEN SALT PROJECT DATA

SRS

Process Developer:	Thagard Research Corporation
Scale:	Approximately 5.0 TPD PDU
Location:	Irvine, California / South Gate, California
Funding:	No Government funding
Sponsor:	Thagard Research / Southern California Edison
Concept:	The Thagard reactor is a high temperature fluid wall reactor that utilizes a method of energy transfer to the reactants that occurs from the heating of finely-divided reactants by the direct impingement of electromagnetic radiation.
Description:	The Thagard reactor consists of a water cooled jacket (pressure vessel) around an insulated shield that houses the radiation heat shield. Inside this radiation heat shield are electrodes that provide make up radiant heat to the reaction chamber which has a tubular core of porous refractory material capable of emitting sufficient radiant energy to activate the reactants fed axially into the tubular space. A gas which is transparent to the radiation passes through the porous core to line the core as a buffer between reactants and core wall.
Operating Conditions:	Temperature: 4000°F Pressure: Reactor operates from atm. to 20 atm. pressure
Reactants:	Coal (or lignite, peat, RDF, residual oils, etc.), oxygen (or air), water (or steam)
Products:	Syngas (products can vary widely depending on reactants)
Status:	Process has been well tested on the present scale for short duration. 200 TPD carbon black product facility is due for start up in 1981. DOE funding being sought for further testing at the 5.0 TPD operating facility in South Gate, California. Process is not well known because of limited information (other than issued U.S. and foreign patents) put in the public domain during the development and testing of the process.

FIGURE 2.9 THAGARD GASIFICATION PROJECT DATA

SRS

Interstate Brick Company and Mountain Fuel Resources are subsidiaries of Mountain Fuel Supply Company. The early development work for this process was done at Eyring Research in Provo, Utah, under contract from the Office of Coal Research beginning in 1974. Process design studies have been done for a 600 TPD commercial unit. The Mountain Fuel process has been identified by the Rockwell Energy Systems Group as a prime candidate to provide hydrogen for the CS/R Hydropyrolysis process because of Mountain Fuel's potential for feeding char and/or coal in a dense dry feed. Summary project data is shown in Figure 2.10.

2.2 SYSTEMS/EQUIPMENT DESCRIPTIONS

The following discussion describes each of the process configurations by system elements and major equipment items and components. The following generic systems are common to most of the processes:

- Coal Pretreatment
- Reactor
- Waste Product/Impurity Removal
- Raw and Treated Water
- Effluent Treatment
- Steam, Oxidant, & Electric Utilities.

The systems/equipment descriptions for each of the processes studied are listed for the Pilot/PDU scale plants and for commercial plants if commercial designs were available.

2.2.1 BELL HIGH MASS FLUX

The major elements of the Bell HMF PDU are the coal feed system (which could be described as a part of the reactor system), the reactor, and the gas cleanup system. Bell is also testing a secondary coal feed system which would be a part of the reactor/coal feed system.

Lignite or bituminous coal is pulverized to specification (70% through a 200 mesh sieve) off-site and sent to the plant in bags packaged in 55 gallon drums. The feed coal has an average moisture content of 7%. The coal is pressurized in a load tank and fed through a transfer line to a coal feed tank. Integral to the feed tank is a weigh system for coal flow rate measurement. Most equipment elements with the exeption of the coal feed tanks are constructed of stainless steel.

The reactor is of columnar design (typical of most advanced entrained processes) and is lined with an alumna-chrome ceramic. Three basic injector

Process Developer:	Mountain Fuel Resources / Ford, Bacon and Davis
Scale:	30 TPD PDU
Location:	Salt Lake City, Utah
Funding:	$6,000,000
Sponsor:	DOE is sponsoring 80% of PDU program cost
DOE Program Manager:	Earl Easton & Louis Jablansky Phone: (301)353-3792 DOE Headquarters, Germantown, Maryland
Concept:	This process features a pressurized, high rate, entrained flow, oxygen blown gasifier which operates at ash slagging temperatures (2800°F). Heat recovery is accomplished with both radiant and convective heat exchangers.
Description:	Pulverized coal is entrained in a stream of recycled product gas and fed to the top of the gasifier. The reaction products pass through a radiant heat exchanger directly below the reactor (slag is accumulated in a chamber at bottom of the heat exchanger). The partially cooled gases, entrained soot and fly ash pass through the convective heat exchanger and into a scrubber for particulate removal. The product gas is then filtered, cooled and after sulfur removal, the medium Btu gas is suitable for boiler fuel or synthesis gas.
Operating Conditions:	Temperature: 2800°F Pressure: 300 psig
Reactants:	Coal, oxygen, steam, recycle gas
Products:	Medium Btu gas or synthesis gas
Status:	DOE contract signed April 14, 1981 for the 30 TPD PDU program. Engineering has been largely completed on Mountain Fuel funds. Product gas from the PDU will be used to fire brick kilns at the Interstate Brick Company near Salt Lake City.

FIGURE 2.10 MOUNTAIN FUEL PROJECT DATA

designs drawn from rocket engine technology have been tested at this facility; a centerline coal injector with tangential air feed against the rotational flow in the chamber; a similar configuration with air feed in the flow direction; and a ring type coal injector with axial air feed. Bolted construction design was used where possible. Pressure is maintained at 200 psig and temperature at 2300-2900°F during runs. The solid grain starter for the reactor is identical to the one used to start the Bell Agena rocket engine.

Slag and some char are removed from the quenching tank at the bottom of the reactor and weighed. Gaseous products flow downstream from the reactor to a cyclone unit where more slag and char impurities are removed. Chemical and weight measurements are made there and further downstream in the condensing unit. Finally, fly ash, water, and product gas are the output of the demister and scrubber. The equipment used in the cleanup systems is nearly all available off-the-shelf.

The major systems/equipment in the Bell Test Facility are:

- Coal Load Tank
- Coal Feed Tank
- Weighing System
- Coal Injector System
- Gasifier
- Slag Removal
- Air Compressor } Air-blown mode
- Air Storage } Air-blown mode
- Heaters
- Solids Removal (condensables extraction, cyclone, demister, scrubber).

2.2.2 BIGAS

The Bigas plant was the largest plant that was visited and the process is the most tested of the processes studied. It is a fully integrated plant which converts 120 TPD of coal to SNG. The main elements of the facility are coal preparation, drying and feeding, a two stage entrained flow high pressure slagging gasifier and gas treatment facilities.

The coal preparation consists of equipment and components that have been used in other coal handling and preparation systems. The main elements of the coal receiving/handling are as follows:

- Dump Hopper
- Vibrating Feeder
- Belt Conveyor System
- Dust Suppression System
- Tramp Iron Magnet
- Sample Cutter
- Coal Bin with Filter, Fan and Actuator
- Flux Bin with Filter, Fan and Actuator
- Slide Gate
- Diverter Valves
- Flux Feeder, Classifier, Grinding Mill, Cyclones
- Curtain Airlock
- Pulverized Flux Bin with Filter, Fan & Actuator, Slide Gate, Feeder, Diverter Valve
- Slurry Blend Tank
- Slurry Drain Sump Pump
- Bucket Elevator (from coal bin)
- Trickle Valve
- Cage Mill
- Airlock
- Coal Cyclone
- Cyclone Overflow Tank
- Grinding Mill
- Cyclone Feed Pump
- Pump Boxes
- Pulp Tank with Agitator
- Sludge Water Tank
- Wet Scrubber
- Thickener Feed Tank
- Thickener Tank with Thickener Mechanism
- Thickener Overflow Pump
- Centrifuge and Feed Tank
- Repulp Tank
- Centrate Pump
- Pulp Storage Tank
- Slurry Transfer Pumps.

The coal is slurried in the coal receiving/handling system and is dried after being brought to the desired pressure. The Slurry Feed Drying section includes the following equipment/components:

- Blend Tank Mixer
- Slurry Blend Tank
- Slurry Circulating Pumps
- Slurry Feed Pumps
- Slurry Preheater
- Spray Dryer
- Water Degassing Tank
- Slurry Discharge Pumps
- Slurry Washer Bottoms Collar
- Recycle Gas Washer
- Washer Water Cooler
- Washer Recycle Pumps
- Compression Suction K.O. Drum
- Recycle Gas Compressor
- Compressor Discharge K.O. Drum
- Recycle Gas Heater.

The dried pressurized coal is sent to the gasifier system which consists of the major elements indicated below:

- Coal Cyclone Vessel
- Coal Cyclone
- Coal Eductors
- Float Slag Lock-Hopper
- Gasifier
- Gasifier Quench Section
- Slag Outlet Lock-Hoppers
- Slag Slurry Cooler
- Slag Slurry Pumps
- Slag Outlet Filters
- Char Eductors
- Char Feed Vessel
- Char Cyclones
- Gasifier Cooling Water Sludge Drum
- Gasifier Cooling Pumps
- Raw Gas Water Cooler
- Gasifier Cooler
- Gas Washer
- Gas Washer Bottoms Strainer
- Gas Washer Recycle Cooler
- Gas Washer Reflux Pumps
- Caustic Metering Pump
- Gas Washer Bottoms Cooler
- Atmospheric Vent Gas Washer
- Atmospheric Washer Reflux Cooler
- Atmospheric Washer Reflux Pumps.

This equipment includes several items that could be considered a part of the gas washer section if a separate section is so specified.

The following equipment and components are a part of the gas clean-up system of the plant:

- Alumina Filters
- CO Shift Feed Heater
- CO Shift Reactor
- Sulfur Conversion Reactor
- Combined Effluent Cooler
- Combined Effluent Trim Cooler
- Combined Effluent K.O. Drum
- H_2S Absorber
- H_2S Solvent Cooler
- Solvent Interchanger
- H_2S Solvent Pumps
- H_2S Stripper Reboiler
- L.P. Flash Tank
- H_2S Stripper
- Flash Tank
- H_2S Stripper Water Return Pumps
- H_2S Stripper Overhead Condenser
- Acid Gas in Line Separator
- H_2S Recycle Compressor Package
- Methanator Gas Exchanger
- Methanator Gas In-Line Separator
- 2nd Stage CO_2 Absorber
- CO_2 Rich Liquid Pumps
- 1st Stage CO_2 Absorber
- CO_2 Trim Cooler
- CO_2 Solvent Pumps
- CO_2 Stripper
- CO_2 Flash Tank
- Stripping Air Cooler
- CO_2 Stripper Air Blowers
- CO_2 Recycle Compressor (package)
- Product Gas Heater.

There are several major sources of effluent that require treatment:

- Cooling Tower
- Demineralizer
- Seal Flush
- Steam Boilers
- Coal Handling
- Sanitary Waste.

The effluent is stored in a holding pond and sent to the Indiana, Pennsylvania Sewage Treatment facility for final treatment.

The systems and equipment that have been listed for the Bigas pilot plant are similar to what would be required for a commercial facility except for scale.

2.2.3 CS/R HYDROPYROLYSIS

The 3/4 TPD plant consists of three major elements: coal feed, reactor, and gas clean-up. Hydrogen is not produced at the plant site and a steam/oxygen gasifier would probably be used to produce hydrogen for a scaled-up plant. Rockwell has also operated a 1 TPH test facility for the optimization of the hydroliquefaction process. The major equipment/components for the CS/R Hydropyrolysis test facility includes:

- Coal loading/feeding
- Dust removal
- Coal feeder/injector system
- H_2 Storage
- Char/vapor separator
- Solids separation (cyclone)
- Pressure letdown
- Condensor

- H_2 Heater
- Preburner
- Reactor
- Water Storage
- Quench (part of gasifier structure)
- Condensor/condensate receiver
- Absorber
- Decantation
- Scrubber
- Gas Sampling
- Flare.

A typical CS/R Hydropyrolysis commercial plant could be designed to produce SNG at 1000 psig or a combination of gas and liquids and would consist of two major subsystems: a direct hydropyrolysis system, and a steam/oxygen gasification system to produce the make-up hydrogen requirement from coal and/or char. The ancillary equipment would be similar to that required by other entrained flow gasifier coal conversion plants.

2.2.4 ROCKWELL MOLTEN SALT

The Rockwell Molten Salt facility includes a 1 TPD PDU and an adjacent 34 inch I.D. test unit for related testing and the associated monitoring equipment. The Molten Salt PDU consists of the following systems:

- Air supply
- Coal feed
- Sodium carbonate feed
- Gasifier
- Quench and ash removal
- Sodium carbonate regeneration
- Particulate removal
- Sulfur removal.

A commercial scale facility would contain much of the usual ancillary equipment/components associated with other processes but would differ mainly in the areas of carbonate supply, feed, and regeneration, and gasification and melt quenching. The 1 TPH PDU located at Santa Susana, California is an integrated facility that contains many of the equipment items that would be required in a commercial scale facility except that the PDU equipment is smaller scale. The major equipment/components contained in the PDU is indicated below:

- Skiploader (coal)
- Conveyor
- Coal mill
- Coal separator
- Coal silo (with filter and vacuum blower)
- Carbonate truck unloader
- Carbonate separator
- Carbonate silo (with filter and vacuum blower)
- Weigh belt feeders
- Spray cooler (product gas)
- Off gas analysis equipment
- Product gas combustor
- Cyclone (product from quench tank)
- Flash tank
- Precarbonator
- Clarifier
- Filter (for ash removal)
- Green liquor storage tank
- Stripper
- Steam boiler.

- Blender/transporter (coal, carbonate, N_2, air)
- Feed hoppers
- Preheat burner (air)
- Gasifier
- Melt withdrawal
- Quench tank
- H_2S Incinerator
- Spray Dryer (for SO_2 absorption)
- Baghouse
- Carbonator
- Calciner
- Centrifuge
- Recycle liquor storage tank.

2.2.5 THAGARD

Test facilities for the Thagard process include a small test facility at the Irvine, California office and a pilot facility at South Gate, California. The large reactor, with a 6 inch inner core diameter and 6 foot total length, is located in South Gate, California. Dedicated utilities are installed including an 1800 KVA substation and self-contained coolant systems. Feed handling equipment is available to introduce solid, liquid or gaseous reactants into the reactor. In addition, an automated data acquisition and processing system continuously monitors the process.

The reactor consists of a porous graphite core 1/2 inch thick. Three carbon cloth electrodes are spaced around the core circumference and run the length of the core. A carbon nozzle shroud is used inside the core when atomized liquid reactants are being handled to minimize erosion of the core wall by direct impact of liquid droplets. This requirement is eliminated in larger diameter devices where the core radius is larger than the mean free path of high velocity atomized particles (typically 4½ feet diameter for 100 μ particles injected at sonic velocity). The core and electrodes are insulated within the reactor jacket by a radiation shield made of multiple layers of Grafoil. The reactor exhaust is equipped with a water-jacketed single-pass heat exchanger. After cooling, the reaction products enter a rectangular collection tank with an adjustable baffle to allow removal of granular and particulate products during operation. The gaseous exhaust is continuously analyzed with on-line stream analyzers. Bomb sampling points are available for trace component analyses.

The Irvine facility is designed around a High Temperature Fluid Wall (HTFW) reactor with 3 inch inner core diameter and 2 foot length. The power source for this system is a 400 KVA 3ϕ AC power supply. All coolant requirements are supplied from a closed-loop system. This system has the same feed handling capabilities for gaseous and solid feeds as the South Gate facility.

Data acquisition and processing is also available but the system is not as sophisticated as that used at the South Gate facility. The reactor core is porous carbon, with porous carbon electrodes, and a zirconia core is also available for special applications. The 3 inch reactor is also insulated with a multi-layer Grafoil jacket and equipped with a glycol-jacketed exhaust cooler. Equipment for continuous and bomb sampling has been installed, including an on-line gas chromatograph.

2.2.6 MOUNTAIN FUEL

The Mountain Fuel process was tested initially in a bench scale unit located at Eyring Research in Provo, Utah. The test facility consists of the following equipment/components:

- Coal lock hopper
- Coal feed hopper
- Gasification reactor
- Radiant heat exchanger
- Slag lock hopper
- Convective heat exchanger
- Scrubber
- Fabric filters
- Recycle compressor.

When this facility was visited in January, 1981, the test reactor had been replaced by one being utilized by Eyring for testing sponsored by Amoco Oil Company. The non-reactor equipment was similar to what was used for the Mountain Fuel testing. The 0.5 TPD capacity reactor, with 3 inch I.D. and 11 inch length, is encased in a 10 inch diameter carbon steel pressure shell. The reaction chamber is refractory lined.

A 30 TPD PDU will be constructed at the Interstate Brick Company at Salt Lake City, Utah. The main elements of this plant will include:

- Coal lock hopper
- Coal feed hopper
- Gasifier
- Radiant boiler
- Slag delumper
- Slag lock hopper
- Convective boiler
- Water preheater
- Venturi scrubber
- Glycol dryer
- Recycle compressor.

Process design studies have been performed for a 600 TPD reactor facility.

3.0 PLANT DESIGN CHARACTERISTICS

The design characteristics of the selected Pilot/PDU plants were analyzed utilizing unrestricted data and proprietary information. The information presented here is unrestricted and does not contain proprietary data. Each plant's design requirements and rationale were analyzed including operating conditions, redundancy, sparing, feedstocks, products, instrumentation and controls, and support facilities.

The chemical or physical phenomena exploited by each of the processes are different. The Bell Aerospace HMF Gasifier, the Mountain Fuel, and the CS/R Hydropyrolysis Reactors utilize rapid mixing injectors to achieve compact reactor sizes. The Bell Aerospace Gasifier, the Bigas Gasifier, and the CS/R Hydropyrolysis Reactors exploit the well known phenomenon that freshly devolatilized coal is extremely reactive and undergoes very rapid reactions with hot hydrogen and steam. The Thagard HTFW Reactor seeks to achieve coal pyrolysis at extremely high rates of heating ($>10^7$ °F/sec) to produce a gas which does not require cleaning to remove potential pollutants. The Bigas Process and the Bell Aerospace Process with secondary coal injection utilize the hot synthesis gas produced by the partial combustion as the source of heat as well as hydrogen for the hydrogenation reactions. The RI Molten Salt Gasifier uses carbonate to remove sulfur from the gas being generated. The Thagard HTFW reactor produces essentially sulfur free gas through the addition of calcium compounds (principally hydrated lime and/or limestone) to react the sulfur to CaS, which is stable under the gasification conditions. If desired, a silicate phase (generally supplied by the ash in the coal) will dissolve the CaS to form a non-leachable slag in the form of free flowing granular beads.

Evaluation of the conversion efficiencies of the processes was made based on information provided by the process developers. A more extensive evaluation of these efficiencies should be made in order to make a comprehensive comparison.

3.1 OPERATING CONDITIONS AND CHARACTERISTICS

Most advanced processes operate at relatively extreme conditions (temperature greater than 1500°F and pressure above 500 psig); however, of the processes studied, only Bigas and CS/R operated at relatively elevated pressures. Bigas operates at 750 psig and will eventually operate at 1150 psig. The CS/R process operates at about 1000 psig. Figure 3.1 is a list of the critical operating conditions and characteristics for the processes. Much of the data shown was developed from information provided by the process developers. Some of the information needed to establish certain operating conditions was not available but should be developed in the future as additional testing and design is accomplished.

3.2 DESIGN PHILOSOPHY, REQUIREMENTS, AND SPECIFICATIONS

The design philosophy for a Pilot/PDU scale plant is basically the development or verification of the reactor concept. The primary systems are the coal feed, reactor, and the minimum necessary slag/ash removel, gas clean-up, and waste treatment for the operation of the reactor. Redundancy or multi-stream design is used only when necessary to allow the plant to operate through the required test duration. Where the intent of the Pilot/PDU plant is to maintain several days continuous operation, redundant streams and the necessary equipment and component spares for replacement must be provided. Most of the processes studied did not have extensive redundant systems because the plants were not designed for extended periods of continuous operation.

The Bigas plant was the most integrated plant that was studied. The redundancy and sparing philosophy for the Bigas plant demonstrates the philosophy that would generally be required for scale-up of other processes. Examples of sparing provided for the Bigas operation include:

- Parallel slurry pumps
- Parallel slurry transfer pumps
- Slag lock hoppers
- Alumina filters
- Shell and tube heat exchangers.

There are several override and by-pass systems in the pilot plant. The requirements for redundancy, sparing, by-pass and override systems in a commercial scale plant for all the processes that were studied appears to be extensive because of the harsh operating environments. The processes that produce a gas or liquid low in sulfur or low in particulate matter content may prove to require less redundant systems than the first and, more developed, second generation processes. The Thagard process, as an example, claims to produce little or no contaminants from the reaction section of the process.

The design specifications and requirements were identified for each process and are summarized below. These specifications and requirements include the feed-

	BELL	BIGAS	CS/R*	MOLTEN SALT	THAGARD	MOUNTAIN FUEL
COAL TYPES	All	All	All	All	All	All
PRETREATMENT	No	No	No	No	No	No
CATALYST REQUIRED	No	No	No	Yes	No	No
FEED RATE	12 TPD	120 TPD	18 TPD**	24 TPD**	5.0 TPD	30 TPD
TEMPERATURE (°F)	2500°	3000°	1800°	1800°	4000°	2850°
PRESSURE (psig)	220	500-1500	1000	15-440	0-50	300
CARBON CONVERSION	90-95%	-	97%	98%	90-95%	94-95%
EFFICIENCY (Cold Gas)	74-83%	69%	64%	78%	85%	73-78%
O_2(or air)/COAL RATIO	0.75	0.5	0.2	0.7	0-.9	0.75
H_2O/COAL RATIO	0.2	0.4	H_2/Coal 0.4	0.5	0-1.1	0.2
CARBON RECYCLE	None in PDU	Yes	No	No	No	No
CATALYST RECOVERY	No	No	No	Yes	No	No
SOLIDS RECOVERY	Yes	Yes	Yes	Yes	Yes	Yes
BY-PRODUCT RECYCLE	No	Yes	Yes	Yes	No	No
COAL SIZE REQUIRED	70% -200 Mesh	-100 Mesh	70% -200 Mesh	-8 Mesh	-100 Mesh	70% -200 Mesh
TURN DOWN (%)	-	40-60	-	High	†	-
NUMBER OF STAGES	1	2	1	1	1	1
THROUGHPUT RATE Lbs/Hr/Sq.Ft.	15,000	3,800	14,000	210	N/A ††	850
REACTION TIME	0.3 Sec.	-	0.03-1.5	-	Millisec.	-

* SNG Mode.

** Feed Rate of PDU.

† Process efficiency is constant from zero throughput to maximum design capacity.

†† Throughput rate is a complex function of gas velocities, feed compositions and form, etc.

FIGURE 3.1 OPERATING CONDITIONS AND CHARACTERISTICS stocks and products, the processing sequence and the capacities of each unit, alternate processing configurations (if any), instrumentation and controls, and unusual support facilities and utility requirements.

The Bell HMF process utilizes pulverized coal and oxygen or air to produce medium or low Btu gas respectively. The air blown version of the Bell High Mass Flux Gasifier may be classified as a pressurized, single stage, entrained flow, slagging gasifier. It shares the advantages commonly ascribed to other entrained flow gasifiers in terms of its simplicity, lack of moving parts, rapid dynamic response, capability to handle a wide range of coals and no by-product tar formation. It is distinguished by its small size, high mass throughput per unit of reactor volume and short reactant residence time.

The concept of the high mass flux gasifier relies on the attainment of primary oxidation which may be designated as pyro or "flash" oxidation. In the process of pyrolysis, short-lived active sites are formed on the small carbon crystallites, located at the edges of the basal planes. These are very reactive to oxygen as well as steam, CO_2 and hydrogen. In heterogeneous reactions, it is desired to maximize the utilization of these active sites. This can be done by making the ratio of resistances of chemical rate of gasification to mass transport rate very high for each coal particle in order that all active sites are "bathed" in nearly the same concentration of oxygen as that which exists in the main gas stream outside of the particle boundary layer. The practical means of achieving this is to inject the coal as small (70%-200 mesh sieve) and uniformly distributed particles into a highly intense gaseous mixing field to provide high particle heating rates and temperature levels. These considerations have served as the model for deriving hardware designs to attain high carbon conversions in superficial residence times of less than 200 milliseconds.

The test facility for the Bell HMF Gasifier was designed specifically to evaluate and characterize the gasifier and obviously is not trying to represent a commercial application; however, the design of the plant does simulate (as near as possible) commercial conditions. An example of this for the air blown version is in the heating of the reactor air inlet to a nominal 600°F to simulate the commercial conditions of an in-line air compressor.

The facility is designed to provide the capability for a testing duration of one hour. Tests have been run on several feedstocks including lignite, subbituminous and less reactive Pittsburgh seam bituminous coal. The main product slate for the process is low Btu gas, medium Btu synthesis gas (without secondary coal feed) or methane enriched product gas (with secondary coal feed).

The nominal feed capacity of the plant is 0.5 TPH for one hour duration. Some of the test equipment such as air feed and coal feed systems could process a slightly larger quantity of coal but other systems tend to limit the capacity. Bell indicated that the present test reactor could process several times more coal with no more than minor changes in the reactor. Figure 3.2 shows a diagram of the 0.5 TPH test facility. A simplified flow diagram of the process used in an industrial fuel gas application is shown in Figure 3.3.

In the test facility the gasification process is initiated by temperature and pressure generated by the combustion of two solid propellant charges. The solid charges are identical to the initiator used to start the Bell Agena rocket engine and is comprised of an initiation squib and a 1.3 pound main solid grain. During the 3.0 seconds that the grains burn, coal and air or oxygen are admitted to the reactor in a controlled sequence and the gasification process is established. Throughout a test, critical reactor and test facility parameters are recorded on strip recorders to facilitate real time monitoring and control. In addition, these measurements and other supporting parameters are recorded on a high speed Beckman digital data acquisition system. Post test, the digital tape is computer processed and a printout of reduced data is available within a few hours of test completion. During a test, air or oxygen flow rate to the reactor is computed from pressure and temperature measurements taken upstream of a calibrated sonic orifice and the coal flow rate is obtained from the coal feed tank weigh system readout. Air/coal mixture ratios are computed and flow rate adjustments are made if required to achieve the desired mixture ratio. Reactor gas samples are taken via water cooled sample probes at selected times. Post test gas samples are analyzed using a gas chromatograph to obtain gas composition. Gas composition is used to compute gas heating value. Solids and liquids collected in the slag tank, char tank, condenser, and demister are weighed and analyzed. Product gas flow rate is measured at a sonic orifice upstream of the scrubber and gas composition at this point is determined by an on-line mass spectrometer. These data, together with reactor feed rate data, are used to establish a material balance and conduct performance analyses.

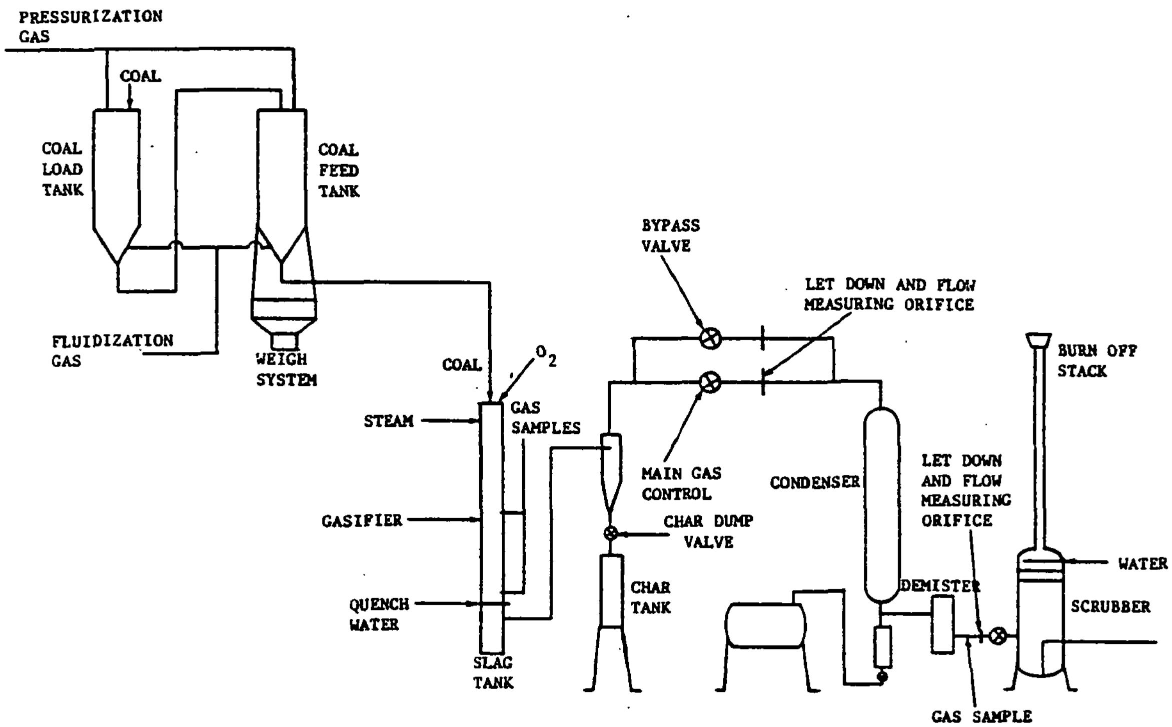

FIGURE 3.2 BELL HMF TEST FACILITY

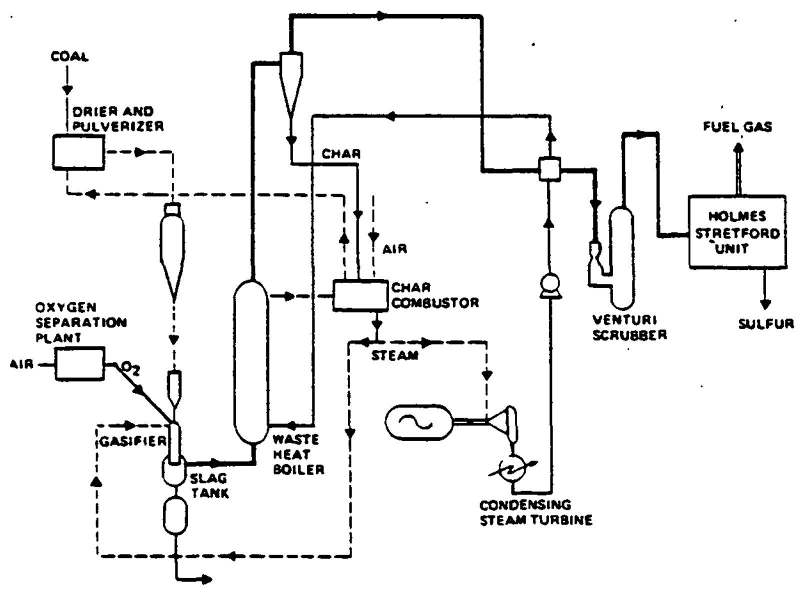

FIGURE 3.3 INDUSTRIAL FUEL GAS APPLICATION

The Bigas Pilot Plant is a grass-roots facility designed to convert up to 5 TPH of coal into high Btu pipeline quality gas. A principal feature of the plant is a two-stage, entrained flow, high pressure, oxygen-blown, and ash slagging gasifier unit. This unit was scaled up from a PDU scale facility and tested by Bituminous Coal Research, Inc. (BCR). The pilot plant, which has been operated since December 1976, is currently solely funded by the U.S. Department of Energy.

The coal prep and feed system is designed to slurry the coal with water and then spray dry the slurry after it has been raised (pumped) to a pressure (765 psia) slightly greater than that of the gasifier. The coal conveyor system could handle about twice the capacity of the plant. The process should handle any coal feedstocks. The basic product of the gasifier is medium Btu gas which is upgraded to high Btu by methanation. A general schematic of the Bigas Pilot plant is shown in Figure 3.4.

Stage II (upper section of the gasifier) is fed with dry pulverized coal through two coal nozzles (the nozzles are opposite one another) using recycle gas as a motivating fluid. A Fisher Vee-ball control valve, operated from the control room regulates the flow of solids through the eductor.

The eductor merely "pumps" the coal through a nozzle tilted upward 30° from horizontal into the gasifier. An outer annulus on the nozzle feeds steam for reaction and temperature control purposes. Since the coal/steam, coal/hydrogen reaction is endothermic, steam flow to Stage II is reduced (via a temperature controller) as coal flow is increased.

Coal feed is detected through a variety of instrumentation. Three differential pressure instruments serve to detect the presence of solids feed or the lack of it. A coal leg thermocouple, located in the line immediately above the eductor, senses the inside line temperature. The coal vessel nuclear level detector shows changes in the coal vessel level.

Typical responses of instruments to initiation of coal feed are as follows: reduction of the coal leg and eductor differential pressure (dP); increase of the nozzle dP; increase of the coal leg temperature as a result of "hot" coal flowing through the leg (several purge gas taps connect to the coal leg for expansion joint purging and dP instrument purges which cool the line when coal is not flowing); approximately 10% reduction in the purge gas flow to the coal

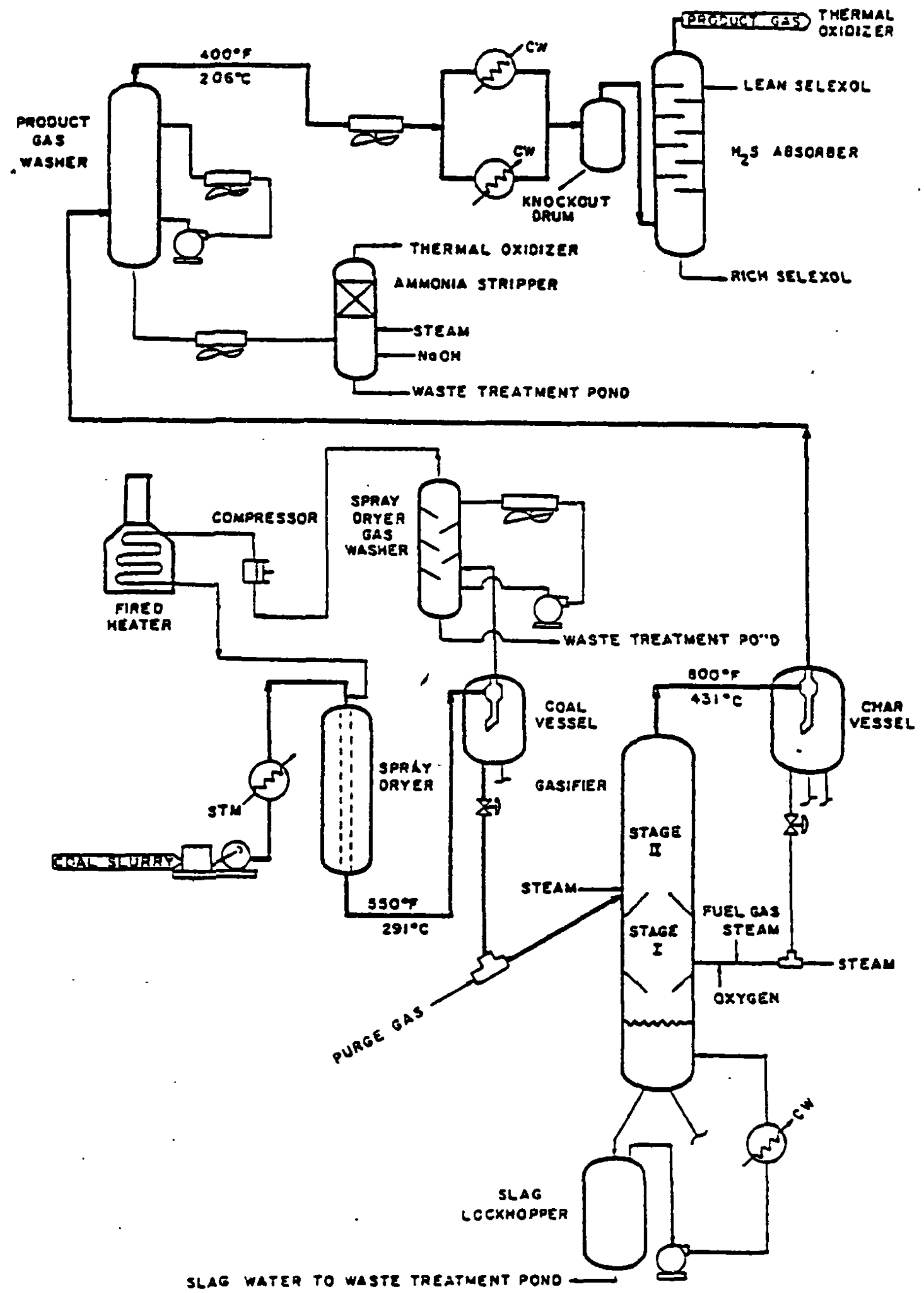

FIGURE 3.4 BIGAS PILOT PLANT SCHEMATIC

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eductors caused by the eductor loading being increased; and reduction in the amount of steam being fed Stage II. The above instrumentation is used primarily as a flow/no flow indication. The mass coal rate to the gasifier is calculated by making a material balance calculation around the spray drying section of the plant.

Stage I of the gasifier is fed with char through three nozzles (120° apart) utilizing an eductor and steam as the motivating fluid. Each char burner is in a horizontal position and has several annuluses as follows: center tube for char, motive steam, and purge gas from instrument taps in the leg; first annulus for supplemental fuel gas and additional reaction steam; second annulus for oxygen; and the third annulus for cooling water to protect the char burner tip.

Major instrumentation for detection of char feed is presented below. Differential pressure taps measure and record the following dP's: top of char vessel to the top of the Vee-ball valve; top of the Vee-ball valve to the eductor suction; eductor suction to the char burner inlet; and char burner inlet to the gasifier. The Argonne acoustic flow monitor is located downstream of the eductor and has been shown to give a char flow/no flow indication. Thermocouples are located in the top and bottom of the vertical section of the char leg. As in the coal system, the thermocouples respond to the "warming" of the leg with improved feed. The char vessel nuclear level indicator and leg density indicator provide similar information to those instruments located in the coal leg.

Char feed is manually controlled through adjustment of the Vee-ball valve to maintain a stable level of char in the char vessel. The oxygen flow (on automatic flow control) is adjusted to 2700°F to 2800°F. Motive and process steam and fuel gas flows are held constant.

Slag is removed from the gasifier through a 4 inch hole in the bottom of the vessel. The tap hole is monitored with a TV camera. The slag tap hole is kept open by a burner under the tap hole pointed upward and maintains the temperature sufficiently high to prevent plugging. A water cooled mechanical arm also operates underneath the slag tap hole to break off stalactites that may form.

Synthetic product gas leaves the char cyclone vessel and undergoes a two step cooling process. The gas is contacted initially with water in the product gas washer and cooled to 350°F. It is then cooled to approximately 80°F, with both water and naphthalene being knocked out, and fed to the H_2S absorber where the stream is countercurrently contacted in the Selexol unit for H_2S removal. The H_2S is then fed to the thermal oxidizer for disposal. If desired, the product gas can be sent through the methanation and CO_2 absorption sections which are available.

The synthetic product gas is cooled to approximately 80°F and sent through a vessel where the water particles are disentrained. An aerial cooler in series with two shell and tube heat exchangers (in parallel with each other) - serves to cool the gas. Each of the shell and tube units, cooled with plant cooling water, condense any naphthalene material in the gas. An excessive pressure drop in each unit (20 to 30 psi) indicates the need to place the parallel unit in service and steam clean the "dirty" exchanger. Steam is fed to both the shell and tube side of the unit which melts and vaporizes the naphthalene. The naphthalene is then sent to the thermal oxidizer. Alternation of the use of these exchangers provides for removal of the naphthalene formed with a minimum of naphthalene being fed to the Selexol H_2S removal unit. Operating history has shown that the need to cycle exchangers occurs once every 24 to 48 hours of operation.

The H_2S absorption system typically reduces the H_2S concentration of the product gas from 1500 to 2000 ppm to less than 1 ppm.

The Cities Service/Rockwell (CS/R) flash hydropyrolysis process features a vertical down flow entrained bed reactor designed to promote the direct hydrogenation of coal with hot hydrogen. A schematic diagram of the process is shown in Figure 3.5. Essentially the same reactor is used for conversion of coal to either liquid (hydroliquefaction) or to gaseous (hydrogasification) hydrocarbon products.

Feedstocks to the reactor are dried pulverized coal and hot hydrogen. The hot hydrogen stream provides the sensible heat needed to raise the mixed reactant temperature to about 1,400°F or higher to initiate the reaction. The overall reaction is exothermic for both the hydrogasification and hydroliquefaction modes of operation. Once initiated, the reaction is self-sustaining.

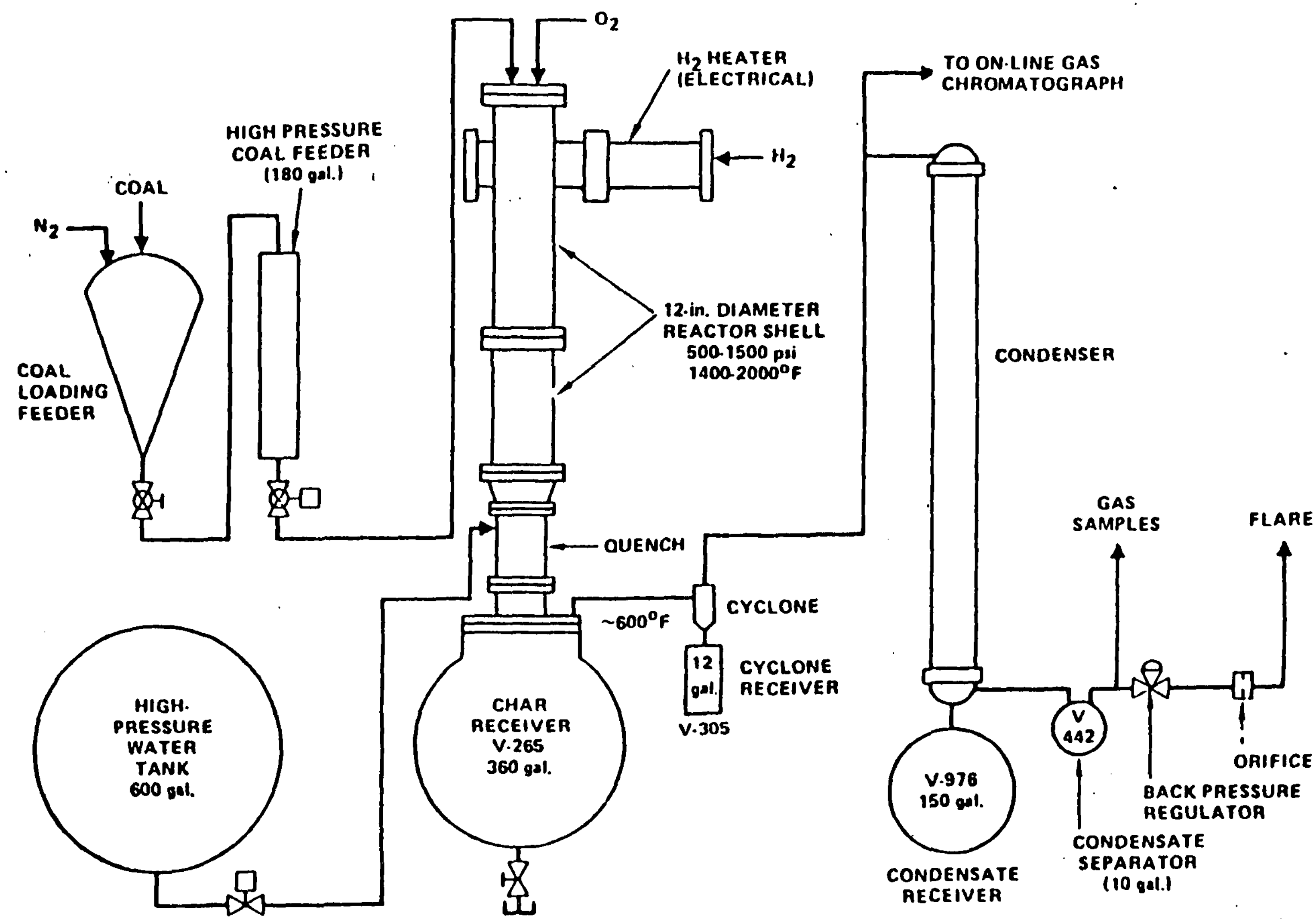

FIGURE 3.5 CS/R HYDROPYROLYSIS 3/4 TPD TEST FACILITY

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The temperature of the hot hydrogen feed is substantially higher than that of the mixed reactant temperature. For a commercial plant, RI envisions the use of conventional heat exchangers to preheat the stream to 1500°F with additional preheat supplied by burning a portion of the feed gas with oxygen.

The dried pulverized coal feed is delivered to the reactor using a dense phase transport technique which RI has developed specifically for the hydropyrolysis project. This technique involves the use of a pressurized feeder vessel where the feed coal is stored. The vessel is pressurized with an inert gas at a pressure which is higher than that of the reactor. The actual pressure difference between the feeder vessel and the reactor used by RI in its pilot facilities is about 100 psi. This pressure difference forces the dried pulverized coal from the conical shaped bottom of the feeder vessel into the feed line to the reactor. The pulverized coal moves along the feed line as a dense phase plug at a velocity of about 15 fps. A small amount of the pressurizing gas represented by the gas occupying the interstitial spaces between the coal particles is fed into the reactor along with the coal. Typically, this interstitial gas may amount to a few percent by weight of the coal fed.

The pulverized coal feed used is ground to 70% less than 200 mesh and dried. Although the dense-phase transport technique can be used for coals containing a certain amount of moisture, the CS/R hydropyrolysis process favors the use of a dry coal feed. Using a dry coal feed reduces the amount of heat which the hydrogen stream needs to supply to vaporize the moisture.

A major feature of the CS/R Hydropyrolysis reactor is the use of special feed injectors to achieve rapid and thorough mixing of the pulverized coal and the hot hydrogen in the reactor. The design of these injectors is based on techniques used in rocket engine combustors. The reactor achieves rapid devolatilization of the coal particles through almost simultaneous reaction of the freshly devolatilized char and coal fragmentation products with hot hydrogen. A high hydrogen concentration is achieved in the reactor due to the high reactivity of freshly devolatilized char and coal fragmentation products. As a result, very short residence times are involved. Commercial reactors for hydroliquefaction may run with residence times in the range of 30 to 120 msec while hydrogasification may run in the 0.5 to 2.0 sec range. It appears also that the intense mixing causes the particles to devolatilize before there is appreciable particle-to-particle or hot particle-to-wall contact so that even highly caking eastern bituminous coal can be fed to the reactor without pre-treatment.

Excess hydrogen substantially above that required by the hydrogenation reaction is fed to the reactor. This excess is needed both to insure a high hydrogen partial pressure throughout the reactor and also to lower the preheat temperature. In a commercial facility an on-site hydrogen source would have to be provided. An oxygen fed gasifier could be a source for the hydrogen, in this case, an oxygen plant would have to be provided.

The Molten Salt Coal Gasification Process, as developed by Rockwell International, was designed to produce low Btu gas in an air-blown molten pool of sodium carbonate. A schematic of the Molten Salt process is shown in Figure 3.6 for the 1 TPH PDU.

In the process, coal is gasified in a highly turbulent pool of sodium carbonate-based melt. The coal is injected beneath the surface of the melt pool together with required sodium carbonate makeup. Air is used to pneumatically convey the solids into the gasifier or, in the case of the medium Btu version, conveying is accomplished by recycling a portion of the product gas.

Dry coal is milled to (-)8 mesh and transported to a silo. Sodium carbonate is stored in a separate silo which receives both makeup material delivered by truck and recycled sodium carbonate from the regeneration system. Coal and carbonate are withdrawn from their silos, metered at a ratio of 38% carbonate to coal (at reference design conditions), and injected into the gasifier through four nozzles fed by pressurized lock hoppers.

The ash and most of the sulfur in the coal are retained in the melt. The sulfur reacts with sodium carbonate to form sodium sulfide which has been found to have a catalytic effect on the gasification reactions which occur at a temperature of 1800°F vs. 2500-3000°F that may be required for rapid and complete gasification to occur in noncatalytic systems.

The product gas exits the gasifier vessel from the top, and a small stream of melt is continuously withdrawn through a side overflow port for ash removal, sulfur removal, and sodium carbonate regeneration. The small stream of melt is continuously removed from the gasifier and replaced by the addition of dry sodium carbonate with the coal in order to prevent excessive buildup of

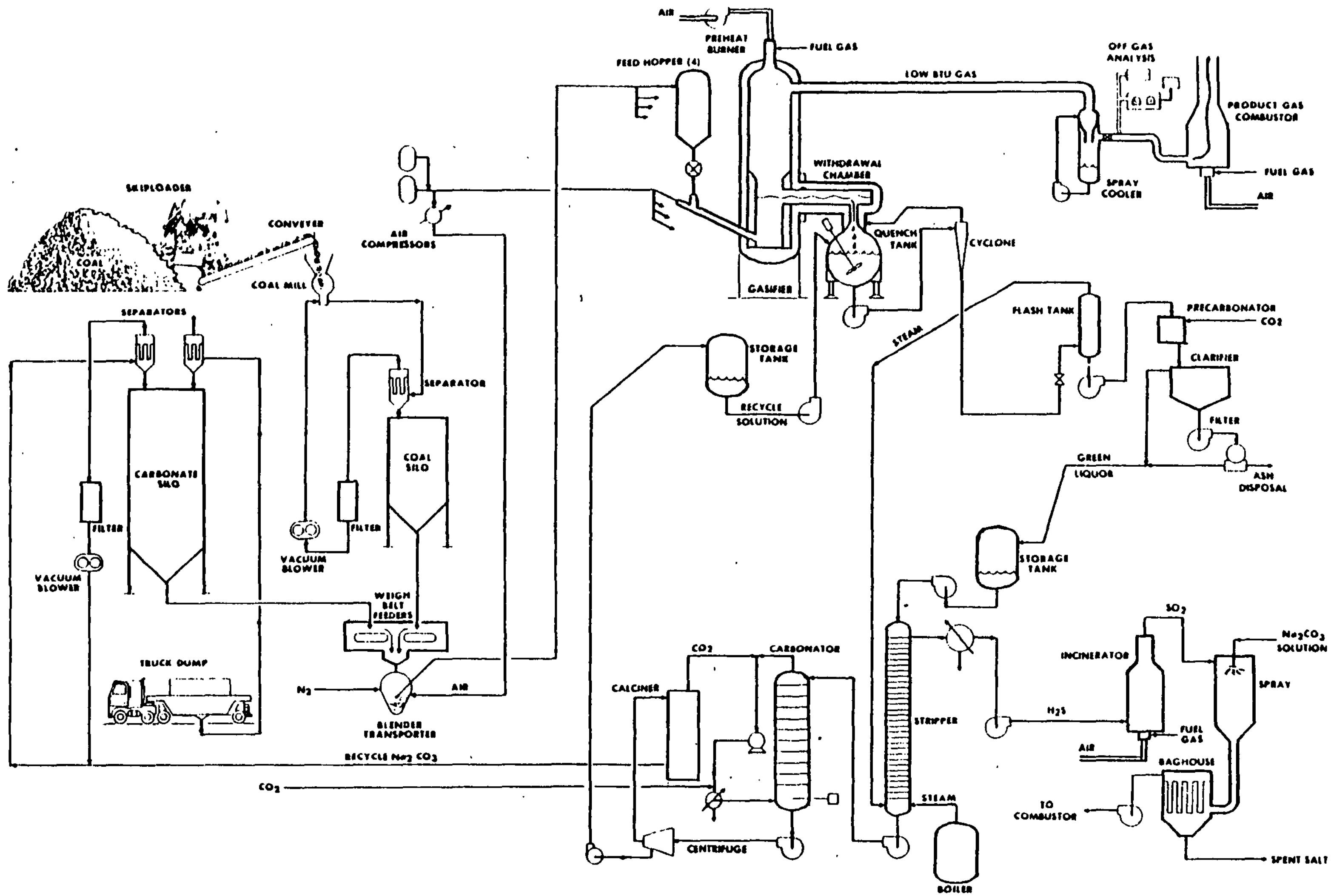

FIGURE 3.6 ROCKWELL MOLTEN SALT PDU

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ash and sodium sulfide. The ash buildup is normally the controlling factor and the sodium carbonate recycle rate is adjusted to maintain a steady-state ash concentration of 20% in the gasifier melt pool.

The aqueous slurry from the quench tank is passed through pressure reduction valves into a flash tank where steam and liquid are separated. Steam produced in the flash tank is used in a subsequent H_2S stripping step and the liquid product is pumped to a precarbonator.

The aqueous solution is sparged with CO_2 in the precarbonator to enhance ash settling and prepare the solution for H_2S stripping. The solids are removed from the system by settling and filtration. The clarified "green liquor" is pumped to a tank which provides surge capacity at this point in the system. Green liquor is pumped from the storage tank to the top of the H_2S stripper tower where it is contacted countercurrently with an upflowing stream of steam. Water is condensed from the H_2S-rich gas exiting the stripper.

The liquid from the H_2S stripper is pumped through a carbonator where CO_2 is absorbed to convert the sodium carbonate to sodium becarbonate crystals. The crystals are separated from the solution, dried, and decomposed in a calciner to produce regenerated sodium carbonate. The remaining liquid is recycled to the quench tank to dissolve additional melt.

The Mountain Fuel process features a high rate entrained flow gasifier which incorporates a heat exchanger system which is designed to optimize the heat recovery. The process has been tested in a 0.5 TPD test facility to manufacture medium Btu gas from a variety of coal feedstocks. Figure 3.7 shows a schematic of the test facility at the time of the completion of testing in late 1978.

The coal handling system consists of a vacuum tank which creates adequate suction to draw coal from the 50 gallon drum through a 1½ inch line to a cyclone separator mounted on the top of the coal lock hopper. A scale is used to weigh the total coal loaded into the lock hopper. The usual loading time for vacuuming the 180 lb. charge is 30 to 45 minutes. After a coal charge, the bag in the vacuum tank is removed and the coal dust weighed. This quantity is then subtracted from the total weight to obtain the net amount delivered to the coal lock hopper.

PROCESS FLOW DIAGRAM

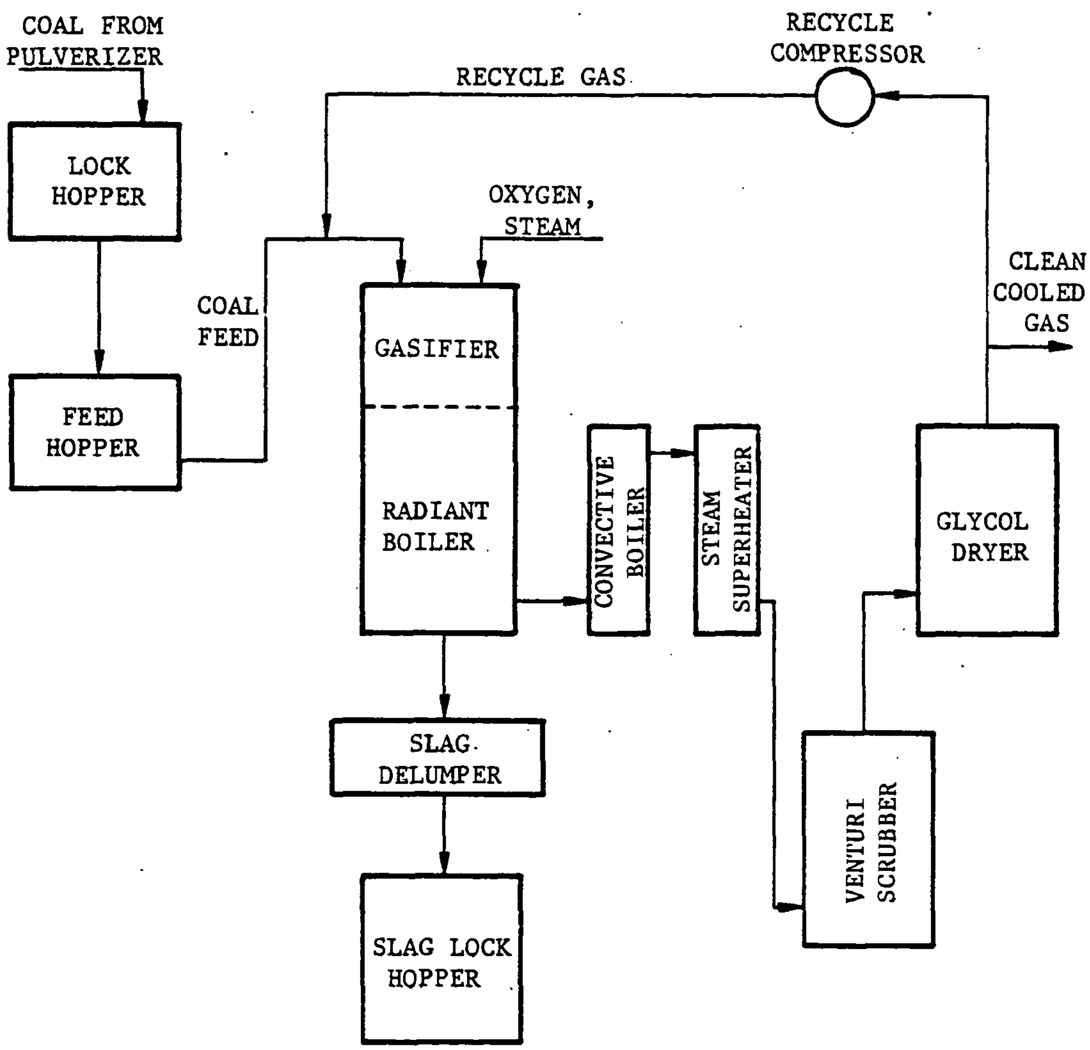

FIGURE 3.7 MOUNTAIN FUEL PROCESS

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Coal is fed from the lock hopper into the coal feed tank. When the level indicator on the coal feed tank goes on, the pressure in the coal lock hopper is balanced with that in the coal feed tank and a valve between the two tanks is opened, dropping the coal. An intromitter, which is a rotating device, keeps the coal feeding continuously to the two augers which, in turn, meter the coal from the feed tank into the coal feed line, a 1/4 inch standard wall stainless steel tube. Recycled gas is injected around the auger screws to entrain the coal dust to carry it over to the injector head on the gasifier. Coal rate is crudely monitored by an orifice meter located immediately downstream of a coal feed valve. Revolution counters on the auger controls assist in setting the feed rate. Calibration of the feed rate is made by replacing the coal feed line with a 1/4 inch bypass line to a filter bank where a timed weight rate of flow is established in a two minute calibration run and monitoring the pressure differential across the augers.

The gasifier is comprised of a double refractory-lined, water-cooled vessel. The inner refractory is an A.P. Creen J-88 "Jade Pack", a dense high temperature ramming mix of aluminum and chromium oxides. The outer lining is an A.P. Green 22 castable, a low density, highly insulating material. Cooling coils line the inside of the outer wall of the chamber.

The radiant heat exchanger is the primary heat exchanger which is a double-walled cylindrical vessel approximately 54 inches long. The best design appears to be an inner cylinder made of a mild steel composition. Examination of such a cylinder after operation revealed that it was coated lightly with soot, but no corrosion was evident. Steam and water pass concurrently up through the annulus removing sensible heat from the combustion products principally by radiative transfer. From the radiant section the steam enters a steam boiler which is not normally used once the plant is up to operating temperature. The saturated steam then enters a steam superheater which increases the temperature to 800°F. It is then mixed with superheated oxygen at the same temperature and injected into the gasifier.

The product gases, cooled to 1000-1200°F, leave the radiant section and move on to the convective heat exchanger. The product gas is further cooled in this countercurrent tube and shell exchanger which is about three feet in length and contains a single spiral wound tube.

The product gas then passes to the scrubber which is an eight foot long by one foot diameter cylinder packed with aluminum rings in the top section above the gas entrance. A level controller maintains the water level in the bottom of the vessel. Water flows through the scrubber at two gpm and exits through a filter and flash tank to the drain. The volatiles absorbed in the scrubber water flash off at atmospheric pressure and are vented to the flare. The product gas travels concurrently to the water flow and leaves the top of the scrubber at near ambient temperature. It then flows through a sock filter and through an orifice-type flow meter and a positive displacement (bellows-type) flow meter. From there the clean, cool product gas goes to the recycle system.

The product gas enters the low pressure recycle gas storage tank at 50 psig. A portion of the gas (about 80%) bleeds through a control valve regulator to the flare and the remainder is shunted through a recycle compressor into a high pressure storage vessel. Recycle gas is drawn from this tank at 190 SCFH for use as entraining gas for the coal feed.

Slag and ash removal is accomplished by periodically opening the valve between the ash receiver on the gasifier and the ash lock hopper. The solids are flushed from the collection vessel with a spray of water and the valve is closed. After depressurizing the ash receiver, a dump valve is opened and the slag is collected in a canvas sack in the ash receiver. After three or four dumps, the sack is replaced with a fresh one.

There are several support systems in the test facility to provide oxygen, nitrogen, water, compressed air, bottled hydrogen and plant monitoring. Cryogenic oxygen is delivered to a 1000 gallon storage tank located behind the gasification facility. The liquid oxygen is converted to a gas by passing through a series of heat exchangers located on the tank. The gas is then metered into the process through a rotometer at a pressure of 200 psig. It is then superheated to 800°F and mixed with the superheated steam and injected into the gasifier.

A bank of three N_2 cylinders is used for initial start-up pressurization and coal entrainment as well as inert purges required periodically during the run. It is also used in the coal feed entrainment for calibration. The nitrogen pressure is maintained at 350 psig.

City water is used for a variety of purposes. It is used directly in ambient pressure cooling applications and is pressurized to about 150 psig for both the process steam and reactor and scrubber sprays. Water is available at hose bibs for lab clean-up.

An air compressor supplies control air to all the air-actuated control valves and bonnets. It maintains a constant 140 psig pressure in a high pressure water vessel.

Compressed air and hydrogen in cylinders are used to start ignition in the gasifier. Once coal feed is started, the gases are shut off.

Most of the plant operations can be controlled and monitored from the panels in the control room, which is separated by two doors from the reactor room. There are, however, several valves and switches that must be operated manually on the equipment.

The Thagard process utilizes a high temperature fluid wall reactor which can process a variety of feedstocks including all types of coal to produce medium Btu gas or synthesis gas. The process is also adaptable for other chemical process applications.

Several general classes of chemical process industry operations have been conducted in the Thagard reactor. For example, pure hydrocarbon feeds have been pyrolyzed to produce carbon and hydrogen. If impurities are present in the feed, addition of scrubbing agents can bind them into an inert solid product. A 12 inch I.D. reactor is currently under construction to produce carbon black and hydrogen from carbon black oil. Hydrocarbons may also be pyrolyzed in the presence of other compounds to produce specialty chemicals. A program is in the planning stage in which coal will be introduced with hydrated lime to co-produce synthesis gas and calcium carbide for acetylene production.

The Thagard reactor also has potential applications in ore processing and metal refining operations. Experimental data have shown that high-purity metals can be produced when a finely-divided metallic oxide feed is introduced into the reactor with a reducing agent. Impurities in the ores are bound in an inert slag which can be separated from the product metal by filtration, magnetic separation, or other conventional processes. Metals may be produced from complex compounds as well as ores. The Thagard Research Center is now conducting a process development program on behalf of a client for the production of polycrystalline silicon from trichlorosilane. The polycrystalline product can be used as Czochralski feed to produce crystalline silicon for semiconductor manufacture. The processing of non-metallic ores may also be enhanced by the use of the Thagard gasifier to produce hydrogen as an ore reductant. The hydrogen-rich syngas stream from the gasifier can be passed through a pressure swing absorber or similar separator to produce high-purity (99+%) hydrogen.

The manufacture of refractory materials is another area of potential application for the Thagard reactor. The high temperatures attainable in the reactor core facilitate the production of ceramic or citreous refractory materials for other high-temperature processes.

The Thagard reactor, shown in Figure 3.8 operating as a coal gasifier, is fed with coal at the top of the reactor. The coal feed may be in the form of dry fines or it may be contained in fine drops derived from the atomization of a coal slurry. As the coal falls through the reactor, either by gravity alone or aided by the movement of a fluid which may be injected simultaneously at the top, its surface is exposed to the high intensity radiation inside the reactor.

The Thagard Research Corporation indicated that the outer layer of any coal particle which has been heated to temperature levels close to that of the reactor wall would be pyrolyzed completely. The depth of the reacted layer and the possible formation of a passivated shell around the unreacted portion of a feed particle is dependent on the sizes of the feed particles and their composition. It appears that the optimum particle size is on the order of (-)100 mesh for most coals. Thagard has also indicated that ash residue from coal gasification can be made essentially carbon free with proper operating conditions. Pyrolysis product, ash and unconverted coal, if any leaves the bottom of the reactor, are collected for further treatment.

The chemical species formed by the pyrolysis of coal in the reactor is of interest. Oxygen present originally in the coal as combined H_2O (not added) reacts exothermally with carbon to form CO. Virtually no CO_2 is produced. All the hydrogen and nitrogen present in the coal, excluding the hydrogen present as moisture, are converted to molecular hydrogen and nitrogen.

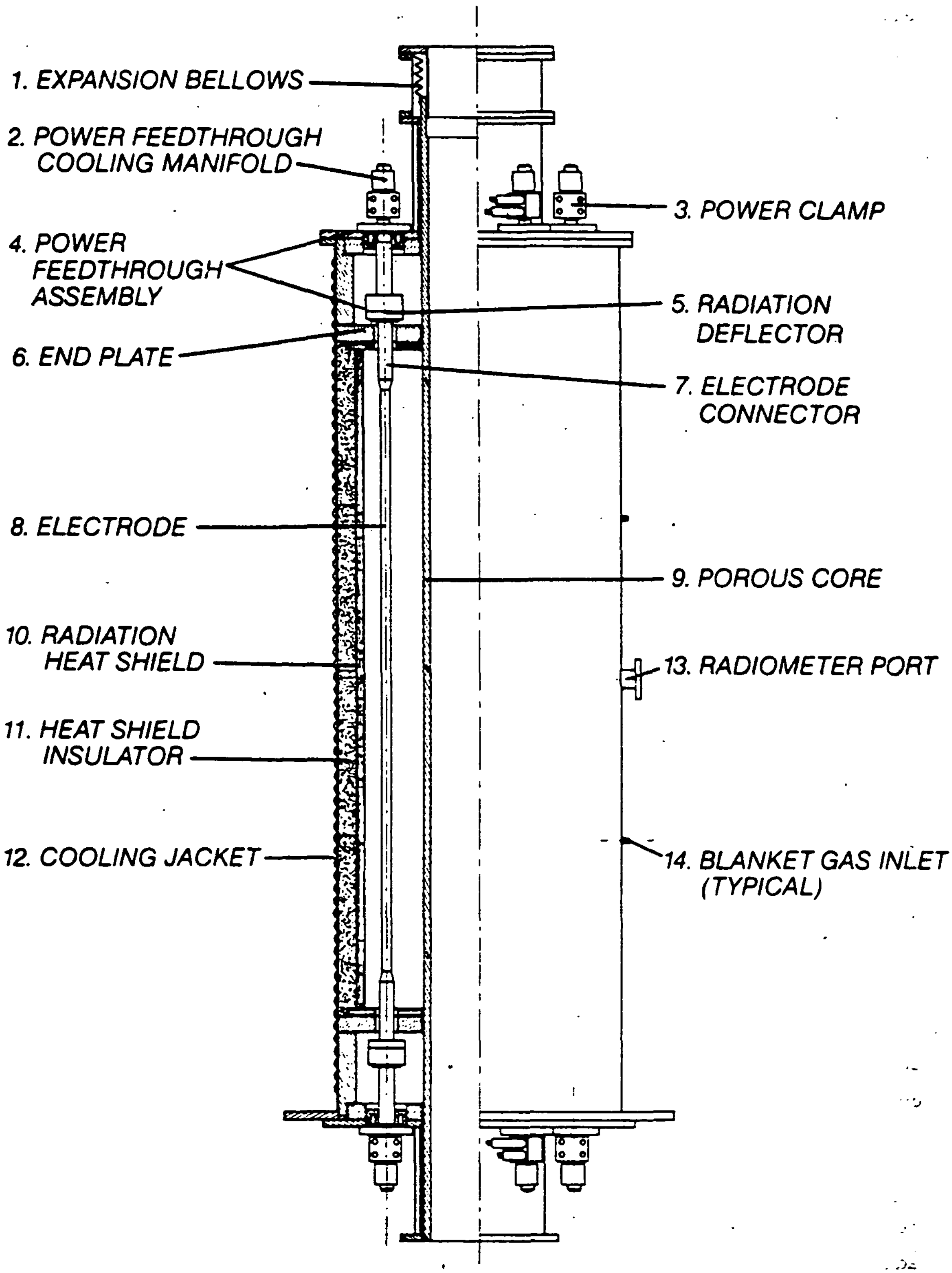

FIGURE 3.8 THAGARD REACTOR

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Sulfur is converted to CaS by the addition of lime to the feed. Moisture, in the coal or entering with the coal, reacts endothermally with excess carbon to produce CO and H_2. A schematic of the process is shown in Figure 3.9.

The process is controlled by core temperature. Continuous monitoring and time-averaging of system variables are performed automatically and the results are stored on flexible disks. Measurements are also recorded on strip charts at the system control panel. A VAX computer is available to produce hard copies and graphs of the stored data and to support parametric analyses.

The reactor system instrumentation is calibrated on a regular basis against external standards. Measurements provide independent crosschecks of major variables for the system mass and energy balances. These data are used to determine the relationships of reactant conversion, energy effects and reactor power consumption. Closures for mass and energy data are in the 99+% range.

The utility requirements for the reactor installation are limited to the coolant system and electrical power source. The results of a specified process definition and development program are used with theoretical and empirical design bases to minimize these requirements. The capability exists, depending on the specific process, to introduce oxidants to further reduce power requirements.

Specific compositions for gaseous and liquid waste treatment are dependent on the feed composition. These can be optimized to produce inert solid waste from the reactor so that no special processing is required beyond cooling to final disposal temperature.

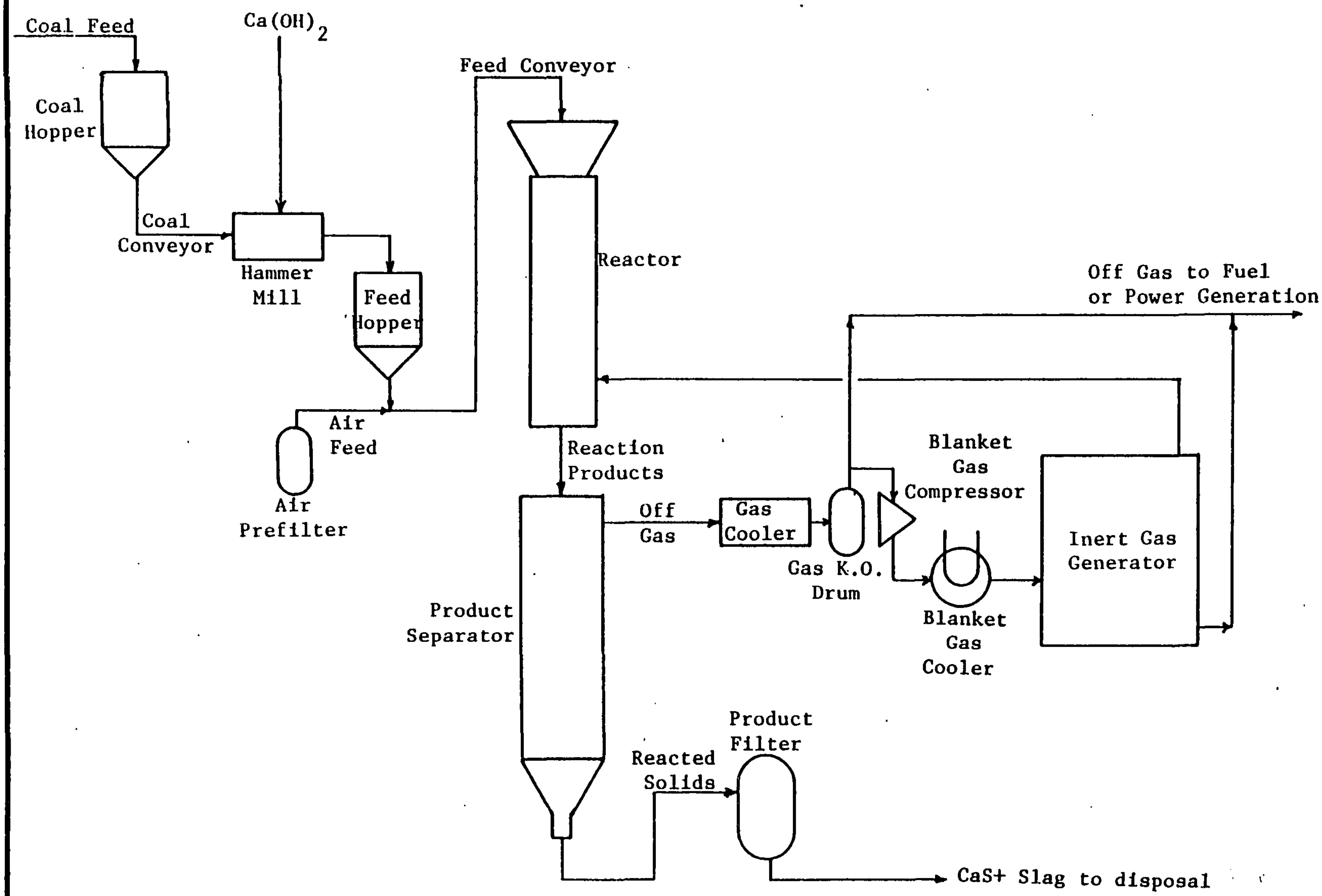

FIGURE 3.9 THAGARD PROCESS

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4.0 OPERATIONAL EXPERIENCE

The operational history for each plant was analyzed to determine major problems and failures, the modifications made to correct the problems, and the performance of equipment and components as compared to requirements. Data was not available on explicit failures for all processes. For the Thagard process for example, no releasable data on problems and failures was available. Thagard has not received DOE funding, therefore, they have no published reports on their operations. Other process developers have provided a reasonable amount of operational problems data. The Bigas plant for example has provided data on most of their major problems. The primary reason is that the Bigas plant has been operating on DOE funds. The operational experience information which was analyzed was obtained from contacts with plant personnel, plant visits, reports to DOE on plant operations and other published data on the process development.

Most of the major problems for the processes described previously were corrected during the early stages of operation of the plants. However, in other coal conversion facilities of larger scales (demonstration and commercial), equipment and component failures continue to be experienced. The high through-put capability of most of the advanced processes require only short duration runs (a few hours) which do not cause as many failures as could be expected in a continuously operating or long run duration facility. The operating conditions on either side of the reactor section of processes are similar to those that have been identified to cause problems in other more tested processes. The non-reactor areas are where many of the equipment failures have occurred and have been maintenance "headaches" and will likely cause startup problems for scaled-up versions of the more advanced processes.

4.1 PROBLEMS AND FAILURES

The operational problems and equipment and component failures were identified and assessed with emphasis placed on major or recurring problems. Failure reports from several sources such as the National Bureau of Standards, DOE evaluation contractors, and process developers were integrated with information obtained from the plant visits to determine the significant failures and problems.

The Bell process has been tested utilizing an air blown reactor with 66 tests being run with durations up to one hour. Several tests have been run using oxygen as the oxidant supply to the reactor. The objective of the air blown test program has been to demonstrate the feasibility of the High Mass Flux Gasifier concept and to evaluate gasifier durability. Four basic types of injection systems have been evaluated and three types of coal have been used.

For all tests conducted, including thirteen tests of between thirty and sixty minutes duration, the operation of the reactor has been smooth and stable and no reactor malfunctions have occurred. With the exception of two tests, which were conducted at lower than desired and uneven coal feed rates, the operation of the dense phase coal feed system has been highly satisfactory. Three injector configurations, the swirl, reverse flow, modified reverse flow and impinging sheet air injectors were used during the test program. For each configuration coal was injected via a central coal inlet port and entered the reaction chamber as an expanding hollow cone.

The air blown High Mass Flux Gasifier operates in the slagging mode at a reaction temperature of nominally 2400°F. With the swirl and reverse flow air injectors, slag accumulation around the air inlet hole was experienced which caused reactor performance to decline with accumulated running time. Introduction of the impinging sheet injection system greatly improved this situation.

No significant failures have been reported by Bell during plant operation. Conceivably, there would be few mechanical equipment failures because of the limited mechanical equipment required in the pilot plant and the short duration runs.

The Bigas plant is of larger scale and has more operational experience than any of the other processes studied. It has been extensively tested under DOE funding. Most of the major problems at the Bigas plant have occurred in the following areas:

- Slag removal
- Measurement instrumentation (temperature, flow rates, and bed levels)
- Materials problems (high temperature, pressure, and velocity areas)
- Char and coal feed system plugging
- Equipment such as pumps and valves (often associated with material failures).

Table 4.1 lists reported failures for the Bigas plant operation during an approximate one year period of operation. The pilot plant operation has not

BI-GAS TEST RUN NUMBER	DATE	RUN DURATION	REASON FOR TERMINATION	RESULTING TURNAROUND WORK
G-6E	Dec. 1, 1978	9 Hours	- Failure of both Stage I thermocouple sheaths. - Leaking high pressure boiler relief valves.	
G-6F	Dec. 13/14, 1978	27 Hours	- Loss of visual confirmation of slag tapping. - Unreliable thermocouple readings. - Unable to relight the slag tap burner. - Problems with slag removal. - Sampling problems and various vessel level control problems.	- Raised slag tap hole. - Reduced size of slag tap hole from 6" to 2". - Installed an agitator in the bottom of the slag quench section.
G-7	Feb. 4, 1979	8 Hours	- Gasifier cooling water leak into Stage I at char burner.	
G-7A	Feb. 24/25, 1979	8 Hours	- Rupture of char burner resulting in fire in the gasifier building.	- Replaced all char burner and coal feed leg 321-SS bellows with incoloy 825 and relocated bellows from the back of the burner to near the face.
G-8	Aug. 4/5, 1979	4.5 Hours	- Loss of 2 Stage I thermocouples. - Poor TV picture. - Problems lighting slag tap burners. - Coal slurry pumping problems. - Coal and char leg plugging. - Level detection problems.	
G-8A	Aug. 14/15, 1979	21.3 Hours	- Erratic coal and char feed. - Char line plugging.	
G-8B	Sept. 5/7, 1979*	33.5 Hours	- Char and coal feed legs plugged. - Poor detection of char line pumps.	- Modification of char burners. - Addition of a natural gas heater prior to injection into char burner.

* Subsequent operation has included several runs of 100-200 hours with continuous coal and char feed.

TABLE 4.1 OPERATIONAL EXPERIENCE - BIGAS PILOT PLANT

SRS

revealed any serious problems with the basic process but most of the problems have been related to mechanical equipment, instrumentation and even severe weather conditions at times. The operation of the plant has become smoother in recent history with better startups relative to previous years, longer test runs, and more planned shutdowns after data collection has been accomplished.

The CS/R Hydropyrolysis process has been tested on a 1/4 TPH, 3/4 TPH, and 1 TPH scale successfully processing various coal types. Both liquefaction and gasification modes have been well tested. Many of the problems have been associated with the coal feed and char lines. Most of the plant operation has resulted in satisfactory runs with normal shutdowns. Table 4.2 is a summary of the tests performed over a one year period with the resultant shutdown causes.

The Rockwell Molten Salt gasifier has been tested in a 1 TPH capacity PDU since November 1978. The plant has been operated as a fully integrated facility. Test durations have been on the order of several days with coal feed at about 75% capacity.

As would be expected during startup and operation of a first-of-a-kind PDU, some operational problems were encountered. The most significant of these has been providing continuous trouble-free removal of melt from the gasifier. The problem is similar to that encountered in all slagging gasifiers (although the melt remains liquid at much lower temperatures than slag) and is also related to the removal of "smelt" in pulp and paper industry chemical recovery boilers. The problem is probably more severe in PDU scale equipment than it would be in a commercial size plant because the melt flow rate is very small (less than 1 gpm), the flow passage is correspondingly small, and heat losses are relatively high. Minor design changes are being made or planned for the PDU melt withdrawal system to assure than melt discharged from the gasifier cannot solidify on surfaces enroute to the quench tank. Table 4.3 shows examples of the operational experience for the Molten Salt facility.

The Thagard high temperature fluid wall reactor has been tested using a wide variety of feedstocks including several types of coal and has been reported by Thagard to operate without problems of any significance. There are no published reports on the Thagard process testing; therefore, most of the information about the process operation was obtained during the plant visit. The problems indicated during the plant visit were primarily in the areas of

Test Number	Test Duration (Minutes)	Test Date	Shutdown Causes
318-11	15.3	07/20/79	Normal Shutdown
318-12	10.7	07/25/79	Normal Shutdown
318-13	19.5	07/27/79	Power Supply Over Temp. Cut- 3 Gas Samples Secured
318-14	1.8	08/04/79	Coal Line Plugged/No Gas Samples
318-15	20.7	08/10/79	Normal Shutdown
318-16	23.2	08/13/79	Normal Shutdown
318-17	4.7	08/15/79	High Preburner Temp. Cut Char carried to next test
318-18	22.2	08/16/79	Normal Shutdown
318-19	23.5	08/20/79	Normal Shutdown
318-20	12.8	08/21/79	Power Supply Shunt Tripped After 2 gas samples
318-21	4.4	08/24/79	High oxygen delta P. Cut after 1 gas sample
318-22	0.2	09/01/79	Malfunctioning BPR* no gas samples
318-23	15.5	09/12/79	Normal Shutdown, reactor tube flattened
318-24	21.8	10/05/79	Normal Shutdown, manual BPR* first 10 minutes
318-25	18.7	10/09/79	Normal Shutdown
318-26	24.2	10/11/79	Normal Shutdown
318-27	22.5	10/15/79	Normal Shutdown
318-28	22.0	10/18/79	Normal Shutdown
318-29	4.6	10/22/79	High oxygen delta P. Cut after 5 minutes, 1 gas sample
318-30	18.4	10/23/79	Normal Shutdown, post test injector damage
318-31	19.0	11/13/79	Normal Shutdown, new injector
318-32	21.3	11/14/79	Normal Shutdown
318-36	25.5	11/28/79	Normal Shutdown
318-37	18.8	12/04/79	Normal Shutdown
318-38	23.1	12/05/79	Normal Shutdown
318-39	8.4	12/06/79	Power failure terminated, run prematurely
318-40	13.8	12/11/79	Normal Shutdown, B-T** analyzer out of order
318-41	23.2	12/12/79	Normal Shutdown
318-50	31.1	02/01/80	Normal Shutdown
318-51	17.0	02/05/80	Area wide power dip, run terminated prematurely
318-52	28.6	02/07/80	Normal Shutdown
318-53	1.7	02/13/80	Coal feed line plugged, cut test
318-54	11.5	12/14/80	Terminated by early condenser plugging
318-55	0	02/21/80	Pressure could not be held at 486 psia since the BPR* reached its wide open limit.
318-56	10.7	02/22/80	Pressure could not be held at 636 psig since BPR* reached its wide open limit
318-57	1.7	02/27/80	BPR* reached its wide open limit even with flow rates reduced
318-58	13.6	02/29/80	Low delta pressure product gas orifice installed, yet pressure control was lost
318-59	22.9	03/04/80	Increasing condenser outlet temperature forced a premature normal shutdown
318-60	13.6	03/06/80	Increasing pressure drop across cyclone culminated in BPR* reaching wide open limit
318-63	0	04/25/80	Test used hot H_2 to check out new recuperator
318-64	5.3	04/30/80	2 out of 3 recuperator inlets plugged
318-65	1.4	05/07/80	2 out of 3 recuperator inlets plugged
318-66	0.6	05/15/80	Redline cut in temperature of H_2 preheater outlet
318-67	18.8	05/23/80	Normal shutdown, recuperator removed, agglomerates in char
318-71	4.9	06/11/80	Redline cut on low delta P hydrogen, agglomerates in char

* BPR - Back-Pressure Regulator
** B-T - Beckman Test

TABLE 4.2 CS/R HYDROGASIFICATION OPERATIONAL EXPERIENCE

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Test Number	Duration (Hours)	Date	Shutdown Cause/Turn-around Work
1	157	11/14/78-11/20/78	Melt withdrawal system plugged.
2	243	03/03/79-03/22/79	Melt withdrawal system plugged. 2 additional burners were installed. Feed nozzle plugged but was freed without interrupting operation.
3	272	05/05/79-05/22/79	Flow interrupted by melt plugging on 5/7/79. Additional burner and wall water wash ring installed, run reinstated 5/10/79. Melt overflow problems terminated run on 5/22/79. Additional modification made to melt removal system including refractory replacement.
4	14	01/06/80-01/08/80	Melt overflow plugging. Slight modification of outlet nozzle.
5	112	02/07/80-02/11/80	Intermittent melt overflow.

Non-Reactor Equipment

- **Compressors**
  - heat exchanger plugging
  - air regulator failure
  - discharge valves corroded
  - other minor problems
- **Solids Feed System**
  - hammermill screens plugged
  - feed storage sliding gates operational problems
  - weight belt electronic controls systems problems
  - mixing conveyor motor overloaded (motor replaced)
  - plugging occurred in the solids feed high pressure distribution system (controls problem)
  - diverted valves failure
  - bridging and "rat holing" in the coal feed hoppers
  - noise level too high in feed hopper venting (mufflers installed)
  - level probes failed
  - rotary feeder seal problems (inert gas purge added)
  - flex lines and nozzle plugging
- **Product Gas System**
  - off gas tee plugged (soot blower installed)
  - spray cooler subsystem recirculation pump failure
  - spray cooler control systems problems
- **Ash Removal System**
  - precarbonator plugging
  - clarifier problems
  - ash filter belt failure
  - pump seal leaks
  - sample lines plugged
- **Regeneration System**
  - blockage in the carbonate underflow pump feed line
  - CO_2 injector blower problems
  - centrifuge overloading
  - calciner CO_2 recirculation system could not be operated
  - level control problems in tanks
- **Sulfur Removal System**
  - atomizer nozzle plugging
  - baghouse problems (mostly solids plugging)
- **Instrumentation and Controls**
  - flow meters
  - control valve plugging
  - level control
  - temperature measurement
- **Facilities and Services**
  - cooling water recirculation pump bearing failure
  - lack of proper weather protection in the electrical power supply system
  - minor piping leaks in the natural gas/propane supply system
  - process water supply hardness caused problems
  - steam supply system heater element burnouts

TABLE 4.3 ROCKWELL MOLTEN SALT OPERATIONAL EXPERIENCE reactor core erosion under certain conditions and feed systems. The plant normally runs for a few hours per test with normal shutdown. The plant can be cycled from cold to operating condition in less than one hour, and shutdown to cold in about two hours.

The Mountain Fuel process has been tested for approximately 800 hours in 296 tests run with the longest run duration of 100 hours. Most of the problems during the start-up and operation of the plant were associated with line plugging, heat control, and the coal feeding system. Table 4.4 is a summary of the problems and conditions associated with the interruption of runs.

4.2 SYSTEMS/EQUIPMENT MODIFICATIONS AND REPLACEMENTS

Generally, the purpose of operating a pilot scale plant has been to prove or optimize the process and not to test or improve equipment/components. As a result, most of the modifications and replacements have been to allow the plant to operate for the required durations to obtain the test data desired. An amount of faulty equipment or poor installation of equipment in most new facilities can be expected and this has been experienced at the pilot plants. These problems normally are corrected or provisions made to operate around them with the problem having minimal impact on the operation of the plant for the run durations desired. The advanced process small scale facility has a limited amount of auxiliary equipment and, therefore, is subject to fewer mechanical problems. Most of the problems encountered are related to the reactor, such as feed systems, refractories, and product/waste removal. The Bigas and the Rockwell Molten Salt have the only fully integrated plants of the processes studied. The Rockwell Molten Salt facility has not been tested enough to experience any recurring problems other than those around the gasifier where most of the test emphasis has been.

For the plants that test for short durations there have been few failures (after shake down and start-up) of auxiliary equipment that recur enough to warrant replacement with anything other than an off-the-shelf item or the original type part that was designed for the unit. In the more integrated larger scale plants, however, there have been repeated failures of equipment/ components and this has caused the operators, by necessity, to find improved

RUN NO.	RUN TIME MINUTES	CHANGES PRIOR TO RUN	OBSERVATIONS, TURN-AROUND CONDITIONS AT RUN TERMINATION
98	55	Removed swirler from coal nozzle of 1S-6S injector	No slag deposits. Recycle compressor on-off cycle upsets coal feed. High CO_2.
99	45	Reinstalled swirler in coal feed nozzle.	Heavy slag deposit on injector face. Fibers around coal swirler.
100	27	Modified 1S-1S injector. Installed pyrometer	Injector clean.
101	45	Replaced recycle gas with air.	Injector clean.
102	69	Filled feeder with classified fine coal.	Injector clean.
103	67	Installed dual coal feed augers and intromitter. Installed swirler in coal nozzle.	Fibers around coal swirler. Injector clean.
104a	67	Removed coal swirler	Injector clean.
104b	20	Increased coal nozzle dia. from 3/32 to 17/64.	
105	47	Modifies scrubber discharge and recycle compressor control.	Injector clean.
106	55	Increased gasifier pressure to 117 psia.	Injector clean.
107	56	Installed 6S injector with pintle coal nozzle recast refractory.	Slag accumulation on injector face. Very uniform run.
108	52	Installed 1S injector with pintle coal nozzle.	Coal nozzle partially plugged with char. Some refractory erosion.
109a	50	Recessed pintle nozzle 1/32 inch from face.	Coal nozzle partially plugged. Some refractory erosion.
109b	10		
110	83	Increased clearance of O_2 steam annulus.	Doubling entrain gas flow during run reduced efficiency.
111	60	Installed 6S injector with pintle nozzle.	Pintle nozzle partially plugged.
112	32	Removed pintle from coal nozzle.	Coal nozzle partially plugged with char.
113a	42	Installed E-4 injector. Recase refractory.	Injector clean. No refractory erosion.
113b	20		
114	48	Increased pressure.	Refractory erosion at base. Injector clean.
115	58	Repaired refractory.	Injector clean. Refractory OK.
116a	65	None	Injector clean. Refractory OK.
116b	30		
117	70	None	Injector clean. Refractory OK.
118	45	Installed refractory baffled.	Baffles partly eroded.
119	45	None	Baffles partly eroded.
120a	32	None	Baffles eroded.
120b	50		
121	40	Recast refractory. Repaired coal auger.	Coal auger twisted off prior to run.
122a	45	None	System OK.
122b	30		
123	55	None	Slag accumulating at bottom of refractory.

TABLE 4.4 MOUNTAIN FUEL 0.5 TPD TEST FACILITY OPERATIONAL EXPERIENCE

SRS

equipment items for replacement if the plant is to be operated for the longer durations desired by the developer.

The Bell test facility has operated for short duration runs and most of the replacements or modifications of equipment/components have been in the areas around the reactor. The dual feed systems employed required modification to optimize the design. Likewise, the injector system was optimized through a series of tests of different injector systems. The plant operators indicate that there has been little problem with such equipment as valves and pumps.

The Bigas pilot plant has modified or replaced equipment/components on a larger scale than the other plants that were visited because it is a larger scale plant and contains the "grass roots" auxiliary equipment not found in the small plants. Even though there has been some testing of new equipment, most of the non-gasifier related equipment has been replaced with spares of the same equipment when failures occurred. Some areas of the plant are similar to a commercial facility in that parallel lines (spares) are provided in order to shift the stream for replacement of on-line equipment.

Major modifications have been done on the Bigas reactor, particularly in the injectors and in the slag removal systems. Other improvements and modifications have been made in the coal handling feed area and in valves used in severe service. Plugging problems required the addition of a screw conveyor in the coal handling system around the bucket elevator which had been used to transport the coal to the rod mill. A coal screen was incorporated into the coal feed system to remove more of the coal fines to improve the operation of the downstream cyclone. The coal injector systems have been modified to improve coal and char feed. Other examples of the modifications and replacements are shown in Table 4.1.

The operation of the CS/R Hydropyrolysis test facilities have been sufficient to obtain the test data desired. The thrust of the process development has been to optimize the reactor and the process results. Test runs have been of short duration and, therefore, excessive wear on equipment and components has not been a major problem. The major modifications occurred in the coal feed/injector systems during the development of the systems. The operation of the test facility is somewhat representative of the operation of an advanced process development facility in that there are many maintenance type turn-around modifications or "fixes" that are made to facilitate the plant operation. Table 4.2 shows some of the turn-around work that was done during a series of test runs.

The Rockwell Molten Salt process has been in operation since late 1978. Most of the necessary operating modifications have been in the area of the gasifier melt removal system. The problem solutions are summarized in Table 4.3 for several runs.

Thagard has not disclosed any major equipment modifications or replacements other than the changes required in the reactor feed system and core materials when the feed stock changes. This involves the changing of the porous carbon core with a zirconia core for special applications. Thagard indicated that the developmental work is continuing to refine the feed handling and dispersion systems for slurried coal and to maximize the corrosion and erosion resistance of the core walls with the short-term emphasis on larger diameter devices.

The Mountain Fuel process is a high rate entrainment flow process and the modifications and replacement of equipment and components have been similar to those of other advanced high rate entrained types. Most of the modifications have been related to the development of the reactor feed system and slag/ particulate removal. Table 4.4 illustrates some of the conditions and modifications associated with a series of test runs. The objectives of the 0.5 TPD reactor development were accomplished in late 1978 and the test facility was dismantled. The process is considered developed well enough to be tested on a 30 TPD scale. At this scale the coal feed/injector and heat exchanger systems configurations should be optimized to provide information for scale-up to commercial size.

4.3 PERFORMANCE VERSUS DESIGN SPECIFICATIONS

The performance of the reactors in the processes has generally met design specifications but have required modifications to the original installations in order to obtain the expected results. The reactors in the pilot/subscale demonstration plants had been previously tested on a smaller scale to provide data for scale-up design. It appears, for all the processes studied, that modifications were required to the reactors in scaling-up from the original design used in smaller scale tests.

Equipment and components that are not associated with the reactor section have received much less attention than the reactor area equipment. The performance of the non-reactor equipment is not well documented, especially for the small scale non-integrated plants. As a rule, mechanical equipment and components have not performed as well as the specifications would indicate they should. The fact that the plants are not designed for equipment testing may have influenced the selection of particular equipment. Off-the-shelf equipment which has not been proven in the harsh environment of coal conversion is generally utilized.

There are many factors that may affect the performance of equipment and components such as materials characteristics, unpredictable stream conditions, design flaws in the equipment, poor installation and operator errors. Figure 4.1 illustrates the performance of various items in an example high throughput entrained flow process during a single run. During this 92 hour test there were nine shutdowns. The run time was 54 hours and the down time was 38 hours. Of the down time, 29.5 hours were caused by non-process related equipment and components and 8.5 hours were a result of inherent difficulties of the process. It can be noted that the longest duration of run time was 12.5 hours without an interruption. Section 4.1 of this report indicated many of the problems associated with the equipment and components. These problems, or lack of them, are major indicators of the performance of the equipment versus specification since the equipment was identified as suitable for the particular application.

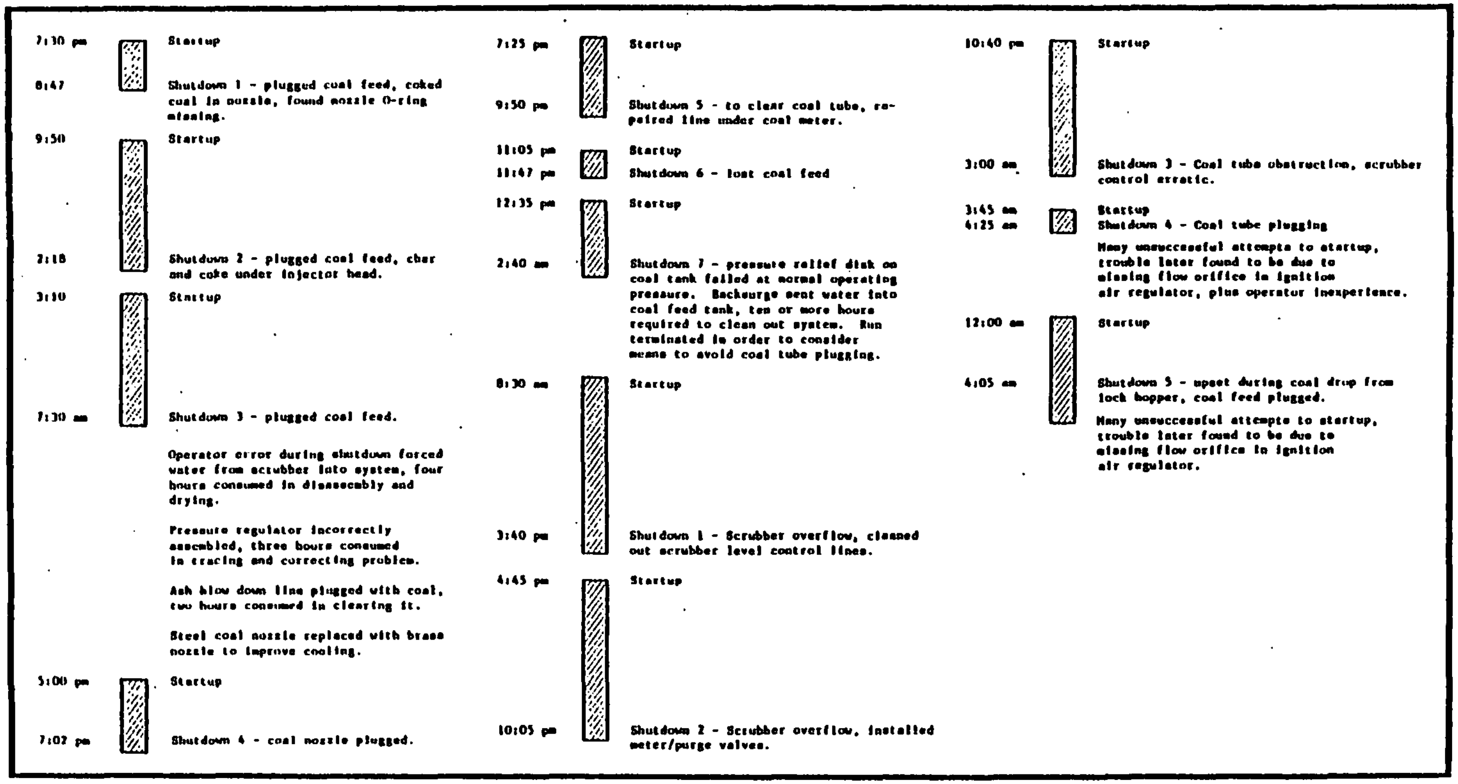

FIGURE 4.1 EXAMPLE PLANT PERFORMANCE FOR 92 HOUR RUN

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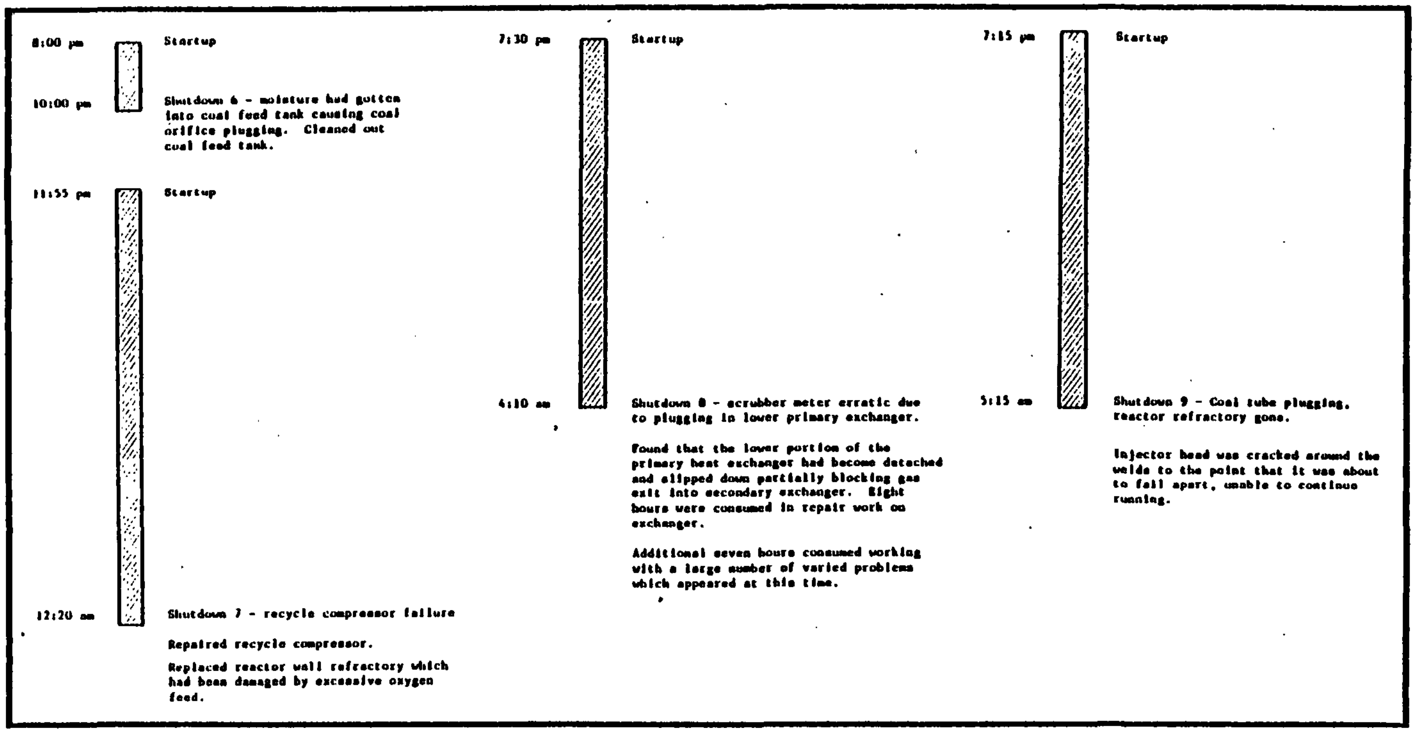


FIGURE 4.1 (CONTINUED)

5.0 DEVELOPMENT REQUIREMENTS

Development requirements, for the purposes of this report, are separated into process development requirements and systems/equipment development requirements. The process development requirements are related to the chemical reaction characteristics that are still questionable after testing or those characteristics that were not verified which are closely associated with the reactor section. The systems/equipment development requirements are primarily related to the mechanical equipment requirements. Many of these requirements have been previously identified in studies of other processes (e.g., references 11 and 13).

The processes studied are advanced processes and therefore there are many areas that need further testing and enhancement. The following discussion is limited to those requirements that can be identified as potentially critical to the operation of a scaled-up, fully integrated version of the present test facility or a commercial scale facility.

5.1 PROCESS DEVELOPMENT REQUIREMENTS

Most of the development requirements for the processes studied were similar to requirements that have been determined for other processes. The high throughput entrained reactors and the Thagard radiant heat reactor present process development requirements that are peculiar to those processes. These development requirements include:

- Verification of process by scale-up of reactor system
- Verification of performance reproducibility
- Kinetics and energy balance continuity
- Process control.

The advanced coal conversion development facilities have verified many of the necessary operational features but some areas such as coal injectors cannot be proven for commercial scale until they have been tested in a larger facility. For example, the CS/R, Bell, and Mountain Fuel coal feed injectors have worked well at their present scale, but the multiple injector feed systems required for commercial scale need to be tested to optimize the design configuration. The reactors for the high throughput entrained flow systems are small (a few inches in diameter and several inches to a few feet in length) and the consistency of flow patterns and reaction characteristics have not yet been proven. A scale-up of any one of the reactors utilizing the high rate injector would help to verify the system. These injectors have feed lines on the order of 1/4 inch diameter in the test facilities and utilize a dense phase flow which needs to be verified on a larger scale. Another area associated with scale-up is the ash/slag removal systems. Most of the larger integrated test facilities have experienced problems with ash/slag removal and, although most of the slag removal problems have been minor, the ash/slag removal systems may require further development for a scaled-up facility. Characteristics of the reactor, such as the coal feed injectors and the reaction flow patterns, need to be demonstrated in scaled-up configurations to verify reproducibility.

The processes studied (except Bigas which has run several days and the Mountain Fuel 0.5 TPD unit which has been run 100 hours) have not produced long duration test runs. The kinetics and energy balances have been verified for most of the processes but only for short duration runs. One of the major requirements is the operation of the reactors for extended periods to obtain run data that will verify material and energy balances, efficiency and other operating conditions. The operation of a high throughput reactor on a larger scale than is currently being tested (a few tons per day) for extended periods focuses attention on the heavy coal consumption and operating cost for a test facility. As an example, one of the process developers indicated that their test reactor could process up to 10 TPH through a single injector element. Obviously, long duration runs of several days with a scaled-up reactor (50-100 TPH) would consume large amounts of coal. A long duration run is generally considered by the industry to be 30 days. The development of the advanced reactors may have to be accomplished with longer duration runs with small reactors or larger reactors with short runs.

Reaction control is a key element in reactor development and involves control of temperature, feed into the reactor and product flow in and from the reactor. The areas of concern include:

- Catalyst requirements
- Control/safety systems
- Slag/char separation
- Heat recovery
- Oxygen/hydrogen consumption.

The ability to optimize the process operation and efficiency may be greatly effected by the ability to control the process. The high temperatures and short reaction times makes the control of the process a difficult task. As larger reactors are utilized, this problem may be more critical and will require more sophisticated control systems.

5.2 SYSTEMS/EQUIPMENT DEVELOPMENT REQUIREMENTS

The success of a commercial coal conversion facility or even a pilot plant is dependent on sustaining operation and performance. As has been pointed out earlier in this report and in other studies, most of the down time at the test facilities has been due to mechanical equipment failures or problems. This has also been shown to be the case in foreign commercial scale facilities which emphasizes the need for more reliable and longer life equipment. Previous studies by SRS indicated that the major second generation process pilot plants had experienced start-up and shake-down problems with mechanical equipment and components and that these problems were often repeated due to replacement of failed items with "same kind" items. Some commercial facilities in other countries have reported that years were required to work out all the major "bugs". This study of advanced processes has reinforced the need to develop better systems and equipment. The development requirements are governed by the stringent specifications in the advanced processes and the size requirements and the availability of equipment that will operate reliably.

Some of the major areas where further development is required include:

- Pumps
- Valves
- Compressors
- Heat recovery
- Solids removal
- Instrumentation and controls.

The operating conditions for the processes studied included temperatures to 3000°F, pressures to 1500 psig and high feed rates. These conditions require that specialized equipment and materials be used to provide reliable operation. The specifications that have been used for much of the coal conversion equipment has been carried over from the petroleum refining industry. Commercial equipment is available to meet the specifications of the petroleum industry, but is often not available to meet the requirements for service in the harsh coal conversion environment. Centrifugal pumps, for example, for slurry applications in excess of 100 psi and/or temperatures of 300°F and above are essentially unavailable and large compressors to supply high-purity oxygen at pressures on the order of 1000 psi have had major operational problems.

The high throughput rates and other operating conditions require that the process (especially the reactor) be closely controlled. Instrumentation to sense temperature excursions quickly and control systems which can respond rapidly need to be developed. Safety related controls are also needed to provide for rapid automatic shutdown in case emergency conditions develop. Instrumentation is a key element and requirements for the enhancement of the technology to perform the measurements and provide controls that are needed has been recognized. A limited amount of diagnostic and performance measurement instrumentation has been utilized at the pilot plants. Critical instrumentation needs are located in the following process systems:

- Transport (dry and slurry)
- Feeding and metering
- Reactor or combustor
- Solids and gas separators
- Solids and liquid separators
- Let-down and transport systems
- Product and output quality assurance.

High priority problem areas include:

- Temperature measurement
- Multi-phase mass flow monitoring
- Pressure let-down
- Phase detection
- On-line analysis
- Level detection
- Viscometry.

Much of the existing instrumentation is too unreliable, inaccurate, or inadequate for the requirements of advanced processes. There appears to be little incentive for advancement of instrument technology from the usual commercial equipment suppliers due to undefined specifications, the lack of a significant market, and the effects of the dynamic nature of synthetic fuel technology development.

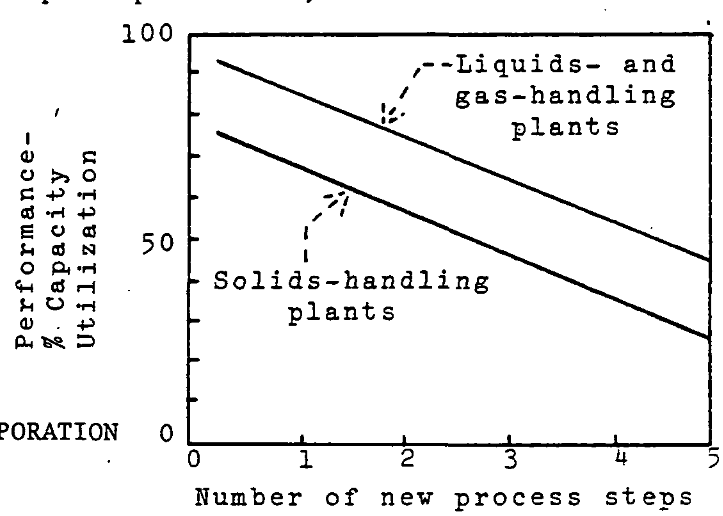
6.0 COMPARATIVE TECHNICAL AND ECONOMIC ASSESSMENT METHODOLOGY

The thrust of this portion of the study was to establish a preliminary systems level methodology which could provide recommendations for the prioritization of advanced coal conversion process development requirements. The comparative methodology established addresses the major factors that influence process technical and economic feasibility including capital and operating costs, process operational and design characteristics, process and related systems development status, scale-up uncertainties, and product slate values.

6.1 APPROACH

The approach entailed the design of a top-down methodology which would permit consistent relative comparison of advanced processes and the associated systems, equipment, and components based on both technical performance and cost and economic potential. The following guidelines were established to limit qualitative factors:

- Deemphasize cost estimates when uncertainty is high - emphasize other process characteristics such as coal feedstock flexibility, conversion efficiency, pilot/subscale unit performance, etc.
- Limit variance in qualitative factors through application of specific criteria and independent evaluations
- Define confidence intervals around estimates using chemical processing and petroleum industry experience in incorporating new technology and empirical data based on the relative importance of comparison factors (Figure 6.1 illustrates the effect of unproven technology and solids handling on plant performance).



SOURCE: RAND CORPORATION

FIGURE 6.1

Comparison factors were defined for assessing process characteristics and included efficiency, process complexity and development requirements, systems and equipment development requirements, and economics. The major elements within each of these factors are indicated in Figure 6.2.

6.2 METHODOLOGY STRUCTURE

The comparative methodology was developed specifically for the systems level assessment of advanced coal conversion processes but is also applicable to processes in general. A schematic of the overall methodology is shown in Figure 6.3 and the major elements are described below.

The comparative assessment is initiated by developing a conceptual commercial scale plant design for a given second or third generation coal conversion process in which all major systems and equipment are defined and gross specifications established. The final conceptual plant configuration is based on the results of a product value analysis to determine the optimum or highest value product slate.

The current value of products from coal conversion plants can vary widely and experience has shown that relative values can change significantly with time. Therefore, both current and projected product slate prices over the operating life of the plant must be considered and weighed against plant costs. One accepted method for product value analysis involves establishing a given product such as gasoline as an index or reference and comparing alternate product values with the current and projected index product value. An example of a product value comparison is shown in Figure 6.4. It should be noted that these

PRODUCT	VALUE FACTOR*
GASOLINE	1.00
SNG	0.52
MEDIUM BTU GAS	0.40
PROPANE	0.78
BUTANE	0.75
BENZENE	1.75
METHANOL	0.40
ELECTRIC POWER	1.05
NAPHTHA	0.82
FUEL OIL	0.82
CHAR	0.37
TAR OIL	0.30

* RATIO OF ACTUAL MARKET VALUE OF PRODUCTS PRODUCED TO THE VALUE OF PREMIUM GASOLINE

FIGURE 6.4 PRODUCT VALUE COMPARISON

- EFFICIENCY
  - PRODUCT SLATE (HHV FUELS OUT/ENERGY IN)
  - PROCESS (TOTAL ENERGY OUT/TOTAL ENERGY IN)
- PROCESS COMPLEXITY
  - REACTION (NUMBER, SENSITIVITY, CONTROL, ETC.)
  - OPERATION (NUMBER OF STEPS, FLOW CONSTITUENTS, CONTROL TOLERANCES, ETC.)
  - OPERATING REGIME (PRESSURE, TEMPERATURE, ETC.)
  - AUXILIARY FACILITIES (SPECIAL UTILITY REQUIREMENTS, CATALYST RECLAIMING, ETC.)
- PROCESS DEVELOPMENT REQUIREMENTS
  - SCALEUP REPRODUCIBILITY
  - KINETICS/ENERGY BALANCE CONTINUITY
  - CONSTRUCTION/FABRICATION
- SYSTEMS/EQUIPMENT DEVELOPMENT REQUIREMENTS
  - STRINGENT SPECIFICATIONS
  - EQUIPMENT/COMPONENT SIZING
  - COMMERCIAL EQUIPMENT APPLICABILITY/AVAILABILITY
- ECONOMICS
  - ENERGY UNIT COST (CAPITAL, O&M, FEEDSTOCKS)
  - PRODUCT VALUE (DEMAND, ENVIRONMENTAL SUITABILITY, ETC.)

FIGURE 6.2 COMPARISON FACTORS FOR ADVANCED COAL CONVERSION PROCESSES

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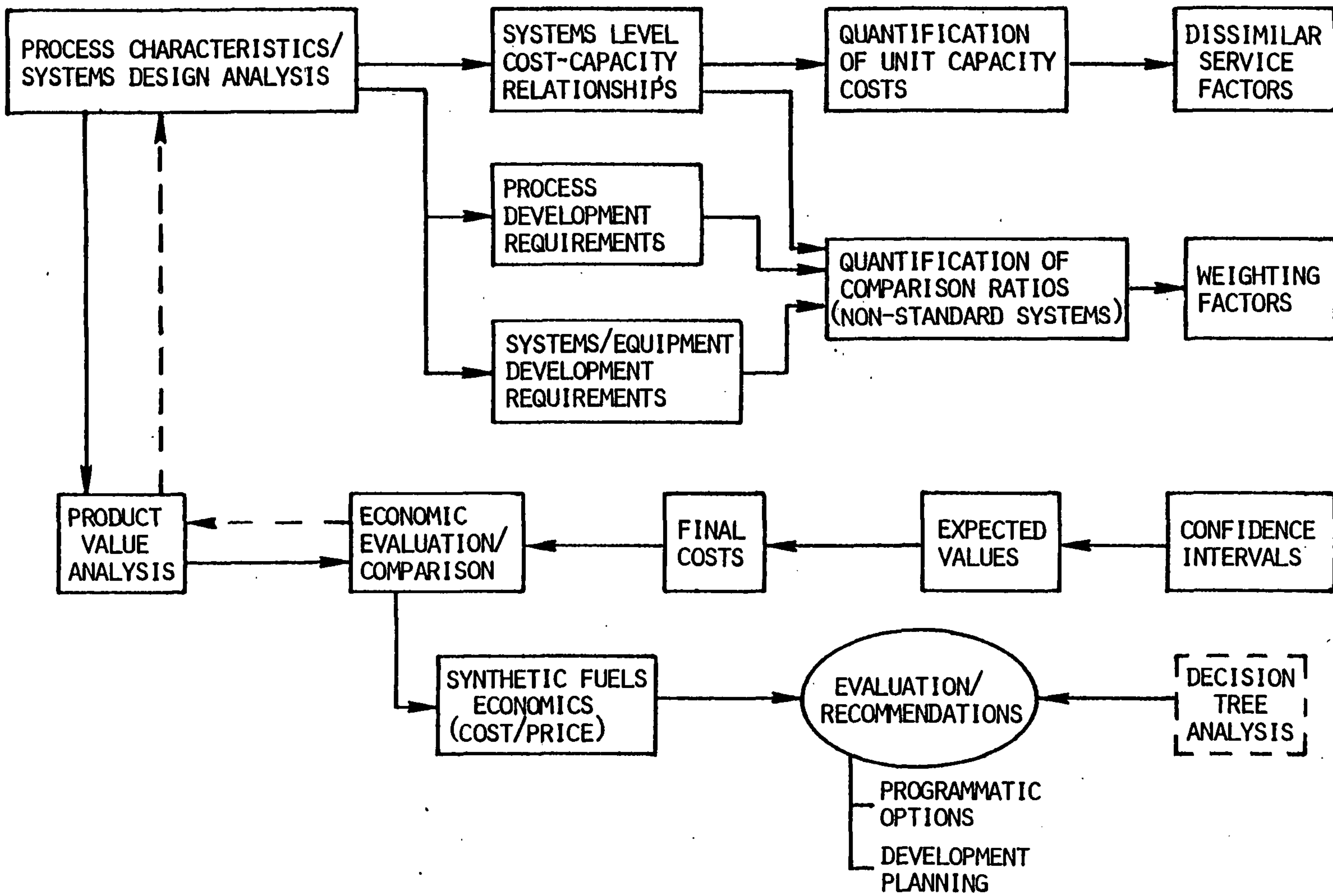

FIGURE 6.3 COMPARATIVE ASSESSMENT METHODOLOGY

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values are illustrative only and do not represent the current product values. These values would require updating to reflect conditions existing at the time a comparative assessment is made.

When the final plant configuration is established and the conceptual systems design completed, all systems are analyzed and categorized as either "Standard" or "Non-Standard." The rationale for categorization of standard systems is applicability or similarity across multiple coal conversion process and the chemical processing and petroleum refining industries. Non-standard systems are those that have unique characteristics or stringent specifications that are inherent to an advanced process such as reactor vessels, gas cleanup and cooling, etc. General facilities such as buildings, roads, sewage treatment, and instruments and controls are analyzed separately. An example of major systems categorization is shown in Figure 6.5.

The next step in the methodology is the determination and quantification of standard systems cost-capacity relationships. An extensive data base exists on costs versus capacity for standard systems and the relationships are widely accepted within industry. Systems level cost can be estimated as follows:

$$\frac{\text{NEW COST}}{\text{REFERENCE}} = \left[\frac{\text{NEW CAPACITY}}{\text{REFERENCE CAPACITY}}\right]^{X}$$

Cost is not a linear function of capacity and measured cost-capacity factors, exponent X, vary from 0.33 to 1.39 but average about 0.6.(A) Variations are attributed to differences in plant types and factors other than size affecting cost, e.g., more stringent oxygen purity specification on an air separation system. The error which can be introduced into cost estimates because of cost-capacity variation is indicated below.

ACTUAL COST-CAPACITY FACTOR (B)

SCALE-UP	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
				PERCENT ERROR					
x 5	+ 89	+ 61	+ 37	+ 17	0	- 16	- 28	- 39	- 48
x 10	+150	+100	+ 59	+ 26	0	- 21	- 37	- 50	- 60

(A) Cecil H. Chilton, "Six-Tenths Factor Applies to Complete Plant Costs," Chemical Engineering.

(B) O. T. Zimmerman, "Capital Investment Cost Estimation," Cost and Optimization Engineering, McGraw-Hill, New York, 1970.

STANDARD SYSTEMS

- COAL HANDLING/PREP
- SULFUR RECOVERY
- AIR SEPARATION
- COMPRESSION
- SOLIDS TREATMENT/DISPOSAL
- PLANT POWER SYSTEM
- STEAM GENERATION/DISTRIBUTION
- RAW WATER MAKE-UP
- COOLING WATER SYSTEM
- WASTE WATER TREATMENT

NON-STANDARD SYSTEMS

- COAL FEED
- REACTOR
- GAS CLEANUP AND COOLING
- ACID GAS REMOVAL
- BY-PRODUCT PROCESSING

SPECIAL CASE

- GENERAL FACILITIES
  - BUILDINGS/ROADS/FENCING
  - GARAGE/MAIN SHOP
  - SEWAGE TREATMENT
  - FIRST AID ROOMS
  - ETC.
- INSTRUMENTS AND CONTROLS

FIGURE 6.5 MAJOR SYSTEMS CATEGORIZATION

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Cost-capacity factors are most accurate for similar systems in similar service. Cost estimation for systems in dissimilar service or with more stringent design and operational specifications requires correlation of additional factors. Gas compression systems, for example, in similar service correlate closely with a cost-capacity factor of 0.6 but variations in gas molecular weight and discharge pressure can significantly affect total cost. For a study case compression system, C_S, cost can be computed, using the cost of a reference system, C_R, with the following relationship:

$$C_S \text{ Cost} = C_R \text{ Cost} \left[\frac{C_S \text{ Capacity}}{C_R \text{ Capacity}}\right]^{0.6}$$

Given that the reference system discharge pressure is 650 psia and gas molecular weight is 21 and the study case system discharge pressure is 350 psia and gas molecular weight is 22, the following dissimilar service capacity factors can be applied to compute an adjusted system cost:

$$\text{Adjusted } C_S \text{ Cost} = C_S \text{ Cost X} \left(\frac{350}{650}\right)^{0.6} \text{ X} \left(\frac{22}{21}\right)^{0.6} .$$

Illustrative standard systems operating conditions and characteristics which must be considered in determining dissimilar service factors are presented in Figure 6.6.

The non-standard systems in a coal conversion plant are fewer in number than the standard systems but can have a great influence on the capital and operating cost of the plant. The major process and equipment development requirements in advanced coal conversion processes are related to the non-standard systems. Both the technical and economic feasibility of processes for commercialization depend on satisfying these requirements. In the assessment methodology, Figure 6.3, development requirements for non-standard systems are separated into process related and equipment/component related requirements. These are expressed in terms of operating conditions, design characteristics and other factors associated with commercial scale operation which serve as a basis for comparison with similar systems. Typical comparison criteria for the non-standard systems are shown in Figure 6.7.

Numerical ratios for each of the comparison criteria can be estimated which provide relative measures of the stringency of specifications, operating characteristics, complexity, efficiencies, etc. These ratios reflect qualitative measures of risk, based on engineering estimates and experience, associated

COAL HANDLING/PREP

- PREHEAT/DRYING REQUIREMENTS
- GRINDING/PULVERIZING REQUIREMENTS
- CATALYST REQUIREMENTS

SULFUR RECOVERY

- % H_2S
- % CONTANINATNS (NH_2)
- TEMPERATURE
- PRESSURE

AIR SEPARATION

- OXYGEN CAPACITY
- NITROGEN CAPACITY
- HYDROGEN REQUIREMENTS
- PURITY REQUIREMENTS

COMPRESSION

- PRESSURE REQUIRED
- MOL. WT.
- CAPACITY REQUIREMENTS

SOLIDS TREATMENT

- STREAM COMPOSITION
- TEMPERATURE
- METHOD OF TREATMENT

PLANT POWER SYSTEM

- QUANTITY REQUIRED
- VOLTAGE LEVEL
- DISTRIBUTION LEVELS

STEAM GENERATION/DISTRIBUTION

- QUANTITY
- TEMPERATURE
- PRESSURE
- NO. OF LEVELS

RAW WATER MAKE-UP

- QUANTITY
- DEMINERALIZED WATER
- CLARIFIED WATER

FIGURE 6.6 STANDARD SYSTEMS DISSIMILAR SERVICE CRITERIA

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COAL FEEDING

- COAL TYPES
- PREHEAT/DRYING
- FEED STATE
- PRETREATMENT
- CHEM/CAT ADDITION

ACID GAS REMOVAL

- GAS FLOW RATE
- TEMPERATURE
- PRESSURE
- % H_2H, COS REMOVED
- % CO_2 OUT
- PROPRIETARY SOLVENT
- REFRIGERATED SOLVENT
- DUAL COLUMN ABSORPTION

REACTOR

- FEEDRATE/CAPACITY
- TEMPERATURE
- PRESSURE
- CARBON CONVERSION
- EFFICIENCY
- OXYGEN/COAL RATIO
- STEAM/COAL RATIO
- CARBON RECYCLE
- CAT/CHEM ADDITION
- CAT & CHEM RECOVERY/RECYCLE
- SOLIDS RECOVERY
- BY-PRODUCT RECYCLE
- COAL SIZE REQUIREMENT
- TURNDOWN
- NO. OF STAGES
- COMPLEXITY

GAS CLEAN-UP & COOLING

- GAS FLOWRATE
- TEMPERATURE
- PRESSURE
- HEAT RECOVERY STAGES
- STM PRESSURE
- COOLING WATER STAGES
- CLEANING STAGES
- MECHANICAL SEP
- WATER SCRUBBING
- % SOLIDS
- % H_2O
- % H_2S, COS
- % HYDROCARBONS (TAR, OIL)
- % CONTAMINANTS (NH_3)
- ASH HANDLING/RECOVERY

FIGURE 6.7 NON-STANDARD SYSTEMS COMPARISON CRITERIA

SRS

with the particular advanced coal conversion process and equipment/component development requirements. Certain requirements have greater potential impact on process commercial feasibility than others. To account for this disparity, weighting factors based on experience in the chemical processing industry with the application of new technology can be applied when computing cost-capacity factors for non-standard systems.

Sources indicate that it is industry practice in estimating the cost of chemical process plants with significant amounts of new technology to include contingencies of up to 30% of total plant cost. This emphasizes the need to place confidence intervals on the cost estimates made for both standard and non-standard systems to provide cost ranges that could occur. The confidence intervals can also reflect industry accepted accuracies of estimates. The estimates for newer technology such as that in the gasification section of a plant would not be expected to be as accurate as those for areas such as solids treatment, therefore, the confidence interval for the gasification system would cover a broader range. After confidence intervals are established for each major plant system capital, operating, and maintenance cost estimate, expected values can be projected and a total plant cost estimate made.

The comparative technical and economic assessment methodology described above, if further refined and enhanced, should be a useful tool in evaluating advanced coal conversion processes on a consistent basis to provide recommendations on development prioritization.

7.0 ADDITIONAL STUDIES

Several special emphasis tasks were performed and results were submitted during the course of this effort which included analyses and assessments in the following areas:

- Development status of the Texaco and Westinghouse gasification processes
- Peat conversion projects
- Major coal conversion demonstration and commercial projects.

The Texaco pilot plant in Montebello, California was visited and discussions were held with operating personnel at the plant. Contacts were also made with TVA personnel concerning the operation of the Texaco gasification plant at the TVA National Fertilizer Development Center in Muscle Shoals, Alabama. Review of the Texaco operations indicate they are similar to other plant operations in that operational problems have occurred especially during the start-up. Observations made during the pilot plant visits indicated that the two major problems with operation of the gasifier were in the areas of slag removal and the refractory lining. The Texaco process appears to be proven at the test scale. The problems reported at the Muscle Shoals plant have been for the most part associated with mechanical equipment although there have been problems with slag removal.

An assessment was made of the Westinghouse process development status and it was found that the testing of this process is well advanced. It has been tested in several modes of operation and several coals have been tested in the plant operated as a fully integrated facility. The process has experienced problems in start-up and operation that have been experienced in other facility operations but appears ready for commercial application. Operating results for the time period of June 1978 - September 1979 are shown in Figure 7.1.

The major coal conversion demonstration and commercial projects in the United States which included:

- Great Plains
- CONOCO
- ICGG
- Memphis
- W. R. Grace
- SRC I
- SRC II
- Low BTU Fuel Gas
- H-Coal
- Exxon Donor Solvent

were reviewed and their programmatic and budgetary status, plant descriptions, and project participants described.

Dates of Run	Run Number	Time	Oxidant	Solid Feed(s)	Highlights of Run	Cause of Shutdown	Inspection	#Sets of Data
June 25-29 1978	TP-018-1	39 hrs	Air	Coke breeze	First attempt at O_2-blown gasification	Numerous mechanical problems.		None
July 17-31	TP-018-2	180 hrs	Oxygen	1. Coke breeze 2. Pittsbg.coal	1. Fed caking coal 46 hrs. without problems in operation. 2. Ran O_2 at 20-36% vol. 3. Product gas HHV 165-260. 4. Tested two temperatures and two steam routes.	Problems with cyclone		Six
Aug 16-23 1978	TP-018-3	99 hrs	Oxygen	Pittsbg.coal	1. Ran coal with steam/02 2. Steam split: air tube and grid. 3. O_2 range 35-50%. 4. Gas from coal at 200-220 HHV 5. All fines collected and recycled.	Plug at cyclone entry .	Reactor had a minor buildup of sintered material at transition pieces.	Three
Sept 12-17 1978	TP-018-4	69 hrs	Oxygen	Pittsbg.coal	1. Ran coal with steam/O_2 for 48 hrs. 2. Tested revised cyclone entry. 3. Ash concentrated to 70%. 4. Gas from coal at 210-235 HHV. 5. All fines collected and recycled.	Plug at cyclone entry.	Minor buildup in reactor.	Two
Sept 25-Oct 5, 1978	TP-018-5	118 hrs	Oxygen	Pittsbg.coal	1. Ran coal with steam/02 for 85 hrs. 2. A 24-hr downtime for repair requ'd during the run. 3. Fines recycled only during last of the run. 4. Gas from coal at 220-240 HHV. 5. Ash contained sintered material.	Plug at cyclone entry.		Five
Oct.18-29 1978	TP-019-1	140 hrs	Oxygen	1. Rosebud coal 2. Indiana coal	1. Ran 70 hrs on Rosebud, with gas at 260-306 HHV. O_2 at 48-70%, 60% ash withdrawn. 2. Ran 20 hrs on Indiana coal, w/gas at 238HHV. O_2 at 57%, 34% ash withdrawn 3. Fines recycled part-time. 4. Wet coal feeding problems.	Packing leak at ash starwheel feeder.	No buildup in cyclone or reactor.	Six

FIGURE 7.1 WESTINGHOUSE PLANT OPERATION

Dates of Run	Run Number	Time	Oxidant	Solid Feed(s)	Highlights of Run	Cause of Shutdown	Inspection	#Sets of Data
Nov 6-17 1978	TP-019-2	180 hrs	Oxygen	1. Indiana coal 2. W.Kentucky coal	1. Ran 90 hrs on Indiana coal, with gas at 180-190 HHV. O_2 at 48%. 2. Ran 60 hrs on W.Kentucky coal, with gas at 210 HHV. O_2 at 35%. 3. All fines collected and recycled. 4. Many problems with wet coal caused upsets, led to poor Ash/char separation.	Plugging at ash removal system due to improper thermocouple installation.		Seven
Jun.14-24 1979	TP-022-1	82 hrs	Oxygen	Pittsburgh coal	1. First test of modified cyclone. 2. Minimum steam input. 3. Oxygen-blown 63 hrs, Coal feed 53 hrs.	Large bridge of solid material at grid area of gasifier	Major solids buildup in cyclone	
Jun.27-July 3 1979	TP-022-2	89 hrs	Oxygen	Pittsburgh coal	1. Had excustion of oxygen flow controller. 2. Idling periods required for starwheel feeder repair. 3. Withdrawal restricted by sintered material. 4. Coal feed 54 hours. 5. Product gas HHV was 300 with highsteam/coal ratio.	Restriction of product gas flow by major buildup in cyclone.	1. Slag buildup on gasifier walls 2. Air tube out of alignment.	
July 26-August 2 1979	TP-023-1	91 hrs	Oxygen	Ohio #9 coal	1. Air tube relocated 9" below grid 2. Water injection used for first time. 3. Withdrawal restricted by sintered material. 4. Oxygen-blown 46 hours, coal feed 30 hrs.	Blocked ash withdrawal port	Cyclone was clean	
Aug. 14-19 1979	TP-023-2	57 hrs	Oxygen	Ohio #9 coal	1. Modified air tube. 2. Lower O_2 concentrations used. 3. Learned more about ash withdrawal system restrictions. 4. Oxygen-blown 29 hrs, coal feed 21 hrs.	Bridging of sintered material in ash withdrawal piping.	Cyclone was clean.	
Sept. 12-29 1979	TP-025-1	223 hrs.	Air	1. Coke Breeze 2. Indiana #7 coal	1. New, smaller annulus in use, gave good responses, lower RG use. 2. Delumper installed but failed early in run. 3. Three idling periods requ'd for repairs. 4. Operation was feed rate limited 5. Longest run to-date.	Blocked ash withdrawal port	1. Blockage of ash withdrawal due to clinkers formed at thermowells. 2. Cyclone was clean.	

FIGURE 7.1 (Continued)

8.0 CONCLUSIONS

The processes studied in this effort are considered to be representative of the advanced processes in terms of development requirements. They were analyzed to the depth required to identify the major problem areas.

It was determined that all the coal conversion processes which were studied had similar mechanical start-up problems in areas such as valves, pumps, and instrumentation. The problems were also similar to those that had been experienced in other pilot plants and in some foreign commercial plants. It appears that the design of the advanced process test facilities were similar (especially the non-reactor equipment) to other pilot plants in that the designs applied the standard commercial practice of utilizing "off the shelf" equipment. The major problems in the advanced process facilities were around the reactors; however, the "normal" mechanical/maintenance type problems often caused more down time than the reactor related problems. Consequently, mechanical equipment and components and instrumentation must be considered as requiring further development to enhance the reliability of larger scale facilities. It should be noted that although most of the problems occur during start-up (which often takes several months) there continues to be various problems in the operation of test facilities that are similar.

The development requirements of a process will eventually be reflected in the cost of a facility. The preliminary comparative assessment methodology presented provides a top-level systems approach for relating the development requirements to the cost of a commercial scale facility on a consistent comparative basis when two or more processes are being considered. This methodology will require further refinement and validation before it can be applied to a wide range of processes. Much of the information obtained in this study that could be utilized as input to the comparative assessment model has been obtained from the developer of the process and not developed by the study team from the raw run data, therefore, data such as the efficiency of a process may not be calculated on a consistent basis with another process. These types of data must be used with care to insure consistency and that the data does not reflect undue optimism.

As more information is developed on the advanced processes, such as more reliable run data (energy and material balances, etc.), equipment performance reports, and larger scale tests the information in this report can be upgraded for utilization in determining development requirements and for comparative assessments.

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10.0 ADVANCED COAL CONVERSION PROCESS COMPENDIUM

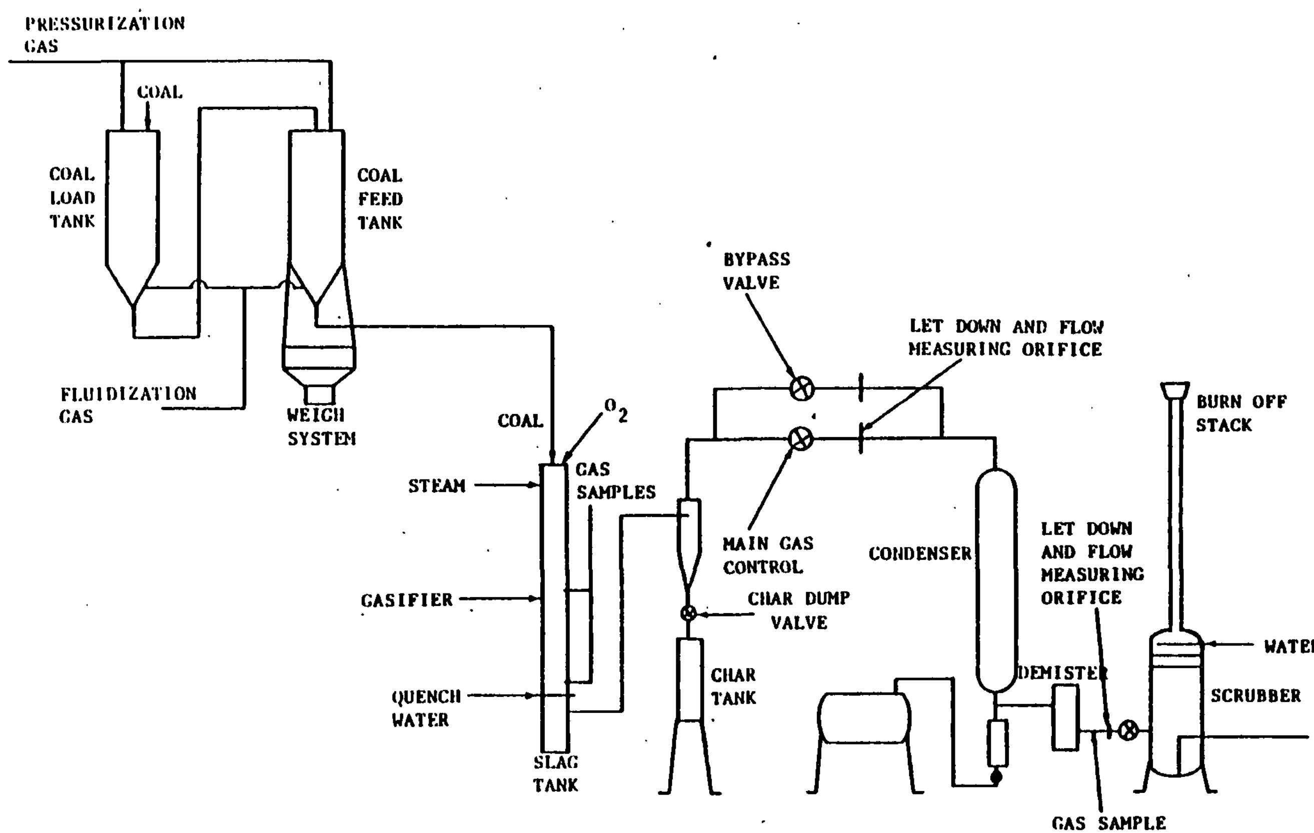
The need for a reference compendium of coal conversion process descriptions was recognized because of the large number of processes that have been developed or investigated in recent years. Summary process characteristics and development status information were compiled to serve as a preliminary reference source and is presented in the following pages. Emphasis was placed on those processes which currently, or relatively recently, had active development programs.

Information on additional processes was compiled, analyzed, and submitted to the COR during the course of the study.

TABLE OF CONTENTS

BELL HMF

Process Developer:	Bell Aerospace Textron
Scale:	0.5 TPH Process Development Unit
Location:	Buffalo, New York
Funding:	\$1.2M 1976-1978; \$0.4M 1978-1980
Sponsor:	DOE, New York State Energy and Research Development Authority (NYSERDA)
DOE Program Manager:	Louis Jablansky (301)353-3792 DOE Headquarters, Germantown, Maryland
Concept:	High efficiency mixing techniques are achieved using rocket engine technology. A high mass flux entrained flow gasifier reactor with rocket combustor-like feed system will decrease the required size of the reactor vessel. The process produces low-Btu gas in an air-blown system. An oxygen-blown system is used to produce medium-Btu gas.
Description:	Coal, oxygen and steam are fed to the single-stage slagging reactor to produce slag and raw gas. The effluent is quenched to 1900°F with water. The slag is separated from the raw product gas and sent to disposal. The raw product gas is cooled from 1900°F to 600°F by generating steam in a heat recovery unit. The gas stream is then sent to a cyclone for char separation and then to simultaneous cooling and water scrubbing for final removal of the solid fines. The scrubbed gas stream (saturated with water) is routed to the shift section to obtain H_2 to CO ratio of 3. The gas stream then proceeds to gas clean up for final gas product.
Operating Conditions:	Temperature: 2530°F Pressure: 500 psia
Reactants:	Coal, oxygen, and steam.
Products:	Low and Medium-Btu gas.
Status:	Process development is continuing under DOE support.

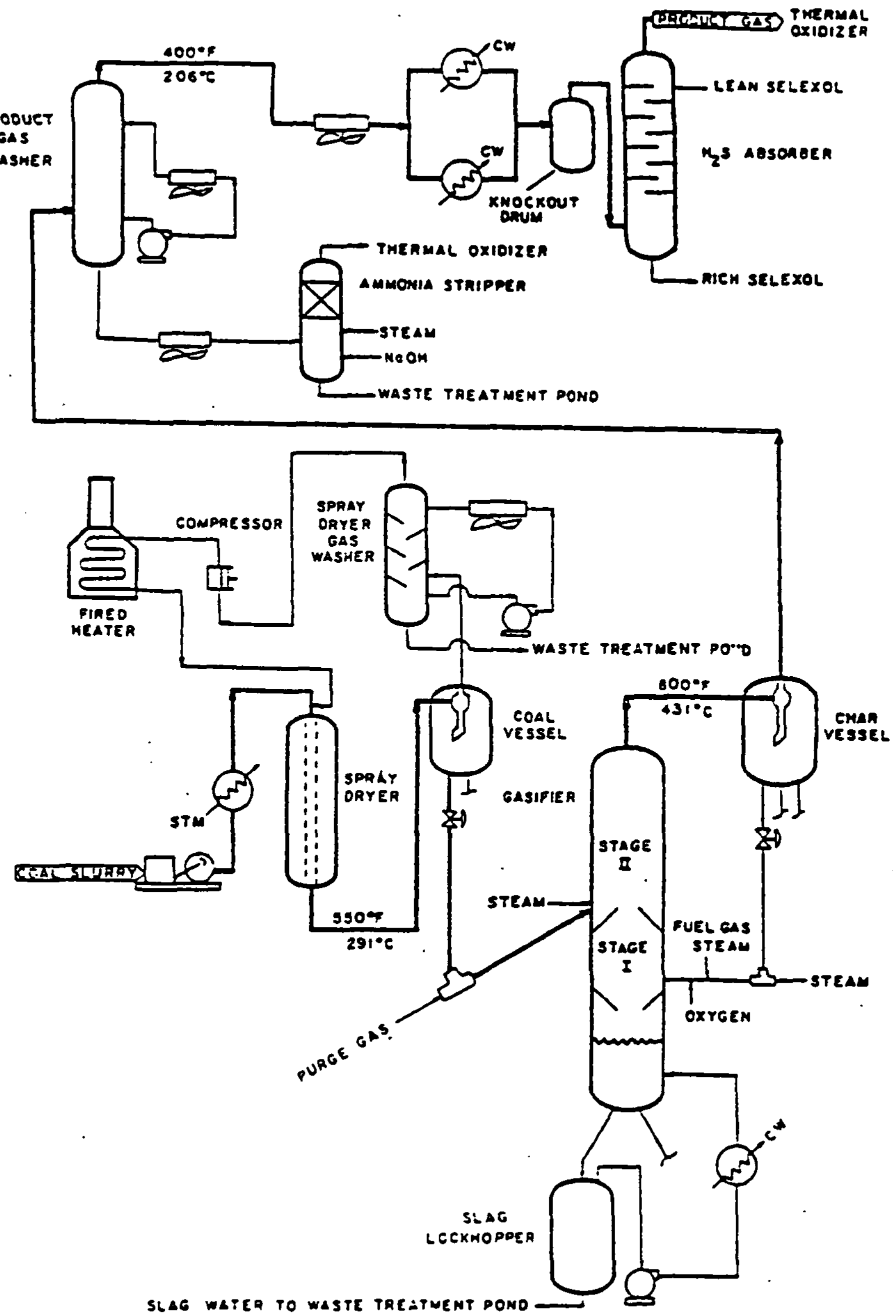


BELL HMF TEST FACILITY

SRS

BIGAS

Process Developer:	Bituminous Coal Research
Scale:	120 TPD Pilot Plant
Location:	Homer City, PA
Funding:	
Sponsor:	DOE
Concept:	Utilizes a three stage entrained gasifier operating at high temperature (2500°F) and pressure (1500 psig) in an oxygen-blown, ash slagging process to produce medium-Btu gas which is methanated to yield high-Btu gas.
Description:	The feed coal is slurried, pulverized, and passed through a spray dryer, then to two eductors. The coal then enters the gasifier through injector nozzles. Steam is injected through a separate annulus in the injector. Two streams combine at the injector tip and join the hot synthesis gas from the bottom stage. The coal is converted to methane, synthesis gas, and char. The raw gas rises through the gasifier, quenched by atomized water and sent to a cyclone separator where it leaves for further processing to yield a medium-Btu gas.
Operating Conditions:	Temperature: 1500 to 3000°F Pressure: 500 to 1500 psig
Reactants:	Coal, oxygen and steam
Products:	Medium-Btu gas
Status:	The Pilot Plant at Homer City, PA has been operating since 1976 - operating of plant to continue at least through FY81.
Advantages:	• Will accept all types of coal • Tars and oils are not produced

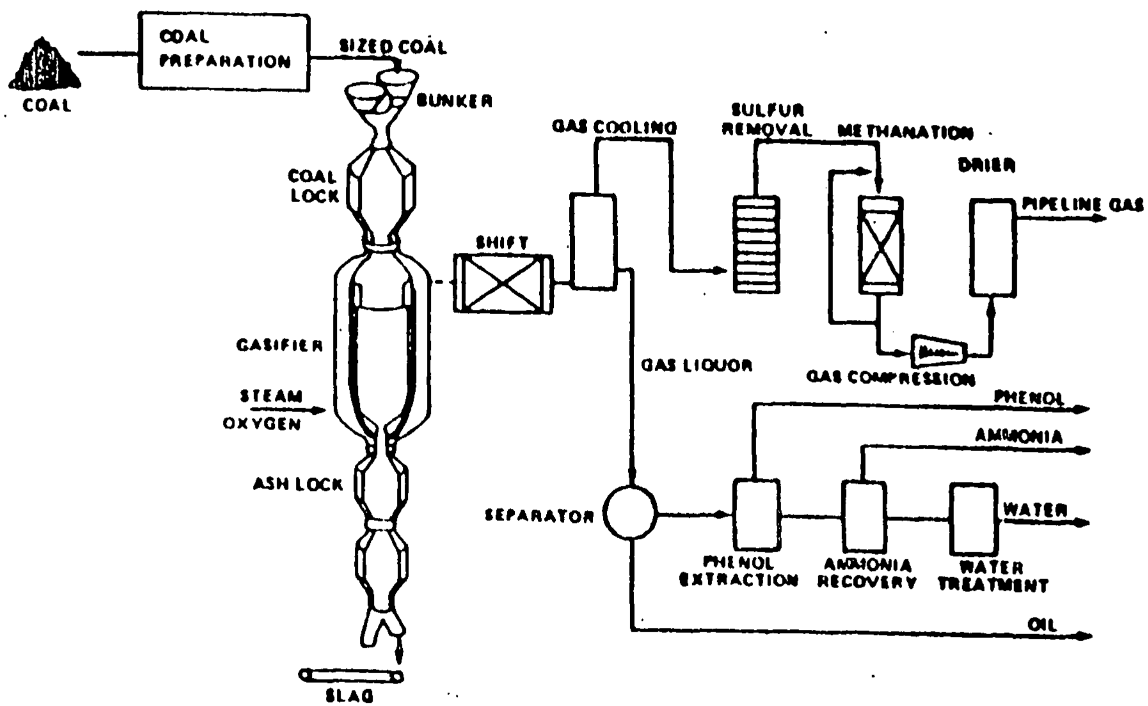


BIGAS PILOT PLANT

SRS

BRITISH GAS SLAGGING LURGI

Process Developer:	British Gas/Lurgi Co.
Scale:	Pilot Plant (about 300 TPD)
Location:	Westfield, Scotland
Funding:	
Sponsor:	DOE and several U.S. companies are funding demo plant
Concept:	This process utilizes a slagging fixed-bed gasifier which is a modification of the commercial lurgi dry ash process. The slagging process will accept caking coals and operates at higher temperatures.
Description:	Sized coal is fed into the gasifier through the top while steam and oxygen are injected into the gasifier through Tuyers. The mixture passes through the gasifier zones, carbon combustion, gasification, devolitization, and drying. The product gas is then scrubbed and cooled to remove tar and oil. The gas then passes through other refining steps to yield high-Btu gas.
Operating Conditions:	Temperature: 2000-2500^{o}F Pressure: 60-445 psig
Reactants:	Coal, steam, and oxygen
Products:	High-Btu gas
Status:	The plant in Westfield, Scotland is currently testing slagging operations of the lurgi gasifiers. Engineering design is underway for a 1200 TPD demonstration plant in Noble County, OH.
Advantages:	• High percentage of coal converted • High coal throughput • Low steam comsumption

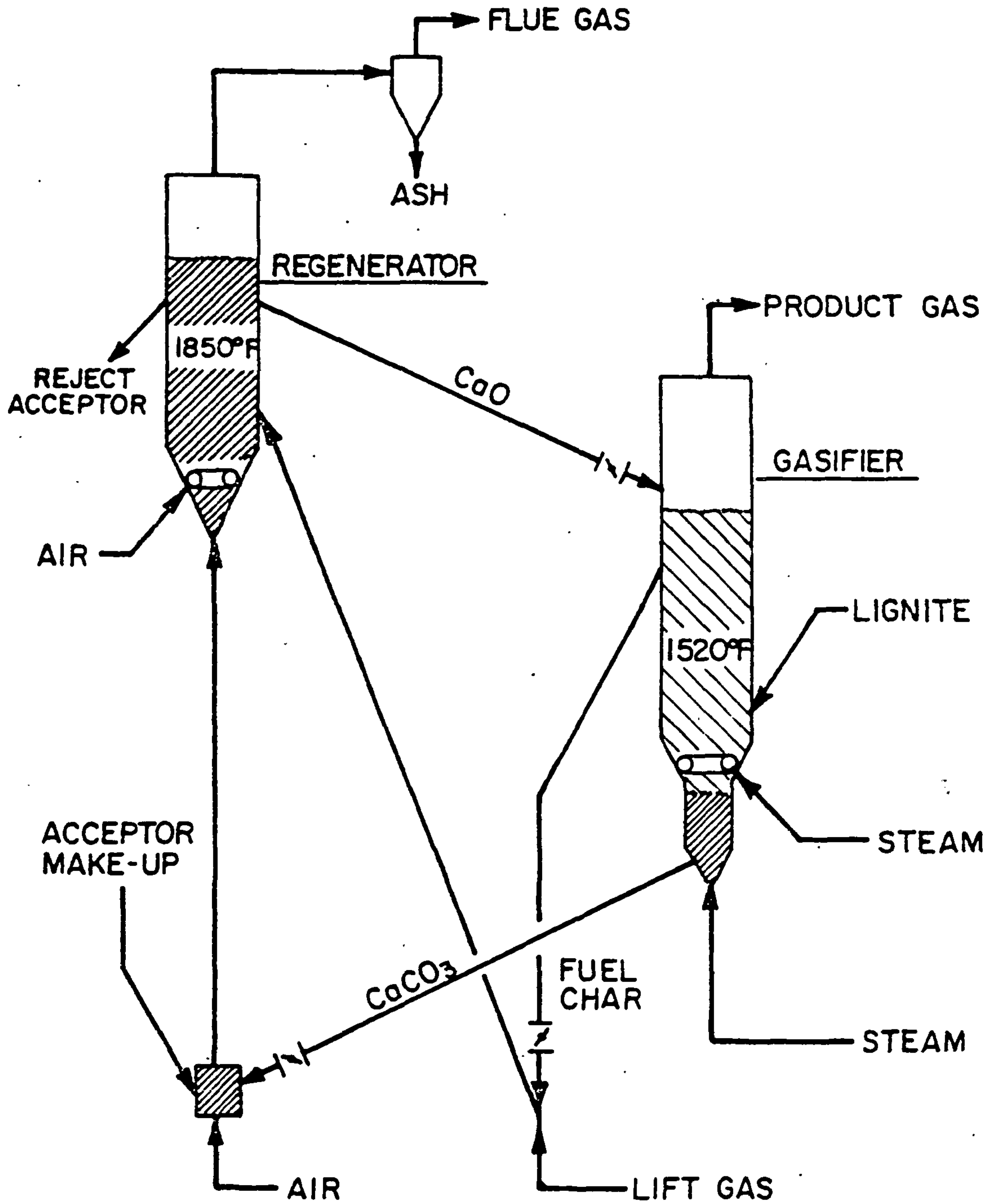


BRITISH GAS/SLAGGING LURGI PROCESS

SRS

CO_2 ACCEPTOR

Process Developer:	Conoco Coal Development Company
Scale:	30 TPD Pilot Plant
Location:	Rapid City, SD
Funding:	
Sponsor:	DOE
Concept:	This process features a continuously circulating regenerated CO_2 acceptor reacting with coal and steam in a fluid-bed reactor to produce a medium Btu gas.
Description:	Coal and steam enter the gasifier as the acceptor (calcined limestone or dolomite) is fed to the top of the gasifier's fluid bed. Spent acceptor is then calcined in a regenerator vessel. Devolatilization and gasification of the coal takes place in the presence of steam, CO, H_2, and the acceptor. The product gas leaves the gasifier through an internal cyclone. It is then cooled and scrubbed to produce a medium-Btu gas.
Operating Conditions:	Temperature: 1500 to 1850°F Pressure: 150 psig
Reactants:	Coal, Acceptor and steam
Products:	Medium-Btu gas
Status:	The testing program at the pilot plant has been completed and the plant has been shut down. Sponsors being sought for demo plant.
Advantages:	• Oxygen plant is not needed to produce Medium Btu gas • H_2S and CO_2 reacts with acceptor thus reducing product gas treatment requirements • Well suited for western lignite

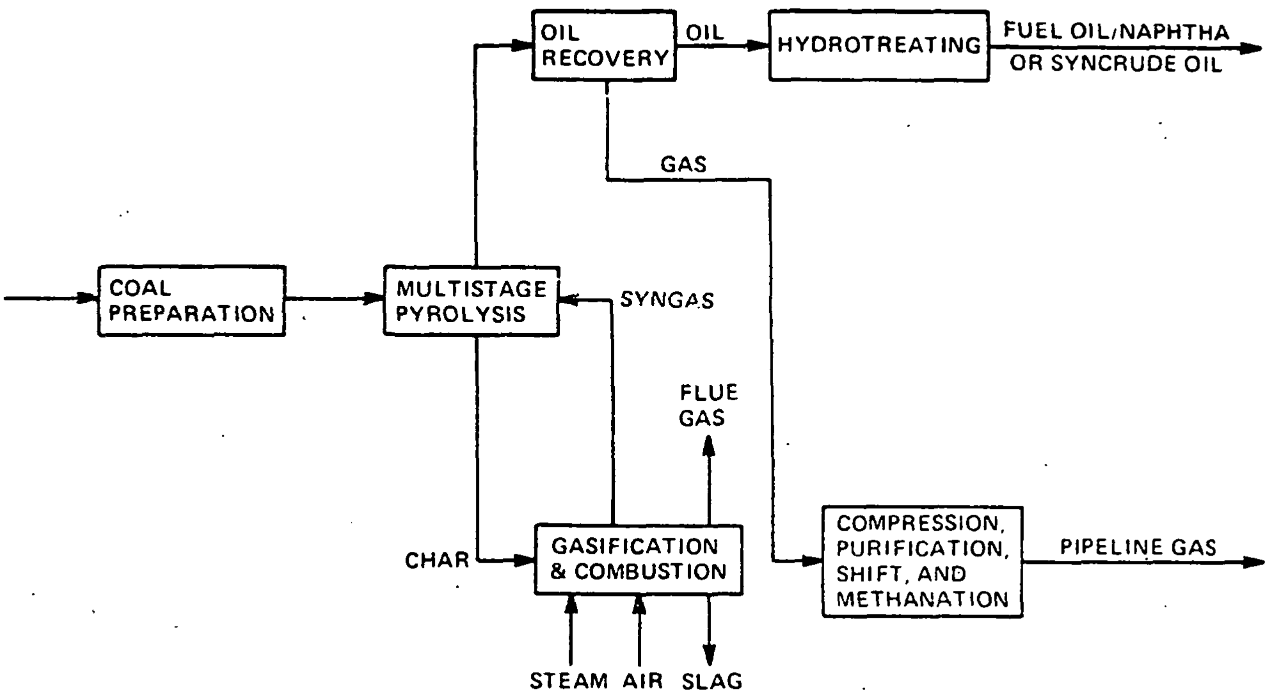


CO_2 ACCEPTOR PROCESS

SRS

COGAS

Process Developer:	Cogas Development Company
Scale:	36 TPD Pilot Plant
Location:	Princeton, NJ
Funding:	
Sponsor:	DOE
Concept:	Coal, synthesis gas, and steam are processed through three sub-units: multi-stage fluid-bed pyrolyzers, a fluid-bed gasifier, and a slagging type char fines combustor. The final product is a medium Btu synthetic pipeline gas.
Description:	Coal is treated in three fluidized bed pyrolysis stages. Heat for the pyrolysis is supplied from hot gases flowing counter-currently to the coal from the gasifier. The fluidizing medium for the first stage is supplied from the gasifier as flue gas. The char product of pyrolysis is fed to the gasifier to produce synthesis gas. The raw oil from the pyrolysis is upgraded to naphtha and fuel oils. The synthesis gas from the gasifier is compressed and cleaned for methanation. The resultant product gas is then methanated, dried, and compressed for utilization as a pipeline gas.
Operating Conditions:	Temperature: 600°F to 1600°F Pressure: 15-50 psig
Reactants:	Coal, synthesis gas, and steam
Products:	Synthetic pipeline gas, and oil
Status:	A Cogas demonstration plant with a capacity of 2210 TPD is currently being designed under DOE sponsorship by Cogas Development Company.
Advantages:	• Has a high thermal efficiency • Expected that the process will handle all types of coal



COGAS PROCESS

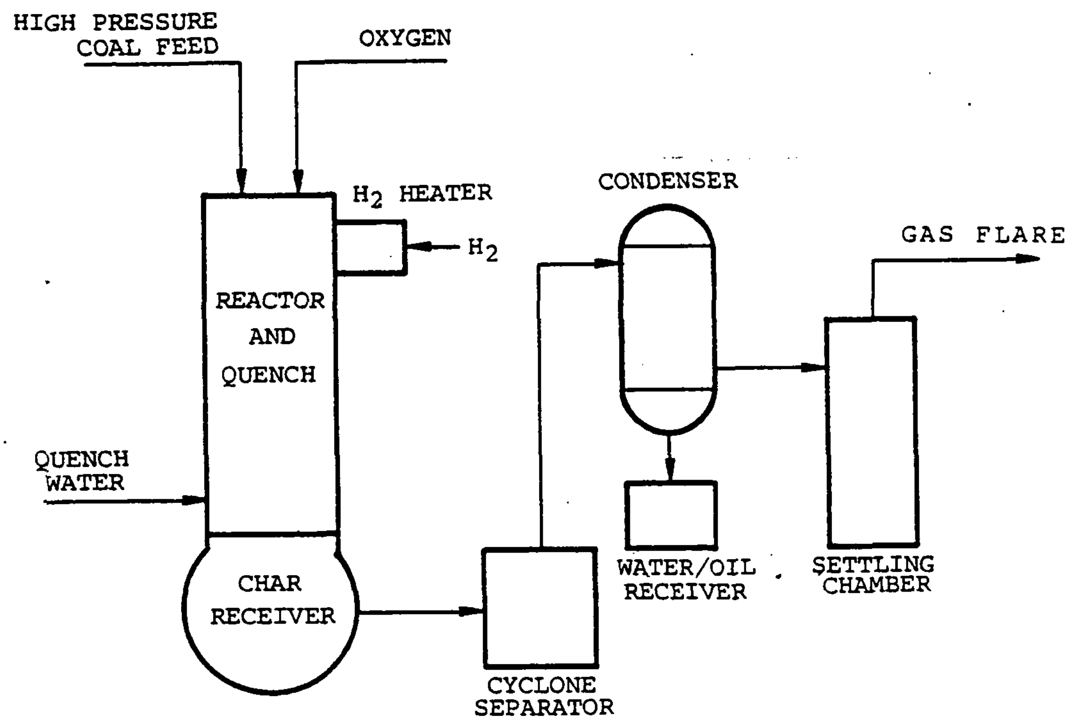
SRS

COMBUSTION ENGINEERING (TWO STAGE ENTRAINED GASIFICATION)

Process Developer:	Combustion Engineering, Inc.
Scale:	120 TPD Pilot Plant
Location:	Windsor, CT
Funding:	
Sponsor:	DOE, EPRI
Concept:	The gasification process is based on an air-blown, atmospheric-pressure, two stage entrained-bed slagging gasifier.
Description:	A portion of the coal is fed to the combustion stage to provide heat for the endothermic reaction. The remainder of the coal is fed to the air deficient reductor portion of the gasifier where it is contacted with hot gases entering the reaction zone from the combustor. The gasification process takes place in the entrainment portion of the reactor where the coal devolatilizes and reacts with the hot gases to produce the desired product gas. The gas is then cooled, cleaned, and passed through the Stretford process for hydrogen sulfide removal.
Operating Conditions:	Temperature: 1700-3200°F Pressure: Atmospheric
Reactants:	Coal, air, and steam
Product:	Low-Btu gas
Status:	The pilot plant began operation in 1978 and is currently operating. Plans are to operate the plant on oxygen. Combustion Engineering has received funding from DOE for preliminary engineering work on a 1800 TPD plant at Lake Charles, Louisiana to provide boiler fuel for 150 MW generating unit.
Advantages:	• Operates at atmospheric pressure • All coals can be processed without pretreatment • Fused ash is produced, minimizing disposal problem • Virtually all carbon in the coal can be consumed

CS/R HYDROPYROLYSIS

Process Developer:	Rockwell International
Scale:	18 TPD PDU
Location:	Canoga Park, CA
Funding:	FY80 \$3 M FY81 \$5 M
Sponsor:	DOE
Concept:	This process employs a rapid non-catalytic coal hydrogenation technique, termed flash hydropyrolysis, in an entrained flow reactor to accomplish the coal/hydrogen reaction.
Description:	Pulverized coal and oxygen is fed to the reactor and entrained rapidly with 2000°F hydrogen using a rocket engine injector element. The reactants react for about 10-100 milliseconds. The reactor effluent is quenched, utilizing a set of water spray nozzles or a heat exchanger, or both and the liquids are condensed.
Operating Conditions:	Temperature: 1500-1800°F Pressure: 35-100 atms.
Reactants:	Coal, hydrogen, oxygen
Products:	Hydrocarbon Liquids, SNG, benzene
Status:	The process has been tested in a 1 TPH short run PDU to develop the reactor. An 18 TPD continuous unit is under construction. Startup may occur in 1981.
Advantages:	• Potentially high process efficiency • No slurry handling in coal feed system • Simple de-ashing • High flexibility of product output



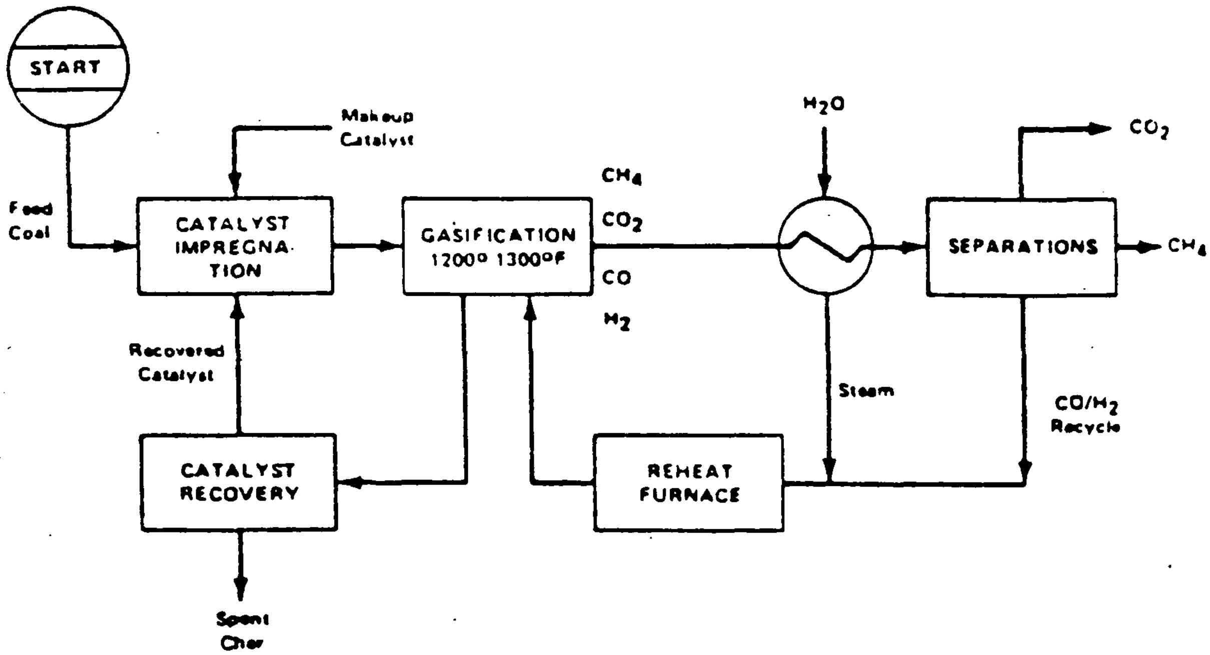
CS/R HYDROGASIFICATION PROCESS

(1/4 TPH UNIT)

SRS

EXXON CATALYTIC

Process Developer:	Exxon Research and Engineering Company
Scale:	PDU 1 TPD
Location:	Baytown, TX
Funding:	
Sponsor:	DOE is funding PDU operation (DOE will not fund pilot)
Concept:	This process features a fluidized-bed, steam-carbon gasification process and methanation using a potassium catalyst.
Description:	Coal is fed to the catalyst impregnator prior to entering the gasifier. After entering the gasifier the coal is reacted with steam and recycled carbon monoxide and hydrogen. The product gas leaving the gasifier goes through heat recovery and then to a separator. In this step carbon monoxide and hydrogen for recycle, product methane, and carbon dioxide are produced. The end product is a medium-Btu gas which is methanated to high-Btu gas.
Operating Conditions:	Temperature: 1500-1700°F Pressure: 45 psig
Reactants:	Coal, steam, catalyst
Product:	High-Btu gas
Status:	The PDU will operate on DOE funds at least through 1980. A 100 TPD pilot is being planned for 1985 operation in Rotterdam, Netherlands.
Advantages:	• Will accept all types of coal . • Coal is converted in a single step • High thermal efficiency • Plant can use air to produce high Btu gas



EXXON CATALYTIC GASIFICATION PROCESS

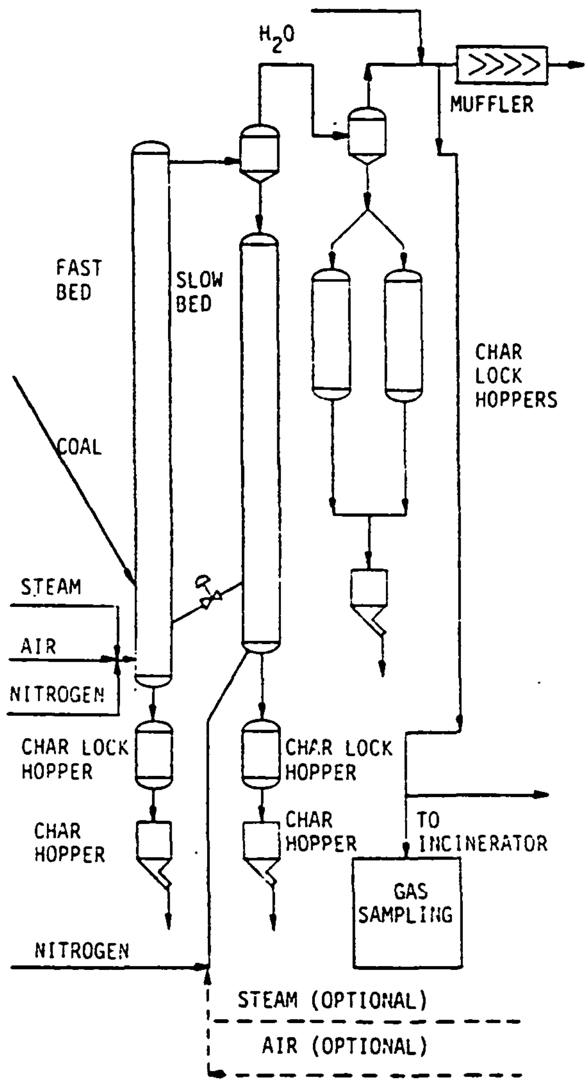
SRS

GFETC SLAGGING FIXED-BED

Process Developer:	Grand Forks Energy Technology Center
Scale:	Pilot Plant 25 TPD
Location:	Grand Forks, ND
Funding:	
Sponsor:	DOE
Concept:	This is a pressurized, slagging, fixed-bed process. The unit is essentially a variation of the dry ash Lurgi process. In the gasifier, the temperature is increased above the fluid temperature of the ash which is removed as a molten slag. The product gas is a medium-Btu synthesis gas.
Description:	The raw coal enters the gasifier through a lock hopper. The coal is first heated by hot gases and as it descends in the gasifier it is devolatized. The coal then enters the gasification zone where it reacts with oxygen and steam. The molten slag drains into a water quench bath. The product gas enters a spray washer, depressurizers, and coolers. The product is a medium-Btu gas.
Operating Conditions:	Temperature: 2800°F Pressure: 5 to 27 atms.
Reactants:	Coal, steam, and oxygen
Products:	Medium-Btu synthesis gas
Status:	Plant has been modified to process caking coals and is currently in operation.
Advantages:	• Coal conversion three to four times better than in dry ash process • Requires only one-fourth the steam as dry ash process

HRI FAST FLUIDIZED-BED

Process Developer:	Hydrocarbon Research, Inc.
Scale:	600 lb/hr PDU
Location:	Trenton, NJ
Funding:	
Sponsor:	DOE
Concept:	This process uses a fast fluid-bed gasifier for coal conversion. Two cyclones are used for solids removal and separation of the product gas.
Description:	The coal and char fed from a companion slow fluid-bed gasifier reacts with air and steam fed into the bottom of the generator. The product gas from the gasifier passes through a primary cyclone to remove solids. Gas and particulates from the primary cyclone are passed to a secondary cyclone for further separation. The final product is a low-Btu gas.
Operating Conditions:	Temperature: 1700°F Pressure: 150 psig
Reactants:	Coal, air and steam
Products:	Low-Btu gas
Status:	A 10 TPD pilot plant has been proposed. Higher temperature testing is being done at the PDU in Trenton, NJ
Advantages:	• Higher throughput • Better turndown capability • No tar formation

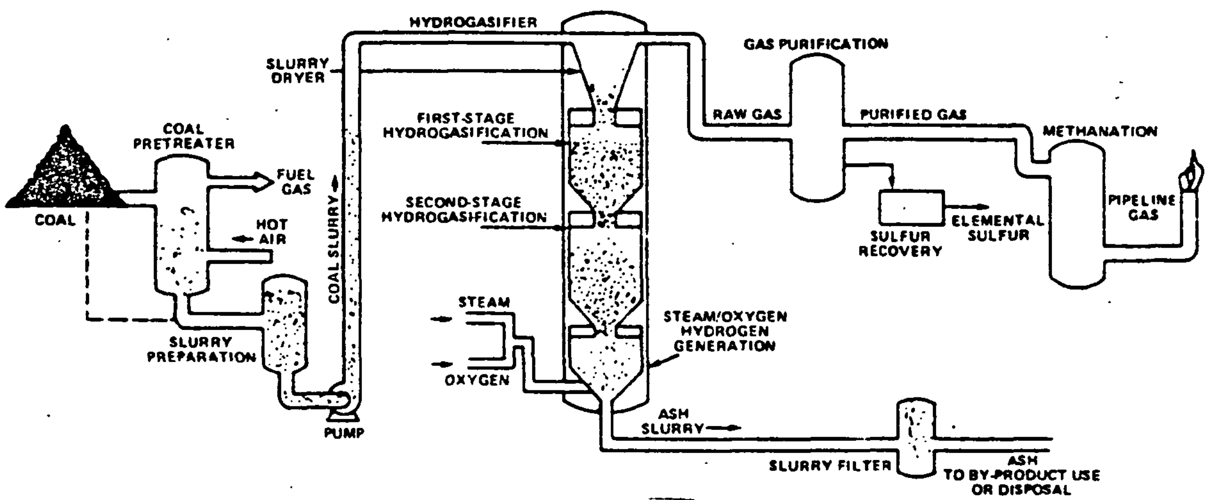


HRI FAST FLUIDIZED BED PROCESS

SRS

HYGAS

Process Developer:	Institute of Gas Technology (IGT)
Scale:	80 TPD Pilot Plant
Location:	Chicago, IL
Funding:	
Sponsor:	DOE
Concept:	The Hygas process is a two-stage hydrogasification process which converts a coal and oil slurry to a medium-btu gas.
Description:	The coal-oil slurry is injected into the gasifier at the top and the oil is driven off as a vapor in the top section of the gasifier. Dried coal falls to the bottom of the first hydrogasification stage where it is entrained upwards with high velocity gas rising from the second stage. The hydrogen in the gas reacts with the coal to form methane. Char falls into the second stage where it reacts with hydrogen and steam. After leaving the hydrogasifiers the raw gas is quenched, scrubbed, shifted, treated for CO_2 and H_2S removal, and methanated to produce a medium-Btu gas.
Operating Conditions:	Temperature: 800 to 1850°F Pressure: 1155 to 1175 psig
Reactants:	Coal, steam, and oxygen
Products:	Medium-Btu gas
Status:	IGT is operating the Pilot Plant in Chicago to confirm design parameters and determine the inherent operability of the process technology for demonstration plant scale-up.
Advantages:	• Offers an integrated system for high pressure hydrogasification • 65% of the methane in SNG production would be formed in the gasifier

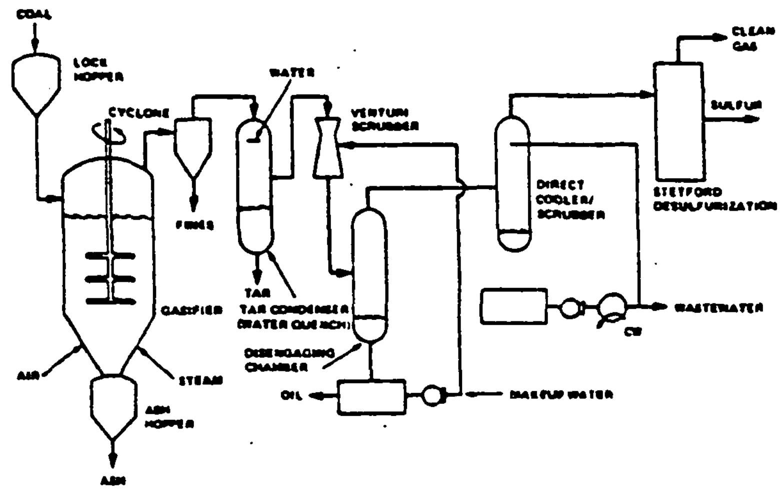


HYGAS PROCESS

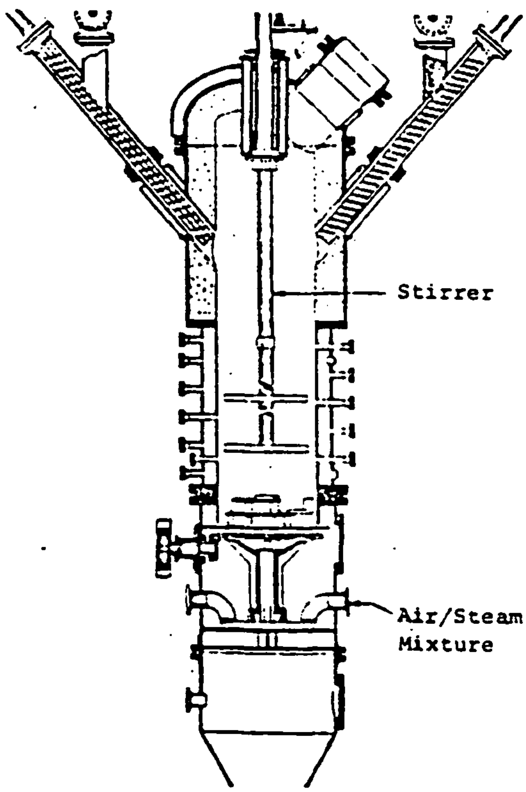
SRS

METC STIRRED FIXED-BED

Process Developer:	Morgantown Energy Technology Center
Scale:	20 TPD Pilot Plant
Location:	Morgantown, WV
Funding:	
Sponsor:	DOE
Concept:	The METC process uses an atmospheric stirred fixed-bed gasifier built by McDowell-Wellman. Recently a Holmes-Stretford gas cleanup system was added. The gasifier was later upgraded to 300 psig operation. The process produces a low-btu gas.
Description:	Coal is gravity-fed into the gasifier to form a bed on the grate. An air-steam mixture is fed from below the grate and flows upward through the descending coal, gasifying and partially burning it. The product gas leaves the gasifier and passes through two pressure letdown orifices, cyclone separator, and other purifying processes to produce a low Btu gas.
Operating Conditions:	Temperature: 250-2400°F Pressure: Atmospheric to 285 psig
Reactants:	Coal, air, and steam
Product:	Low-Btu gas.
Status:	The METC operation has been continually upgraded to process many types of coal. The pilot plant is currently operating.
Advantages:	• Stirred system agitates bed to prevent plugging of system by caking coals



STIRRED FIXED BED GASIFICATION PROCESS



GASIFIER

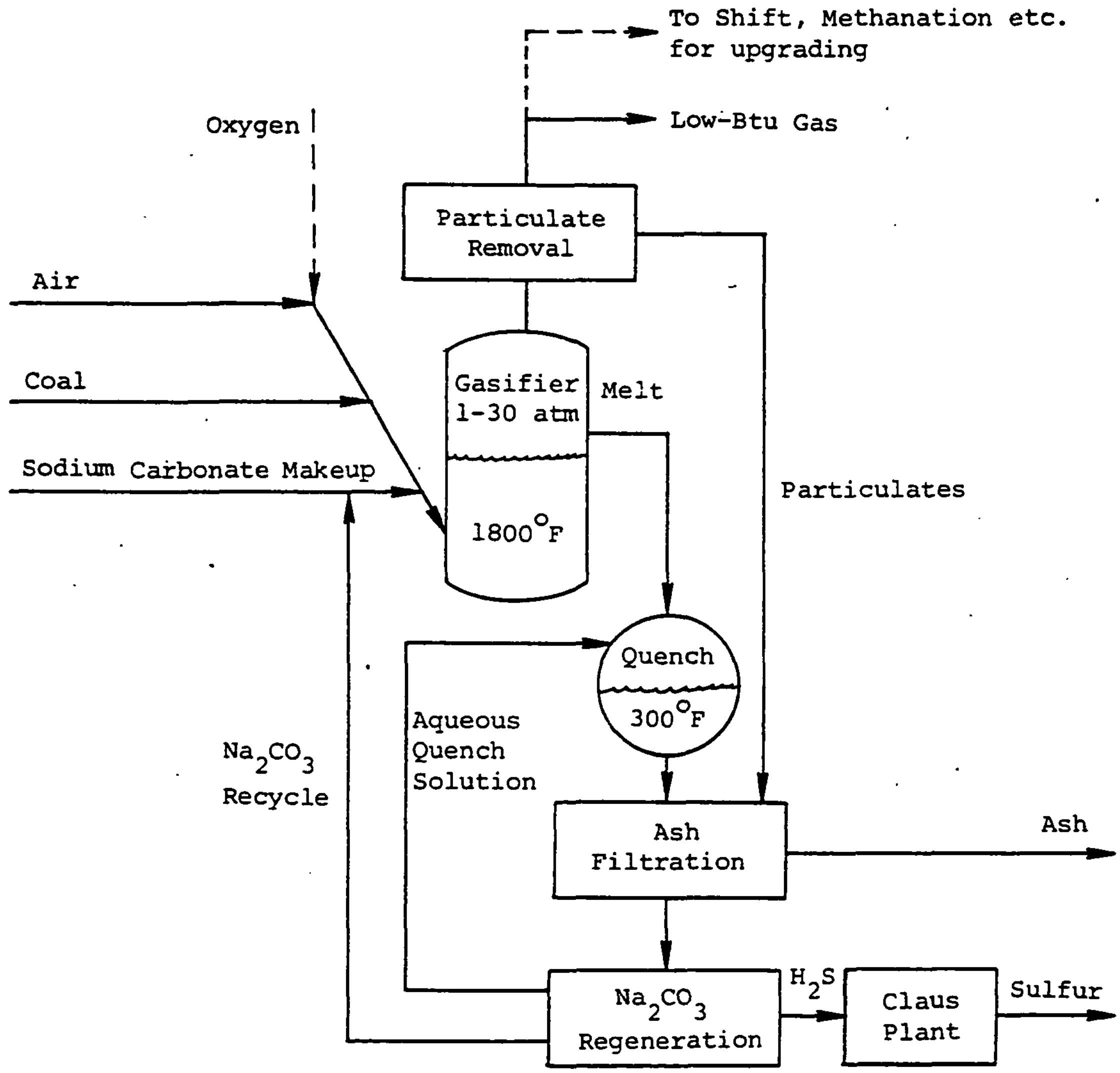
MOLTEN SALT

Process Developer:	Atomics Internation, Div. of Rockwell; M.W. Kellogg Co.
Scale:	PDU
Location:	Santa Susana, California
Funding:	FY80 ~ \$2 M FY81 ~ \$2 M
Sponsor:	DOE
Concept:	Low-or Medium-Btu gas is produced from reaction in a molten bath of sodium salts which results in high oxidation rates in the pressurized (10 atm) gasifier with ash and sulfur being trapped in the ash melt.
Description:	Crushed coal, sodium carbonate and air or oxygen are fed to the reactor where product gas is produced and sent to a cooling and particulate removal step. Ash and sulfur are retained in the molten bath and must be continuously withdrawn and treated to regenerate the salt for return to the gasifier. The ash is removed and the sulfur is removed in a Claus plant. After particulate removal the gas from the gasifier can be used as low-Btu fuel or upgraded to Medium-Btu gas or SNG.
Operating Conditions:	Temperature: 1800^{o}F Pressure: Atmospheric to 400 psi
Reactants:	Coal, Sodium Carbonate, air
Products:	Low-Btu gas, sulfur
Status:	During 1980 the 24 TPD PDU was operated successfully with air blown operation. Plans for the process includes operating the PDU in 1981 using oxygen to produce a medium Btu fuel/synthesis gas. Evaluation of the process for commercialization should come in early 1982.
Advantages:	The molten salt coal gasification process offers the following potential advantages:

- The process can handle caking coals without pretreatment
- The coal need not be finely pulverized, yet fines can be handled effectively
- The gas as it comes from the gasifier is essentially free of sulfur compounds, ash, coal tar, and nitrogen oxides
- The gasification reaction zone and hence the gasifier vessel are small because of the catalytic effect of the molten salt

- The process has good load-following capability because gasifier operation is not strongly affected by gas velocity.
- A major part (about 90 percent) of the heating value of the coal is retained in the product gas.

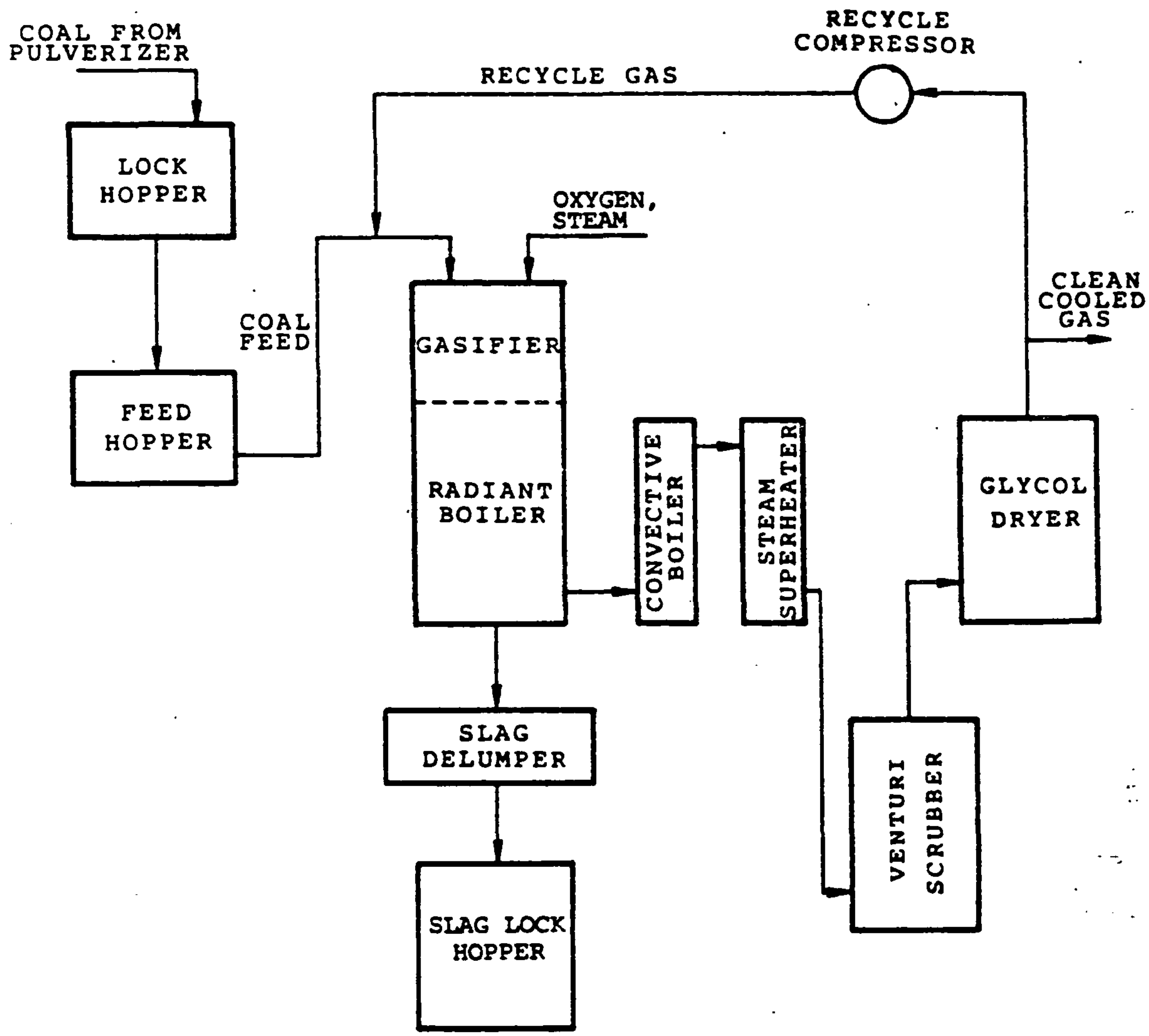
PROCESS FLOW DIAGRAM:



MOLTEN SALT GASIFICATION PROCESS

MOUNTAIN FUEL

Process Developer:	Mountain Fuel Resources/Ford, Bacon & Davis
Scale:	0.5 TPD PDU
Location:	Salt Lake City, Utah
Funding:	
Sponsor:	DOE is sponsoring Pilot Plant on 50/50 Basis
Concept:	This process features a pressurized, high rate, entrained flow, oxygen blown gasifier which operates at ash slagging temperatures (2800°F). Heat recovery is accomplished by both radiant and convective heat exchangers.
Description:	Pulverized coal is fed to the top of the gasifier and entrained in a stream of recycled product gas. The reaction products pass through a radiant heat exchanger directly below the reactor (slag is accumulated in a chamber at bottom of the heat exchanger). The partially cooled gases, entrained soot and fly ash pass through the convective heat exchanger and into a scrubber for particulate removal. The product gas is then filtered, cooled and after sulfur removal the medium btu gas is suitable for boiler fuel or synthesis gas.
Operating Conditions:	Temperature: 2800°F Pressure: 150 psig
Reactants:	Coal, oxygen, steam, recycle gas
Products:	Medium-Btu gas or synthesis gas
Status:	DOE is funding the 30 TPD Pilot Plant on a 50/50 basis. Engineering has been done and start of the project is awaiting contract signing by DOE. The Pilot Plant will fire brick kilns at the Interstate Brick Co. near Salt Lake City.
Advantages:	• Simple design • Small size for available throughput • Heat recovery can generate steam to increase efficiency • No phenols or hydrocarbons are produced



MOUNTAIN FUEL PROCESS

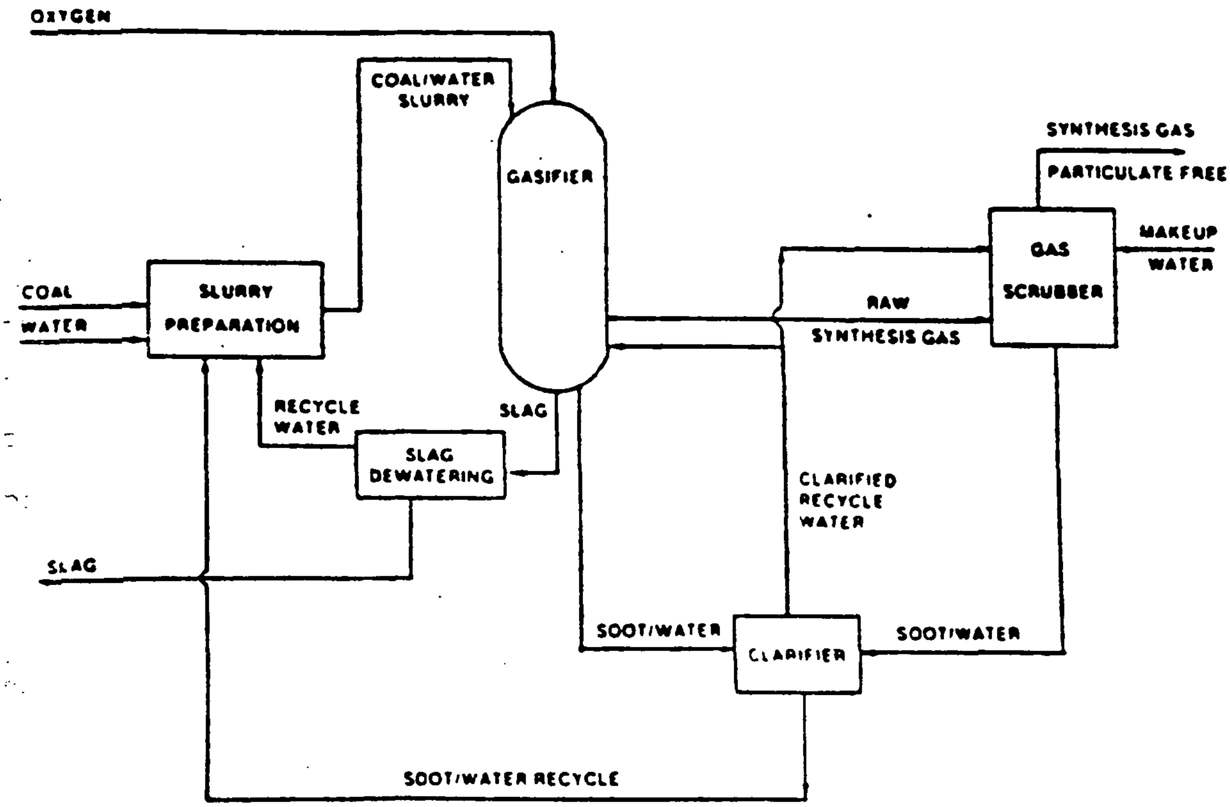
SRS

SYNTHANE

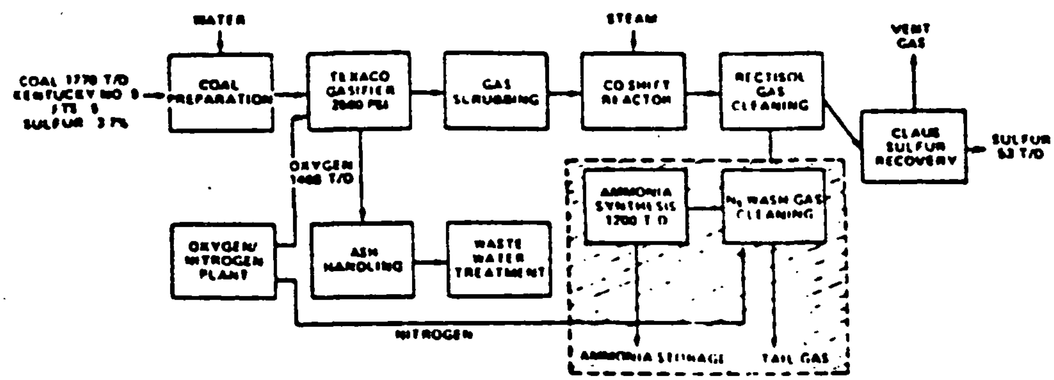
Process Developer:	Pittsburgh Energy Research Center
Scale:	72 TPD Pilot Plant
Location:	Bruceton, PA
Funding:	
Sponsor:	DOE funded the development of the process
Concept:	The synthane gasifier is a vertical, cylindrical, fluidized-bed reactor which operates at approximately 1000 psig and up to 1800°F. The product is a medium-Btu gas.
Description:	Pretreated coal enters at the top of the fluidized-bed gasifier, falls through hot gases rising from the fluidized-bed and is devolatilized. Steam and oxygen enter the gasifier just below the fluidized gas distributor. The gasification reaction occurs within the fluidized-bed. The product gas is passed through a venturi scrubber, a water scrubber (to remove char and tars), and other filtration processes. The purified gas must be reacted catalytically to convert hydrogen and carbon monoxide to methane.
Operating Conditions:	Temperature: 800 to 1800°F Pressure: 600 to 1000 psig
Reactants:	Coal, steam, and oxygen
Products:	Medium-Btu gas
Status:	Start-up of the pilot plant was in 1976 and operated until 1979, is currently mothballed. The plant could be used for other process development with minor modification.
Advantages:	• Accepts all types of coal

TEXACO

Process Developer:	Texaco Development Corporation
Scale:	170 TPD Pilot/Demonstration Scale
Location:	Muscle Shoals, AL
Funding:	
Sponsor:	TVA
Concept:	Coal, steam, and oxygen are reacted in an entrained gasifier under slagging conditions to produce medium-Btu gas.
Description:	Steam and oxygen are reacted with pulverized coal in the partial oxidation chamber and the resulting gas flows downward. A water spray beneath the partial oxidation chamber cools the gas which still contains some particulate matter. This particulate is removed by a water scrubber. Entrained slag is separated from the gas in the slag quench bath and discharges through the slag pot. The gas leaving the water scrubber is passed through a shift converter step and then to acid gas removal. The resulting gas is a medium-Btu synthesis gas.
Operating Conditions:	Temperature: slagging-3000°F; product gas-500°F Pressure: 300 to 1200 psig
Reactants:	Coal, steam, and oxygen
Products:	Medium-Btu gas
Status:	Texaco is currently operating a 15 TPD pilot plant in Montebello, CA and a 160 TPD pilot plant in West Germany; also the 170 TPD pilot plant in Muscle Shoals is undergoing start-up.
Advantages:	• Texaco gasifier has been proven with liquid and gaseous hydrocarbons • Hydrogen to carbon monoxide ratio is high, which is desirable if the gas is to be converted to methane or ammonia



TEXACO COAL GASIFICATION PROCESS



TEXACO GASIFIER FOR AMMONIA PRODUCTION

SBS

THAGARD

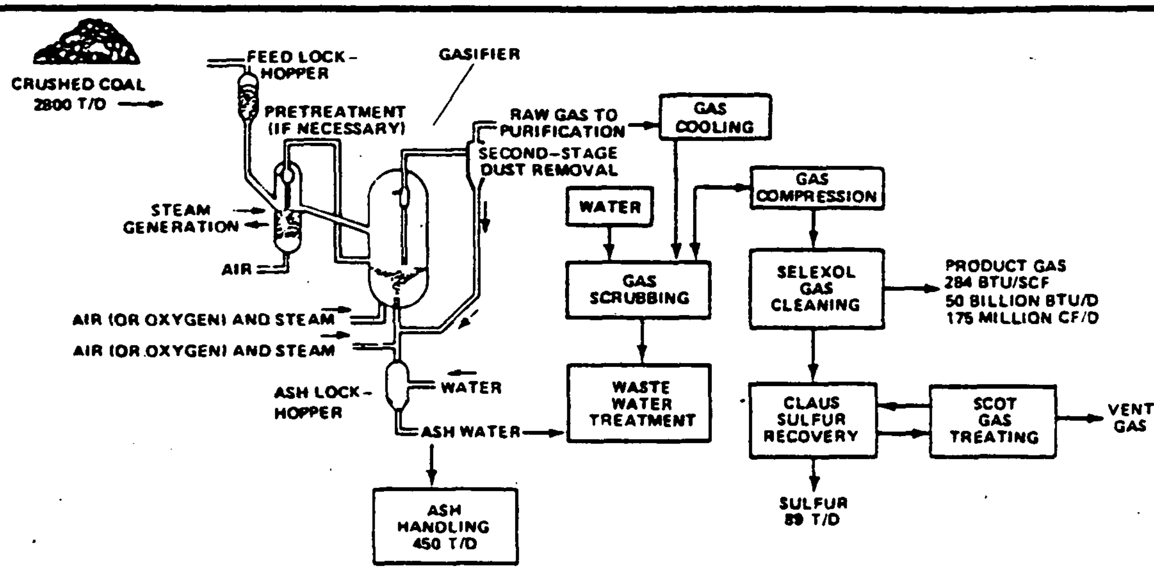
Process Developer:	Thagard Research Corporation
Scale:	Approximately 0.5 TPD PDU
Location:	Irvine, California / South Gate, California
Funding:	No Government funding
Sponsor:	Thagard Research / Southern California Edison
Concept:	The Thagard reactor is a high temperature fluid wall reactor that utilizes a method of energy transfer to the reactants that occurs from the heating of finely-divided reactants by the direct impingement of electromagnetic radiation.
Description:	The Thagard reactor consists of a water cooled jacket (pressure vessel) around an insulated shield that houses the radiation heat shield. Inside this radiation heat shield are electrodes that provide make up radiant heat to the reaction chamber which a tubular core of porous refractory material capable of emitting sufficient radiant energy to activate the reactants fed axially into the tubular space. A gas which is transparent to the radiation passes through the porous core to line the core as a buffer between reactants and core wall.
Operating Conditions:	Temperature: 4000°F Pressure: Reactor operates from 1-20 ATM
Reactants:	Coal, oxygen, catalyst
Products:	Syngas (products can vary widely depending on reactants)
Status:	Process has been well tested on the present scale for short duration. 200 TPD carbon black product facility due for start up in 1981. DOE funding being sought for further testing at the 24 TPD operating facility in South Gate, CA. Process is not well known because of limited information that has been put in the public domain during the development and testing of the process.

BCR (TRI-GAS)

Process Developer:	Bituminous Coal Research, Inc.
Scale:	1.2 TPD PDU
Location:	Monroeville, PA
Funding:	
Sponsor:	DOE funded through 1980
Concept:	The BCR process is a three stage, fluidized-bed gasifier. The goal of the multiple fluid-bed process is the gasification of both caking and non-caking coals with a low-Btu fuel gas as the only product.
Description:	The tri-gas process involves a three-stage gasification sequence. Stage 1 receives the raw coal and devolatilizes it. Stage 3 flue gas is used as the fluidized medium for Stage 1. The coal then flows by gravity to Stage 2 where devolatized coal is gasified with air and steam to generate the desired product gas. Stage 1 flue gas is fed to Stage 2 where the entrained tars and oils are gasified. The remaining char from Stage 2 is consumed in Stage 3 by fluidized combustion. The product gas is cooled and cleaned to produce a low-Btu Gas.
Operating Conditions:	Temperature: 800-2000°F Pressure: Up to 250 psig
Reactants:	Coal, air, and steam
Products:	Low-Btu fuel gas
Status:	The PDU began operation in 1976. Plant has been tested in the three stage mode and is currently being operated to test feasibility and range of coals to be used.
Advantages:	• Both caking and non-caking coals can be used • No wastes or by-products are produced

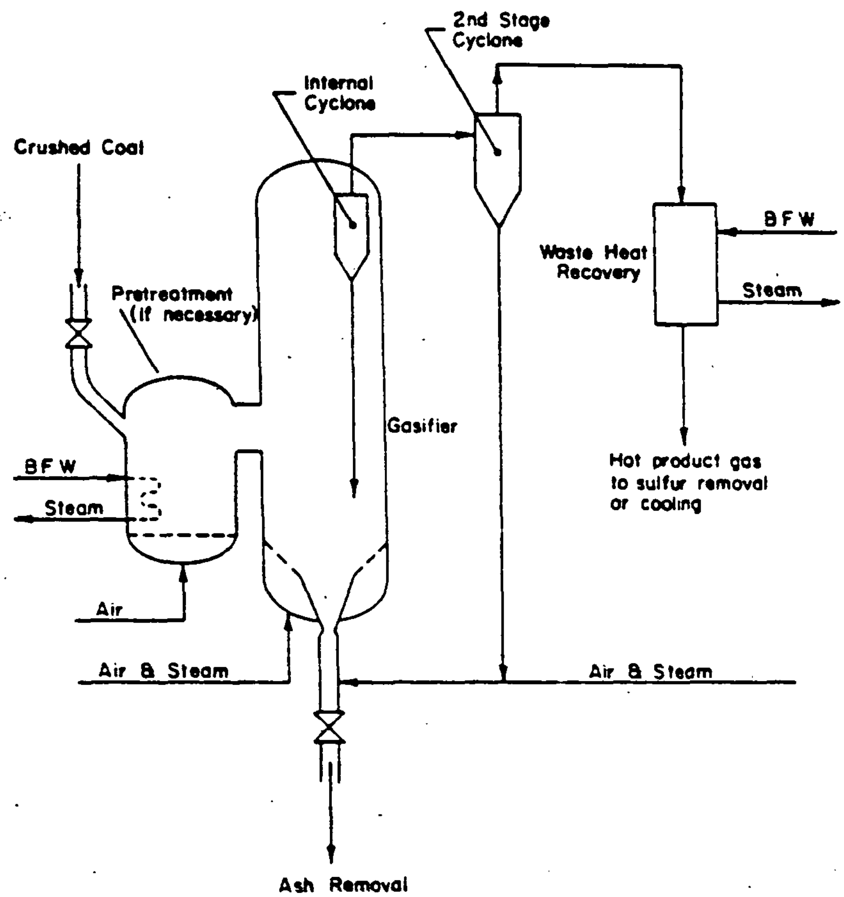
U-GAS

Process Developer:	Institute of Gas Technology (IGT)
Scale:	6 TPD Pilot Plant
Location:	Chicago, Illinois
Funding:	
Sponsor:	DOE
Concept:	The U-Gas process is a fluidized bed, oxygen-steam process operating under conditions which promote the formulation of ash agglomerates in the lower part of the bed and produces medium Btu gas.
Description:	The coal, steam, and oxygen are fed into the fluidized bed gasifier. The gases leaving the gasifier are passed through heat exchangers for heat recovery and fed to a venturi scrubber for the removal of ammonia, hydrogen sulfide, and coal dust. The fuel gas is then compressed to 195 psig and treated in a Selexol acid-gas absorption process to remove essentially all of the hydrogen sulfide and organic sulfur compounds and part of the carbon dioxide. The purified gas is ready for distribution.
Operating Conditions:	Temperature: 1900°F Pressure: 50-350 psi
Reactants:	Coal, oxygen, and steam
Products:	Medium-Btu gas
Status:	IGT is currently operating a 6 TPD pilot plant in Chicago; Memphis Light, Gas and Water was awarded a contract by DOE for design of a 2800 TPD demonstration plant in Memphis, TN.
Advantages:	• Can be used in combine-cycle power generation or to produce low-Btu industrial fuel gas. • Process has been chosen for scale up to demonstration plant.



U-GAS PROCESS

LOW-BTU FUEL GAS DEMONSTRATION PLANT (MEMPHIS)

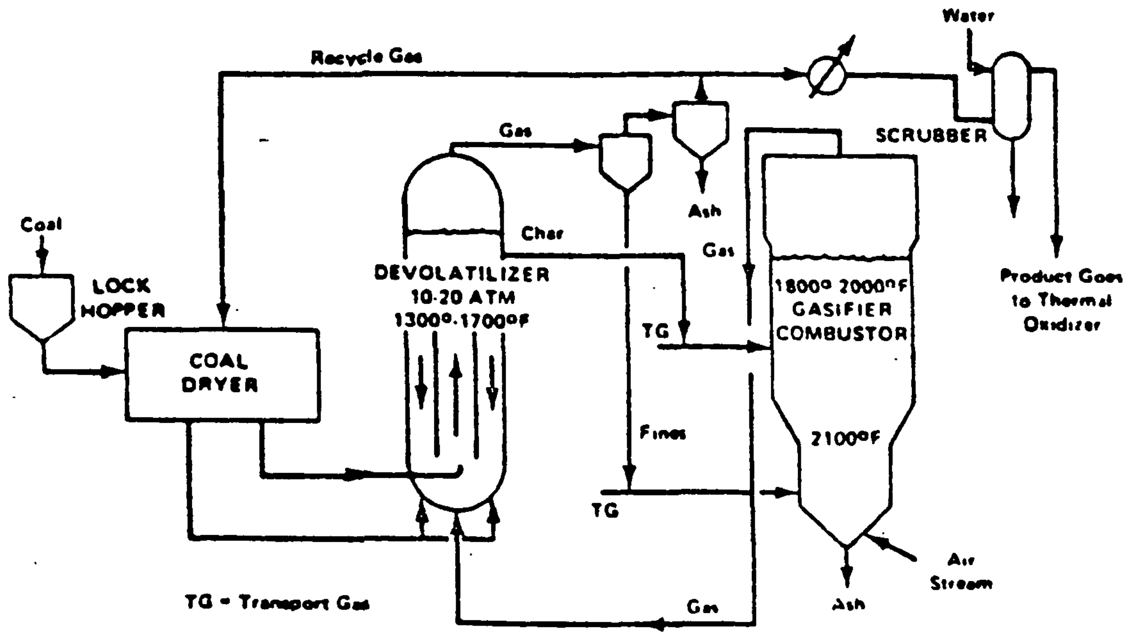


U-GAS GASIFIER

SRS

WESTINGHOUSE

Process Developer:	Westinghouse Electric Corporation
Scale:	15 TPD PDU
Location:	Waltz Mill, PA
Funding:	
Sponsor:	DOE
Concept:	This process consists of two principal process units (a pressurized fluid-bed devolatilizer and and a fluidized-bed gasifier combustor. The production of low-Btu gas is to be from a feed of caking coals without pretreatment.
Description:	Coal is introduced to the devolatilizer unit through a central draft tube. The coal and recirculating char are carried upward through the draft tube by hot gas entering the devolatilizer from the gasifier-combustor. This gas provides most of the heat to the devolatilizer; the gas devolatilizes and partially hydrogasifies the coal. Desulfurized gases exit at the top of the devolatilizer and flow to the cyclone collector. Fines are removed in the cyclones and recycled to the gasifier/agglomerator. The gas is then cooled and scrubbed with water to yield clean low Btu-gas.
Operating Conditions:	Temperature: 1500 to 2000°F Pressure: 200-250 psig
Reactants:	Coal, dolomite, air, and steam
Products:	Low-Btu gas
Status:	A 15 TPD PDU has been in operation in Waltz Mill, Pennsylvania since 1975.
Advantages:	• Expected to accept all types of coal • Generates no oils or tars • Gas produced is low in sulfur



WESTINGHOUSE TWO STAGE PROCESS

BATTELLE (COAL CATALYZATION PROCESS)

Process Developer:	Battelle Columbus Lab
Scale:	PDU 0.5 TPD
Location:	Columbus, Ohio
Funding:	
Sponsor:	DOE
Concept:	This process was developed to support DOE sponsored coal desulfurization studies and not as a process development.
Description:	
Operating Conditions:	
Status:	The PDU is still operational but there is no intention of developing the process to a higher scale because it is not economically feasible to scale up
Advantages:	

BERGIUS

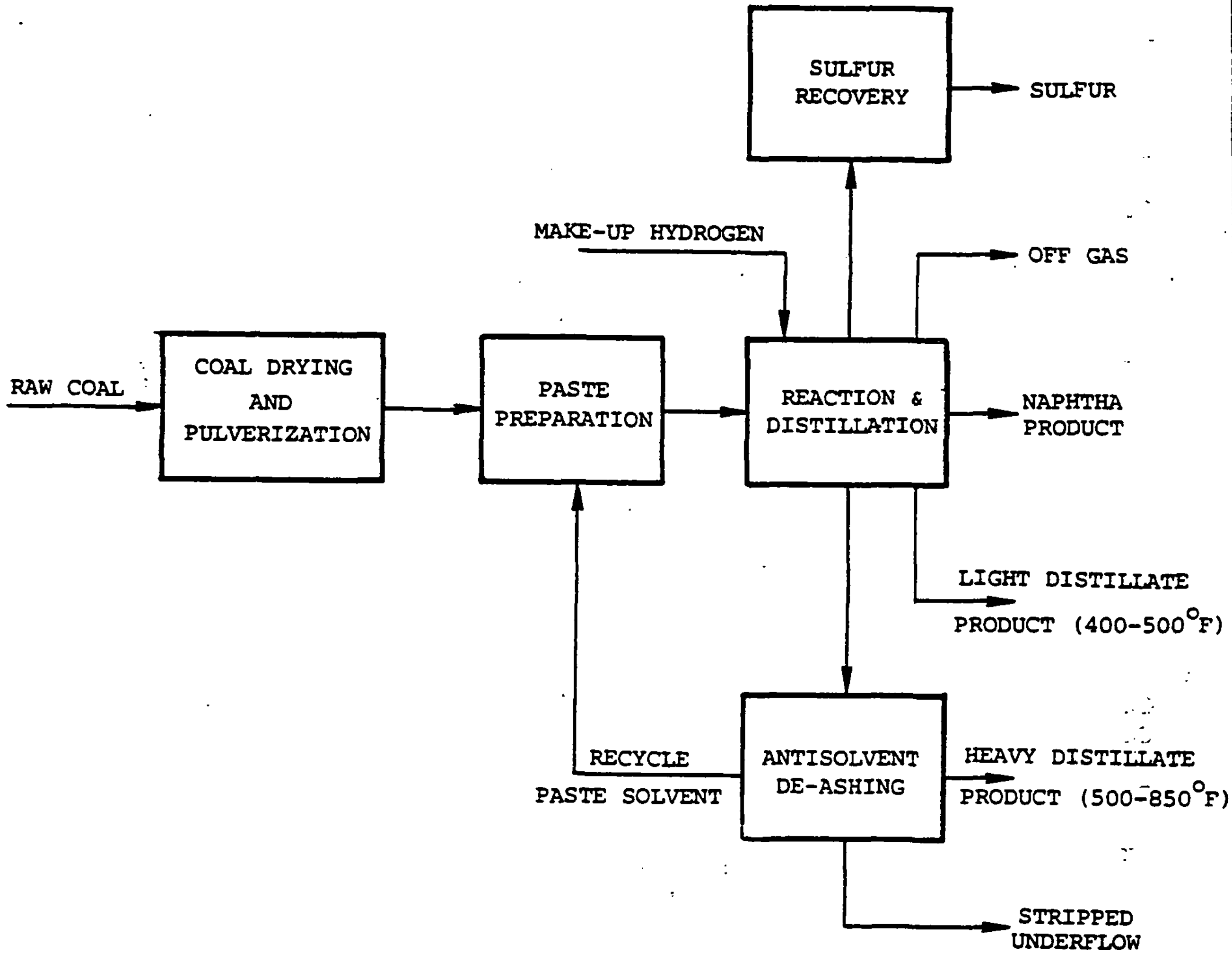
Process Developer:	Friedrich Bergius
Scale:	Was commercial during World War II
Location:	Germany
Funding:	
Sponsor:	
Concept:	This process features the hydrogenation of a mixture of coal, a process derived oil, and a catalyst (usually iron oxide) to produce light oil.
Description:	Coal is first ground to a fine size and mixed with a process-derived hydrocarbon liquid and a catalyst. This mixture is reacted with hydrogen (produced by the gasification of coal) at pressures up to 10,000 p.s.i. The products from the first reactor are separated into light, middle and bottom fractions. The middle fraction is further treated over a catalyst in a vapour phase and under relatively mild conditions to produce petroleum - like products. The bottom fraction is filtered to remove solids (unreacted coal, catalyst and ash) and the remaining liquid utilized as a mix with fresh coal being processed in the first reaction.
Operating Conditions:	Temperature: 900^{o}F Pressure: 3000-10,000 psig
Reactants:	Coal, catalyst and recycle oil
Products:	Light oils
Status:	Not an active process. There are have been no producing plants since early 50's.
Advantages:	

CLEAN COKE PROCESS (USS)

Process Developer:	U.S. Steel Corp.
Scale:	PDU 0.5 TPD
Location:	Monroeville, PA
Funding:	
Sponsor:	DOE Funded Development of the PDU
Concept:	This process uses fluid-bed carbonization and hydrogenation/liquefaction to convert high sulfur coals to low-sulfur metallurgical coke, chemical feedstocks, and liquid and gaseous fuels.
Description:	After benefaction and sizing, part of the coal is processed through a carbonization unit and the remainder of the coal is slurried with a process derived oil and is hydrogenated to convert a large proportion of the coal to liquid. The liquid products are processed through a liquids treatment unit converting the liquid to low-sulfur liquid fuels, chemical feedstocks, and recycle fractions. A portion of the recycle fractions are further processed to form coke.
Operating Conditions:	Temperature: 1200-1400°F Pressure: 900-1400 psig
Reactants:	Coal & recycle hydrogen
Products:	Liquid products, gas, char for coker
Status:	PDU operation ceased in late 1978. A proposal has been submitted to DOE for engineering design of a 3,600 TPD Demonstration plant in southern Illinois.
Advantages:	• The coke preparation cycle is a closed system and no significant emissions are produced • Hydrogen for the process is produced in the process

CLEAN FUEL FROM COAL (CFFC)

Process Developer:	C.E. Lummus Co. (Combustion Engineering)
Scale:	PDU 30 lbs per hr.
Location:	Bloomfield, NJ
Funding:	
Sponsor:	DOE
Concept:	This process features direct catalytic hydroliquefaction in a multistage, ebullated-bed reactor and a proprietary solvent de-ashing system to produce a low sulfur fuel oil.
Description:	Coal is crushed, sized, dried and slurried with a recycle solvent and fed into the bottom of the reactor where hydrodesulfurization occurs. The slurry passes from the reactor to de-ashing and fractionation and finally after some naphtha and light oil is removed in the fractionation step, is stripped of recycle solvent to produce low-sulfur fuel oil. Hydrogen generation is accomplished by feeding a portion of the coal through a gasification step which also produces some fuel gas for in-plant use.
Operating Conditions:	Temperature: 750-850°F Pressure: 1400-4000 psig
Reactants:	Coal, recycle solvent and hydrogen
Products:	Fuel oil or gasoline
Status:	Process studies continuing. Preliminary engineering design of a pilot plant to be available in 1982 based on results of PDU operation.
Advantages:	• Superior control of reactor conditions • Low hydrogen consumption • Proprietary solvent de-ashing system has potential scale up advantages



CLEAN FUEL FROM COAL

SRS

CONSOL (CFS) (PROJECT GASOLINE)

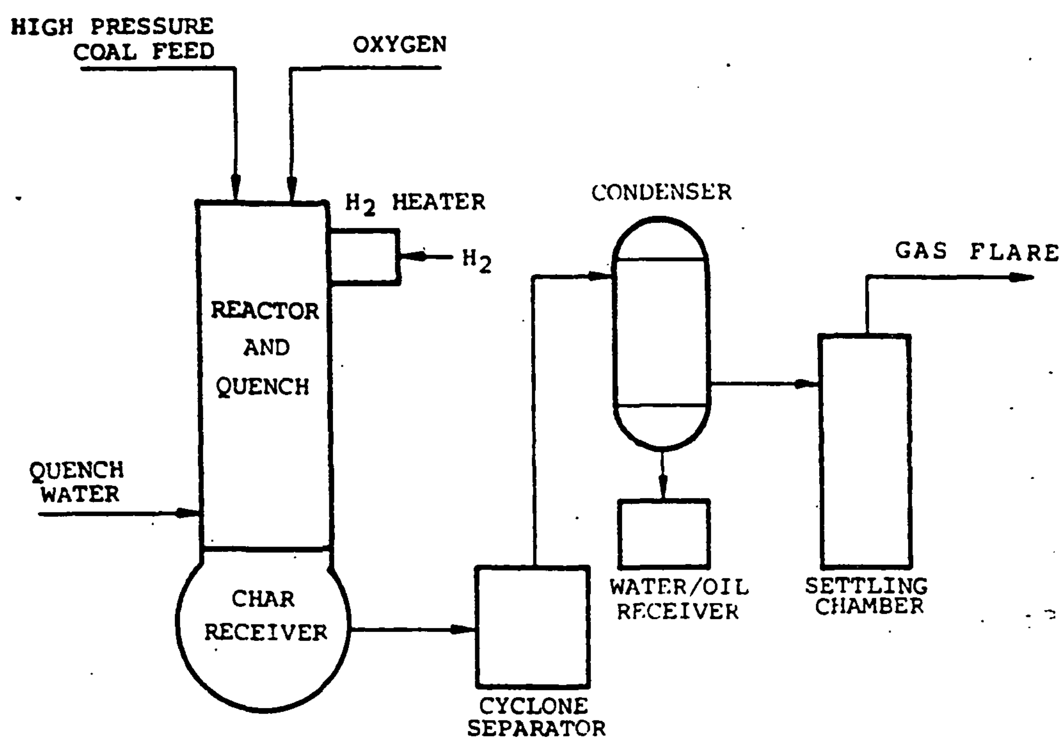
Process Developer:	Consolidation Coal Company (Continental Oil Co.)
Scale:	20 TPD Pilot Plant
Location:	Cresap, WV
Funding:	Office of Coal Research funded the process development
Sponsor:	
Concept:	This process is similar to the Pott-Broche Process in that coal slurrying solvent is a hydrogen donor. The process is a combination of the conversion of coal into an extract, followed by hydrogenation of the extract to yield a synthetic crude.
Description:	Coal is crushed, dried, preheated and slurried in a process-derived solvent. The slurry is pumped into a solvent extraction vessel where liquids, solids and vapors are produced. Vapors from the reactor are processed in a fractionation section and solvent recovery section. The liquid products from the reactor are separated from the solids in hydrocyclones and the liquids are further processed by solvent recovery, fractionation and hydro-treatment to produce naphtha. The solids, gases and other liquids are processed to produce oils, naphtha and gases.
Operating Conditions:	Temperature: 765-925^{O}F Pressure: 10-3,000 psig
Reactants:	Coal, hydrogen, recycle solvent, and air
Products:	Naphtha, oil and gas
Status:	Operation of plant was terminated in 1970. The plant was refurbished in 1977 for a coal liquefaction test facility and was mothballed in 1979. Plant is being maintained in mothballed condition.
Advantages:	

CO-STEAM (GRAND FORKS LIQUEFACTION PROCESS)

Process Developer:	Pittsburgh Energy Technology Center/Grand Forks Energy Technology Center
Scale:	PDU 3-5 lbs/hr.
Location:	Grand Forks Energy Technology Center
Funding:	
Sponsor:	DOE
Concept:	The process utilizes the reaction of carbon monoxide and steam with or without a catalyst to process low rank coal such as lignites. The coal is reacted in a stirred reactor to produce an oil that can be processed to produce fuel oil and gas.
Description:	A slurry of pulverized coal and product oils is pumped with carbon monoxide, or a CO-rich synthesis gas, into a stirred reactor. The steam for the reaction is derived from the moisture of the coal. Products from the reactor go to a receiver where the raw oil is separated from the product gas. Unreacted coal and minerals are removed from the product oil by a centrifuge or a pre-coal filter.
Operating Conditions:	Temperature: 800°F Pressure: 4000 psig
Reactants:	Coal, carbon monoxide, steam
Products:	Fuel oil, gas
Status:	Operation of PDU to continue to define process variables and low-rank coal liquefaction properties.
Advantages:	• Processes low grade, high moisture content coal • Process can operate without a catalyst

CS/R HYDROPYROLYSIS

Process Developer:	Rockwell International
Scale:	18 TPD PDU
Location:	Canoga Park, CA
Funding:	FY80 $3 M FY81 $5 M
Sponsor:	DOE
Concept:	This process employs a rapid non-catalytic coal hydrogenation technique, termed flash hydro-pyrolysis, in an entrained flow reactor to accomplish the coal/hydrogen reaction.
Description:	Pulverized coal and oxygen fed to the reactor and entrained rapidly with 2000^{o}F hydrogen using a rocket engine injector element. The reactants react for about 10-100 milliseconds. The reactor effluent is quenched, utilizing a set of water spray nozzles or a heat exchanger, or both and the liquids are condensed.
Operating Conditions:	Temperature: 1500-1800^{o}F Pressure: 35-100 atms
Reactants:	Coal, hydrogen, oxygen
Products:	Hydrocarbon Liquids, SNG/gas (SNG) Benzene
Status:	The process has been tested in a 1 TPH Short run PDU to develop the reactor. An 18 TPD continuous unit is underway optimize the process. Startup may occur in 1981.
Advantages:	• Potentially high process efficiency • No slurry handling in coal feed system • Simple De-ashing • High flexibility of product output



CS/R HYDROGASIFICATION

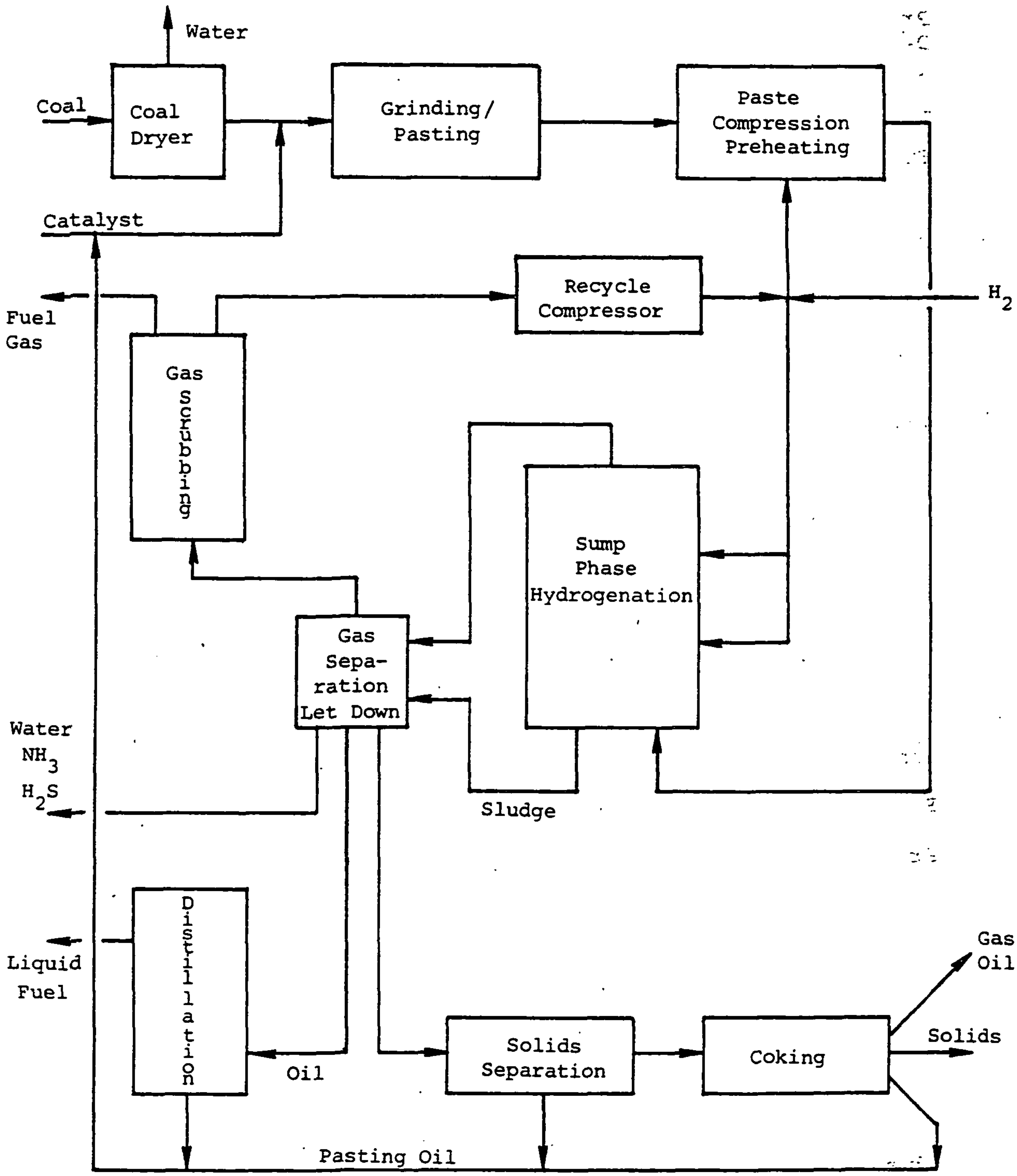
(1/4 TPH UNIT)

SRS

DISPOSABLE CATALYST HYDROGENATION

Process Developer:	PETC, GFETC & MERRIAM P&M LAB
Scale:	PDU
Location:	PETC; Bruceton, Pennsylvania
Funding:	FY80-$9.5M FY81-$4.2M
Sponsor:	DOE
Concept:	This is a hydrogenation process which is an extension of the technology employed in the World War II German Bergius process. Improved reactor design and new catalyst combinations have improved on the Bergius process to remove sulfur, reduce pressure, reduce hydrogen consumption and reduce residence time.
Description:	Recycle gas and make-up hydrogen are added to a preheated, compressed (2,000-3,000 psi) paste to a make-up of dried coal, process-derived oil and disposable catalyst. This paste is reacted by hydrogenation in a pressure vessel. The discharge from the reactor is a coal-oil-catalyst slurry and a gaseous product; both are sent to a gas separator/letdown unit. The gas from the separator is sent to a scrubber from which part of the gas is recycled and part is given off as fuel gas. The oil from the separator is distilled to yield liquid fuel and recycle pasting oil.
Operating Conditions:	Temperature: approximately 450°F Pressure: 2000-3000 psi
Reactants:	Coal, catalyst, hydrogen
Products:	Light oils
Status:	The process has been tested in a 25 lbs/day bench scale at Merriam P&M Lab, a 1200 lbs/day plant at PETC and on a bench scale at GFETC. Auburn, Penn State, and North Dakota Universities, Sandia Lab and Air Products are also involved in a coordinated program. The major goal of the current effort is to find more active catalyst species of which the most promising can be tested in existing pilot plants. The process is also to be further evaluated.
Advantages:	The major advantages of this process are: - uses inexpensive catalyst (can use mineral matter in coal) - the catalyst is disposable (no catalyst recovery or regeneration) - reduced hydrogen consumption - reaction severity can be reduced to increase selectivity of liquids.

PROCESS FLOW DIAGRAM:



DISPOSABLE CATALYST HYDROGENATION PROCESS

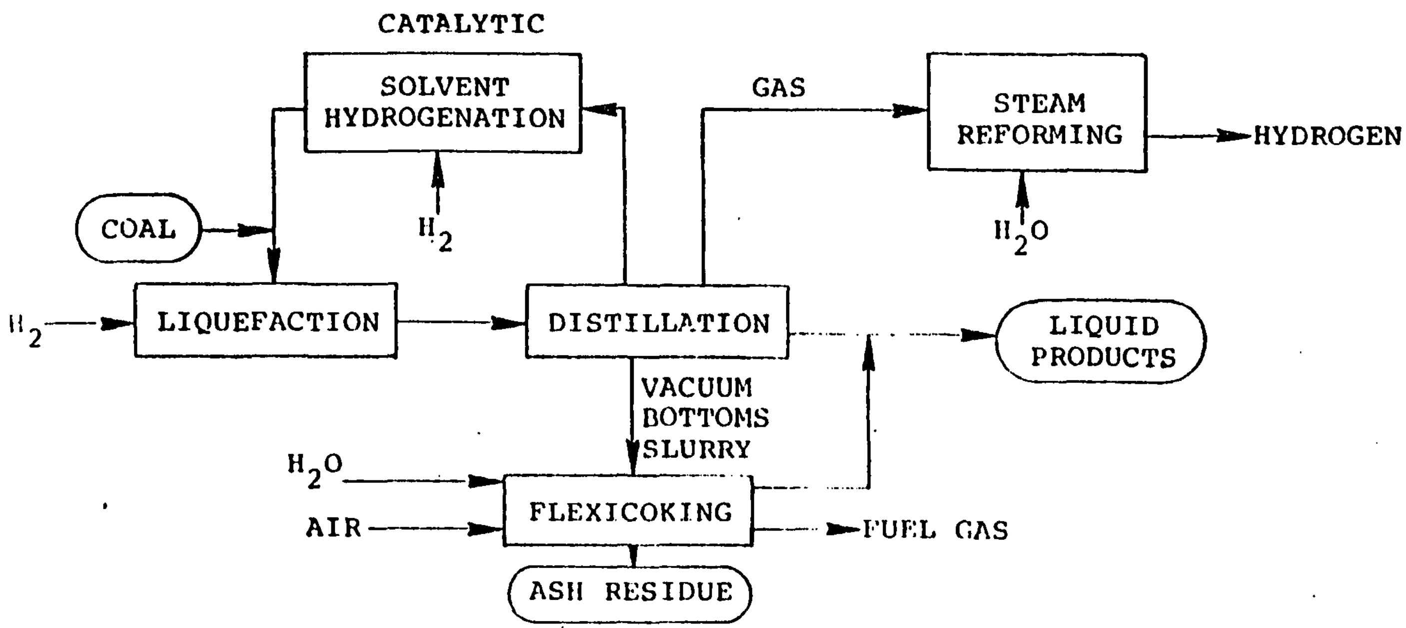
SRS

DOW CATALYTIC LIQUEFACTION

Process Developer:	Dow Chemical
Scale:	0.1 TPD PDU
Location:	Midland, MI
Funding:	
Sponsor:	
Concept:	This process utilizes catalyst, water, and oil emulsion mixed with coal to react with hydrogen in preheat and pressure reaction steps after which products are processed off and successive remaining heavier products are processed by separation and gasification to produce a varity of liquid products and recycle gases and oils.
Description:	Coal is crushed and dried and mixed with a process derived oil and catalyst is added. The catalyst and oil go through a short residence time preheater and hydrogen is added. The slurry then passes to a pressure vessel reactor where asphaltenes and oils are produced. The light oils and gases pass off the top of the reactor and the solids and asphaltenes processed to produce LPG and naphtha and fuel gas. The heavier products from the reactor go through solids separation (hydroclone, de-asphaltes) to obtain de-asphalted oil (part is recycled), a low sulfur fuel and bottoms (processed in a gasifier and gas clean up system to produce recycle hydrogen and CO).
Operating Conditions:	Temperature: 450-460^{o}C Pressure: 2000 psig
Reactants:	Coal, catalyst, hydrogen, steam and oxygen
Products:	Naphtha, fuel gas, LPG, oil and recycle hydrogen
Status:	A conceptual design for a commercial scale plant has been completed and is being evaluated for a decision on viability of process for scale-up.
Advantages:	• Uses an expendable catalyst • Utilizes a novel liquid-liquid extractor to obtain low sulfur, solids free product oil and a high solids concentrate suitable for a gasifier feedstock

EXXON DONOR SOLVENT (EDS)

Process Developer:	Exxon
Scale:	250 TPD Pilot Plant
Location:	Baytown, TX
Funding:	FY80 - $30 M FY81 - $32 M
Sponsor:	DOE
Concept:	This process utilizes a recirculated donor solvent to react with coal to generate a variety of liquid products. The product slate can vary according to the process conditions.
Description:	Ground coal, recycle donor solvent, and hydrogen are preheated and reacted in a tubular reactor for a product yield that goes through several stages of separation units (primarily distillation) to produce gas, naphtha, middle distillates, and bottoms (residue from processing). The bottoms are processed in a FLEXICOKER to produce additional liquids and low-Btu gas for in-plant use.
Operating Conditions:	Temperature: 800 - 880°F Pressure: 1500-2000 psig
Reactants:	Coal, hydrogen, donor solvent
Products:	Naphtha, fuel oil, gas
Status:	Start up of 250 TPD pilot plant began in mid 1980. Engineering and procurement began on a 70 TPD Flexicoker to process vacuum bottoms began in FY 1980.
Advantages:	• Process conditions may be varied to change slate of end products • Plant is self-sufficient in both process fuel and hydrogen



DONOR SOLVENT LIQUEFACTION PROCESS

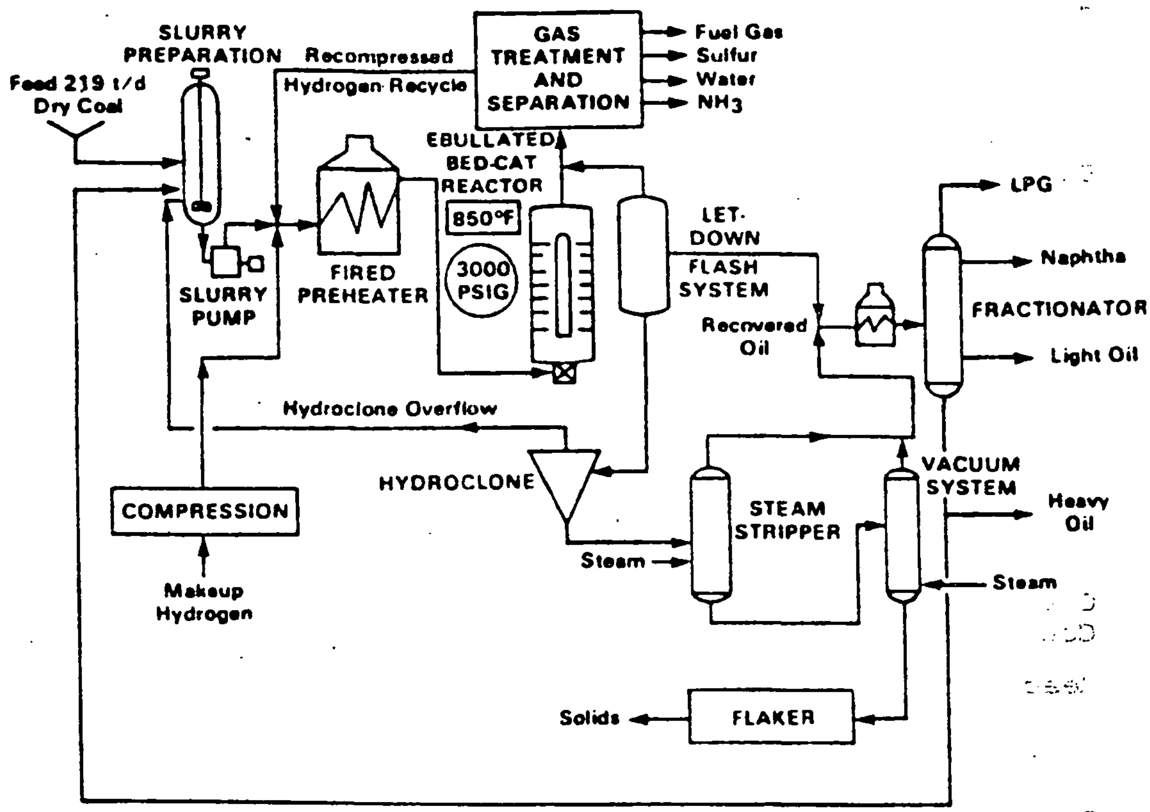
SRS

FISCHER-TROPSCH

Process Developer:	M.W. Kellogg Co. (U.S. early 50's Synthol process) Fischer and Tropsch (Germany late 20's)
Scale:	27,000 TPD Commercial Plant
Location:	South Africa
Funding:	
Sponsor:	Sasol
Concept:	Fischer-Tropsch synthesis is the second step of a two-step process for converting coal to liquid fuels. In the first step, the coal is gasified to produce a synthesis gas consiting mainly of carbon monoxide and hydrogen.
Description:	The SASOL plant produces synthesis gas using Lurgi gasifiers. The synthesis gas may be produced by any synthesis gas producing process. The synthesis of the gas is carried out in a fluid bed catalytic reactor and the resulting liquid product is fractionated to separate the various product liquids.
Operating Conditions:	Temperature: Pressure:
Reactants:	Synthesis gas and catalyst
Products:	Gasoline, diesel fuel, kerosene and waxes
Status:	SASOL has another 27,000 TPD plant under construction and several U.S. companies are planning commercial plants that will use Fischer Tropsch process. These include a 28,600 TPD plant in Henderson, Kentucky area by Texas Eastern Corp., 50,000 B/D plant by Occidental Petroleum Corp.
Advantages:	It is a commercially proven process

H-COAL

Process Developer:	Hydrocarbon Research Inc. (HRI)
Scale:	200/600 TPD Pilot Plant
Location:	Catlettsburg, KY
Funding:	FY80 - $64.5M FY81 - $57.0M
Sponsor:	
Concept:	The H-Coal process is a catalytic hydroliquefaction process that converts high-sulfur coal to either a boiler fuel that will meet sulfur emission regulations or to a refinery syncrude.
Description:	Coal, recycle oil and hydrogen are, after being preheated, continuously fed to a catalytic reactor. The catalyst is retained in the gasifier while the gas and liquid products as well as unconverted coal and ash move upward and leave the reactor. The vapor product from the reactor is cooled to condense the heavier components as liquids. The liquid-solid product from the reactor is fed to a flash separator step and the product fuel is fractionated to obtain the main products. The bottoms from the flash separator can be further processed to obtain additional usable products.
Operating Conditions:	Temperature: 850°F Pressure: 2250-2700 psig
Reactants:	Coal, oil, hydrogen
Products:	Syncrude, fuel oil
Status:	600 TPD pilot plant in undergoing start-up at Catlettsburg at Ashland Oil Co. site.
Advantages:	• Process has been thoroughly tested on PDU scale • Easy catalyst replacement • High level of isothermal operation and efficiency

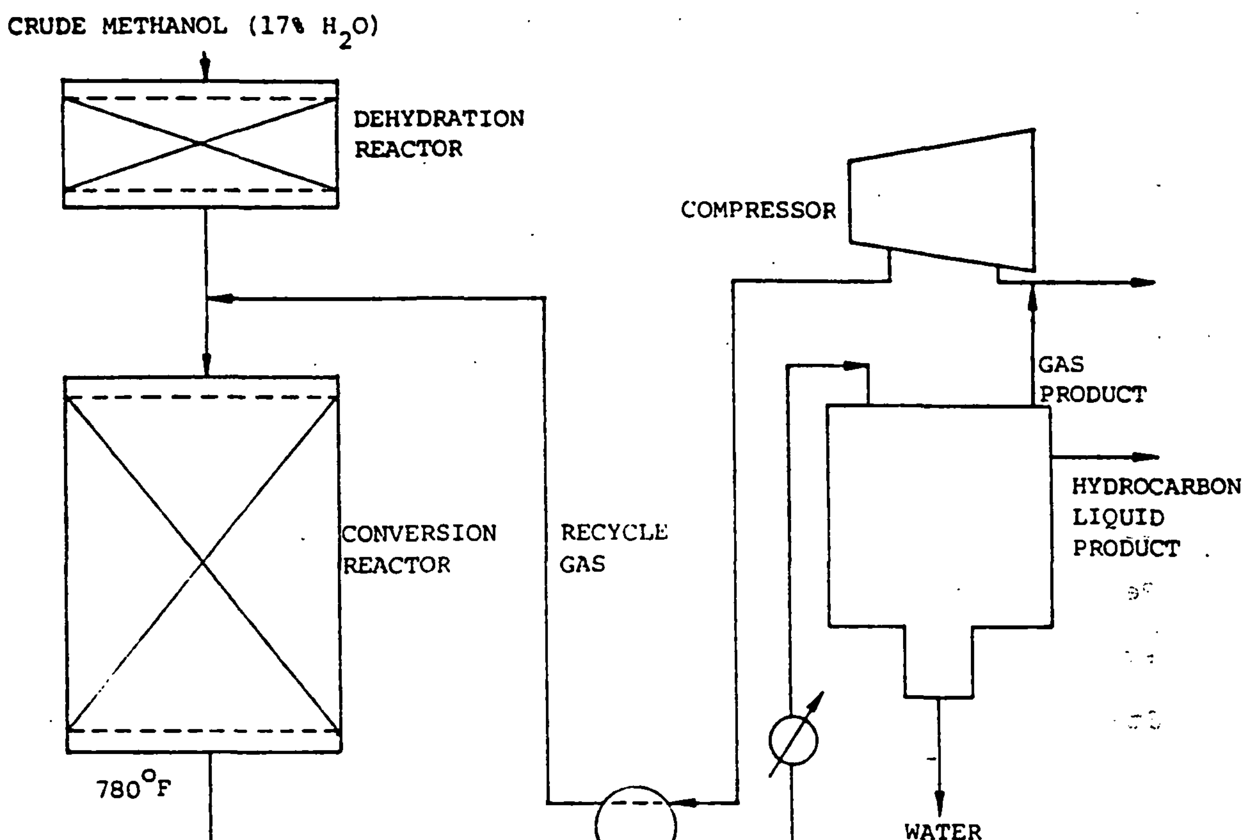


H-COAL PROCESS, SYNCRUDE MODE

SRS

MOBIL M-GASOLINE

Process Developer:	Mobil Oil
Scale:	4 Bbl Pilot Plant
Location:	Paulsboro, NJ
Funding:	To W.R. Grace for 50,000 Bbl/D Plant Using Mobil M
Sponsor:	
Concept:	The Mobil process is an indirect liquefaction process that represents the final link in conversion of coal to motor fuel through a synthesis gas - methanol - gasoline route. The process can be used with either fixed-bed or fluid-bed reactors.
Description:	The fixed-bed process consists of two reactors in series; the dehydration reactor and the conversion reactor. Methanol is fed to the dehydration reactor via a preheater and is converted to an equilibrium mixture of methanol, dimethylether, and water. These products are mixed with recycle gas and by reaction with a conversion catalyst in the second reactor forms hydrocarbons. This product is cooled and flashed in a high pressure separator to produce the liquid product.
Operating Conditions:	Temperature: 775°F Pressure: 25 psig
Reactants:	Methanol, catalyst
Products:	Gas, LP gas, gasoline
Status:	Lab work is being done in several areas to find potential improvements on the process. DOE is sponsoring 50,000 bbl/day plant to be built by W. R. Grace at Baskett, KY.
Advantages:	High methanol conversion to gasoline yields



MOBIL M-GASOLINE PROCESS

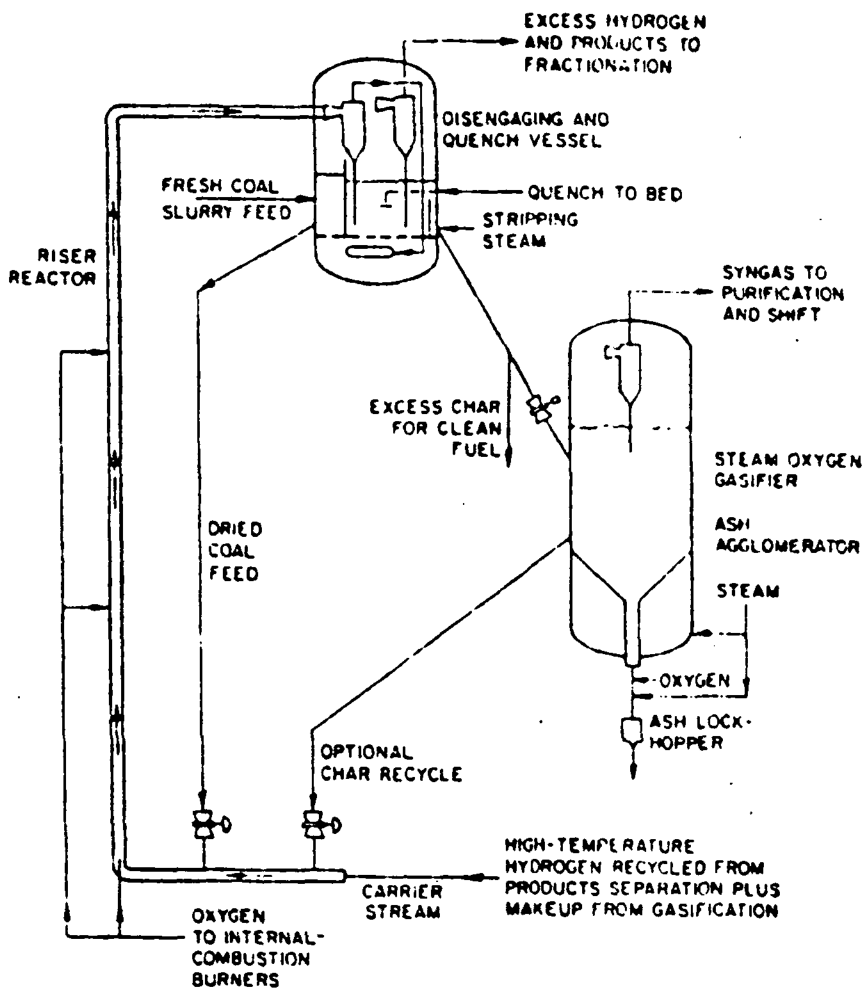
SRS

OCCIDENTAL FLASH PYROLYSIS (GARRETT'S COAL PYROLYSIS)

Process Developer:	Occidental Research Corporation (Occidental Coal Pyrolysis)
Scale:	0.2 TPD Pilot Plant / 3.0 TPD PDU
Location:	Irvine, Calif. / LaVerne, Calif.
Funding:	
Sponsor:	DOE sponsored development of process but not pilot plant
Concept:	This process consists of rapidly pyrolyzing crushed coal in an entrained stream of hot coal char and a gas, substantially free of oxidizing constituents in a short residence time operation to produce a relatively high yield of liquid.
Description:	Milled and screened coal is transported to the pyrolysis reactor (via heated nitrogen) where the coal is mixed with recycle hot char (the char recycle is about five to ten times the coal feed) to produce char which is processed through a series of cyclones. Pyrolysis vapors from the cyclones are quenched and vacuum flashed to produce oil. The remaining char is either heated for recycle or collected as product char.
Operating Conditions:	Temperature: 950-1700°F Pressure: Atm.
Reactants:	Coal, recycle char
Products:	Char, oil
Status:	PDU concluded operation in 1978. Operation of pilot began in 1980. Process is being evaluated by Occidental for possible scale up.
Advantages:	• Short residence time • High liquid yields

RISER CRACKING

Process Developer:	IGT
Scale:	1.2 TPD PDU
Location:	Chicago, IL
Funding:	None
Sponsor:	
Concept:	Riser cracking is a short residence time hydropyrolysis of coal to produce methane, ethane, benzene, and oil.
Description:	Heated hydrogen and coal (about 1200°F) are fed to the Riser Reactor traveling concurrently upwards before entering a disengaging vessel to separate unreacted char from the hydrogen carrier and product vapors by means of a pair of cyclones. Char from the disengaging vessel is fed to a steam-oxygen gasifier operating at reaction system pressure (up to 2000 psig). Hydrogen and product vapors pass from the second cyclone of the disengaging vessel to further cooling and separation. Raw gas from the gasifier proceeds to acid-gas removal and a CO-shift reactor to generate makeup hydrogen.
Operating Conditions:	Temperature: 1500°F Pressure: 2000 psig
Reactants:	Coal, hydrogen, oxygen
Products:	Methane, benzene, gasoline and aromatic fuel oil
Status:	Plant has operated since June 1979. Operation is to continue to develop the process.
Advantages:	• Absence of tars • Desirability of product slate



RISER CRACKING FLOW DIAGRAM

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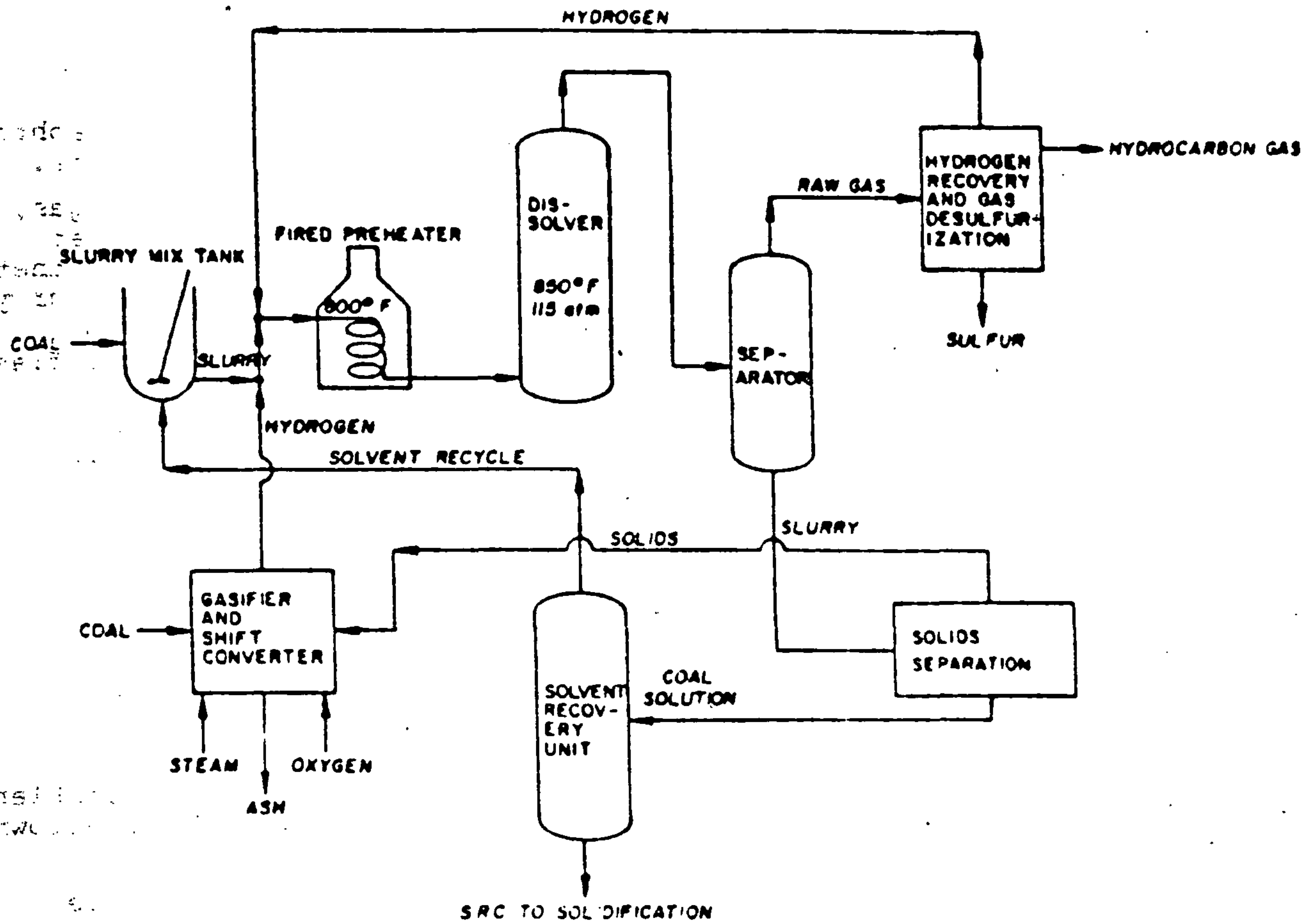
SRC I

Process Developer:	Gulf Oil (Pittsburgh & Midway Coal Mining Co.)
Scale:	6 TPD Pilot Plant Operating
Location:	Pilot - Wilsonville, AL
Funding:	FY80 - $62 M FY81 - $208 M
Sponsor:	DOE
Concept:	A coal and process derived solvent slurry is preheated and reacted in a dissolver to produce a liquid product which goes through a series of separation, filtration and fractionation steps to produce a solid SRC product that is essentially sulfur and ash free.
Description:	Raw coal, hydrogen and a process derived slurry are fed to a reactor (dissolver) after a preheat step. The product from the dissolver is separated into vapor and slurry phases by flash separators. The slurry phase from the separator is then filtered and preflashed to remove light hydrocarbons and then fed to a vacuum flash where the bottoms fraction (residue) is removed and solidifies as SRC. Raw gas and solvent are removed at various points in the process for production of recycle solvent and recycle hydrogen and for production of gas product.
Operating Conditions:	Temperature: 850°F Pressure: 1500 psi
Reactants:	Coal, recycle hydrogen, recycle solvent
Products:	
Status:	The 6 TPD Pilot Plant in Wilsonville, AL is in operation and a 6000 TPD demonstration is due for construction start in FY81.
Advantages:	• Produces a coal replacement that contains less than 1% sulfur and 0.2% ash • Process appears to be cost competitive



SRC I PROCESS

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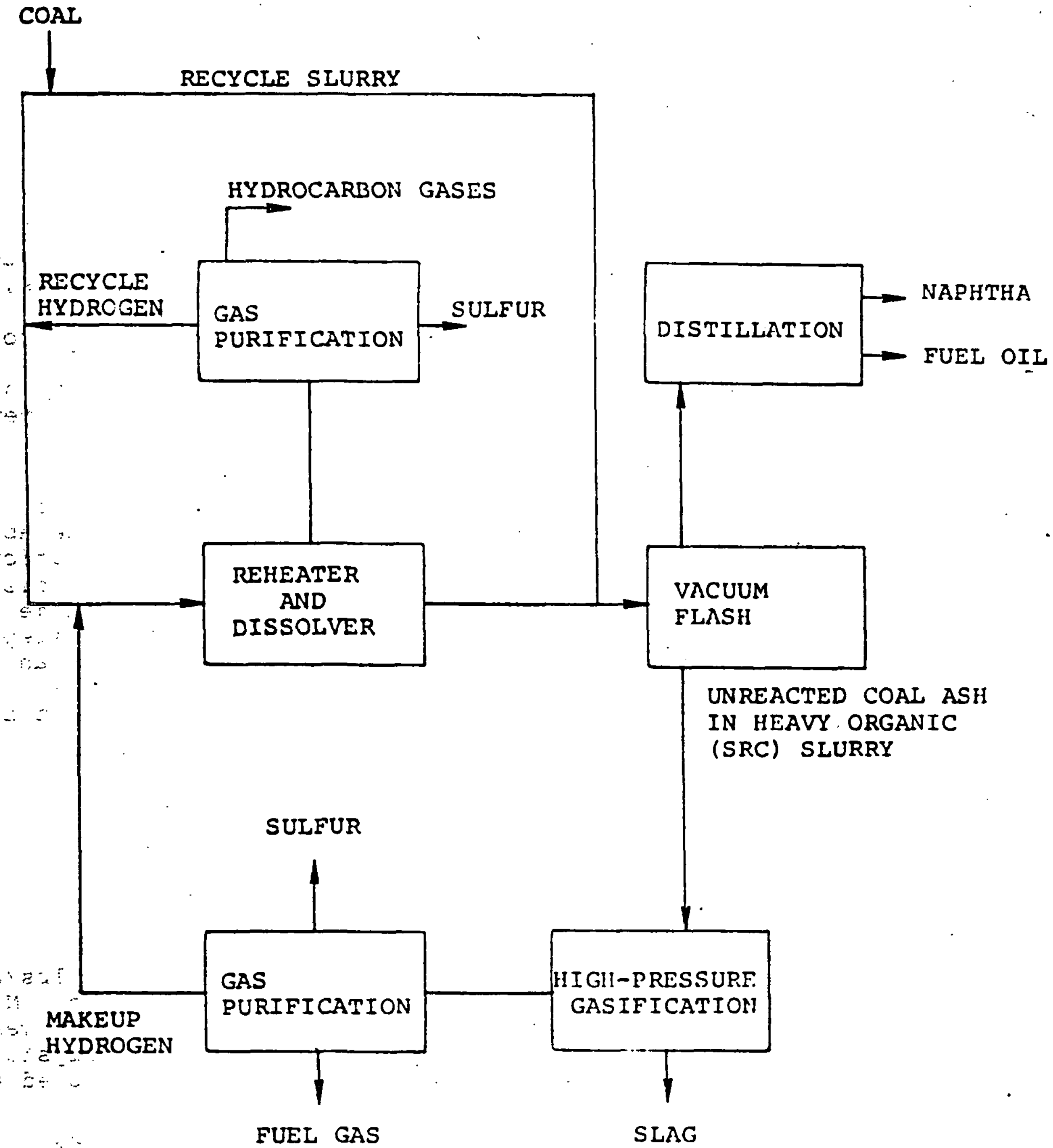
SRC II

Process Developer:	Gulf Oil Co. (Pittsburgh & Midway Coal Mining Co.)
Scale:	50 TPD Pilot Plant
Location:	Ft. Lewis, Washington
Funding:	FY80-$54 M FY81-$195 M (DOE Funding)
Sponsor:	DOE
Concept:	This process reacts coal, hydrogen and recycle solvent in a reactor (dissolver) to produce naphtha, middle heavy distillates, and hydrocarbon gases.
Description:	Dried pulverized coal, hydrogen rich recycle gas, and recycle solvent are reacted after a preheat step in a dissolver which generates a product that is sent through a separation step where the slurry is separated from the gas and light hydrocarbon liquids. The slurry is then sent to a vacuum flash unit to remove more light hydrocarbons. The vacuum flash condensate along with the liquid light hydrocarbons are fractionated to produce naphtha and other distillates.
Operating Conditions:	Temperature: 850°F Pressure: 1900 psig
Reactants:	Coal, hydrogen, recycle solvent
Products:	Naphtha, fuel oil, and SRC
Status:	The process is being tested in a 50 TPD Pilot Plant and a 6000 TPD Demonstration Plant near Morgantown, W.V. is due for construction start in FY82.
Advantages:	• Process is well tested on Pilot Plant Scale • Produces low sulfur products from high sulfur coal



SRC II PROCESS

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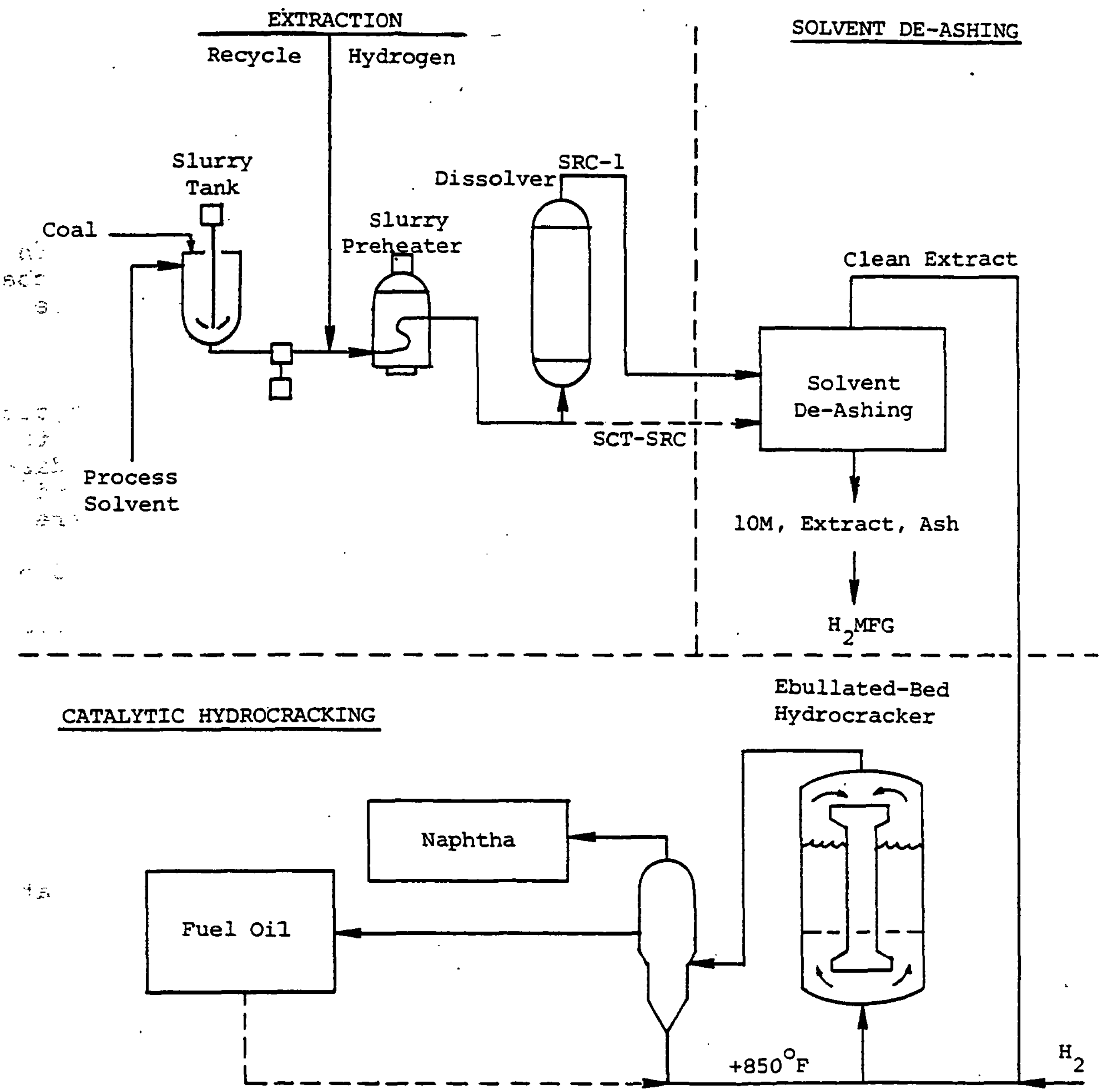
TWO-STAGE LIQUEFACTION

Process Developer:	PETC, CE Lumus, Cities Service
Scale:	PDU
Location:	New Brunswick, NJ
Funding:	FY80-$3.6M FY81-$3.6M
Sponsor:	DOE
Concept:	The Two-Stage Liquefaction process is designed to convert coal into high quality distillate fuels. This process involves a hydroextraction stage similar to a short contact time SRC I process for the first stage and an expanded-bed catalytic hydrocracking (Combustion Engineering's LC-Fining) for the second stage with a solvent deashing step between stages.
Description:	Dried coal mixed with a process derived oil is fed to a preheater (750-850°F). The residence time in the preheater is adjusted to dissolve about 90% of the coal at a minimal hydrogen consumption. The slurry from the preheater is sent to the dissolver and SRC I extract and short contact time SRC is removed and sent to the solvent deashing step which is the Lummus antisolvent process. Clean extract from the deashing step is sent to the catalytic hydrocracking unit where the product is cracked into naphtha and fuel oil.
Operating Conditions:	Temperature: 750-850°F Pressure:
Reactants:	Coal, process solvent, recycle hydrogen
Products:	Fuel oil, naphtha
Status:	During 1980 the process was tested in a 450 lbs/day PDU at Combustion Engineering's New Brunswick, NJ facilities. A coordinated program with Amoco was established to test novel and improved catalysts for the second stage. Operations are scheduled at least through 1981.
Advantages:	• High quality liquids at high liquid yeilds • Low hydrogen consumption • Upgrading of SRC product

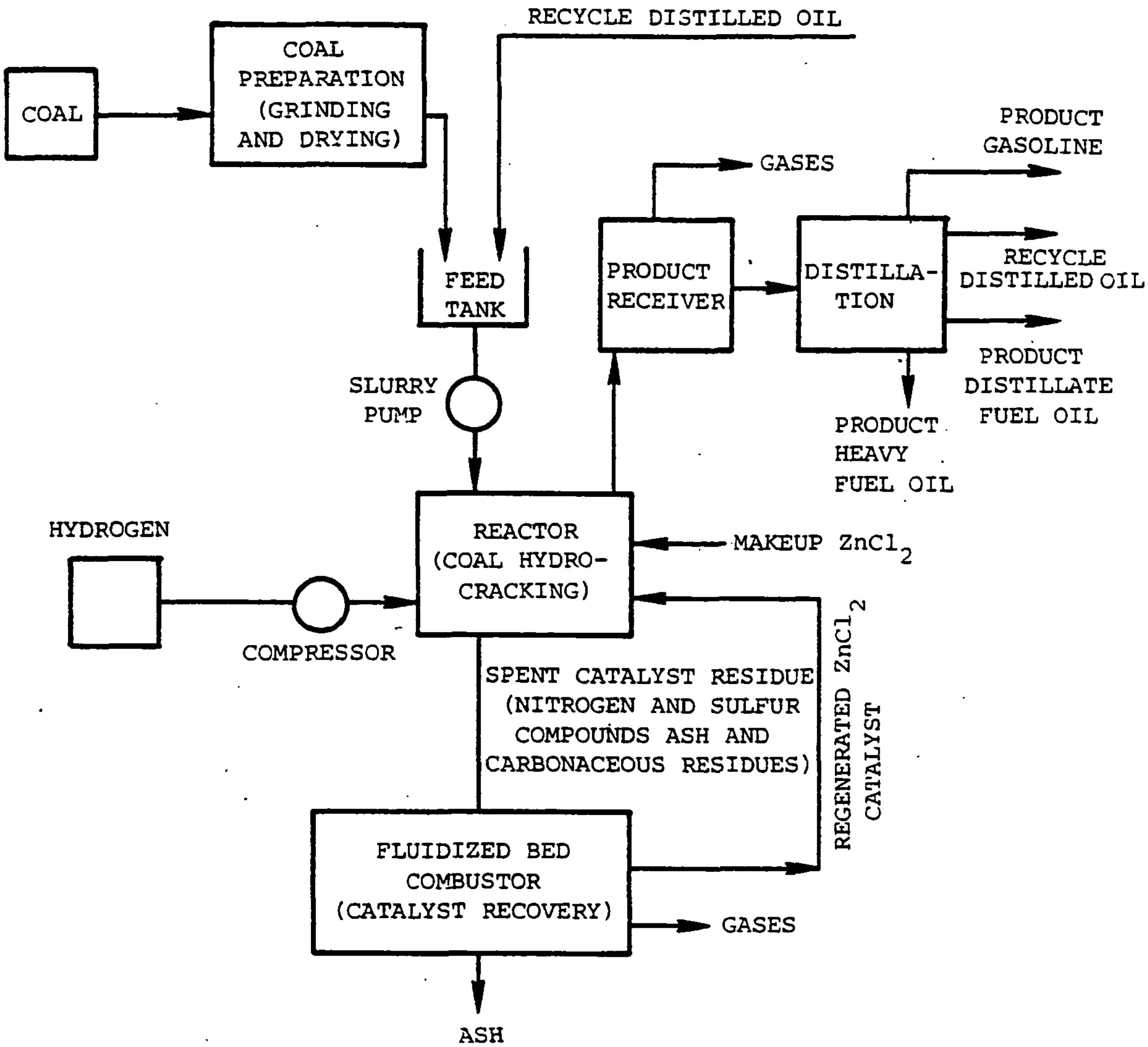


TWO-STAGE LIQUEFACTION PROCESS

SRS

ZINC HALIDE (ZINC CHLORIDE)

Process Developer:	Conoco Coal Development Co.
Scale:	PDU 100 lbs/hr.
Location:	Library, PA
Funding:	FY81 - None
Sponsor:	DOE Sponsored Development of Process
Concept:	This process uses a zinc halide catalyst for the hydrogenation and hydrocracking of coals and coal extracts to produce high octane gasoline while recovering the catalyst by regeneration.
Description:	Dried and pulverized coal are slurried with a process derived recycle oil and fed to the hydrocracking reactor where the slurry is mixed with hydrogen and $ZnCl_2$. The coal is cracked to distillates (primarily in the gasoline range) and these products go to a product separator where the liquid is separated and further processed to gasoline. Solids are discharged from the hydrocracking reactor and fed to a fluidized-bed combustor where $ZnCl_2$ is separated and recycled to the hydrocracking reactor.
Operating Conditions:	Temperature: 675 - 825°F Pressure: 1500 - 3500 psig
Reactants:	Coal, $ZnCl_2$ catalyst, hydrogen
Products:	Gasoline, fuel oil, gases
Status:	Project terminated in FY80 due to problems that made scale up improbable.
Advantages:	



ZINC CHLORIDE CATALYST PROCESS

SRS