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Assessment of Advanced Coal-Gasification Processes

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ABBREVIATIONS AND TERMS USED

AGA	American Gas Association
Bench Scale Unit	A small scale laboratory unit for testing process concepts and operating parameters as a first step in the evaluation of a process.
BFW	Boiler feed water
Bi-Gas Process	A two-staged, slagging, entrained flow coal gasification process being developed by Bituminous Coal Research, Inc. in a 100 TPD pilot plant in Homer City, Penn.
BTX	Benzene, toluene, xylene
CCG	Catalytic Coal Gasification
CS/R	Cities Service/Rockwell
DAF	Dry ash-free
Demonstration Plant	A fully integrated process plant containing all units required to convert coal to SNG in a near commercial unit sized facility.
Dense Phase Feeding	The transport of pulverized coal by pressurized gas vehicle where solids predominate.
DOE	Department of Energy
EPRI	Electric Power Research Institute
ERDA	Energy Research and Development Administration
Eyring R. I. Gasifier	A single-stage, slagging, entrained flow, 100 lb/hr coal gasifier operated by the Eyring Research Institure of Provo, Utah.
FBG	Fluid Bed Gasifier
FGD	Flue Gas Desulfurization
GPM	Gallons per minute
GRI	Gas Research Institute
HHV	Higher (or gross) heating value
High BTU Gas	Gas with a higher heating value over 900 Btu/SCF
HMF	High mass flux

ABBREVIATIONS AND TERMS USED (Cont.)

HTG	High Throughput Gasifier
Integrated Process Development Unit (IPDU)	Several integrated systems used to study the effects of process variables on performance, sized between a bench-scale unit and a pilot plant.
Low Btu Gas	Gas with a higher heating value less than 350 Btu/SCF
LPP	Large Pilot Plant
Maceral	A solid, naturally occurring organic material of plant origin found in coal.
MAF	Moisture, ash-free
Medium Btu Gas	Gas with a higher heating value frm 350-900 Btu/SCF
MF	Moisture free
M-Gasoline	A high octane gasoline product produced from methanol by the M-Gasoline process.
MHD	Magnetohydrodynamics
MMSCFD	Million standard cubic feet per day
msec	Milliseconds
MW	Megawatt
PDU	Process Development Unit; a system used to study the effects of process variables on performance, sized between a bench-scale unit and a pilot plant.
Pilot Plant	A process plant containing many of the processes of a commercial unit but on a smaller scale for the purpose of studying the technical and economic feasibility of the process.
Saarberg/Otto Process	A single-stage, slagging, entrained flow coal gasifier being developed by Dr. C. Otto and Co. G. m.b.H. in a 264 TPD demonstration plant in West Germany.
SCFM	Standard cubic feet per minute
SNG	Substitute or synthetic natural gas conforming to pipeline gas standards.
SRT	Short residence time
Synthesis Gas (Syngas)	A gas mixture consisting mostly of CO and H_2.

ABBREVIATIONS AND TERMS USED (Cont.)

ST/SD	Standard tons (2000 lbs.) per stream day
T/D (TPD)	Tons per day
Thermal Efficiency	Equal to 100% times the HHV of the product SNG divided by the sum of the equivalent HHV of the feed coal plus imported electricity.
TPH	Tons per hour
Vitrain	A series of macerals that form the humic fraction of coal seams and are produced by the gelification and gradual metamorphosis of cell wall substances.

ABSTRACT

This report represents a technical assessment of the following advanced coal gasification processes:

- AVCO High Throughput Gasification (HTG) Process
- Bell Single - Stage High Mass Flux (HMF) Process
- Cities Service/Rockwell (CS/R) Hydrogasification Process
- Exxon Catalytic Coal Gasification (CCG) Process

Each process is evaluated for its potential to produce SNG from a bituminous coal. In addition to identifying the new technology these processes represent, key similarities/differences, strengths/weaknesses, and potential improvements to each process are identified. The AVCO HTG and the Bell HMF gasifiers share similarities with respect to: short residence time (SRT), high throughput rate, slagging and syngas as the initial raw product gas. The CS/R Hydrogasifier is also SRT but is non-slagging and produces a raw gas high in methane content. The Exxon CCG gasifier is a long residence time, catalytic, fluidbed reactor producing all of the raw product methane in the gasifier. The report makes the following assessments:

1) while each process has significant potential as coal gasifiers, the CS/R and Exxon processes are better suited for SNG production;

2) the Exxon process is the closest to a commercial level for near-term SNG production; and

3) the SRT processes require significant development including scale-up and turndown demonstration, char processing and/or utilization demonstration, and reactor control and safety features development.

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SECTION I
OVERVIEW AND ASSESSMENTS

1.0 INTRODUCTION

1.1 Origin

This report was written at the Jet Propulsion Laboratory under an Interagency Agreement with NASA and the Department of Energy. The project had its origin at DOE Headquarters, Office of Coal Conversion and was transferred to the Morgantown Energy Technology Center for implementation.

1.2 Purpose of Assessment

The production of SNG from coal is an attractive way of utilizing coal in an environmentally acceptable way to produce a product which is totally interchangeable in today's energy market. However, today there are no large coal gasification plants producing SNG in the United States as the relative abundance and low price of natural gas has made the economic feasibility for SNG plants unattractive. As the price of natural gas is being deregulated, and as our gas reserves become depleted and gas becomes more expensive to recover, the production of SNG from coal will become more attractive. Since the coal gasification technology that is commercially available today has considerable potential for improvement, research and development of new gasification processes is underway to make coal gasification more efficient, more economical, and more environmentally acceptable than the older processes.

The purpose of this study is to provide a technical assessment of four of these new gasification processes. As the research and development work on these processes is proceeding, continual evaluation of these emerging technologies and their potential for commercialization is required. This study should be useful in planning and preparing the development programs in coal gasification.

Two premises inherent in this work are pointed out here to assist in the proper application of the findings:

(a) The assessment of the processes does not constitute a comparison of the processes

An effort was made to limit comparisons between processes except where useful to the overall assessment and where comparisons could easily be made. Each process was assessed separately and is reported individually in Sections II, III, IV and V. Section I, although containing several comparison tables, is meant to serve more as a summary or overview of the processes in a grouping rather than as a comparison between processes.

(b) The assessment is a technical assessment

Emphasis was placed on identifying new technology and its inherent advantages and disadvantages. Although the most comprehensive barometer of a process's potential is the required product selling price in dollars per MMBtu, these numbers are not reported here since economics have not been developed on equal bases between processes and hence publishing product prices would invite unfair comparisons (however, economics were used to evaluate potential improvements to each process on an incremental basis). The assessment should be viewed as a technical assessment of four different processes at their current stage of development.

1.3 Processes Assessed

Four processes were chosen by DOE for technical assessment by JPL and a brief description of these processes is given below:

1.3.1 AVCO HTG (High Throughput Gasifier) Process:

A two-stage entrained flow, short residence time, slagging gasifier employing a rapid pyrolysis stage and a char combustor stage. Coal, oxygen, and steam are reacted to produce a syngas containing some methane. The process is being developed by AVCO Everett Research Laboratories, Inc. of Everett, Massachussetts.

1.3.2 Bell Single-Stage HMF (High Mass Flux) Process:

A single-stage, entrained flow, short residence time, slagging gasifier. Coal, oxygen, and steam are reacted to produce a syngas with very little methane. The process is being developed by the Bell Aerospace Textron Company of Buffalo, New York.

1.3.3 CS/R (Cities Service/Rockwell) Hydrogasification Process:

A single-stage, entrained flow, short residence time gasifier. Coal and hydrogen are reacted to produce a raw product gas high in methane. The process is being developed presently by the Rockwell International Corporation of Canoga Park, California and Cities Service Corporation.

1.3.4 Exxon CCG (Catalytic Coal Gasification) Process:

A single-stage, fluidized bed, catalytic gasifier. Coal impregnated with catalyst and steam in the presence of syngas are reacted to produce methane and CO_2. The process is being developed by the Exxon Corporation of Baytown, Texas.

1.3.5 Stage of Development

An arbitrary classification of three stages of development can be made which clarifies why the four processes are termed "advanced" or "emerging":

Stage of Development	Years to Commercialization	Coal Gasification Processes
Commercial	0	Lurgi (dry bed) Koppers-Totzek
Transition	Less than 5	Lurgi (slagging) Shell-Koppers Texaco
Advanced or Emerging	More than 5	AVCO HTG Bell HMF CS/R Hydrogasification Exxon CCG

The term advanced is used to highlight one or more of the potential advantageous features of the new technology areas that each process has compared to the commercial or transition processes as follows:

- Higher carbon conversion to methane during gasification
- Higher overall thermal efficiency
- Shorter gasifier residence time
- Negligible tars or undesirable liquids produced in gasifier
- Improved coal feeding and injection systems
- Effective catalytic gasification
- Simpler overall processing scheme to produce SNG

As the assessment progressed, it became obvious that each process fulfilled some of the above features but none fulfilled all of them. For example, the AVCO HTG and Bell Single-Stage HMF processes produce a syngas with little methane yet they do give higher overall thermal efficiencies, shorter residence times, yield negligible tars, and include improved coal feeding systems. In the case of the Bell Single-Stage HMF process, the methane yield from the gasifier and the overall thermal efficiency compared to the other advanced processes are lower. By making such a comparison, the Bell process could be discounted as a coal gasification process (assuming capital costs for each are similar). Again, the assessment loses much of its value if comparisons are seen as the main thrust of this study rather than the technical assessment aspect. In assessing each individual process, rather than comparing the four processes, the individual merits of the emerging technology with respect to commercial or transition coal gasifiers can be highlighted. It was recognized that the advanced processes might have merits that could be synergistically combined or that could be utilized in the commercial or transition processes as cost-effective improvements.

1.3.6 SNG versus Syngas

Although the assessment was initiated by targeting on gasification processes to produce SNG, it was recognized during the course of the study that a distinction should be made between good methane producers and good syngas producers. However, the further development of good syngas generators should not be overlooked since it is expected that the syngas generators will have a wider application in coal conversion than the SNG generators. In this regard, the AVCO HTG and Bell Single-Stage HMF reactors are classified as good syngas generators and the CS/R Hydrogasification and Exxon CCG as good methane generators.

1.4 Economic Incentives

As mentioned above, this is a technical assessment and economic comparisons between the four processes are not made. However, it is worthwhile discussing the incentives for further developing these processes. These incentives are expressed as thermal efficiency and relative capital costs to the Lurgi (non-slagging) process as given below:

Coal to SNG (1)

	% Thermal Efficiency	Relative Capital Cost
Lurgi (dry bed)	55	1.0
AVCO HTG	68	0.75
CS/R Hydrogasification (No BTX yield)	58	0.89

Coal to Med BTU Gas (2)

	% Thermal Efficiency	Relative Capital Cost
Lurgi (dry bed)	52%	1.0
Bell Single-Stage HMF	76%	0.69

The above numbers were taken from comparisons made in the literature; they do not represent a detailed engineering design and should be considered preliminary. They are used here only to show the potentially significant efficiency and capital cost improvements of the Bell, AVCO and CS/R processes over the Lurgi process (no such comparison for the Exxon CCG was available in the literature).

2.0 STATEMENT OF WORK

The objectives of this assessment are to review four advanced coal gasification processes (AVCO, Bell, Rockwell and Exxon) for the production of SNG and to:

- Characterize and evaluate these new technologies
- Identify key similarities/differences, strengths/ weaknesses, and potential improvements for each process.
- Recommend activities for further development.

This assessment is based on the following main elements included in the original scope of work:

- Identify and characterize new technology items in each gasification process.
- Evaluate new technologies in the framework of a conceptual system block flow diagram with material and heat balances projected to a commercial level producing SNG at a rate of 250 billion Btu/day.
- Identify areas of potential improvements relative to the gasifier and the conceptual overall process
- Identify key similarities and differences and essential strengths and weaknesses of each process.
- Recommend activities for continued development.

Included in this scope were visits, meetings and discussions with each developer to view facilities and to determine the current status of development. Investigating the status of development resulted in varying degrees of information on test results and the data upon which the developers' overall process concepts were based. In some cases a material balance and/or a complete process concept was not available. Much of the effort was involved in establishing these in conjunction with the developers before the analysis could proceed.

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3.0 SUMMARY

3.1 General

Four advanced coal gasification processes were reviewed in this assessment. These included processes based on the AVCO HTG, the Bell Single-Stage HMF Gasifier, the CS/R Hydrogasification and the Exxon CCG. The AVCO HTG and the Bell HMF gasifiers share similarities with respect to: short residence time (SRT), high throughput rate, slagging, and syngas as the initial raw product gas. The CS/R Hydrogasifier is also short residence time but is non-slagging, and produces raw gas high in methane content. The Exxon CCG gasifier is a long residence time catalytic fluid bed reactor producing all of the final product methane in the gasifier. The Exxon CCG process is the only one of the four which does not require a separate shift converter or methanator.

While both the CS/R Hydrogasification and the Exxon CCG processes are considered to be methane producers, they are quite different in gasifier design and subsequent processing steps. The CS/R process employs an SRT gasifier in a hydrogen-rich environment to produce methane, while the Exxon CCG process gasifies catalyst-impregnated coal in a fluid bed reactor with steam in a syngas environment to produce methane. Due to these differences in the gasification mechanism, the CS/R process needs a hydrogen plant and an oxygen plant to support the hydrogasification reaction, while the Exxon CCG process does not. Exxon CCG needs a catalyst recovery plant to enhance the economics of the process.

The above features are highlighted in Table I-1 and compared to the Lurgi and Texaco gasifiers. The Exxon process utilizes K_2CO_3 catalyst effectively to give the highest carbon conversion to CH_4 and subsequently the least complex gas processing scheme. However, the solids processing is probably the most complex of all processes, including the Lurgi and Texaco processes, since catalyst impregnation and recovery are required. The CS/R process has a relatively high carbon conversion to CH_4. However, its overall thermal efficiency while higher than the Lurgi process, is perhaps the lowest of the advanced gasification processes which is reflected by the high complexity of its gas/liquids processing scheme. The CS/R also produces BTX liquids, a clean and valuable by-product (if the HHV of BTX is included, the thermal efficiency increases to 61%). The AVCO and Bell processes as pointed out above are very similar yet the overall thermal efficiency for AVCO is significantly higher than any of the processes.

The AVCO and Bell processes are in an early pilot stage of gasifier testing. The CS/R process is in a pilot and PDU stage and the Exxon is in a PDU stage. The Exxon CCG is the most advanced in development among the four processes.

More summary detail relative to the individual processes can be found in the Summary Section of the respective process.

The remainder of this Summary contains the following sub-sections:

- A general comparison of the four process schemes.
- A listing of key similarities and differences of the four processes.

The next sub-section is titled Assessments. This is comprised of recommendations and conclusions reached as a result of this investigation.

3.2 Comparison of Overall Process Schemes

The following briefly describes the process scheme of each of the following advanced coal gasification processes:

- AVCO High Throughput Gasification (HTG) Process
- Bell Single-Stage High Mass Flux (HMF) Process
- CS/R (Cities Service/Rockwell) Hydrogasification Process
- Exxon Catalytic Coal Gasification (CCG) Process

The above processes are also depicted on Figure I-1, for comparing the differences of the four processes with respect to the major components in each process plant. Table I-2 summarizes the major units of each process.

3.2.1 AVCO HTG Process

Feed coal is pulverized to 70% through 200 mesh and dried to about 2 wt.% moisture. The coal and steam are injected into the pyrolyzer which operates at 550 psig. Hot gases from the combustor entrain the feed coal and gasify about 48% of its carbon, to produce H_2, CO, CO_2 and CH_4. The raw product gas and the char exit the pyrolyzer into a cyclone where the char is separated. The char is then recycled to the upstream combustor where the char is totally combusted with oxygen. The resultant hot gases then proceed to the pyrolyzer supplying the required heat for coal pyrolysis. The coal minerals form a molten slag in the combustor and continuously flow down onto the inner wall surface as a protective refractory. The excess slag is trapped out at the bottom of the combustor, water quenched and disposed off-site.

The gas from the cyclone downstream of the pyrolyzer is routed to a heat recovery system where the sensible heat of the gas is recovered to produce H.P. (1500 psig) steam. Then the gas is water scrubbed to remove the remaining solid fines.

The solid-free gas flows through the CO-shift, the acid gas removal, and the bulk methanation system. Approximately 8 volume percent of the treated gas is withdrawn downstream of the acid gas removal unit and consumed as the plant fuel. The remaining gas is routed to the bulk methanation system for producing pipeline quality SNG.

3.2.2 Bell Single-Stage HMF Process

Coal, oxygen and steam are fed to the single-stage slagging reactor, operating at 2530°F and 500 psia where 90% of the coal carbon is gasified. The reactor effluent is quenched to 1900°F with water. The shattered slag is then separated from the raw product gas and sent to disposal. The raw product gas, containing unconverted char, proceeds to the heat recovery system which cools the gas stream from 1900°F to 600°F by generating steam. The gas proceeds 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 system at 345°F, where the reaction is controlled to produce an effluent stream with a H_2 to CO ratio of 3. The gas stream then proceeds to a selective acid gas removal unit where the H_2S rich stream is routed to the sulfur recovery unit, and the CO_2 stream to disposal. The cleaned syngas then proceeds to the bulk methanation unit for SNG production. The produced SNG is then compressed and dehydrated to pipeline specification for sales.

3.2.3 CS/R Hydrogasification Process

The CS/R hydrogasification process includes a coal hydrogasification SRT reactor followed by a char oxygasifier reactor to produce H_2. It uses a hot gas and solids heat recovery step to partially preheat the recycle H_2. It also can produce BTX by-product along with the raw product gas. Due to the high carbon conversion to CH_4 in the hydrogasifier (45% per pass) only trim methanation is required with no shift conversion in the product gas stream. An O_2 plant is required mainly for the char/coal oxygasifier for H_2 production but also for preheating of the recycle H_2 by partial combustion. No catalyst is employed.

3.2.4 Exxon CCG Process

The coal is crushed, dried, impregnated with potassium catalyst, dried again, and then fed to the fluidized bed gasifier. The gasifier also receives steam and recycle syngas (H_2 and CO) which is preheated to 1550°F. The gasifier operates at 1275°F and 500 psig. The CCG gasifier involves the reactions of coal gasification, shift and methanation. The resultant heat of reaction is essentially thermo-neutral. The net heat requirement for the gasifier is provided by preheating the recycle syngas stream. Approximately 51% of the coal carbon is converted to CH_4 in the gasifier.

The raw product gas from the gasifier proceeds through cooling (by generating H.P. steam) from 1257°F to 540°F, water scrubbing for fine solids removal from 540°F to 373°F and then low level heat recovery from 373°F to 313°F. The gas is cooled to 120°F prior to entering the selective acid gas removal unit where the H_2S rich stream is fed to the sulfur recovery unit, and the CO_2 stream is sent to disposal. The treated process gas stream is then routed to the cryogenic separation unit where methane is separated from the syngas stream (CO and H_2). The latter is recycled to the gasifier, and the methane fraction is heat exchanged and compressed to the SNG pipeline pressure for sales.

Approximately 90 percent of catalyst is recovered from the char/ash in the Catalyst Recovery Unit by a $Ca(OH)_2$ digestion process. The recovered catalyst is recycled and added to catalyst makeup to be reused in impregnation.

3.3 Comparison of Process Gasifiers

The following are brief descriptions of the advanced coal gasifiers:

(The schematic drawing of each of the gasifiers is depicted on Figure I-2 which shows the essential elements of the gasifier such that an overall general comparison can be made. Table I-3 summarizes the comparison of the gasifiers.)

3.3.1 AVCO HTG Gasifier

The AVCO gasifier consists of two parts. The first part is a char combustor, and the second a coal pyrolyzer. The flow directions for the combustor and the pyrolyzer are down and horizontal flows, respectively. Both reactors are close coupled and operated in an entrained flow regime. The combustor operates at 600 psig and 2400 to 2900°F, and the pyrolyzer at 550 psig and 1600°F measured at the exit. The gas residence time in the pyrolyzer is in a range of 20 to 40 milliseconds.

The raw gases H_2, CO, CO_2 and CH_4 are produced by pyrolysis followed by a steam-volatiles stabilization. The remaining char is separated from the raw gas and recycled to the combustor where the char is burned with oxygen. The resultant hot gas from the combustor supplies the heat requirement for the downstream pyrolysis.

The coal minerals in the form of molten slag are trapped out at the bottom of the combustor by quenching in a water bath attached thereto. The shattered slag is then disposed of off-site.

3.3.2 Bell Single-Stage HMF Gasifier

Coal is fed to the central injector nozzle and is impinged by a co-axial stream of oxygen followed by a steam injection immediately downstream. The exothermic reaction of coal and oxygen produces enough heat to gasify the coal at 2530°F and 500 psia. At these conditions, the coal minerals form a molten slag.

The product gas consists mostly of CO and H_2 (56% and 31%, respectively) and lesser amounts of H_2O, CO_2, H_2S, N_2 and CH_4 in that order. The overall reaction can be expressed as follows:

$$\text{Coal} + \text{Steam} + \text{Oxygen} \longrightarrow \text{Raw Syngas} + \text{Slag} + \text{Char}$$

The effluents are quenched with water to 1900°F. The slag is solidified, and separated for disposal. The char is separated in a cyclone following the heat recovery from the raw syngas.

3.3.3 CS/R Hydrogasification Gasifier

Recycle plus makeup H_2 is heated to reaction temperature by reacting with O_2 in a preburner prior to mixing with the feed coal in the Hydrogasifier which operates at 1000 psi. The exit gas temperature of the raw product gas is 1746°F. Before quenching, this stream containing char solids exchanges heat with the recycle H_2 stream. The char is separated after quenching and fed to a char oxygasifier with some additional coal to produce the required makeup H_2 for the main hydrogasifier reaction.

The net overall reaction can be expressed by:

$$\text{Coal} + H_2 \xrightarrow{\text{heat}} CH_4 + \text{BTX} + \text{Char}$$

3.3.4 Exxon CCG Gasifier

The Exxon Catalytic Coal Gasifier is a fluidized bed reactor, integrating gasification, shift reaction and methanation in the single reactor. The steam gasification reaction is highly endothermic, the steam-gas shift mildly exothermic, and the methanation highly exothermic. The composite of these three reactions is essentially thermo-neutral, and results in a significant net production of CH_4 and CO_2. The net overall reaction can be expressed by:

$$\text{Coal} + H_2O\ (\text{steam}) \xrightarrow[K+\ \text{catalyst}]{} CH_4 + CO_2$$

The gasifier receives catalyst-impregnated feed coal, preheated by a slip stream of the recycle syngas. Catalyst is impregnated on the coal to catalyze the heterogeneous steam gasification and gas phase methanation reaction plus eliminate any agglomeration problems in the gasifier using caking coals. The coal bed is fluidized by the syngas-steam mixture, also preheated to compensate for the heat losses of the gasifier vessel. The gasifier is operated at 500 psig and 1275°F.

All gas phase reactions in the gasifier essentially reach equilibrium. Once the recycle syngas stream is established, there is no significant net production of CO and H_2. The net carbon conversion is approximately 90%, producing CH_4, and CO_2. The unconverted char and ash are disposed off-site following recovery of the catalyst.

3.4 Key Similarities and Differences

Table I-4 summarizes the key similarities and differences of the advanced coal gasification processes, including

- AVCO HTG
- Bell Single-Stage HMF
- CS/R Hydrogasification
- Exxon CCG

The comparisons involve the gasifier characteristics as well as the key process units included in the overall gasification plants.

3.5 Assessments

As a result of this study, considering the characteristics of each gasification process, the process strengths, weaknesses, advantages and disadvantages, potential improvements and development needs, the following nine assessments are submitted. These include recommendations for further development.

3.5.1 General Assessments

1. The four gasification processes in this assessment were applied to the production of SNG. The question may be asked whether this is the best application for each gasifier. The Exxon and Rockwell Gasifiers were designed to produce a high methane product gas. AVCO and Bell gasifiers are better suited to producing a lower Btu product gas or some form of synthesis gas for further conversion to other products such as methanol, gas turbine fuel, Fischer-Tropsch liquids, hydrogen, etc.

It is recommended that this distinction be made so that the most suitable application of these gasifiers to the required end product be considered.

2. Considering the stages of development, relative efficiencies and basic principles (excluding economics), if one of these gasifiers had to be selected today for the production of SNG it would be Exxon's. The CS/R Hydrogasifier shows high potential but is at an earlier stage of development and requires selection, demonstration and design of several companion processes and unit operations for an integrated SNG process. The AVCO and Bell gasifiers require much more development and are in a very early stage with respect to an SNG application.

3. The success of the SRT gasifiers will depend greatly upon how well they can be scaled up and controlled. The compact size of the reactors may require multiple units or modules to reach the commercial scale. Multiple units will require feed splitting and other measurement and control devices to operate with high precision. These devices have yet to be developed or demonstrated. In the case of Rockwell, it is proposed to split the total coal feed to as many as 36 modules. This must be demonstrated and proven to be reliable. In the case of AVCO's slagging wall concept, the successful control

of slag flow, tapping and containment will be influenced by scale of operation. This also must be demonstrated.

The turn down capability of all of the SRT gasifiers will be strongly influenced by scale. The smaller the individual module or the greater the number of modules, the greater the turn down capability of the total gasification section. The slag layer and its limitations may be critical to the turn down capability and therefore scale of the gasifier module. In another respect, as the CS/R Hydrogasifier is turned down, the residence time increases and the product composition changes (e.g., reduced benzene yield).

4. In many of the gasifier processes, char is a common intermediate product. Due to the emphasis to develop the primary coal gasification process, there is scant information developed concurrently on the chars. It is recommended that, to the extent feasible, the resulting chars be defined and characterized including analyses, chemical and physical properties, handling characteristics, reactivities and suitability to further processing and use. This would eliminate a great deal of doubt and uncertainty in closing material balances in many gasification processes. In the case of Rockwell's process, the char is a major intermediate for the production of hydrogen and considerable more data are needed beyond composition.

5. As the data base increases for each process, the modeling effort should continue to be updated to fit the data. Accurate kinetic models should be developed as they could be utilized as follows:

- To optimize the reactor design
- To predict yields of untested coals.
- To perform trade-off process design studies.
- For use in scale-up design studies.
- For use as an operational and control guide in pilot plants.

6. It is recommended that, as part of DOE funded gasification development projects, each developer compile and publish a summarized reference book which should include:

- Sources of information, including basic physical and chemical data.
- Extent of testing.
- Process flow diagram of test facilities including equipment sizes, control schemes, etc.
- Selected test results including heat and material balances, conditions, lengths of runs, feed and product analyses and characterization.
- Data correlations.

It is suggested that such a reference book be updated and published at least once per year.

3.5.2 Specific Assessments

7. AVCO HTG Process

a) Continue development of pyrolysis data base:
Much of the pyrolysis data has been extracted from small-scale batch equipment. Verification of data using larger scale, continuous flow reactors needs to be done.

b) Components integration:
The combustor stage has yet to be operated using coal char as a fuel. The current flow scheme for planned coal pyrolysis experimentation includes the burning of No. 2 fuel oil to produce the hot gases for the pyrolysis stage. It is recommended that the combustor be run using char. It is also recommended that the char combustor and pyrolysis stages be run simultaneously as early as possible. It makes little sense to continue fine tuning 1/2 of the system for optimum pyrolysis yields without addressing operability and characteristics of the other 1/2 of the system. Testing in the near future should include integration of the combustor and pyrolyzer so that development of special control schemes, which undoubtedly will be necessary, can proceed. Also, any unexpected effects of using char for the generation of hot gases versus using No. 2

oil on pyrolysis yields, fines removal, slag layer coating, handling of hot recycle char, etc., would be detected.

c) Combining MHD with coal gasification:
The combination of coal plus char combustor, an MHD channel and the rapid-pyrolysis stage could be employed to produce syngas and power. Further analysis to determine the technical and economic feasibility of such a system should be carried out.

8. Bell HMF Process

a) Continue development of data base for single-stage gasifier:

(1) Single-stage carbon conversion: the projected carbon conversion at the given oxygen to coal ratio for bituminous coal should be demonstrated;

(2) Recovery of ungasified carbon: the form of the ungasified carbon should be identified; in addition, recovery of the carbon as char should be demonstrated;

(3) Demonstrate the slag/char separation: the assumption that the slag captured in the slag pot will be essentially char free and that little carryover of the slag with the syngas should be demonstrated;

(4) Char composition: at this time, no data on the char composition is available;

(5) Reactivity of recycle char: once the upgraded (refer to Section III - Development Status Details, Figure III-8) facility is working, char from cyclone separation should be tested for its reactivity and carbon conversion in the gasifier by itself and as a mix with fresh coal;

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(6) Char use as a boiler fuel: once the upgraded facility is working, a program to collect sufficient char for testing in a boiler should be developed.

(7) Testing with other chars: it is recommended that chars produced from other coal conversion plants be tested as a potential application for syngas generation.

(8) Validation of material balances: at this time, Bell has been unable to make a complete material balance. Material balances have been assumed by differences. Procedures should be developed in order to make an entire material balance.

b) Develop secondary injection data base: (Refer to Section III - Potential Improvements)

Operational problems with secondary-injection of coal are anticipated including agglomeration of coal particles. It is recommended that an operational, secondary-injection configuration be developed by Bell regardless of initial failures or difficulties to determine the degree of enhanced methane yield possible in a high temperature, short residence time reactor. Also, analysis procedures for detection of trace quantities of tar and soot formed by secondary-injection should be developed and utilized in this testing.

c) Investigate hydropyrolysis with secondary- injection:

Once the secondary-injection configuration is successfully tested, a stream of hot hydrogen should be added to the secondary-injection section at various rates to determine the hydrogasification to CH_4. This is suggested to determine what the methane yield in a hydrogasifier would be at temperatures (2400°F) where equilibrium suggests negligible methane yields. The Bell test facility lends itself to testing various gasifier configurations rather easily. The gasifier is made of several removable parts; hence, fabrication and testing of different configurations can be done easily and rapidly.

d) Investigation of molten-slag bath concept:
It is suggested that an investigation of the molten-slag bath concept as applied to the Bell HMF process be made. The potential offered by this concept is a higher single pass carbon conversion which could eliminate anticipated char utilization problems. Also, a concept using the molten-slag bath with a second-stage pyrolysis section is recommended for further investigation (see Section III-Potential Improvements).

e) Catalyst application testing:
In a high temperature reactor, catalyst use is thought of as being marginally beneficial, since the reaction rates are so fast anyhow. However, some benefits could be attained including operation at lower temperatures for the same conversion, higher methane yields, reduced slagging accumulation problems, lower sulfur compounds in the syngas, and higher carbon conversions. It is recommended that performance testing be done with promising catalyst materials (see Section III - Potential Improvements).

9. CS/R Hydrogasification Process

a) It is recommended that the H_2 to coal ratio in the hydrogasifier be reduced to an optimum minimum. This will reduce the size of the process units which are gas flow limited downstream of the gasifier and in the H_2 recycle loop. It may also reduce the H_2 production to the extent that the H_2/coal ratio is reflected in H_2 losses. It should also reduce the overall utility requirements.

b) Since the production of the coproduct benzene appears to have a beneficial economic effect, it is recommended that benzene be increased to an optimum maximum.

c) The overall efficiency and feasibility of the CS/R Hydrogasification process to produce SNG will depend heavily on the process selected or developed for converting char to hydrogen. This secondary gasification process is regarded to be as important as the primary hydrogasification process and an assessment of the hydrogasification alone is incomplete for the production of SNG.

4.0 FLASH PYROLYSIS - A GENERAL COMMENTARY

Flash pyrolysis may be defined as rapid heating of pulverized coal such that devolatilization occurs in the range of milliseconds to a second. It is also termed short residence time, or SRT, gasification here to highlight the fact that all of the reactants experience the gasification conditions from milliseconds to several seconds.

For the advanced gasification processes assessed, the AVCO HTG, Bell Single-Stage HMF and the CS/R Hydrogasification are also termed flash pyrolysis reactors with the CS/R process more accurately termed flash hydropyrolysis. In addition to the development work being done on these processes, much research work is being done on flash pyrolysis and hydropyrolysis by others in order to better understand the complex chemistry and kinetics involved (see Sections II and III for a more detailed discussion of flash pyrolysis hypotheses for the AVCO and Bell processes). It is appropriate, also, that the basic research continue in parallel with the process development of the three SRT processes so that insights gained relative to the kinetics and chemistry can ultimately effect a more optimized process and a speedier development to commercialization. For example, while a pilot unit is operating to demonstrate long term runs and stability, basic research could be doing parametric studies to determine optimum yield conditions.

These three SRT processes all have similar aspects which make them attractive candidates for coal gasification as follows:

1. Small Reactor Size

The small reactor size is best typified by comparing calculated throughput in terms of pound per hour of coal per internal ft^3 reactor volume for the SRT gasifiers and other gasifiers as follows:

	lb coal/hr/ft^3
SRT-AVCO	14,000
SRT-Bell	2,800
SRT-Rockwell	50-2,000
2nd Gen. Modern Koppers-Totzek (3)	34
2nd Gen Texaco Montebello (3)	300
Lurgi (dry bed) (2)	30

Hence the installed cost of SRT reactors will be significantly cheaper than more developed gasifiers due to the following:

a) Less metal and refractory required,
b) Smaller reactors can be factory assembled and tested, and
c) Spare reactors or duplication costs are minimized.

2. Handling of Caking Coals Without Problems

The coal is injected at relatively low temperatures and well dispersed in the reactor before temperatures are reached which could cause softening and agglomeration. The coal injectors, which are developed from rocket combustor technology for the CS/R Hydrogasification and Bell HMF Processes, efficiently mix the caking coal with reactant gas in such a way to avoid agglomeration.

3. Selectivity of Devolatilization Products

The SRT gasifiers combine high temperature and short residence time features that can affect selectivity to valuable products, such as BTX. The high temperatures ensure rapid and almost instantaneous devolatilization. Heavy tars and oils, which are undesirable devolatilization by-products, are essentially hydrocracked to extinction very quickly. By limiting the residence time, however, the BTX fraction formed from the pyrolysis or hydropyrolysis reaction may be recovered by quenching before it is reacted further to form other less valuable products. A calculation of equilibrium composition indicates that the BTX fraction, which is a valuable by-product of the CS/R Rockwell Hydrogasification process, would not exist. This same feature of non-equilibrium selectivity could also be utilized for higher methane yields. Methane formed in flash pyrolysis and hydropyrolysis, especialy for the Bell Single-Stage HMF and AVCO HTG processes, would tend to decompose at the high temperatures. By optimizing the temperature and residence time combination, methane decomposition could be minimized.

While the SRT gasifiers offer the above noteworthy features, other aspects need to be addressed and resolved before the SRT can be commercialized. For example, where oxygen is used, sophisticated, quick-response control systems will have to be developed to prevent temperature excursions, equipment damage, and potential explosions. Also the scale-up of the SRT gasifier system could prove more difficult than for larger gasifiers. For example, scale-up of the Bell and CS/R gasifiers is expected to be done by clustering of many injector modules into the same gasifier vessel. This is similar to the clustering of propellant-oxidant injectors in rocket combustors. While the scale-up of the gasifier itself is not expected to be difficult, the feed splitting and flow control of coal solids in many different lines, plus the additional gasifier control problems associated with having a multitude of feed lines, could prove to be significant in delaying the development of the processes.

5.0 REFERENCES

(1) Patel, N. K., Roszkowski, R. T. and White, G. A., "A Screening Evaluation of Rapid Devolatilization Processes," performed by the Ralph M. Parsons Company for GRI, August 1978.

(2) Morel, W. C., "An Economic Comparison of the Bell HMF Gasifier with the Texaco and Lurgi Gasifiers," Report No. 79-1, Morgantown Process Evaluation Office, November 1978.

(3) Bissett, L. A., "An Engineering Assessment of Entrainment Gasification," published by the U. S. Department of Energy, MERC/RI-78/2, April 1978.

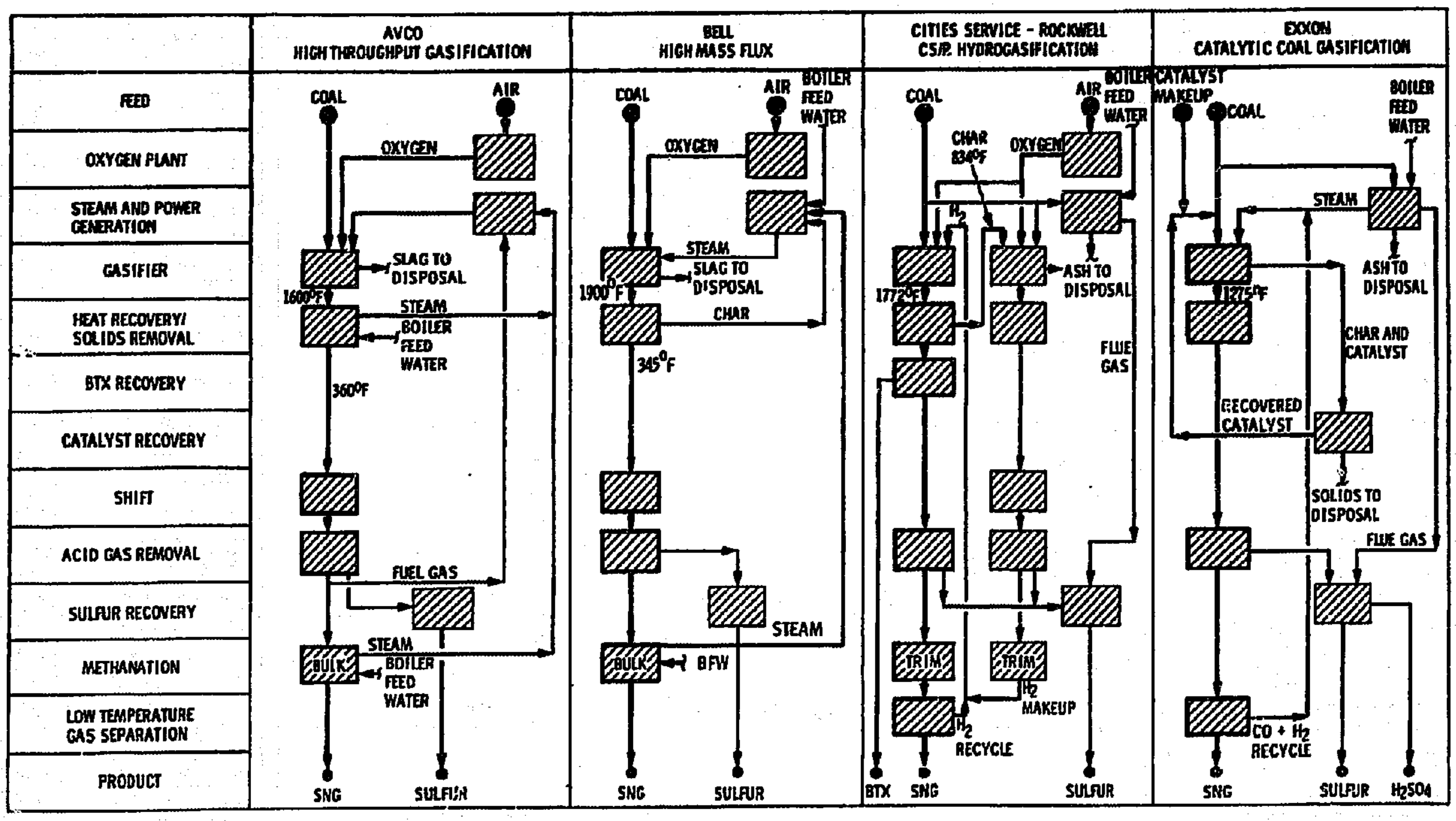

FIGURE I-1. Advanced Coal Gasification Processes - Conceptual Commercial Plant Overall Key Block Comparison.

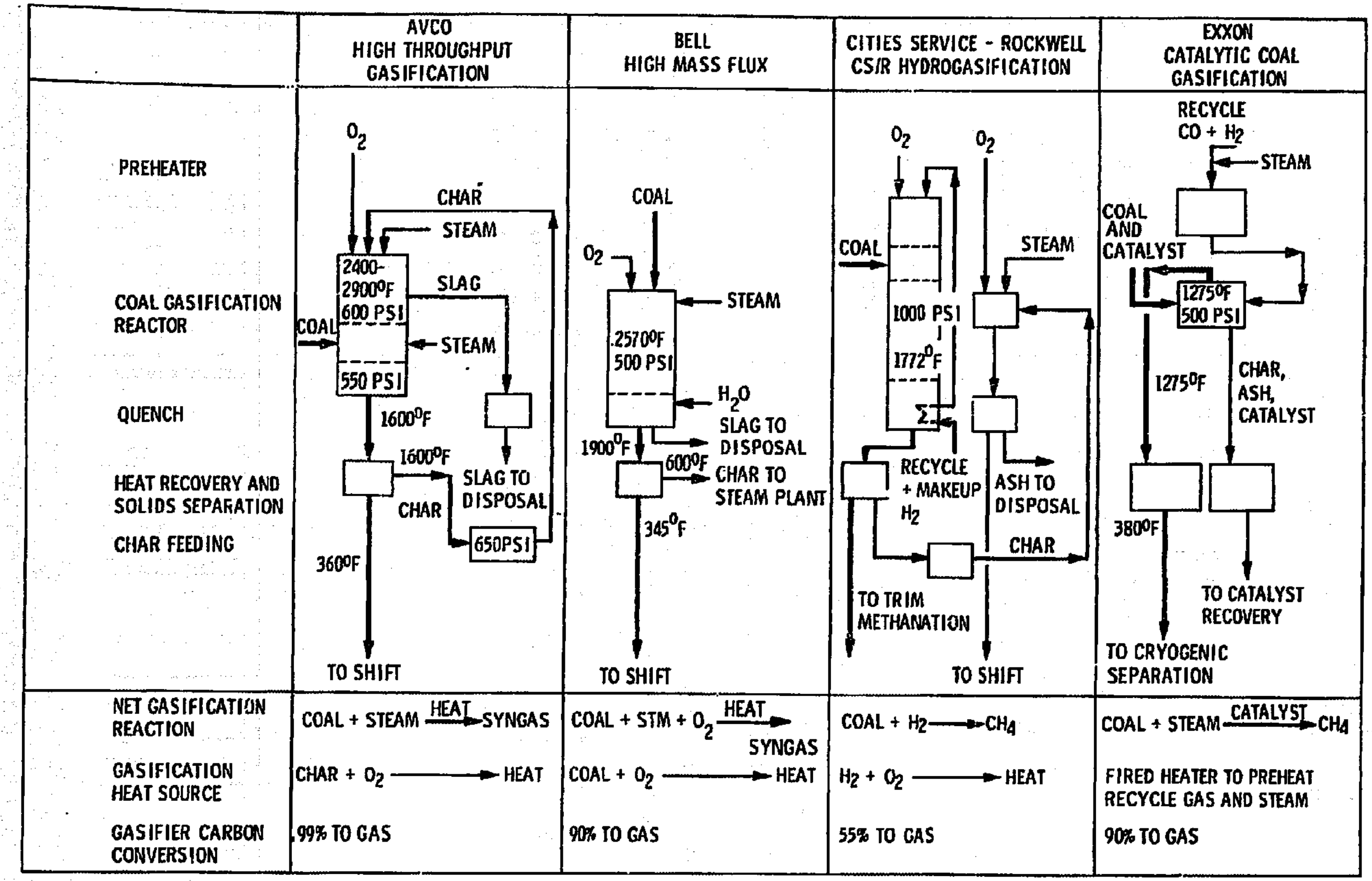

FIGURE I-2. Coal Gasification Reactors - Schematic Comparison.

	% C TO CH_4 IN GASIFIER	OVERALL THERMAL EFFICIENCY	GASIFIER RESIDENCE TIME	LIQUIDS & TARS	COAL FEED SYSTEM	CATALYST	RELATIVE COMPLEXITY TOTAL PROCESS	
							SOLIDS	GAS/LIQ
LURGI (DRY BED)	15	55	MINUTES	TARS +	L.H. + DILUTE PH.	NONE	MED	HIGH
TEXACO	0.5	N/A	SECONDS	NONE	WATER SLURRY	NONE	LOW	MED
AVCO HTG	11	68	0.03 SEC (PYR.)	NONE	L.H.+ DENSE PH.	NONE	HIGH	MED
BELL HMF	0.02	59	0.5 SEC	NONE	L.H.+ DENSE PH.	NONE	HIGH	MED
ROCKWELL CS/R	45	58	1-3 SEC	BTX (C_6H_6)	L.H.+ DENSE PH.	NONE	HIGH	HIGH
EXXON CCG	51	61	10 - 12 HR	NONE	L.H.+ DENSE PH.	K_2CO_3	HIGH	LOW

TABLE I-1. Comparative Features of Gasifier Processes.

TABLE I-2. Summary of Major Process Units

	AVCO HTG	BELL HMF	CS/R Hydrogasification		EXXON CCG
			Hydrogas.	Oxygas.	
o Oxygen Plant	X	X	X		-
o Steam/Power Generation	X	X	X		X (steam only; power imported)
o Catalyst Impregnation	-	-	-	-	X
o Gasifier	X	X	X	X	X
o Heat Recovery/ Solid Separation	X	X	X	X	X
o BTX Recovery	-	-	X	-	-
o Catalyst Recovery	-	-	-	-	X
o Shift	X	X	-	X	-
o Acid Gas Removal	X	X	X	X	X
o Sulfur Recovery	X	X	- X		X
o Methanation	X (Bulk)	X (Bulk)	X (Trim)	X (Trim)	
o Cryogenic Gas Separation	-	-	X	-	X

TABLE I-3. Summary of Gasifiers' Comparison

	AVCO HTG	BELL SINGLE-STAGE HMF	CS/R Hydrogas.	EXXON CCG
Type	SRT(1)	SRT	SRT	Fluid Bed
Coal Feed				Catalyst Impregnated
Reaction Heat Source	Char + O_2	Coal + O_2	H_2 + O_2	(2)
Reaction Conditions °F/PSI	1600-2900/600	2570/500	1771/1000	1275/500
Gasifier Waste	Slag	Slag	Ash	Char/Ash
Gasifier Char Utilization	Recycled to Combustor	To Steam Generation	To Oxygasifier	-
Quench to Control Reaction	Yes	Yes	Yes	No
Net Gasification	Coal + Steam	Coal + Steam	Coal + H_2	Coal + Steam
Net Product	Syngas	Syngas	CH_4	CH_4
Carbon Conversion to gas, %	48 (Pyrolysis) 99 (Pyrolysis + Combustor	90	55	90

KEY SIMILARITIES AND DIFFERENCES	AVCO HTG	BELL, SINGLE-STAGE HMF	CS/R HYDRO-GASIFICATION	EXXON CCG
GASIFIER –				
CATALYST	NO	NO	NO	YES
FLUID BED	NO	NO	NO	YES
SRT	YES	YES	YES	NO
ROCKET-ENGINE TYPE	NO	YES	YES	NO
SYNGAS PRODUCER	YES	YES	NO	NO
CH_4 PRODUCER	NO	NO	YES	YES
SLAGGING	YES	YES	NO	NO
COAL & STEAM, NET REACTANTS	YES	YES	NO (COAL + H_2)	YES
C + O_2, HEAT SOURCE	YES	YES	NO (O_2 + H_2)	NO
QUENCH TO CONTROL REACTION	YES	YES	YES	NO
CARBON CONVERSION, %	48	90	55	90
CHAR USAGE	RECYCLED	STEAM GENERATION	H_2 GENERATION	DISPOSED
OPERATING, PSIG	550	500	1000	500
^oF	2000 (AVG)	2570	1772	1275
OXYGEN PLANT	YES	YES	YES	NO
STEAM/POWER GENERATION	YES	YES	YES	YES (STEAM ONLY)
BTX RECOVERY	NO	NO	YES	NO
CATALYST RECOVERY	NO	NO	NO	YES
SHIFT	YES	YES	YES (OXYGEN)	NO
METHANATION	YES	YES	YES (TRIM)	NO
CRYOGENIC GAS SEPARATION	NO	NO	YES	YES

TABLE I-4. Key Similarities and Differences.

SECTION II

ASSESSMENT OF AVCO HTG PROCESS

1.0 SUMMARY

The AVCO HTG process as presented in this section is the result of a conceptual application of laboratory scale coal pyrolysis data to a commercial size plant to produce pipeline SNG. The conceptual process design of the coal to SNG plant was extracted from a study performed by the R.M. Parsons Co., for the Gas Research Institute. Other data on the AVCO HTG process in this section are the results of meetings and discussions with AVCO and literature surveying. Details of the conceptual reactor design and configuration were discussed but are not reported here since they are considered proprietary at this time.

The AVCO HTG reactor is a two-stage entrained flow gasifier employing a rapid pyrolysis stage and a char combustor stage. Pulverized coal and steam are fed to the pyrolysis stage, and char, oxygen and steam to the combustor stage.

The HTG reactor should be considered in an early stage of development especially in regards to coupling the pyrolysis and combustor stages as this has never been done.

The AVCO HTG has the following noteworthy features:

ADVANTAGES

- Extremely high pyrolysis-stage throughput rates (14,000 lb/hr of coal per ft^3 reactor)
- High overall coal to SNG thermal efficiency (68%)
- Protective slagging wall in the combustor stage
- Can handle caking coals

DISADVANTAGES

- Low coal-to-methane conversion (11%)
- High steam requirement (1.62 lbs steam per lb MAF coal)
- Moderately high oxygen requirement (0.64 lbs O_2 per lb MAF coal)

A comparison of the AVCO and the Bi-Gas two-stage coal gasifiers showed AVCO to be significantly lower in methane yield while higher in steam and oxygen consumption. Hence, a potential improvement in the AVCO process is suggested by adopting higher pressures and slightly longer gas residence times, approaching that in the Bi-Gas process. These measures should allow the same degree of conversion at lower oxygen and steam consumption.

2.0 CURRENT STATUS OF DEVELOPMENT

Work on the AVCO HTG Gasifier began in 1974 for ERDA in the Low Btu Gas Program. Initial testing for coal gasification was done in an entrained flow gasifier with coal feed rates of up to 120 lbs/hr. Pittsburgh Seam Coal was devolatilized by injecting it into a hot stream of combustion gases formed from the burning of No. 2 fuel oil with oxygen enriched air. Over 30 data points collected indicated thermal devolatilization in the range of 35 to 68% of the original DAF coal carbon into low Btu gas was possible with a typical residence time of 50 msecs. However, it was recognized that without adequate mixing with a background gas (e.g., steam and CO_2) during devolatilization, considerable soot was formed from the unstable volatiles.

From 1975 thru 1979, AVCO continued investigating devolatilization yields in a Single-Pulse Gasifier apparatus under the sponsorship of AGA and GRI. The experimental apparatus was used to simulate the HTG conditions by flowing a pulse of coal into a preignited stream of H_2 and O_2. The important observations from these experiments are:

1. Carbon conversion increases as the temperature of the preignited mixture increases;

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2. increasing the turbulence during pyrolysis has a dramatic effect on the carbon conversion with a more pronounced effect at lower temperatures;

3. carbon conversion at a given temperature seems to be independent of whether pyrolysis is in the presence of N_2 or CO_2.

In pyrolysis PDU work sponsored by AVCO, a reactor which had been originally developed for research in coal combustion for an MHD program, was used as a horizontal flow, entrained bed HTG. Hot gases are produced by the combustion of No. 2 fuel oil with oxygen enriched air; coal is injected into the hot gases at a rate of 1 TPH. The reactor is operated at 4 atm and has a run duration limit of about 1 hour. Typical gas residence time is about 2 msec. Early tests results have shown volatile yields comparable to that obtained with the Single-Pulse Gasifier.

As of yet, the HTG has not operated with the combustion gases being supplied by the combustion of char. Hence, actual operation of the AVCO HTG, which is a two-stage process, has not been demonstrated. However, operation of the combustor with coal and oxygen has been demonstrated in previous (MHD) programs. Operation with char and oxygen is assumed to be very similar.

MHD technology which AVCO has applied to the conceptual design of the HTG includes:

- slag utilization to form a protective slag layer on the reactor internal wall from MHD channel slagging work.
- char combustor from previous MHD coal combustor work.

Details of a conceptual design of the two-stage HTG reactor made by AVCO are not presented in this report as they are considered proprietary at this time.

Further details of the development status are at the end of this section.

3.0 PROCESS DESCRIPTION

The following describes the overall conceptual process plant of the AVCO High Throughput Gasifier Process producing SNG from coal by sections in accordance with the Process Block Flow Diagram, Fig. II-1 and the Material Balance, Table II-1. This preliminary process design is extracted from an evaluation study performed by the R.M. Parsons Company under GRI Contract No. 5010-322-0048.

3.1 Coal Preparation and Feeding

The coal used for the material balance is a Pittsburgh Seam No. 8 coal with the following properties:

Proximate Analysis, as-received,	Wt. %
Moisture	6.0
Volatile Matter	31.9
Fixed Carbon	51.5
Ash	10.6
	100.0

Ultimate Analysis (dry)	Wt. %
C	71.50
H	5.02
N	1.23
O	6.53
S	4.42
Ash	11.30
	100.00

Heating Value of Dry Coal Btu/lb (HHV)	13,190
Heating Value of Coal As-Received Btu/lb (HHV)	12,400

Raw coal received from stockpile is crushed to 70 percent minus 200 mesh and dried to 2 weight percent moisture in the coal preparation section.

The prepared coal is fed to a lockhopper system. A portion of the raw product gas from the Heat Recovery section is used in the lockhopper recycle system for pressurizing the lockhoppers and feeding the coal to the pyrolyzer.

3.2 Gasification

3.2.1 Stage I - Char Combustor

The recycled char, oxygen, and steam are injected into the combustor through nozzles located near the top of the vertical down flow combustor. The char-oxygen mixture is fed through the center port of the injector, while the steam passes through the outer annulus.

Oxygen and steam are regulated to the combustor for total combustion of the residue carbon. The combustor effluent gas having a temperature of 2400°F and pressure of 600 psia flows directly into the pyrolyzer as the only heat source for coal gasification in the pyrolyzer.

The coal minerals form a molten slag on the combustor inner wall surface which is continuously replenished. The slag coating serves as the protective refractory for the combustor. Excess slag is trapped out at the bottom of the combustor and quenched in a water bath attached at the bottom of the combustor. The shattered slag separated from the quench water is delivered to battery limits for disposal.

3.2.2 Stage II - Coal Pyrolyzer

Pulverized coal and steam are injected radially into the horizontal flow entrained bed pyrolyzer which contains high temperature gas from the close-coupled char combustor. Thermal devolatilization of coal and homogeneous gas phase reaction are accomplished by effective mixing of the feed coal, the hot gas, and the injected steam. At 550 psia and a reactor outlet temperature of about 1600°F, 48 weight percent of the coal carbon is gasified.

3.3 Char Separation

The pyrolyzer effluent gas is routed to a dry cyclone separation system where the char together with coal-ash is separated from the gas. The cyclone off gas is routed to a heat recovery system. The solids, containing char and ash, are recycled to the combuster via a char feeding system.

3.4 Char Feeding

The char feeding system consists of lockhoppers similar to the coal feed hoppers. The hot char is pressurized to about 650 psia in the hoppers and fed to the combustor in a dense phase flow condition. The carrier gas is the same gas used in the coal feed lockhoppers.

3.5 Heat Recovery

The gas from the cyclone proceeds to a heat recovery system. The sensible heat of the gas is recovered in heat exchangers to generate 1500 psig steam and to preheat boiler feed water. The cooled gas is then scrubbed with the process condensate from downstream of the shift converter to remove the solid fines which are not removed by the cyclones. These fines are dried and then recycled to the char combustor.

3.6 Shift

The solid free gas is delivered to the shift converter after being reheated to about 600°F by back exchanging with the shift converter effluent gas.

3.7 Acid Gas Removal

The shifted gas is cooled to approximately 140°F, condensate separated, and the gas fed to the Acid Gas Removal section. Sulfur-containing gases and CO_2 are selectively removed from the gas in a physical solvent absorption system such as the Selexol process.

Approximately eight percent of the desulfurized syngas is taken for plant fuel and for supplementing the fuel required for superheating steam. The balance of the syngas is reheated to 700°F and passed over cobalt moly catalyst and zinc oxide to remove the trace sulfur compounds in the gas. The syngas is then routed to the catalytic methanation section.

3.8 Methanation

A high temperature methanation system such as the RM Process® (1) is employed here to recover maximum quantity of heat released in the methanation system for production of 1500 psig steam. Thirty percent of the gas from the zinc oxide reactor is fed to the first of the five bulk methanation reactors. A small quantity of steam is added to moderate the temperature rise across the catalyst bed in the first reactor. The remaining seventy percent of the fresh feed is fed to the second methanator. The effluent gas streams from the first and the second reactors are combined and fed to the remaining three methanators connected in series. Through this bulk methanation system, the process gas temperature is progressively lowered by heat recovery in the exchangers placed between the reactors. After the final methanation, the gas is cooled to condense the steam.

3.9 Drying and Compression

The gas stream from the bulk methanation system is then compressed to the desired product pressure and passed through the trim methanator for production of specification SNG. The dehydration of the product SNG is effected by a glycol dehydration unit.

3.10 Sour Water Stripping

The sour condensate collected downstream of the shift converter is routed to a sour water stripper. The stripped condensate supplemented with condensate recovered in the methanation system is routed to the plant water system for treating and reuse.

3.11 Sulfur Recovery

The sulfur-containing gases from the Acid Gas Removal section and from the Sour Water Stripping section are delivered to the Sulfur Recovery section. The latter includes a Claus sulfur plant and a tail gas treating plant for producing elemental sulfur as a by-product.

3.12 Water Treating, Steam Superheating, and Power Generation

This unit consists of water treating for BFW preparation, steam superheating, and power generation as required for the entire plant.

3.13 Oxygen Plant

The oxygen plant consists of commercially available air separation units delivering oxygen at 600 psia to the char combustor.

4.0 STRENGTHS AND WEAKNESSES

4.1 Strengths

- Effective utilization of oxygen. An advantage of the AVCO HTG two-stage concept is that valuable oxygen is used to combust and burn out the more difficult to react char in the STAGE I combustor. The high temperature combustion gas is then used to supply the heat required for the thermal pyrolysis of coal in the STAGE II pyrolyzer. The steam injected to the STAGE II pyrolyzer is used for homogeneous gas phase stabilization reactions; no steam-coal/char heterogeneous reaction is claimed to occur in the pyrolyzer.

- High throughput rate; short residence time. AVCO estimates that the pyrolysis reactor can be operated at a coal feed rate of 14,000 lbs/hr per ft^3 of reactor volume at the prescribed process conditions. This corresponds to a residence time of 40 milliseconds.

- Slagging wall combustor. Since the temperature in the char combustor can be in excess of 3000°F, the coal ash is converted into molten slag. A continuously replenishable steady state slag coating which is formed on the wall structure serves as a protective refractory material.

- High carbon utilization. The coupled combustor-pyrolyzer gasifier is potentially capable of operating at nearly 100% carbon utilization. Coal ash is the only solid effluent stream produced in the plant.

- High thermal efficiency. 68.4% of the thermal energy input in the coal feed is converted to the SNG product (cold gas efficiency).

- Clean process. Ammonia and tar/oil liquid hydrocarbons may be produced only in a negligible quantity. No extensive liquid effluent treatment is required in the process.

- No utility coal requirement. Sufficient high pressure steam (1500 psig) can be generated with the process heat recovered in the heat exchangers and by utilization of a high temperature methanation unit. No coal-fired steam boiler is required to supplement the plant steam requirement.

- Self-sufficient plant fuel requirement. A small slip stream of desulfurized product syngas (prior to methanation) is used to supply the plant fuel gas requirement. No additional flue gas desulfurization is required.

- Dense phase feeding. Both the process coal and the residual char are fed as dry solids in dense phase mode; hence, less volume of carrier gas and smaller transfer lines are expected.

- Flexible application. The gasifier produces H_2, CO, CO_2 and a lesser quantity of CH_4. With selected downstream processing, the gasifier can be used for generating low Btu gas, medium Btu gas, synthesis gas, or high Btu gas. Also, caking coals are acceptable feeds to the HTG.

4.2 Weaknesses

- Low coal-to-methane conversion. Experiments indicated a typical pyrolyzer effluent gas contains about 6.5 volume percent of methane on a dry basis, representing a carbon conversion to CH_4 of only about 10-15%. In the conceptual process shown in Figure II-1, only about 30% of the total SNG is produced in the HTG reactor.

- **Weak data base.** The conceptual process design is based on the information extracted from laboratory experimental data. Most of the research work was performed on a batch process explosion chamber reactor. No data from a continuous steady-state run are yet available at this time. Further development work is mandatory to substantiate the preliminary data used for the conceptual design.

- **High material consumption.** A comparison on the feeds per MM Btu of product SNG is tabulated below. The BCR Bi-Gas process is very similar functionally to the AVCO HTG; the major difference is that the AVCO HTG has much higher reactor throughput.

	AVCO HTG	BCR BI-GAS(2)
Lbs O_2	62.98	43.04
Lbs process steam	159.18	82.64
Lbs DAF coal		
Process	98.35	85.88
Utility	-	13.02
Total (lbs. per MM Btu SNG)	320.51	224.58

- **Critical components need further development work:** The following areas need significantly more development work:
  - hot char recyle including char recovery, repressurizing, and dense phase flow to the combustor
  - heat recovery from the high temperature syngas and entrained solids to generate high pressure steam
  - control scheme to keep close control on the flow of two solids streams, coal and hot char, which if either were interrupted, would shut the gasifier down.

5.0 POTENTIAL IMPROVEMENTS

The following items are being suggested as potential solutions to problem areas that appear to exist as the process is now proposed by the developer. These also take into account the stage of development of the overall process and the conceptual status of many of the companion operations to and around the proposed gasification step. They are the result of reviewing items mentioned in other sections such as weaknesses, alternates, disadvantages and status of development. It is not suggested that these are the final solutions. They are potentials only, viewed from the perspective of this assessment, and will require more detailed investigation and evaluation prior to testing. It is for this reason that they are called potential improvements.

5.1 Oxygen/Steam Utilization

The two-stage HTG concept proposed by AVCO is to use the valuable oxygen to combust and burn the less reactive char in the combustor stage and to use steam + CO_2 to stabilize and react with the more reactive volatiles evolved from coal in the pyrolyzer stage. This is contrasted with a single-stage gasifier, e.g., the Texaco gasifier, where the valuable oxygen is consumed by heterogeneously reacting with the char and by reaction with the volatiles.

However, a comparison of the steam and oxygen consumption of the AVCO two-stage gasifier to that of the Bi-Gas two-stage gasifier(2) shows 46% higher oxygen and 93% higher steam usage per MMBtu of SNG final product. Also, the coal carbon converted to CH_4 in the AVCO two-stage gasifier is much lower: 11% versus 24% for Bi-Gas.

It is suggested that AVCO investigate in their PDU the following:

(a) higher pressures, approaching 1000 psia

(b) higher pyrolysis residence times, in the order of several seconds

(c) lower pyrolyzer outlet temperatures

The purpose of suggesting the above is to maximize the CH_4 yields in the gasifier by allowing the gas phase and heterogeneous reactions to produce more methane. The objective would be to reduce the oxygen and steam consumption to that of the Bi-Gas system while simultaneously increasing the CH_4 yield. It is realized that the yields of the Bi-Gas reactor as given in the Braun report (reference 2) are probably optimistic. For example, the carbon conversion to CH_4 in that report is calculated to be 24%. However, previous experimental data by Bituminous Coal Research, Inc., on a Pittsburgh Seam coal showed conversions from 12 to 20%;(3) with N. Dakota Lignite, conversions from 11 to 17% were achieved(4). Conditions of the testing were similar to AVCO except the pressure was about 1000 psia and the residence times ranged from 2 to 16 sec. Hence, although a yield of coal carbon to methane of 24% seems optimistic, higher conversion than AVCO has realized are entirely possible by pressure and residence time adjustments.

5.2 Synthesis Gas Production

The AVCO HTG pyrolyzer produces a significant, but relatively small amount of methane: only 11 percent of the coal carbon is converted to CH_4. When producing SNG, or a fuel gas to be used for combustion, the methane yield should be maximized. However, where a syngas is to be used for hydrogen production, Fischer-Tropsch synthesis, methanol synthesis, etc., the production of methane should be minimized so that costly separation of the CH_4, e.g., by cryogenic separation, can be eliminated. It is suggested that AVCO investigate in their PDU the conditions required to give essentially no methane. Higher pyrolyzer temperatures and lower steam usage are methods which should reduce the methane yield.

5.3 Combined Gas and Power Production

To capitalize on AVCO's knowledge of coal pyrolysis and MHD power generation, it is suggested that they further investigate the integration of the combustor, channel, and pyrolyzer. This arrangement has the advantage of producing gas as well as power which could be used for plant requirements. The added complexity is seed injection and separation as required in an MHD power cycle.

6.0 COMPONENTS REQUIRING DEVELOPMENT

6.1 Dense Phase Feed System

In the proposed HTG gasification process, two dense phase feed systems are required; one for coal feeding and one for char feeding. At the present stage of development, the actual feed system has not yet been selected by the developer. Pressurized lockhopper systems must be used. The developer is considering to use raw product gas as the lock gas. A gas recovery and recycle system would be necessary to minimize the valuable gas venting to atmosphere.

AVCO has experience with dense phase coal transport and feeding up to 2 hours duration. A continuous feeding system for a longer time scale has yet to be demonstrated.

The coal/char is injected at a point of high Reynolds number and near sonic velocity in the main stream in a manner that encourages fast turbulent mixing of the solids and main stream. The injection of a coal stream into a main stream of near sonic velocity, yet maintaining optimum turbulent mixing, may present difficult fluid mechanic problems.

6.2 Char Combustor

The design of a char combustor to operate in series with the pyrolyzer would also be designed on the concept of high temperature rapid gasification. The slagging wall combustor concept is based on related work performed by AVCO in their coal-fired MHD program. However, the properties of the char are undoubtedly different from the properties of the coal. Mechanical features, combustion stoichiometry, effects of ash composition and concentration, and gas molten-slag separation require special attention in the development of the char combustor.

6.3 Reactor Turn Down

The reactor turn down capability of the proposed HTG system has not yet been studied. The turn down ratio is an important parameter to the application of slagging reactor wall structure technology and to the process engineering of the process.

Establishing and maintaining a continuous steady flowing layer of molten slag on the reactor wall is controlled by the shear and body forces on the slag and the slag viscosity, which is dependent on temperature. Limits of these controlling factors and the effect of changing the gas solids stream flow pattern may require further study.

From a process engineering point of view, a piece of equipment which has limited turn down ratio can be the bottle-neck of the entire process. Costly plant shut down could be caused by not allowing for an adequate reactor turn down ratio in the process design.

6.4 Control and Safety Systems

At the present stage of development, the control/instrumentation and safety systems for a two-stage HTG reactor have not been developed on any scale. The following items represent some major points which require special attention:

- a reliable, high-sensitivity flow control system for solids.
- a safety control system which can prevent the possibility of an oxygen explosion caused by upset conditions such as loss of char feed, loss of coal feed, loss of steam, etc.
- a suitable instrumentation system which can adequately control this very short residence time gasifier.

7.0 DEVELOPMENT STATUS DETAILS

AVCO's experience in MHD development entailed new studies of coal and gas behavior at high temperature and related technologies. Basic and applied research on coal utilization led to a conceptual two-stage gasifier system: Stage I is a char combustor and Stage II is a coal pyrolyzer. The proposed two-stage gasifier has not yet been fully tested in the laboratory. Details of the conceptual design are considered proprietary at this time. Most of the pyrolysis data gathered are from single-pulse gasifier experiments. The technological information and development status of the related components which have been tested or are under testing are given as follows:

(1) Pyrolysis Work

- <u>Entrained Flow Gasifier Experimentation</u>
- <u>Single-Pulse Gasifier (batch) Experimentation</u>
- <u>Pyrolysis PDU (high velocity) Experimentation</u>

(2) Slag Utilization

(3) MHD Coal Combustor Work

(4) Analytical Modeling Work

(5) Future HTG Gasifier PDU Development

7.1 Pyrolysis Work

7.1.1 Entrained Flow Gasifier Experimentation

- Funding Agency: ERDA - Low Btu Gas Program

- Project Period: 1974-1975

- Project Objectives:

  Exploration of the rate and extent of coal devolatilization using the MHD combustor overhead gas as the heat source.

- Test Facility:

The entrained bed gasifier experiment set-up is shown in Fig. II-2. The system consisted of a vertical down-flow gasifier with top mounted oil burner and auxiliary equipment with coal feed rates of up to 120 lb/hr.

- Test Conditions:

Coal (70%-200 mesh) was fed through three radially-aligned injectors at a rate of 50 to 120 lbs/hr. The coal particles were heated up rapidly and devolatilized as they got entrained in the hot gases produced by combustion of No. 2 fuel oil with oxygen-enriched air.

The volatiles and char were intermixed and reacted with the hot gases as the stream flows downwards. All the reactions were quenched by cold water jets at the bottom of the gasifier. Char particles were collected in the char collector for char analysis. Gas samples sucked through the sampling probe were analyzed by on-line IR detector or by gas chromatography.

The gasifier was operated at atmospheric pressure. Gas temperature (without coal) was measured in a range of 2780° to 3590°F. Coal-gas mixture residence time was set in a range of 7 to 70 milliseconds.

- Test Results:

Over 30 data points indicated thermal devolatilization in the range of 35 to 68% of the original DAF coal carbon into low Btu gas with a typical residence time in the order of 50 msecs.

It was also acknowledged that inadequate mixing of volatiles and background gas during devolatilization caused significant soot formation.

7.1.2 Single-Pulse Gasifier Experimentation

- Funding Agencies: AGA/GRI
- Project Period: 1975-1979
- Project Objectives:

Investigation on volatile yields of pulverized coal under extreme conditions of initial coal-gas mixing, temperature and heating rate.

- Test Facility:

The experimental apparatus is shown in Fig. II-3. The batch process explosion chamber is made of an aluminum cylinder (25 cm ID x 24 cm) with steel end plates. Piezoelectric pressure transducers, one on each end flange, were used to measure the very rapid pressure change.

A coal holder with perforated bottom plate was mounted in the chamber bottom flange. A pressurized gas reservoir was isolated from the explosion chamber by a quick acting ball valve.

- Test Conditions:

Before each run, coal was placed in the coal holder and the chamber was evacuated. Depending on the experiment, O_2, O_2 + CO_2, or O_2 + N_2 was then loaded in the chamber to about 1 atmosphere. Coal was blown into turbulent suspension by H_2 gas from the reservoir.

Rapid gas phase combustion by spark ignition of stoichiometric hydrogen-oxygen mixture resulted in a superheated steam environment.

The combustion was followed by heating of the coal particles by the newly formed steam, devolatilization, and the reaction of volatiles with the background gas.

At the end of each run, the product was cooled by heat transfer to the walls of the chamber.

Evaluation of the experiment was based on examination of the gas and char which remained at the end of the run.

- Test Results:

The stabilized gas composition varies with experiment. Typical gas yields on a dry basis consists of H_2, 45.1%, CO, 29.0%, CO_2, 19.4%, CH_4, 6.5%. The experimental results were summarized in four groups and are given as follows.

(a) Steam as background gas

Parameter investigated:
coal mass loading

Post Explosion*	
T, °F	P, Atm
5800	N/A

EXPERIMENTAL RESULTS:

Mass Loading lb. DAF Coal/ lb. Steam Generated	Number of Data Points	Gas Yield % Carbon Convers.
0.3	1	80
0.6	2	70,85
0.8	3	60,61,65
1.2	1	50
1.6	1	42
2.0	1	38
2.1	1	35
2.5	1	32
5.5	1	18
9.2	1	10

As is evident from the above data, the % carbon conversion decreased as the coal/steam ratio increased.

(b) CO, CO_2, and steam as background gas (initial gas $CH_{1.84}O_{2.12}$):

Parameter investigated:
different temperature at a constant mass loading of 0.33 DAF coal/total gas.

Experimental Results:

		Number of	Gas Yield	
*Post	Explosion	Data	% Carbon	% Carbon[δ]
T, °F	P, atm	Points	Convers.	Conversion
4330	13.8	6	20, 21, 25, 30	41, 47
4800	15.3	4	35, 46	69, 76
5350	17.3	4	55, 60	64, 74

From the above data, two important observations can be made:

(1) As the temperature of the steam produced in the explosion chamber goes up, the carbon conversion increases

(2) Increasing the turbulence has a dramatic effect on the carbon conversion with a more pronounced effect at lower temperatures

(c) CO_2 and steam as background gas:

Parameter investigated:
different temperatures achieved by varying the CO_2 concentration at a constant mass loading of 0.8 lbs. DAF coal/lb. steam.

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*Post Exp. Temp = Calculated adiabatic temperature for H_2 and oxygen reactants only before coal is injected.

δ Increased turbulent mixing.

Experimental Results:

CO_2/O_2	T.°F	Number of Data Points	Gas Yield % Carbon Conversion
0	5700	2	62, 66
0.5	5200	2	57, 65
1.0	4700	2	49, 49
1.5	4250	2	49, 51
2.2	3850	2	45, 49
3.0	3500	2	40, 41
3.5	3150	2	40, 41

As shown by the above data, decreasing the temperature by the addition of CO_2 as a diluent decreases the % carbon conversion.

(d) N_2 and steam as background gas:

Parameter investigated:
different temperature levels achieved by varying the N_2 concentration..

Experimental Results:

Mass lb. DAF con. / Lb. steam	N_2/O_2	T,°F P,atm*	Number of Data Points	Gas Yield % Carbon Convers.
0.8	0	5600	5	62,66,75 76, 80
	1	5300	2	60, 70
	2	4750	2	49, 50
	3	4300	2	46, 46
	3.5	4100	2	51, 53
	4	3900	2	46, 46
	5	3450	2	51, 51
	6	3100	4	45, 46 46, 47
	7	2850	4	44, 45 46, 50
	8	2600	2	44, 45
	9	2400	3	45, 45, 45

---

*Pressure in a range of 10 to 20 atms.

As shown by the above data, decreasing the temperature decreases the % carbon conversion similar to what was observed when CO_2 was used as the diluent. The interesting observation here is that the CO_2 didn't appear to help carbon conversion since the results at total mass loading of 0.8 are similar for CO_2 and N_2. Hence, heterogeneous reaction of CO_2 and char were apparently negligible.

7.1.3 Pyrolysis PDU Experimentation

- Funding Agency: AVCO internal funds
- Project Period: Continuing
- Project Objectives:

Demonstrate thermal pyrolysis of coal in a high velocity entrained bed reactor producing comparable volatile yields with the yields obtained in the batch reactor experiments (Single-Pulse Gasifier).

- Test Facility:

The reactor, developed originally for research in coal combustion for open cycle MHD, has been operated as a horizontal flow, entrained bed pyrolysis PDU. The reactor has internal dimensions of 15 cm diameter and 180 cm long. Coal feed rate is about 1 TPH.

- Test Conditions:

Hot gas was produced by combustion of No. 2 fuel oil with oxygen enriched air. Coal was injected into the hot gas at a rate of 1 ton per hour. The reactor was operated at 4 atmospheres. Total run time is limited to about 1 hour which is set by the coal feed hopper capacity. Typical gas residence time is about 2 msec.

- Test Results:

Early test results have shown volatile yields were comparable with the results obtained for the Single-Pulse Gasifier experiments. Results were reported as a composite of test data points.

Mass Loading (lbs DAF Coal/ lb gas)	Reaction Conditions T, °F	P, ATM	N_2/O_2	Gas Yield %Carbon Convers.
0.4	4300	4	N/A	65
0.8	4300	4	N/A	50

Recent efforts were directed to the areas which would more nearly represent the elements of the proposed two stage gasification concept.

More experiments were performed in the direction of lowering the reaction temperature. The nitrogen concentration is reduced by replacing N_2 with water/steam.

Preliminary findings revealed that the stabilization of pyrolysis products such as CO, H_2, and CH_4 is sensitive to the composition of the background gas stream and to the placement of the coal injectors. The experiment results are still in the process of analysis; data have not been released yet.

7.2 Slag Utilization

- Funding Agency: EPRI
- Project Period: 1975 - 1977

- Project Objectives:

  Investigation on the requirements for development of a continuous, stable layer of slag for structural protection in MHD systems.

- Test Facility:

  The test duct was about 80 cm long, with a fixed height of 6 cm, and adjustable width, entrance and exit geometry to control Mach number distribution. The test structure exposed to the two-phase product flow normally included two or three different ceramic filled test wall structures, bare copper, and nickel-plated copper. Stainless steel 304 was used as end blocks in the supersonic configuration. In some cases, the convergent section between the combustor and MHD channel was made of cold copper (non-slagging) with about 10 cm contraction length; in others controlled contour slagging contraction was used.

- Test Conditions:

  The experiments employed coal slag resulting from injection of either pulverized coal, fly ash, or fly ash plus other minerals, into a fuel oil fired combustor.

  Typical test conditions were summarized as follows:

Combustor:	AVCO MK VI	EPRI
Primary Feed:	O -N -CH	O -N -CH
Mach Number:	0.6 - 0.7	1.1 - 1.6
Residence Time(msec):	15	9
Initial Pressure (psia):	30 - 35	55 - 63
Initial Temperature:	2800 - 2900	2500 - 2600
Replenishment feed:	Penn Rilton Seacoal (Pittsburgh Seam)	Fly ash

- **Test Results:**

  Experiments under both subsonic and supersonic conditions indicated that a steady state continuous flow of a slag layer coating on the metal wall structure was achieved in a typical time of 30 minutes. The slag surface temperature was found to be about 2500° to 3000°F and the metal wall temperature as low as 300°F.

  The effects of combustion stoichiometry, ash composition, flow field, and wall structure on the slag coating transport process were studied.

  The technology has been demonstrated by hundreds of hours of long duration runs at AVCO's laboratory.

7.3 MHD Coal Combustor Work

- Funding Agency: DOE
- Project Period: 1976 - Present
- Project Objectives:

  Phase 1 - Investigated the burn out and combustion air preheating facility.

  Phase 2 - Designed and built a coal combustor for an MHD system.

  Phase 3 - Test the combustor. MHD channels will be coupled to the combustor.

- Test Facility:

  A coal-fired combustor was designed for a 20 MW MHD system. The combustor is designed to operate with a slagging wall.

- Test Conditions:

  The combustor is operated at about 4800°F and 5 atm with a coal feed rate of 2 tons per hour.

- Test Results:

  Several of 90 minute runs have demonstrated the viability of the slag protected reactor walls and good combustion performance. The reactor design approach is verified.

7.4 Analytical Modeling Work

- Pyrolysis and Combustion

Input:	Fuel; oxidant; flow description
Model:	Mixing and flow dynamics Heat, mass, momentum exchange Pyrolysis kinetics Heterogeneous reaction Thermochemistry
Capability:	Performance prediction Optimization calculations Equipment sizing calculations

- Slag Flow

Input:	Gas Flow; wall structure
Model:	Heat, mass, momentum transport Viscosity dependence Stability
Capability:	Slag layer thickness, temperature, flow calculations Transient flow calculations Optimum wall structure calculations Optimum slag tapping calculations

7.5 Future HTG Gasifier PDU Development

Development of the High Throughput Gasification (HTG) PDU is visualized by AVCO in terms of the following milestones:

- Pyrolysis stage coupled with a liquid fueled combustor with oxygen and steam as input. Primary emphasis will be placed on exploring coal injection and particle size for maximum pyrolysis yield. The tests will be done under conditions appropriate to char recycle condition. Fly ash will be added to provide a slag source.
- Char combustor development will be done based on the technology evolved from the coal combustor for open cycle MHD program.
- Development of high temperature cyclones to separate char from the pyrolysis product gas. AVCO expects to capitalize on the experience obtained during the operation of the BCR Bi-Gas plant.
- Development of an integrated system consisting of char combustor, coal pyrolyzer, cyclone separation, and char recycle.

8.0 FUNDAMENTALS OF SRT GASIFICATION AS APPLIED TO THE AVCO HTG GASIFIER

The AVCO HTG Process consists of two stages: the pyrolysis stage and the char combustor stage. Although each stage is dependent on the other, the following discussion will treat the stages separately.

8.1 Pyrolysis Stage

AVCO has given considerable effort to the basic understanding of rapid pyrolysis in an entrained-flow coal gasifier. By combining data extracted from the literature and from their own pyrolysis experiments, AVCO has postulated a mechanism for rapid coal pyrolysis(5,6).

Pulverized coal (70% minus 200 mesh) is injected into hot combustion gases from the char combustor. The hot gases, which are at temperatures around 3000°F and consist mostly of CO, CO_2 H_2 and H_2O, are injected into the pyrolyzer stage at high velocities to effect good mixing with the coal (note that the pressure drop of the combustion gases from the combustor to the pyrolyzer effluent is 50 psi). By the combination of high temperature combustion gases, small coal particles and intense mixing, heating rates of up to 200,000°F/sec are attained. This means that the coal particles are heated to pyrolysis reaction temperatures of around 2000°F in about 10 msec.

As the coal is being heated up, pyrolysis reactions occur with CO, CO_2 and H_2O being the primary compounds driven off at temperatures up to about 800°F(7). Subsequent heating produces heavier hydrocarbon gases such as CH_4, C_2-C_5 gases, and aromatics such as benzene and polycyclic compounds. AVCO has postulated the rapid devolatilization reactions by suggesting two competing first-order reactions. Each describes the coal decomposition (approximated by CH_x, where $0 < X < 1$) to residual chars R_1 and R_2 and volatiles, V_1 and V_2. The reactions then are written as follows:

$$\begin{tikzcd}
 & (1-\alpha_1)\ R_1 + {}_1 V_1 \\
\text{coal} \arrow[ur, "K_1"] \arrow[dr, "K_2"'] & \\
 & (1-\alpha_2)\ R_2 + {}_2 V_2
\end{tikzcd}$$

where K_1 = Arrhenius rate constant for reaction 1
K_2 = Arrhenius rate constant for reaction 2
$\alpha_{1 \text{ or } 2} = X/X_n$
X = Atomic (H/C) of coal
X_n = Atomic (H/C) of volatiles V_n, $n=1,2$.

From curve fitting of data in the literature, the first reaction was found to dominate at temperatures to about 1800°F and the second reaction at higher temperatures. Calculated activation energies E_n for the Arrhenius rate equation ($k_n = k_o \exp[-E_n/RT]$) were 17.6 and 60.0 kcal/mole respectively. For calculational purposes, the volatiles evolved by the first reaction are assumed to be ethylene type aromatic hydrocarbons while those evolved by the second reaction are assumed to be benzene type aromatic hydrocarbons. However, the conditions of the HTG gasifier in the material balance given in Table II-1 are such that the first reaction predominates due to the relatively low temperatures. Nevertheless, the volatiles yield as a percentage of DAF coal is about 60 wt.%. With this quantity of volatiles evolved, which is about 1-1/2 times the ASTM VM of the coal, the gas-phase cracking of unstable volatiles to H_2 and CO will occur. This degasification of volatiles to soot can occur basically in two regions: within the pores of the coal where the volatiles are still escaping or in the dispersed gas after the volatiles are free of the coal surface. It has been determined that about 80-90% of the sooting takes place in the gas phase and hence would be swept away from the coal particle before having a chance to adhere to the coal. Since soot is very fine and difficult to recover, sooting is extremely undesirable. By providing sufficient reactive gas species in the hot combustion gases (CO, CO_2 and H_2O), the unstable but reactive volatiles are reacted in the gas phase thereby suppressing soot formation. This is termed the "stabilizing" effect of the background gases. Gas composition is assumed to be close to equilibrium with methane yields apparently slightly above equilibrium (an equilibrium calculation of the pyrolyzer effluent gas from Table II-1 showed slightly lower methane than is reported).

The total residence time in the pyrolysis stage is less than 100 msec; therefore, slow heterogeneous reactions between the newly formed char and gas are assumed to be negligible.

8.2 Char Combustor Stage

In this stage, the heterogeneous reaction of char (from coal pyrolysis) with oxygen is essentially the only reaction that converts the char to gas. Some steam is added to the combustor stage as a means of temperature control. Any residual volatiles from the pyrolysis stage will devolatilize and combust with the oxygen also.

Gases formed at these high temperatures (3000°F) are assumed to be in equilibrium.

Although this stage is titled the "char combustor stage", it does not combust all of the carbon in the char to CO_2, nor is it necessary to do so.

As indicated in stream 6 of the material balance in Table II-1, considerable CO and H_2 are produced here. Hence, the "char combustor" is more like a partial oxidizer producing a syngas containing CO, H_2, CO_2 and no methane.

Figure II-4 is presented here to facilitate a qualitative discussion on the heat load required by the pyrolysis stage and the heat supplied by the combustor stage. Curves presented are the author's concept of the relationship between the two stages in order to point out certain indigenous features of this relationship.

Curve ① represents the percent of coal that is available to the char combustor as recycle char versus the percent MAF coal devolatilized in the pyrolysis stage. The relationship takes into account that the less devolatilization in the pyrolysis stage, the higher the char availability to the combustor stage. It also recognizes an absolute maximum amount of devolatilization in pyrolysis shown by the asymptote to the dotted line. It should be pointed out that if all of the char HHV is to be utilized in the char combustor, then all of the carbon in the gas phase is converted to CO_2. Curve ② represents the percent of the coal feed HHV required for pyrolysis as a function of the percent MAF coal devolatilized. This curve shows the obvious relationship that the heat load to pyrolysis increases as the volatiles yield increases. The curve also suggests that the heat load for the initial stages of devolatilization is a small quantity of the feed coal HHV, but as the percent devolatilization increases, a sharp increase in the heat requirement occurs. The shaded section labeled "Area A" represents the difference in heat available to the char combustor and the heat required by the coal pyrolyzer. As long as this difference is positive, then some syngas, i.e., CO + H_2, is generated in the char combustor along with CO_2. As the volatiles yield increases, this difference decreases until it reaches a balance point labeled "char balance point" where only CO_2 is generated in the char combustor. Beyond this point, the char combustor will have to be augmented by a supplemental coal feed to supply the difference in heat load required by pyrolysis from that available from the char combustor, shown graphically in Area B.

p

The reason for submitting this graph is to point out that maximizing of pyrolysis yields in the pyrolysis stage beyond the "char balance point" is not beneficial; also, the generation of CO and H_2 in the char combustor is inevitable.

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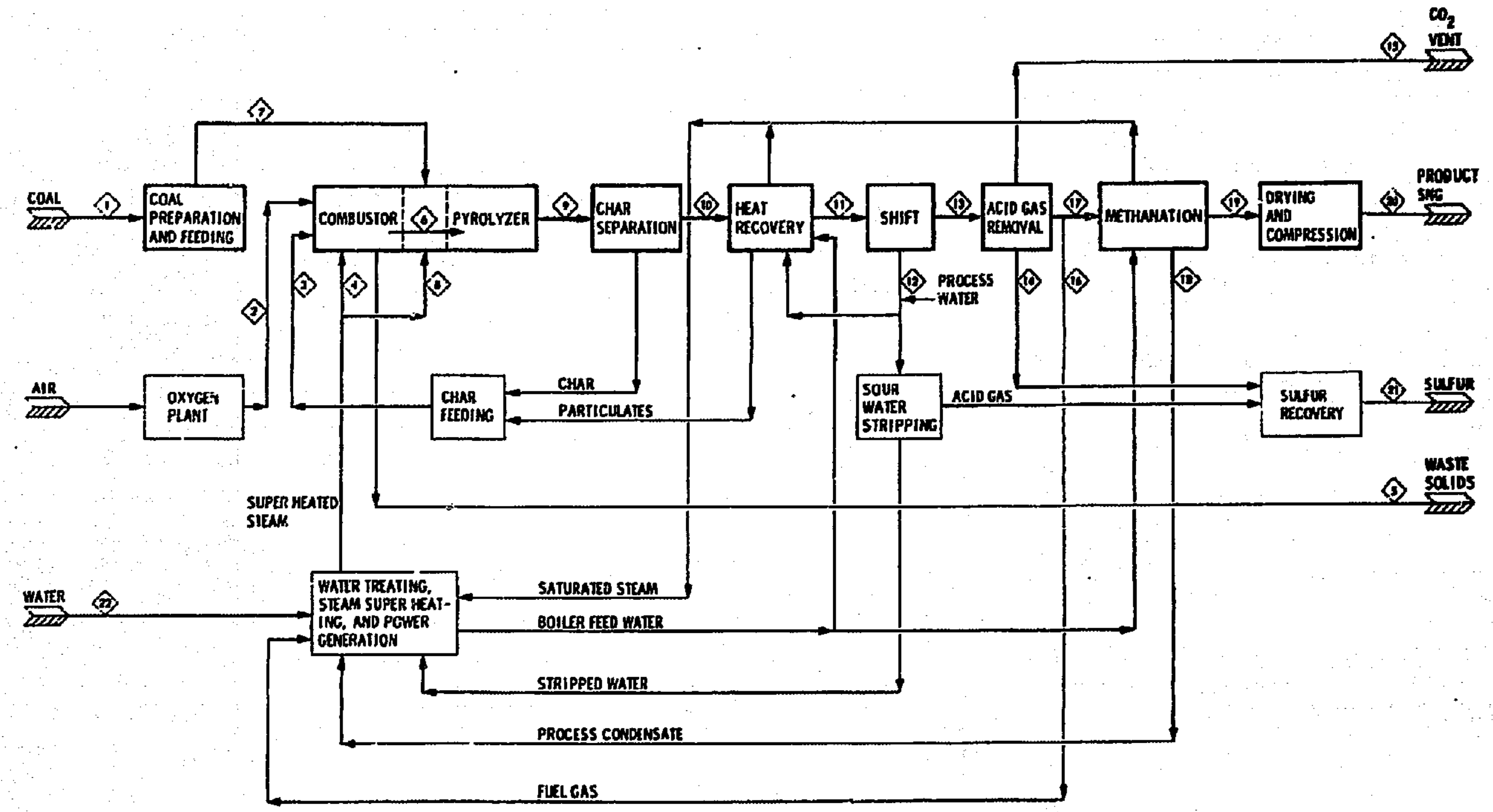


FEED	
COAL	14,740 ST/SD
OXYGEN	7,991 ST/SD
WATER	GPM

PRODUCT	
SNG	261.65 MMSCFD
SULFUR	612 ST/SD

FIGURE II-1. AVCO HTG Coal-to-SNG Process - AVCO HTG Process Block Flow Diagram.

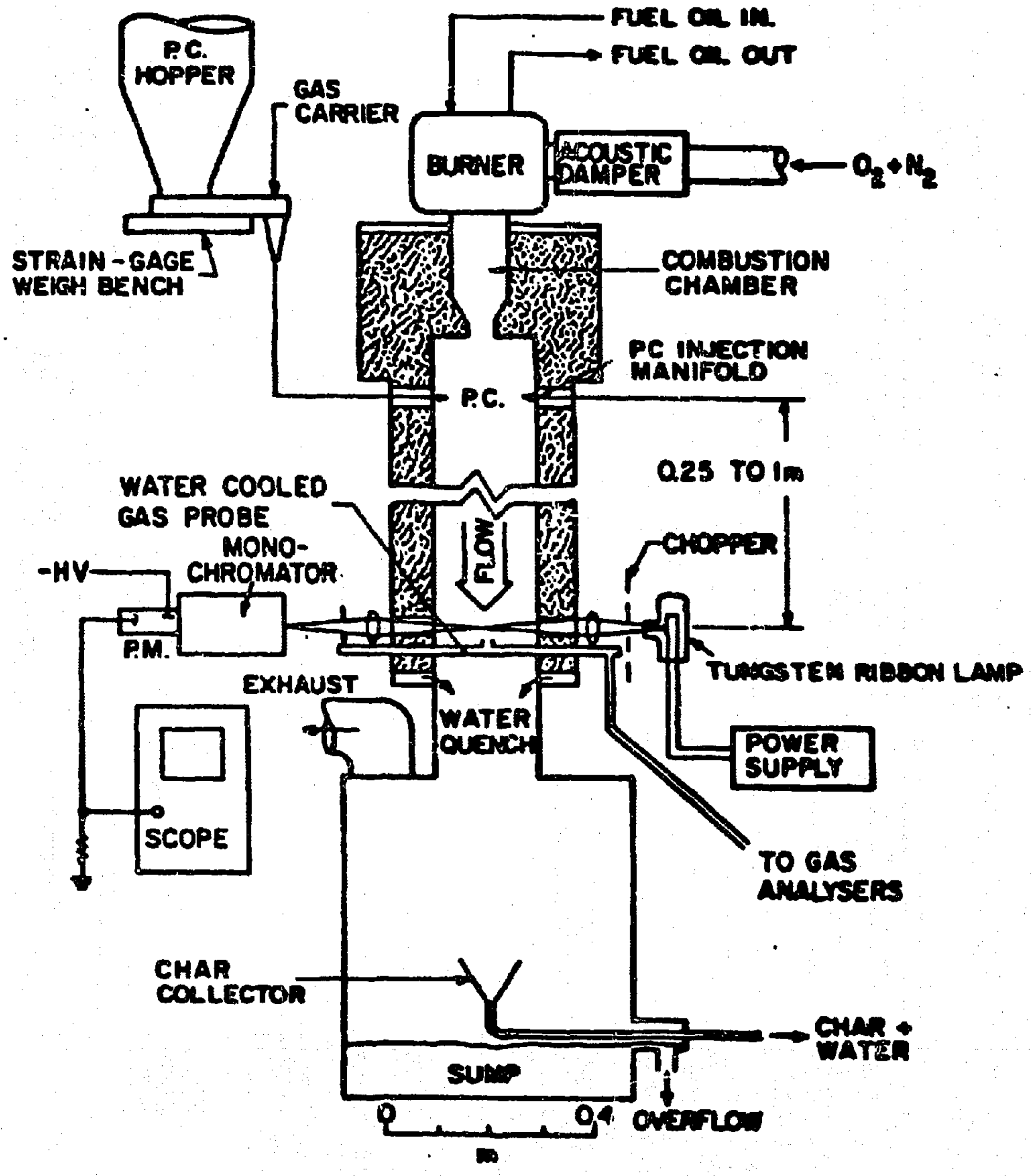
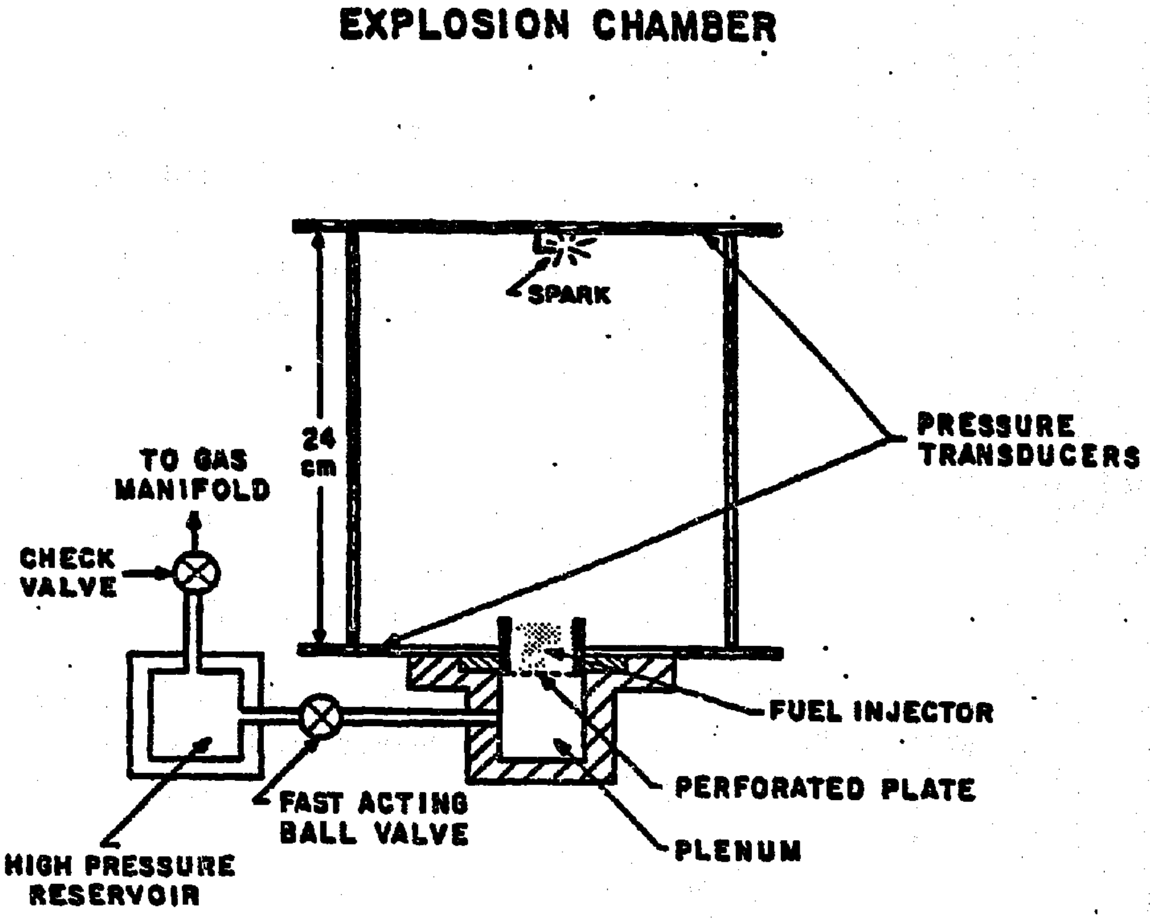


FIGURE II-2. AVCO Entrained Bed Gasifier Used in Low Btu Gas Program.



EXPLOSION CHAMBER

- 12 LITRE VOLUME
- PULVERIZED COAL
- O_2, H_2, CO GASES, P ~ 1 ATM
- IMPULSIVE BLOWING COAL DISPERSION
- SPARK IGNITION

FIGURE II-3. AVCO Explosion Chamber for Single-Pulse Coal Pyrolysis Experiments.

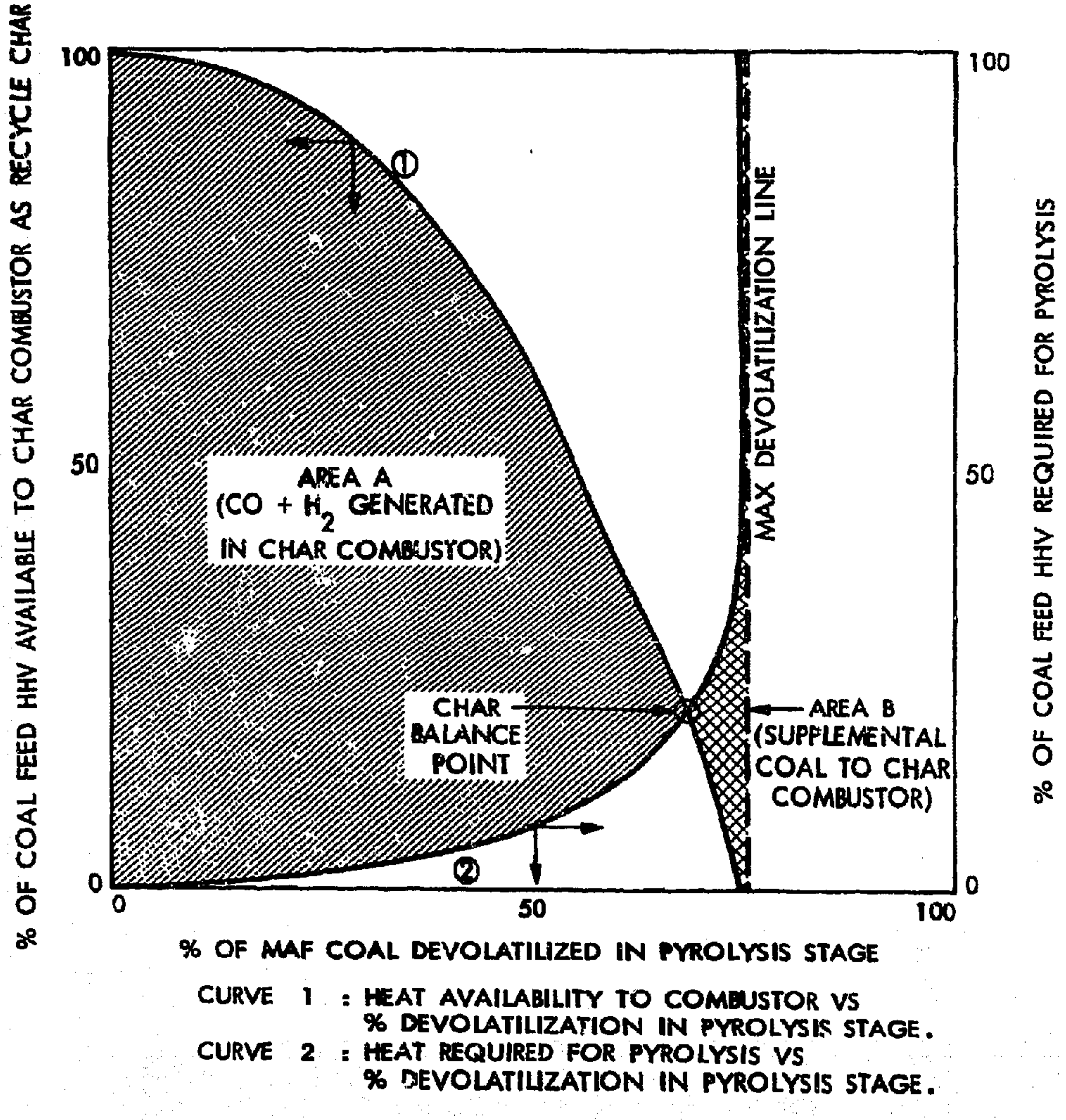


FIGURE II-4. Pyrolysis/Char-Combustor Heat Load Relationships.

STREAM NUMBER	2	3	4	5	6	7	8	9	11	13	16	17	20
STREAM NAME	OXYGEN TO COMBUSTOR	CHAR TO COMBUSTOR	STEAM TO COMBUSTOR	SLAG FROM COMBUSTOR	COMBUSTION GAS TO PYROLYZER	FRESH COAL TO PYROLYZER	STEAM TO PYROLYZER	PYROLYZER EFFLUENT	SYNGAS TO SHIFT	SHIFTED GAS TO AGR	FUEL GAS TO STEAM SUPERHEATER	METHANATION FEED GAS	PRODUCT SNG
COMPONENTS, lb-mol/hr													
CO					24,658			37,380	37,380	9,128	730	8,394	3
CO_2					10,716			23,322	23,322	51,600	1,064	12,246	551
H_2					5,093			50,302	50,302	78,554	6,281	72,244	290
CH_4								7,628	7,628	7,628	610	7,004	27,064
C_2H_6													
C_6H_6(BTX)													
H_2S								1,551	1,551	1,577			
COS								40	40	14			
SO_2													
NH_3													
N_2	357				357			863	863	863	69	794	794
O_2	20,498												
SUBTOTAL - DRY GAS	20,855				40,824			121,086	121,086	149,364	8,754	100,682	28,724
H_2O			15,188	2,516	10,095	1,400	76,826	55,059	55,059	1,065	28	319	4
TOTAL GAS lb-mol/hr	20,855		15,188		50,919	1,400	76,826	176,145	176,145	150,429	8,782	101,001	28,728
Mlbs/hr	666		274	45	1,364	25	1,384	3,369	3,369	2,906	92	1,060	482
SOLIDS Mlbs/hr													
MAF (COAL, CHAR, SULFUR)		429		5		1,024		429					
ASH (MINERAL MATTERS)		131		131		131		131					
TOTAL SOLIDS Mlbs/hr		560		136		1,155		560					
TOTAL GAS & SOLIDS Mlbs/hr	666	560	274	181	1,364	1,180	1,3[illegible]	3,929	3,369	2,906	92	1,060	482
MMSCFD - GAS										1,370.11	79.99	919.92	261.65
MOLE WEIGHT - GAS										19.31	10.50	10.50	16.77
TEMPERATURE, °F		1,600	980		2,800		980	1,600	360	140	100	100	105
PRESSURE, psia	600	600	600		600	600	600	550	490	470	450	450	1000

TABLE II-1. Material Balance for AVCO HTG Coal-to-SNG Process.

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SECTION III
BELL HMF PROCESS

SECTION III
ASSESSMENT OF BELL HMF GASIFICATION PROCESS

1.0 SUMMARY

The assessment of the Bell HMF Gasification Process for making SNG was based on meetings and discussions with the developer as well as available literature. Since gasifier tests as of this writing have only been performed in a Single-Stage Gasifier, projected yields supplied by Bell for the Single-Stage were used to complete a material balance for a 250 MMSCFD SNG plant from coal. Other concepts of the Bell HMF reactor, including char recycle, secondary injection, and secondary-injection with char recycle, were assessed as potential improvements to the Single-Stage process when making SNG. However, discussion of these alternates is limited as the projected yields are considered proprietary by Bell.

The Bell HMF (high mass flux) gasifier is an entrained flow, slagging gasifier which reacts pulverized coal, oxygen and steam to produce a synthesis gas. The assessment that follows pertains to the Single-Stage concept where coal, steam and oxygen are reacted in the same zone of the gasifier. The Single-Stage gasifier has the following noteworthy features:

ADVANTAGES

- high throughput rates (5000 $lb/hr/ft^3$)
- low steam consumption
- wide application (products and feeds)

WEAKNESSES

- low CH_4 gasifier yields
- high oxygen consumption

The data base for the Single-Stage gasifier is presently being developed at Bell's test facility feeding bituminous coal at 1/2 TPH for short duration runs, up to 1 hour in length.

In order to increase the methane yield and decrease the oxygen consumption, a program to investigate secondary-injection of coal is underway. This concept, and the recycling of char, could significantly improve the potential of applying the Bell HMF Gasifier to make SNG. Other potential improvements, such as a molten-slag bath and catalyst applications, need further investigation.

Components requiring development include control and safety systems, solids feeding, slag pot, high temperature gas/solids heat recovery, char fines separation, and scale-up aspects to a commercial size design.

2.0 CURRENT STATUS OF DEVELOPMENT

The Bell HMF Gasifier program was initiated in 1976 under contract to ERDA to determine the feasibility of using a rocket-type reactor to economically produce a low Btu gas from air/coal combinations and to evaluate the reactor operating characteristics. From 1976 to 1978, Bell tested their HMF air-blown gasifier with up to 1/2-TPH coal feed rates and one hour test duration. Much of the early testing involved developing a reactor configuration to minimize slag accumulation effects. An impinging sheet injector was identified as the best injector configuration of 4 tested. Coals tested included North Dakota Lignite, Montana Rosebud Sub-bituminous and a Pittsburgh Seam Coal. The most promising results were with the lignite and somewhat less promising results with the sub-bituminous coal. Limited testing with the Pittsburgh coal indicated its conversion to be substantially less than the others. In addition to the reactor injector and coal type variables, the following variables were identified with respect to their effects on carbon conversion:

- Coal and air injection velocities
- Air to dry coal feed ratios
- Residence times
- Mass flux rates

In 1978 and 1979, Bell continued development of their HMF gasifier under company funds and a contract with the New York State Energy and Research Development Authority. Development was aimed at producing a medium Btu gas as an intermediate product for SNG production. Several short-duration (less than 10 min) oxygen-blown tests were performed with steam injection added to enhance the yields. Pittsburgh seam coal was tested and results indicated difficulty in achieving high carbon conversions. Variables identified with respect to carbon conversion were:

- Oxygen and steam injection velocities
- Residence time
- Oxygen/coal feed ratios

In late 1979, Bell was awarded a one year contract to continue the development of the HMF Gasifier to produce SNG feedstock. Included in this contract are:

- Upgrading of the 1/2-TPH facility to permit more detailed analyses of gas and solid products.
- Testing with bituminous coal and evaluation of the performance characteristics
- Testing and evaluation of a secondary coal injection system

Testing in the upgraded facility is expected to begin in mid-1980.

Further details of the development status are at the end of this section.

3.0 PROCESS DESCRIPTION

This is a description of the overall conceptual process for a SNG plant utilizing the Bell Single-Stage HMF coal gasifier. The overall process of coal to SNG is graphically represented in Figure III-1, and a material balance is given in Table III-1.

Bell's single-stage HMF gasifier has been chosen for evaluation since test data are available only with the single-stage configuration at this time. However, there is another two-stage configuration being developed for SNG production, under contract with DOE and GRI; it consists of the single-stage into which secondary coal is injected to produce a methane enhanced gas.

The following sections and the accompanying material balance are preliminary and conceptual in nature; they have been submitted by Bell Aerospace Textron as a "single-stage gasifier subsystem" as follows:

- o Bell Single-Stge HMF Gasifier
- o Heat Recovery
- o Char Separation
- o Gas Scrubbing
- o Shift Conversion

(The other sections represent typical, additional units required to convert coal to SNG. The selection of these sections does not represent the optimum choice; the selections were made in order to assess the Bell HMF Single-Stage Gasifier as it applies to SNG from coal.)

3.1 Coal Preparation and Feeding

The coal used for the material balance is a Western Kentucky Bituminous Coal with the following properties:

Proximate Analysis, as received	Wt. %
Moisture	6.0
Volatile Matter	37.0
Fixed Carbon	48.1
Ash	8.9

Ultimate Analysis (dry),	Wt. %
C	70.5
H	5.1
O	9.3
N	1.4
S	4.2
Ash	9.5
	100.0

Heating value of dry coal, Btu/lb (HHV)	12,866

The raw coal feed (stream No.⟨1⟩) is crushed to 70% minus 200 mesh and dried to 2 wt. percent moisture in the coal preparation section.

Crushed and dried coal is fed into lockhoppers which are sequentially pressurized with CO_2 pressurizing gas from the Acid Gas Removal section to over 600 psia.

The coal and a portion of the CO_2 pressurizing gas are pressurized into a transfer line where the flow conditions are "dense phase".

3.2 Gasification

The gasification section consists of 2 identical and parallel gasifier trains; each train can process a maximum of 8200 TPD of coal. Each gasifier consists of several identical coal and oxygen feed elements arranged symmetrically in the reactor head. Process steam is injected into each reactor element to produce operating conditions of nominally 500 psia and about 2500°F. The reactor syngases (⟨11⟩) consists mostly of CO and H_2 and lesser amounts of H_2O, CO_2, H_2S, N_2 and CH_4, respectively. The resulting overall reaction is as follows:

$$\text{Coal} + O_2 + H_2O\ (\text{steam}) \longrightarrow \text{Reactor Syngas} + \text{Slag} + \text{ungasified carbon}$$

The reactor syngas plus solids exit the gasifier into a wider diameter slag-pot where water is sprayed to quench the reactants to 1900°F and to freeze the slag. Most of the solidified slag drops to the bottom of the slag pot; the remaining slag and ungasified carbon is entrained with the raw, hot syngas (⟨13⟩).

3.3 Heat Recovery

The raw hot syngas with entrained solids is routed to the Heat Recovery section where high pressure (600 psi) steam is generated and superheated by cooling of the syngas and solids from 1900°F to 600°F by indirect heat exchange.

3.4 Char Separation

The raw, cooled syngas (14) with entrained solids is routed to the Char Separation section where most of the solids are recovered by cyclone separation; the recovered char is routed to steam boilers in the Steam Generation Section.

3.5 Gas Scrubbing

The syngas from the cyclone (16) is routed to a Venturi scrubber system which simultaneously removes the particulates from the gas, humidifies and cools the syngas to its water dewpoint of 345°F. The particulates are removed as a slurry which is subsequently routed to the Solids Disposal section.

3.6 Shift

Process steam (600 psia, 530°F) is added to the dust free syngas in the Shift section, where the H_2 to CO molar ratio is adjusted to 3 via the water-gas shift reaction as follows:

$$CO + H_2O \xrightarrow[\text{Catalyst}]{\text{Sour Shift}} CO_2 + H_2$$

The shifted syngas is cooled to 100°F; the water that condenses from the syngas is separated in a knock-out drum and contains H_2S and trace amounts of NH_3. This sour water is then routed to the Sour Water Stripper.

3.7 Acid Gas Removal

The Shifted syngas (21) is routed to the Acid Gas Removal section which consists of an H_2S absorber, an H_2S stripper, a CO_2 absorber and a CO_2 stripper. The overhead stream from the H_2S stripper is routed to the Sulfur Recovery section. The CO_2 from the CO_2 stripper is split into two streams: part of the gas is recycled back to the Coal Feed section where it is used as "pressurizing gas," the rest of the CO_2 is vented to the atmosphere.

3.8 Methanation, Compression and Drying

The clean syngas (24) is routed to the methanation section where it is converted to a final product gas interchangeable with natural gas. The methanation reaction is as follows:

$$3H_2 + CO \xrightarrow[\text{Catalyst}]{\text{Ni}} CH_4 + H_2O$$

The above reaction is highly exothermic, and control of the reaction temperature is exercised by a combination of heat recovery and hot product gas recycle. The hot recycle allows the recovery of essentially all of the methanation heat of reaction as high level useful energy.

After methanation, the gas is cooled, compressed, and dehydrated in a triethylene glycol drier. The product gas then leaves the plant.

The following sections are considered supporting or utility units.

3.9 Oxygen Plant

The Oxygen Plant consists of commercially available air-separation plants where liquid oxygen is produced and pumped to its final pressure (600 psia +). The pressurized liquid oxygen is then vaporized by heating to 77°F and routed to the gasifier. The oxygen purity is 99.6 volume percent.

3.10 Sour Water Stripper

The sour water from the Shift section (◇20) is stripped to produce a reusable process condensate using low pressure steam. The stripper overhead (◇29) is routed to the Sulfur Recovery section.

3.11 Sulfur Recovery

The Sulfur Recovery section includes a Claus unit and a tail gas treating unit. The Claus unit converts over 90% of the sulfur in the form of H_2S to elemental sulfur via the following overall reaction:

$$H_2S + 1/2\ O_2 \xrightarrow[\text{Catalyst}]{\text{Alumina}} S + H_2O$$

The conversion takes place in a reaction furnace and catalytic reactors; since the reaction is exothermic, steam is generated in heat exchangers which also condenses the sulfur vapors formed. The tail gas from the Claus unit is passed to a Beavon-Stretford tail gas plant. Here, all unconverted sulfur compounds are catalytically converted to H_2S; the gas is subsequently scrubbed with a solution and oxidized to elemental sulfur. The purified tail gas is odorless and contains typically less than one PPMV of H_2S and less than 50 PPMV of total sulfur compounds.

3.12 Solids Disposal

The Solids Disposal section handles all the waste solids of the plant including the boiler ash from the steam boilers, the Dry Slag (⟨12⟩) from the Gasification section, and the Particulates Slurry (⟨18⟩) from the Scrubbing section. The Solids to disposal is a 70 wt.% solids slurry sent back to the mine-site.

3.13 Water Treatment, Steam and Power Generation

This section includes all water, steam, and power generation as required for the entire plant.

Steam is generated by burning the unconverted carbon from cyclone separation (⟨15⟩). It is assumed that this char is essentially sulfur free; hence, flue-gas desulfurization is not required.

3.14 General

The Bell HMF, single-stage coal-to-SNG gasification process is preliminary and conceptual as presented. The basic yields from the Bell HMF Gasifier are yet to be demonstrated, especially as regards the following:

(a) 90% carbon conversion to gas at the assumed oxygen/coal feed ratio;
(b) the physical form and size of the 10% ungasified carbon;
(c) the composition of the char used for boiler fuel.

The overall process described did <u>not</u> include a detailed engineering design; the purpose of the material balance is to identify strengths and weaknesses of the process. Also, a preliminary cost estimate was generated in order to further identify strengths and weaknesses of the process and hence be able to make cost-effective recommendations to improve the process.

The overall process is shown as a self-sufficient operation with coal, air and raw water as the only feed requirements. It has been assumed that no supplemental coal is required for steam and power generation; i.e., the steam and power are generated from efficient process heat utilization and from the burning of the unconverted char in steam boilers with subsequent power generation. It has also been assumed that the unconverted char is essentially sulfur-free; hence, flue gas desulfurization is not required on the boiler flue gas. However, particulate removal of the flue gas will be necessary.

Because of the preliminary nature of the process design, it is suggested that any comparative conclusions with other processes be made with caution regarding overall process efficiency (i.e., coal HHV to SNG HHV).

An overall material balance of the plant is as follows:

IN	(lb/hr)
Coal (6% moisture)	1,452,700
Air to O_2 Plant	4,202,752
Air to Boilers	1,346,718
Air to Sulfur Plant	124,880
Raw Water	4,520,440
	11,629,490
OUT	
CO_2 Vent	1,672,644
SNG	484,503
Sulfur	57,355
Clean Stack Gases	1,859,116
Solids to Disposal	185,161
Water Losses	4,200,000
N_2 from O_2 Plant	3,170,711
	11,629,490

4.0 STRENGTHS AND WEAKNESSES

The following strengths and weaknesses refer to the single-stage gasifier as presented in the Process Description:

4.1 Strengths

- High Throughput Rates

  The Bell HMF process charges 5,000 lb/hr of reactants (coal, steam and oxygen) per ft^3 of internal volume in the gasifier reaction section. This is over 70 times the rate for a Lurgi gasifier operating at similar pressures.

- Small Reactor Size

  The small reactor size when scaled to a commercial plant size represents the following advantages:

  a) Use of best corrosion resistance materials in critical areas as an economical alternative in design.

  b) Use of water cooling of reactor with failsafe features in the event of overheating as an economical alternative in design.

  c) Small inventory of reactants allows for rapid quenching and shutdown of reactor in case of overheating.

  d) Ability to move quickly from pilot plant to demonstration plant scale with minimal hardware cost.

  e) Ability to build and test a commercial size reactor at the factory prior to shipping to the field.

  f) Minimal cost for gasifier duplication if separate trains required.

- Low Steam Consumption

  The Bell HMF reactor has a low steam to dry coal ratio; it is about 10% of the Lurgi gasifier.

- <u>Pressure Independent</u>
  The syngas yield is essentially pressure independent (provided that the superficial gas residence times are the same).

- <u>High, Single-Pass Carbon Conversion</u>
  85% carbon conversion was measured during initial oxygen blown tests using Pittsburgh seam coal. It was also observed during testing that with design modifications, 90% conversion is feasible at lower oxygen to coal rates.

- <u>Wide Application</u>
  The $CO + H_2$ represents 87 volume percent of the reactor syngas make; hence, the Bell HMF gasifier can be used to generate syngas from coal to produce a variety of end products, such as SNG, hydrogen, methanol, M-gasoline, ammonia, medium-Btu fuel gas, low Btu fuel gas (air-blown), power from combined cycle plants, power from fuel cell applications, etc.

- <u>Sulfur Free Char</u>
  If the ungasified char is sulfur-free, then the use of it as a boiler fuel without flue gas desulfurization represents a significant cost savings.

- <u>No Supplemental Coal Requirements</u>
  The carbon in the ungasified char represents about 10% of the carbon in the coal. By burning this char in a steam boiler and utilizing the process generated steam, the entire plant is self-sufficient; therefore supplemental coal firing in a steam boiler is not required.

- <u>Negligible Tars or Liquids Produced</u>
  The gasifier produces essentially zero hydrocarbon liquids or tars.

- <u>Dense-Phase Feed Transfer Lines</u>
  The transfer lines from the coal lockhoppers to the gasifier are dense phase thereby minimizing the size of the transfer lines and the volume

of gas carried with the coal feed. Use of dry dense-phase feed as opposed to a slurry feed minimizes the sensible heat and therefore the oxygen needed to reach reactor operating temperature.

- Operability With a Wide Range of Coals
  Coals that were successfully tested include Montana Rosebud, N. Dakota Lignite and Pittsburgh seam; hence, caking coals present no apparent operational problems.

4.2 Weaknesses

- Low CH_4 Yield
  In the single-stage configuration, the methane yield from the reactor is only 0.1% of the syngas make. (However, a secondary coal injection concept has been proposed to enhance the methane concept.)

- High Temperatures
  The gasifier operates at about 2400-2500°F which requires refractory design and possibly expensive metals. Also, the high temperatures produce a liquid slag that can resolidify and accumulate in the gasifier and other downstream equipment causing a reduction in throughput, fouling, etc.

- Solids in Gas Heat Recovery
  Heat recovery of the gasifier effluent involves difficult solids and gas heat exchanger design.

- High Oxygen Consumption
  The oxygen to dry coal weight ratio is 0.71.

- Difficult Coal Feed Control
  The commercial scaled design includes multiple coal and oxygen injector elements; this means solids distribution to each element must be controlled carefully.

- <u>Lockhopper System</u>
  The cumbersome lockhopper system is required to pressure the coal into the dense-phase transfer line.

- <u>Data Base</u>
  Several key areas require further development and demonstration:

  - 90% carbon conversion in a single pass gasifier using a bituminous coal at the O_2 to carbon ratio projected from observed trends.

  - The form and composition of the ungasified carbon

  - The sulfur distribution to H_2S, COS and char

  - Heat recovery of solids and gas streams including possible soot in gas

  - Scalability to full scale reactors (commercial size) including multiple feed injection elements

  - HMF control and safety systems, including difficult solids flow control to multiple feed injectors

5.0 POTENTIAL IMPROVEMENTS

In this section, the potential improvement items are being suggested as potential solutions to problem ares that appear to exist as the process is now proposed. These also take into account the stage of development of the overall process and the conceptual status of many of the companion operations to and around the proposed gasification step. They are the result of reviewing items mentioned in other sections such as weaknesses, alternates, disadvantges and status of development. It is <u>not</u> suggested that these are the final solutions but they are potentials only viewed from the perspective of this assessment and will require more detailed investigation and evaluation prior to testing. It is for this reason that they are called potential improvements.

To assess the potential improvement items, it was decided to develop SNG gas costs since this is the most comprehensive way of accounting for the overall effect. Cost information from the literature was used to calculate SNG gas costs from the capital and operating costs of a 250 MMSCFD SNG plant; SNG gas costs for each potential improvement item are then compared to that for the Bell Single-Stage Coal-to-SNG process as described in previous sections.

The following potential improvements were assessed as to their potential cost effectiveness compared to Bell's Single-Stage configuration described in the previous sections:

Case 1: Single-Stage (as described in Process Description and herein referred to as the Base Case)

Case 2: Single-Stage + Char Recycle

Case 3: Secondary Injection

Case 4: Secondary Injection + Char Recycle

Case 5: Use of Molten-Slag Bath with Single-Stage

Case 6: Separation of Stages with Molten-Slag Bath

Case 7: Catalyst Application

Case 8: Use of Lower Grade Coals

Cases 2, 3 and 4 are reactor configurations that have been suggested by Bell as alternatives to the Single-Stage Base Case configuration. However, only

Case 1, the Single-Stage Base Case, has been tested in the 1/2-TPH facility; Cases 2, 3 and 4 are to be tested in an upgraded facility still being constructed as of May, 1980. Hence, yields from Cases 2, 3 and 4 are entirely hypothetical. JPL elected to use the Single-Stage configuration as the Base Case in the assessment since this is the only alternate with any test data. (Although some test data for the Single-Stage Base Case configuration exists, the Base Case yields also represent hypothetical extrapolations f data; the effects of these extrapolations will be presented later in this section.) Theoretical yields for Cases 2, 3 and 4 were supplied by Bell at the request of JPL in order to assess the effect they have on SNG gas cost compared to the Base Case gas cost.

Cases 5, 6, 7 and 8 are modifications proposed by JPL as potential improvements. In suggesting these modifications, it is realized that yields would have to be hypothesized where possible as was done by Bell for Cases 2, 3 and 4. It was also recognized that much of the Base Case yields represent hypothetical extrapolation of data; if in subsequent testing the projected yields for the Base Case and Cases 2, 3 and 4 are not realized, Cases 5,6, 7 and 8 as suggested by JPL represent modifications which could improve the yields. However, as was stated earlier, these improvements would require more detailed investigation and evaluation prior to testing as they would involve considerable revamping to Bell's 1/2-TPH facility.

5.1 Assessment of Reactor Configurations to be Tested in Bell's 1/2-TPH Facility

5.1.1 Case 2: Single-Stage + Char Recycle

This alternate has the same configuration as the Base Case except that the ungasified carbon, recovered as char in the Char Separation section (cyclones), is recycled back to the main coal feed system. It is then fed with the coal into the gasifier. Bell has assumed that the char will attain a high, single-pass carbon conversion rate as is assumed for the parent coal. In this way the char is eventually recycled to extinction.

The effect of recycling the char compared to the Base Case is listed in Table III-2. The percent carbon conversion in the gasifier is nearly 100 percent but as shown by the Relative Gas Costs of 1.01 compared to the Base Case, there is apparently no significant advantage to recycling the carbon to the gasifier. In fact, there is a slight penalty mainly due to the increase in capital costs from the addition of a Flue Gas Desulfurization (FGD) Unit in Case 2. In the Base Case, it had been assumed that the ungasified carbon could be recovered in the Char Separation section (cyclones) as a sulfur-free char and used as a boiler fuel for the plant utility needs. Other predicted results could be identified for their effects; however, the predicted yields for the Recycle Case are considered by Bell to be proprietary at this time thereby precluding any detailed explanation of the effects. Nevertheless, a general analysis of the chemistry involved in recycling char can be made.

In the Base Case, the overall gasification reaction of coal to syngas can be described as follows:

$$\underbrace{CH_{0.86}O_{0.10}}_{\text{coal}} + \underbrace{0.39\ O_2}_{\text{oxygen}} + \underbrace{0.16\ H_2O}_{\text{steam}} \longrightarrow \underbrace{0.87CO + 0.03\ CO_2 + 0.48H_2}_{\text{syngas}} + 0.11\ H_2O$$

$$+ \underbrace{0.10C}_{\text{Ungasified Carbon}}$$

At the gasifier temperature of over 2500°F, there is very little methane in the product as any produced is essentially reformed to CO and H_2. It can be seen that most of the hydrogen produced comes from the coal (.43 out of .48) with little steam decomposition (0.05 out of 0.16). In Case 2, where the ungasified carbon is recycled to the reactor for further reaction, it is obvious that essentially all of the hydrogen would be produced by the steam carbon reaction as follows:

$$C + H_2O \longrightarrow H_2 + CO$$

However, this reaction is endothermic which would reduce the overall gasification reaction temperature. Hence, an exothermic reaction is needed to balance the endothermic reaction above such that the reactants are kept around 2500°F. By introducing additional oxygen to react the char to form CO (assuming little CO_2 exists at this temperature), the overall reaction can be adjusted by the relative oxygen to steam ratio to maintain the gasifier at 2500°F. This oxygen-to-steam ratio is calculated to be 1.7 to 2.0 depending on the temperature of the reactant char, steam and oxygen. This oxygen to steam ratio of 1.7 to 2.0 to gasify the recycle char by itself compares with an oxygen-to-steam ratio of 2.4 (0.39/.16) for the Base Case. An overall reaction to gasify the additional char can now be written with the minimum stoichiometric amount of oxygen and steam required to react all of the recycle carbon as follows:

$$\underbrace{C}_{\text{Recycle Char}} + 0.39\ O_2 + 0.22\ H_2O \longrightarrow CO + 0.22\ H_2$$

Since CO_2 will be formed to some extent in the above reaction of the char, then the oxygen demand a priori will be higher than the 0.39 moles O_2 per mole of carbon for the recycle char. Hence it can be concluded that the moles of oxygen per mole of carbon for the recycle char will be higher than that for the parent coal since the oxygen to carbon for the Base Case is 0.39 also.

The stoichiometry above is discussed to estimate a lower limit on the oxygen demand to the gasifier in order to achieve essentially 100% carbon conversion. This minimum oxygen demand can be calculated to be around 0.40 moles of oxygen per mole of carbon or about 0.75 pounds of oxygen per pound of dry coal.

In order for the overall carbon conversion to be nearly 100 percent, the percent recycle carbon gasified must approach 80-90 percent in order to keep the recycle quantity to an acceptable level. However, the mechanism by which the char is gasified, i.e., by heterogeneous reactions of the char with the available gaseous compounds, could severely limit the conversion of the recycle char in a short residence time reactor. Of the various heterogeneous reactions possible, the following are considered to be the most probable:

(1) $\mathrm{C\ (char)} + 1/2O_2 \longrightarrow CO$

(2) $\mathrm{C\ (char)} + H_2O \longrightarrow CO + H_2$

(3) $\mathrm{C\ (char)} + CO_2 \longrightarrow 2CO$

(4) $\mathrm{C\ (char)} + 2H_2 \longrightarrow CH_4$

Reaction rate constants for reactions (1), (2) and (3) have been reported in the literature$^{(1)}$ to be 1900 $(\mathrm{sec})^{-1}$ $(\mathrm{atm}\ O_2)^{-1}$, 3.3 (sec^{-1}) $(\mathrm{atm}\ H_2O)^{-1}$, and 1.9 (sec^{-1}) $(\mathrm{atm}\ CO_2)^{-1}$ respectively at 3100°F. Another source$^{(2)}$ has reported the initial reaction rates for reactions (1), (2), (3) and (4) to be 100 sec^{-1}, 0.0001 sec^{-1}, 0.001 sec^{-1}, and 0.00005 sec^{-1} respectively at 1 atm and 2000°F. Hence it is advantageous when recycling char to design the reactor so that reaction (1) is favored. Since the oxygen is in great demand in the reducing atmosphere of the gasifier, the recycle char will compete for the oxygen with the other reactive compounds. Since the reaction rates of the coal volatiles are even faster than the oxygen-char rates, reaction (1) could be enhanced if the oxygen and char were fed in a separate injector from the coal injectors within the same gasifier. In this way, the activation energy of the char-oxygen reaction would be supplied by radiation in the gasifier to react all of the char to CO. Then, the CO formed would react with the steam and pyrolyzed volatiles from neighboring injector elements.

5.1.2 Case 3: Secondary Injection

This alternate has the same configuration as the Base Case except a secondary stream of fresh coal is injected into the gasifier where it reacts with the hot gases produced from gasification of primary coal. The effect is to produce a methane enhanced syngas.

Details of this configuration are considered by Bell to be proprietary at this time.

As mentioned above, this is a hypothetical case since it has yet to be tested. However, if the yields given by Bell to JPL can be realized, this case has significant advantages over the Single-Stage Base Case as shown on Table III-2 by the Relative Gas Cost of 0.92 to the Base Case. The saving is mainly due to a substantial reduction in the oxygen requirement, a smaller Methanation section, and a smaller Acid Gas Removal section.

In addition to proving that the methane yields are substantially enhanced, Bell will have to demonstrate the reactor's operability with secondary injection. Considerable operational difficulties were experienced by the Eyring Research Institute in experiments with a secondary injection of coal into their high mass flux, entrained gasifier such that they abandoned the secondary injection approach. Specifically, Eyring's problem centered on coal agglomeration and coal particles sticking to the walls of their pyrolysis section.

When considering the methane enhancement of the syngas from the Base Case, an analysis of the mechanism for methane production is beneficial. Methane may be viewed as forming in the pyrolysis section of a gasifier by the following reactions:

1) $\text{Coal} + \text{heat} \longrightarrow \text{char} + \text{gas (including } H_2, CH_4, CO, CO_2$ and $C_2 - C_4) + \text{liquids } (C_5+)$

2) $2C \text{ (char)} + 2H_2O \longrightarrow CH_4 + CO_2$

3) $C \text{ (char)} + 2H_2 \longrightarrow CH_4$

4) $CO + 3H_2 \longrightarrow CH_4 + CO$

From stream 11 of Table III-1 for the Base Case, which is essentially the hot gases that secondary coal could be injected into, the hydrogen partial pressure is calculated to be 150 psi. This is very low for any significant hydrogenation reactions as are indicated by reactions 3 and 4. Since the partial pressure of H_2O is low also (10 psi), reaction 2 is limited to a low conversion to methane also. Hence, the main contributor for methane enhancement is from reaction 1. Methane enhancement from secondary injection is a result of the pyrolytic reactions of the secondary coal. The coal devolatilizes to char, gas, and liquids. As the temperature is increased, the liquids yield will decrease and the gas yield increase as shown in a plot of tar and gas yield vs. temperature for devolatilization of Pittsburgh HvAb coal in the literature(3). It should be noted that for short residence time reactors, chemical equilibrium has not been reached which explains the existence of liquids in the above mentioned plot at temperatures as high as 2100°F; i.e., a calculation of equilibrium composition at 2100°F would show no hydrocarbon liquids. Such is the case for methane also, as a higher methane yield is possible in a short residence time reactor than an equilibrium calculation would predict. However, by calculating the methane yields for devolatilization of a Pittsburgh seam coal from data presented by Mentser(3), there appears to be a maximum methane yield around 1800°F. The methane yield calculated is about 3 pounds CH_4 per 100 pounds of a vitrain element cut from the Pittsburgh coal (Vitrain was selected since it represents the most abundant maceral, about 80-90 volume percent of the petrographic components of Pittsburgh coal). For this Pittsburgh coal, the percent carbon in the feed coal that is pyrolyzed to CH_4 is estimated to be less than 5 percent at the optimum temperature of 1800°F.

5.1.3 Case 4: Secondary Injection + Char Recycle

This alternate is a combination of Cases 2 and 3; the ungasified carbon from the gasifier, including char from primary and secondary coal, is captured in cyclones and recycled back to the primary coal feed system. The assumed carbon conversion of this recycle char is high as is assumed for primary coal carbon conversion. In this way, any ungasified carbon is eventually recycled to extinction.

Details of this configuration are considered by Bell to be proprietary at this time.

As previously mentioned, this is a hypothetical case since it has yet to be tested. However, if the hypothesized yields can be realized, this case also has significant advantages over the Single-Stage Base Case as shown on

Table III-2 by the Relative Gas Cost of 0.91 to the Base Case. As is true for Case 3, the savings is mainly due to a substantial reduction in the oxygen requirement, a smaller Methanation Section, and a smaller Acid Gas Removal Section. In addition, the coal usage for Case 4 is significantly lower than the Base Case as indicated by the value of the Relative Operating Cost of 0.93. This case, since it is a combination of Cases 2 and 3, represents the furthest extrapolation from actual test data. The discussion on conversion of recycle char in Case 2 and the discussion on methane enhancement by secondary coal injection in Case 3 applies to this case also.

5.2 Comments on Bell's Critical Assumptions Made in Case 1

Although the Single-Stage gasifier for this case has been operated in the 1/2 TPH test facility, much of the data base remains to be demonstrated. Of particular importance are the following assumptions.

5.2.1 Assumption that 90% carbon conversion is attained at the given oxygen ratio of 0.71 for a bituminous coal:

From the performance data for the Single-Stage HMF gasifier reported by Bell, the gasification of Pittsburgh Seam coal to a high carbon conversion could be a difficult task at the oxygen to coal ratios suggested by Bell. This is evident by comparing the "Bell Data" point with the "Bell Projection" point on Figure III-2. Also shown in Figure III-2 is data for the Eyring coal gasifier(4) which is very similar to the Bell Single-Stage gasifier using coal, steam and oxygen. The plotted Eyring data also suggests that the 90% carbon conversion at 0.71 steam to carbon ratio could be difficult to obtain from Pittsburgh Seam Coal (conversion of W. Kentucky and Pittsburgh Seam Coal is expected to be very similar); i.e., 90% carbon conversion could require a significant increase in the oxygen/coal ratio.

To illustrate the importance of oxygen consumption on the overall production cost of SNG from coal, a rough estimate of the gas cost was made using the "Bell Projection" point on Figure III-2 and the "Bell Data" point for the Single-Stage configuration. Increasing the O_2/coal ratio from 0.71 to 0.85 has the effect of increasing the product gas cost by about 16 percent as shown in Table III-3. Hence, it is obvious that if the Bell process is to be economically feasible, the oxygen consumption will have to be reduced. Bell has recognized this and by optimizing the following variables, they expect to substantially decrease the oxygen consumption:

- Oxygen injection velocity
- Steam injection velocity
- Residence time
- Coal injector refinements.

5.2.2 Assumption that the ungasified carbon can be recovered and used in steam boilers

If the ungasified carbon is in the form of soot (soot is defined here as being the product of the gas-phase cracking of an unstable mixture to form carbon and other products), then it is not likely that cyclones will recover the soot. However, if the ungasified carbon is in the form of a char (char is defined here as being that part of the coal which is not gasified), then cyclone recovery is a practical way to recover the heating value of the ungasified carbon.

To illustrate the effect that this has on the overall production cost of SNG from coal, a comparison was made of the gas cost for the Single-Stage (Base Case) and what the cost would be if the ungasified carbon was not recovered. In this case, additional coal is required to generate plant steam and power and the additional cost of a flue gas desulfurization unit is added. The overall calculated effect is that the gas cost is increased 6 percent over the Base Case as shown in Table III-3.

5.2.3 Assumption that the unrecovered char is essentially sulfur free:

If the recovered char is sulfur free, then flue gas desulfurization would not be required in the Base Case where the recovered char is used to generate process and utility steam.

To illustrate the effect this assumption has on the overall production cost of SNG from coal, a comparison was made of the gas cost for the Single-Stage (Base Case) and what the cost would be if the boiler flue gas required desulfurization. The overall effect calculated is that the gas cost increases 2 percent over the Base Case, as shown in Table III-3.

5.3 Preliminary Assessment of Potential Improvements Suggested by JPL

5.3.1 Case 5: Use of Molten-Slag Bath with Single-Stage

If the single stage gasifier were operated with a molten-slag bath, potential carbon conversion could be further increased at the same oxygen consumption (Refer to Figure III-3). The Saarberg/Otto (5) synthesis gas process is a process similar to the slag bath concept for producing medium or low Btu gas from coal, char, or liquid hydrocarbons. A 264 TPD demonstration plant is in operation now in Saarbergwerke AG, West Germany. A 99 percent carbon conversion has been reported at 0.82 pound oxygen per pound coal and 0.72 pound steam per pound coal. Certain constituents in the ash, such as iron oxide, are believed to act as an oxygen transfer medium via the following reactions:

$$Fe_2O_3 + C \longrightarrow 2\,FeO + CO$$
$$2\,FeO + 1/2\,O_2 \longrightarrow Fe_2O_3$$

If a molten-slag bath is maintained in the slag pot, ungasified char particles would be thrust onto the surface of the slag. Hence, it is postulated that carbon conversion will tend to increase via the mechanism suggested above and by the fact that the char particles will remain at the high, slagging temperature for a longer period of time.

If the single-pass carbon conversion were increased to essentially 100 percent, the net effect would be similar to that for Case 2, where the ungasified carbon is recycled to extinction. The gas cost, relative to the Base Case, is 1.01. Although this case calculates to be more expensive than the Base Case, this suggestion is made with the Critical Assumptions indigenous to the Base Case kept in mind. Since demonstration of all the critical assumptions seems improbable, suggestions which add to the probability of success are considered here to be a potential improvement. For example, if the Base Case used the present conversion data from the test facility, the relative gas cost would be 1.16 as shown in Table III-3. Hence, the relative gas cost for this case would then be 0.87 (= 1.01/1.16).

5.3.2 Case 6: Separation of Stages with Molten-Slag Bath

The effect of methane enhanced yields on the process is significant as evidenced by the relative gas cost for the Secondary-Injection Case in Table III-3 of 0.92. This is mainly due to the reduction in the oxygen requirement as previously discussed. To realize the enhanced methane yield and the subsequent lower oxygen requirement, a two-stage process is suggested using the Molten-Slag Bath concept for the first stage and an efficient mixing, reverse flow injector for the second stage. A schematic of the gasifier configuration is shown on Figure III-4. Inherent beneficial features to this configuration are as follows:

(a) The two-stage process yields higher methane with a subsequent lower oxygen demand: methane formation from flash pyrolysis can be enhanced if the temperature is lowered to around 1700-1900°F.

(b) The high single-pass carbon conversion for the first stage minimizes the char recycling since essentially 100 percent of the carbon in the coal and in the recycle char from the second stage is converted in the Molten-Slag Bath, first stage.

(c) The molten-slag is kept separate from the secondary coal to prevent agglomeration. The agglomeration problem is what caused Eyring Research Institute to abandon the secondary injection concept. By keeping the molten-slag in the first stage, the problem of agglomeration of secondary coal is minimized.

(d) The hot gases from the first stage are injected into the second stage utilizing an efficient reverse flow injector to better mix with the secondary coal. Bell has observed better yields with the reverse flow injector; however, it was abandoned due to slag accumulation problems.

(e) Interruption of char flow doesn't shut the system down. In other two stage gasifiers (e.g., AVCO and the Bi-Gas processes), an interruption in char flow would of necessity shut the gasifier down. In this case, as is true for Cases 3 and 4, the interruption of char flow wouldn't necessitate a system shutdown as coal would continue to flow to the first stage.

It is expected that the methane enhancement will not be as high as Bell has assumed for the Secondary Injection plus Char Recycle Case; however, the methane will be increased thereby giving it all the advantages of Case 4 except to a lesser degree. Hence, the relative gas cost to the Base Case is expected to be between 0.91 to 1.0.

5.3.3 Case 7: Catalyst Application

By applying a catalyst to the secondary coal, the formation of methane could be enhanced by promoting the following heterogeneous reactions:

$$C + 2H_2O \longrightarrow CO_2 + CH_4$$
$$C + 2H_2 \longrightarrow CH_4$$

In addition to possible enhanced methane yields in the secondary-injection section, the catalyst will also increase the reactivity of the recycle char as it is recycled to the first stage.

At the present time, no data were found in the literature for catalytic high mass flux entrained gasifiers. However, early entrained gasifier development in a single-stage gasifier at Morgantown (6) showed that when lime was added to the coal, the following effects were noticed:

(a) Slagging accumulation problems were significantly reduced apparently due to a lowering of the slag viscosity by the lime;

(b) The H_2S and COS contents were reduced by 71 percent and 89 percent, respectively, in the syngas;

(c) Carbon conversion may have been increased.

These observations with a single-stage gasifier further suggest that potential improvements by the addition of another material to the coal could have advantages in addition to the catalytic effects of producing more methane (in a two-stage or secondary injection reactor) and yielding higher carbon conversions. Any improvements gained, however, will have to be offset by the additional costs of the catalyst, the catalyst application technique, and the catalyst recovery technique. It is suggested that this potential improvement be further investigated to better define the overall effects of catalyst application in the Bell HMF Gasifier.

5.3.4 Case 8: Use of Lower Grade Coals

Air-blown test with N. Dakota Lignite and Montana sub-bituminous coals indicated higher carbon conversion in the single-stage, 1/2-TPH facility. A comparison of W. Kentucky bituminous coal, Montana sub-bituminous coal and N. Dakota Lignite is shown below:

Ultimate Analysis (dry wt.%)	W. Kentucky Bituminous	Montana Sub-bituminous	N. Dakota Lignite
C	70.5	68.0	64.34
H	5.1	4.4	4.27
N	1.4	1.0	0.87
S	4.2	1.0	1.53
O	9.3	14.3	18.76
Ash	9.5	11.3	10.23
	100.0	100.0	100.0

The most notable differences in the elemental analyses are the sulfur and oxygen contents between the bituminous and the lower grade sub-bituminous and lignite coals. Since the sulfur is lower, sulfur removal facilities will obviously be lower. The oxygen difference has the direct effect of lowering the oxygen consumption for the Single-Stage Base Case when using a lower grade coal. This is supported by early data(6) using an entrained flow coal gasifier at Morgantown to gasify a sub-bituminous and bituminous coal. The following results were observed:

(a) For 90 percent carbon conversion, the sub-bituminous coal required about 70 percent of the oxygen that the bituminous coal required;

(b) If the total oxygen available to the reaction were considered (total oxygen=oxygen in gas feed + oxygen in coal feed), then the total oxygen to carbon ratio for 90 percent carbon conversion was identical.

If the relationship expressed in b) above holds true for the Bell HMF Gasifier at 90 percent carbon conversion, then the oxygen to dry coal ratios can be predicted as below:

	W. Ky. Coal (Base Case)	Montana Sub-Bit.	N. Dakota Lignite
Oxygen in coal per carbon (lb/lb)	0.13	0.21	0.29
Oxygen in gas per carbon (lb/lb)	1.01	0.93	0.85
Total Oxygen per Carbon (lb/lb)	1.14	1.14	1.14
Oxygen Plant Requirement:			
(Tons O_2/Ton Dry Coal)	0.71	0.63	0.55

In addition to requiring less oxygen from the expensive oxygen plant, the high conversion of the lower rank coals is expected to be easier due to higher reactivities compared to older rank coals. If a N. Dakota lignite is used in place of the W. Kentucky coal in the Base Case Single-Stage gasifier, the relative gas cost is found to be about 0.70 compared to the Base Case with W. Kentucky coal. The main factors contributing to the reduction are as follows:

(a) Substantially less raw material costs: W. Kentucky coal price used was $25/Ton, whereas, N. Dakota Lignite was priced at $5/Ton.
(b) Substantially smaller oxygen plant.
(c) Substantially smaller sulfur plant.

6.0 COMPONENTS REQUIRING DEVELOPMENT

The following components are recommended for further development:

1. <u>Control and Safety Systems:</u>

The high throughput rates of the Bell HMF gasifier at high temperatures require the gasifier to be closely controlled. If the reactant coal were to cease flowing and the oxygen continued to flow into the hot reactor, the gasifier and equipment downstream of the gasifier could be exposed to extreme temperatures and pressures in a short period of time. Instrumentation to sense temperature excursions quickly and quick-reacting control systems need to be developed.

In addition, safety systems for automatic shutdowns need to be further developed (Bell has a shutdown system now that reacts to pressure instability).

2. <u>Solids Feed System:</u>

The dense phase feed and lockhopper system need to be integrated. Also the feeding of hot char as a recycle needs to be developed.

3. <u>Slag Pot:</u>

The recovery of the slag in the slag pot will have to be further developed including the depressuring and quenching of the slag. The 1/2-TPH coal test facility in place now is a pot which is quenched with an over abundant quantity of water and at atmospheric pressure.

4. <u>High Temperature Heat Exchangers to Cool Syngas and Char:</u>

The syngas and char from the gasifier will require cooling from either 1900°F to 600°F (Single-Stage) or 1000°F to 600°F (Secondary Injection). The char and possible soot and entrained slag could tend to foul the exchanger surface. Also, the corrosive gases and solids mixture at high temperature will require special metallurgy.

5. <u>Char Fines (or soot) Separation from Syngas:</u>

Scrubbing to remove small char and soot particles will need to be tested to insure efficient removal.

6. Scale-Up Aspects to Commercial Size Design:

The maximum size of the injection element needs to be investigated including the method of clustering several elements into a scaled-up gasifier. Also, the method of solid feed splitting and feed control systems in the scaled design need to be developed.

7.0 DEVELOPMENT STATUS

In order to ascertain the current status of the Bell process, the following areas of development are discussed.

(1) Air-Blown Gasifier Development: 1976-1978
(2) Oxygen-Blown Gasifier Development: 1978 to August, 1979
(3) Planned Oxygen-Blown Gasifier Development
(4) Data Base From Test Runs

7.1 Air-Blown Gasifier Development:1976-1978.

Work was initiated in 1976 by Bell for E.R.D.A. (now D.O.E.) under contract no. EX-76-C-01-2204 for $1,205,079; D.O.E. continued sponsoring the work through 1978. The scope of Bell's work was to investigate the feasibility of using an entrained flow gasifier, operating at very high mass throughput per unit of reactor volume to economically convert coal into gas. The following pertains to work under this program.

7.1.1 Reactor Test Facility (See Figure III-5)

a) Size:
  - 1/2 TPH coal feed
  - up to 1 hour run duration

b) Performance Testing:
  - o 66 tests @ 1/2 TPH coal flow rate
    - 13 runs @ 1/2 to 1 hour duration
    - 5 atmospheres pressure, air blown, no steam
  - o slagging accumulation effects and improved design (impinging sheet injector) identified

- 3 coals tested - North Dakota Lignite
  - Montana Rosebud Subbituminous
  - Pittsburgh Seam Bituminous
- stable continued operation observed on tests as evidenced by no reactor upsets
- 80-90% observed carbon conversion for lignite and subbituminous coal using impinging sheet design; limited testing showed bituminous coal carbon conversion to be approximately 65%
- pressurized dry coal feed system operated successfully
- gasifier material balances made based on coal and air flows in and gas compositions out; ungasified organics and ash were not measured but assumed by difference; only gases recorded in balances were CH_4, H_2, O_2, N_2, CO and CO_2; H_2O was assumed to be converted to H_2S.

7.1.2 The following reactor variables were identified and assessed as follows:

(a) Coal Type: Reactor performance as measured by percent carbon conversion as similar in tests for Montana Rosebud and North Dakota Lignite (about 90%); limited data for Pittsburgh Seam Coal indicated substantially lower carbon conversion than obtained with the above two coals (about 65%).

(b) Injector Configuration: Several injector types were tested including a "swirl air injector," a "reverse flow air injector," a "modified reverse flow injector," and an "impinging sheet injector." The main effect of the different injectors was the degree of slag accumulation experienced during a test period in the reactor head.

In this regard, the magnitude of the performance change following slag accumulation was about 12% reduction in carbon conversion and 15% reduction in HHV. (Performance testing with N. Dakota lignite using the impinging sheet injector indicated minimal slag accumulation and no performance decay over a one hour test period.).

(c) Coal and Air Injection Velocities: Comparison of test runs where the coal injection velocity was reduced by nominally 50% indicated essentially no difference in carbon conversion using the reverse flow injector configuration. Comparison of 2 runs where the air injector was reduced indicated an increase in performance level using the reverse flow injector configuration.

(d) Air to Dry Coal Ratio (lb/lb): Using the impinging sheet injector and N. Dakota lignite, as the ratio is increased from 3.0 to 3.6, the percent carbon gasified increased from 78 to 92% and the HHV of the product gas stayed essentially constant at 100 Btu/SCF (dry).

(e) Residence Time: Air blown test measurements have shown that all of the oxygen has reacted in less than 0.145 sec superficial residence time; at this point, up to 80% of lignite carbon is converted to gas. Doubling the residence time to less than 0.100 sec converts another 10% of the carbon. It is believed that the life-time of active-sites in the ungasified char may be up to 0.200 sec.

(f) Steam/Dry Coal Ratio (lb/lb): The effect of steam addition upon carbon conversion was not assessed; however, it is believed that steam injection would increase the carbon conversion by reacting with the ungasified char at the active sites mentioned above.

(g) Total Mass Flux (lb/hr per ft^3 Reactor Volume: A decrease in mass flux from 20,000 to 10,000 showed an increase of around 10% carbon conversion.

(h) Temperature: Reactor temperature varies proportionately to the air/dry coal ratio. The temperature was set in order that the slag formed will flow freely from the gasifier without accumulating.

(i) Pressure: The effect of pressure has not been evaluated using the gasifier test facility.

7.1.3 Theoretical Analyses

- Thermodynamics analyses based on equilibrium calculations were performed.

7.1.4 Process and Economic Analyses

- Process and Economic Analyses were performed by Gilbert Associates under a Bell funded contract on an air-blown HMF gasifier application to a combined cycle power plant.

7.2 Oxygen-Blown Gasifier Development: 1978 to present

Bell continued development of the gasifier using oxygen plus steam rather than air to gasify the coal. The work was performed using company funds. A contract was awarded to Bell by the New York State Energy and Research Development Authority (NYSERDA) for $400,000 in 1979 to conduct dense phase flow and wall-slagging investigations in support of gasifier development. Alfred University has assisted Bell in the area of slag characteristics and chemistry evaluation during this time frame.

A schematic of the oxygen-blown test facility is shown on Figure III-6; a typical gasifier configuration is shown on Figure III-7. Development during this period is as follows:

- Several O_2-blown, short duration (less than 10 min.) gasifier tests completed.
- Different basic injector configurations evaluated (see Figure III-7)
- Operation and control of facility and reactor satisfactory
- Data analysis procedures developed

- Reactor variables identified and assessed as to their influence on carbon conversion. Variables identified are as follows:
  - Oxygen Injection Velocity
  - Steam Injection Velocity
  - Residence Time
  - Oxygen/Coal Operating Ratios
- Process and economic analysis:
  (1) Performed by Gilbert Associates under a Bell-funded contract to estimate the cost of a plant to produce 50 billion Btu per day of medium Btu gas (298 Btu/dry SCF) and 18 MW of electricity from North Dakota Lignite.

  (2) Performed by DOE's Morgantown Process Evaluation Office as a separate process evaluation. The report was entitled "An Economic Comparison of the Bell HMF Gasifier with the Texaco and Lurgi Gasifiers - 50 Billion Btu/day Industrial Fuel Plant." Coal feed was North Dakota Lignite.

7.3 Planned Oxygen-Blown Gasifier Development

In October 1979, DOE and GRI awarded to Bell a one year contract for $1,500,000 (Contract No. DEc-AC01-79ET-14674). The long range objective of the DOE/GRI program is to develop the HMF gasifier to produce SNG feedstock which:

- Minimizes oxygen and steam consumption
- Maximizes methane content
- Minimizes tar and other liquid by-products
- Eliminates or minimizes char recycle
- Is scalable to large capacity (100-TPH coal feed)

Specific tasks to be completed in this one year contract are as follows:

1. Investigate the process and determine its performance using an upgraded 1/2-TPH facility (see Figure III-8);

2. Test with bituminous coal, oxygen and steam at 15 atm pressure;

3. Evaluate the primary performance characteristics, and

4. Evaluate the performance of a secondary coal injection system.

The long range program plan is to test at increased pressures, high throughputs and for extended periods of operation. Provisions for this future growth are being made in test system modifications being made under the current DOE/GRI contract. Continuous operation is planned for the 1981-82 time frame.

7.4 Data Base From Test Runs

In Table III-4, selected data from the Bell gasifier testing is listed. Included in the table are selected runs from the air blown gasifier work and yields expected in the oxygen plus steam gasifier.

The most notable result shown in the Air-Blown Test Data is that at the high mass flux rates used (10,000 lb/hr per ft^3), 90% carbon conversion for lignite was obtained whereas for Montana Rosebud, only 80% carbon conversion. Both runs used about the same air to dry coal ratios, 3.5 and 3.6, respectively.

During the company sponsored oxygen blown test program, Bell conducted parametric sensitivity testing. It was observed that for each 0.1 change in the oxygen to coal ratio, the carbon conversion efficiency increased approximately 10%. Other variables, including oxygen and steam injection velocities, reactor residence time and coal injector variables were evaluated for their performance sensitivity.

Using Pittsburgh seam coal and operating at an oxygen to coal ratio of 0.85:1, Bell obtained a carbon conversion efficiency of 90%. Applying the performance sensitivity factors and allowing for the lower carbon content, a carbon conversion of 90% at an oxygen to coal ratio of 0.71:1 for Western Kentucky coal is projected by Bell, as indicated in Table III-4.

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8.0 FUNDAMENTALS OF SRT GASIFICATION AS APPLIED TO THE BELL HMF GASIFIER

The Bell HMF Gasifier has basically two configurations which could be utilized according to the end product desired:

1. The Single-Stage HMF Gasifier configuration where coal, oxygen and steam are fed into the gasifier to react basically to CO and H_2. This configuration can apply to any process where syngas can be used as a fuel or as an intermediate product.

2. The Two-Stage HMF Gasifier configuration where a secondary coal stream is injected into the gasifier to mix and interact with the syngas formed in the first stage to form CO, H_2, and some CH_4. This configuration is applicable where an intermediate Btu fuel gas is desired or where SNG is the final product after a methanation step.

The following is a discussion of the fundamental mechanisms of coal gasification as applied to both configurations:

8.1 Single-Stage Gasifier

A schematic of Bell's Single-Stage, entrained flow gasifier is shown in Figure III-9. The gasifier is divided into 3 zones which describe the basic reaction mechanisms of the gasifier as follows:

8.1.1 Zone 1A: Pyrolysis Zone

In this zone, the volatiles from the coal are pyrolyzed by the hot gases surrounding it after injection into the reactor. This region is extremely turbulent with the combustion gases recirculating from zone 1B plus radiation effects supplying the heat for the endothermic pyrolysis reactions. A general reaction can be written as follows:

$$\text{Coal} + \text{heat} \longrightarrow \text{char} + \text{volatiles}$$

where volatiles include CO, H_2, CO_2, H_2O, CH_4, H_2S, N_2, C_2-C_5 hydrocarbons and C_6^+ hydrocarbons containing mostly aromatics, tars and unstable heavy hydrocarbons.

A kinetic equation expressing the rate of pyrolysis as proportional to the amount of volatile content remaining in the char is written as follows:

$$\frac{dV}{dt} = K\ (V_{init.} - V)$$

where $K = K_o\ \exp(-E/RT)$, sec^{-1} (Arrhenius' equation)

$V_{init.}$ = the initial volatiles in the coal, lb/100 lb coal

and V = volatiles evolved, lb/100 lb coal.

This reaction rate is extremely fast and describes the rate controlling step of devolatilization for pulverized coal particles. If the particles were larger, then the rate of heat transfer to the coal or the mass transfer of the volatiles from the coal would be the limiting step to devolatilization. This is one basic difference between entrained, flash pyrolysis gasifiers and moving, fixed bed, or fluidized bed reactors. The entrained gasifiers can be designed such that heating rates of 2,000°F/sec to 700,000°F/sec are attained by using fine particles to minimize heat and mass transfer resistances.

Pyrolysis of caking coals presents no problem to the Bell HMF gasifier since the particles are well dispersed. Also, since the heating rates are so high, the compounds which "plasticize" coal are quickly pyrolyzed from the coal particle before agglomeration can occur.

8.1.2 Zone IB: Volatiles Combustion

This zone is probably indistinguishable from Zone IA as there is backmixing of hot combustion gases which help pyrolyze the coal. If pyrolysis products are available to the oxygen in Zone IA, then volatiles combustion occurs in Zone IA as well as Zone IB since the reaction rate of oxygen with volatiles such as CO and H_2 is fast enough to be considered instantaneous.

The volatiles combustion reactions can be written as follows:

$H_2 + 1/2\ O_2 \longrightarrow H_2O$

$CO + 1/2\ O_2 \longrightarrow CO_2$

other volatiles + $O_2 \longrightarrow CO_2 + CO + H_2 + H_2O$.

The additional volatiles, including CH_4, C_2-C_5, and C_{6+} hydrocarbons will partially be oxidized to CO_2, CO, and H_2, depending on the availability of the oxygen and the temperature level. Since tests in the 1/2-TPH facility have shown little or no evidence of tars or heavy liquids in the gasifier product, it is probable that the tars are completely destroyed in this zone.

The temperatures reached in this zone are around 3000°F and are directly proportional to the oxygen to coal ratio.

8.1.3 Zone IC: Char Gasification

The pyrolysis reactions in Zone IA leave a char intermediate product entering Zone IB. The char does recirculate with hot, pyrolysis products from Zone IB back to Zone IA. This is evidenced by the accumulation of a thin, slag rim which accumulates around the oxygen inlet annulus as shown in Figure III-9. The unreacted, but now highly reactive char enters Zone IC where steam is injected to further gasify the char. Air-blown testing by Bell showed that essentially all of the oxygen was consumed in 0.045 msec; hence, since all of the oxygen has been reacted before Zone IC, the heterogeneous reaction of char with oxygen is not likely. The primary reactions in this zone are as follows:

$C(Char) + H_2O \longrightarrow CO + H_2$

$C(Char) + CO_2 \longrightarrow 2CO$

$C(Char) + H_2 \longrightarrow CH_4$

The overall reaction rate of the char can be described as follows:

$$\frac{dC_s}{dt} = -C_s \left(k_{H_2O}\, C_{H_2O} + k_{CO_2}\, C_{CO_2} + k_{H_2}\, C_{H_2}\right)$$

where C_s = concentration of carbon in char (moles/volume)

$k_{H_2O}, k_{CO_2}, k_{H_2}$ = Arrhenius rate constants for char H_2O, char-CO_2, and char-H_2 reactions (vol/moles/sec)

$C_{H_2O}, C_{CO_2}, C_{H_2}$ = concentration of gaseous species (moles/volume)

The initial reaction rates of the three heterogeneous reactions above have been shown to be about the same at partial pressures of 35 atm(2); however, at 1 atm partial pressure, the fastest reaction is suggested to be the char-CO_2 reaction, then the char-H_2O reaction and finally the char-H_2 reaction. An analysis of the stoichiometric quantities of the gases entering Zone IC indicates that H_2 has probably the lowest partial pressure of the reacting gaseous species. Hence, the most dominant heterogeneous reactions in Zone IC are the char-CO_2 and char-H_2O reactions.

As the heterogeneous reactions are occurring, the gas phase reactions are simultaneously reacting to approach equilibrium composition. For the high temperatures (2500-2600°F) of the Bell Single-Stage Reactor, there is hardly any CH_4 existing and CO and H_2 make up close to 90 vol % of the gaseous species. The equilibrium gas composition of the Single-Stage Raw Syngas is given as follows:

	Vol.%
CO	55.9
H_2	31.0
H_2O	7.0
CO_2	4.0
H_2S	1.4
N_2	0.7
CH_4	0.01

All the heavy volatiles have disappeared through gas phase reactions occurring in Zones IA, IB, and IC. In the cracking reactions which do occur, pyrolytic soot may be formed which could represent a penalty to the process as soot is so fine it is hard to recover.

8.2 Two-Stage Gasifier

Bell's Two-Stage, entrained flow gasifier includes all the elements of the Single-Stage gasifier with a secondary-injection Zone IIA and secondary char gasification Zone IIB added as shown in Figure III-9. The coal is injected in Zone IIA in order to devolatilize the coal quickly as occurs in Zone IA of the Single-Stage. However, heat for pyrolysis is supplied by the 2500°F gases from Zone IC rather than combustion gases recirculating from Zone IB. The devolatilized char formed from the secondary coal is very reactive at this point as it enters Zone IIB. The main reactions available are the char-H_2O, char-CO_2, and the char-H_2 reactions as described above. However, in this section the reaction that will prevail initially is the char-H_2 reaction since the H_2 partial pressure is the highest. Hence, methane yields are enhanced from pyrolysis and the char-H_2 reactions. Since the temperatures are still high, the gas-phase equilibrium would show little methane in the gasifier product if equilibrium were attained. Hence, rapid quenching by water sprays is done immediately following Zone IIB to "freeze" the methane before it decomposes.

9.0 REFERENCES

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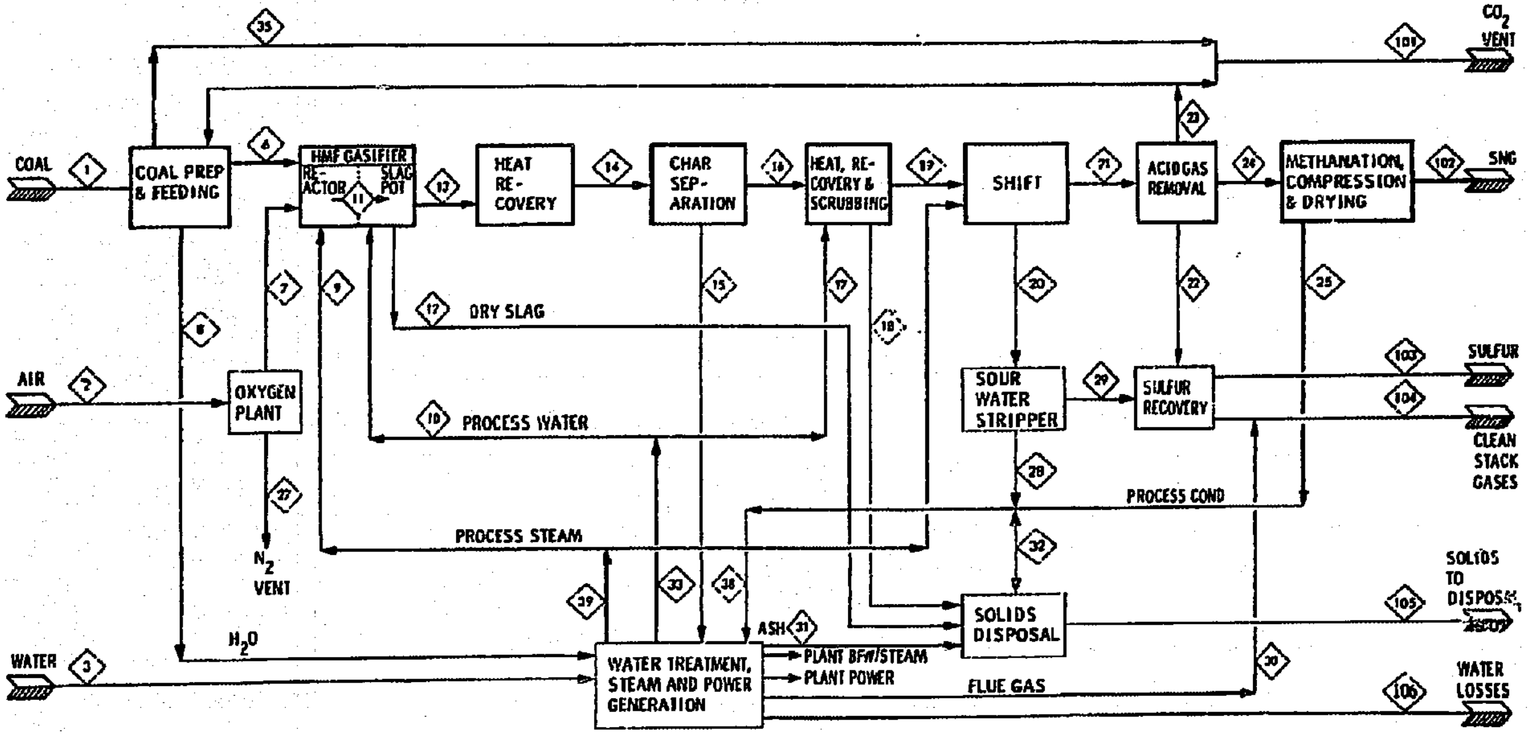


FEEDS		PRODUCTS	
COAL (6% MOIST)	17,432 ST/SD	SNG	260 MMSCFD
OXYGEN	11,615 ST/SD	SULFUR	688 ST/SD
WATER	9,005 GPM		

Fig. III-1: Bell Single Stage HMF Coal-to-SNG Block Flow Diagram

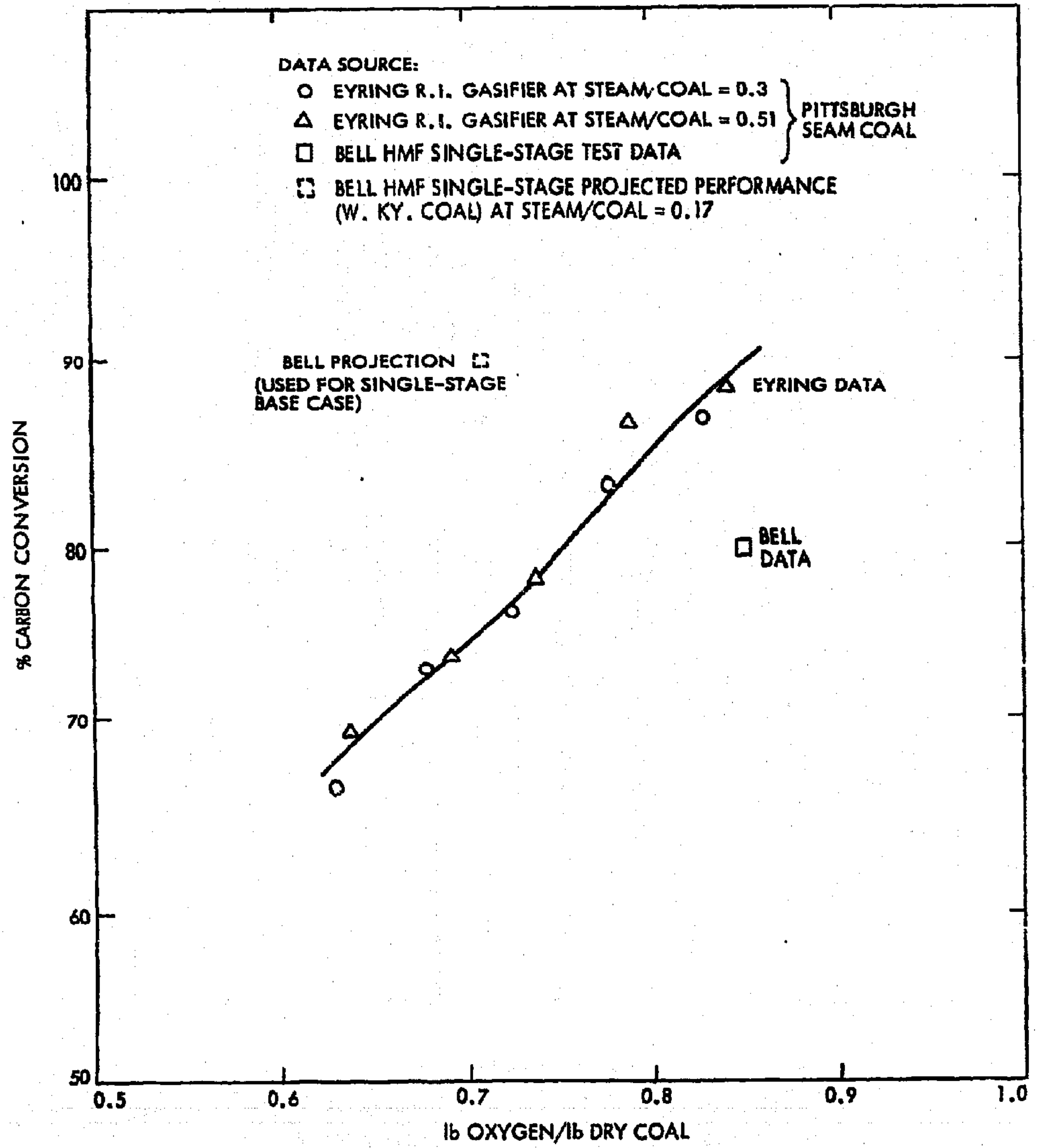
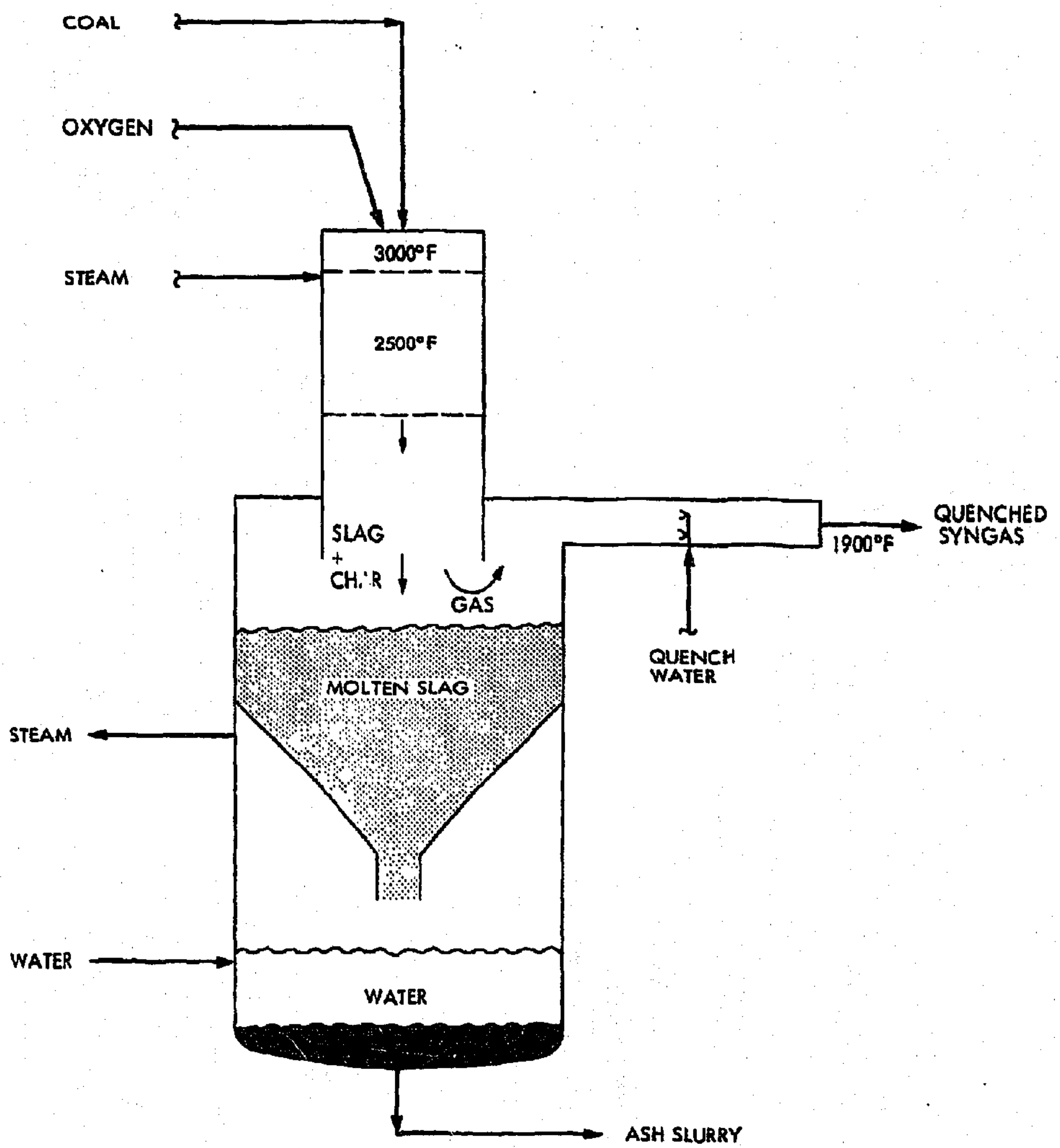


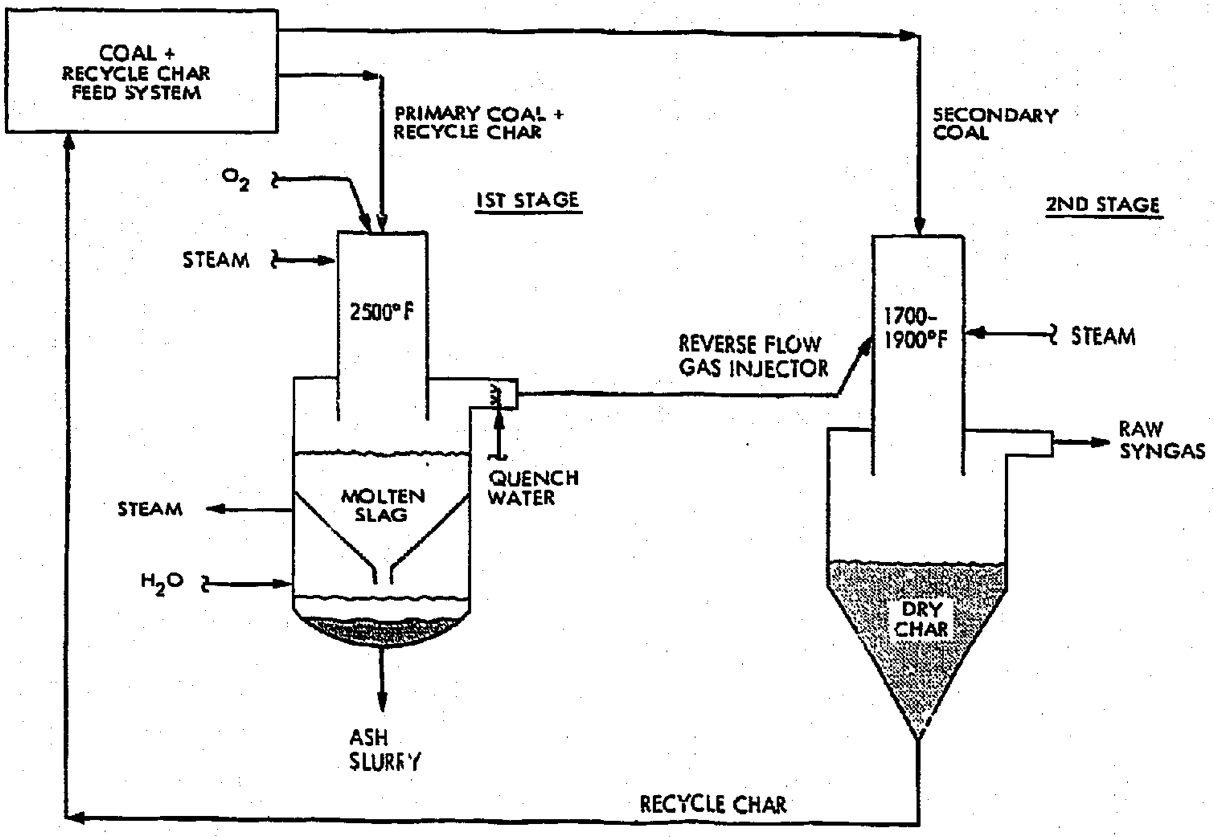
Fig. III-2: % Carbon Conversion vs. Oxygen/Coal Ratio
for Bituminous Coal



BENEFICIAL FEATURES

- UNGASIFIED CHAR FROM REACTION ZONE IMPINGES ON SURFACE OF SLAG POOL WHICH COULD ACT AS AN OXYGEN TRANSFER AGENT
- UNGASIFIED CHAR REACTION ZONE IS AT HIGH TEMPERATURE FOR A LONGER TIME

Fig. III-3: Molten-Slag Bath Concept for Bell's Single-Stage HMF Gasifier



BENEFICIAL FEATURES

- TWO-STAGE PROCESS WITH HIGHER METHANE YIELD AND LOWER O_2 CONSUMPTION
- HIGH SINGLE-PASS CARBON CONVERSION MINIMIZES CHAR RECYCLING
- MOLTEN SLAG KEPT SEPARATE FROM SECONDARY COAL TO PREVENT AGGLOMERATION
- HOT GASES FROM 1ST STAGE INJECTED INTO 2ND STAGE UTILIZING EFFICIENT REVERSE FLOW INJECTOR TO MIX THOROUGHLY WITH SECONDARY COAL
- INTERRUPTION OF CHAR FLOW DOESN'T SHUT SYSTEM DOWN

Fig. III-4: Molten-Slag Bath with Secondary Injection for Bell's HMF Gasifier

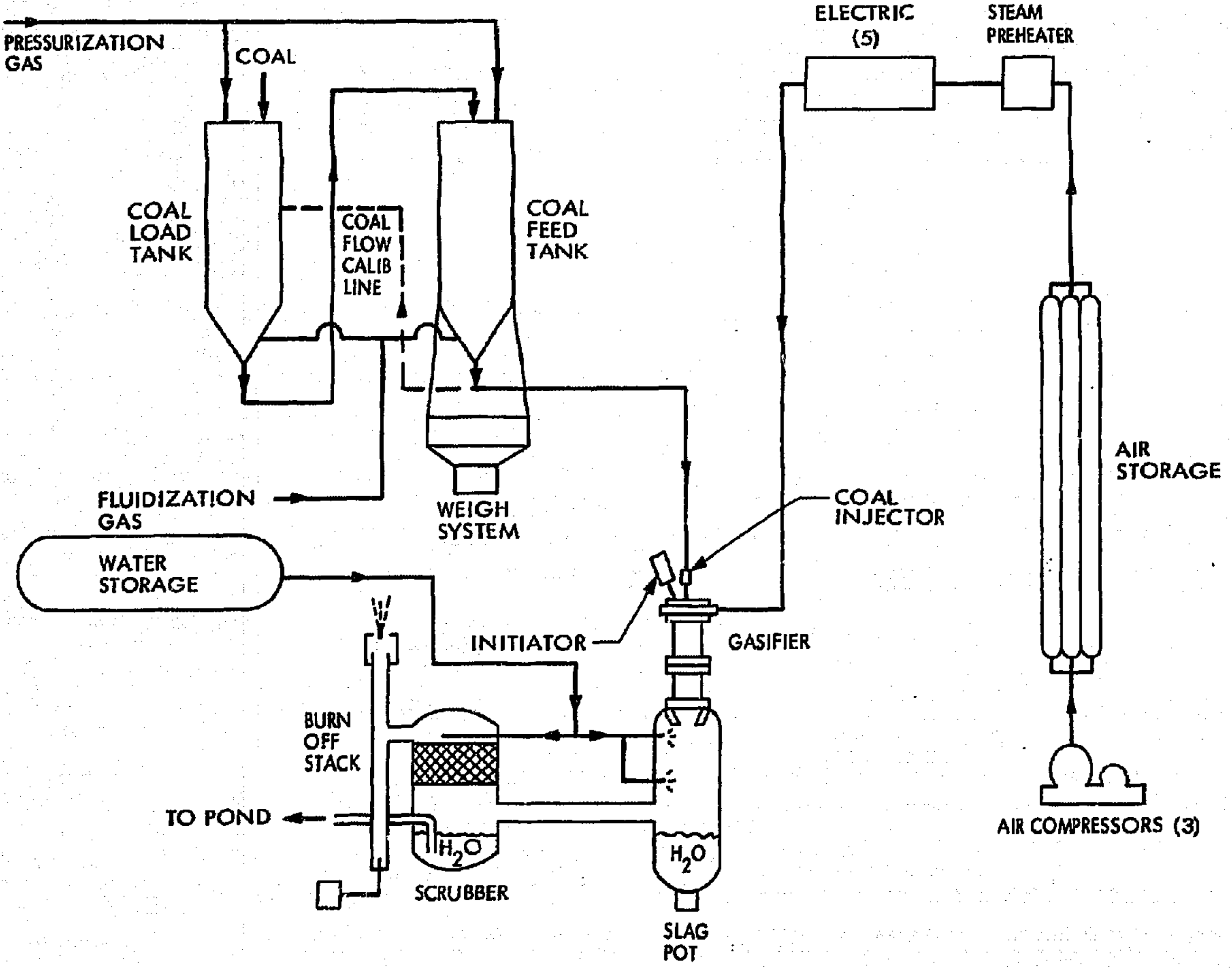


Fig. III-5: Air-Blown Bell HMF Gasifier Test Facility Schematic

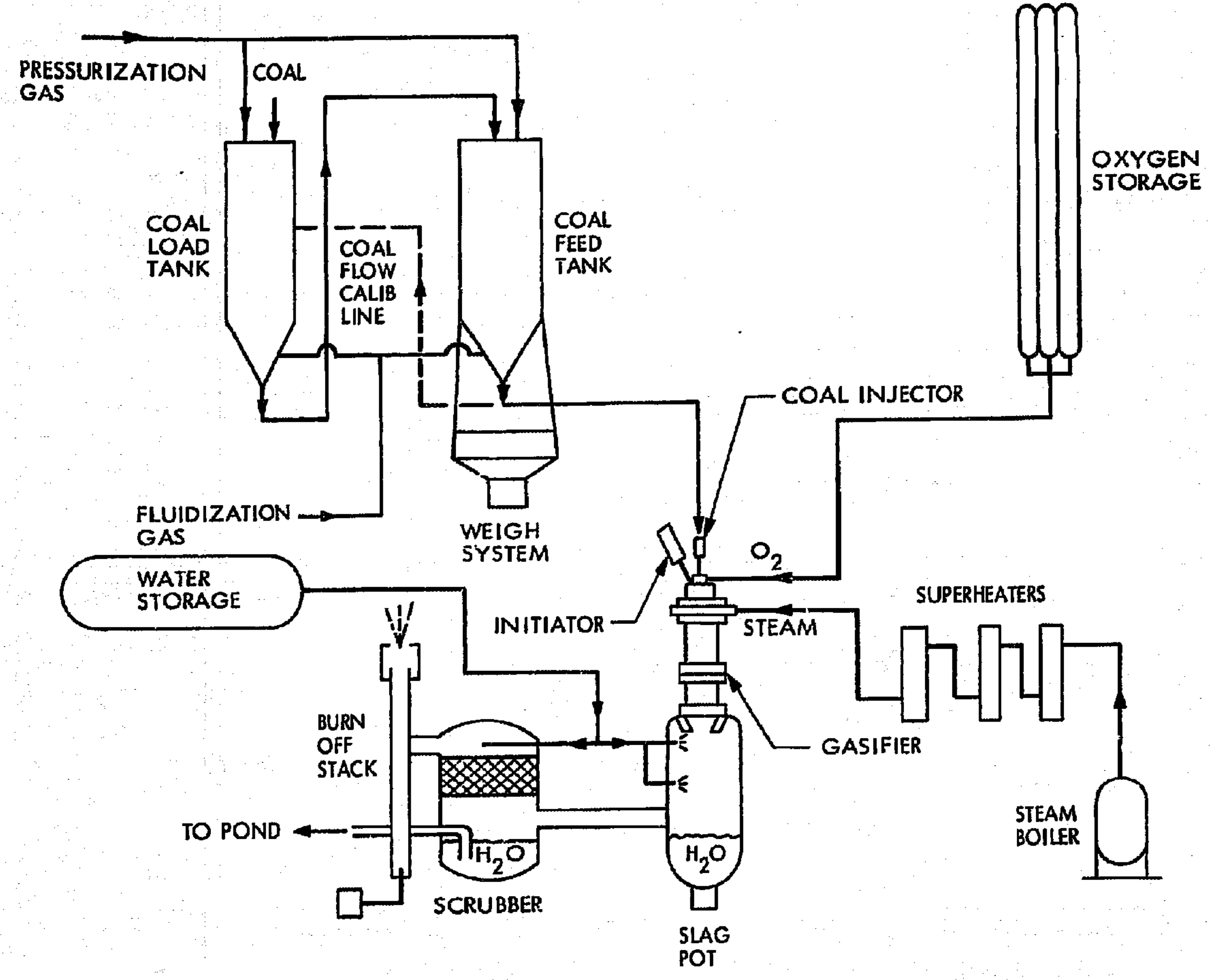


Fig. III-6: Oxygen-Blown Bell HMF Gasifier Test Facility Schematic

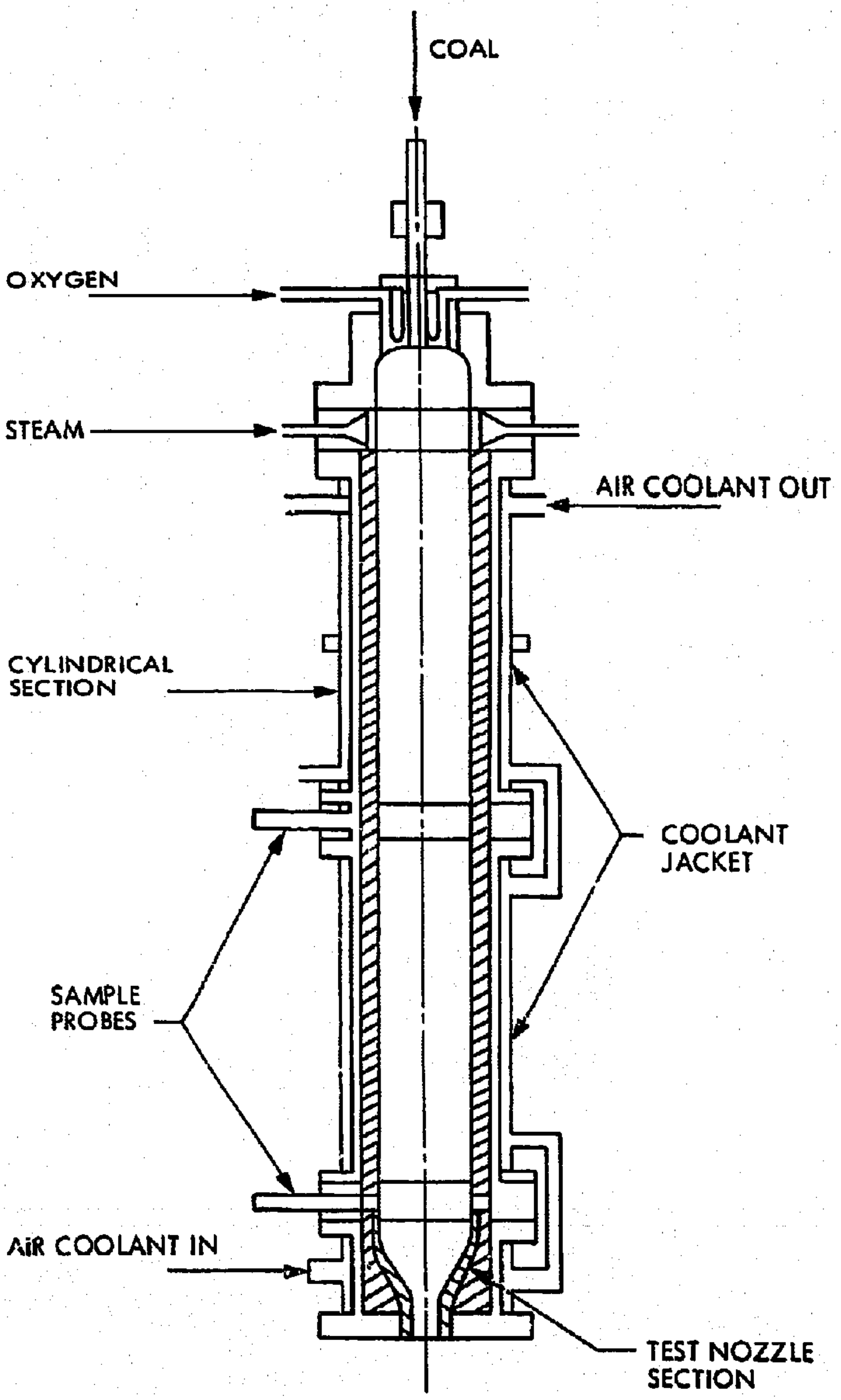


Fig. III-7: Typical Reactor Configuration Used in Bell HMF Oxygen-Blown Testing

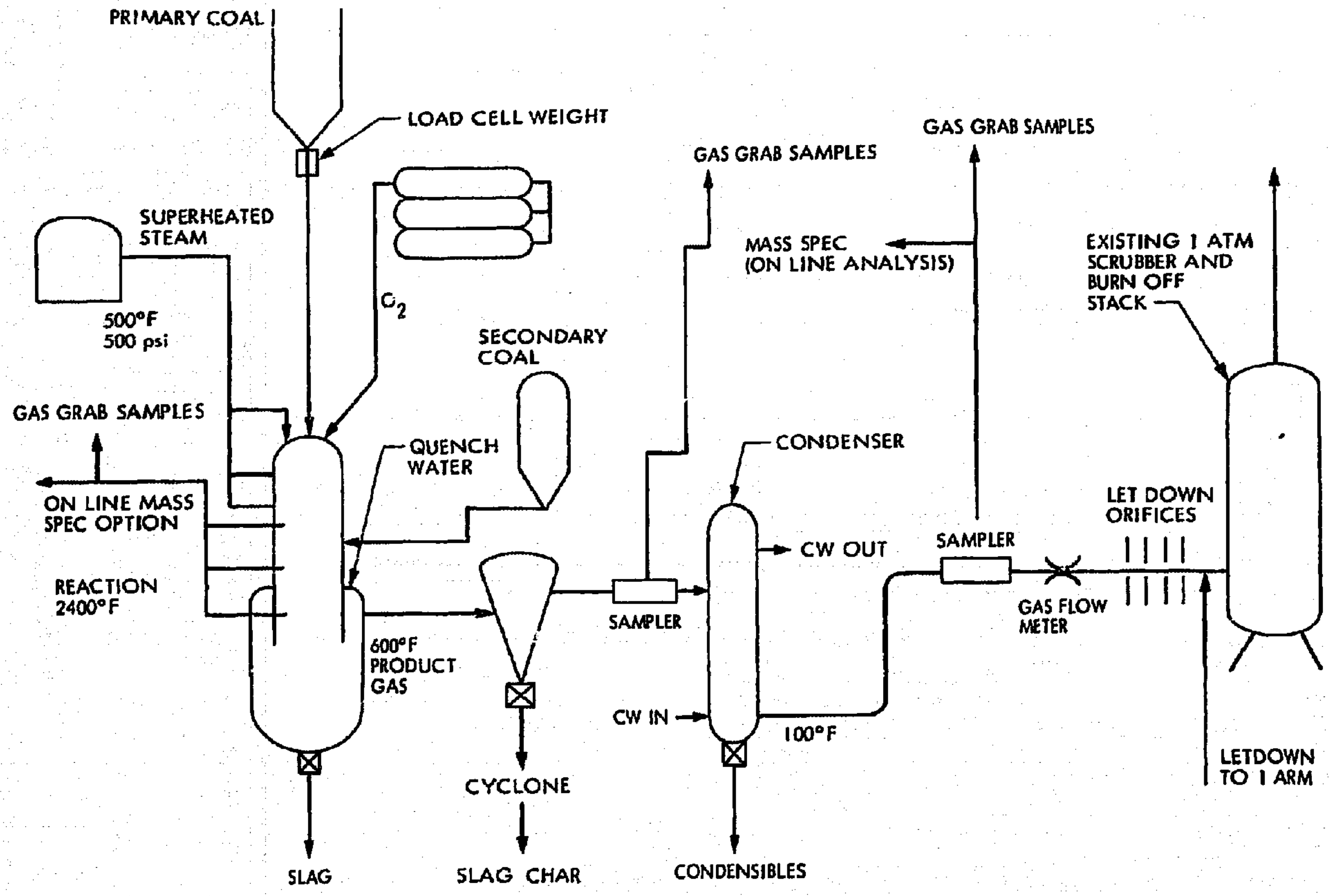


Fig. III-8: Upgraded Bell HMF Test Facility Schematic for Oxygen-Blown Reactor Program

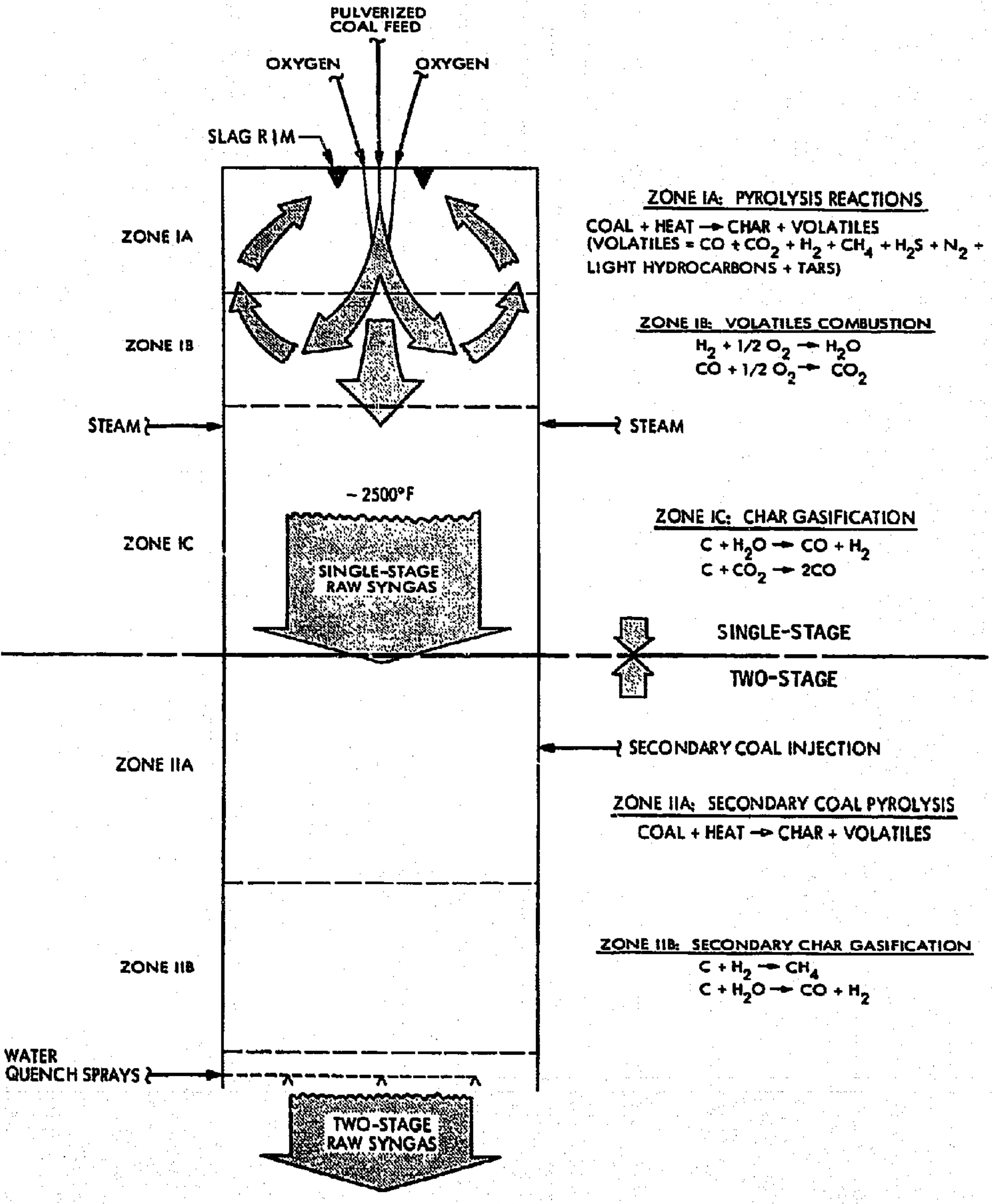


Figure III-9. Schematic of Reaction Fundamentals of Bell's Single-Stage and Secondary Injection HMF Gasifier.

Table III-1: Material Balance for Bell Single-Stage HMF Coal-to-SNG Process

STREAM NO.	1	6	7	9	11	13	14	15	16	19	21	24	102	103	105
STREAM NAME	COAL FROM MINE	DENSE PHASE COAL FEED	O_2 TO GASIF	PROCESS STEAM TO GASIF	REACTOR SYNGAS	SEA. HOT SYNGAS	BAA. COOLED SYNGAS	CHAR TO BOILERS	SYNGAS FROM CYCLONE	DUST-FREE SYNGAS	SHIFTED SYNGAS	CLEAN SYNGAS	SNG TO PIPELINE	SULFUR	SOLIDS TO DISPOSAL
COMPONENTS, lb-mol hr															
CO	-	-	-	-	70,047	70,047	70,047	-	70,047	70,047	27,167	27,167	-	-	-
CO_2	-	2,948	-	-	5,032	5,032	5,032		5,032	5,032	47,912	570	570	-	-
H_2	-	-	-	-	38,631	38,631	38,631	-	38,631	38,631	81,511	81,511	10	-	-
CH_4	-	-	-	-	15	15	15	-	15	15	15	15	27,182	-	-
C_2H_6	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
C_6H_6(OR BTX)	-	-	-	-	-	-		-		-	-	-	-	-	-
H_2S	-	-	-	-	1,787	1,787	1,787	-	1,787	1,787	1,787	-	-	-	-
COS	-	-	-	-			-	-	-	-	-	-	-	-	-
SO_2	-		-	-	-	-		-	-	-	-	-	-	-	-
NH_3	-	-	-	-	16	16	16		16	16	-	-	-	-	-
N_2	-	-	147	-	830	830	830		830	830	830	830	830	-	-
O_2		-	30,120	-	-	-	-		-	-	-	-	-	-	-
SUBTOTAL-DRY	-	2,948	30,267	-	116,344	116,344	116,344	-	116,344	116,344	159,222	110,093	28,597	-	-
H_2O	4,838	1,523		12,217	8,752	28,208	28,208	-	28,208	41,936	324	5	5	-	3,083
TOTAL GAS + LIQUIDS, lb-mol hr	4,838	4,471	30,267	12,217	125,096	144,552	144,552	-	144,552	158,280	159,546	110,098	28,597	-	3,083
lbs hr	87,162	157,180	967,958	238,124	2,502,886	2,654,006	2,654,006	-	2,654,006	3,101,330	3,124,106	973,944	484,503	-	55,543
SOLIDS, lbs hr															
MAF (COAL, CHAR, SULFUR)	1,235,920	1,235,920	-	-	96,596	96,596	96,596	96,596		-	-	-	-	57,355	-
ASH (MINERAL MATTER)	129,618	129,618	-	-	129,118	12,972	12,972	12,429	543	-	-	-	-	-	129,618
TOTAL SOLIDS, lbs hr	1,365,538	1,365,538	-	-	225,714	109,568	109,568	109,025	543	-	-	-	-	57,355	129,618
TOTAL (GAS, LIQ, SOL) lbs hr	1,452,700	1,522,718	967,958	238,124	2,728,600	2,763,574	2,763,574	137,075	2,654,549	3,101,330	3,124,106	973,944	484,503	57,355	185,161
MMSCFD - GAS	-	-	275.67	120.30	1,138.97	1,316.58	1,316.58	-	1,316.58	1,441.61	1,453.14	1,002.77	260.46	-	-
MOLE WEIGHT - GAS	-	-	31.98	18.02	20.01	19.74	19.74	-	19.74	19.59	19.58	8.85	16.94	-	-
TEMPERATURE, °F	77	77	77	530	2530	1900	600	600	600	345	100	100	100	280	-
PRESSURE, psia	14.7	601	600	600	500	498	498	488	488	470	450	430	1000	147	-

TABLE III-2: Effect of Potential Improvements of the Bell HMF Gasifier to be Investigated by Bell.

Case No.	1	2	3	4
Description	Single-Stage (Base Case)	Single-Stage + Char Recycle	Secondary Injection	Secondary Injection + Char Recycle
% Carbon Conversion	90%	90%	Information is proprietary at this time	
% Carbon Utilization	100%	100%	same as above	
O_2 to Dry Coal Weight Ratio	0.71	Proprietary	same as above	
Flue Gas Desulfurization Required	NO	YES	same as above	
Relative Gas Cost	1.0	1.01	0.92	0.91
Relative Capital Cost	1.0	1.03	0.87	0.89
Relative Operating Cost	1.0	1.0	0.95	0.93

TABLE III-3: Base Case Gas Cost Sensitivity to Critical Assumptions

Alternate Description	CRITICAL ASSUMPTIONS			Relative Gas Cost
	% Carbon Conversation @ O_2/Coal Ratio	Ungasified Carbon is Recovered as Char for Boiler Fuel	Char is Sulfur Free	
o Base Case	90% @ 0.71	YES	YES	1.0
o Base Case with present conversion data	80% @ 0.85	YES	YES	1.16
o Base Case with char discarded	90% @ 0.71	NO	YES	1.06
o Base Case with sulfur in char	90% @ 0.71	YES	NO (requiring FGD Unit)	1.02

Table III-4: Bell-HMF Gasifier Data

	SELECTED TEST DATA			PROJECTED YIELDS BASED ON OBSERVED TRENDS	
	AIR BLOWN DATA		O_2 BLOWN		
COAL:	N. DAKOTA LIGNITE	MONTANA ROSEBUD	PITTSBURGH SEAM	W. KENT.	
INJECTOR CONFIGURATION:	IMPING SHEET	IMPING SHEET	NOTE (1) DATA IS PROPRIETARY AT THIS TIME	IMPING SHEET	
RUN No.:	3106	3110		-	
REACTOR PRESSURE (psia):	218	186		500	
REACTOR TEMPERATURE (°F):	~2400	~2600		2500	
RUN DURATION (min):	30	60		-	
AIR/DRY COAL AVG (lb/lb):	3.5	3.6		NONE	
OXYGEN/DRY COAL (lb/lb):	-	-		0.71	
STEAM/DRY COAL (lb/lb):	-	-		0.20	
AVG REACTOR MASS FLUX (lb/hr/ft^3):	10,400	10,300		≈5,000	
SUPERFICIAL GAS RES. TIME (ms):	80	80		350	
AVG GASIFIER EFFLUENT GAS COMPOSITION (VOLUME PERCENT) NOTE (2) CH_4	0.1	0.2		0.01	
H_2	8.1	6.8		30.90	
N_2	61.4	64.0		0.66	
CO	22.0	20.0		56.02	
CO_2	8.6	8.9		4.02	NOTE (3)
H_2O	NOT ANALYZED	NOT ANALYZED		6.96	
H_2S	NOT ANALYZED	NOT ANALYZED		1.43	
COS	NOT ANALYZED	NOT ANALYZED		-	
NH_3	TR	TR		-	
AVG CARBON CONVERSION: (% OF CARBON IN COAL IN GAS PHASE)	90	80		90	
AVG COLD GAS EFFICIENCY: $100\% \times \left(\frac{\text{HHV OF CO, } H_2 + CH_4 \text{ IN EFFL GAS}}{\text{HHV OF COAL FEED}}\right)$	55	45		78	
AVG GAS HHV (BTU/DRY SCF):	98	88		301	
UNGASIFIED CARBON, ASH AND SLAG					
% UNGASIFIED CARBON TO CHAR:	10%	20%		10%	
% ASH IN COAL RECOVERED IN SLAG TANK:	NOT ANALYZED	NOT ANALYZED		90%	
% ASH IN COAL RECOVERED IN CHAR:	NOT ANALYZED	NOT ANALYZED		10%	
CHAR ANALYSES (WT %) ASH: CARBON:	NOT ANALYZED	NOT ANALYZED		11% 89%	

NOTES:

(1) Data not available on Pittsburgh seam tests

(2) Gas compositions averaged from several samples during test with CH_4, H_2, N_2, CO, and CO_2 only gases analyzed

(3) Includes 2.31% CO_2 as pressurizing gas in coal feed