4.0 TECHNICAL REVIEW

One of the purposes of this study is to make a technical appraisal of all processes covered. Since the processes are in various stages of development, this part of the study should lend further insight into the ultimate prospects for commercial success.

As a general comment it is felt that any fully integrated process that can be operated continuously on a small scale can be made to succeed on a large scale. There are no impediments to commercialization due to lack of control or analytical equipment. At present, no needs exist to develop special devices to accomplish coal conversion. There will always be possibilities for improvement but no noticeable change in coal conversion viability or economics is expected from instrumentation developments.

The areas where significant development could affect commercial prospects include:

1. Methods to allow more coal types to be used effectively.
2. Improved practical systems to achieve maximum recovery of usable energy.
3. Reactor and process improvements to achieve better yields and greater product selectivity.
4. Improved chemistry to reduce environmental problems further and cheaper.
5. Improved high-temperature gas turbine materials technology.
6. Better hot gas cleaning processes.

The first item would enhance application. All the subsequent improvements would result in lower cost for the product.

4.1 PROCESS COMPLEXITY

All of the processes studied for this report were analyzed to determine both the common and the singular features. Most had many common unit operations and comparable overall complexity. A list of significant considerations which have been factors in process development to-date was prepared. To this were added items which do differentiate some of the processes to a degree that labor requirement or reliability for an actual plant could be affected. The list used and values for Process Complexity are shown in Table 4.1.

It is apparent from the list of considerations used to develop the Process Complexity Index that the items are not of equal weight. Thus the Complexity Index values show a number for identified complexities but should not be construed to be directly proportional to operational difficulty, reliability or labor requirements. It is apparent that many unit operations common to practically all of the processes are not included on the list. This is particularly true for proven operations used in existing process industries. There are many examples of distillation columns, acid gas removal-regeneration systems and Claus plants that operate with relatively little attention.

The reasoning behind the items used to determine complexity is as follows:

- High Pressure and Temperature: Relatively more difficult conditions and possible material-construction problems.
- Ebullated or Fluidized Bed: More sophisticated system with greater start-up difficulty and less forgiving to changes in operating conditions.
- Ash Fusion: Can lead to unreliable performance and reactor shutdown.
- Recycle Pump or Compressor: Recycle fluid streams can contain higher residual solids leading to seal leakage and erosion. In the case of H-coal, the internal recycle pump can give severe maintenance problems. These items are high energy users if heads are high.
- Solid-Fuel Separation: Not always a problem - depends on actual values for density difference or fluid properties.
- Solids Handling: Solids handling always entails higher maintenance and less reliability than comparable for fluids.
- Power Turbine: These equipment items are still being developed and subject to damage by process upsets.
- Oxygen: A potentially dangerous material requiring extreme and continuing safety precautions.
- Tar Products: Viscous liquids that sometimes cause line plugging problems and general handling and disposal problems.
- Chemical Complexity: Highly sensitive reactions or fragile catalysts.
- Fired Preheater: Subject to coking and tube damage directly affecting equipment reliability.

Table 4.1: PROCESS COMPLEXITY

Item	SRC-I	SRC-II	EDS	H-Coal	F-T	M-Gas	HYGAS	Synthane	CO_2 Acc	Lurgi	Bigas	West	CE
1. Highest Pressure of Group				X							X		
2. Highest Temperature of Group							X	X	X			X	X
3. Ebullated or Fluidized Bed				X			X	X	X			X	
4. Multi-Fluidized Beds							X	X	X				
5. Ash Fusion Problems										X	X		
6. Cumbersome Recycle Pump or Compressor				X		X	X						
7. Solid-Fluid Separation Problem	X						X	X			X		
8. Signficiant Solids Handling	X							X	X		X		
9. Power Turbine Critical to Cycle												X	X
10. Oxygen Used in Process							X	X		X	X		
11. Tar Products					X			?		X			
12. Chemical Reaction Complexity			X		X	X							
13. Fired Preheater Used	X	X	X	X									
Complexity Value	3	1	2	4	2	2	6	6	4	3	5	3	2

(Note that a lower value indicates less complexity. The items shown do not have equal importance and thus the Complexity Value scale is not linear and may not be monotonous.)

Even though the table shown for compexity can have qualitative value, it is clear that this comparison alone can not be used to choose or eliminate a process.

4.1.1 Reactor Comparison

Because the reactor system is the chief area where differences exist between competing processes, the subject requires special study. The reactors are where the highest temperatures and pressures occur and where most of the materials-of-construction problems are found.

Because of the higher mobility of gases than liquids within a reactor vessel, and the presence of 3 phases, from a transport phenomena standpoint, all gas reactors tend to be more complex internally than liquid phase reactor systems. This is in addition to the higher operating temperature associated with coal gasification reactors. Thus, generally all of the gasification reactors are more complex than any of the liquefaction reactors. Within the group of gasification reactors, those with all three phases normally present must be judged the most complex. This touches on the key to coal handling problems (due to caking) and the belief that the Bigas process is probably not viable due to continuing slag removal difficulties.

Fluid beds are considered more complex than other types of solids contacting systems. They are, furthermore, constrained with respect to process modulation compared with non-fluid bed reactors. The other general reactor problem is bypassing within the vessel. This is a recognized area where good design is required. However, simple and economical methods such as baffle use or nozzle modification can reduce problems from this source.

Particular reactor problems encountered with some of the various processes will be discussed below in Section 4.2. Table 4.2 shows conditions in the reactor. The actual values during operation may vary for different coals. Data shown are from reports by the process developers.

Table 4.2: **REACTOR CONDITIONS**

Process	Reactor Type	Temperature $^{\circ}$C in/bulk/mix	Pressure ATM Normal/Max.	Recycle Phase	Coal Residence Time	H_2 Consumption
SRC - I	Empty Dissolver	450	120	Liquid Solvent & H_2 Gas	0.5 hrs	8 MSCF/ton coal
SRC - II	Empty Dissolver	/460/	130/	Liquid with Unreacted solids & H_2 Gas	1.0 hrs.	17 MSCF/TON Coal (oxygen = 5.3 MSCF/ton coal)
EDS	Empty Dissolver	450/450/450	135/	Unspecified H_2 Gas Stream	36 min.	11.1 MSCF/ton coal
H-Coal Fuel Oil	Ebullated Bed of Solid Catalyst	355/455/	205	Liquid & Gas	N/A	13.8 MSCF/ton coal
H-Coal Syncrude		355/455/	205	Liquid & Gas	N/A	18.5 MSCF/ton coal
Fischer-Tropsch	Fluid Bed or Fixed Bed of Catalyst	180/335/	28/	Gas Internal Recycle	Depends on gasifier	H_2 used for catalyst reduction only
M-Gasoline	Fluid Bed or Fixed Bed of Catalyst	N/A	N/A	None	Depends on gasifier	No separate H_2 production

Table 4.2: REACTOR CONDITIONS
(continued)

Process	Reactor Type	Temperature° C in/Bulk/Max.	Pressure ATM Normal/Max.	Recycle Phase	Coal Residence Time	H_2 Consumption
CO_2 Acceptor	Fluidized Bed Hi Btu Low Btu	830/1010/	8/10	Solid Acceptor	N/A	None None
Hygas	Fluidized Bed 4 stages in one vessel	300/725	69/	Oil Slurry	75 min.	O_2 = 141 lbs/ton coal (Maximum)
Bigas	2 Stage Entrained Bed	900	83/		N/A	O_2 = 249lbs/ton coal
Synthane	Fluid Bed	980	68/	Steam	N/A	O_2 = 254lbs/ton coal
Lurgi	Fixed Bed	620/850	24/32	None	1 hr.	O_2 = 315lbs/ton coal
Combustion Engineering	Entrained Bed	920/1760/	1	Solid Ash + Carbon	2½ seconds	None
Westinghouse	Fluid Bed	700/1100/1500	18	None	N/A	(Syngas O_2=1,148 lbs/ton)

N/A = Not available

4.2 PROCESS COMPARISONS

The coal conversion processes must be compared and evaluated from both a technical and an economic standpoint. The two approaches will necessarily be interdependent and the ultimate goal is to develop the most inexpensive substitutes for raw coals, natural gas and petroleum fuels. The purpose for process comparison is to determine which of the options have the best prospects and should be pursued and optimized. The national needs are for processes which:

1. Provide affordable, abundant fuels.
2. Minimize waste of existing resources.
3. Accomplish the conversion with acceptable environmental impact.

The required additional processing to meet existing environmental standards is included in all processes and costs shown. For a number of the cases, the primary reason for the processing of the coal is to produce a fuel which will be more environmentally acceptable and more economical than conventional coal burning with flue gas scrubbers.

It must be assumed at this stage that no improvements or cost savings will be achieved. It is expected that some improvements will be achieved but these will be largely confined to internal systems and future costs of machinery due to experience and production economics. There are many who believe that increased demands for further environmental restriction will offset all other hopes for product cost decreases. Hopefully, some progress will be made in the assessment of values achieved and total effects on environment, economy and living standards.

No single measure can pinpoint a best process for coal conversion. Some major users have flexibility in their operations and can utilize any of the energy forms listed in Table 4.5. In other cases the choice is limited to one type of fuel and a product cost from a site specific study is needed to choose the best process.

The various criteria included in Table 4.4 are discussed in Section 2.0 and further below.

4.2.1 Efficiency

Process efficiency is shown in Table 4.4 if it was reported by the design firm for the particular source study used for this report.

The product efficiency was calculated from the product data used for this report. The reason for showing both values is that a significant difference between the two values allows the implication that there are potential process improvements, most likely waste heat recovery and possible conversion to electric power. It should be noted that if all light oil naphtha products were upgraded to gasoline, the product efficiency would decrease.

4.2.2 Process Development Status

The Confidence Index column in Table 4.4 lists a two part alpha-numberic identifier which assigns a level for both process development and economic reliability. As shown in Table 4.3, there are four possible choices for each category.

Table 4.3: Process Confidence Index

Process Development	Economic Reliability
D - Exploratory stage - not beyond simple bench tests	4 - Screening estimate, very approximate
C - Development stage - operated on small integrated scale only	3 - Incomplete definition for estimates used
B - Pre-commercial - successful pilot plant operation	2 - Firm basis for values developed
A - Complete - process demonstrated sufficiently to insure commercial success	1 - Values considered to be satisfactory for commercial venture

The fact that few of the processes studied are rated higher than C-3 is a warning that numbers shown for product cost are not of high reliability. While this often automatically triggers a tendency to add a contingency or "safety factor", it can also hopefully indicate that at least some of the processes should have lower costs with more development work.

Table 4.4: PROCESS SUMMARY

Process	Developer	Primary Product	Secondary Product	Feed Coal Type/Size	Year Begun	Conf. Index	% Efficiency Process/Product	Remarks
SRC - I	Southern Co. Services + EPRI + DOE + Gulf	Solid Boiler Fuel	Naphtha	All types	1962	B-3	71/70	
SRC - II	Gulf + DOE	Liquid Boiler Fuel	Gas LPG Naphtha	All types with ash restrictions	1976	B-4	70/70	
EDS	Exxon	Liquid Boiler Fuel	LPG Naphtha Gas	All acceptable	1966	C-3	66/64	
H-Coal Fuel Oil	HRI	Fuel Oil	Naphtha Gas			C-2	/74	
H-Coal Syncrude		Syncrude				C-2	/69	
Fischer-Tropsch	Standard Technology used over 50 years	Range of Hydrocarbons	LPG Alcohols No. 2 Oil Fuel Oil Gas	All coal is gasified	Before 1930	A-2	/48	Depends on gasifier efficiency
M-Gasoline	Mobil for Methanol to Gasoline Conversion	Premium Gasoline	LPG	Any gasifier to methanol process may be used		C-3	/52	
Methanol		Methanol	—	Depends on gasifier	—	A-2	/57	

Table 4.4: PROCESS SUMMARY
(continued)

Process	Developer	Primary Product	Secondary Product	Feed Coal Type/Size	Year Begun	Conf. Index	% Efficiency Process/Product	Remarks
CO_2 Acceptor	Conoco Coal Development Co.	High Btu Gas Low Btu Gas	None	Lignite or Sub-Bituminous /8x100 mesh	1968	B-2	68/67	Claimed to be the only fluidized bed process that can handle lignites
Hygas	IGT	High Btu Gas	Naphtha	All with pretreat	1954	C-3	78/66	
Bigas	Bituminous Coal Research	High Btu Gas	None	All	1963	C-4	64/60	
Synthane	BuMines PERC Lummus	High Btu Gas	Char	All/20 to max 20%-200	1961	C-3	65/63	
CE	Combustion Engineering	Low Btu Gas Electric Power	None	All	1974	C-4	/40	
Westinghouse	Westinghouse	Electric Power Medium Btu Gas	None None	All	1972	C-4 C-4	/38.4 /83	Efficiency shown with induction
Lurgi	Lurgi	High Btu Gas	Tar, Oils Char Naphtha Coal Fines	Non-to low caking	Before 1930	A-2	72/59	Based on 1975 FPC application by ANG-analyzed by Stearns-Roger

As suggested above, costs are very important criteria. The cost for product takes into account all significant money and time requirements including capital investment, financing charges, construction period, plant maintenance and expected life. These are explained in further detail in Section 5: Economics. In addition to the values described above, Table 4.4 presents a summary description of key considerations for all of the processes studied.

Further description of the amounts and specifications for delivered products is given in Table 4.5 and Appendix 1.

4.3 PRODUCTS

As discussed above, all of the main products from coal conversion processes are replacements for existing commodities now in the marketplace. The immediate need is to produce products compatible with existing equipment to perform in conformance with all environmental constraints.

Table 4.5 gives a listing of all products produced for each of the processes studied. Any fuels consumed within the plant are not listed. Fuel amounts are shown as barrels (42 gallons/barrel) per operating day for liquids, tons per operating day for solids, and million standard cubic feet per operating day for gases. The last column gives value factors. The value factor, f_i, is the ratio of market value of the actual product produced to gasoline as the reference fuel.

Most of the processes included here are covered by several published reports showing much laboratory data and projected product qualities and quantities. Where the reported results were recent and appeared compatible with the purposes of this study, they were adjusted to the same basis and used. Source reports are identified. For those processes where either recent material balances were not published or if those available were not based on optimum design, the process developer was contacted. An "A" in the data source column of Table 4.5 indicates the information used for energy and material balances was received directly from the process developer. Even though a few of the processes may

Table 4.5: PRODUCTS SUMMARY

BASIS: PLANT FEED RATE = 25,000 TONS/DAY DRY COAL (NOTES 1,2)

Process	Data (5) Source	Product	Quantity B_i Amount/Day	Value Factor Gasoline Reference f_i
SRC-I	B-18	SRC Solid	10,880 Tons	.50
		Fuel Oil	7,500 Bbl	.56
SRC-II	A	LPG	5,500 Bbl	.86
		Naphtha	10,700 Bbl	.82
		Fuel Oil	45,300 Bbl	.56
		Gas	23.1 MMSCF	1.00
EDS	B-5	Propane	3,270 Bbl	1.08
		Butane	3,500 Bbl	1.07
		Naphtha	19,900 Bbl	.82
		Fuel Oil	28,700 Bbl	.56
		C2-Gas	41.9 MMSCF	1.00
H-Coal Fuel Oil	A	Naphtha	18,200 Bbl	.82
		Fuel Oil	42,200 Bbl	.56
		Gas	19.7 MMSCF	1.00
H-Coal Syncrude	A	Naphtha	31,900 Bbl	.82
		Fuel Oil	24,300 Bbl	.56
		Gas	56.3 MMSCF	1.00
F-T	B-19	Gasoline	18,200 Bbl	.90
		LPG	18,800 Bbl	.86
		No. 2 Oil	1,200 Bbl	.82
		Fuel Oil	2,000 Bbl	.56
		Med. Btu Gas	90.7 MMSCF	1.00
		C2-Gas	37.2 MMSCF	1.00
M-Gasoline	B-12	Premium Gasoline	52,700 Bbl	1.00
	20	LPG	7,300 Bbl	.86
Methanol	B-20	Methyl Fuel	113,400 Bbl	.96
		Methanol	8,400 Bbl	1.00
HYGAS	A	SNG	333.8 MMSCF	1.00
		Naphtha	6,800 Bbl	.82
Synthane	B-10	SNG	350.0 MMSCF	1.00
		CHAR	1,344 Tons	.47
CO_2 Acceptor	B-17	SNG	397.9 MMSCF	1.00
LURGI	B-17	SNG	326.4 MMSCF	1.00
		Tar Oil	4,500 Bbl	.85
		Naphtha	2,200 Bbl	.82
BIGAS	B-1	SNG	388.2 MMSCF	1.00
CO_2 Acceptor	B-17	SYNGAS	1143. MMSCF	1.00
Westinghouse	A	SYNGAS	1272 MMSCF	1.00
Westinghouse	A	Electric Power	2625 MW	2.60
CE	A	Electric Power	2838 MW	2.60

NOTES:
1. Source data has been corrected to zero electric power requirement using 10,000 Btu/kWh for on-site generation.
2. Products have been adjusted for source coal HHV to a common basis of 11,200 Btu/LB-Dry.
3. In the above Table, fuel oil means low sulfur boiler fuel comparable to No. 6 oil.
4. Gases shown as MMSCF = Million Standard Cubic Feet (20°C, 1ATM).
5. Data sources: A - Direct data from process developer.
   B - Obtained from published report cited.

include an optimistic bias as to product yields, no bases for adjustment is available and thus the data was used as presented.

4.3.1 Solid Products

The general public will undoubtedly continue the aversion to the use of solid coal and solid derivatives for residential heating. This attitude was a factor in the 40-year shift to oil and gas. Labor savings and better system reliability are major reasons for the preference. It would require a significant cost incentive to encourage greater use of solvent refined coal solid or char for home heating. On the other hand, the utility and large industrial market is a realistic goal for solids. Far less cost incentive is required to win these markets.

4.3.2 Liquid Products

The major markets for liquid coal derivatives are boiler fuel and transportation fuels. The specifications for the products will necessarily make their use environmentally acceptable. The major national benefit will be reduced dependence on imported petroleum.

Liquids have advantages over other energy products in being both economical to transport and store. The liquids produced are close enough to petroleum products to be able to totally replace conventional crude oil by coal liquids. Some additional processing would be required to make coal-derived liquids completely interchangeable with all refined petroleum products.

4.3.3 Gaseous Products

The final properties of the product from gasification processes can be varied depending upon the use to be made of the gas. The heating value of gas destined to be used as industrial boiler or process heating fuel, can be as low as 100 Btu/SCF while high-Btu gas for general utility service must have a heating value over 900 Btu/SCF. Similarly, the specifications governing contaminants and diluents, including sulfur compounds and nitrogen, are more flexible for industrial fuel gases.

Nevertheless, good practice requires that the gasification process produce a gas which will not excessively corrode the transportation and utilization equipment and not create unacceptable stack emissions when burned.

While no specific product quality standards exist for comparing low-Btu and intermediate-Btu processes, the gas produced must be coordinated with the proposed use. Thus low-Btu gas which would be used directly in combustion processes must either be of sufficiently high heating value to independently sustain combustion or it must be delivered to the combustor at an elevated temperature. A gasifier system used with a gas turbine must deliver a product free of particulate matter which might damage turbine blades. Synthesis gas used as a chemical feedstock would normally contain a minimum of diluents such as methane or nitrogen in order to maximize the reactive gas (CO and H_2) content. Chemical feedstock gas would also normally be scrubbed to remove all sulfur compounts to avoid catalyst poisoning.

The quality specifications for high-Btu gas have been much more rigidly defined. The primary standard is that the gas must be fully interchangeable with pipeline quality natural gas. Heating values as low as 900 Btu/SCF may be permissable if other quality standards are met and the gas is mixed with natural gas. Some states set minimum quality standards. In addition to heating value, other combustion characteristics must match those of natural gas. These properties, lifting, flashback and yellow tipping, are affected by the chemical constituents but, so long as methane constitutes most of the combustible gas content, these requirements are easily met. Sulfur compounds and carbon monoxide are the contaminants most often found in high-Btu gas. Carbon monoxide concentration is limited to 0.1 volume percent while total sulfur content may not exceed 10 grains/100 SCF. Hydrogen sulfide is objectionable even in low concentrations. The allowable level is 0.25 grains/100 SCF. Water is objectionable in that it may cause corrosion in pipeline systems. Normal moisture content acceptable for pipelines is 7.0 lbs. of water per million SCF.

4.3.4 By-Products

By-products are produced in significant quantities by conversion plants processing 25,000 tons/day of coal. Except for a few special cases, most of the processes export pure sulfur and ammonia as convenient forms to dispose of the sulfur and nitrogen from the raw coal. These are salable products with ammonia in particular having a place in the fertilizer market.

Some capital investment and expense will be involved in marketing and shipping these materials. At the least, the net disposal of by-products should not add to the cost of plant fuel products. At most, the amount of by-products is small and even if high market prices are obtained by current standards, the effect will not reduce major product price from the plant by as much as five percent.

4.3.5 Power

Two of the processes studied, CE and Westinghouse, are specifically designed to produce electrical power as the final product. Electricity is a premium form of energy and assignment of appropriate value is discussed later.

For coal conversion process designs that require electric power import, adjustment of products and capital are made to allow for on-site generation of all required power via coal burning to generate steam for driving turbine-generators. Most of the processes were essentially power independent due to effective waste heat recovery.