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ADVANCED STAGED COMBUSTION SYSTEM FOR POWER GENERATION

by

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ADVANCED STAGED COMBUSTION SYSTEM FOR POWER GENERATION

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ABSTRACT

To respond to the increasing market need for a new generation of plants with a substantial improvement in efficiency and a reduction in capital cost, the Institute of Gas Technology has developed an advanced staged, fluidized-bed combustion system concept. The staged fluidized-bed partial combustor produces the fuel gas at about 1500°F. The fuel gas, after particulate removal, is directed to a gas turbine followed by a steam cycle. Adequate sulfur capture and solids waste stabilization are attained by separating calcination, carbonization, and gasification/combustion steps in the staged fluidized beds. Intermediate gas cooling is avoided during the process to maximize the power production. The coal-to-electricity conversion efficiency of the system approaches 49 percent, which exceeds the efficiencies of the other emerging technologies.

INTRODUCTION

There exists a market need for a new generation of plants that can operate with substantially improved efficiencies and availabilities. In addition, this new breed of plants must be considerably simpler than those being currently used commercially. The capital cost, construction lead times, ability to accept lower quality fuels, ability to meet present and future New Source Performance Standards (NSPS), modular construction, and lower risk of surplus capacity play a decisive role in determining which of the new technologies will penetrate the utility market.

The current developments in Integrated Gasification Combined Cycle (IGCC), as well as Second Generation Pressurized Fluidized-Bed Combustion (PFBC), are responses to these needs of the marketplace. However, these developments are still impeded by the complex nature of the systems. For example, in the IGCC system application for a high-sulfur coal, the issues of sulfur capture and solid waste stabilization still remain to be resolved. In the PFBC system (Robertson *et al.*), the complex relationship between the gasification/carbonization step and the combustion step (which determines the plant efficiency), as well as a complex system for solids transfer between the stages, tends to block its acceptance in the marketplace.

The system presented here improves upon the developing technologies in the areas of solids transfer, simplicity in design and concept, and solid waste stabilization, while increasing the efficiency of the process. The elimination of a large number of processing steps from the emerging technologies makes this Advanced Staged Combustion scheme attractive in terms of capital cost and operating costs, and subsequently in terms of a reduction in the cost of electricity.

The targets for the new development include a 49 percent efficiency (based on the higher heating value of coal) and a cost of electricity at least 20 percent lower than that of a conventional Pulverized Coal (PC) combustion plant with a stack gas scrubber. The current scheme utilizes data already available in the literature: coal carbonization (Rehmat and Goyal, 1987; Rehmat *et al.*, 1989; Goyal *et al.*, 1989b), *in-situ* sulfur capture (Goyal *et al.*, 1990), and char gasification (Patel, 1980; Leppin and

Goyal, 1981; Goyal *et al.*, 1989a). As a result, the development time for this generating plant will be minimized.

PLANT CONCEPT

The proposed plant concept for the Advanced Staged Combustion System (ASCS) is shown in Figure 1. Essentially, coal is fed to the pressurized partial coal combustor to produce a low-Btu gas. After passing through a filter to remove entrained particles, the fuel gas is fired in the gas turbine to produce energy to drive the gas turbine. The gas turbine drives a generator and a compressor that feeds air to the partial combustor and the turbine combustor. Steam generated in the heat recovery steam generator (HRSG) downstream of the gas turbine drives the steam turbine generator that produces the balance of the electric power.

The key component of the Advanced Staged Combustion System for generating electricity from coal consists of a specially designed staged fluidized-bed partial combustor (Figure 2), which provides the main functions of partially combusting incoming coal, maximizing retention of sulfur in the solid residue, maximizing evolution of fuel-bound nitrogen as molecular nitrogen (thus preventing formation of oxides of nitrogen in the later stages), producing environmentally benign residue, and retaining maximum heat in the fuel gas in the form of sensible and chemical heat for generating power from a relatively more efficient gas turbine prior to utilizing residual heat in the relatively less efficient steam cycle. The fuel gas exits the staged partial combustor at a temperature of about 1500°F and passes through a barrier filter, which removes elutriated fines from the fuel gas, before entering gas turbine combustor and subsequently the gas turbine. Depending upon the gas turbine employed, the partial combustor will operate at pressures between 10 and 20 atmospheres. The description of the partial combustor follows.

DESCRIPTION OF THE STAGED FLUIDIZED-BED PARTIAL COMBUSTOR

The fluidized-bed partial-combustor vessel (Figure 2) is comprised of three stacked fluidized-bed stages, referred to here as the calcination-stage upper fluidized bed, the carbonization-stage middle fluidized bed, and the char combustion/gasification-stage lower fluidized bed.

The fluidizing air is supplied to each stage from a turbine compressor using booster air compressors that take inlet air from the turbine compressor. This hot air is first cooled by indirectly raising process steam before entering the booster compressor. In this way, the air temperature is reduced to minimize the compressor power requirements while supplying steam to the lower combustor stage for temperature control. Of the total stiochiometric air needed for the overall combustion in the system, only 30 percent is used for the partial staged combustor. All other air, including the necessary excess air for combustion, is directed to the turbine combustor to burn the fuel gas produced from the partial staged combustor.

Calcination Stage

In the upper fluidized-bed calcination stage, crushed sorbent (limestone or dolomite) is added using a gravity feed system. The feed rate is controlled by a variable-speed rotary feeder. The sorbent is heated from ambient temperature to about 1500°F utilizing the heat contained in the fuel gas rising from the fluidized-bed carbonization stage below. The primary purpose of this fluidized-bed stage is to calcine the sorbent feed and recuperate heat. The quantity of sorbent introduced is such that the molar ratio of calcium in the sorbent to sulfur in the coal is about 1.5 to 2.0.

The two main reactions occurring in the calcination stage with the sorbent (limestone and/or dolomite) are as follows:

$$CaCO_3 \xrightarrow{\text{Heat}} CaO + CO_2 \quad (1)$$

$$CaCO_3{\bullet}MgCO_3 \xrightarrow{\text{Heat}} CaO{\bullet}MgO + 2CO_2 \quad (2)$$

With the fuel gas entering this stage from the carbonizer at 1600° to 1700°F and with the addition of some air, a complete calcination of the sorbent is expected if permitted by equilibrium, depending upon the operating pressure and the composition of gases entering this stage. The calcination in this stage utilizes the sensible heat in the gas from the middle stage to calcine the sorbent, thereby increasing the overall thermal efficiency of the system as well as eliminating the need to cool the fuel gas before filtering.

The heated and/or calcined sorbent from this fluidized-bed stage is transferred into the middle fluidized-bed carbonization stage via simple overflow pipes. The bed level in the upper stage can be controlled through the use of these overflow pipes and the sorbent feed rate.

The calcination stage also serves a secondary purpose of further reducing the sulfur in the fuel gas by acting as a scrubber. The 1500°F fuel gas passing through this calcination stage will be expected to lose most of the remaining sulfur not removed in the middle carbonizer stage according to these reactions:

$$CaO + H_2S \rightarrow CaS + H_2O \quad (3)$$

or

$$CaCO_3 + H_2S \rightarrow CaS + CO_2 + H_2O \quad (4)$$

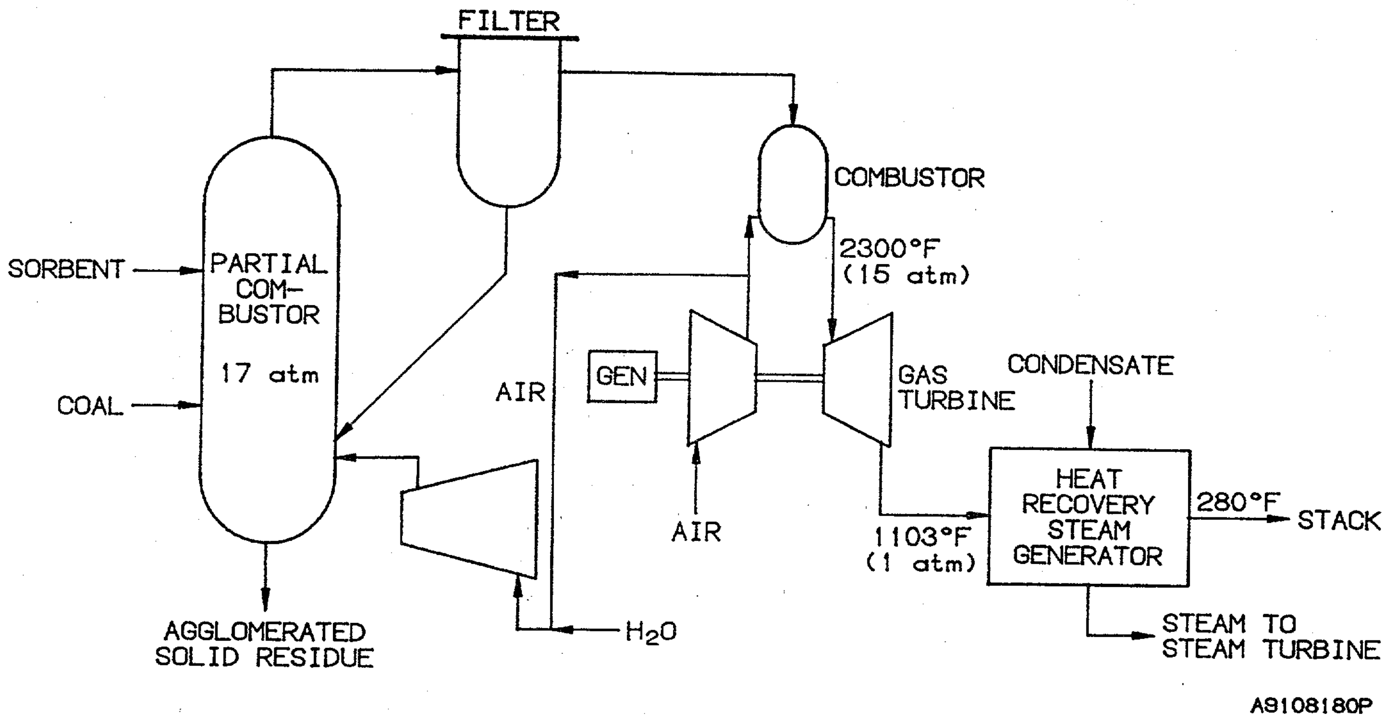

Figure 1. SCHEMATIC DIAGRAM OF ADVANCED STAGED COMBUSTION SYSTEM FOR POWER GENERATION

The upper calcination stage also acts as a gas filter, removing trace quantities of tars and oils present in the fuel gas. Very little tars and oils are expected in the fuel gas because of the high temperatures of the lower two stages. However, the remainder of the surviving tars will be cracked by the sorbent according to the following reaction:

$$\text{tar} \xrightarrow{\text{Ca}} C + CH_4 + \text{other HC} \qquad (5)$$

To prevent elutriation of the sorbent from this calcination bed, mechanical impingement separators are installed above this bed.

Alternatively, the upper fluidized-bed stage can be replaced by a cyclone through which the sorbent and additional air (as needed) are introduced to maintain the exit fuel gas temperature of about 1500°F (Figure 3). The preheated and/or calcined sorbent is collected by the cyclone and returned to the middle carbonizer stage.

Carbonization Stage

Coal from the bunkers is fed through variable-speed screw feeders and pneumatically conveyed using compressed air into the middle fluidized-bed carbonization stage. The coal size is not critical, but the preferred coal size is 1/4 inch X 0.

The sensible heat of the gas from the lower combustion stage and the addition of some air to this stage are used to maintain a temperature of about 1600° to 1700°F in the middle carbonizer stage. The primary purpose of this stage is to capture sulfur and carbonize (devolatilize) coal. About 10 percent of the stiochiometric combustion air is required in this stage.

At a controlled temperature of about 1600° to 1700°F and in reducing conditions, sulfur-bearing molecules undergo a reaction to produce H_2S. The ability to control the temperature of this coal carbonization stage independently of the other stages permits sulfur capture to be maximized according to the reactions shown in Equations 3 and 4 above.

Furthermore, in the temperature range of about 1600° to 1700°F, up to 90 percent of the nitrogen in the coal (depending on coal type) is released. Because reducing conditions are present, the fuel nitrogen is released as molecular nitrogen, ammonia (NH_3), amines (RNH_2), and cyanide (HCN). The quantities of these nitrogen by-products depend largely on the coal type being used. However, based on the available data, up to 75 percent of this nitrogen ends up as molecular nitrogen.

The hot gases produced in this stage pass through the upper calcination stage, whereas the char and spent sorbent containing calcium sulfide are transferred to the lower combustion/gasification stage.

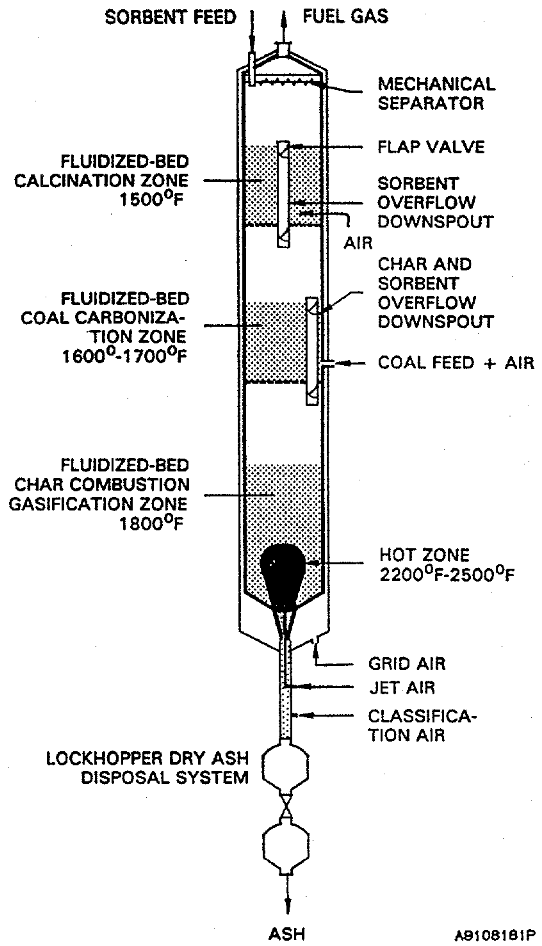

Figure 2. STAGED FLUIDIZED-BED PARTIAL COMBUSTOR

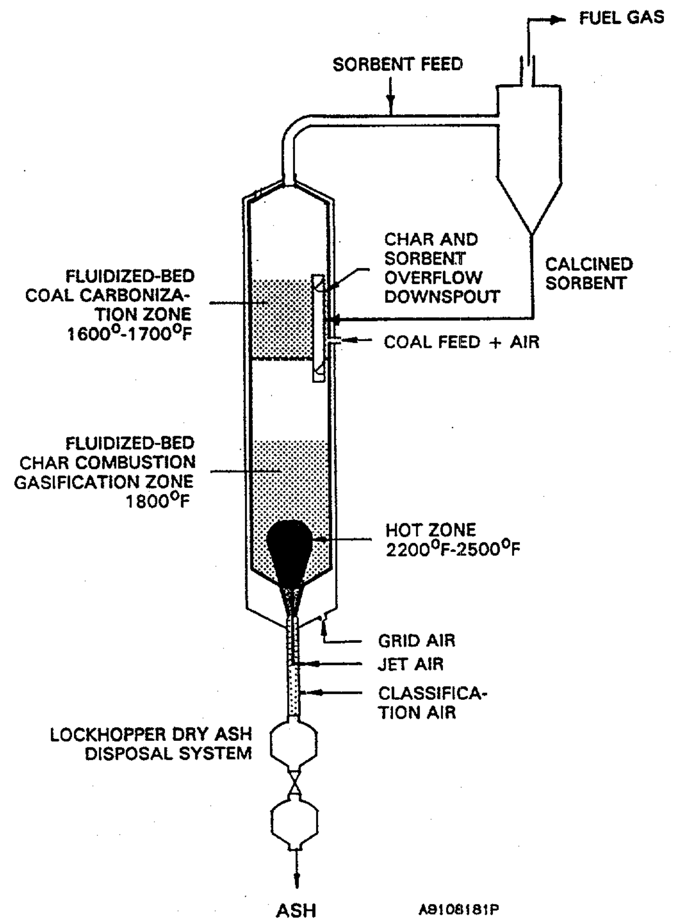

Figure 3. PARTIAL COMBUSTOR WITH CYCLONIC CALCINER

Char Combustion/Gasification Stage

The devolatilized and desulfurized coal char from the middle carbonizer stage enters this lower combustion stage again via simple overflow pipes. Unreacted CaO, $CaCO_3$, and CaS are also transferred down to this combustor stage. Combustion/gasification of the char occurs in this stage at a substoichiometric air-to-coal ratio. Less than 25 percent of the required oxygen for complete stoichiometric combustion is supplied to this stage.

The temperature in this combustor stage is maintained at approximately 1800°F. The actual temperature of the bed will depend primarily on the type of coal. This combustor stage has a central zone in which sodium-based flux could be introduced to reduce the fusion temperature of the ash/spent sorbent mixture and to produce glass from the solid residue. The formation of glass stabilizes the residue and therefore no further treatment is necessary. The temperature control in this lower stage is provided by the endothermic carbon steam reaction, thus eliminating the need for in-bed heat-transfer surfaces.

Approximately 90 to 95 percent of the sulfur present in the coal is captured in the partial combustor; the extent of this capture depends largely upon equilibrium constraints.

The fuel gas emanating from the staged partial combustor is passed through a barrier filter. The clean fuel gas is then directed to the turbine while the captured fines are directed into the lower combustion stage for vitrification.

ADVANTAGES

The advantages of the Advanced Staged Combustion System can be summarized as follows:

- Simplicity
- High coal-to-electricity conversion efficiency -- approaching 49 percent

- Environmental superiority -- integrated solid waste stabilization and reduction in NO_x through air and fuel staging
- Favorable economics
- No heat-transfer tubes in the fluidized bed
- Minimum development requirement
- Modular construction.

These and other advantages will become apparent in the next section, where the current technology is compared with other emerging technologies.

COMPARISON WITH OTHER DEVELOPING TECHNOLOGIES

Table 1 summarizes the distinguishing features of the Advanced Staged Combustion concept over Integrated Gasification Combined Cycle (IGCC) as well as Second Generation Pressurized Fluidized-Bed Combustion (PFBC) systems. The primary drivers for the development of the advanced staged combustor include superior coal-to-electricity conversion efficiency, simplicity in overall plant design, reduced capital cost, and superior waste disposal. These advantages, combined with minimum development requirements, make it a very attractive candidate for meeting the current and future needs of the utility market.

POWER GENERATION AND EFFICIENCY

The power generation and efficiency calculations are based on a turbine operating with a 2300°F inlet temperature. The turbine exhaust gas is cooled to a 280°F stack temperature via an HRSG producing 2400 psig/1000°F steam for the steam cycle.

The material and energy balance for the partial combustor shown in Figure 4 is based on 1000 pounds of moisture-free Illinois No. 6 bituminous coal (Table 2) along with limestone (Table 3) for *in-situ* sulfur capture. The operating pressure is 17 atmospheres to facilitate the 14:1 pressure ratio in the gas turbine. The fuel gas emerges from the combustor at 1500°F, which is also the temperature of the calcination stage. The carbonization stage operates at 1650°F, while the bottom combustor/gasifier operates at 1800°F. The limestone is added to the unit such that the Ca/S ratio is maintained at 1.75 mole/mole.

The air temperature from the turbine compressor is 711°F. This air is cooled by indirectly raising process steam before recompressing in the booster compressor. Enough steam is raised to maintain the steam-to-feed carbon ratio of 0.3 mole/mole in the bottom combustion/gasification stage. Before flashing, the boiler feed water recovers the heat from the solid waste such that the temperature of the solids discharge drops to below 250°F. The overall carbon conversion is assumed to be a conservative 95 percent. The solid waste consisting of ash, CaS, CaO, and $CaCO_3$ is vitrified into glass for stabilization by adding a sodium-based flux into the bottom stage.

The data for deriving the fuel yield from the partial combustor are based on Illinois char gasification as well as coal carbonization developed from the literature (Goyal *et al.*, 1990, 1989a; Leppin and Goyal, 1981; Patel, 1980).

The composition of the fuel gas exiting the partial combustor is given in Table 4; the composition of solid waste discharge is given in Table 5.

Based on a feed rate of 1000 lb/h of moisture-free coal, and the fuel combusted in the turbine combustor at 2300°F, the power generated from the gas turbine is 1247 kW, while the steam turbine yields 411 kW. Thus an overall efficiency approaching 49 percent is realized.

CONCLUSIONS

The development of an Advanced Staged Combustor has definite technical merits based on its simplicity, efficiency, and potential. Although economic comparisons have not been performed so far, it is obvious from the comparison chart in Table 1 that the capital cost requirement for this system will be considerably less than either IGCC or PFBC.

The component that needs to be demonstrated is the solid waste stabilization through vitrification process. The work is proceeding in this area under the sponsorship of the Illinois Clean Coal Institute. The design, economic, and sensitivity studies will be undertaken as needed in support of this development.

ACKNOWLEDGMENTS

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Table 1, Part 1. COMPARISON OF ASCS, IGCC, AND PFBC SYSTEMS*

ASCS	IGCC	PFBC
1. CONCEPT		
a. Involves three stages for total coal combustion	a. Two stages for total coal combustion	a. Three stages for total coal combustion
b. Two stages operate with substoichiometric air; one stage operates with excess air. Best prospect to evolve fuel-bound nitrogen as molecular nitrogen. Almost 90%-95% fuel-bound nitrogen evolves as molecular nitrogen, rest as NH_3 and HCN	b. One stage operates with substoichiometric air; the other stage with excess air. About 10%-25% fuel-bound nitrogen appears as NH_3 and HCN in the first stage	b. One stage operates with substoichiometric air; the remaining two stages operate with excess air. About 10% of fuel-bound nitrogen appears as NH_3 and HCN in the first stage. The fate of residual fuel-bound nitrogen in char is potential NO_x generator in combustion stage
c. One substoichiometric combustion stage operates at 1600°-1700°F (coal carbonization); one substoichiometric stage can operate up to 1800°F; and the combustion stage operates at 2300°F (turbine or topping combustor)	c. The substoichiometric stage operates at 1800° to 1900°F (up to 2300°F in some cases); the combustion stage operates at 2300°F (turbine combustor)	c. The substoichiometric stage operates at 1500°-1700°F (carbonizer); one combustion stage operates at 1500°-1600°F (char combustor); and the final combustor operates at 2300°F (topping combustor)
d. Operating pressure 15-17 atm	d. Operating pressure 15-17 atm	d. Operating pressure 15-17 atm
e. Exit gas temperature of about 1500°F from the reactor system	e. Exit gas temperature 1800°-1900°F (2300°F in some cases)	e. Exit gas temperature 1500°-1700°F from the reactor system
f. Only 30%-35% of overall stoichiometric air used in first two stages	f. About 40% of overall stoichiometric air used in first stage	f. 110%-130% of stoichiometric air used in first two stages
g. Gas heating value ≈150-200 Btu/SCF	g. Gas heating value 110-150 Btu/SCF	g. Gas heating value 150-200 Btu/SCF, exclusive of flue gases from char combustor

* ASCS = Advanced Staged Combustion System; IGCC = Integrated Gasification Combined Cycle System; PFBC = Pressurized Fluidized-Bed Combustion System (Robertson *et al.*, 1990).

Table 1, Part 2. COMPARISON OF ASCS, IGCC, AND PFBC SYSTEMS*

ASCS	IGCC	PFBC
2. GAS CLEANUP		
A. SULFUR		
a. Sulfur is captured *in-situ* for which three stages are provided (calcination, carbonizer, and combustor zones of the reactor). About 90%-95% sulfur is removed using sorbent as additives. No post cleanup	a. Sulfur is captured *in-situ* in a single-stage. Only 80%-85% sulfur is captured with the sorbent. Requires post sulfur removal step	a. *In-situ* sulfur capture is carried out in first two stages yielding capture of 90%-95% sulfur with a sorbent
b. Solid waste is stabilized by encapsulating CaS and coal ash in glassy matrix at 1800°F by addition of fluxes	b. Solid waste is treated in a separate reactor to convert CaS to $CaSO_4$ at maximum temperature of 1650°F	b. Solid waste is stabilized in the second combustion stage in the form of $CaSO_4$ at maximum temperature of 1650°F
c. Post treatment of flue gases from solid waste stabilizer is not required	c. Post treatment of flue gases from auxiliary waste stabilizer combustor may be necessary	c. Post treatment of flue gases from combustor may be necessary
B. PARTICULATE REMOVAL		
a. Based on total product of combustion, only 10% of stoichiometric combustion gases required to be filtered	a. About 10%-15% of stoichiometric combustion gases need to be filtered	a. 110%-130% of stoichiometric combustion gases need to be filtered
b. Gases are not required to be cooled prior to filtration	b. Gases are cooled to 1000° to 1100°F before filtration	b. Gases are not cooled prior to filtration
3. MECHANICAL		
a. A single reactor utilizing simple solid overflow pipes for solids transfer	a. Two rector trains, one for substoichiometric combustion and other for solid waste stabilization	a. Two reactor trains interconnected with complex solid-transfer loops
b. Utilizes proven gas distributor for ash/sorbent agglomeration and stabilization	b. Not applicable	b. Not applicable

* ASCS = Advanced Staged Combustion System; IGCC = Integrated Gasification Combined Cycle System; PFBC = Pressurized Fluidized-Bed Combustion System (Robertson *et al.*, 1990).

Table 1, Part 3. COMPARISON OF ASCS, IGCC, AND PFBC SYSTEMS*

ASCS	IGCC	PFBC
3. MECHANICAL, Cont.		
c. Front-end system consists simply of one reactor, one cyclone, and one filter -- no heat-recovery system required	c. Front-end system consists of one reactor, two cyclones, one to two filters, post desulfurization system, ash combustor, solid-transfer system, and extensive heat-recovery system	c. Front-end system consists of two reactor systems, two cyclones, two filters, solid-transfer system, and heat-recovery system
d. Dry solid waste with little or no fines	d. Dry solid waste with considerable fines	d. Dry solid waste with considerable fines
e. No in-bed heat-transfer surfaces required	e. No in-bed heat-transfer surfaces required	e. Requires extensive in-bed heat-transfer surfaces
4. POWER GENERATION		
a. Utilizes 2300°F gas turbine technology	a. Utilizes 2300°F gas turbine technology	a. Utilizes 2300°F gas turbine technology
b. All coal heat is directed first to gas turbine followed by power generation in steam cycle. This is because gas is not required to be cooled prior to its ultimate combustion in turbine combustor	b. Sizeable quantity of heat is directed to steam cycle prior to power generation because gas from first-stage sub-stoichiometric combustion requires considerable cooling prior to post gas treatment	b. Sizeable quantity of heat is directed to steam cycle prior to gas turbine since large quantity of heat is generated in the char combustor
c. Overall coal-to-electricity conversion efficiency of up to 49%	c. Overall coal-to-electricity conversion efficiency of up to 42%	c. Overall coal-to-electricity conversion efficiency of up to 45%
5. CAPITAL COST		
a. Minimum due to least front-end equipment requirement	a. Small cost of sub-stoichiometric combustor is outweighed by cost of expensive complexities such as post sulfur removal and solid waste combustor	a. Expensive due to large number of front-end equipment and design complexity of solids transfer and heat recovery

* ASCS = Advanced Staged Combustion System; IGCC = Integrated Gasification Combined Cycle System; PFBC = Pressurized Fluidized-Bed Combustion System (Robertson *et al.*, 1990).

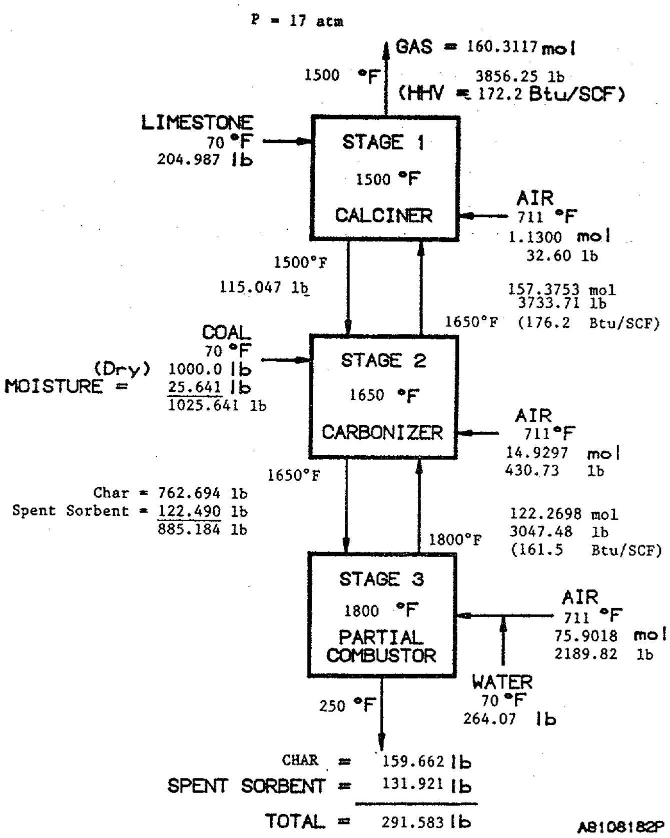

Figure 4. MATERIAL AND ENERGY BALANCE FOR THE PARTIAL COMBUSTOR

Table 2. COAL FEED ANALYSIS
(Coal: Illinois No. 6 Bituminous)

Proximate Analysis, wt % (as fed)	
Moisture	2.50
Volatile Matter	37.44
Fixed Carbon	48.06
Ash	12.00
Total	100.00
Ultimate Analysis, wt % (dry)	
Carbon	69.41
Hydrogen	4.39
Oxygen	8.56
Nitrogen	1.68
Sulfur	3.65
Ash	12.31
Total	100.00
HHV, Btu/lb (dry)	12,510

Table 3. LIMESTONE COMPOSITION

Component	wt %
$CaCO_3$	97.28
$MgCO_3$	2.11
Inerts	0.61
Total	100.00

Table 4. FUEL GAS COMPOSITION

Component	mole %
CO	28.53
CO_2	4.70
H_2	16.01
H_2O	2.73
CH_4	2.20
C_2H_6	0.02
C_2H_4	0.03
O_2	0.00
N_2	45.61
H_2S	0.03
NH_3	0.14
Total	100.00
HHV (wet basis), Btu/SCF	167.5

Table 5. SOLID WASTE COMPOSITION

Component	wt %
C	11.90
H	0.15
O	0.00
N	0.11
S	0.38
Ash	42.22
$CaCO_3$	0.00
CaO	18.11
MgO	0.71
CaS	25.99
$CaSO_4$	0.00
Inerts	0.43
Total	100.00

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