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## ABSTRACT

The Advanced Staged Fluidized-Bed Coal Combustion System (ASC) is a novel clean coal technology for either coal-fired repowering of existing boilers or for incremental power generation using combined-cycle gas turbines. This new technology combines staged combustion for gaseous emission control, in-situ sulfur capture, and an ash agglomeration/vitrification process for the agglomeration/vitrification of ash and spent sorbent, thus rendering solid waste environmentally benign.

The market for ASC is expected to be for clean coal-fired repowering of generating units up to 250 MW, especially for units where space is limited. The expected tightening of the environmental requirements on leachable solids residue by-products could considerably increase the marketability for ASC.

ASC consists of modular low-pressure vessels in which coal is partially combusted and gasified using stacked fluidized-bed processes to produce low-to-medium-Btu, high-temperature gas. This relatively clean fuel gas is used to repower/refuel existing pulverized-coal, natural gas, or oil-fired boilers using bottom firing and reburning techniques.

The benefits of ASC coal-fired repowering include the ability to repower boilers without obtaining additional space while meeting the more stringent environmental requirements of the future. Low $NO_x$, $SO_x$, and particulate levels are expected while a nonleachable solid residue with trace metal encapsulation is produced. ASC also minimizes boiler modification and life-extension expenditures. Repowered efficiencies can be restored to the initial operating plant efficiency, and the existing boiler capacity can be increased by 10%.

Preliminary cost estimates indicate that ASC will have up to a $250/kW capital cost advantage over existing coal-fired repowering options.

# INTRODUCTION

Currently in the United States there are approximately 40 gigawatts of oil- and gas-fired electrical capacity and 50 gigawatts of coal-fired capacity that are being generated by plants that are over 30 years old. By the year 2000, there will be about 800 fossil-fired plants over 40 years old. As each of these existing generation plants gets older, decisions have to be made whether to retire or maintain the units.

There are three major issues that arise when making decisions about older generating units. The first is that plant maintenance programs need to be much more aggressive to arrest the degradation of the generating plants. This higher level on maintenance implies a much higher maintenance cost as the plant ages. Often a large capital improvement program (life-extension program), especially for the boiler, must be initiated to continue plant operation.

The second factor that must be considered is that the older generating plants are operating at much lower average efficiencies than their original design levels. This makes these plants noncompetitive with newer generating units.

Lastly, these older generating plants are unable to meet current pollution requirements, and future emission standards will become increasingly more stringent, perhaps prohibiting the operation of many of these older units unless a clean coal repowering technology is implemented.

Aggregate electrical demand and the current low level of new construction dictate that the majority of these older generating plants will have to be maintained rather than retired. A plant life-extension program alone will usually not be enough to continue plant operation because of the need to meet emission control requirements. Coal-fired repowering options with simultaneous $NO_x$ and $SO_x$ emission control are needed.

A review of currently available coal-fired repowering technologies with simultaneous $NO_x$ and $SO_x$ control reveals that economical options do not exist. This is particularly true for small generating units in the 50-to-250-MW range. At first look, some of the coal-fired repowering technologies appear to have promise, but problems with space limitations, higher-than-forecasted emission levels, and the economic unattractiveness of these technologies for small generating units reveal that these existing technologies are not suited to the majority of the potential repowering candidates. Therefore, a new coal-fired repowering technology is needed.

## DESCRIPTION OF ASC PROCESS

The ASC system (Figure 1) has the potential to become the new repowering option that can capture the majority of the repowering cases, particularly for small generating units (50 to 250 MW).

ASC is a staged, low-$NO_x$, low-$SO_x$ combustion process where coal is used as the feedstock to repower/refuel existing coal-, oil-, or gas-fired generating units. This repowering can be performed within the existing space and with minimum modifications to the existing boilers.

The unique feature of the ASC process is the use of staged combustion in several zones. Each zone of the ASC process provides a primary function, and in some zones, multiple functions are carried out. The first stage of combustion occurs in fluidized partial-combustor vessels. The second stage of combustion occurs within the existing boiler. Each of these stages is comprised of several zones. The use of the different stages and combustion zones allows temperature and stoichiometric conditions to be set to achieve optimum results from each combustion reaction.

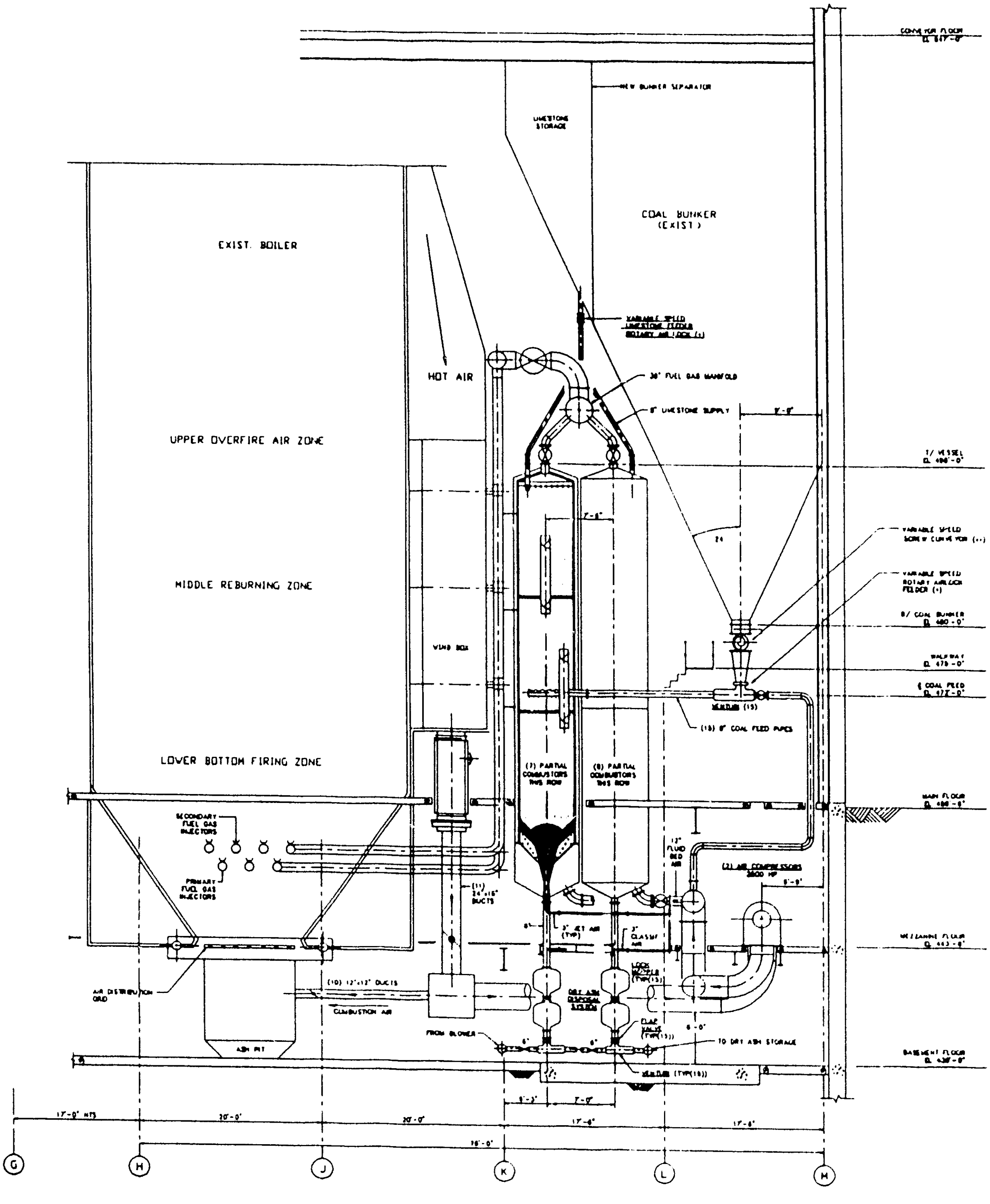
A block diagram showing the ASC process is shown in Figure 2. This diagram outlines the functions of the different stages and zones of the ASC process. A cross section through one of the fluidized partial-combustor vessels is shown in Figure 3. A typical heat and material balance of the ASC process is shown in Figure 4.

### Fluidized-Bed Partial Combustors

The fluidized partial-combustor vessel (Figure 3) is comprised of three stacked fluidized-bed zones. The required number of these modular vessels for a particular retrofit is determined by the required heat input of the existing boiler. As an example, 15 of these vessels each with a 6-foot internal diameter are required to repower a 150-MW unit. The heat available from the fuel gas is comprised of both the chemical and sensible heat.

The partial-combustor vessels operate under a maximum pressure of 30 psia. Each vessel is typically a 6-foot internal diameter and operates between 6 to 10-foot-per-second superficial velocity.

Fluidized-bed air is supplied to each vessel using air compressors that take inlet air from the existing boiler air preheater outlet. This hot air is first cooled through the use of water injection before entering the compressors. In this way the



NOTES

1 • - ONE PER VESSEL
2 •• - ONE PER COAL BUNKER

Figure 1. TYPICAL ARRANGEMENT FOR COAL-FIRED REPOWERING 150-MW UNIT UTILIZING ASC CONCEPT

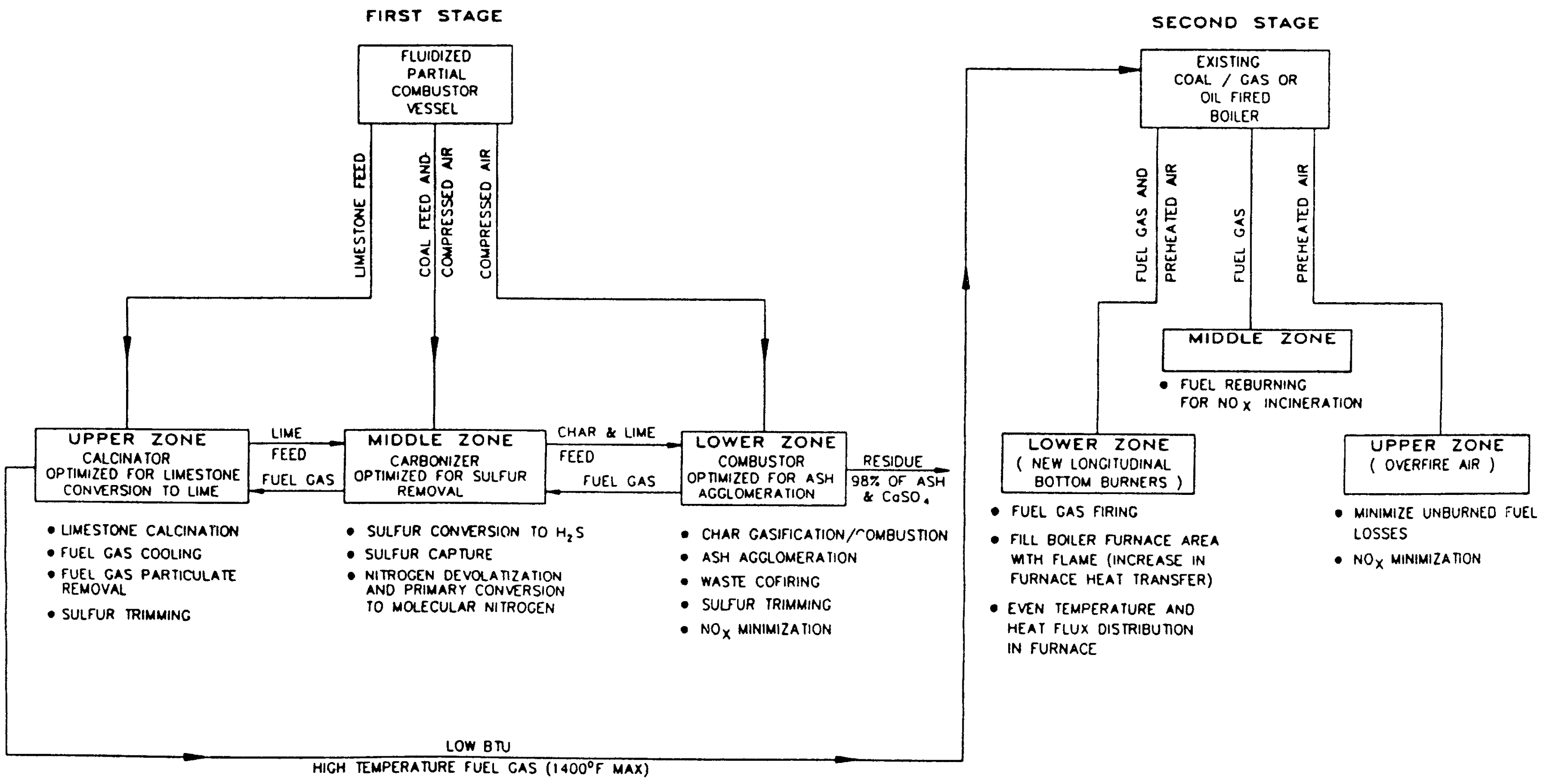


Figure 2. THE ADVANCED STAGED COMBUSTION PROCESS (ASC) BLOCK DIAGRAM COAL-FIRED REPOWERING-STEAM CYCLE

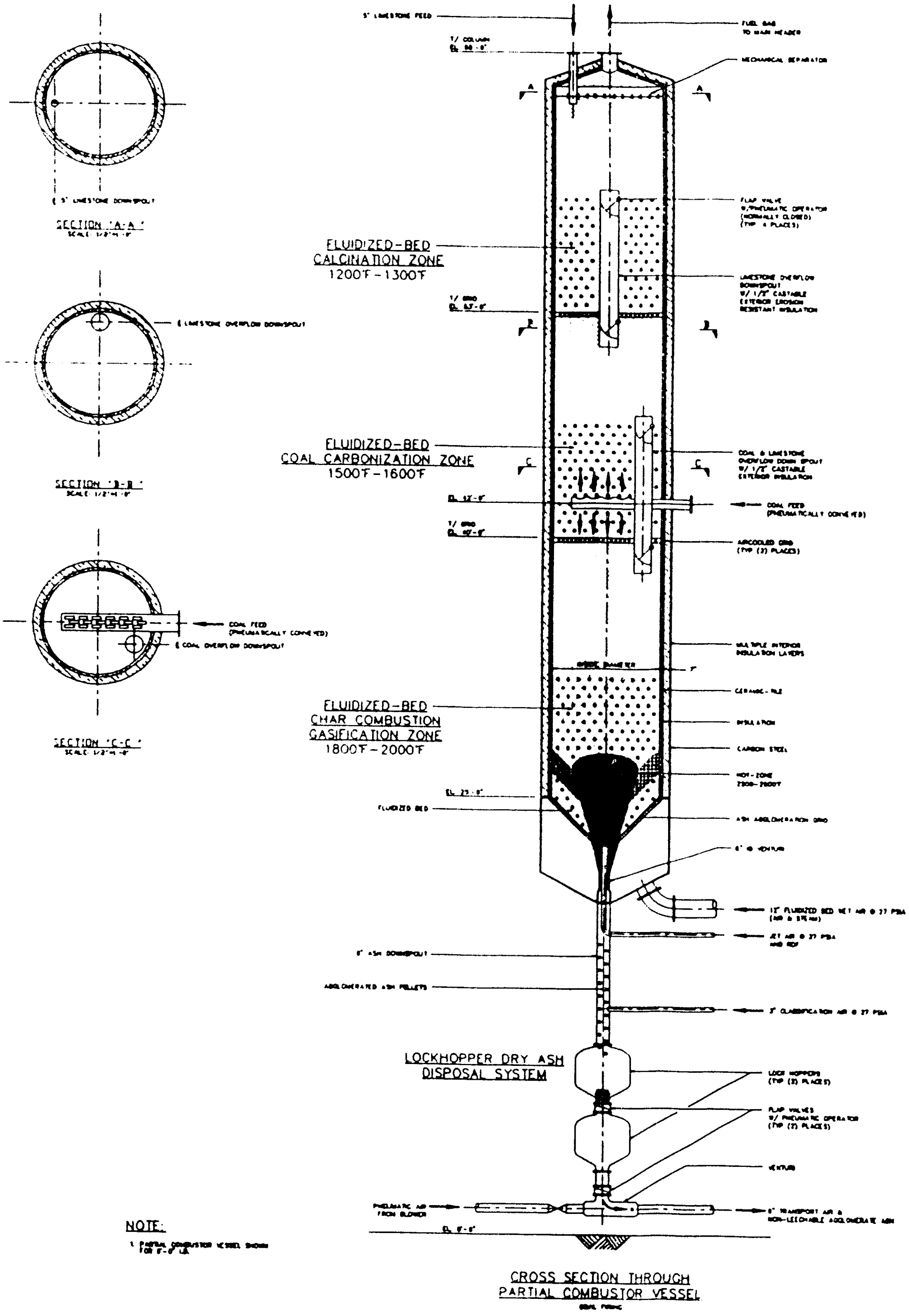
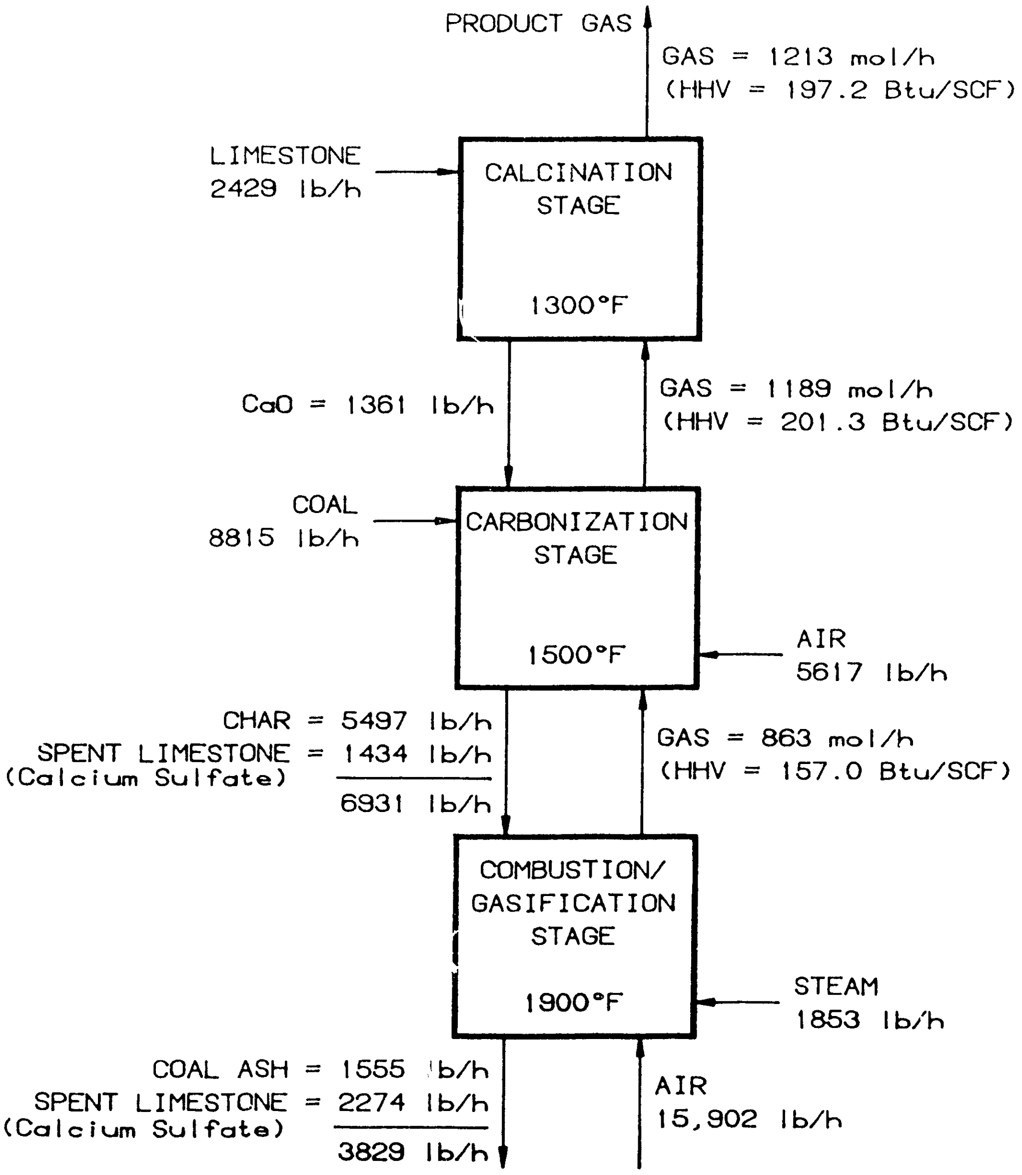


Figure 3. CROSS SECTION OF FLUIDIZED-BED PARTIAL COMBUSTOR



| PRODUCT GAS COMPOSITION, mol % | |
|---|---|
| CO | 25.67 |
| $CO_2$ | 5.88 |
| $H_2$ | 13.43 |
| $H_2O$ | 2.10 |
| $CH_4$ | 2.08 |
| $C_2H_6$ | 0.33 |
| $C_2H_4$ | 1.04 |
| $C_3H_6$ | 0.13 |
| $H_2S$ | 0.04 |
| $N_2$ | 48.77 |
| OTHERS | 0.53 |
| | 100.00 |

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Figure 4. TYPICAL BALANCE
100 X $10^6$ Btu/h PRODUCT GAS HEAT OUTPUT
(Includes HHV + Sensible Heat)

fluidized-bed air temperature can be reduced to minimize the compressor power requirements while supplying steam to the partial-combustor vessels for fluidized-bed temperature control.

Of the total air needed for overall combustion, about 30% is compressed for the partial-combustor vessel. All other air, including the necessary excess air for combustion, is directed to the boiler with a fan to burn the fuel gas produced in the partial-combustor vessels.

## Upper Fluidized-Bed Zone -- Calcinator Zone

In the upper calcinator fluidized-bed zone, crushed limestone/dolomite is added using a gravity feed system. The feed rate is controlled by a variable-speed rotary feeder. This limestone/dolomite is heated from ambient temperature to about 1450°F from the heat contained in the fuel gas rising from the fluidized beds below. The primary purpose of this fluidized bed is for limestone/dolomite calcination. The fluidization velocity in this zone is maintained at 7 to 10 feet per second depending on the type and size of the sorbent used.

The two main reactions occurring in this upper calcination zone with dolomite and/or limestone are as follows:

$$CaCO_3 + \text{Heat} \dashrightarrow CaO + CO_2$$

$$MgCO_3 + \text{Heat} \dashrightarrow MgO + CO_2$$

With the fuel gas entering this zone from the middle carbonizer zone below at 1550°F, almost complete calcination of the limestone or dolomite is expected. The calcination in this zone reduces the time necessary for sulfation in the middle carbonizer zone below, and therefore raises the sulfur-capture efficiency of the middle zone.

The calcium oxide (lime, CaO) and magnesium oxide (MgO) produced in this fluidized bed are transferred into the lower carbonizer fluidized-bed zone via internal fluidized-bed overflow pipes. These overflow pipes have pneumatic motor-operated flap valves at each end that can be controlled to introduce measured amounts of calcium oxide to the middle carbonizer zone below. Through the use of these overflow tubes, the frequency of operation of the flap valves, and limestone/dolomite feed rate, the bed level in the upper zone can be controlled.

This upper calcination zone also serves the secondary purpose of further reducing the sulfur in the fuel gas by acting as a scrubber. The 1550°F fuel gas passing through this calcination zone will be expected to lose the remaining sulfur not removed in the middle carbonizer zone located below according to the reaction:

$$CaO + H_2S \dashrightarrow CaS + H_2O$$

This upper calcination zone also provides the additional features of fuel gas cooling, and also acts as a gas filter removing a high level of particulate and traces of tars and oils. Only traces of tars and oils are expected in the fuel gas because of the high temperatures of the lower two zones. However, the remainder of the surviving tars will be cracked by the lime according to the following reaction:

$$CaO + tar \overset{Ca}{\dashrightarrow} C + CH_4 + \text{other } HC$$

The fuel gas rising from the lower fluidized beds enters the upper calcinator zone at approximately 1550°F. The final temperature of the gas leaving this zone will depend on the rate of the limestone/dolomite feed.

To prevent elutriation of the limestone/dolomite from this upper calcination bed, mechanical impingement separators are installed above this bed.

## Middle Fluidized-Bed Zone -- Carbonizer Zone

Coal from the coal bunkers is fed through variable-speed screw feeders and pneumatically conveyed using compressed air into the middle fluidized-bed carbonization zone. The coal size is not critical but the preferred coal size is 1/4 inch x O. Calcium oxide produced in the upper calcination zone is transferred into this middle carbonizer fluidized-bed zone via internal fluidized-bed overflow pipes.

Heat from the lower combustion zone and the addition of air are used to maintain a temperature of 1500° to 1600°F in the middle carbonizer zone. The primary purpose of this fluidized-bed zone is for sulfur capture and coal carbonization (coal devolatilization). About 10% of the stoichiometric combustion air is required in this zone.

At a controlled temperature of 1500° to 1600°F and in reducing conditions, sulfur-bearing molecules will undergo a reaction at this temperature to produce $H_2S$. The ability to control the temperature of this coal carbonization process independently of the other processes maximizes sulfur capture. Maintaining this zone at 1550°F would maximize sulfur capture according to the following equation:

$$CaO + MgO + H_2S \dashrightarrow CaS + MgO + H_2O$$

At the bed temperature of 1550°F, up to 90% of the nitrogen in the coal (depending on coal type) will be released also. Because reducing conditions are present, the fuel nitrogen will be released as molecular nitrogen, ammonia ($NH_3$), amines ($RNH_2$), and cyanide (HCN). The quantities of these nitrogen by-products greatly depends on the coal type fired and will be greatly reduced in the second stage of the ASC process (the existing boiler).

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

## Lower Fluidized-Bed Zone -- Combustor Zone

The devolatilized and desulfurized coal (char) from the middle carbonizer zone enters this lower combustion zone again via the internal overflow pipes. Unreacted CaO and CaS are also transferred down to this fluidized-bed combustor zone. The char passing to the lower combustor zone has a high Ca/S ratio because the majority of the sulfur was removed in the zone above.

Combustion/gasification of the char occurs at a substoichiometric air-to-coal ratio. Less than 25% of the required oxygen for complete stoichiometric combustion is supplied to this zone.

Fluidized-bed air is supplied to the partial-combustor vessel through the use of air compressors. These air compressors take heated air from the furnace windbox; after being humidified by water injection and lowered in temperature, this air/steam mixture is supplied to the air compressor inlet. The compressed air from the compressor is then sent to the partial-combustor vessels through fluidizing bed grids below the combustor zone.

The temperature in this combustor zone varies in the range of 1800° to 2000°F. The actual temperature of the bed will depend on the type of coal and will change to maintain nonslagging conditions of the ash. This combustor zone has a central hot zone in which the temperature of about 2500°F is maintained. This central hot zone governs the ash agglomeration process.

The CaS and MgO produced in this combustor zone is discharged out from the bottom of the vessel against the air stream where it reacts with oxygen to produce benign $CaSO_4$ and MgO according to the following reaction:

$$CaS + MgO + 2O_2 \dashrightarrow CaSO_4 + MgO$$

Alternatively, the CaS and ash from the char can be vitrified in this zone to form a stable residue. Again, because of the substoichiometric conditions, the remaining fuel-bound nitrogen is expected to be released as molecular nitrogen.

Under relatively high temperatures in this zone (above 1800°F), low oxygen concentrations, and in the presence of CO, some of the sulfated lime may be regenerated to CaO according to the following reaction:

$$CaSO_4 + CO \dashrightarrow CaO + SO_2 + CO_2$$

This reaction occurs in conventional Atmospheric Fluidized-Bed Combustors (AFBCs), but in the ASC process any $SO_2$ released in the lower combustor zone will be recaptured in the upper fluidized-bed zones. The above reaction is unlikely to occur in the central hot zone of the combustor bed because of the presence of oxidation conditions.

Approximately 90% to 95% of the sulfur present in the coal is captured in the partial combustor.

The second stage of the coal-fired ASC repowering process involves burning the resultant product fuel gas from the first stage partial-combustor vessels in the existing boiler. This fuel gas is burned in upper, middle, and lower zones of the boiler.

## BOILER REPOWERING

### Lower Fuel Gas Combustion Zone

The majority of the fuel gas is burned in the lower zone of the existing boiler through the use of new primary and secondary burners. These burners are longitudinal-type diffusion burners designed to distribute the flame throughout the bottom of the boiler furnace with uniform temperature, producing a heat release similar to what the boiler was originally designed for. The use of these types of burners and the air distribution grid will allow the superheater and reheaters sections of the boiler to operate at their originally designed temperatures.

Combustion air for these primary and secondary bottom furnace burners comes from the main windbox duct below and is distributed uniformly across the boiler cross section through the use of an air distribution grid. This high pressure-drop grid in the bottom of the boiler will be designed for a pressure drop equal to the pressure of the windbox (about 3 inches $H_2O$) and the negative pressure at the bottom of the boiler (about 2 inches $H_2O$), for a total pressure drop of around 7 inches $H_2O$. Therefore, uniform oxygen conditions can be maintained throughout the cross section of the boiler furnace.

The $NO_x$ emission level for low-Btu fuel gas firing will be expected to be in the range of 100 ppm. Kinetic modeling studies suggest $N_2O$ is unlikely to form within the flame zones because of its rapid removal according to the following equations:

$$N_2O + H \rightarrow N_2 + OH$$

$$N_2O + 1/2O_2 \rightarrow 2NO$$

$$2NO + 2CO \rightarrow N_2 + 2CO_2$$

Therefore, $N_2O$ and other nitrogen-bearing by-products from the partial-combustor vessel fluidized-bed zones will be completely incinerated in this zone.

## Middle Fuel Gas Reburning Zone

In the middle zone of the existing boiler, a portion of the product fuel gas will be fired again with only the remaining oxygen from the lower combustion zone. The purpose of this zone will be for $NO_x$ incineration. This procedure has been used commercially and is called fuel reburning. Through this reburning, any $NO_x$ produced in the lower zone can be reduced by half in this middle zone. The use of this reburning technique should allow total $NO_x$ emissions of less than 50 ppm.

In addition to any $NO_x$ produced in the lower zone of the boiler, any amines and cyanide nitrogen compounds will also be reduced in the middle fuel gas reburning zone. The oxidation of the amines will not produce measurable levels of $NO_x$. These reactions will start in the lower boiler burner zone and proceed according to the following equation:

$$2RNH_2 + O_2 \rightarrow N_2 + H_2O + CO$$

The reaction of the cyanides generally produces toxic $N_2O$ at low AFBC temperatures according to the following equation:

$$2HCN + 2O_2 \rightarrow N_2O + 2CO + H_2O$$

In the ASC process, however, $N_2O$ will be eliminated in the lower high-temperature boiler zone and through fuel gas reburning in the second stage of combustion in the existing boiler.

In the middle zone of the boiler, the reburning of the fuel gas will cause the NO to proceed to molecular nitrogen ($N_2$) according to the following equation:

$$2NO + 2CO \rightarrow N_2 + 2CO_2$$

## Upper Fuel Gas Over-Fire Air Zone

In the upper part of the boiler furnace, a portion of the fuel gas will be burned by over-firing the fuel gas with air. For reburning techniques this zone is often called the oxidation zone. This will bring the fuel utilization efficiency above the 99.5% level.

Final $NO_x$ production from the ASC process is expected to be up to 50 ppm. For some existing boilers, the lower furnace combustion zone could operate with a reducing atmosphere, and the existing burners will be modified for staging combustion with over-fired air. The $NO_x$ level will be expected to be higher, but the simpler furnace modification and operation could become an important issue.

## ADVANTAGES OF ASC IN BOILER RETROFIT

Repowering the retiring boiler with ASC offers the following advantages.

- The entire process can be installed in place of the existing fuel-feed system. This allows coal-fired repowering of the unit without the necessity of obtaining any additional space.
- The other advantage is the possibility of converting pulverized-coal units to a clean coal technology at an overall cost lower than any of the available or emerging alternatives. Preliminary estimates indicate that coal-fired repowering could be achieved at a cost of $150 to $200/kW without life-extension costs. Depending on the amount of life extension required, this cost can rise to between $300 to $350/kW. Comparable coal-fired repowering options range from $500 to $1400/kW (Table 1).
- The ASC process provides advantages in particulate control over other available and emerging coal-fired repowering options. Existing particulate-control systems suffer severe impacts from most coal-fired repowering options. Using an AFBC, micronized coal, pulverized coal (LIMB), or using a two-stage pulverized coal-slagging combustor requires modifying or upgrading the existing particulate-control system. This is necessary because of the increased ash loading of the system and the increased ash resistivity.
- The high sulfur-capture rate, low $NO_x$ production, and low particulate emissions of ASC coal-fired repowering without the use of post-combustion technologies are far superior to any of the available or emerging coal-fired repowering options.

## Table 1. COMPARISON OF COAL-FIRED REPOWERING OPTIONS

| | | Commercial Status | Repowering Average Capital Cost with LE $/kW | Comparable Plant Efficiency % (1) | Generating Capacity Increase % | Level of Boiler Life Extension Required | Emissions (Meets Current Levels) | | | Future Emissions (Exceeds Current Levels) | | | Solids Residue Ash Sorbent | Additional Area Required |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | $NO_x$ | $SO_x$ | Particulate Control Achieved | $NO_x$ | $SO_x$ | HCL | | |
| 1 | PC Fired Steam Generation, FGD Retrofit, Low $NO_x$ Combustion System | Available | $800 | 33% | 0% | High | Yes | Yes | Yes | Yes(3) | Yes(3) | N/A | Leachable | Yes |
| 2 | Atmospheric Fluidized Bed Combustion -- AFBC (Bubbling Bed) | Available | $500 to $600 | 31% | 0-10% | Medium | Yes(2) | Yes | Yes May require new control | No | No | N/A | Leachable | Yes(4) |
| 3 | Advanced Staged Combustion ASC | Research | $250 to $300 | 36% | 0-10% | Medium | Yes | Yes | Yes | Yes | Yes | Yes | Nonleachable | No |

NOTES:

1. Base efficiency for PC fired plant w/o emission control is 34%.
2. Possible high N2O levels due to the low temperature combustion process.
3. High additional investment required.
4. Modified particulate control, new air preheater, increased boiler cross-section.

- The ability to produce a nonleachable residue is important as more and more areas attempt to treat coal waste as a hazardous waste. The current Clean Air Act is a federal obligation, but local and state agencies can enforce more stringent guidelines. Disposal cost of leachable residue, if it is considered a hazardous waste, can go as high as $200/ton as compared to $17/ton for disposal of nonleachable residues. For a 600-MW coal-fired plant burning 2.5%-sulfur coal with 15% ash, there could be a 100 million dollar savings in ash-disposal costs alone for a process that produces nonleachable residues.

The expected overall performance from ASC retrofit is illustrated in Table 2. The performance of AFBC is also included for comparison.

## CASE STUDY

To illustrate the use of the ASC process for coal-fired repowering, a 150-MW existing power station (Station X) was selected. This plant was typical of older pulverized coal-fired stations. The station was a four-unit plant built in the early 1950's. Each of the four units had a nominal capacity of 150 MW. Each 1,000,000-lb/h steam generator served a single 150-MW steam-turbine generator without any interconnections to other units.

To perform the ASC coal-fired repowering, the first step was to remove the pulverizers, disc feeders, coal crushers, and exhausters with related pulverized-coal piping. The second step was to arrange the required partial-combustor vessels as close to the existing boiler as possible.

To repower one of the units at Station X, fifteen partial combustor vessels with a 6-foot internal diameter, or seven vessels with a 9-foot diameter, were required. The installation cost of the large vessels will be lower but will require more space in front of the boiler. Because of the space limitations of the station, the 6-foot-diameter vessel configuration was chosen.

These vessels were placed in two staggered rows. The first row closest to the boiler contained seven vessels, and the second row contained the remaining eight vessels. The distance between these two rows was 7-1/2 feet. This "closed-pack" arrangement allowed all of the vessels to be installed in the width of the existing boiler with a column-to-column distance of 58 feet.

## Table 2. COMPARISON OF PROJECTED PERFORMANCE ASC PROCESS AND AFBC COAL-FIRED REPOWERING[a]

| | AFBC (Bubbling Bed) | ASC |
|---|---|---|
| Total Excess Air | $>25\%$ | $<10\%$ |
| Superficial Velocity -- ft/s (Maximum allowable) | 12 | 15 |
| Carbon Burnout | $<97\%$ | 99.9% |
| Boiler Efficiency | 86-87% | 90-91% |
| Bottom Ash Removal | 30% | 98% |
| Ash Type | Leachable | Non-Leachable |
| Ca/S Molar Ratio ($SO_2$ removal) | 3 | 2 |
| Ca/S Molar Ratio (Cl removal) | N/A | 2 |
| CO Emissions | $<150$ vppm | $<100$ vppm |
| $NO_x$ Emissions (w/o SCR Installation) | 300-400 ppm | 50-100ppm[b] |
| THC Emissions | 50 vppm[c] | 50 vppm |
| TSP Emissions | | Virtually 0 |
| Sulfur Emissions Reduction | $<90\%$ | $>95\%$ |
| Turndown Ratio | 3 to 1 | 4 to 1[d] |
| Availability | $>85\%$ | $>90\%$ |
| Fuel Requirements | Varied | Varied<br>Waste cofiring allowed |

[a] Emission data corrected to )% $O_2$.

[b] Depends on burner retrofiting method and combustion reburning techniques.

[c] Depends on existing particulate-removal system.

[d] The turndown ratio for the partial combustor vessels is 3:1. The total turndown ratio will depend on the number of vessels employed and the burner design features.

Coal to the partial-combustor vessels was fed from the existing three coal bunkers through three new variable-speed conveyors with inlet rotary airlock vanes to variable-speed rotary airlock coal feeders. One variable-speed rotary airlock coal feeder was required per partial-combustor vessel. Of the three variable-speed conveyors, two were used to supply coal to twelve variable-speed rotary coal feeders (six per screw conveyor), and one located in the middle was used to supply coal to only three coal feeders.

At the partial-combustor vessels, the coal from the variable-speed rotary airlock coal feeders was pneumatically conveyed into each vessel. The coal was introduced into the carbonizer zone using a pneumatic venturi system with 30-psia compressed air. This air was used to keep the temperature in the middle carbonizer zone at the required temperature level of 1550°F.

Limestone/dolomite feed to the partial-combustor vessels was similar to the coal feed. Each of the three existing coal bunkers was modified to create a separate coal and a smaller limestone/dolomite compartment. The limestone/dolomite from the storage in the modified coal bunker gravitated through new variable-speed rotary airlock feeders and lockhoppers to the calcination zone of the partial-combustor vessels. Here, because the limestone/dolomite fell vertically, pneumatic transport was not required.

The nonleachable ash pellets produced in the ASC process fell to the bottom of the partial-combustor vessel and entered the dry ash-disposal system. This system consisted of lockhoppers and small storage tanks where the agglomerated ash was cooled by circulating water coils.

Ash transport was accomplished by using two high-pressure air blowers installed on the basement floor to convey ash from each partial-combustor vessel to a common manifold. The cooled agglomerated ash was then further pneumatically transported outside of the boiler building for trucking or direct landfill disposal.

The largest new pieces of equipment were two axial air compressors that were installed on the existing floor. These two air compressors supplied the combustion air to all fifteen of the partial-combustor vessels. Each compressor was 15 feet long and was easily accommodated within the width of the boiler island.

Inlet air to the air compressors at 30% of the total quantity required for complete coal combustion was taken from the existing boiler air-preheater outlet at a temperature of 600°F. This air was cooled to 210°F before sending to the air compressor using a spray attemperator. The resultant air-steam mixture had about 10% relative humidity.

For this site, the steam was supplied to the gasification process as a air-steam mixture. Compressed air with a temperature of about 375°F was supplied at 30 psia for the combustion and fluidization inside the partial-combustor vessels.

The resultant low-Btu fuel gas left the partial-combustor vessels at about 1250°F and at a pressure of 40 inches of water. This gas was collected in a manifold before being sent to the existing boiler. Because the gas produced in the partial combustor vessels was tar- and dust-free, it could be sent directly to new bottom "staged-fuel" designed burners and to the middle boiler zone for reburning.

Air for the new bottom burners was taken from the air preheater (70% of the total required for complete coal combustion) and directed to the bottom burners and to the upper over-fire air zones at a temperature of about 600°F. The proposed bottom firing burner with "staged-fuel" design arrangement minimized boiler modification and considerably improved boiler performance and reliability. This type of burner has been designed for a variety of fuels including low- and medium-Btu gases. The existing boiler ash pit was used as an air chamber to provide even air distribution and, therefore, even flame distribution in the boiler furnace.

Table 3 summarizes and compares the projected performance of the ASC coal-fired repowered plant with the existing pulverized coal-fired plant.

A summary of the major advantages of ASC coal-fired repowering versus continued operation as a pulverized-coal plant are given below:

- Net additional plant power is 110 MW.
- The plant will be able to operate on a wide variety of fuels including high-moisture coals, high ash-content coals with the additional possibility of co-firing municipal solid waste (MSW) and refuse-derived fuels (RDF).
- Low $NO_x$ and $SO_x$ emissions are in compliance with New Source Performance Standards (NSPS). There are significant decreases in THC, CO, and particulates.
- There is a 3% net plant heat rate improvement -- lower excess air, decreased carbon loss, no boiler fouling, elimination of sootblowing, and better efficiency at lower loads.
- There are better turndown and cycling capabilities. In a "stand-by" mode, no supplemental fuel was required.
- There is better steam generator reliability.

## Table 3. PERFORMANCE COMPARISON OF PULVERIZED COAL-FIRING AND ASC COAL-FIRED REPOWERING

| | Units | Pulverized Coal (Existing) | ASC Coal-Fired Repowering |
|---|---|---|---|
| Boiler Output | lbs/h | 1,000,000 | 1,200,000 |
| Steam Turbine Output | MW | 150[a] | 180 |
| Required Heat Input to the Boiler | Btu/h | 1,380,000 | 1,600,000 |
| Burner/Combustor Capacity | Btu/h | 18 burners @ 780,000[b] | 15 combustor @ 107,000,000[c] |
| Turndown Capability | -- | 4:1[d] | 4:1[e] |
| Excess Air (Boiler Output) | % | 25 | 10 |
| Auxiliary Power | kW | 9,000 | 11,500 |
| Turbine Heat Rate | Btu/kWh | 7,875 | 7,900 |
| Boiler Efficiency | % | 87.6 | 89 |
| Operating Efficiency | % | 95 | 97 |
| Plant Net Efficiency | % | 34 | 35.0 |
| Net Plant Heat Rate | Btu/kWh | 10,040 | 9,750 |

[a] Inadequate mill grinding and drying capacity for the turbine demand. Coal can be used with moisture content no more than 12%.

[b] Burners as well as the boiler can be forced up to 20% more than the normal capacity.

[c] Partial combustor can be forced up to 150 X $10^6$ Btu/h, which allows some combustors to be repaired while the unit remains in service at full load.

[d] May require oil to maintain stable combustion.

[e] Turndown by partial-combustor vessels is 3:1. One of 15 combustor vessels can be in operation to maintain the boiler in a "stand-by" mode. The burner design may allow a 30:1 turndown ratio.

## COST ANALYSIS

An estimation was made for the cost of ASC repowering of an existing generating unit and a comparison was also made with an atmospheric bubbling-bed fluidized-bed technology. This technology was chosen because it represents the only currently available process for repowering power plants in the 150-MW range without the necessity of much additional space for new equipment. This estimate is reflected in Table 4.

Table 4. COST COMPARISON OF MODIFICATION REQUIREMENTS FOR AFBC AND ASC COAL-FIRED REPOWERING

| | <---------- $/kW ---------- > | |
|---|---|---|
| | AFBC* Repowering (Bubbling Bed) | ASC** Repowering |
| 1. Steam generator system modification including the air preheater, etc. | 185-235 | |
| 2. New burners and reburning systems. | | 15 |
| 3. Material-handling and ash-transport system. | 65 | 60 |
| 4. Operating and emission control. | 45 | 45 |
| 5. Partial-combustor installation. | | 50 |
| 6. Balance of plant (ID, FD fans, booster fans, precipitator upgrade, ash recycling, etc. | 60 | -- |
| 7. Compressor installation | | 10 |
| 8. Demolition work and structural modification, including losses during construction. | 95 | 20 |
| 9. Life-extension program | 100 | 100 |
| Total with Life Extension | 550-600 | 300 |
| Total without Life Extension | 450-500 | 200 |

* Actual.

** Preliminary estimates.

# CONCLUSIONS

The Advanced Staged Combustion concept for boiler retrofit holds a great promise in terms of economics, simplicity, and practicality. It offers the promise of reducing $SO_x$, $NO_x$, and particulate matter to meet more stringent emission regulations because of the flexibility of the process and flexibility of operation.

This technology can be easily adapted for repowering existing pulverized-coal-fired boilers despite the limitations in an available space. It offers an equally attractive option for refueling of gas- and oil-fired boilers. The system also has the potential to co-fire municipal or other wastes. Additionally, with the pressurized partial combustors, the gas turbine combined-cycle system would yield a substantial increase in overall plant efficiency.

# END

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