CAIRE® ADVANCED COMBUSTOR DEVELOPMENT

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Background

The trademark **CAIRE**®, pronounced "CARE" is an acronym for **C**ontrolled **AIR E**missions; this name has been applied to the staged coal combustor being developed by Florida Progress Corporation through its subsidiary, Florida Power Corporation. The staged combustor is designed for reduction of NOR, and removal of sulfur and slag in the combustor proper, thus controlling on the front end of the combustion process, the quantity of pollutants that enter the furnace.

Nitrogen oxides are reduced by firing the coal in a sub-stoichiometric air condition in the first stage, thus reducing the quantity of NO_X produced from fuel bound nitrogen. Further, the second stage of combustion, taking place after slight inter-cooling, is designed to reduce the production of thermal NO_X. The coal sulfur is removed via introduction of alkali, such as $CaCO_3$ or $Ca(OH)_2$ to produce calcium sulfide, which becomes tied up in a slag eutectic. A high percentage of the molten coal ash slag is removed from the first stage of combustion, thus much of the sulfur and slag, which would normally enter the furnace, are removed from the products of partial coal combustion prior to second stage combustion at the furnace entry. The CAIRE Combustor offers a future low capital and operating cost cleanup alternative to utilities and industries that are currently burning high sulfur coal.

At present status, the CAIRE Combustor technology has been developed through pilot plant construction and operation. The pilot unit was designed for a 12 MM Btu/hr coal feed throughput. The design and construction phase of the project required 9½ months. Following construction, the unit was started up and pilot testing was completed. The pilot plant tests were run in 1984. The entire project costs were privately funded and no formal papers were ever written on the pilot plant development. Florida Progress Corporation has two U.S. Patents, #4,395,975, #4,423,702 and several foreign patents (Canada, Spain, and Republic of South Africa) covering the staged combustor technology.

Due to uncertainties concerning utility environmental regulations, Florida Progress Corporation put the combustor development on hold after completion of pilot plant testing at the end of 1984. With the passage of the U.S. Clean Air Act Amendments of 1990 (October 26, 1990), the company opted to further develop and commercialize the staged combustor technology.

The Energy and Environmental Research Corporation, which has technical expertise in the fields of staged combustion and NO_X reduction technology, has been asked by Florida Power Corporation, a subsidiary of Florida Progress Corporation, to assist it in the commercial development of the technology.

Pilot Plant Description

A simplified flow diagram of the pilot unit is shown in Figure 1. Received coal was dried, then stored in a coal bin. From the bin the coal was dropped onto a weigh belt feeder, which in turn fed a pulverizer. Here the coal was pulverized to a size consist of 70% minus 200 mesh. The pulverized coal fell into an air eductor for pneumatic transport of the coal to the combustor. Co-currently, pulverized limestone (or hydrated lime), from a separate bin that incorporated load cells, was dropped into a screw feeder, which fed a second air eductor. The limestone was pneumatically conveyed to the pneumatic coal feed line prior to a spouting bed coal distributor. The distributor provided for intimate mixing of coal and limestone prior to the solids exiting four distributor pipes that fed the four burner nozzles on the combustor. The distributor also provided equal solids flow to each of the four nozzles.

The combustor was designed with a carbon steel water jacketed shell with a thin slag resistant refractory lining covering all, internal surfaces. A water level was maintained at the top of the water jacket, insuring that all interior surfaces exposed to the high gasification temperatures were backed with water in the jacketed outer wall. The first stage incorporated a 1.5 MM Btu/hr startup burner. The four-coal/limestone burner nozzles were designed such that the flame circle radius within the cylindrical portion of the first stage could be varied, Coal and limestone (or hydrated lime) with a sub-stoichiometric air rate were fired into the combustor at two locations. There were two burners per location, directed to fire in a secant-to-tangential and downward direction into a swirling molten slag bath. Coal ash containing alkali and sulfur made up the composition of the molten slag, which flowed through a slot in an internal gas baffle into a water quench tank. Due to the tangential firing of the coal/limestone/air, the product fuel gases (2600 to 2800°F) left the molten slag bath in a swirling motion, passing up and over the internal gas baffle into the boiler.

Secondary air was added to complete combustion (second stage) at the boiler entry point. The flue gas from the boiler passed through the primary air preheater, through a water spray cooling section and entered a gas cyclone for large fly ash removal. The flue gas exiting the cyclone entered an atmospheric stack.

Pilot Plant Operation and Test Results

The modus operandum for pilot plant operation was to startup and run for approximately 6-10 hours and then was shut down to prepare for the next run. Upon initial startup of the combustor, five pilot plant runs, over a total run time of some 23 hours were required to resolve all of the mechanical and auxiliary system problems with the combustor. Following resolution of the initial startup problems, which were minor, nine operation runs over a total run time of some 66 hours were completed.

The thrust of the work during these runs was to improve the coal gasification rates. Work centered on burner modifications to facilitate more rapid gasification rates to provide a greater reducing condition (greater H_2 and CO concentrations) within the first stage of combustion. The purpose of trying to yield a more reducing condition was to enhance the capture of sulfur with the molten alkaline slag.

The coal used for all of the combustion tests was a Pittsburgh Seam #8 Coal provided by Allegheny Power Systems' Arkwright/Osage Mine. Laboratory analyses completed on this coal are shown in Table 1. Also shown in the table is the chemical composition of the limestone and hydrated lime used to capture sulfur. The chemical composition of the coal ash and the limestone (hydrated lime) affects the slag viscosity, which is a critical parameter in the operation of the CAIRE Combustor. For ease of slag removal from the first stage of the combustor, the slag viscosity should be approximately 10 poise.

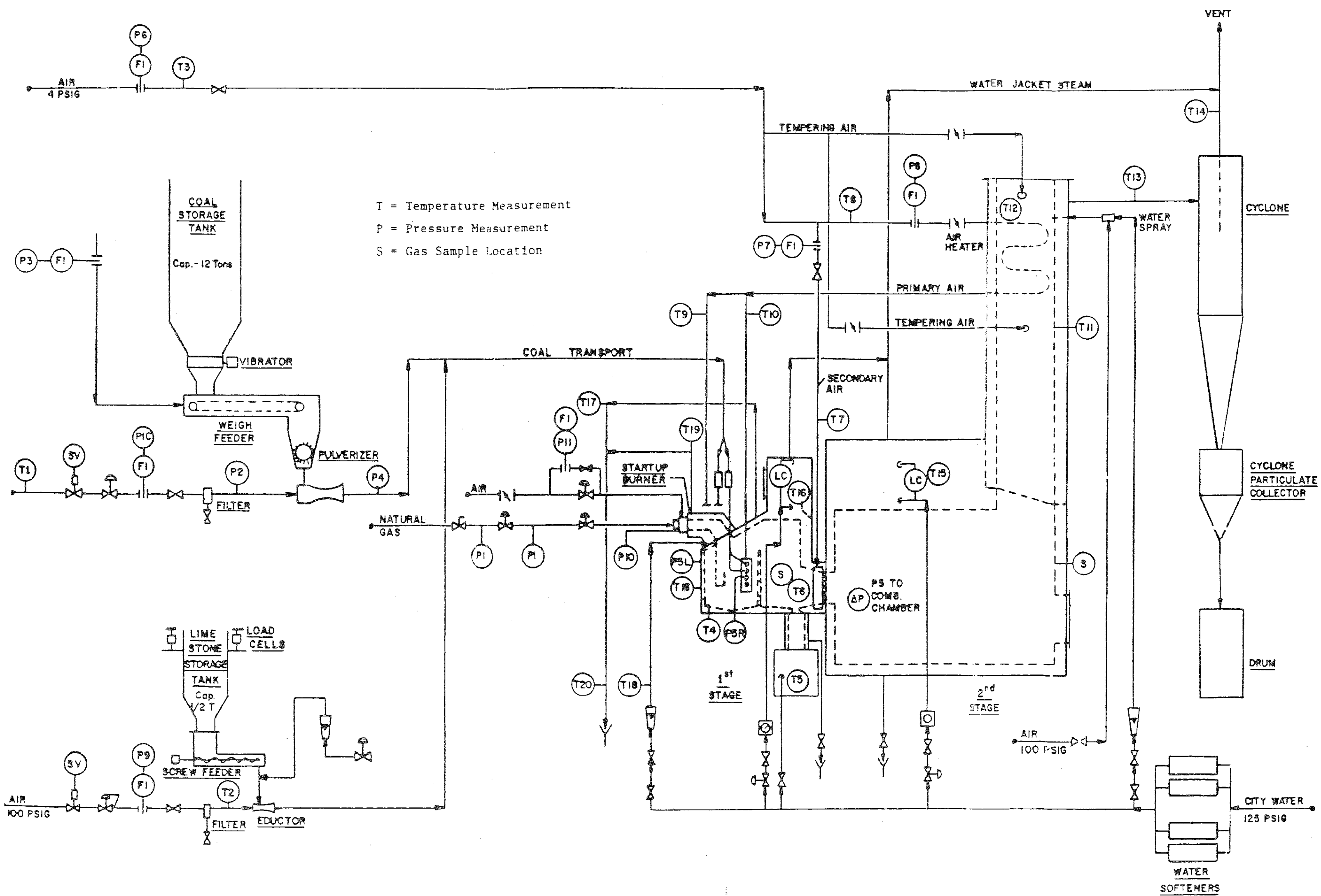

Figure 1. Pilot Unit Simplified Process Flow Diagram

TABLE 1

Pittsburgh Seam #8 Arkwright/Osage Coal Laboratory Analyses

Ultimate Analysis, wt%:	
C	69.88
H	4.71
O	4.53
N	1.35
S	2.92
Cl	0.10
Ash	10.76
H_2O	5.75
Total	100.00
Proximate Analysis, wt%:	
Carbon	47.44
Volatile Matter	36.05
Higher Heating Value (as received), Btu/lb	12,609
Lbs SO_2/MM Btu Coal Fired	4.63
Ash Composition, wt%:	
SiO_2	41.10
Al_2O_3	22.10
Fe_2O_3	18.60
TiO_2	1.13
CaO	6.50
MgO	1.32
K_2O	1.61
Na_2O	0.80
SO_3	6.15
P_2O_5/MnO_2 0.45	
Undetermined	0.24
Total	100.00

Alkali Chemical Analysis

Composition, wt%:	Greer Limestone	Hydrated Lime
$CaCO_3$	93	
$Ca(OH)_2$		96.44
$MgCO_3$	5	
MgO		0.83
SiO_2		0.99
Al_2O_3		1.99
Fe_2O_3		0.38
Total	100	100.00

The temperature required to reach a slag viscosity of 10 poise (T_{10}), based on as silica ratio is shown in Figure 2. This correlation for predicting slag viscosity was developed by the British Gas Council. For a Ca/S ratio of approximately 1.0, the T_{10} for the Arkwright/Osage coal ash/limestone mix was 2640 °F.

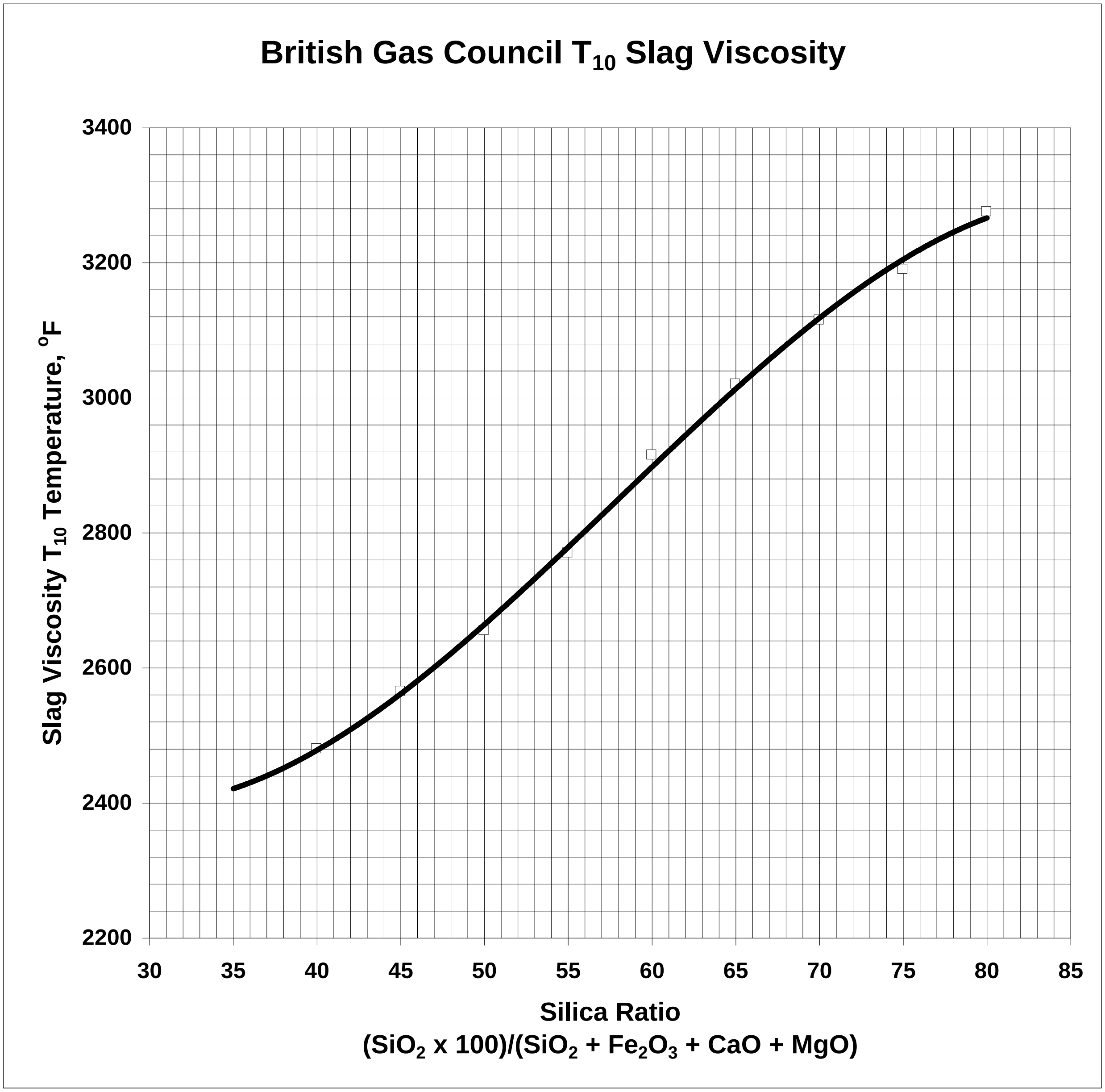

Figure 2. T_{10} Temperature versus Slag Composition

The CAIRE Combustor pilot plant test results for the last five runs completed are shown in Table 2. The test results are summarized as follows:

Sulfur Capture, wt%	**12.8 to 44.7**
NO_X Emissions, lb/MM Btu	**0.25 to 0.38**
Combustion Efficiency, wt% carbon conversion	**95.0 to 98.7**
Stage 1 Particulate Capture, wt%	**42.4 to 61.9**

TABLE 2.

CAIRE Combustor Pilot Test Results

Arkwright/Osage Pittsburgh Seam #8 Coal

[Overall Run Averages in Regular Font, Specific End of Runs in Italics]

Run #:	7	8	9	10*(ave)*	*end of 10*	11*(ave)*	*end of 11**
Coal (Pittsburgh Seam #8)							
Feed - Lb/hr	853	853	727	852		853	
- 10^6 Btu/hr	11.15	11.14	9.48	10.85		10.78	
Coal - Btu/lb	13,077	13,058	13,035	12,740		12,637	
Sulfur (as fed), wt%	2.44	2.11	2.70	2.47		2.69	
Alkali							
Type	$CaCO_3$	$CaCO_3$	$CaCO_3$	$CaCO_3$	*$CaCO_3$*	$Ca(OH)_2$	*$Ca(OH)_2$*
Purity, %	92	92	92	92		96.44	
Feed - Lb/hr	72	77	56	66		48	
Ca/S Molar Ratio	1.02	1.26	0.84	0.92		0.87	
Combustion Air							
1st Stage Stoich., Vol.%	63	63	67	67		67	
% Overall Excess Air	121	125	114	125		124	
Steam Injection							
Lb steam/lb coal	0	0	0	0.17	*0.24*	0.23	*0.23*
Combustion Efficiency							
Carbon conversion, wt%	98.7	98.6	95.5	97.5		97.3	
Particulate							
1st. stage removal, wt%	51.1	61.9	47.2	42.4		42.7	
2nd stage fallout, wt%	8.9	4.1	8.2	10.6		9.1	
Cyclone removal, wt%	27.9	22.5	25.0	27.9		20.1	
Flue gas, wt% by diff.	12.1	11.5	19.5	19.1		28.1	
Sulfur Capture							
Molten slag, wt%	2.1	2.3	1.7	1.1	*1.5*	2.3	*4.8*
2nd stage fallout, wt%	1.9	1.1	1.6	2.5		1.9	
Cyclone particulate, wt%	4.0	3.2	3.0	4.5		2.0	
Fine particulate, wt%	4.9	3.0	27.8	18.3		39.0	
Overall, wt%	12.9	9.7	34.1	26.4	*35.5*	45.3	***58.8***
NO_x Emissions							
NO_x as NO_2, lb/10^6 Btu	0.31	0.31	0.28	0.36		0.38	
1st Stage Fuel Gas Analysis (measured w/Draeger tubes)**							
H_2S, ppmv	600-1000	350-600	600-800	750-1700		0	
SO_2, ppmv	30-50	15-50	20-40	1000-1500		0	
CS_2, ppmv	-	-	-	16		0	
NO_x, ppmv	100-250	0	50-400	100-700		100	
NH_3, ppmv	-	-	-	0		-	

* End of run sulfur in slag increased five-fold

** Several samples were taken per run

The sulfur capture for most of the run periods centered primarily on fly ash capture. However, during Run #11 when using hydrated lime rather than limestone, at low stoichiometric air rates near the end of the run, a five-fold increase in sulfur capture by the slag was observed. At that same time, 58.5 wt% of the coal sulfur was being captured. Runs #10 and #11 were set up to run at similar conditions, the only difference being that limestone was used as the alkali for sulfur capture in Run #10, and hydrated lime was used to capture sulfur in Run #11. In Figure 3, sulfur concentrations in the flue gas for both runs are shown versus time; the hydrated lime clearly was more reactive concerning sulfur capture. However, it had a smaller size distribution (more surface area) than the Greer limestone

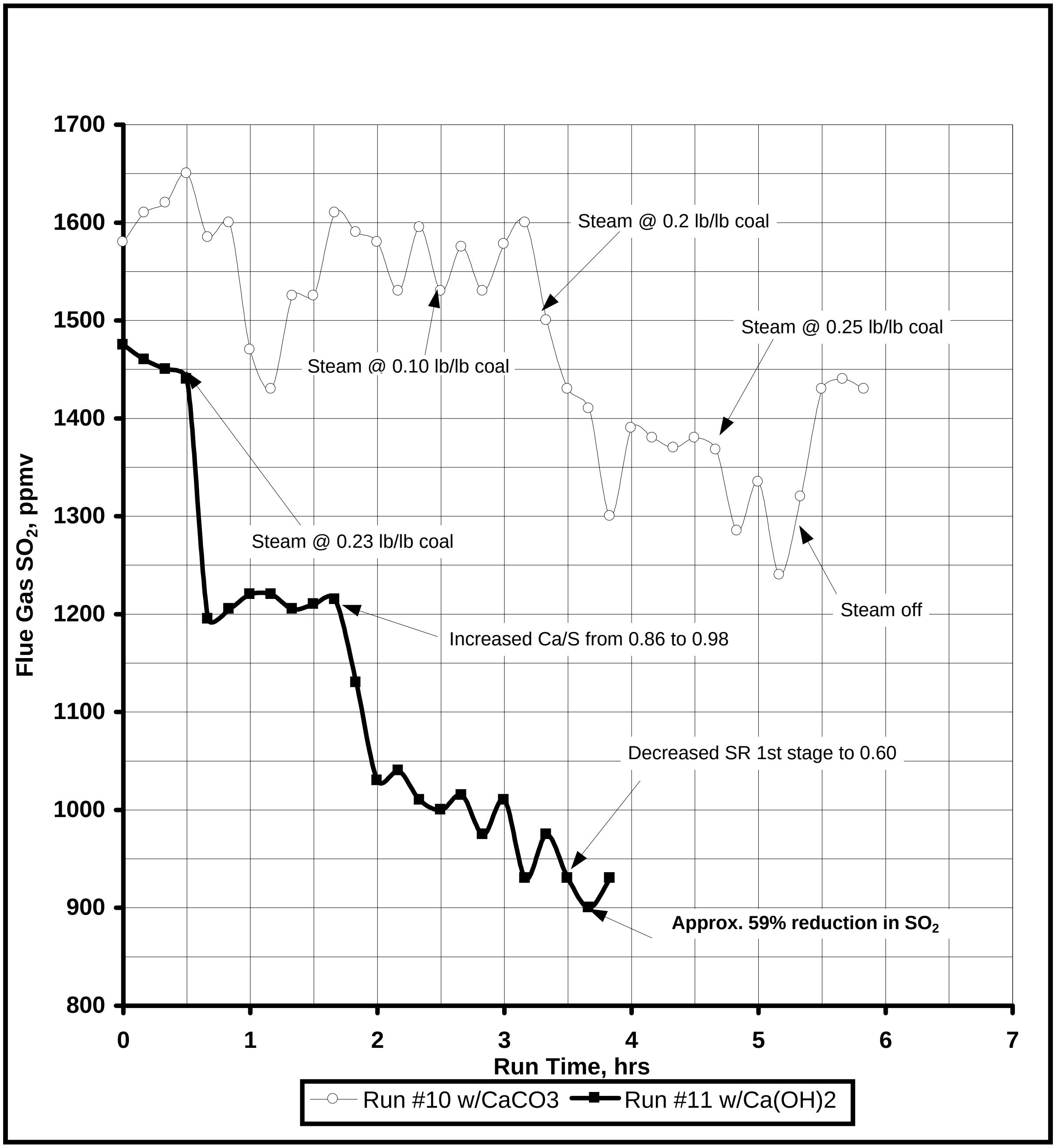

Figure 3. SO_2 Concentration in Flue Gas vs. Time

The nitrogen oxide emission rates were very low considering no design provisions were included in the second stage of combustion to reduce thermal NO_x production. The NO_x emission rates were approximately 10% of the amount that would be generated if all fuel bound nitrogen were converted to nitrogen oxides. A staged combustor, designed with a second stage to reduce thermal NO_x, should be capable of yielding one-half or less of the NO_x emissions experienced with the best low NO_x coal burners on the market today. There was a period of that is not shown wherein NO_x was reduced to 0.25 lb/MM Btu.

The combustion efficiency, 95.0 to 98.7-wt% carbon conversion, was fairly high taking into account design improvements that could be incorporated in the second stage of combustion. Further, unlike a conventional utility boiler that has a relatively large volume hot furnace zone, the flue gas from the second stage of combustion entered a low volume flue gas zone in the water-jacketed boiler. The boiler had no refractory lining, so the flue gas was quenched more rapidly than would occur in a conventional coal fired utility or industrial boiler.

The combustion efficiency of this system when applied to a conventional utility boiler should meet or exceed the combustion efficiencies experienced with the best pulverized coal fired burners, i.e. carbon conversion efficiencies of 99 to 99+ %.

The particulate capture in the first stage was not as good as expected; the highest capture being some 62-wt% of the coal ash plus alkali fed. With the pilot unit design the combustor internal gas baffle was slotted for slag removal. From the view port observation, it was clear that slag droplets were being blown through the slot into the boiler. During the pilot operations four different coal nozzles were tested and one of these gave superior results. The best performing nozzle will be incorporated in the new combustor design, which is briefly described in the next section.

New Combustor Design

Based on the knowledge accrued during the pilot plant operational phase, a new combustor design was developed that eliminated certain design constraints associated with the pilot unit combustor. A simplified diagram of the new design is shown in Figure 4. Many of the design parameters that are incorporated in the new combustor design are proprietary, but we can mention a few parameters that were incorporated. First of all, the pilot unit combustor had four coal burners, two located, one above the other, at two locations. With the multiple burner design, flame flow pattern interference occurred. The new design includes only one coal nozzle. The nozzle that will be used was the best performing nozzle that was tested during pilot plant operations.

Another design parameter was to construct the combustor in such a way that the hot fuel gases in the first stage remain in intimate contact with the slag until slag removal. The reason for doing this is to yield a low slag viscosity so that the slag will run freely out of the combustor into the water quench tank.

A further design parameter was to construct the combustor to yield a low-pressure drop to minimize air fan power requirements. The 1st stage of the new combustor is designed for approximately an 8 inch W.C. pressure drop. Even though this may be slightly higher than a conventional coal fired burner, only one half of the total air is introduced into the first stage. The remaining second stage combustion air can be delivered at a conventional wind box pressure.

There are several other key design parameters that must be employed to facilitate the capture of sulfur and further reduce NO_x beyond that experienced in the pilot plant. However, we are not at liberty to discuss these features.

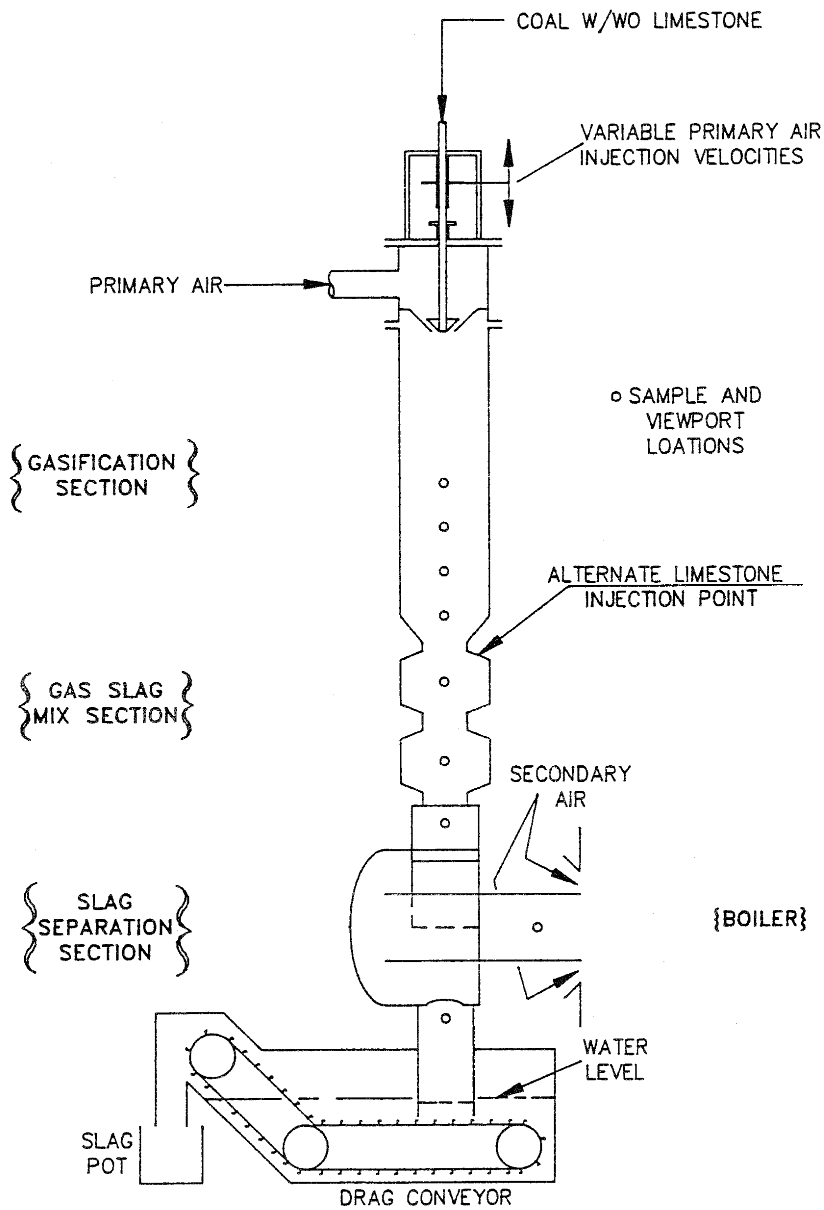

Figure 4. CAIRE Combustor New Pilot Unit Design

Economics

Prior to the construction and testing of the pilot unit, capital and operating costs were developed by an independent engineering-construction company that compared the CAIRE Combustor with a fluid bed boiler and a conventional coal fired unit with stack gas scrubber. The comparison was based on the construction and operation of a new 1 MM Btu/Hr steam capacity boiler.

From a capital cost perspective, the CAIRE Combustor was 67% of the cost of a conventional coal fired unit with scrubber, and 76% of the cost of a fluid bed boiler. In regard to operating cost, the CAIRE Combustor was 40% of a conventional coal fired unit with scrubber, and 60% of a fluid bed boiler.

The projected capital cost to retrofit CAIRE Combustor technology to a conventional coal fired unit is estimated, in 1992 Dollars (US), at $35 to $45/kW.

Technical Advantages of the CAIRE Combustor

There are several technical advantages of the CAIRE Combustor over alternative technologies. The key to these advantages is that pollutant emissions are controlled in the combustor proper.

Fuel bound and thermal NO_X control takes place in the 1st and 2nd stages of the combustor, respectively. The original pilot plant results showed NO_X emissions at approximately 0.3 lbs/MM Btu of coal fired, With the new combustor design it is expected that lower levels than these can be achieved.

The alkali additive enters the 1st stage, and reacts with sulfur species being liberated from the coal; here most of the sulfur and alkali are removed, along with the coal ash. The new CAIRE Combustor is designed to remove 70-80% of the coal ash plus alkali (including captured sulfur). The molten slag runs from the combustor into a sealed water quench tank. The sulfur captured by the slag is in a non-reactive eutectic, so conventional landfill disposal of the slag is all that is required, no special landfill linings are required. Whereas the highest sulfur capture experienced in the pilot unit operation only reached 58.5%, through data and thermochemical equilibria analyses it was determined that higher sulfur capture is possible with a newly designed combustor. With the new design, sulfur capture levels of 70-95% are expected.

Staged combustion of coal, with the advanced technology represented with the CAIRE Combustor, holds the key to low cost and environmentally acceptable high sulfur coal combustion.

Future Plans of Development

Florida Power Corporation and the Energy and Environmental Research Corporation are currently evaluating the development steps for the CAIRE Combustor. The first stage of development will be the design and construction of a pilot unit based on the new combustor design. Following successful pilot plant results, the next stage will be commercial demonstration of the technology.

Note: There has been some minor editing of the original paper