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PROCEEDINGS

Volume II

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Coal-Fired High Performance Power Generating System

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INTRODUCTION

The need for generating electric power with increased efficiency and decreased emissions is widely accepted. This is especially true for coal-burning power plants. In fact, according to the DOE's National Energy Strategy of 1992, the use of coal for power generation will increase steadily over the next 50 years, doubling by the year 2030, even for a minimum growth scenario. When this growing demand for coal is considered along with the fact that by the year 2000 44 percent of the coal-fired powerplants in the U. S. will be 30 years old or more, the opportunity for new systems and designs becomes evident

For the short term (approximately 5 years) the low price of natural gas favors the use of gas turbine combined cycle plants as a reasonable alternative for filling growing demands for electric power. In the longer term the limitations on infrastructure and perhaps the increased cost of natural gas will necessitate a return to coal-fired designs. Several options are available in addition to the normal pulverized coal steam boilers. The use of pressurized fluidized bed combustion (PFBC) in a combined cycle and the integrated gasification combined cycle (IGCC) have received considerable attention in recent years. While these approaches appear to be attractive in some applications, they are limited by difficulties with hot gas cleanup and high capital costs.

All the proposed options for coal-fired powerplants have technical risks and uncertainties in costs, both capital and operating. While direct comparisons of the various alternatives are difficult, some guidelines are possible. Any design must be capable of using a range of coals, suitable for large installations >300 MW_e and be economically viable early in the 21st century. A recent study by the International Energy Agency (IEA) indicates all of the new technology approaches have difficulties in producing electricity at competitive prices. Only when the additional requirements of increased efficiency and reduced emissions are considered, do most of these technologies have increased appeal.

The primary objective of this program is to demonstrate the technical and economic feasibility of an advanced power concept for a high performance power-generation system (HIPPS) by: 1) producing conceptual designs for key components; 2) comparing the economics of our concepts with alternative approaches, and 3) preparing a development plan that will lead to a commercial demonstration before the end of the century. Our plan is to demonstrate the feasibility of the high temperature combustor/air heater system (HITAF) and prepare a design for a commercial generating plant to instill confidence in the economic viability of the UTRC design approach.

Our HIPPS design has been planned to meet the requirements set by DOE for the commercial plant. These specifications are:

- a minimum conversion efficiency, coal pile to busbar, of 47%
- NO_x less than 0.15 lbs (as NO_2) per million BTU of fuel input
- SO_x less than 0.15 lbs (as SO_2) per million BTU of fuel input
- particulates less than 0.0075 lbs per million BTU of fuel input
- all solid waste streams must be benign
- initially fuels will be coal and natural gas, with coal providing at least 65% of heat input and ultimately 95%
- the commercial plant will have a 65% annual capacity factor and generated electricity at a 10% lower cost

CYCLE OPTIMIZATION

Preliminary cycle optimization studies have identified a baseline plant concept, shown schematically in Fig. 1, consisting of two HITAF units, one gas turbine and a single steam turbine producing an overall plant output of about 268 MWe at a projected heat rate of 6867 BTU/kWh.

This diagram and the accompanying table of state points (Table 1) serve as the basis for the commercial plant design. The performance of the system is estimated to 48.1% (HHV).

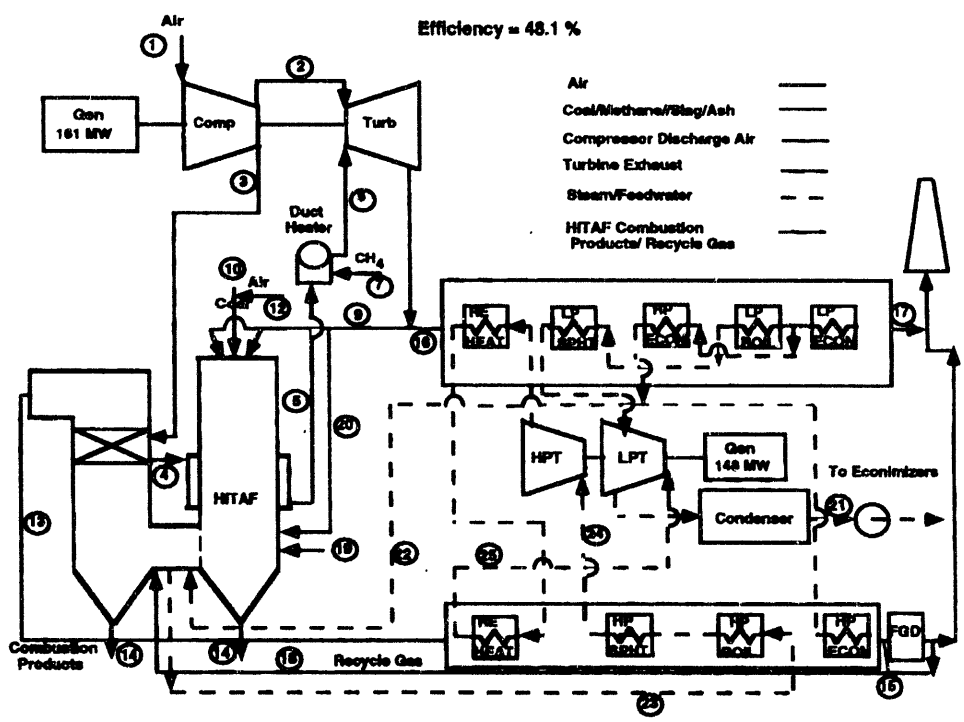


Figure 1. Baseline HITAF System.

HITAF CONVECTIVE AIR HEATER

Preliminary concept screening for various convective air heater configurations has been completed. A finned-tube-sheet design (Fig. 2) has been selected for further study. The tube sheets are spaced 4" apart and

Table 1. State Points – Baseline System

Point No.	Fluid	Temp - F	Pressure - PSIA	Flow - lb/sec	Comments
					Points Same as Bechtel
1	Air	59	14.7	918	
2	Air	731	236	191.6	
3	Air	731	236	726.5	
4	Air	1300	232	726.5	
5	Air	1700	229	726.5	
7(6)	Methane	611	275	8.58	After Heater
8	Air	2495	225	736.1	
9	GT Exhaust	1005	15.6	926.6	
10	Coal	138	22	30.13	
12(11)	Air	138	22	52.3	After Heater
13	Flue Gas	1256	14.8	686.1	
14	Solid Waste			3.5	Sum of Both Streams
15	Flue Gas	240	14.4	686.1	
16	GT Exhaust	1005	15.6	289.5	Stoichiometric Flow
17	GT Exhaust	115	14	431.3	T0 Induced Draft Fan
					Additional Points
18	Flue Gas	258	15.1	233.9	Recycle for Quench
19	Coal Fines				Reburn - Inc in 10 (8%)
20	GT Exhaust	1005	15.6	65.6	Excess Air (20%)
21	Condensate	91	0.72	214	
22	Feedwater	682	2750	214	
23	Wet Steam	682	2670	214	From HITAF Waterwall
24	Steam	1000	2400	214	
25	Steam	1000	540	211	

consist of 1″ I.D. cylindrical tubes spaced 3" on center in the baseline design. Four variants of this design are to be evaluated with the objective of minimizing ash deposition on the surfaces of the heat exchanger. The four designs are:

1) In-line cylindrical tubes (Fig. 3)
2) Staggered cylindrical tubes (Fig. 4)
3) In-line, 5:1 aspect ratio ellipsoidal tubes (Fig. 5)
4) Staggered, 5:1 aspect ratio ellipsoidal tubes (Fig. 6)

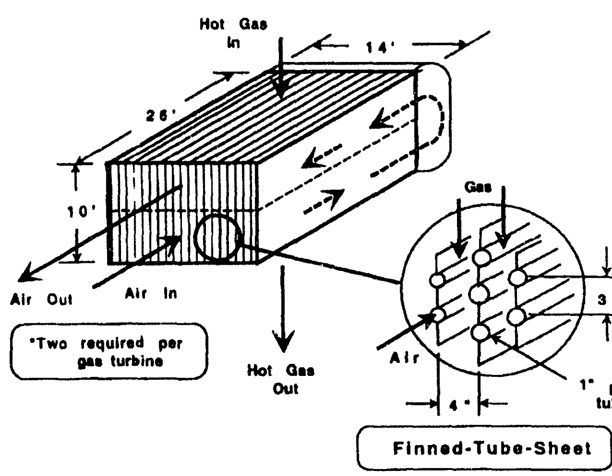
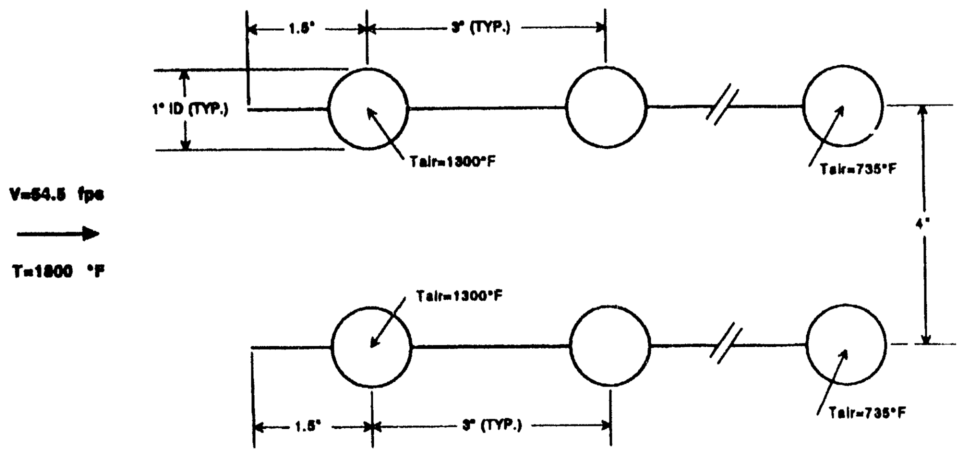


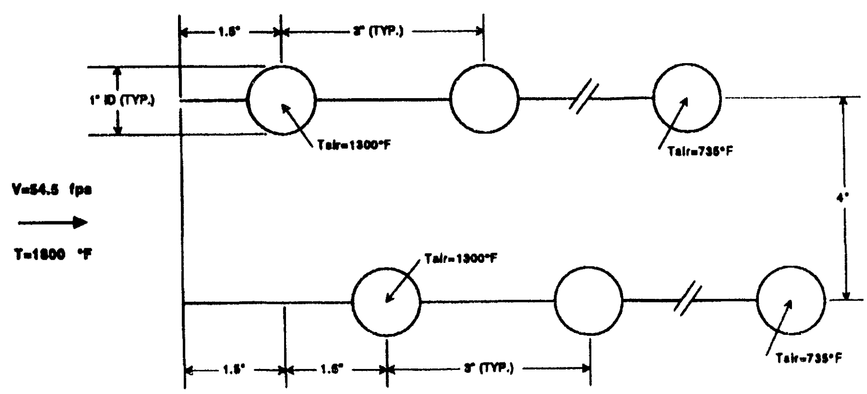
Figure 2. Convective air heater.

Note that the elliptical tubes have been sized to provide the same cross-sectional area as the cylindrical tubes. The hot gas inlet conditions are: p=1 atm, T=1800°F and V=54.5 ft/s. Air temperatures inside the tubes are 1300°F and 735°F at the hot gas inlet and outlet of the heat exchanger, respectively. Wall temperatures are estimated to be 1445°F and 885°F at the inlet and outlet, respectively. Two cases for ash particle mass loading are given in Table 2.



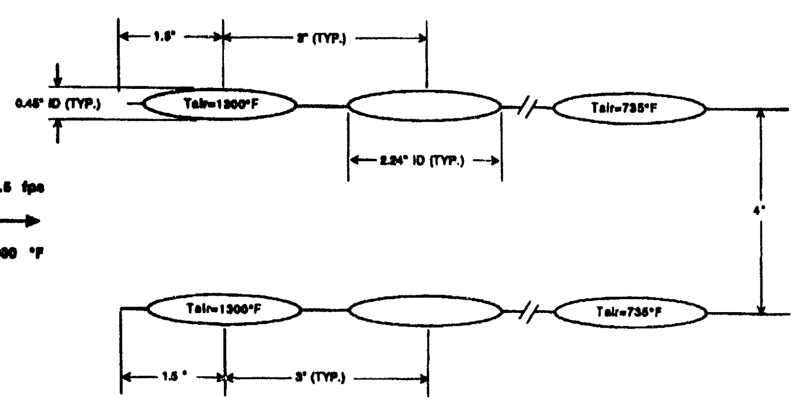
NOTES: 1) Repeat pattern 40x for a total length of 10 feet
2) Tube thickness 0.25"
3) Fin (or web) thickness 0.50"

Figure 3. In-line tube array.



NOTES: 1) Repeat pattern 40x for a total length of 10 feet
2) Tube thickness 0.25"
3) Fin (or web) thickness 0.50"

Figure 4. Staggered tube array.



NOTES: 1) Repeat pattern 40x for a total length of 10 feet
2) Tube thickness 0.25"
3) Fin (or web) thickness 0.50"

Figure 5. In-line tube array – 5:1 aspect ratio ellipsoidal tubes.

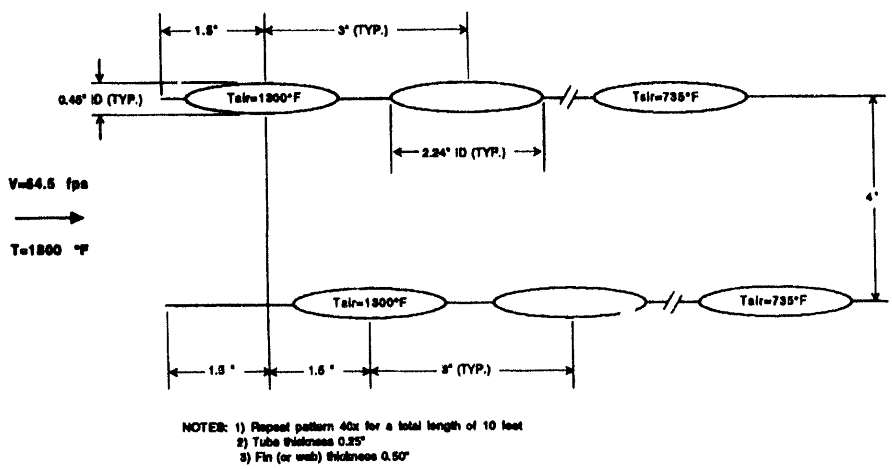


Figure 6. Staggered tube array – 5:1 aspect ratio ellipsoidal tubes.

Table 2. Ash particle size distribution at inlet of HITAF convective air heater.

Particle Size Range (μm)	Ash Loading [kg/m³] Case 1 (before Slag Screen)	Ash Loading [kg/m³] Case 2 (after Slag Screen)
1 - 2.5	7.71E-06	9.31E-06
2.5 - 5	8.96E-05	1.08E-04
5 - 10	2.40E-04	2.60E-04
10 - 20	3.69E-04	1.78E-04
20 - 40	3.08E-04	0
40 - 80	1.38E-04	0
TOTAL	1.15E-03	5.55E-04

Computational fluid dynamics (CFD) is being used to analyze the particle-laden flow within the heat exchanger to provide estimates of the rate of deposition of particulates on the heat exchanger surfaces. The code being used is FLUENT, a commercially developed code that solves the governing conservation equations in body-fitted coordinates using a collocated grid method; that is, all flow variables, including the Cartesian velocity components, are stored at the same grid locations.

The code was used to predict the flow distribution for heat exchanger designs that incorporate tubes of either circular or elliptical cross-sectional area arranged in rows in which the tubes are aligned or staggered with respect to each other. The ratio of major to minor axis length was five for the elliptical tubes. Generally, the computational domain consisted of three tubes in each row, although a case was also run in which five tubes were analyzed to determine if the number of tubes affects the particulate distribution rate. The effects of different values of free stream turbulence intensity and tube wall temperature were also examined.

All cases were run with an inlet velocity of 54.5 ft/s and an inlet temperature of 1800 F. The cases are listed in Table 3.

Table 3. Geometry and flow conditions.

Case	Cross-section	Number	Arrangement	Turb. Int. percent	T_w °F
HX1	Circ.	3	Inline	1	1445
HX2	Circ.	3	Inline	1	885
HX3	Circ.	3	Inline	10	1445
HX4	Circ.	3	Staggered	10	1445
HX5	Circ.	5	Inline	10	1445
HX6	Ellip.	3	Inline	10	1445
HX7	Ellip.	3	Staggered	10	1445

Initial estimates of particulate deposition rates were obtained by assigning a spatially uniform distribution of particles at the inlet plane; the particle size distribution was representative of distributions with or without slag screens. FLUENT provides the capability to compute particle trajectories either deterministically or stochastically. In the deterministic model, particle trajectories are computed using the mean flow field only. In the stochastic model, the trajectories are calculated with the effects of random fluctuations of the gas due to turbulence included. Thus, it can be expected that the trajectories of larger particles are determined essentially by inertial effects (that is, they can be computed essentially from the mean flow field) while the trajectories for smaller particles will be influenced by turbulent fluctuations.

Generally, it was determined that the results were insensitive to the tube temperature assumed; the remaining cases were run using the higher temperature, representative of the tubes in the upstream section of the heat exchanger.

Increase turbulent intensity was found to increase the rate at which smaller particles are trapped by the surface due to turbulent diffusion. The higher value of turbulent intensity (ten percent) was used for the remaining cases. This value is more representative of the levels encountered in industrial equipment.

Stream lines for cases HX3, HX4, HX6 and HX7 have been calculated. For the inline arrangement, it was necessary to compute the flow in only one-half of the passage between tube banks. For the circular tubes, the recirculation zone on the downstream side of each tube is evident. Essentially no recirculation zones are predicted to occur in the passages using the more aerodynamic elliptical tubes.

Trajectories for some of the larger (30 micron) particles are shown in Figs. 7 and 8 for the circular and elliptical tubes, respectively. For these larger particles, the effects of turbulent fluctuations are relatively small although these effects cannot be ignored completely, as is evident by the fact that some of the trajectories appear to cross at downstream locations. For the circular tube case (Fig. 7), particles with initial positions essentially below the top of the tubes impinge on the upstream side of the first tube; the outer particles bypass the tube row completely.

It is found in other simulations involving a larger number of particles that a few of the particles in the outer region may enter the recirculation zone. One implication of these results is that it may be beneficial to replace the first tube with a sacrificial rod that can be used to remove the larger particles that are otherwise likely to impinge on the heat exchanger.

Note that similar results were obtained for case HX5 with five tubes. Obviously, deposition of large particles becomes unimportant farther downstream as particles are removed by the upstream tubes.

For the elliptical tube case with 30 micron particles (Fig. 8), it is seen that the first tube is much less effective in removing particles. It is anticipated that several of the tubes in this case will accumulate deposits of larger particles.

Results using the smallest particles considered (1.25 microns) are presented in Figs. 9 and 10 for the circular tube and elliptical tube cases, respectively. Particle dispersion due to turbulent diffusion is evident here. For the circular tube case (Fig. 9), particles are seen to impinge on the surface between tubes. Preliminary results using a much greater number of realizations suggest that small particles will impinge more or less uniformly on the entire surface in the upstream section of the heat exchanger. For the elliptical tube case (Fig. 10), the same situation is likely to occur.

Essentially similar results were obtained for the staggered tube cases. The tube banks are far enough apart that the interaction of the particles with either surface occurs independently.

During the next reporting period, more detailed particle dispersion results will be obtained and will be used to estimate deposition rates. The most favorable design will be selected for further analysis. Conjugate heat transfer calculations will be performed to evaluate heat transfer performance and to determine material temperatures for input to a finite element stress analysis code.

Ash deposition rates for cases HX3 and HX6 have been calculated. The results show that the highest deposition rates occur on the first tube and that this rate is about a factor of two higher for the circular tubes than for the elliptical ones. There is no significant difference in deposition rates between the in–line and staggered configurations. Of course, the present analysis does not account for the reduction in cross–sectional flow area which will occur as the deposits build on the tubes. Conceptually, the staggered arrangement should be advantageous in this regard. The first tube captures the majority of the 15 μm and larger particles in the flow. The presence of a slag screen upstream of the heat exchanger serves to eliminate particles greater than about 20 μm which results in a factor of two reduction in the particulate mass loading of the heat exchanger inlet stream. The resulting reduction in the deposition rate on the first tube is a factor of four for circular tubes and a factor of three for elliptical tubes. These results clearly show that a slag screen should be included in the design and also that it will be beneficial to replace the first tube with a sacrificial circular rod that can be used to remove the larger particles that are otherwise likely to impinge on the heat exchanger.

Deposition rates on the downstream tubes, about 0.025 inches/hr, are over an order of magnitude lower than for the first tube. The analysis is conservative, since 100% sticking is assumed (impaction=deposition). A soot blowing frequency of approximately once every 10 hours will be required to keep the ash layer thickness below 0.25 in. on the downstream tubes.

Based on these results, a staggered, elliptical tube, air heater design has been selected for further study. Conjugate heat transfer calculations will be performed to evaluate heat transfer performance and to determine material temperatures for input to a finite element stress analysis code.

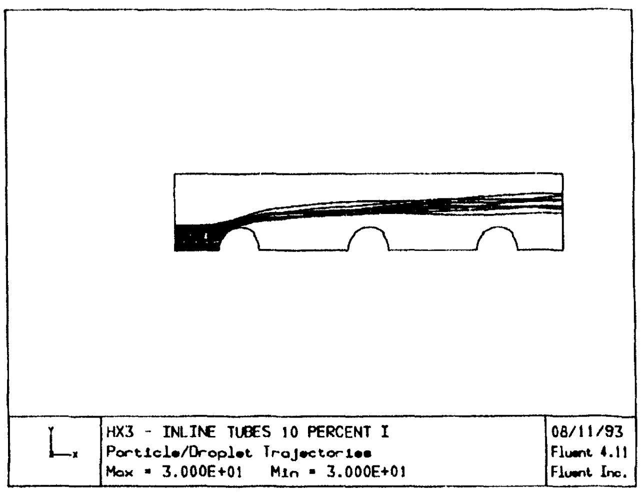


Figure 7. In-line tubes 10 percent I.

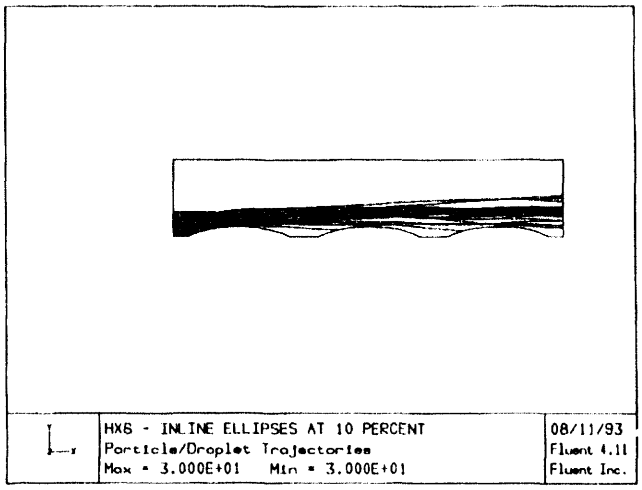


Figure 8. In-line ellipses at 10 percent.

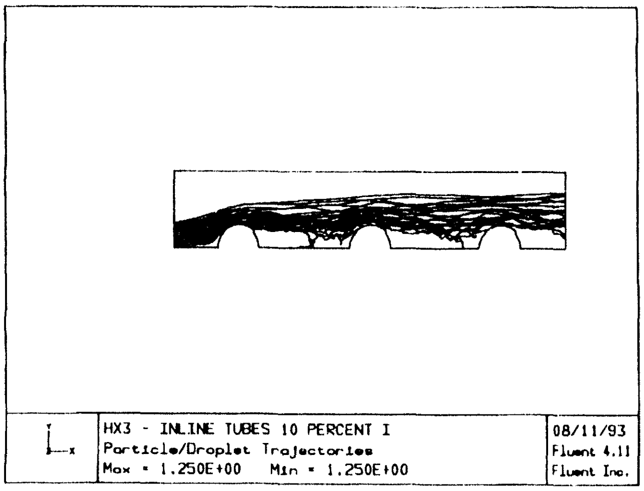


Figure 9. In-line tubes 10 percent I.

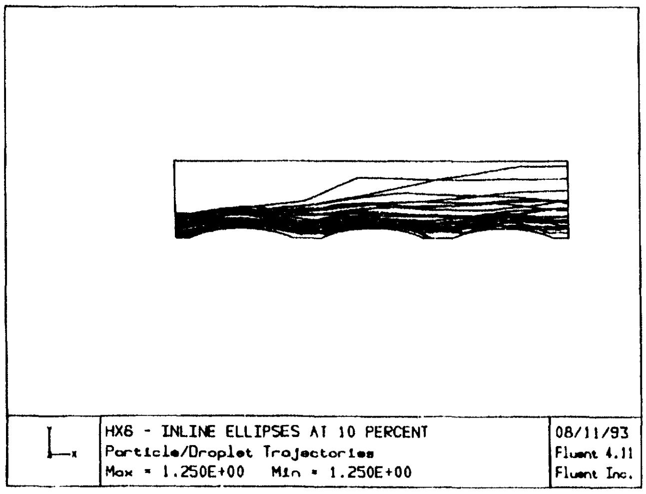


Figure 10. In-line ellipses at 10 percent.

MATERIALS SUPPORT FOR THE DEVELOPMENT OF HIGH TEMPERATURE ADVANCED FURNACES (HITAF) - A COMPARISON OF SELECTED MECHANICAL PROPERTIES FOR THREE SiC-BASED CERAMICS

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INTRODUCTION

The purpose of this project is to compare structural ceramic materials proposed for use in the air heater of a coal fired high temperature advanced furnace (HITAF) for power generation. The work will provide necessary initial strength and statistical material parameters for design of a prototype system. Two teams are currently funded by Pittsburgh Energy Technology Center (PETC) under the Combustion 2000 program to develop such a system. One team is led by the United Technologies Research Corporation, and consists of UTC Turbo Power and Marine Division, Bechtel, Oak Ridge National Laboratory (ORNL) and a Joint Venture of Physical Sciences Inc. (PSI) Technologies, Reaction Engineering International (REI) and University of North Dakota Energy & Environmental Research Center (UNDEERC); the other team is led by Foster Wheeler Development Corporation, and members are AiResearch Division of AlliedSignal Aerospace Systems & Equipment, Research Cottrell, TRW, General Electric and Bechtel.[1, 2]

MATERIALS AND EXPERIMENTAL PROCEDURE

The following key properties are being evaluated in the present task: (1) Fast fracture strength at room temperature, 1100°C, and 1400°C; (2) Statistical analysis in the form of a Weibull analysis; (3) Necessary fractography; (4) Slow crack growth properties evaluated by the dynamic fatigue method; and (5) Creep/creep-rupture effects measured through interrupted static fatigue experiments. Initial corrosion experiments are being performed in cooperation with UNDEERC, where ORNL is performing fast fracture measurements of corroded specimens.

Three materials have been compared. These are β-SiC from Coors Ceramics Company, NT230 siliconized SiC from Saint-Gobain/Norton and Lanxide DIMOX $SiC_{particulates}/Al_2O_3$ from DuPont Lanxide Composites. The manufacturers' data on material properties are summarized in Table 1. β-SiC is sintered silicon carbide with a fine grain structure and high density. NT230 SiC is siliconized silicon carbide and contains free silicon alloy (8 vol%) and some residual porosity. The SiC_p/Al_2O_3 which is manufactured by the Lanxide Direct Oxidation process (DIMOX) contains 48 vol% SiC_p, 38 vol% Al_2O_3 and 13 vol% Al-alloy, and some residual porosity. The SiC ceramics were tested as machined while the Lanxide DIMOX was reoxidized by the manufacturer after machining.

The fracture strength of ceramic materials is most commonly measured in four-point flexure.[3] In this test, a specimen of 4x3x50 mm is subjected to bending in a fixture providing an inner span of 20 mm and an outer span of 40 mm. The specimen is loaded to fracture while load and deflection are monitored, and the flexure strength is calculated according to standard beam theory. The flexure method offers the possibility of testing a large number of samples at a reasonable price, and, since the load train arrangement is relatively simple, several specimens may be tested simultaneously.

Table 1. Properties of the selected materials.

Coors ß-SiC Sintered Silicon Carbide (SiC), Coors Ceramics Company	
99.9% SiC	Density 3.1 g/cm^3
	Thermal Conductivity 110 W/mK
	Thermal Expansion 4.4×10^{-6} /°C
	Fracture Toughness 3.0 $MPam^{1/2}$
NT 230 Siliconized Silicon Carbide (SiC), Saint-Gobain/Norton	
8 Vol% Si - alloy	Density 3.1 g/cm^3
90 Vol% SiC	Thermal Conductivity 120 W/mK
2 Vol% Pores	Thermal Expansion 4.4×10^{-6} /°C
	Fracture Toughness 3.0 $MPam^{1/2}$
Lanxide DIMOX Aluminum Oxide with Silicon Carbide Particles, DuPont Lanxide Composites	
48 Vol% SiC	Density 3.4 g/cm^3
38 Vol% Al_2O_3	Thermal Conductivity 60 W/mK
13 Vol% Al - alloy	Thermal Expansion 6.8×10^{-6} /°C
1 Vol% Pores	Fracture Toughness 4.5 $MPam^{1/2}$

Weibull analysis is the statistical tool most commonly used to analyze fracture data for structural ceramics.[4] Due to the brittle nature of ceramic materials, the fracture strength of a set of specimens may vary as much as 100% from the average strength, necessitating a statistical analysis of the data. The Weibull modulus, m, and the Weibull scaling factor, σ_0, will be obtained by the maximum likelihood method.[5,6,7]

The term "fatigue" as used for structural ceramics is different from that commonly used for metals. For ceramics the term fatigue is often used to describe the decrease in strength due to the combined action of *static* stress and degrading environment. The mechanism which causes this is known as slow crack growth (SCG) and is the growth of small preexisting cracks or voids at stress levels less than those needed to cause catastrophic failure. This happens because the individual atomic bond strength is decreased by exposure to certain environments. Eventually, a small crack will grow to a size large enough to cause catastrophic failure at the given stress level. In order to predict the lifetime for components in a given environment, the velocity at which cracks grow at a given stress in the specific environment must be known.[8]

A static fatigue experiment is performed by loading a specimen to a given stress in the given environment and recording the time to failure. This type of test can be extremely time consuming (> 1000 h) and several specimens are needed at each condition in order to obtain the required statistics. A common way to accelerate the test is to perform a dynamic fatigue experiment in which the specimens are loaded to failure at several given stressing rates and the fracture strength is recorded as a function of applied stressing rate.[9] If a material is susceptible to SCG, the fracture strength will decrease as a function of decreasing stressing rate, and by applying fracture mechanics, the SCG parameters may be determined. In the case of the dynamic fatigue experiment, the time to failure is:

$$t_f = B\,(n+1)\,\sigma_i^{n-2}\,\sigma_f^{-n} \tag{1}$$

and the fatigue strength is a function of the stressing rate and the SCG parameters n and B:

$$\sigma_f^{n+1} = B\,(n+1)\,\sigma_i^{n-2}\,\dot{\sigma} \tag{2}$$

where

t_f is time to failure,

σ_f is fatigue strength,

σ_i is fast fracture strength (inert), and

$\dot{\sigma}$ is applied stressing rate.

The fatigue parameter n is then obtained from a graph of $\log\sigma_f$ vs $\log\dot{\sigma}$. Combining the dynamic fatigue equations with the Weibull statistics, a time to failure at a given level of failure probability can be predicted:

$$\ln t_f = \ln B + \frac{n-2}{m} \ln\ln\left[\frac{1}{1-P_f}\right] + \ln(n+1) + (n-2)\ln\sigma_0 - n \ln \sigma_f \quad (3)$$

where

P_f is the level of probability.

Hence, it is seen that the estimated time to failure is a function of the slow crack growth parameter n and the Weibull parameters m and σ_0 for the inert strength distribution.

The Weibull theory assumes that all failures used to generate the Weibull parameters are similar in nature, i.e., stem from the same type of flaws. This may not always be the case, most notably there will be a difference in flaws stemming from the powder pressing and sintering process and flaws stemming from machining and handling of the components. The purpose of performing careful fractography is to identify the different sources of failure origins, and take that information into account by appropriately censoring the Weibull distributio[illegible] Further, fractography is a necessary tool in assessing the SCG behavior. If strength degradation as a function of time is observed, the microscopic investigation can aid in determining the mechanisms for the degradation, whether SCG or other strength degrading mechanisms are operative.

As a first measure of the materials resistance to coal ash corrosion, coupons of two of the materials and two additional ceramics of interest were exposed in a muffle furnace at UNDEERC. The materials were covered with known amounts of coal ash of two types; Wyodak and Illinois #6 at 1093°C and 1370°C for 300 h. After exposure the corrosion behavior was evaluated by microscopy at UNDEERC,[10,11] and the coupons were then machined into flexure bars keeping the exposed tensile surfaces intact, and the residual strength measured at room temperature at ORNL. The fracture strength and failure mechanisms were then evaluated as a function of exposure environment and exposure temperature.

EXPERIMENTAL RESULTS AND DISCUSSION

Fast fracture of the unexposed materials as a function of temperature is shown in Fig. 1. The Weibull distributions of the three materials are shown in Figs. 2, 3, and 4 for room temperature, 1100°C, and 1400°C, respectively. The measured strengths as a function of stressing rate are shown in Figs. 5 and 6 for the three materials at 1100°C and 1400°C, respectively.

NT230 at 1400°C was the only material-temperature combination which showed any strength degradation over time and the SCG parameter n was calculated to be equal to 15.5 according to Eq. 2. The Lanxide DIMOX material could only be tested up to stressing rates of 0.01 MPa/s at 1400°C because at the slower stressing rates creep became so pronounced that the four-point flexure fixtures could no longer accommodate the specimens. Also at the 0.01 MPa/s stressing rate the creep was measurable, and the strength values calculated according to beam theory are therefore overestimating the strength of Lanxide DIMOX at this condition.

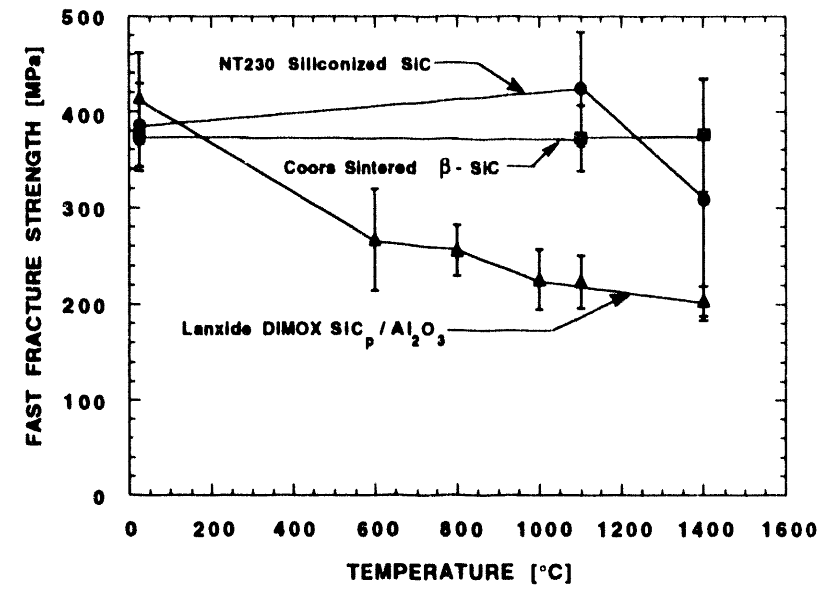

Figure 1. Fast fracture strength as a function of temperature for the three ceramics.

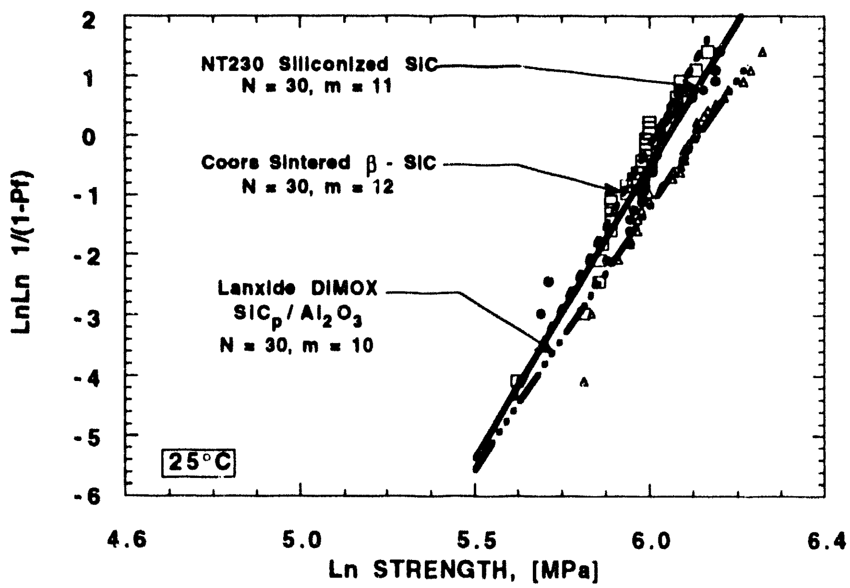

Figure 2. Weibull distribution of the room temperature fast fracture strength for the three ceramics.

The fractography results confirmed the dynamic fatigue results. In general the failure mode for Coors β-SiC was fast fracture from pores in the microstructure, and this did not change as a function of stressing rate or temperature, see Fig. 7. Lanxide DIMOX failed in general from metal rich areas, but at 1400°C at the slower stressing rates, creep became pronounced and the specimens failed due to accumulated creep damage (Fig 8.). NT230 was delivered to ORNL in two batches, probably with a slight difference in Si - alloy content or composition. At room temperature and at 1100°C the failure modes for both batches were similar; fast fracture from pores in the microstructure. At 1400°C there was a clear difference between the two batches in the fast fracture test; one batch failing from a combination of pores and metal-rich inclusions, the other failing from pores as was observed at the lower temperatures. At the slower stressing rates where strength degradation was observed, the specimens failed from metal-rich areas that had grown in size during the test, and the batch difference became insignificant, see Fig. 9.

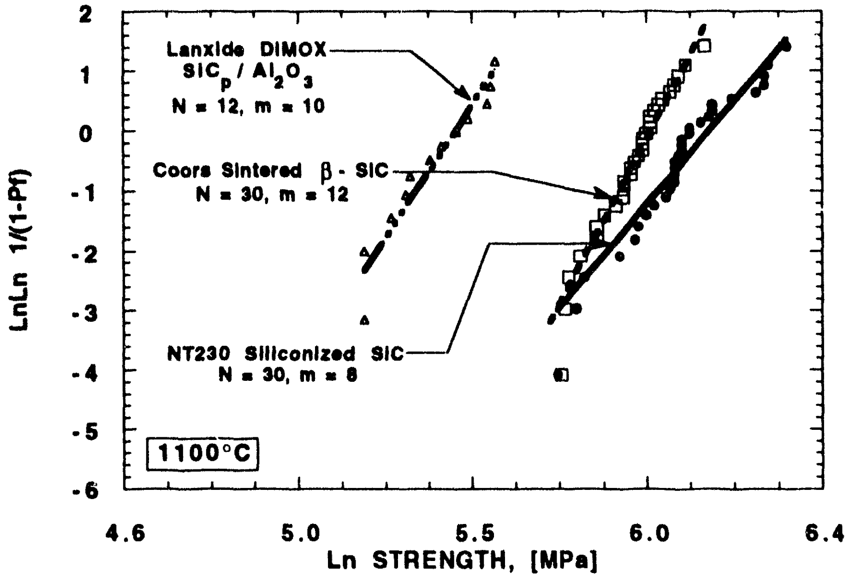

Figure 3. Weibull distribution of the 1100°C fast fracture strength for the three ceramics.

The strength of unexposed specimens of the three ceramics under consideration as a function of temperature is as expected for these materials. The Coors β-SiC showed no strength reduction at the temperatures under consideration, while the two other materials exhibit a drop in strength at the temperatures where the metal in these materials softens and melts. The Weibull analyses of the three ceramics reveal some important differences. At room temperature both the Weibull modulus and characteristic strength are comparable for the three materials, as can be seen in Fig. 2. At the elevated temperatures, however, it is seen that the Weibull modulus stays relatively unchanged for Lanxide DIMOX and Coors β-SiC, while for NT230 a gradual reduction of the Weibull modulus is seen. At 1400°C the Weibull modulus was m = 2.8, an unacceptably low value for a structural material. The reasons for this can be found by investigating the microstructures and by performing careful fractography. The lower Weibull modulus at 1100°C and 1400°C for NT230 is due to the variability in the size of pores in the material and due to the fact that the NT230 was delivered in two batches with slight difference in Si-alloy content or composition. This effect is most pronounced at 1400°C as seen in the fast fracture results. The dynamic fatigue experiments, shown in Figs. 3 and 4, show that there is no strength reduction with time at 1100°C for any of the ceramics. At 1400°C a pronounced strength reduction is seen for NT230. This strength reduction is due to the subcritical growth of pore-like cracks, often containing metal rich inclusions.

As a result of the fractographic investigation, the fast fracture Weibull distribution obtained at 1400°C was censored, resulting in a change in the Weibull modulus from 2.8 to 7.4. This is illustrated in Fig. 10, where the Weibull distributions for NT230 at all the stressing rates at 1400°C are shown.

By combining the SCG parameters n and B obtained from the dynamic fatigue experiments with the Weibull data obtained at the fast stressing rate, Eq. 3 can be utilized to predict the lifetime of a specimen at a given stress level. This is illustrated in Fig. 10 for NT230 at 1400°C where it can be seen that for the uncensored set of NT230 the lifetime will vary widely from 0 to 14 h, depending on the desired level of certainty of the prediction. Censoring the data, which resulted in higher Weibull parameters, will also improve both the lifetime and the uncertainty of the prediction that is made, see Fig. 11.

The materials exposed to coal ash at UNDEERC were fractured at room temperature in four point flexure. The resulting fracture strengths are given in Table 2 and illustrated in Fig. 12.

The coal ash exposure experiments show several important things. The present experiments were intended as an initial set of conditions to compare several materials, coal slags and temperatures. By exposing the ceramics to static coal slag in a muffle furnace, significantly different levels of corrosion attack were observed, and reduction in strength values was observed for some of the combinations of ceramics, coal ash and temperature. The subsequent fractography showed that the materials which experienced a strength reduction also had a change in failure mode and that the coal ash in some cases produces severe corrosion pits. The material which had strengths that were unaffected by the exposure (Lanxide DIMOX) failed in a similar manner before and after exposure. A thorough discussion of the coal ash corrosion mechanisms can be found elsewhere.[10,11]

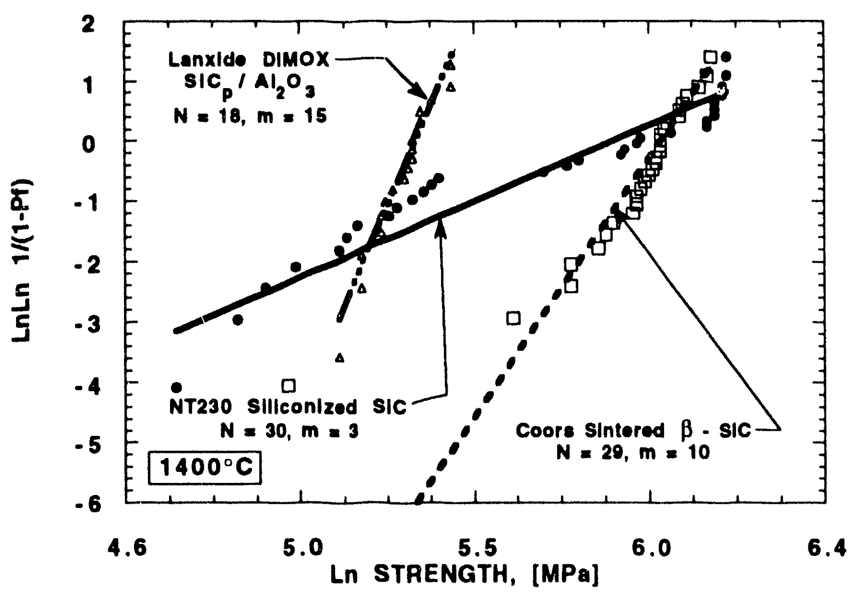

Figure 4. Weibull distribution of the 1400°C fast fracture strength for the three ceramics.

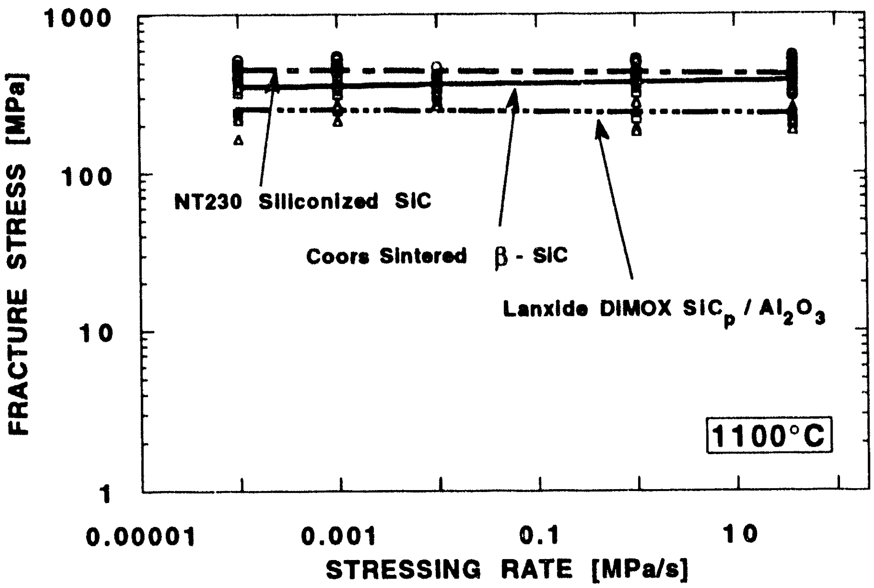

Figure 5. Strength as a function of stressing rate at 1100°C.

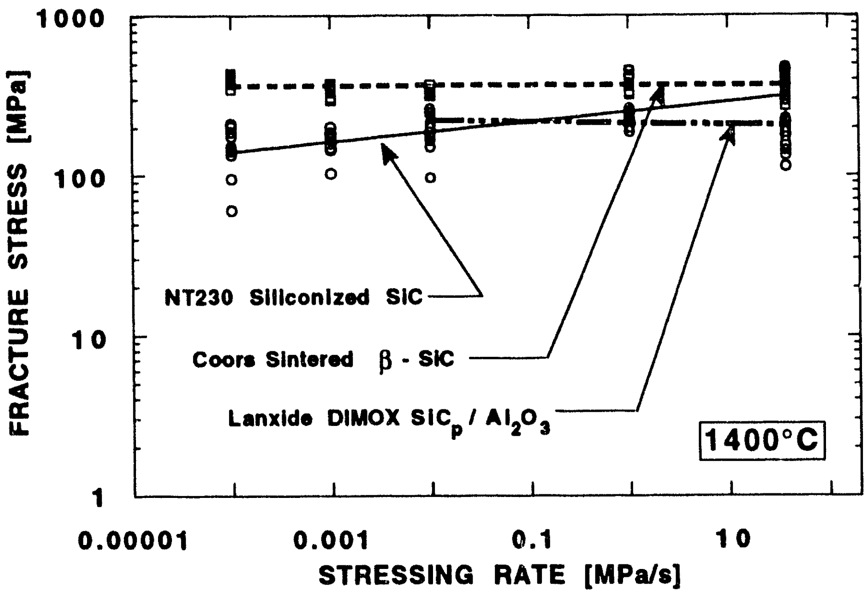

Figure 6. Strength as a function of stressing rate at 1400°C.

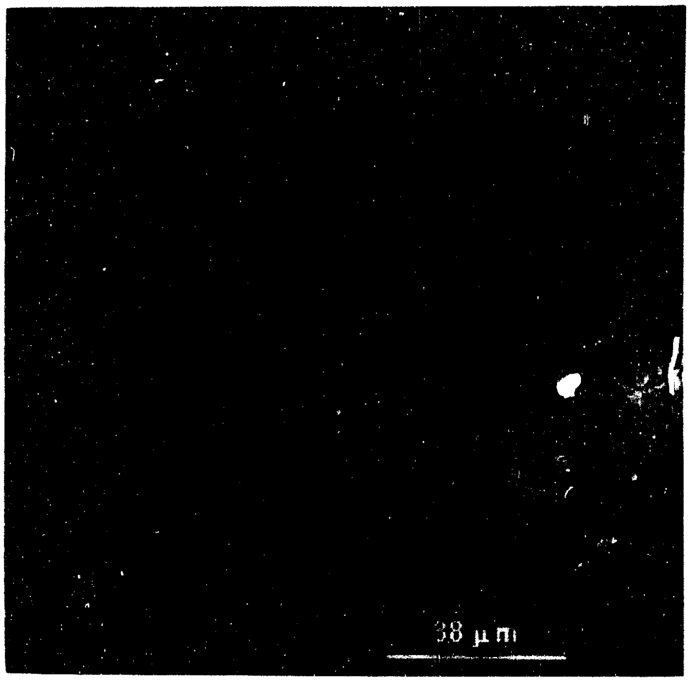

Figure 7. Typical fracture initiating flaw in Coors β-SiC at 1400°C; a pore located near the surface.

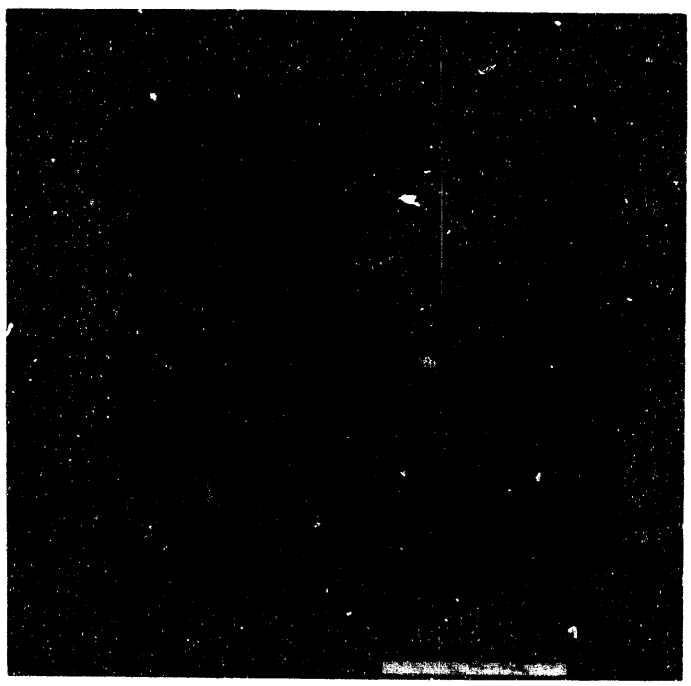

Figure 8. Creep damage in Lanxide DIMOX after failure at 1400°C
at a stressing rate of 0.01 MPa/s.

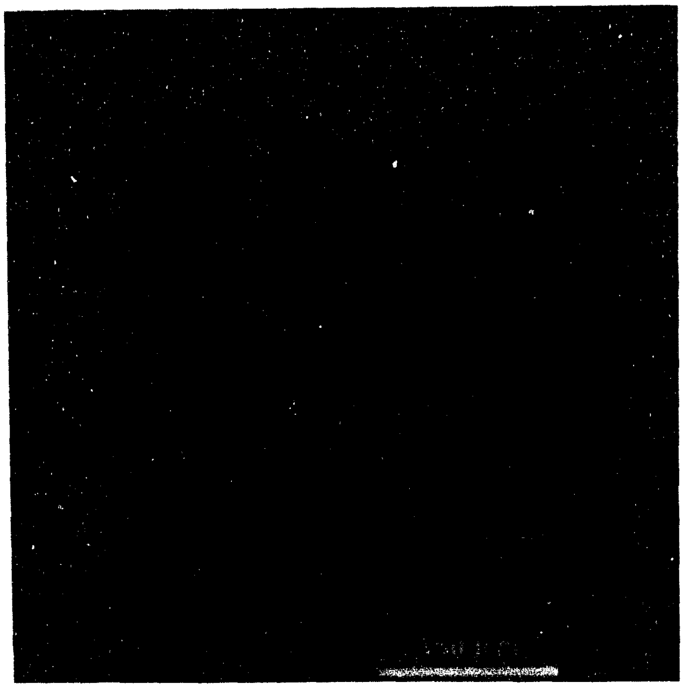

Figure 9. SCG zone in NT230 acting as failure initiation point at 1400°C at a stressing rate of 0.0001 MPa/s.

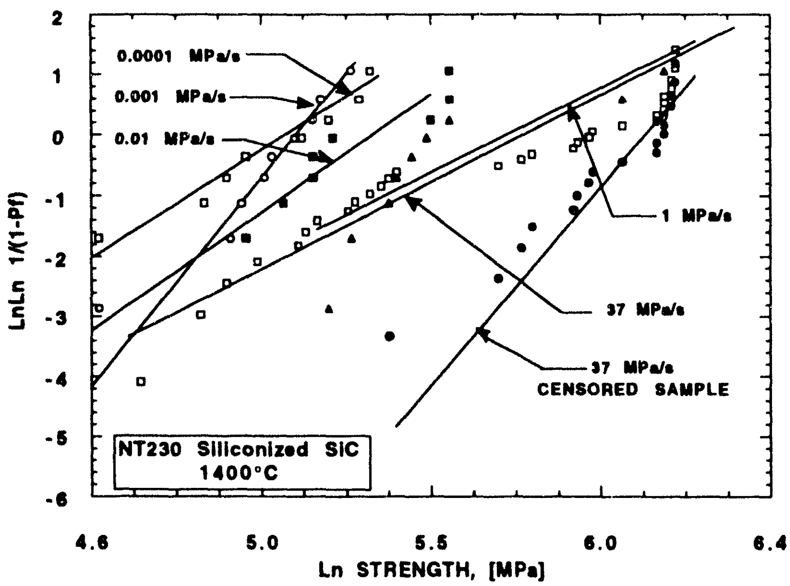

Figure 10. Weibull analysis of the dynamic fatigue data for NT230 at 1400°C.

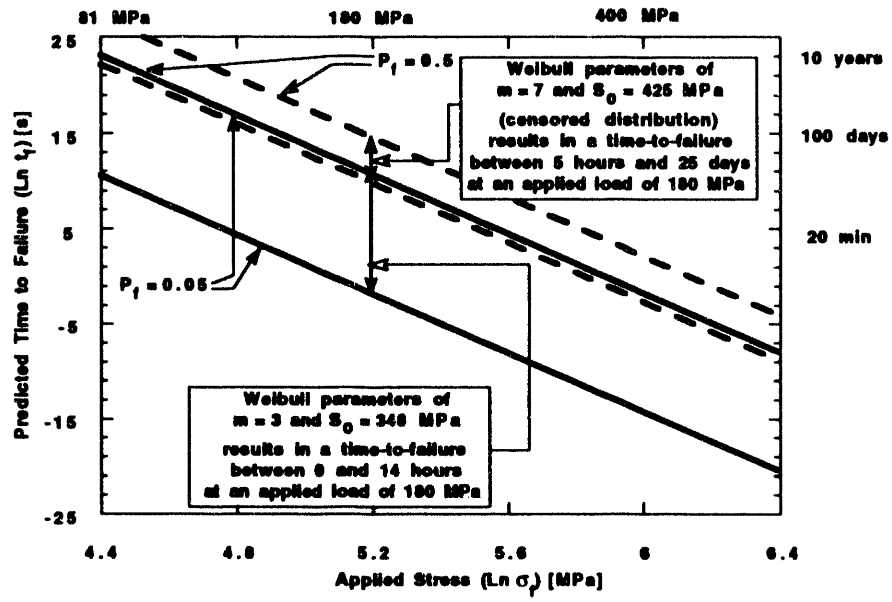

Figure 11. Lifetime prediction for NT230 at 1400°C.

Table 2. Remaining room temperature strength after exposure for 300 h at two temperatures and two coal ashes.

NT230				
RT As-received	W/1093°C	I#6/1093°C	W/1260°C	I#6/1260°C
386 MPa	340 MPa	208 MPa	175 MPa	204 MPa
N=30	N=7	N=5	N=6	N=5
Lanxide DIMOX				
RT As-received	W/1093°C	I#6/1093°C	W/1260°C	I#6/1260°C
414 MPa	365 MPa	352 MPa	364 MPa	388 MPa
N=30	N=6	N=6	N=5	N=6
Lanxide DIMOX Experimental Grade				
RT As-received	W/1093°C	I#6/1093°C		
414 MPa*	343 MPa	287 MPa		
	N=4	N=6		
Hexoloy SA				
RT As-received	W/1093°C		W/1260°C	I#6/1260°C
400 MPa	339 MPa		321 MPa	259 MPa
(Hecht Ref. 12)	N=7		N=6	N=6

W = Wyodak coal ash
I#6 = Illinois #6 coal ash
N = number of specimens
* Assumed same as Lanxide DIMOX

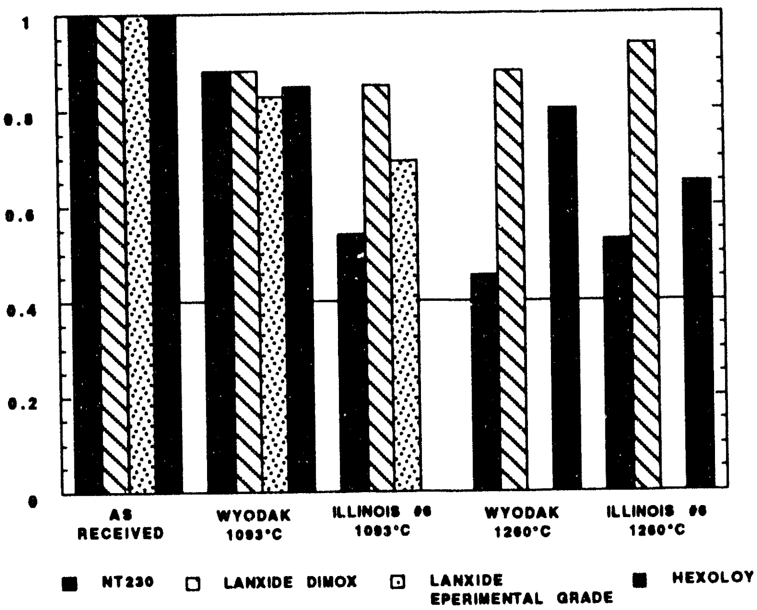

Figure 12. Retained fast fracture flexure strength in percent of the as received strength for specimens tested after exposure to coal ash.

SUMMARY

The results show that the unexposed Coors β-SiC had good mechanical properties at the two temperatures considered. No SCG was observed during testing times up to 1000 h at 1400°C. This material was, however, not tested for coal ash corrosion, but the very similar α-SiC showed strength degradation after coal ash exposure. The unexposed Lanxide DIMOX material showed loss of strength at 600°C, and considerable creep was observed at 1400°C. At 1100°C, the material showed no SCG or creep during the dynamic fatigue experiment. The Lanxide DIMOX withstood the corrosive coal ash environment well, and experienced only insignificant loss of strength after 300 h of coal ash exposure. Unexposed NT230 had good mechanical properties at 1100°C with a reasonable strength and no SCG. At 1400°C, however, the ceramic showed loss of strength and SCG. This ceramic was attacked by both coal ashes at both experimental temperatures.

Future research needs to concentrate on establishing the properties of the materials under a combined action of stress and environment. The various coal ashes have different viscosities at different temperatures, and temperature regimes must be established in which the combination of mechanical properties and corrosion resistance will give the specific ceramic under consideration an appropriate lifetime.

ACKNOWLEDGMENTS

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Laboratory Postdoctoral Research Program, administered jointly by the Oak Ridge National Laboratory and the Oak Ridge Institute for Science and Education.

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DEVELOPMENT OF A HIGH-PERFORMANCE COAL-FIRED POWER GENERATING SYSTEM WITH A PYROLYSIS GAS AND CHAR-FIRED HIGH-TEMPERATURE FURNACE

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Contract Number: DE-AC22-91PC91154

Period of Performance: March 1992 through April 1994

INTRODUCTION

A high-performance power system (HIPPS) is being developed. This system is a coal-fired combined-cycle plant that will have an efficiency of at least 47 percent based on the higher heating value of the fuel. Emissions of NO_x and SO_2 are each to be no more than 0.15 lb/10^6 Btu, and particulates must be less than 0.0075 lb/10^6 Btu. Initial versions of this system are allowed to have 35 percent of the heat input from natural gas, but the ultimate goal is to have 95 percent heat input from coal. Foster Wheeler Development Corporation is leading a team effort with Allied Signal Aerospace, Bechtel, Research-Cottrell, Foster Wheeler Energy Corporation, and TRW.

The heart of system is a high-temperature advanced furnace (HITAF), which is a combination air heater/boiler. The HITAF is used to indirectly heat the gas turbine air up to 1800°F. The air is heated in alloy tubes to 1400°F and then in ceramic tubes to 1800°F. This temperature is the current practical limit that can be achieved with indirect heating. The temperature is then further raised by firing natural gas in a topping combustor.

A ceramic air heater (CAH) requires special design considerations to limit corrosion and thermal stresses. Our approach is to convert the coal into a low-Btu fuel gas and char. The fuel gas can then be fired in a separate furnace upstream of the CAH. It can be cleaned of alkalies and particulates to prevent alkali corrosion and ash deposition in the CAH.

Char from the pyrolyzer is used as fuel in portions of the HITAF where the lower temperature air heating is accomplished. In these sections of the HITAF, alloy tubes are used, and ash deposition can be controlled with sootblowing and conventional design techniques. Heat is also transferred to the steam cycle at various locations in the HITAF where it makes sense structurally and thermodynamically.

Gas turbine exhaust is used as combustion air in the HITAF. The use of this air for combustion increases the thermodynamic efficiency of the system. The gas turbine exhaust that is not used for combustion goes through a heat-recovery steam generator (HRSG) before entering the stack. NO_x is removed from the HITAF flue gas with a selective noncatalytic reactor (SNCR) system. SO_2 is removed with a modified Wellman-Lord process.

Research and development for the HIPPS plant has been done in several areas: Cycle development, gas turbine, pyrolyzer, HITAF, char combustor, emissions systems, and ceramic air heater. Some of this research and development is discussed in this paper.

CYCLE DEVELOPMENT

Because of the interactions between the various components of the system, optimization of the cycle was done as an iterative process. Initial parameters were established for the various subsystems, and a plant heat and material balance and a performance analysis were generated. All the team members then did preliminary design and analysis of their equipment relative to the plant data. These analyses uncovered problem areas and areas where performance could be improved or costs lowered. New plant analyses were then generated based on the results of the subsystem studies. This process was repeated until we were satisfied that the plant would meet the HIPPS design criteria while minimizing cost and achieving maximum reliability.

Figure 1 is a process flow diagram of the system; flow stream conditions are listed in Table 1. The pyrolyzer, shown in the lower left corner, converts the coal into a low-Btu fuel gas and char. The fuel gas is cleaned of particulates and alkalies by cooling the gas to 1200°F and removing the particulates and condensed alkalies. The fuel gas is then fired in a furnace, and the products of combustion go through the CAH.

The char from the pyrolyzer goes to a TRW slagging combustor. A precombustor raises the temperature of the air going to the main slagging stage. This precombustor is presently fired with coal, but research is being done to determine whether char can be used. The char combustor is operated substoichiometrically to minimize NO_x. Combustion is then completed in a furnace constructed of refractory-coated superheater surface. Both flue gas streams then join, and the combined stream goes through the metallic air heater and various parts of the steam cycle. SO_2 is removed with a scrubber, using a modified Wellman-Lord process. Particulates are removed with either a baghouse or an electrostatic precipitator.

The 1800°F air from the CAH is heated further with natural gas-fired topping combustors. The temperature entering the gas turbine is 2350°F after mixing with the gas turbine cooling air. The exhaust from the gas turbine goes through a recuperator and then a heat recovery steam generator (HRSG).

Considerable work was done to determine the best cycle arrangement. This optimization is complicated because it involves more than just cycle efficiency. Functional and design limits of components and subsystems also must be considered. The system depicted in Figure 1 and described in Table 1 was developed considering both cycle performance objectives and equipment capabilities. The cycle efficiency is 47 percent, and the emissions goals of 0.15 lb/10^6 Btu SO_2 and NO_x are achieved.

PYROLYZER

The pyrolyzer is a circulating bed operating at 1700°F. Coal and limestone are fed to the bed along with sufficient air to maintain the bed temperature under substiochiometric conditions. Except for the heat losses from the insulated vessels, the process is adiabatic, and a low-Btu fuel gas and char are produced. Foster Wheeler has done considerable development of this process as part of another DOE project [1]. That project uses a pyrolyzer operating at similar conditions as part of a second-generation pressurized fluidized bed (PFB) system. Tests were done in a pilot plant with coal flows of up to 500 lb/h and both jetting and circulating bed arrangements.

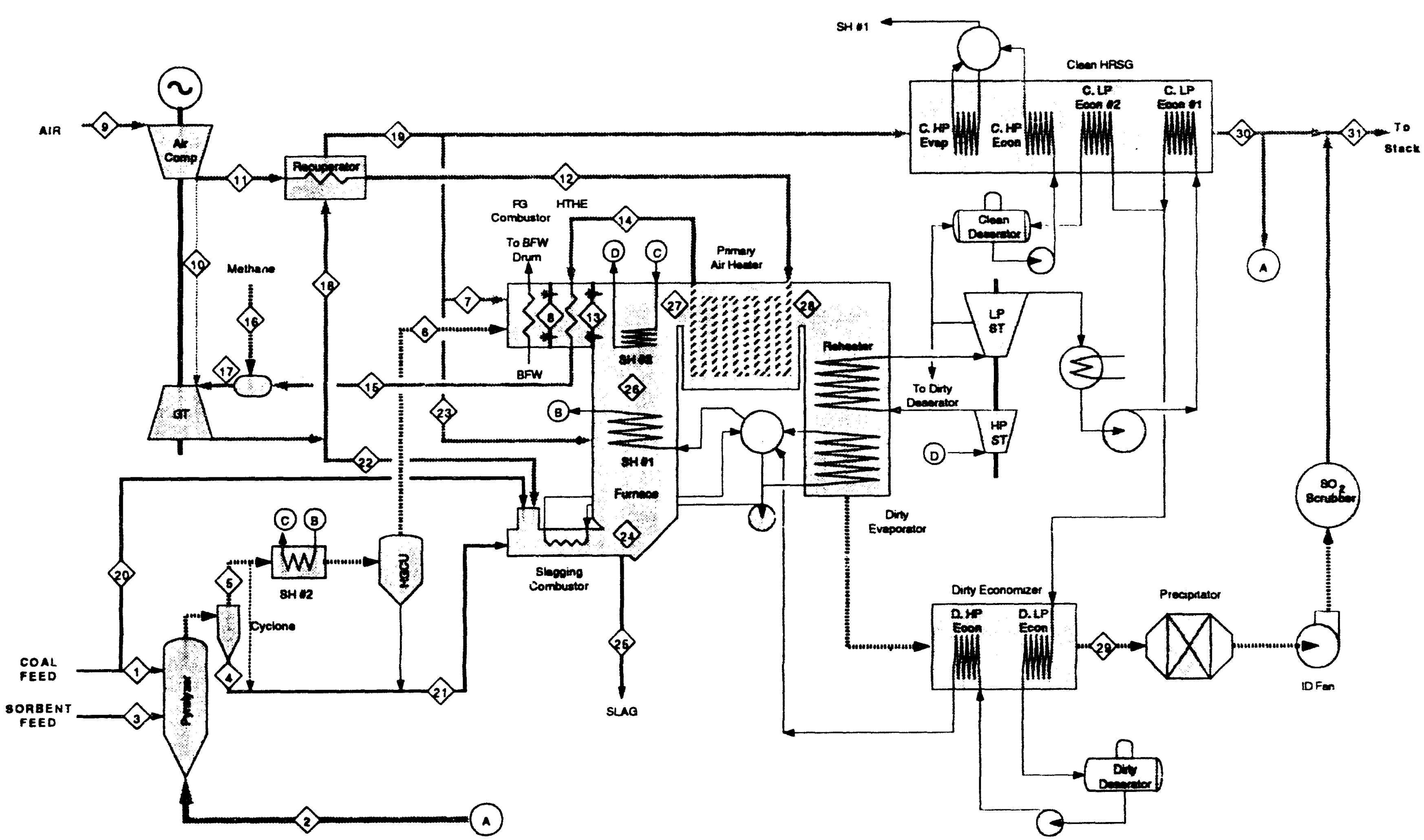


Figure 1 H!PPS Process Flow Diagram

Table 1 Process Flow Streams

Stream	Component	Temperature (°F)	Pressure (psia)	Flow Rate (lb/h)
1	Coal/Steam	70	49.4	112,075
2	Vitiated Air	350	32.3	253,804
3	Sorbent	70	34.4	9,431
4	Char/Sorbent	1700	29.4	43,930
5	Fuel Gas	1700	29.4	331,171
6	Fuel Gas	1200	21.4	328,974
7	Vitiated Air	870	15.3	561,513
8	Flue Gas	2903	14.7	890,497
9	Air	60	14.7	3,307,300
10	Air	735	218.0	761,400
11	Air	735	218.0	2,545,900
12	Air	1053	217.0	2,545,900
13	Flue Gas	1915	13.9	890,497
14	Air	1400	212.1	2,545,900
15	Air	1800	207.1	2,545,900
16	Natural Gas	200	250.0	30,701
17	Vitiated Air	2591	199.7	2,576,601
18	Vitiated Air	1138	16.0	2,931,776
19	Vitiated Air	870	15.3	2,931,776
20	Coal	60	16.0	9,013
21	Char/Sorbent	1700	16.0	46,127
22	Vitiated Air	1138	16.0	406,225
23	Vitiated Air	870	15.3	203,113
24	Flue Gas	3235	14.5	647,305
25	Ash	2400	14.5	16,985
26	Flue Gas	2715	14.2	647,305
27	Flue Gas	1903	13.9	1,537,802
28	Flue Gas	1311	13.8	1,537,802
29	Flue Gas	210	15.1	1,537,802
30	Vitiated Air	130	15.0	2,167,151
31	Flue Gas	220	14.7	3,451,149

The research done for the second-generation PFB has been very useful in the HIPPS project. In addition to establishing the pyrolyzer yields for the system cycle analysis, actual char/sorbent material was available for laboratory-scale testing. This material was used in combustion tests and corrosion tests of ceramic materials.

The estimated fuel gas composition is shown in Table 2. The fuel gas is similar in composition and heating value to blast furnace gas, which is already used as a commercial fuel. Although low in volatiles, the char is fairly reactive—primarily because of its high porosity.

Table 2 Fuel Gas Composition

Gas	wt%
CO	21.77
CO_2	12.52
H_2	1.18
H_2O	5.22
CH_4	1.32
NH_3	0.156
H_2S	0.042
N_2	57.79

CHAR COMBUSTOR

In the TRW slagging combustor (Figure 2), vitiated air from the recuperator is used for combustion. Coal is fired in the precombustor to heat this air to 2000°F. The heated air enters the main combustor tangentially, causing a cyclonic flow. Char is also injected into the main combustor, and the char particles are entrained by the air. Most of them are burned in flight. Molten ash particles deposited on the combustor walls as a result of the swirling gas flow are removed from the burner through a slag tap. The main combustor operates at a stoichiometry of 0.8 to minimize NO_x production. Products of combustion leave the main combustor at 3170°F. Secondary air injected into the furnace then completes the combustion.

A combination of laboratory testing and analytical modeling has been used to characterize the char and predict its performance in the slagging combustor. Flat-flame burner tests were run at Brigham Young University (BYU) to determine the char burnout, surface area, and apparent density at different residence times in the flame. These tests were done for the parent coal and for char from the FWDC pyrolyzer [2]. The results were then applied to the TRW slagging combustor computer model to predict operating conditions with the char [3]. This model has successfully predicted operation for TRW's 40 x 10^6 Btu/h combustor with a variety of coals.

A plot of NO_x vs. stoichiometry, predicted by the model, is shown in Figure 3. As the plot shows, the optimum range of stoichiometry is 0.75 to 0.85. At higher stoichiometries, increased operating temperatures and oxygen concentration combine to yield higher levels of NO. At lower stoichiometries, excessive amounts of NO_x precursors, such as HCN and NH_3, are produced. These NO_X precursors are readily oxidized to NO when additional air is added in the furnace.

Another important consideration is the overall carbon burnout that can be obtained with the char. Figure 4 compares the carbon burnout with Pittsburgh No. 8 coal and char derived from Pittsburgh No. 8 coal. These data are also based on the TRW computer model and the laboratory testing. At stoichiometry of 0.8, there is very little difference between the two

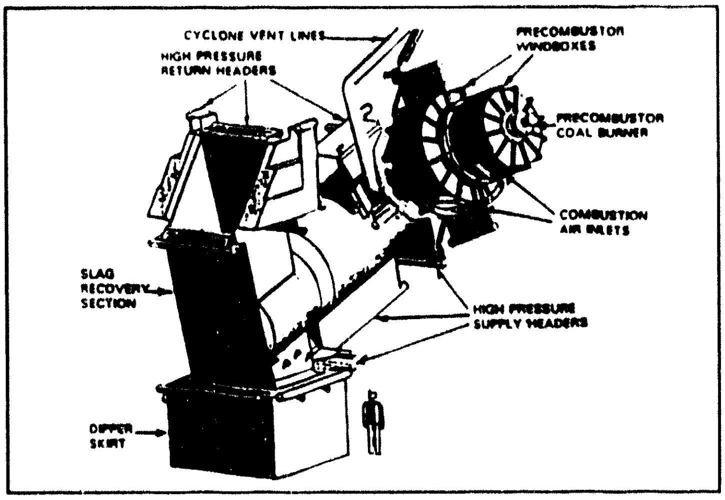
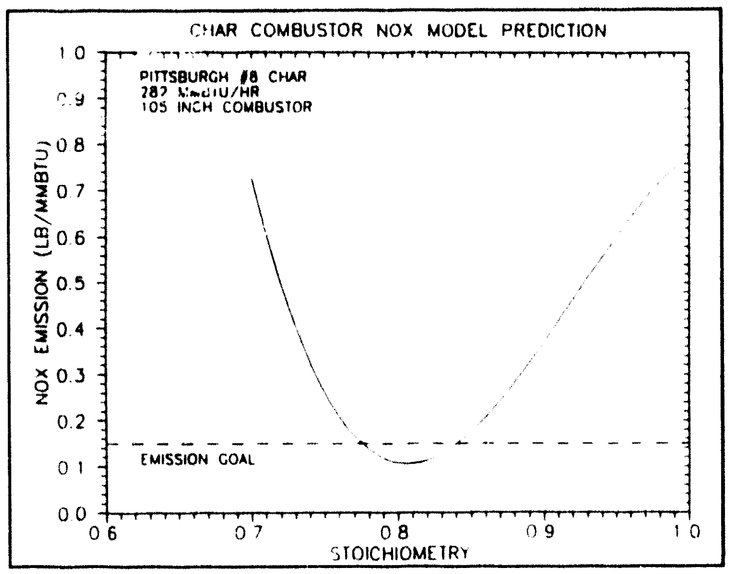


Figure 2 Char Combustor

Figure 3
NO_x Generation vs. Stoichiometry



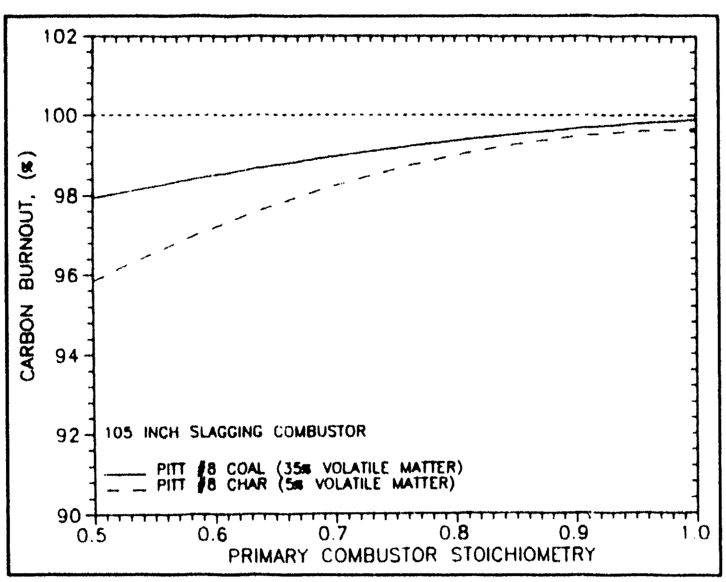


Figure 4
Carbon Burnout vs. Stoichiometry

fuels. Under these conditions, the particle residence time is sufficient to get almost complete burnout with or without the volatiles.

CERAMIC AIR HEATER

Preliminary research and development on the CAH has been in the areas of thermal performance, stress analysis, and material evaluation. The air heater is shown in Figure 5. Four of these modules will be required for a 290-MW plant. The CAH is made up of tube/header modules; they have been analyzed with the ANSYS Code for an air heater made with sintered alpha silicon carbide. The main factors affecting the stress level are the pressure and the relative thermal expansion of the tubes between the two headers. The difference in temperature of the tubes is caused by the gas temperature drop as the flue gas passes by successive tube rows and by imbalances in the flue gas flow distribution.

The analysis reveals that the highest stress is very localized at the point where the tubes and header join. Without any reinforcement, the maximum principal stress in this area is 12.2 ksi. The stress level in the tubes and header away from the joint is less than 2.0 ksi [4]. Because failures in ceramics are primarily caused by defects in the material, a statistical method is used to evaluate structures. At the time this paper was written, this analysis had not been completed; however, the localized nature of the highest stresses will tend to increase the probability of survival. Also, reinforcement in the joint area can be used to lower the stress further.

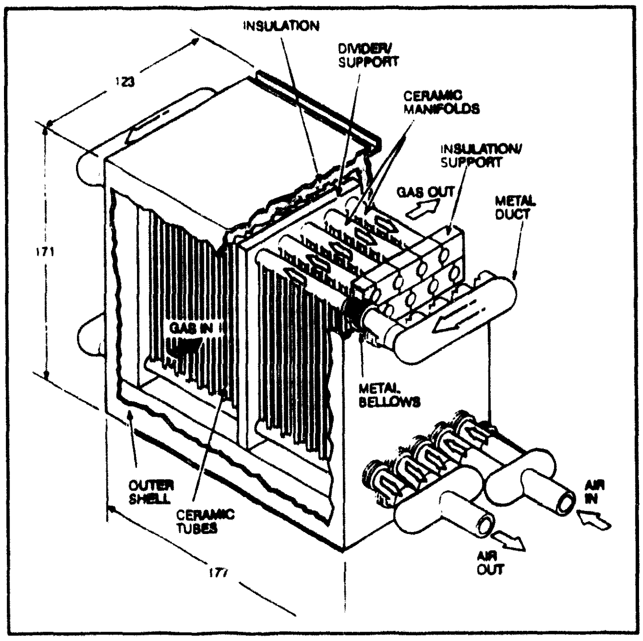


Figure 5 Ceramic Air Heater

The effects of corrosive products in the flue gas were evaluated for three ceramic materials. A benefit of the pyrolysis-based HIPPS is that the fuel gas can be readily cleaned of solid-phase and gaseous-phase alkalies. Laboratory tests were run to get an estimate of the degree of cleaning that would be required and also to assess the relative performance of candidate materials under corrosive conditions. In these tests, coupons were coated with representative ash and then maintained at temperature in electric furnaces. Ash was added at 100-hour intervals in amounts to simulate different deposition rates, and each test was run for a total of 500 hours. The gas environment in the furnaces was simulated flue gas.

Coupons of sintered alpha silicon carbide, siliconized silicon carbide, and silicon carbide particulate-reinforced alumina were tested in this manner at 2300°F and 1800°F. At 2300°F, with loadings that simulated operation without substantial particulate removal from the flue gas, all the materials showed significant wastage. With lower loadings that could be achieved by using a barrier filter in the fuel gas stream, the effects of corrosion on the sintered alpha silicon carbide and the silicon carbide particulate-reinforced alumina were minor.

The tests run at 1800°F used ash that was doped with additional alkalies to simulate alkalies that could condense out of the flue gas as it cools. Ash with sodium sulfate levels of 7 and 42 wt% was tested. At the lower alkali level, all the materials performed satisfactorily. At the higher alkali level, only the silicon carbide particulate-reinforced alumina resisted corrosion. The amount of alkalies that would condense on the tubes is difficult to predict. An alternative approach is to remove the gaseous-phase alkalies from the fuel gas before combustion. A worst-case thermodynamic analysis of the fuel gas indicates that fuel gas concentrations of sodium can be reduced to about 10 ppm if the fuel gas is cooled to only 1200°F. If the gas is cooled to 1000°F, the concentration is reduced to less than 1 ppm, and these concentrations are further reduced after combustion.

Based on the results of the corrosion tests, the materials selected were sintered alpha silicon carbide and silicon carbide particulate-reinforced alumina. A fuel gas cooler and barrier filter were also included in the conceptual plant design.

SUMMARY

A conceptual design has been developed for a coal-fired combined-cycle plant. This design was based on cycle performance analysis and preliminary equipment design. It meets the performance and emissions goals of the HIPPS project. Research has been done in several important areas, and this research will be expanded as the project continues.

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COMBUSTION 2000 LOW-EMISSION BOILER SYSTEMS PROJECT

THE ABB TEAM'S PHASE I ACTIVITIES

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RAYTHEON ENGINEERS & CONSTRUCTORS, INC.

Contract No.: DE-AC22-92PC92159

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OBJECTIVES

The overall objective of the Project is the expedited commercialization of advanced coal-fired low-emission boiler systems. The specified primary objectives are emissions of NOx and SOx less than one-third NSPS, particulates less than one-half NSPS, and air toxics in compliance. Secondary objectives are improved ash disposability, reduced waste generation, and increased generating efficiency. All primary, and all or some secondary objectives must be met without increasing the cost of electricity from a current "NSPS" plant. Because emission requirements vary from site to site, ABB elected to have two NOx targets (the contract target of 0.2 lb/million Btu and approximately 0.05 lb/million Btu) and to favor SOx and particulate control technologies which can be designed for emission levels lower than the contract targets with minimum impact on costs.

The final deliverables are a design data base that will allow future coal-fired power plants to meet the stated objectives and a preliminary design of a commercial generation unit. (Figure 1.) The deliverables for Phase I are a Project Work Plan covering all four phases, concept and component evaluation and selection, an R&D and Test Plan, a preliminary Commercial Generating Unit design, and a Phase I report.

APPROACH

The work in Phase I, which will cover a 24-month period, includes the following: Task 1-Project Planning and Management, Task 2-Concept Development, Task 3-Research, Development, and Test Planning, Task 4-Component Definition, Task 5-Commercial Generating Unit Design, and Task 6-Phase I Report. This paper documents the work done to date in Phase I.

The project is being managed by ABB Power Plant Laboratories Division of Combustion Engineering, Inc. (ABB CE) as the contractor and the work is being accomplished and/or guided by this contractor and the following team members:

- ABB CE (NOx, efficiency, waste disposability, cost of electricity)
- ABB Environmental Systems (SOx, particulates, waste reduction)
- Energy and Environmental Research Corporation (Air toxics)
- Raytheon Engineers and Constructors (Plant-wide evaluations, cost of electricity, A/E Services)
- Technical Consultants and Industry Advisors

CONCEPT DEVELOPMENT

Methodology

The process began with identification of candidate technologies and the selection of coals through literature search and in-house sources. The team selected those candidates judged to have the potential of meeting the Project's primary objectives and one or more of the secondary objectives and to become commercially feasible within the Project's timeframe. Commercial feasibility in this sense encompasses not only technical and economic feasibility but also acceptance by the utility industry.

Near-term technologies were screened to determine those that best fit the criteria described above. From the remaining candidates, rough economic comparisons were made to compare system installation costs and annualized operation and maintenance costs. Five SO_x/particulate and five NO_x candidates were selected and subjected to comprehensive technical assessment and systems analysis and a "short list" was developed. Finally, six combinations of the short-listed subsystems were evaluated for technical, economic, and commercial feasibility as integral parts of an advanced supercritical power generation system.

Three test coals were selected and one was identified as the design coal to serve as the baseline test coal. The remaining test coals will be used in R&D and testing to determine process sensitivities to variations in coal characteristics. The test coals were selected so that the results of the engineering development work will be broadly representative of large classes of US coals whose current production is extensive, with significant remaining minable and uncommitted reserves. The sulfur content of the design coal, on entering the boiler, is at least three pounds of sulfur per million Btu. Illinois No. 6, Pittsburgh No. 8, and Upper Freeport were selected to be the project test coals and Illinois No. 6 will be the design coal.

The next step in the process was to select the plant steam cycle. A comprehensive evaluation was carried out which compared a conventional subcritical cycle with throttle conditions of 2400 psig/1000°/1000° to an advanced supercritical cycle with throttle conditions of 4500 psig/1100°/1100°/1100°. The supercritical cycle was selected because of its higher plant efficiency. This not only provides performance improvements but it will reduce the amount of pollutant produced per kilowatt of electricity generated, regardless of the emissions technologies involved. The steam generator and turbine generator performance and cost values reflect this selection. Supercritical technology is generally viewed by the utility industry as technically acceptable and commercially feasible.

Subsystem Technologies for Emissions Control

Using the methodology described above, the team developed the following short list of subsystem technologies:

NOx Control-

*1. Advanced Tangential Firing.
*2. Coal Reburn.
*3. High-temperature SNCR.
*4. Catalytic Filter (fabric or ceramic).
5. SCR for cost comparison.

SO_x/Particulate Control-

*6. Advanced Wet Limestone Scrubber with EP or FF.
*7. ThioClear Scrubber Process with EP or FF.
*8. SNOX Process with Baghouse.
9. Catalytic Baghouse with WSA Tower.
10. Catalytic Baghouse with Wet Scrubber.

*Selected for systems analysis

Brief descriptions of each selected subsystem follow. A fuller understanding of these subsystems and their integration into a system can be obtained from Figure 1.

Advanced Tangential Firing. This combustion system is the basis of the low NO_x approach for the continuing evolution of tangential firing. Pilot-scale tests have demonstrated NO_x emissions below the Project's target with reasonable carbon loss. This technology will continue to be developed under internal funding and advances will be applied to this Project as they evolve.

Coal Reburn. Fuel staging, commonly known as 'reburning', involves the reduction of NO formed in the initial fuel burning stage by active chemical species (radicals) produced by the fuel introduced into the second stage under substiochiometric conditions. Coal reburn was used with good results on a cyclone boiler and will be tested on a 175 MW wall fired boiler. At this time, it is believed that meaningful NO_x reductions can be obtained by adding coal reburning to the advanced burners.

High-temperature SNCR. Recent work has shown that high temperature reagent injection may overcome the drawbacks of "conventional" SNCR. Bench-scale tests will be conducted to answer some unknowns in this area.

Catalytic Filter. The catalytic filter is an integral step in the SNOX systems. (See below.) Also, post combustion NO_x reduction will facilitate an alternate lower NO_x emission goal.

Advanced Wet Limestone Scrubber with EP or FF. Evolutionary improvements to these established technologies continue and they will be retained as options.

"ThioClear Scrubber Process with EP or FF". The ThioClear process is in principle very similar to the Wet Limestone process. The primary difference from the wet limestone system is that magnesium, not calcium, provides the required alkalinity to absorb the acid gas. The makeup chemical is magnesium enhanced lime and the by-products are gypsum and magnesium hydroxide.

SNOX Process. The SNOX (Sulfur and Nitrogen Oxide Reduction) technology utilizes two catalytic reactors to control NO_x and SO_x in the flue gas stream and to produce a saleable commercial grade sulfuric acid. No sorbents are added and no other by-products are formed. The process is capable of greater than 97% SO_2 removal, 95% NO_x removal and essentially complete particulate removal while producing commercial grade sulfuric acid and heat. The process was developed in the early 1980's and has been successfully tested in Europe and Asia in pilot scale units as well as on a full scale 310 MWe coal-fired unit in Denmark. In the United States, it was demonstrated under DOE's Clean Coal Program as a 35 MWe slipstream facility on a Ohio utility unit burning high-sulfur coal. Following successful demonstration, the host utility elected to continue operation on a commercial basis. The by-product sulfuric acid is sold locally.

The SNOX Hot Scheme is an adaptation of the SNOX process that, by taking advantage of a hot particulate collection system with integral NO_x SCR catalyst, allows reduction in capital equipment as well as an improvement in the thermal efficiency of the steam cycle. (See Figure 1). The process is expected to achieve greater than 97% SO_2 removal and 80% NO_x removal. Technical concerns with the Hot Scheme process include filter life. Since the flue gas will be coming straight from the boiler system, the flue gas temperature will be approximately 750°F. This elevated temperature will require a more heat-resistant fabric than normal baghouse applications or use of a ceramic filter. Fabric testing is being conducted. Another candidate is the CeraMem ceramic catalytic filter. In testing a 60 lb/hr combustor, NO_x removal efficiencies of 90% or greater were achieved with less than 25 ppm ammonia slip (which would be eliminated downstream) and no detectable SO_2 oxidation.

SYSTEMS ANALYSIS AND SELECTION

The subsystem technologies described above were evaluated as integral parts of six advanced supercritical power generation systems. The six alternative systems and their assessments are as follows:

	System	Potential for Commercialization	Relative C.O.E*
1	Advanced Burners Advanced Wet Limestone FGD Advanced Electrostatic Precipitator	Very high	0.976
2	Advanced Burners with Coal Reburn Advanced Wet Limestone FGD Advanced Electrostatic Precipitator	Moderate to High	0.990
3	Adv. Burners + High-Temp SNCR Advanced Wet Limestone FGD Advanced Electrostatic Precipitator	Very High <u>if</u> the SNCR technology works	0.987
4	Advanced Burners ThioClear FGD Advanced Electrostatic Precipitator	High	0.973
5	Advanced Burners SNOX	High	0.964
6	Advanced Burners SNOX Hot Scheme	High	0.954

*Compared to a current "NSPS" design's Cost of Electricity.

Contractors were required to select one system as the basis for the commercial generating unit (CGU) design. Since all the primary and secondary objectives can be met by each of the six systems, the main evaluation criteria came down to the potential for commercial success and the cost of electricity. Based on evaluation of these concepts, the Team selected the SNOX Hot Scheme (System 6). In addition, systems 1 and 4 (wet FGD) were selected for collateral development until such time as one system is shown to be clearly superior to the other. Systems 1 and 4 meet the contract NO_x target and System 6 meets the optional target. All of these systems can be designed for SO_x and particulate emissions lower than the contract targets. Also, since Systems 4 and 6 both produce saleable by-products, they both meet the waste reduction objective.

A specific ash disposal technology was not selected. Because the choice is highly site-specific, the team only identified and assessed candidate technologies and reduced the list to three: (1) chemical fixation with lime for stabilized landfill, (2) production of light-weight aggregate from flyash, (3) vitrification. The latter two are being commercialized under other projects and all three will remain as options in future work on this Project.

The requirement that air toxics be "in compliance" is undefinable at this time since regulations have not been established. Therefore, control technologies cannot be fixed. When regulations are in place, there may be a shift in LEBS technologies.

DESIGN UNCERTAINTIES ANALYSIS and R, D & T PLAN

The purpose of the Design Uncertainties Analysis was to identify key design uncertainties of the subsystem technologies. This work built directly on analysis of the subsystems described above and served as a prerequisite for the preparation of the R, D & T Plan for the balance of Phase I. Analysis of the subsystem technologies showed that some additional information is required for design of the following major subsystems:

- Coal Reburn
- High Temperature SNCR
- Particulate Control
- SO_2 Control
- Particulate/NO_x/SO_2 Control
- Control System
- Firing System Application

It was concluded that a combination of engineering analysis, experimental research, and modeling will provide much of the information required for design of the subsystems, the Proof-of-Concept Test Facility (POC), and the Commercial Generating Unit (CGU).

COMPONENT DEFINITION

Analysis of the key uncertainties for the subsystems showed that those which addressed NO_x, especially Coal Reburn and High Temperature SNCR, would benefit from a combination of Engineering Analysis, Experimental Research and Modeling work. The information required to address uncertainties with the remaining subsystems was obtainable through Engineering Analysis alone. This section deals primarily with progress in connection with the NO_x-related subsystems.

Figure 2 provides an overview of subsystem integration into the plant design. This is a very important part of the analysis process and the feedback provided by this analysis will dictate whether subsystem performance is satisfactory or whether changes are required to provide acceptable performance.

Key areas identified for additional data generation were as follows:

Low NO_x Firing	Unburned Combustibles Performance of Various Fuel Types Fuel Fineness Sensitivity
Coal Reburn	Mixing Requirements Optimum Chemistry Fuel Fineness Requirements
High Temperature SNCR	Process Sensitivities To: - Temperature - CO Levels Reactant Utilization Efficiency

Figure 3 shows a schematic work flow diagram of how the data for the Low NO_x Firing Subsystem will be produced. Validated combustion/NO_x prediction models will use, as inputs, the information generated from the fuels characterization testing. Output from the models will directly address the areas that have been previously identified for the specific coal of interest. A similar approach is used to address the uncertainties identified with Coal Reburn and High Temperature SNCR Subsystems.

Progress to date, relative to the NO_x reduction technologies subsystems, has primarily involved the characterization of Illinois No. 6 coal, in particular the evolution of nitrogenous species during pyrolysis. The Low NO_x Firing Subsystem will operate under substoichiometric conditions, which are conducive to N_2 formation rather than NO_x formation. The data produced from the fuel characterization studies will provide input for the validated models.

A Drop Tube Furnace System (DTFS) was used to perform the fuel characterization studies. The DTFS is a laminar flow reactor comprised of a preheater (primary furnace) for the carrier gases and a vertical test section (secondary furnace) which provides the temperature controlled conditions required for fuel characterization. Fuel is introduced with a small amount of carrier gas into the controlled reaction zone through a water-cooled injector. Importantly, particle heating rates of 10^4 °C per second simulate the rates of heating in a commercial furnace. Following this rapid heating rate the coal particles are subjected to either combustion or pyrolysis conditions, depending on the objective, for a time that is dictated by transit distance. All reactions are then rapidly quenched in a water-cooled and steam-heated sampling probe. Solid products are separated from gaseous products in a small filter housing. An aliquot of the effluent gas is sent to the Fourier Transform Infrared (FTIR) spectrometer, Gas Chromatograph (GC) and/or the Gas Analysis System (GAS) for measurement of the concentrations of various major and minor gaseous constituents. In the case of the pyrolysis tests tar yields were also measured.

As previously noted, the plan is to use the information generated from the DTFS in concert with the validated combustion model to evaluate the performance of the specific LEBS coal, namely Illinois No. 6. In the case of the Low NO_x Firing Subsystem the plan is to use the combustion kinetic parameters generated from the DTFS, namely the activation energy and the frequency factor, in the two-dimensional combustion model (Jasper) that was used to simulate the DTFS. By employing the combustion kinetic parameters in Jasper and comparing the predicted carbon conversion results with actual measurements from the DTFS, validation and/or adjustment of the kinetic parameters (normally frequency factor) would be addressed as warranted. The validated kinetic parameters will then be used as inputs to a previously validated three-dimensional combustion model. The three-dimensional combustion model will now be used in combination with CHEMKIN, a kinetics-based code that will make NO_x predictions.

Inputs to the CHEMKIN code include tar yields, HCN, NH_3, NO, NO_x, N_2O, and TBN (total bound nitrogen). Figures 4 through 7 illustrate the kind of information generated by the DTFS on the Illinois No. 6 coal under pyrolysis conditions. Note, for example, in Figure 4 that the evolution of nitrogenous species (FNC) is proportionately greater (60%) than the pyrolysis efficiency (45%). This is advantageous since the nitrogen that is released during devolatilization would be subjected to substoichiometric conditions with the concomitant tendency to form molecular nitrogen. Tar yields are dramatically affected by residence time, dropping from about 4.4% at a residence time of 0.075 seconds to less than 0.5% at 0.55 seconds. (See Figure 5.) Figure 6 shows the evolution of HCN as a function of residence time at various temperatures and finally Figure 7 shows the evolution of NO as a function of residence time at various temperatures.

The objective of the fuel characterization and modeling tasks is to address the uncertainties previously listed and to provide information that will allow optimization of the operating conditions in the Low NO_x Subsystems, and subsequently in the secondary NO_x reduction subsystems.

FUTURE WORK

The remainder of this initial phase of the LEBS Project is devoted to completing the preliminary design of a commercial generating unit. Work in future phases of the Project includes pilot scale testing of subsystem technologies and the design, construction, operation, and testing of a 25+ MWe Proof-of-Concept Test Facility.

REFERENCES

1. Regan, J.W., et al, 1993, "Conceptual Development and Design of an Advanced Low-Emission Boiler System", presented at the International Joint Power Generation Conference, Kansas City, MO.

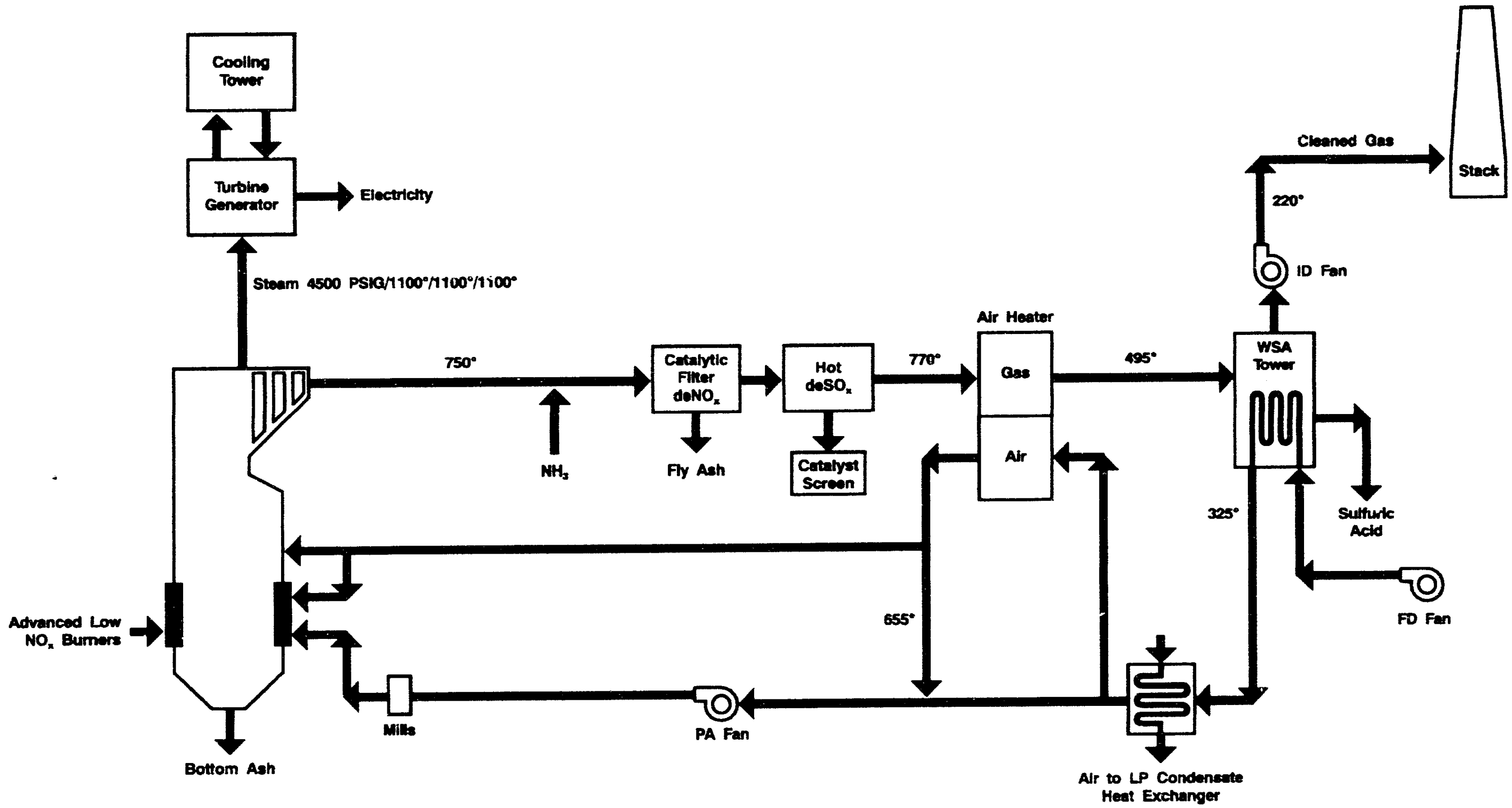

Figure 1 System Diagram

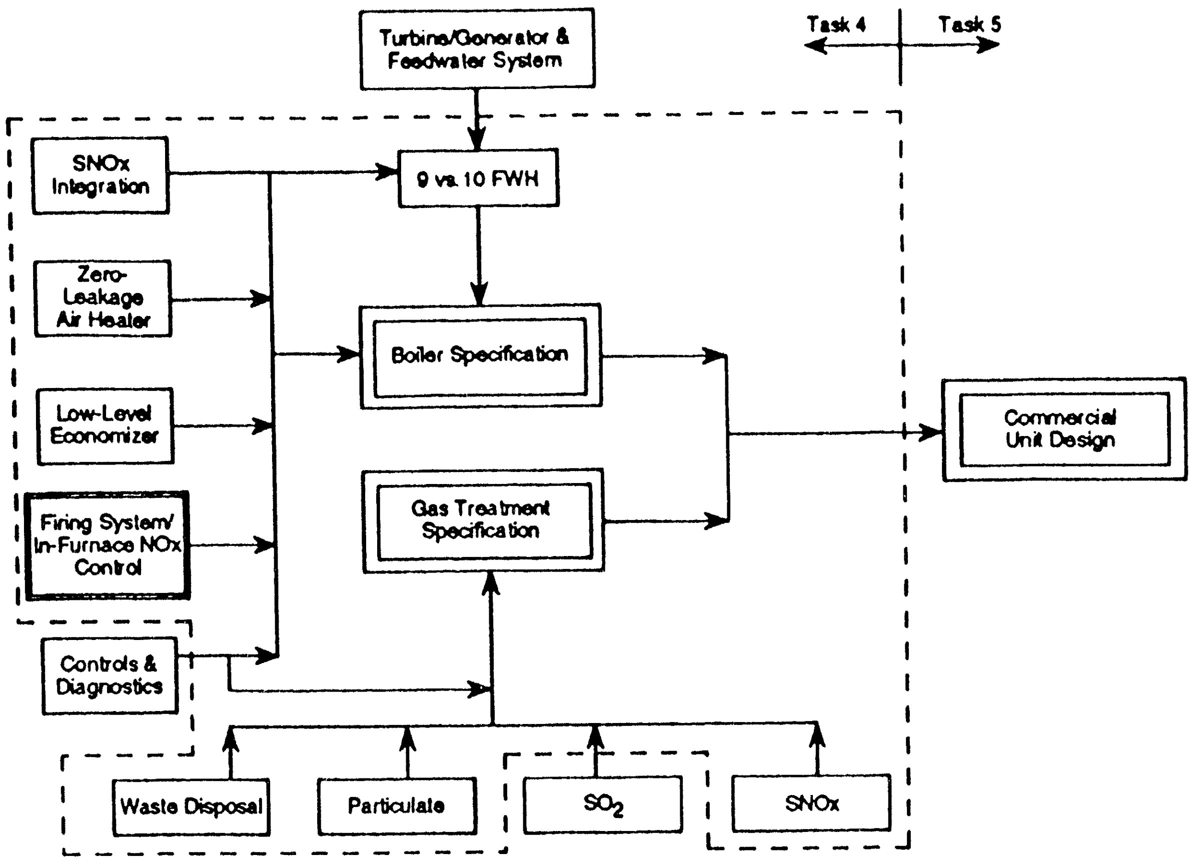

Figure 2 Overview

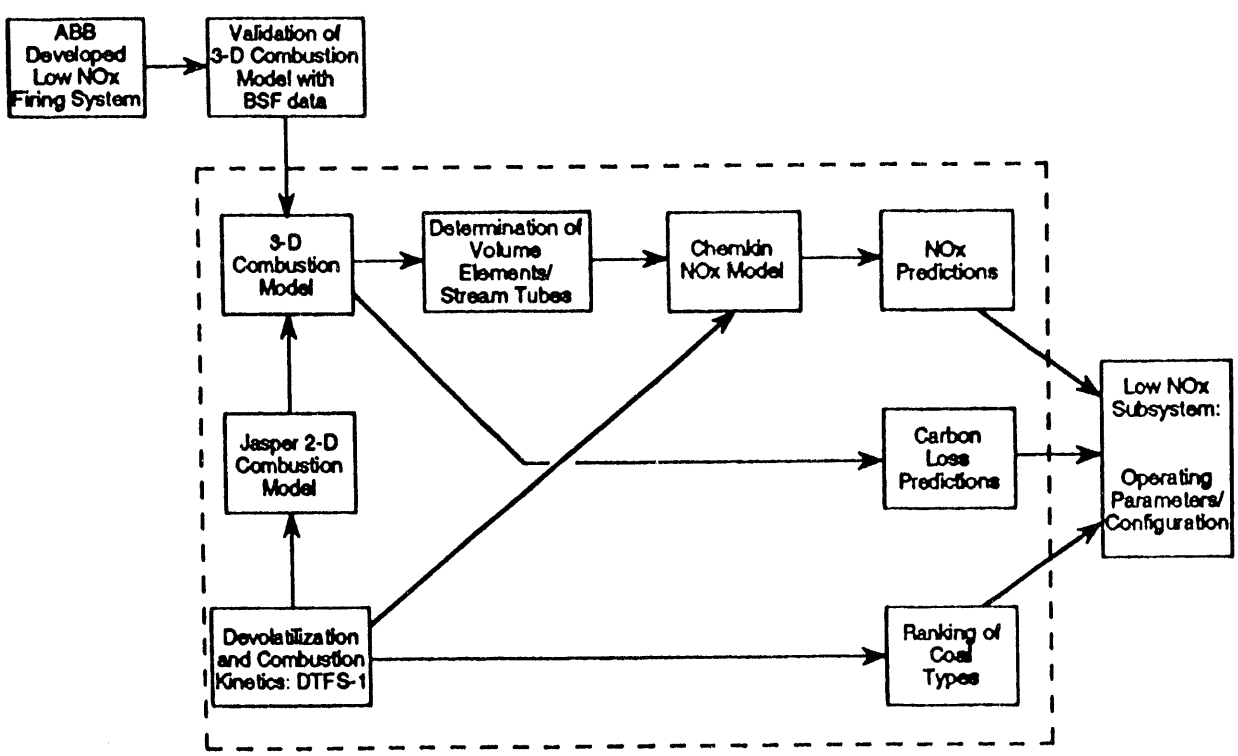

Figure 3 Low NOx Firing Subsystem

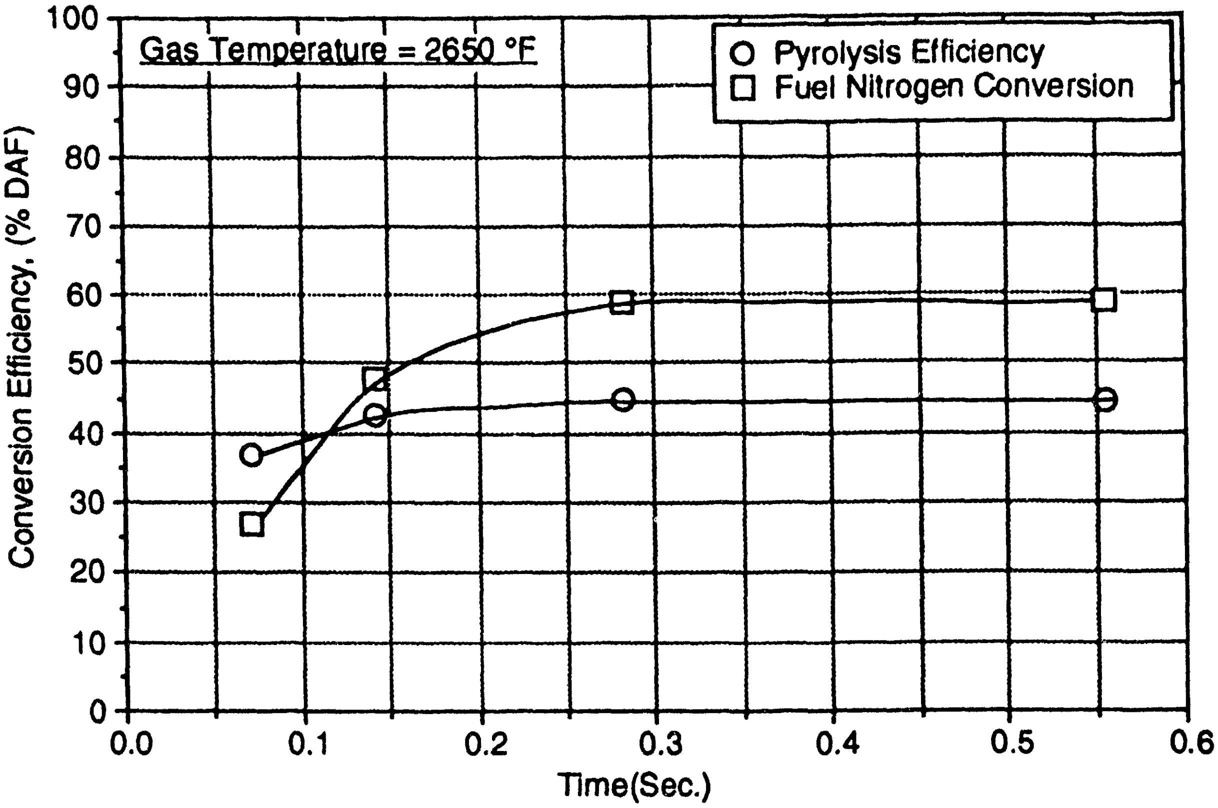

Figure 4 DTFS-1 Pyrolysis Data for 400 x 0 Mesh Illinois #6 Coal

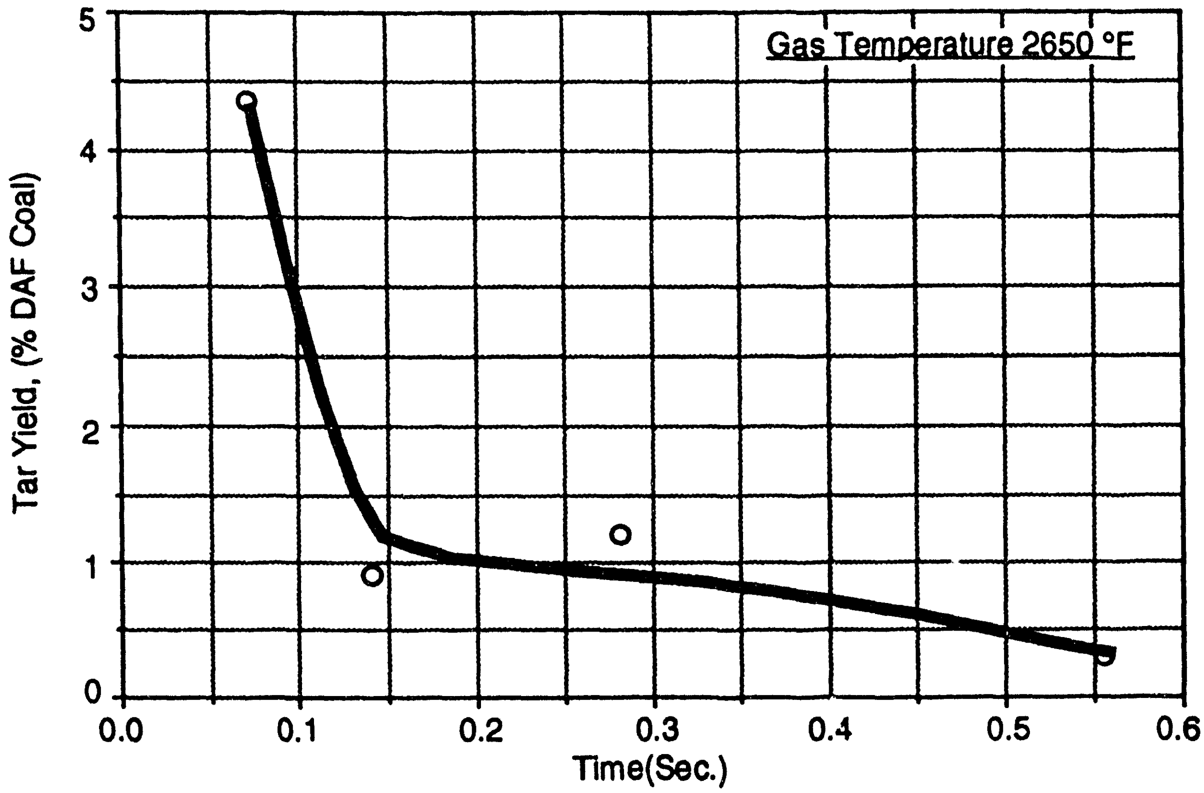

Figure 5 Tar Yield During DTFS-1 Pyrolysis of 400 x 0 Mesh Illinois #6 Coal

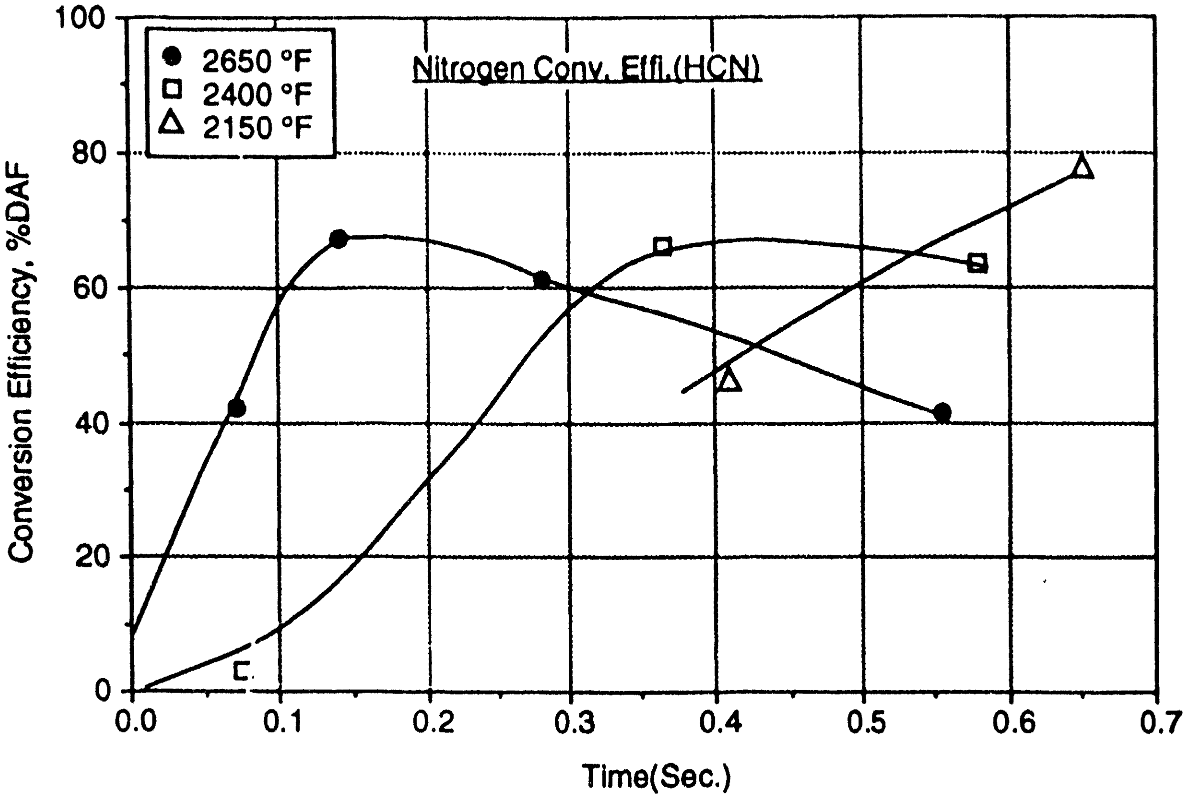

Figure 6 DTFS-1 Pyrolysis of 400 x 0 Mesh Illinois #6 Coal - Fuel Nitrogen to HCN

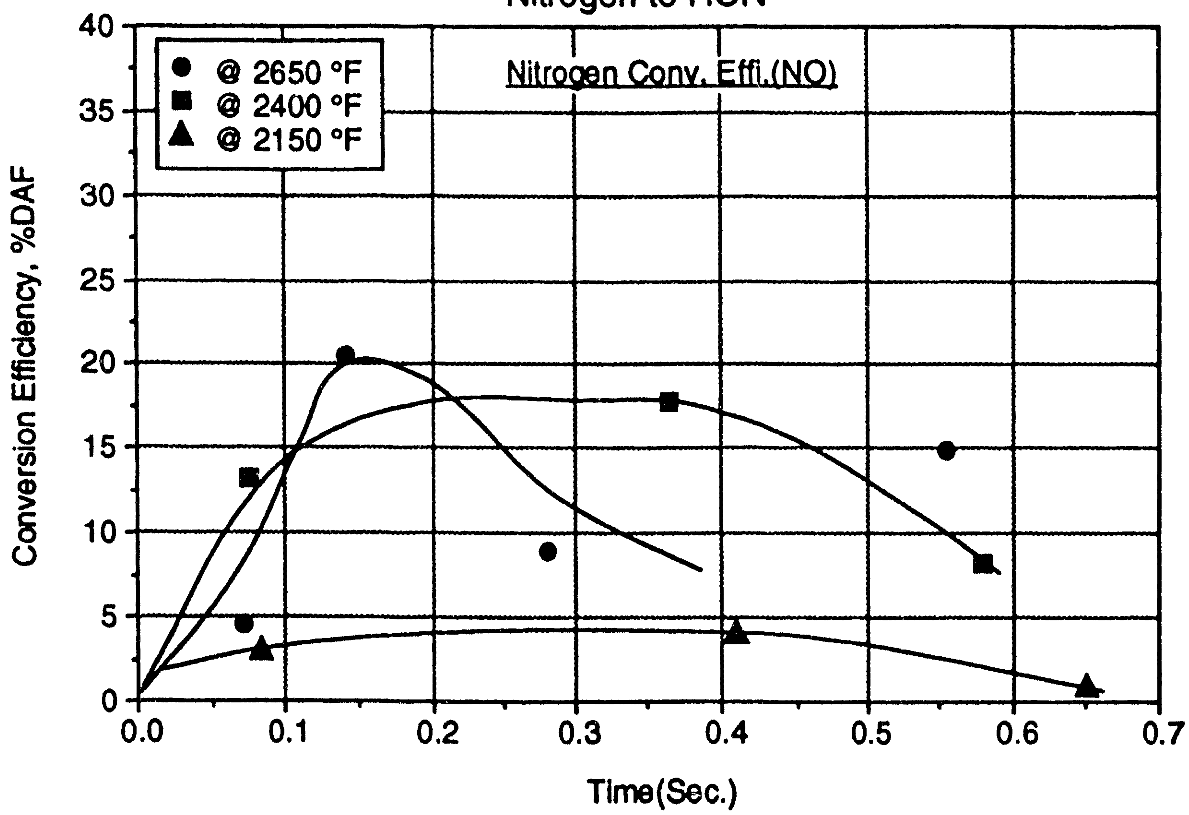

Figure 7 DTFS-1 Pyrolysis of 400 x 0 Mesh Illinois #6 Coal - Fuel Nitrogen to NO

ENGINEERING DEVELOPMENT OF AN ADVANCED COAL-FIRED LOW-EMISSION BOILER SYSTEM

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INTRODUCTION

Riley Stoker Corporation is leading one of three teams in a program for the expedited development of a new generation of pulverized coal-fired boiler systems. The overall objective is to develop relatively near term technologies to produce Low-Emission coal-fired Boiler Systems (LEBS) ready for full scale commercial generating plants by the end of the decade. The specific goal of this team is to develop a LEBS incorporating an advanced slagging system capable of meeting all emission and performance goals.

The Riley project team consists of the following organizations: Riley Stoker/Deutsche-Babcock, Reaction Engineering International, Research Cottrell, Sargent & Lundy Engineers, Tecogen, and Textron Defense Systems.

PERFORMANCE GOALS

The primary performance requirements are all emissions-related and correspond to one-third to one-half of current Federal NSPS limits: NO_x, less than 0.2 lbs/million Btu; SO_2, less than 0.2 lbs/million Btu; particulates, less than 0.015 lbs/million Btu. However, any new plant design will need to include the flexibility to meet lower emission limits. Therefore, this team has established goals of 0.1, 0.1, and 0.010 lbs/million Btu for NO_x, SO_2, and particulates.

Secondary objectives include improved ash disposability, reduced waste generation, and increased efficiency, with a goal of 40% to 42% net plant efficiency (HHV basis).

PROGRAM STRUCTURE

The total program comprises four phases with these major tasks:

- Phase I: Work Plan; Concept Development; R&D Test Plan, Component Definition; Commercial Generating Unit Preliminary Design.
- Phase II: Component Development and Optimization; Preliminary Proof-of-Concept (POC) Test Facility Design; Subsystem Test Unit Design, Construction, Operation.
- Phase III: Revised Commercial Generating Unit Design; POC Test Facility Detailed Design, Test Plan.
- Phase IV: POC Test Facility Construction, Testing, and Evaluation.

This paper gives a summary of the project nearing the completion of Phase I.

SYSTEM COMPONENTS

Design Fuels. The LEBS Commercial Generating Unit (CGU) design is based on a high-sulfur Illinois No. 6 coal. This coal meets program selection requirements of extensive reserves and production, sulfur content, and representativeness. Two alternate test coals have been selected to examine fuel effects, and to broaden the range of application of the technology being developed. The alternate coals are a medium sulfur, Pittsburgh No. 8 bituminous, and a Wyoming subbituminous coal.

Boiler and Steam Cycle. The efficiency goals for the LEBS are challenging, particularly with the demands environmental controls place on auxiliary power. The EPRI SOAPP (State-of-the-Art Power Plant) project has selected the 4500 psi/1100°F double reheat cycle as maximizing plant efficiency while minimizing generating costs. This program will incorporate the SOAPP base case cycle.

The LEBS design will incorporate a high-efficiency, once-through boiler design known as the Benson. Significant improvements in availability and operating flexibility have made this boiler design the system of choice for European power generation over the last fifteen years. The preliminary design of the boiler is shown in Figure 1. In order to maximize efficiency, an advanced low temperature heat recovery system is integrated into the feedwater heating system of the supercritical cycle.

Firing System

Granulated slag from slagging, or "wet" firing systems is lower in volume, and is more stable from the standpoint of leachability than fly ash. Although ash can be used in the manufacture of construction materials, slag is more broadly usable as a byproduct. There is a renewed interest in slagging firing for ash management both domestically and in the world market.

Slagging systems typically exhibit higher NO_x emissions and have had historically higher maintenance costs and lower availability than dry systems. Due to NO_x emissions, few wet firing systems have been constructed since the 1970's. However, many advances have been made in materials for slagging combustors, and good availability is now possible.

System Selection. Advances in combustion NO_x control have also been made for slagging systems, but the controlled NO_x is still high relative to current requirements and the program goals. A major element in Phase I of this program has been the evaluation of two options for controlling NO_x while vitrifying essentially all of the coal ash:

- An experimental and engineering evaluation of the Toroidal Vortex Combustor or TVC.
- An engineering and modeling evaluation of an advanced concept developed from the commercially proven U-fired slagging design.

NO_x control, while key, was only one of many criteria in this evaluation. Other important factors included scale up, constructability, integration with the boiler, materials, and operating cost. Based on this evaluation, the advanced U-fired concept has been selected for development as a LEBS firing system.

U-fired Slagging NO_x Control Experience. The DB experience list includes forty-nine U-fired slag tap boilers in capacities up to 350 MW_e, with additional units in construction. The U-fired slag-tap boiler design will produce the vitrified coal ash desired for the LEBS concept, however, additional development is required to reduce NO_x emissions. Recent retrofit programs to control NO_x from existing U-fired boilers have included staged air addition, flue gas recirculation, and pulverizer upgrades to improve coal fineness. These measures have resulted in reduction of NO_x emissions from 1.6 to 0.8 lb/MBtu with the existing burners. Retrofit of new low-NO_x burners in conjunction with the current air staging design is projected to reduce NO_x to 0.6 lb/million Btu.

U-Fired Adaptation for Reburning. To meet the goals of the LEBS program additional combustion NO_x control will be achieved through the application of reburning technology to the U-fired boiler design. The U-firing configuration is ideally suited to the reburn process, especially for a new boiler design. A preliminary engineering design showing the application of the reburning process to a U-fired slag-tap furnace configuration is shown in Figure 2. The high temperature and well-controlled stoichiometry at the bottom of the slag chamber provide conditions for rapid reduction of NO_x with significantly less reburning fuel than is typically required. The long residence time in the radiant furnace following the slag chamber also allows the NO_x reduction, final air addition, and completion of combustion to be optimized while using coal as the reburn fuel. In the preliminary design shown, there is approximately 0.75 s available between fuel injection and the first level of tertiary air, and an additional 1 s available between final air addition and the furnace exit. The projected NOx reduction of 70% with reburning, in conjunction with low NOx burners and air staging, will give a furnace exit NO_x of 0.2 lb/MBtu.

Through the use of flyash reinjection all of the coal ash can be removed as vitrified slag and high overall carbon conversion efficiencies are also insured. The fine coal grinds which can be achieved by dynamic classification will also contribute to the effectiveness of tnis design.

Back End Heat Recovery

Air heat only. Ideally, all of the low temperature heat would be recovered into the combustion air entering the boiler. Typically a 40°F reduction in flue gas temperature increases boiler efficiency by about 1%; in turn, the net plant efficiency would improve by about 1% relative or about 0.4 percentage points from a 40% base value. This relationship simply assumes that recovered heat enters the steam cycle and is converted at the overall net turbine heat rate (NTHR). The exit temperature effects net plant heat rate (NPHR) only through the change in boiler efficiency.

However, the extent to which flue gas can be cooled is limited by the heat balance between the combustion air and flue gas, the requirement for high temperature combustion air to maintain combustion efficiency, and the driving force available at the hot end of the exchanger, or hot end approach. The heat balance of the steam cycle constrains the flue gas design temperature at economizer outlet/air heater inlet. For the design coal with a conventional economizer outlet temperature, the flue gas exit temperature would be about 280°F at a 50°F hot end approach, and the limiting temperature (zero hot end approach) is about 240°F. Additional heat recovered from a regenerable SO_2 control system would further limit the extent to which the final gas temperature can be reduced by air preheating alone.

Condensate heating. The condensate offers another low temperature medium to which heat may be transferred from the relatively cool flue gas. In contrast to the air heat only case, however, one cannot simply calculate a new boiler efficiency for the lowered flue gas temperature and apply it to the existing NTHR. The efficiency at which the heat is converted to energy depends strongly on where in the cycle the sensible heat of the flue gas is used to replace turbine extraction steam normally used for feedwater heating.

Several configurations were examined to recover the heat in the low temperature flue gas stream, and illustrate the variability in conversion efficiency of the recovered heat. Initially, simple configurations were evaluated in which the full condensate stream is heated in a heat exchanger in series with a conventional air heater. In order to reach a low flue gas exit temperature, this requires that the flue gas heat replace extraction steam from one or more of the three lowest temperature feedwater heaters The conversion efficiency of recovered heat was very low in this arrangement.

In order to replace higher value steam, and yet allow a low final flue gas temperature, an arrangement incorporating parallel air and feedwater heating was developed. The concept itself is not entirely new; the present work focuses on integrating it into the advanced steam cycle. A portion of the flue gas is diverted from the air heater to heat a portion of the feedwater, reducing the extraction steam demand in selected stages. A second air heater extracts the final heat from the flue gas. With this arrangement, both high air preheat temperature and low final flue gas temperature can be maintained, and the additional heat can be used quite efficiently. The configuration developed for the LEBS design is illustrated in Figure 3. The conversion efficiency of recovered heat in this concept closely approaches that of the overall cycle.

Emissions Control

The LEBS concept incorporates a moving bed copper oxide system, a dry, regenerable SO_2/NO_x control process which has significant integration advantages for particulate control as well as heat recovery. In combination with a slagging firing system for ash management, this approach minimizes waste and emissions from all streams leaving the power plant.

Overview of regenerable approach. Figure 4 shows the integration of the regenerable process into the low emission boiler system. Primary NO_x control is achieved through firing system design, as discussed previously. The flue gas leaving the boiler economizer at about 750°F is desulfurized in a moving bed reactor. The sorbent, alumina impregnated with copper oxide, is regenerated in a separate reactor.

The primary function of the absorber is to remove sulfur dioxide from the flue gas. The size and cost of the absorber is driven by desulfurization requirements for the high sulfur design coal. However, the absorber provides important additional benefits. First, the copper oxide/copper sulfate bed acts as a selective catalyst for NO_x reduction. Thus, NO_x may be reduced to very low levels without significant added capital cost by the addition of an ammonia injection system, either to address deficiencies in combustion NO_x control or to meet stringent site-specific requirements.

Second, the sorbent bed removes a substantial amount of particulate from the flue gas. While the moving bed will not clean the flue gas to the very low levels required at the stack, the reduced ash loading will allow downstream heat exchangers and the final particulate control device to be more compact. Finally, the adsorber removes essentially all of the SO_3 from the gas, so that acid corrosion in the downstream devices is reduced or eliminated.

The hot desulfurized flue gas is then split to transfer heat to the feedwater in a low level economizer and an air heater. These heat exchangers benefit from the fact that the flue gas has been largely desulfurized and partially cleaned of particulate matter.

The relatively cool flue gas is then thoroughly cleaned of particulate matter in a pulse jet baghouse. The baghouse is compact as a consequence of the low particulate loading leaving the absorber, offsetting part of the higher capital cost and plan area associated with regenerable SO_2 removal.

The flue gas then passes through the ID fan and the second air heater. The second air heater cools the flue gas to approximately 180°F. The arrangement of the two air heaters and the condensate heater allows the heat recovered even at this low flue gas temperature to be converted to power at efficiencies approaching that of the overall cycle.

The injection of small amounts of sorbent (eg, lime for HCl or active coke for organics or mercury) into the baghouse could provide an option for toxics reduction if this is required.

Heat Effects. The SO_2 absorption reaction is exothermic, and the energy can be recovered in the downstream heat exchange equipment. The regeneration reaction requires a reducing gas, such as methane, CO or H_2. Regeneration is endothermic, however, the net reaction of the absorption and regeneration steps is exothermic. One advantage of this process is that the optimum absorption and regeneration temperatures are similar. The two processes can be operated without intermediate heating and cooling steps, reducing equipment and auxiliary fuel requirements, and allowing the energy of the reducing gas to be recovered efficiently.

The concentrated sulfur dioxide stream resulting from regeneration may be oxidized to sulfur trioxide and condensed to sulfuric acid, or it can be converted to elemental sulfur in a Claus Plant. The production of acid byproduct provides a significant gain in thermal efficiency of the plant, whereas the sulfur byproduct may be desirable from the aspects of storage, transportation, and market value. This byproduct flexibility allows the FGD byproduct to be directed toward the better of the two markets.

The Claus plant requires additional reducing gas. Production of acid rather than sulfur eliminates the additional reducing gas requirement, and adds a significant heat gain. Note that plant heat rate efficiency calculations must include the reducing gas as a fuel input for consistency since the heat gain is taken as a credit.

SUMMARY

A Low Emission Boiler System design meeting emission, efficiency, and waste minimization goals has been developed. Key components to be developed and optimized in Phase II subsystem tests are the firing and emission control systems.

The author gratefully acknowledges the contributions of the project team, and the DOE COR, Dr. Soung S. Kim.

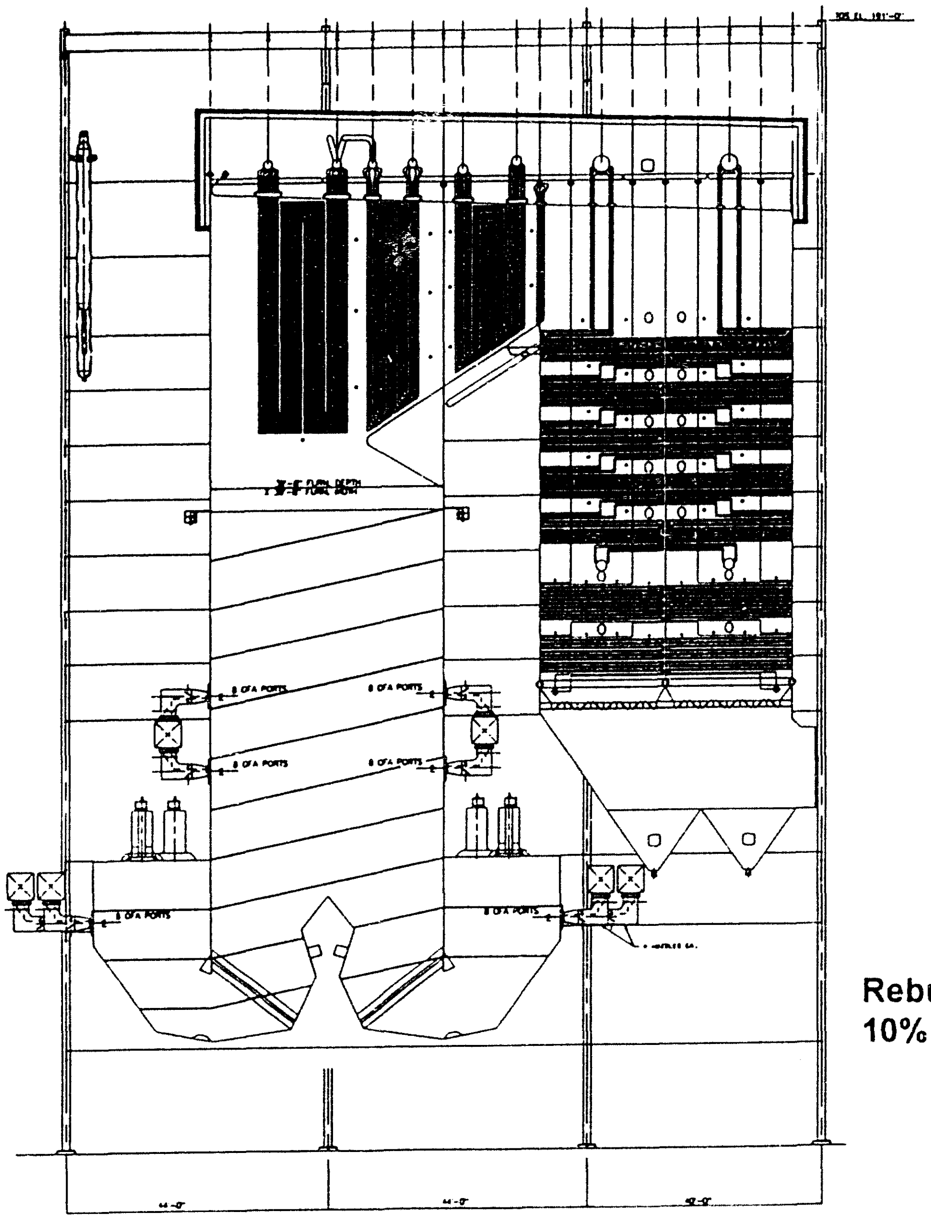

Figure 1. Preliminary Design of Supercritical U-Fired Boiler.

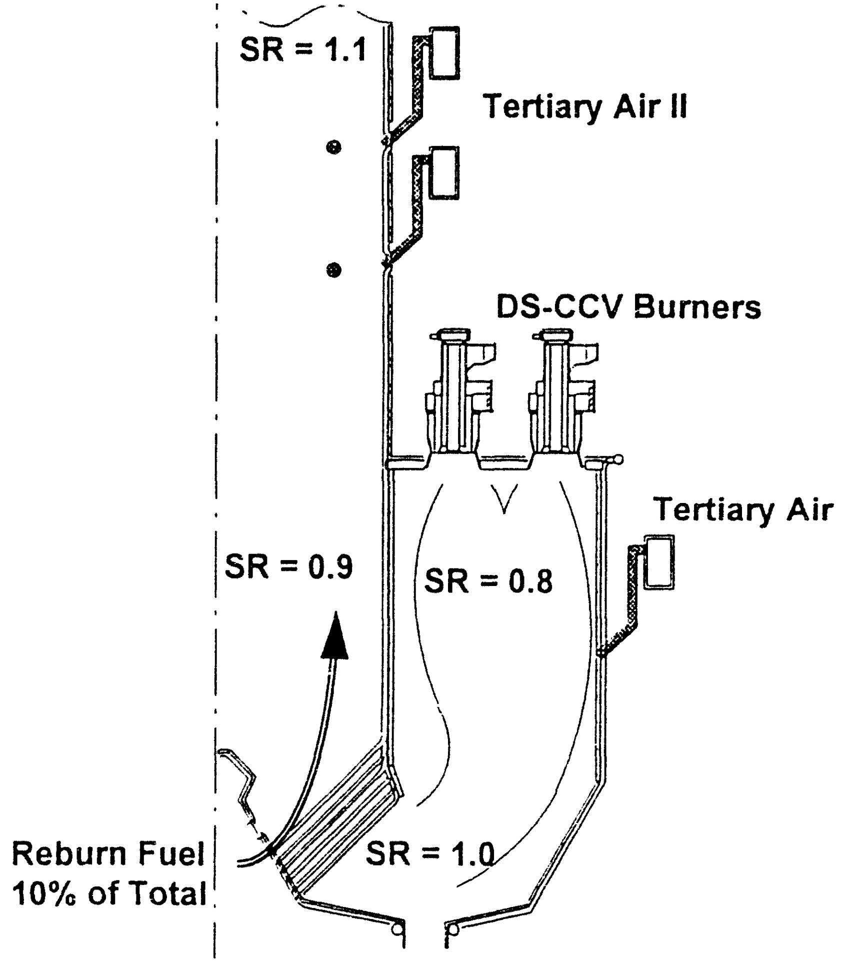

Figure 2. Advanced U-Fired Design Using Reburning.

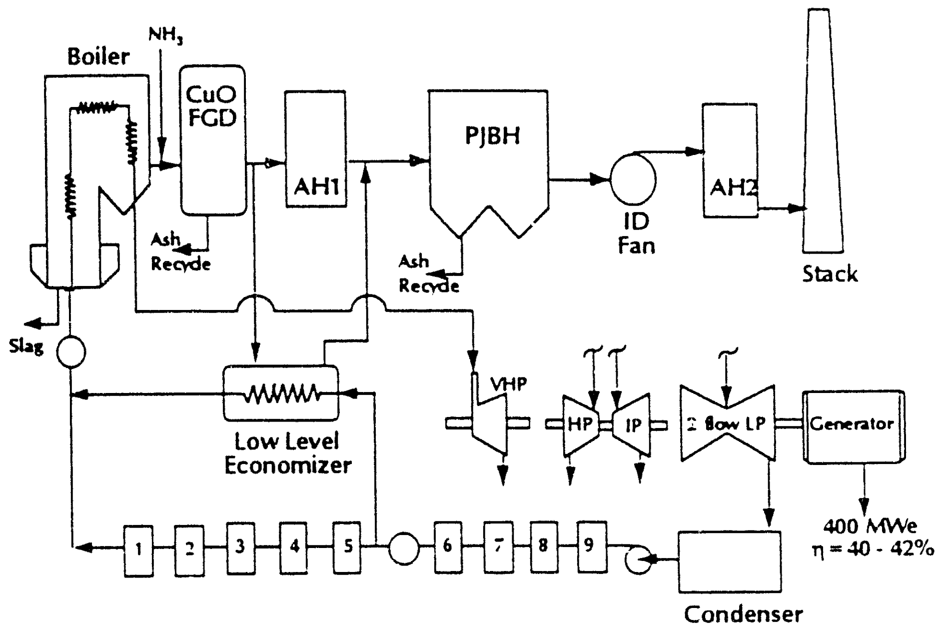

Figure 3. Low Temperature Heat Recovery System.

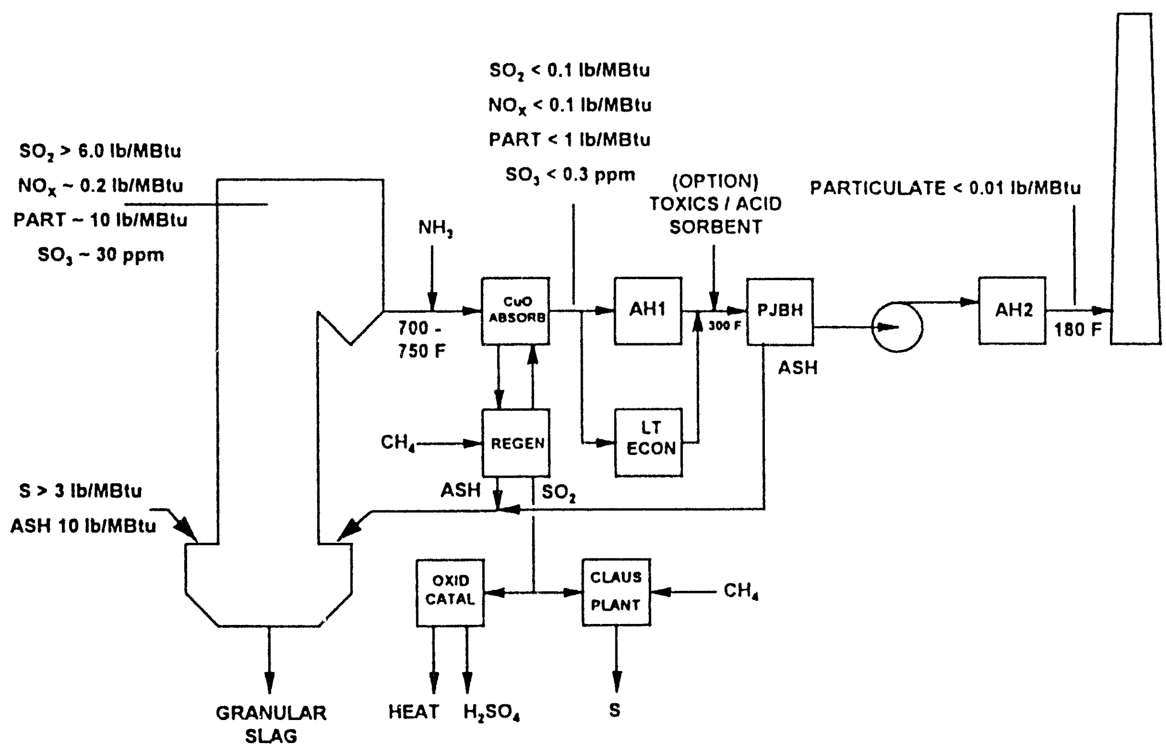

Figure 4. Emissions Control Concept.