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ENGINEERING DEVELOPMENT OF COAL-FIRED HIGH-PERFORMANCE POWER SYSTEMS

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TECHNICAL PROGRESS REPORT 5
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ABSTRACT

A High Performance Power System (HIPPS) is being developed. This system is a coal-fired, combined cycle plant with indirect heating of gas turbine air. Foster Wheeler Development Corporation and a team consisting of Foster Wheeler Energy Corporation, AlliedSignal Aerospace Equipment Systems, Bechtel Corporation, University of Tennessee Space Institute and Westinghouse Electric Corporation are developing this system. In Phase 1 of the project, a conceptual design of a commercial plant was developed. Technical and economic analyses indicated that the plant would meet the goals of the project which include a 47 percent efficiency (HHV) and a 10 percent lower cost of electricity than an equivalent size PC plant.

The concept uses a pyrolyzation process to convert coal into fuel gas and char. The char is fired in a High Temperature Advanced Furnace (HITAF). It is a pulverized fuel-fired boiler/airheater where steam and gas turbine air are indirectly heated. The fuel gas generated in the pyrolyzer is then used to heat the gas turbine air further before it enters the gas turbine.

The project is currently in Phase 2 which includes engineering analysis, laboratory testing and pilot plant testing. Research and development is being done on the HIPPS systems that are not commercial or being developed on other projects. Pilot plant testing of the pyrolyzer subsystem and the char combustion subsystem are being done separately, and then a pilot plant with integrated pyrolyzer and char combustion systems will be tested.

In this report, progress in the pyrolyzer pilot plant preparation is reported. The results of extensive laboratory and bench scale testing of representative char are also reported. Preliminary results of combustion modeling of the char combustion system are included. There are also discussions of the auxiliary systems that are planned for the char combustion system pilot plant and the status of the integrated system pilot plant.

EXECUTIVE SUMMARY

The High Performance Power System is a coal-fired, combined cycle power generating system that will have an efficiency of greater than 47 percent (HHV) with NO_x and SO_x less than 0.025 Kg/GJ (0.06 lb/MMBtu). This performance is achieved by combining a coal pyrolyzation process with a High Temperature Advanced Furnace (HITAF). The pyrolyzation process consists of a pressurized fluidized bed reactor which is operated at about 926°C (1700°F) at substoichiometric conditions. This process converts the coal into a low-Btu fuel gas and char. These products are then separated.

The char is fired in the HITAF where heat is transferred to the gas turbine compressed air and to the steam cycle. The HITAF is fired at atmospheric pressure with pulverized fuel burners. The combustion air is from the gas turbine exhaust stream. The fuel gas from the pyrolyzation process is fired in a Multi-Annular Swirl Burner (MASB) where it further heats the gas turbine air leaving the HITAF. This type of system results in very high efficiency with coal as the only fuel.

We are currently in Phase 2 of the project. In Phase 1, a conceptual plant design was developed and analyzed both technically and economically. The design was found to meet the project goals. The purpose of the Phase 2 work is to develop the information needed to design a prototype plant which would be built in Phase 3. In addition to engineering analysis and laboratory testing, the subsystems that are not commercial or being developed on other projects will be tested at pilot plant scale. The FWDC Second-Generation PFB pilot plant in Livingston, New Jersey is being modified to test the pyrolyzer subsystem. The FWDC Combustion and Environmental Test Facility (CETF) in Dansville, NY is being modified to test the char combustion system. When these tests are complete, an integrated pilot plant including both the pyrolyzation and char combustion systems will be built and tested at the University of Tennessee Space Institute (UTSI). This pilot plant will have a coal input of 2724 Kg/h (6000 lb/h).

In the current Quarter, work has proceeded on the modification of the Livingston, New Jersey pilot plant for the pyrolyzation tests. Shakedown and the start of testing is scheduled to start in the last Quarter of 1996. This testing will be in the bubbling bed mode. The most extensive area of plant modification for this test series is the coal feed system. This system is being modified to safely handle the pulverized coal that will be used for the HIPPS testing. The final equipment required for this system is due in late October 1996. In early 1997, the pilot plant will be further modified for testing in a circulating bed mode. This testing is scheduled to start in the Spring of 1997.

Modifications to the CETF are being made as they can be practically scheduled with other test programs. The furnace is being modified for arch-firing, and systems are being designed to simulate HIPPS firing conditions. The design of a burner is in progress, and this effort is being assisted with laboratory and bench scale testing of the char as well as computer modeling. In the current Quarter, considerable work was done in these areas.

Char from the Second-Generation PFB tests has been characterized and compared with other low -volatile fuels. This char was generated from Pittsburgh No.8 coal which is the coal we will be using for all the HIPPS tests. The char chosen for analysis was from the primary cyclone catch which should be closest to the type of char we will generate under HIPPS conditions. Chemical analyzes of the char and ash were run along with the T_{15} reactivity and Thermogravimetric analysis (TGA). In addition to these standard laboratory tests, drop tube furnace tests were run. The results of all the testing indicated that we should get good carbon burnout with the char. The char had a lower burnout temperature in the TGA tests than typical anthracite and low-volatile bituminous coals.

This result was also confirmed in the drop tube furnace tests. These tests are closer to actual operation because the fuel particles are maintained at furnace temperature and excess air levels for typical furnace residence times. This is accomplished by dropping a stream of fuel particles through a heated tube with an air flow for a specific excess air level. It takes 2 seconds for the particles to pass through the tube which is typical of furnace residence times. At the bottom of the tube, the particles are cooled rapidly, and the carbon in the ash is measured. This test will give an indication of the relative burnout that can be expected for various fuels.

Drop tube tests were run with the char, Narcea anthracite, Wannian anthracite and Wangzhuang low-volatile bituminous coals. In this manner, the char was compared to fuels where there is commercial scale information on performance. Tests with a range of drop tube operating parameters are contained in this report. In all cases, the char had greater carbon burnout than the other fuels. At 1500°C (2732°F), the char had a very high carbon burnout of 97.4 %. Under these conditions the anthracites averaged a carbon burnout of 82%, and the low-volatile bituminous coal had a burnout of 94%. NO_x levels were also measured in the drop tube tests. In this area, the char did not perform as well as the other fuels. With the char, 44% of the fuel nitrogen went to NO_x whereas only 20-25% went to NO_x with the other fuels. The reason for the higher NO_x levels has not been ascertained as yet. Combustion tests will be run with chars devoid of sorbent to determine if there is a catalytic effect.

The T_{15} reactivity tests and the TGA tests give an indication of the fuel ignition potential. The lower the T_{15} reactivity and the lower the ignition temperature in the TGA, the easier the fuel is to ignite. The results of these tests indicate that the ignition potential of the char is similar to the ignition potential of the Narcea anthracite. That fuel requires oil support fuel for maintaining flame stability in arch-fired boilers in Spain. This indicates that support fuel may be required for the char. The char combustion pilot plant tests will investigate what level of support fuel is required if any.

Computer modeling was done on the furnace that will be used in the combustion system pilot plant tests. The code used was PCGC-3 which has been developed at Brigham Young University. The results so far are considered preliminary, but the particle burnout predicted by the model is 99.5%. The oxidation rate model in the code is going to be modified to be more accurate and to be more compatible with the empirical data that is used for the fuel specific parameters.

INTRODUCTION

In Phase 1 of the project, a conceptual design of a coal-fired high performance power system was developed, and small scale R&D was done in critical areas of the design. The current Phase of the project includes development through the pilot plant stage, and design of a prototype plant that would be built in Phase 3.

Foster Wheeler Development Corporation (FWDC) is leading a team of companies in this effort. These companies are:

- Foster Wheeler Energy Corporation (FWEC)
- AlliedSignal Aerospace Equipment Systems
- Bechtel Corporation
- University of Tennessee Space Institute (UTSI)
- Westinghouse Electric Corporation

The power generating system being developed in this project will be an improvement over current coal-fired systems. Goals have been identified that relate to the efficiency, emissions, costs and general operation of the system. These goals are:

- Total station efficiency of at least 47 percent on a higher heating value basis.
- Emissions:
  NO_x < 0.06 lb/MMBtu
  SO_x < 0.06 lb/MMBtu
  Particulates < 0.003 lb/MMBtu
- All solid wastes must be benign with regard to disposal.
- Over 95 percent of the total heat input is ultimately from coal, with initial systems capable of using coal for at least 65 percent of the heat input.
- Ten percent lower cost of electricity (COE) relative to a modern coal-fired plant conforming to NSPS.

The base case arrangement of the HIPPS cycle is shown in Figure 1. It is a combined cycle plant. This arrangement is referred to as the All Coal HIPPS because it does not require any other fuels for

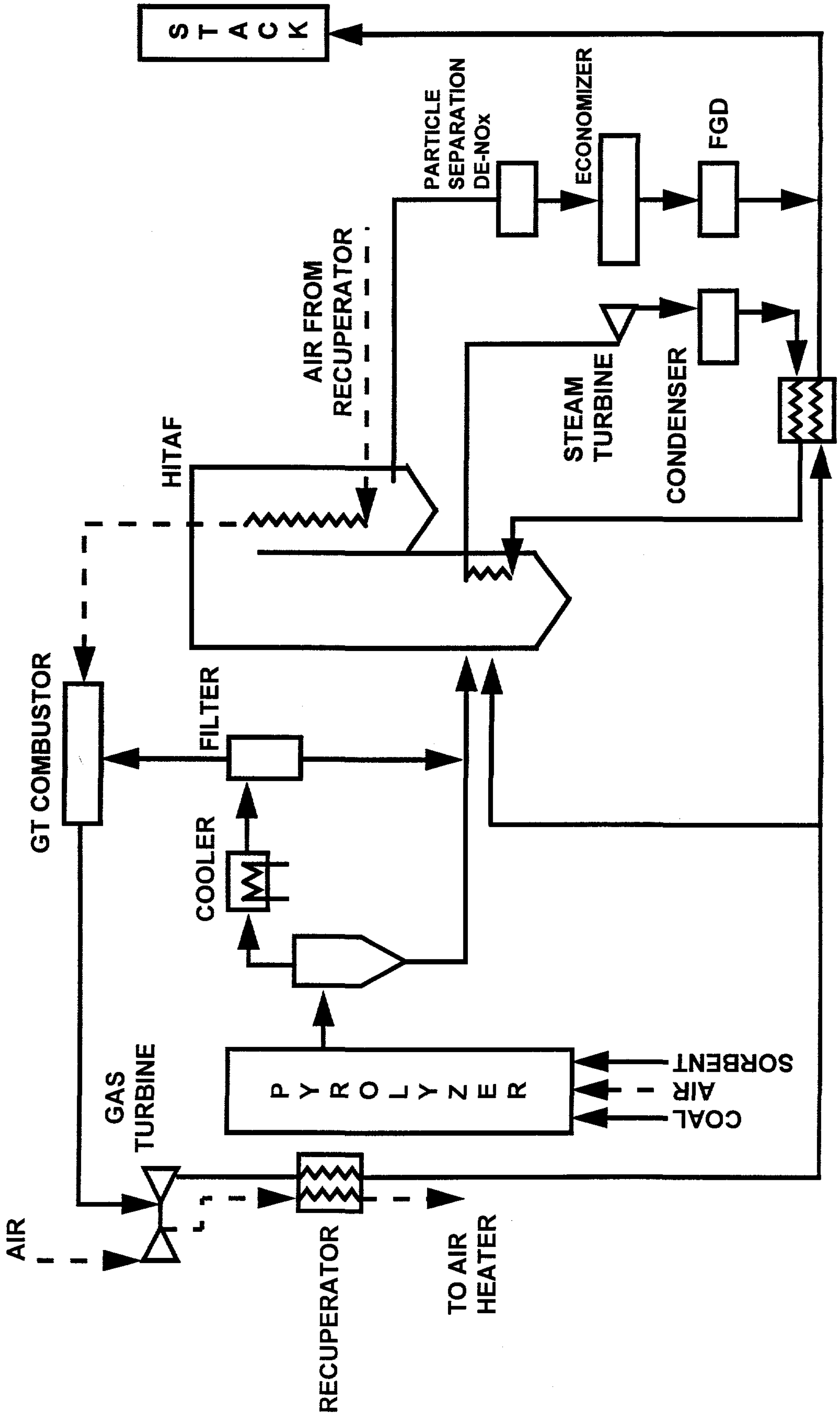


Figure 1 All Coal Fired HIPPS

normal operation. A fluidized bed, air blown pyrolyzer converts coal into fuel gas and char. The char is fired in a high temperature advanced furnace (HITAF) which heats both air for a gas turbine and steam for a steam turbine. The air is heated up to 760°C (1400°F) in the HITAF, and the tube banks for heating the air are constructed of alloy tubes. The fuel gas from the pyrolyzer goes to a topping combustor where it is used to raise the air entering the gas turbine to 1288oC (2350°F). In addition to the HITAF, steam duty is achieved with a heat recovery steam generator (HRSG) in the gas turbine exhaust stream and economizers in the HITAF flue gas exhaust stream.

An alternative HIPPS cycle is shown in Figure 2. This arrangement uses a ceramic air heater to heat the air to temperatures above what can be achieved with alloy tubes. This arrangement is referred to as the 35 percent natural gas HIPPS, and a schematic is shown in Figure 2. A pyrolyzer is used as in the base case HIPPS, but the fuel gas generated is fired upstream of the ceramic air heater instead of in the topping combustor. Gas turbine air is heated to 760°C (1400°F) in alloy tubes the same as in the All Coal HIPPS. This air then goes to the ceramic air heater where it is heated further before going to the topping combustor. The temperature of the air leaving the ceramic air heater will depend on technological developments in that component. An air exit temperature of 982°C (1800° F) will result in 35 percent of the heat input from natural gas.

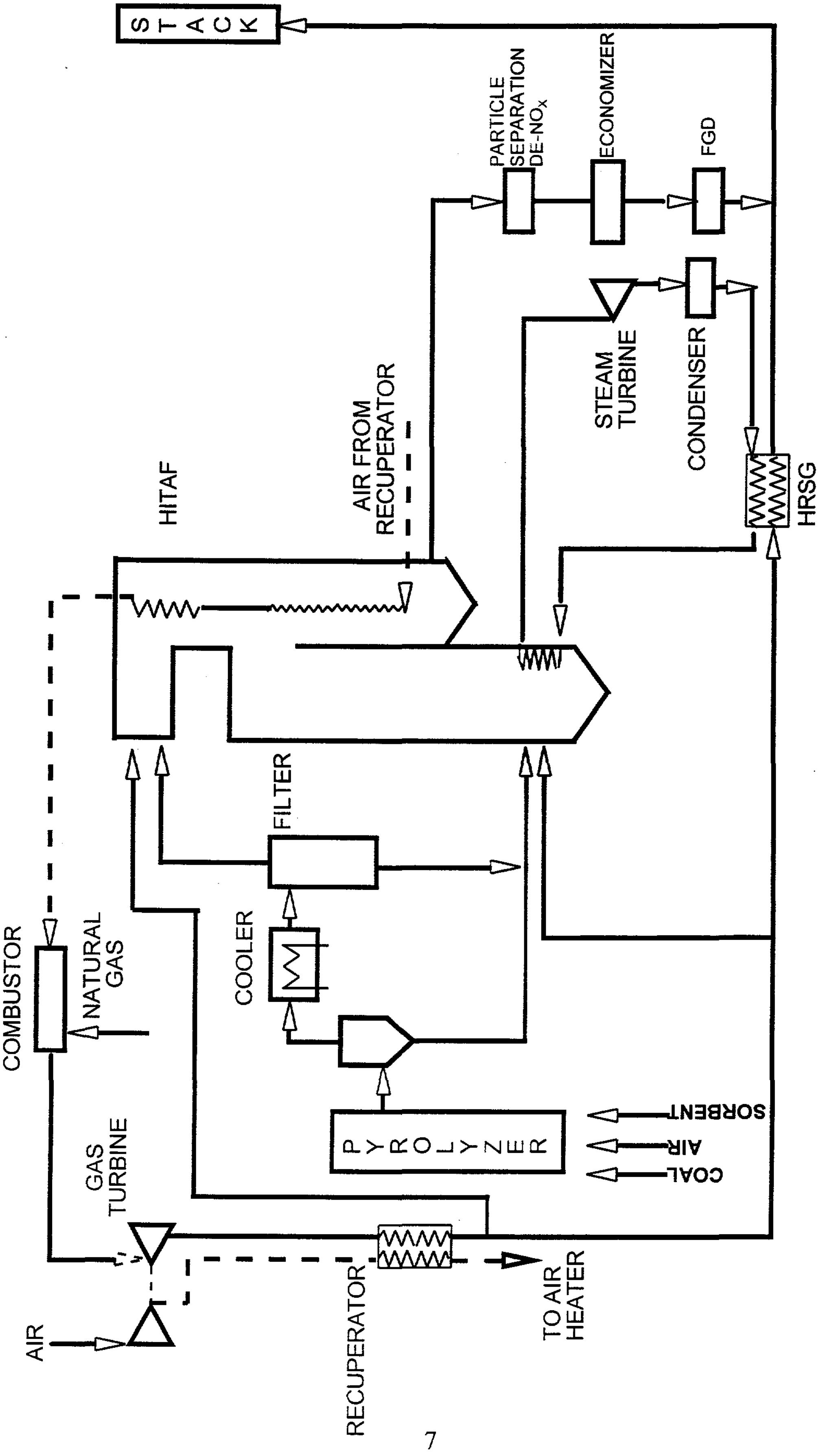


Figure 2 35-Percent Natural Gas HIPPS

TECHNICAL PROGRESS

Task 1 - Project Planning and Management

Work is proceeding in accordance with the Project Plan.

Task 2 - Engineering Research and Development

Subtask 2.4 - Char Combustor Analysis

During this Quarter, work has been done on both the characterization of char in laboratory tests and computer modeling of char combustion in an arch-fired furnace. The laboratory tests included standard laboratory coal characterization tests and drop tube furnace tests. The computer modeling was done on PCGC-3 a combustion code developed at Brigham Young University.

Char Characterization

Tests Performed
Extensive characterization was performed of Pittsburgh No. 8 char. This char was produced during pilot plant testing of Second-Generation PFB and was taken from the cyclone catch of the bubbling bed carbonizer. This drain location was chosen to minimize the amount of sorbent in the sample. Laboratory characterization included char chemical analysis and reactivity evaluation by several bench-scale tests. Char reactivity is of particular importance, especially in terms of burner and furnace design. These reactivity tests are summarized below in Table 1.

Table 1 Summary of Bench-Scale Reactivity Tests

TEST	DIAGNOSTICS	PURPOSE
T_{15}	Measures temperature when sample has 15°C/min rise	Ignition index. Harder to ignite fuels have higher T_{15}
TGA	Weight loss vs temperature at constant heating rate 20°C/min	Relative fuel reactivity. Measures char ignition and burnout temperatures
Drop Tube	Char combustion efficiency and NO_x emissions	Determines parameters at conditions similar to boiler -- particle heating rate, excess air, residence time

First, the T_{15} reactivity was measured to give an indication of fuel ignition potential. The T_{15} temperature is defined as the temperature at which a standard size sample sustains a temperature rise of 15°C/min as it is heated in a furnace. Based on FWEC Engineering Standards, coals with a T_{15} greater than 275°C have traditionally been arch-fired in boilers in order to maintain flame stability.

Thermogravimetric analysis (TGA) was also performed on char samples for a qualitative comparison with fuels of known performance in the field. TGA tests can provide a relative indication of fuel reactivity by determining ignition and burnout temperatures. Although this test can be used to rank the relative reactivity of fuels, it cannot simulate the particle heating rate and excess air levels of a full-scale boiler.

Drop tube tests were conducted with char and anthracites at conditions more representative of a utility boiler. In this test, a pulverized fuel sample was combusted in a tube reactor at temperatures up to 1500°C (2732°F) and air levels ranging from near stoichiometric to 100 percent excess. The particle residence time in the furnace was about two seconds. The combustion efficiency of samples was determined by analysis of the ash and carbonaceous material collected during the tests. In addition, a real time gas analysis train at the furnace exit provided continuous measurements of O_2, CO_2 and NO_x.

Char Chemical and Physical Analyses

The proximate and ultimate analyses of the Pittsburgh No. 8 char are shown in Table 2, along with those of other selected coals. This char sample was taken from the carbonizer cyclone drain during TR-4 of the Phase 2 Second Generation Pilot Plant tests in 1992. As shown in Table 2, the char contained 31.7% ash, with the ash chemistry of the char and raw coal listed in Table 3. Based in these ash chemistries, it appears that about 60% of the char ash is composed of sorbent material. This rough estimate was obtained by assuming that all of the silica or alumina in the coal exited the carbonizer in this drain.

The proximate analysis for the char shows that it contains a significant amount of volatiles (8.21%). This volatiles content appears much higher than that obtained for similar cyclone drain samples in 1992 (< 1% VM). The apparent higher volatile content of the more recent sample may be due to moisture. The sample appeared very wet when taken from the drum after several years of storage. This moisture may have caused some hydration of the sorbent or ash, which was not removed during the moisture analysis. As a result, it appears that only a fraction of the moisture is being released during the moisture determination of the proximate analysis, with the remainder being reported as volatiles.

The particle size distribution of the cyclone drain sample is shown in Table 4. As expected this sample was relatively fine and had a D_{50} of about 60 microns. For drop tube tests, a 100 x 140 mesh sample was utilized (~127 microns) as will be discussed later. This size fraction was chosen for two reasons. First, oversize material (>200 mesh) is usually responsible for carbon loss in pulverized

Table 2 Proximate/Ultimate Analysis of Char and Coals

	Pittsburgh No. 8 Char (after storage*)	Pittsburgh No. 8 Char (as generated)	Narcea Anthracite	Wannian Anthracite	Wangzhuang Bituminous
Proximate Analysis, %					
Fixed carbon	53.07	68.79	62.48	79.28	63.04
Volatile matter	8.21	0.40	5.80	2.01	12.48
Ash	31.70	30.38	22.23	16.59	19.01
Moisture	7.02	0.43	9.49	2.12	5.47
Ultimate Analysis, %					
Carbon	56.94	64.45	65.19	77.36	70.19
Hydrogen	0.34	0.39	1.61	1.09	3.43
Oxygen	0.74	0	0.05	1.56	0.38
Nitrogen	0.74	1.64	0.74	0.87	1.29
Sulfur	2.52	2.71	0.69	0.41	0.23
Ash	31.70	30.38	22.23	16.59	19.01
Moisture	7.02	0.43	9.49	2.12	5.47
Equil. moist, %	9.22	--	7.58	0.74	4.82
HHV, Btu/lb	8618	9898	9814	10743	11499
Sulfide S, %	0.43	1.73	--	--	--
Carbonate C, %	0.55	0.79	--	--	--

*Stored char picked up moisture. It is believed that some of the moisture hydrated the sorbent in the ash which gives an erroneous volatile measurement.

Table 3 Ash Chemistry of Pittsburgh No. 8 Coal and Char

Component, wt%	Coal	Char
SiO_2	47.4	20.3
Al_2O_3	21.4	8.7
TiO_2	1.1	0.5
Fe_2O_3	18.9	14.8
CaO	5.0	22.6
MgO	1.3	15.0
Na_2O	0.7	0.1
K_2O	2.0	0.7
SO_3	1.2	17.2

Table 4 Size Distribution of Pittsburgh No. 8 Char

Screen	Microns	% On	% Thru
No. 16	1180		100.0
No. 30	600	0.06	99.94
No. 50	300	8.02	91.92
No. 100	150	17.97	73.95
No. 200	75	19.77	54.18
No. 325	45	16.29	37.89
Pan		37.89	0

fuel boilers. Second, this size would not have too high a terminal velocity, resulting in insufficient particle residence time in the test rig.

The proximate and ultimate analyses are also shown in Table 2 for several other coals, including a Spanish Narcea anthracite and Chinese Wannian anthracite and Wangzhuang bituminous. The Narcea anthracite contains 5.8% volatiles on an as-received basis and requires 5% oil support (total fuel HHV) to maintain flame stability in arch-fired boilers.

The Wannian anthracite and Wangzhuang bituminous are the design fuels for the Hangfeng Project (2 x 660 MW arch-fired boilers). The Wannian anthracite is extremely low in volatile matter (2.0% as-received and 2.5%, dry-ash free), which nearly classifies it as a meta-anthracite. The Wangzhuang coal is a low volatile bituminous (12.5% as-received and 16.5% dry-ash free), which is a very common rank of coal used for steam raising in China.

T_{15} Reactivity Index

The reactivity index for each of the selected fuels is shown in Table 5. The reactivity index is determined by heating about 1 gram of sized sample (12 x 20 mesh) in oxygen in a laboratory furnace. The reactivity index or T_{15} is the temperature at which the rate of oxidation of a sample attains an adiabatic self-heating rate of 15°C per minute. This index is determined graphically by plotting both the sample temperature and the furnace temperature. From this definition, the higher the reactivity index T_{15}, the less reactive or ignitible the fuel. Typically, fuels with a T_{15} greater than 275°C are specified to be arch-fired by FWEC standards.

Table 5 Summary of Reactivity Index and TGA Results

Fuel	VM (daf), %	Reactivity Index, °C	TGA Fuel T_{ig}, °C	Char Surface Area m^2/gC	TGA Char T_{bo}, °C
Pitt #8 char	0 - 0.5	429	475	163.8	650
Narcea	8.5	413	480	20.6	790
Wannian	2.5	519	580	11.8	860
Wangzhuang	16.5	261	430	2.0	800

As shown in Table 5, the reactivity index of the anthracites and char were all relatively high (>400°C). The low volatile bituminous coal had a much lower reactivity index of 261 °C. Typically, a the reactivity index decreases with increasing fuel volatile content as shown in Figure 3. The fuels selected for this study also follow this correlation; however, the Pittsburgh No. 8 char has a significantly lower reactivity index than the Wannian anthracite even though its volatile content is lower. It should be noted that the reactivity index of the char is similar to that of the Narcea anthracite which does require 5% oil support fuel to maintain flame stability in arch-firing. As a result, a support fuel (such as oil or coal) will probably be required for arch-firing of char.

TGA Reactivity

TGA reactivity tests were conducted on both the raw and devolatilized fuels. In the TGA test with the raw fuel, a 10 mg sample passing a 200 mesh screen is heated in air at 20°C per minute. The corresponding weight loss is determined as a function of temperature to yield the burning profile. The burning profiles of the selected fuels are shown in Figure 4 as a plot of sample weight versus temperature. As shown in this figure, the char also had an ignition temperature in the TGA which was similar to that of the Narcea anthracite (~475°C). The Wangzhuang low volatile bituminous had the lowest ignition temperature of the fuels due to its considerably higher volatile content. The ignition temperature shown in Table 5 may actually correspond to a combination of devolatilization/char combustion. The burning profiles of the raw fuels in Figure 4 show that the char burns out at a significantly lower temperature than the other fuels, especially the anthracites.

In order to have a better assessment of burnout characteristics, the fuels were first devolatilized in the TGA prior to burning. This devolatilzation was accomplished by heating the fuels at 20°C per minute under nitrogen up to a temperature of 1000°C. The resultant devolatilized fuels were then burned in air at conditions similar to the raw fuels. The burning profiles of these samples are shown in Figure 5 with their burnout temperatures listed in Table 5. The burnout temperature of the devolatilized fuels gives a good indication of the potential for carbon loss due to incomplete combustion. The Pittsburgh No. 8 char had a much lower burnout temperature than the other fuels; this characteristic can probably be related to the much higher porosity available in the char. Also shown in Table 5 are the surface areas of the devolatilized samples as measured by BET nitrogen adsorption (Coulter SA-3100). These devolatilized samples were prepared by heating the raw fuels in a covered crucible according to the proximate analysis VM test (2 minutes at 950°C). The surface area of the Pittsburgh No. 8 char was over an order of magnitude higher than the other fuels. This much higher surface area would allow increase combustion rate compared to the other fuels which do not develop significant porosity. Consequently, excessive carbon loss due to incomplete combustion would not be expected from the Pittsburgh No. 8 char, based on TGA reactivity tests.

Drop Tube Furnace Tests

A laboratory test rig was recently commissioned at FWDC for evaluating fuel reactivity and emissions. Determination of the carbon burnout and NO_x emission for the fuels was carried out in a vertical, electrically-heated drop tube reactor (DTR) capable of simulating the heating rate, temperature profile, and particle residence time of a utility boiler. A schematic diagram of the reactor is shown in Figure 6. The DTR has an alumina muffle tube which is 2.5 inches in internal diameter and 48 inches long with a maximum temperature zone of 24 inches. The tube is heated by 18 silicon carbide (SiC) "glow bars" and can maintain a maximum temperature of 1500°C (2732°F).

Figure 3 Reactivity Index Versus Fuel Volatile Content

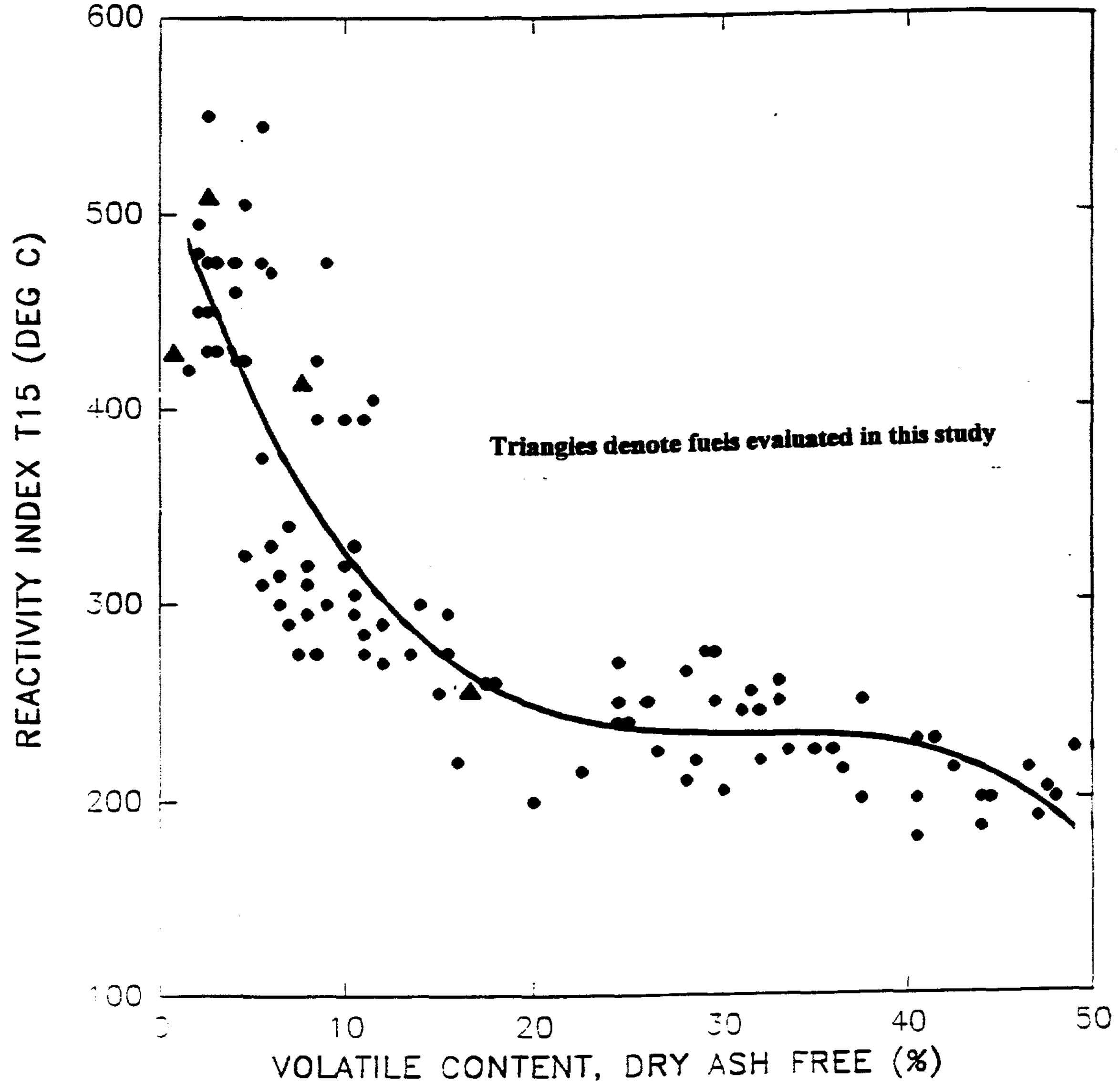


Figure 4 TGA Burning Profiles of Raw Undevolatilized Fuels

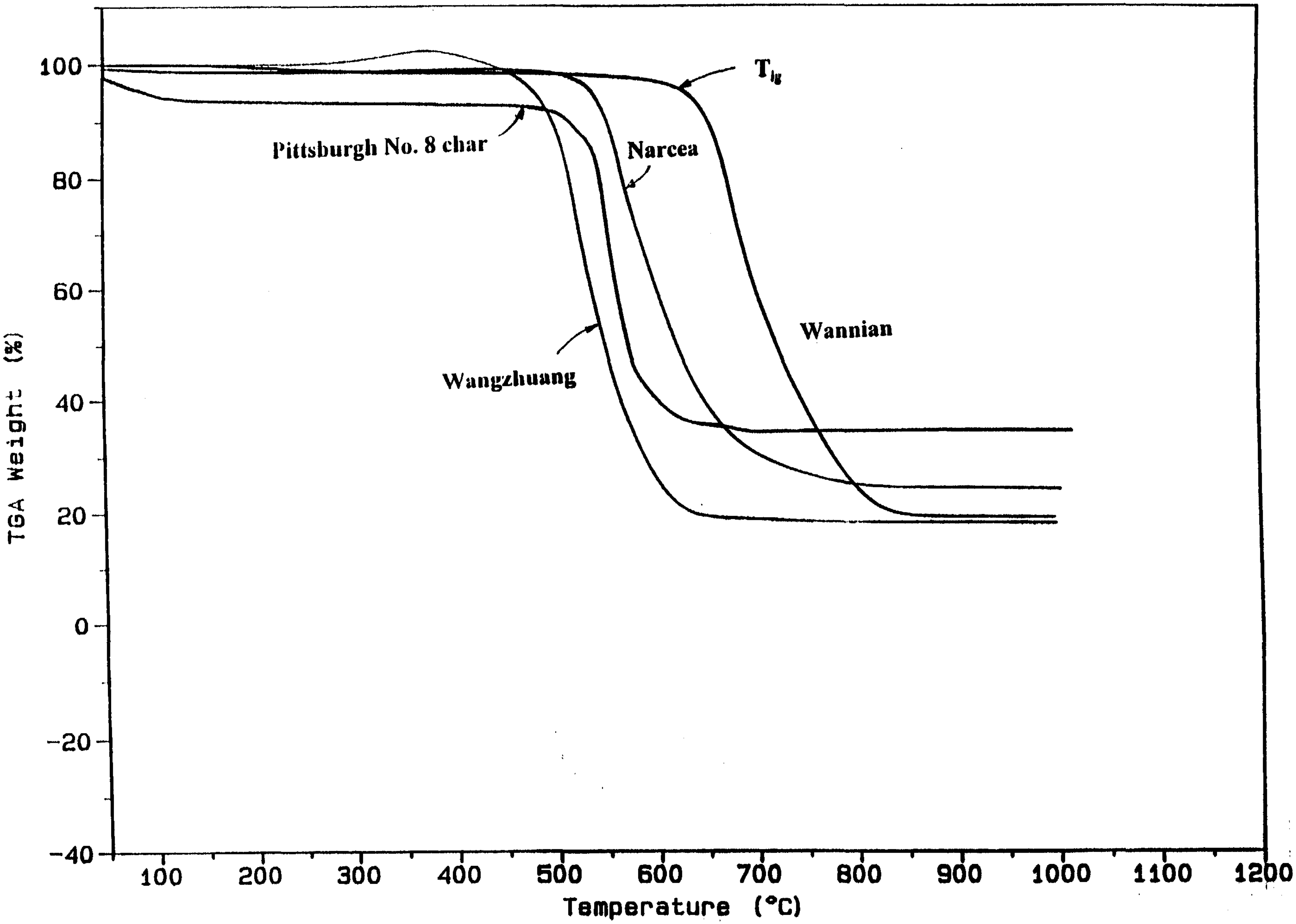
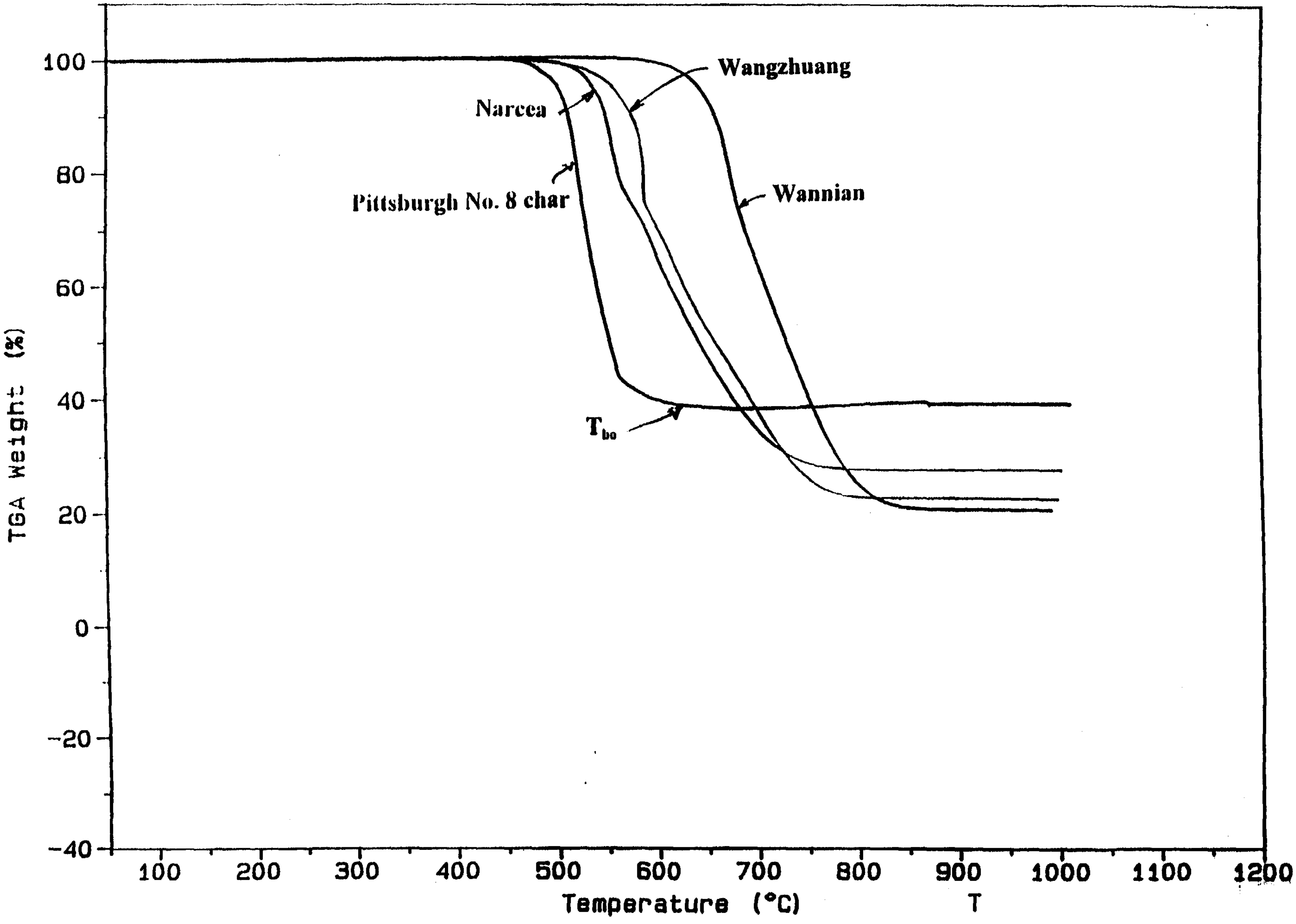


Figure 5 TGA Burning Profiles of Devolatilized Fuels



A preheater/injector system uses another electrical furnace to heat the secondary air to a maximum temperature of 1200°C (2192° F) prior to entering the main furnace. A stainless steel flow straightener with 1/8 in. ID tubes is used to provide laminar flow of secondary air from the preheat/injector system.

A thin stream of coal particles was introduced into the muffle tube along with a primary air stream of about 1.5 standard liter/min using a miniature screw feeder capable of feeding between 0.1 and 1.0 gram/min. The feed rate was checked before the start and after completion of a test. The mixture of coal and primary air was injected into the furnace through a water cooled stainless steel injector probe. The preheated secondary air (900°C) was introduced at a rate of 2 to 2.5 standard liters/min, resulting in a total air flow of 3.5 to 4 standard liters/min. The fuel feed rate was then adjusted to yield the desired excess air level in the furnace, typically around 25 percent.

The particle residence time in the furnace hot zone was similar for all the fuels evaluated in this study. The residence time was calculated based on the sum of the particle terminal velocity and the gas velocity in the muffle tube. The particle terminal velocity was calculated from correlations dependent on particle size and density [1]. For these tests, a 100 x 140 mesh size (~127 microns) was utilized; the particle density of each fuel was determined in the laboratory and found to match well with data from literature [2]. In order to maintain a similar particle residence time for each fuel, the secondary air flow was adjusted to account for differences in particle terminal velocity.

A plot of particle residence time versus furnace temperature is shown in Figure 7 for the Pittsburgh No. 8 char. The furnace temperatures were measured with thermocouples located in the preheater (one) and in the main furnace (three). As shown in this figure, the particle residence time in the 1500°C hot zone was about 1 second and total residence time in the furnace was about 2 seconds. This temperature profile is similar to that encountered in a full-scale utility boiler furnace, particularly above the burner region.

During each test char/fly ash was collected using a water-cooled probe placed at the furnace exit. The collected material was analyzed for carbon conversion using an ash tracer technique. The equation used for carbon burnout calculation is:

$$C = 100\,[\,1 - A_0\,(100 - A')\,/\,A'\,(100 - A_0)\,]$$

where C = carbon burnout, %
A' = ASTM ash of the dry fly ash
A_0 = ASTM ash of the raw fuel

The assumption involved in using this equation is that mineral matter in the fuel does not undergo transformations which would change the quantity of ash produced upon ashing of the material collected from the drop tube. Calcium sulfide (CaS) is a constituent in char which can undergo oxidation and yield an increase in ash weight. The sulfide sulfur level of the char used in these tests

Figure 6 Schematic of Drop Tube Reactor

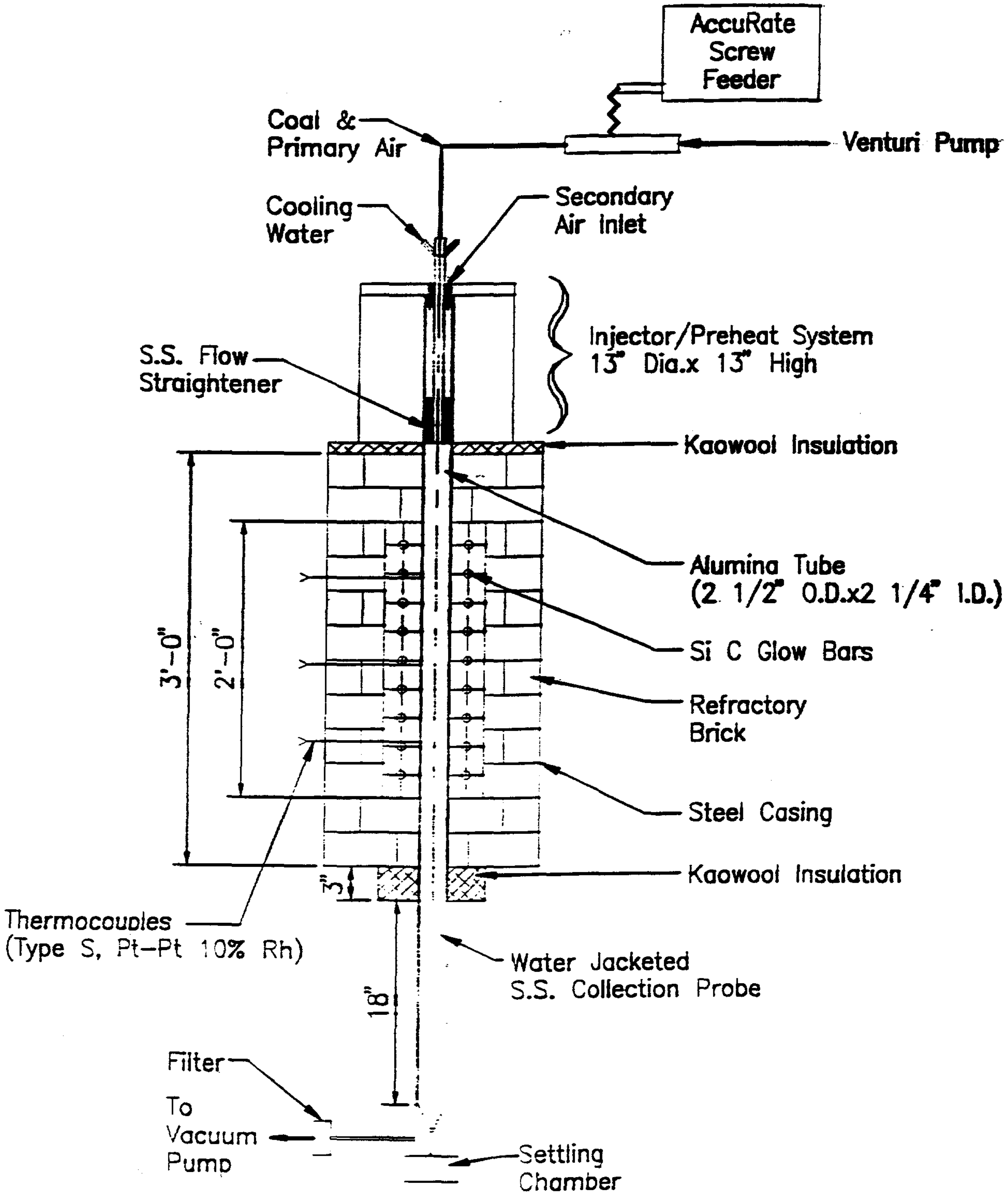
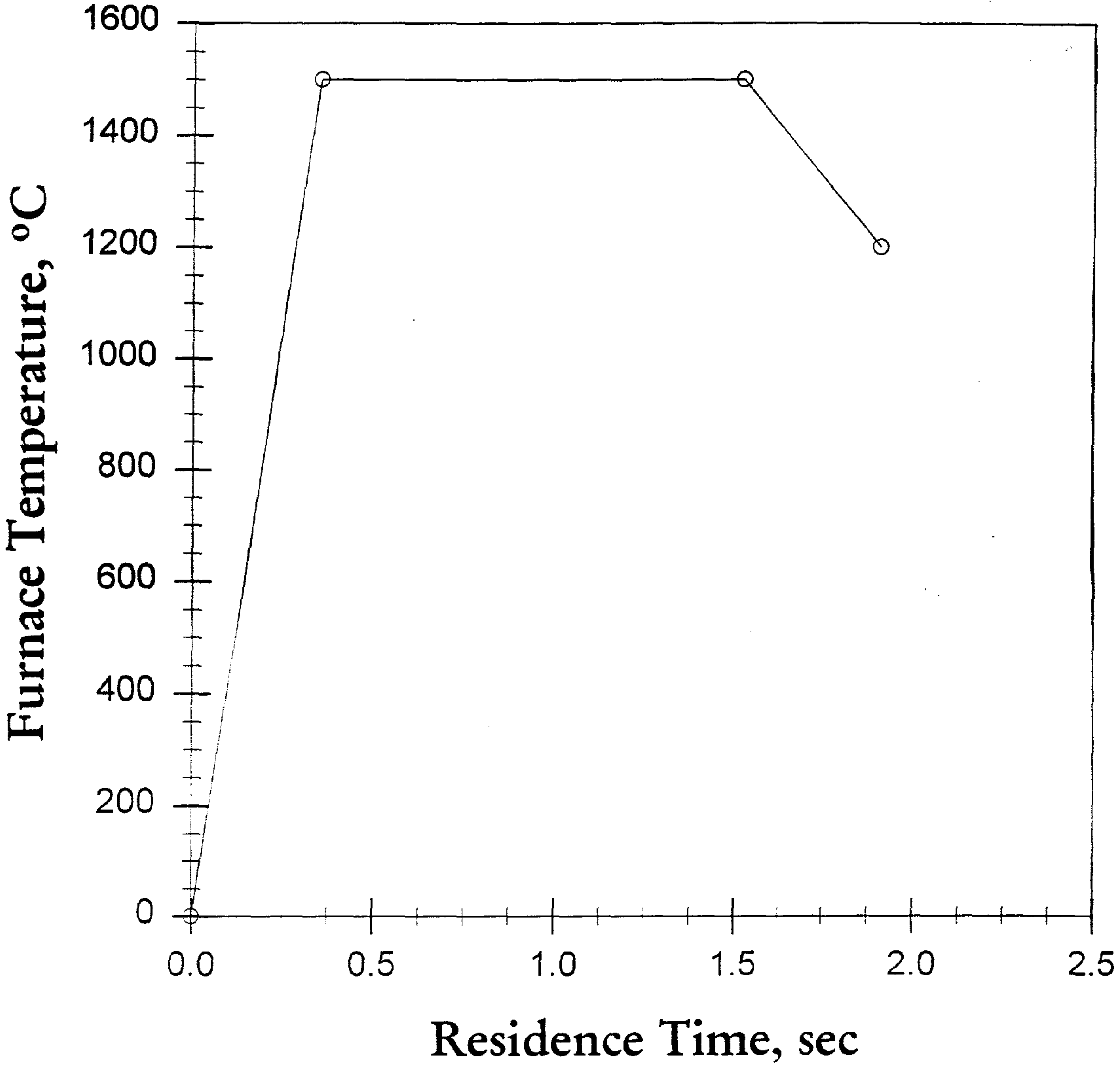


Figure 7 Char Residence Time Versus Furnace Temperature



was not very high (0.43%), and its effect on ash weight gain was not significant. This conclusion was substantiated by measuring the sulfide level in the char after combustion in the drop tube. Tests were generally run in duplicate or triplicate with the results averaged for each test point condition.

In addition to determining fuel carbon conversion, the levels of O_2, CO_2, and NO_x were measured with an on-line gas analysis train. The O_2 and CO_2 were measured to confirm the feeder was performing correctly and providing the desired furnace stoichiometry. The NO_x was measured to give an indication of the potential for fuel nitrogen conversion as a function of fuel properties (rank, VM content) and operating conditions (temperature and excess air). The baseline, thermal NO_x was measured before each test with only air going through the drop tube.

A summary of the test results for the different fuels at nominal test conditions is shown in Figure 8 and Table 6. For this comparison the baseline conditions are referred to as: 1500°C, ~ 25% excess air, and 2 second total furnace residence time. As shown in Figure 8, the Pittsburgh No. 8 char had a very high carbon conversion of 97.4%. On the other hand, the burnout of the anthracites was considerably lower than the char and averaged 82%. As expected the low volatile Wangzhuang coal had a moderate burnout of 94%. The high level of burnout for the Pittsburgh No. 8 char agrees with the TGA results which indicate a low burnout temperature. Once again, the high surface area of the char provides increased reactivity compared to the other fuels in this study.

Also shown in Figure 8 is the fuel nitrogen conversion to NO_x for each fuel. The nitrogen conversion was much higher for the char compared to the other coals (44% versus 20-25%). Low volatile fuels generally have higher nitrogen conversion to NO_x than higher volatile coals. However, the mechanism for significantly higher conversion of the char nitrogen is not certain, but could be due to catalytic effects of calcium in the char. Future combustion tests will be performed with chars without sorbent to ascertain this potential catalytic effect.

Also evaluated in this study were the effect of furnace temperature and excess air on burnout and NO_x emissions. As shown in Table 6, the carbon burnout for the Pittsburgh No. 8 char decreased by about 10 percent as the furnace temperature was decreased from 1500°C to 1400°C (97.4% to 86.3%). Likewise a significant reduction in NO_x emissions was observed and the conversion of fuel nitrogen was reduced from 44.1% to 28.4%. An even greater reduction in carbon burnout was observed for the Wannian anthracite as the furnace temperature was reduced from 1500°C to 1400°C. As shown in Table 6, the burnout decreased from 81.8% to 64.0%. This greater reduction in burnout with temperature is probably due to the much lower reactivity of the anthracite compared to the Pittsburgh No. 8 char.

Figure 8 Comparison of Drop Tube Test Results for Different Fuels

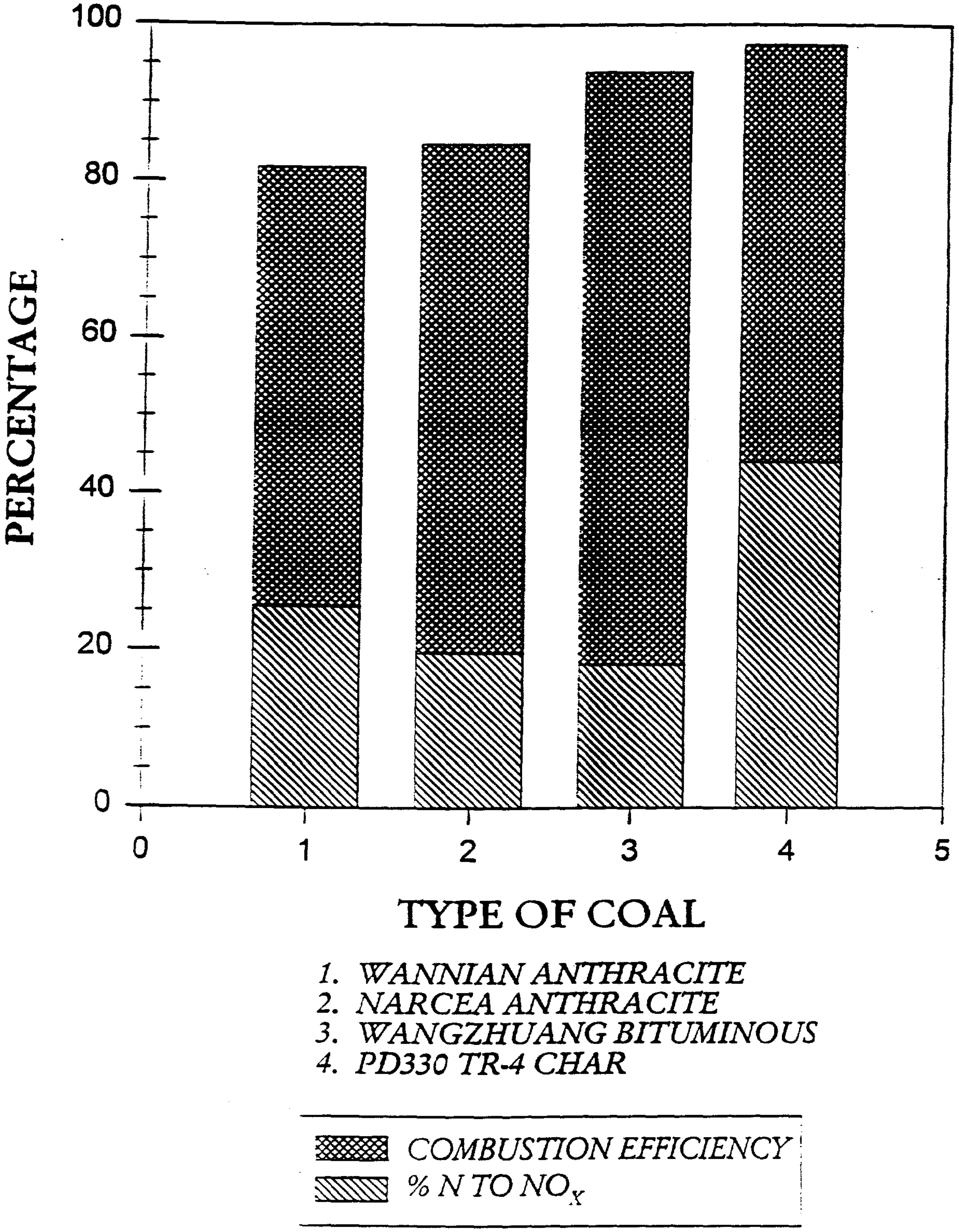


Table 6 Drop Tube Combustion Test Results for Different Fuels

Fuel	Furnace Temperature,°C	Excess Air, %	Carbon Burnout, %	Fuel NO_x, ppm	N conversion to NO_x, %
Pittsburgh No. 8 char	1500	25	97.4	642	44.1
	1500	25	97.4	623	44.1
		Avg.	97.4	633	44.1
Pittsburgh No. 8 char	1400	21	*	359	29.1
	1400	21	89.8	373	28.2
	1400	21	82.7	411	27.9
		Avg.	86.3	381	28.4
Narcea anthracite	1500	25	80.1	*	*
	1500	25	85.1	238	16.7
	1500	25	*	323	22.7
		Avg.	82.6	280	19.7
Narcea anthracite	1400	25	65.8	*	*
	1400	25	65.8	*	*
	1400	25	64.1	*	*
	1400	25	60.3	*	*
		Avg.	64.0	*	*
Wannian anthracite	1500	25	83.4	401	25.8
	1500	25	80.2	393	25.3
		Avg.	81.8	398	25.6
Wangzhuang LV bituminous	1500	11	95.2	431	18.7
	1500	11	93.4	617	26.8
		11	93.4	*	*
		Avg.	94.0	524	22.8

100 x 140 mesh feed size
~2 seconds total furnace residence time

The effect of excess air was also evaluated in the drop tube tests. As shown in Figure 9, a significant increase in char carbon burnout was noted as the excess air level was increased from near stoichiometric to 25 percent. However, the burnout did not increase as the excess air was increased further from 25% to 70%. Excess air only had a moderate effect on NO_x emissions as it was increased above 25 percent as shown in Figure 10.

The effect of excess air at different temperatures was also evaluated for the Wannian anthracite as a shown in Figures 11 and 12. Increasing the excess air had a more dramatic effect on increasing carbon burnout for the Wannian anthracite compared to the Pittsburgh No. 8 char (Figure 9). Once again, this higher increase may be due to the lower reactivity of the anthracite, compared to the char. Excess air also had a more significant effect on fuel nitrogen conversion to NO_x for the Wannian anthracite, especially above 25 percent as shown in Figure 12.

Conclusions

Laboratory tests were conducted with a representative sample of Pittsburgh No. 8 char from PFB pilot plant tests. The objective of these tests was to evaluate the combustion and NO_x emissions potential of char as related to arch-firing for the HIPPS Project. These tests included T_{15} reactivity, TGA and drop tube combustion. Based on these tests, high carbon loss due to incomplete combustion does not appear to be a concern with char. Both TGA and drop tube tests indicate excellent combustibility of the char, probably due to its high surface area. However, ignition and flame stability may be a potential concern with char since it contains practically no volatile matter. Both the T_{15} reactivity and TGA tests show a low ignition potential for the char, which is similar to that of the Narcea anthracite. The Narcea anthracite requires oil support fuel for maintaining flame stability in arch-fired boilers in Spain. As a result, a support fuel will probably be required for the char in arch-fired designs. The level of support fuel required should be investigated in burner testing at the Dansville CETF.

The Pittsburgh No. 8 char also showed a high potential for NO_x emissions, based on drop tube tests. The conversion of fuel nitrogen to NO_x was nearly double that of the anthracites tested in this study. Future tests will be conducted to determine if sorbent in the char has a catalytic effect on NO_x emissions. If sorbent has an effect on NO_x emissions, means of lowering the level of sorbent in the char should be investigated.

Figure 9 Effect of Excess Air on Char Combustion Efficiency

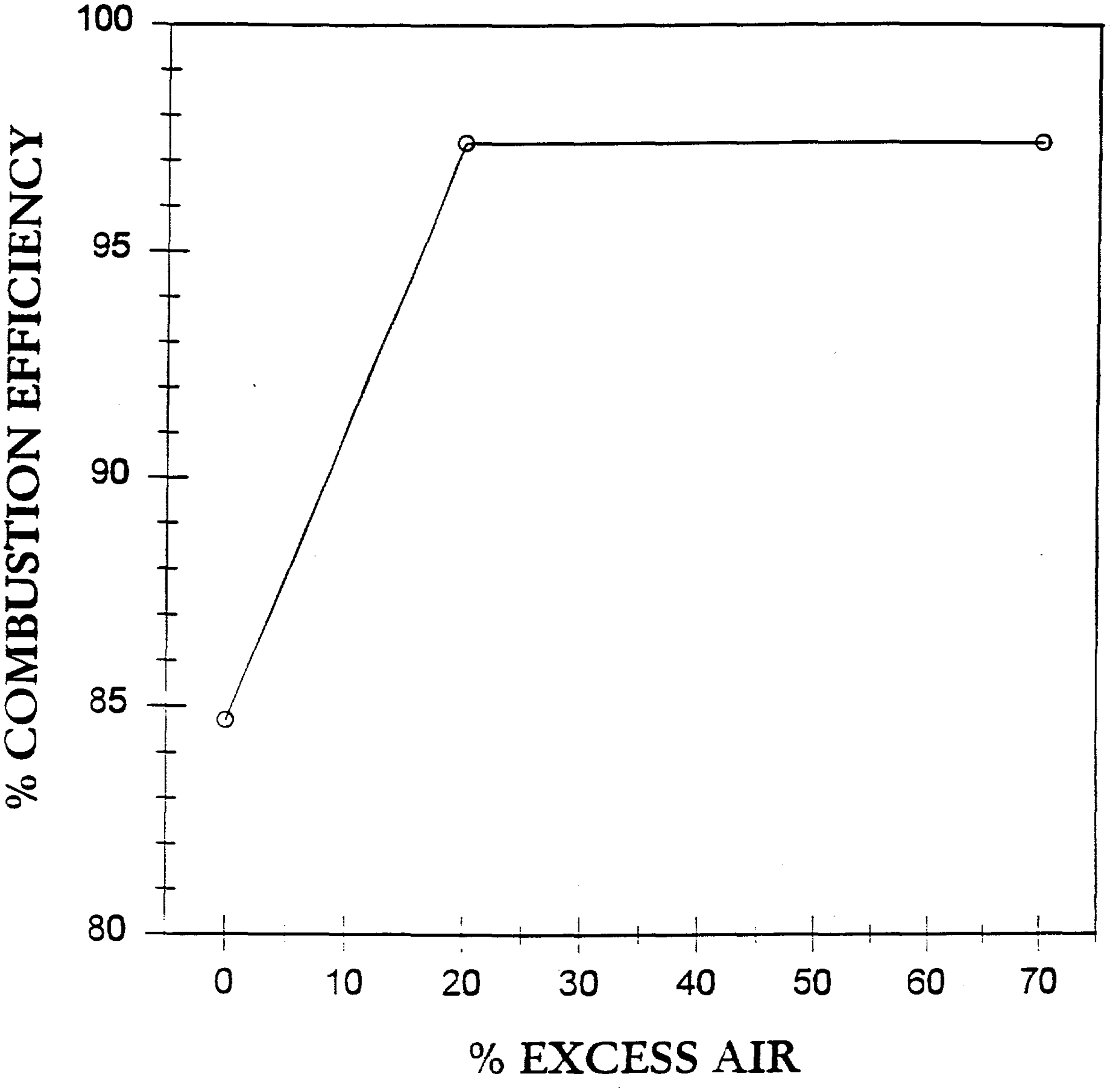


Figure 10 Effect of Excess Air on Char Nitrogen Conversion to NO_x

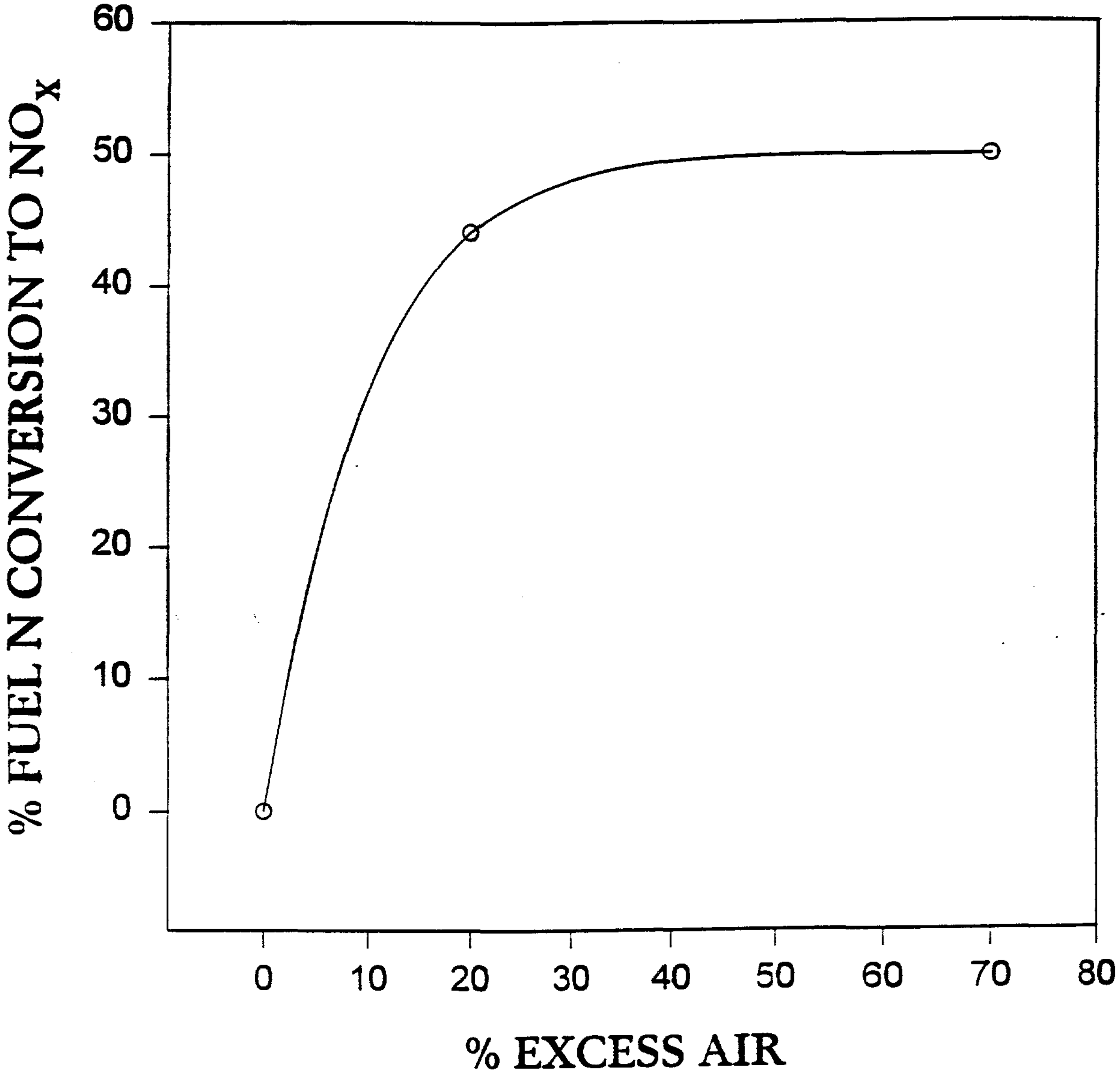


Figure 11 Effects of Excess Air and Temperature on Combustion Efficiency of Wannian Anthracite

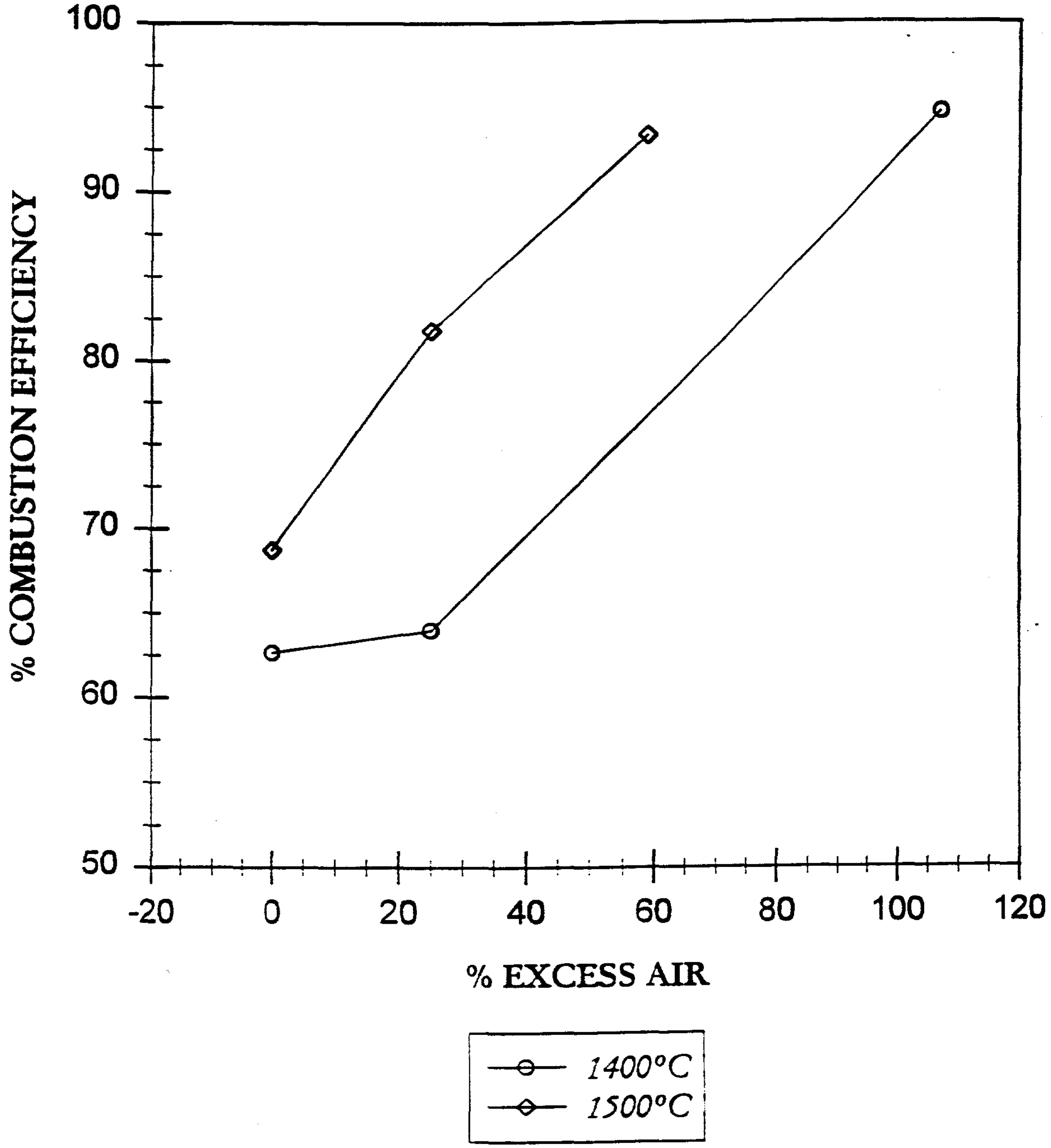
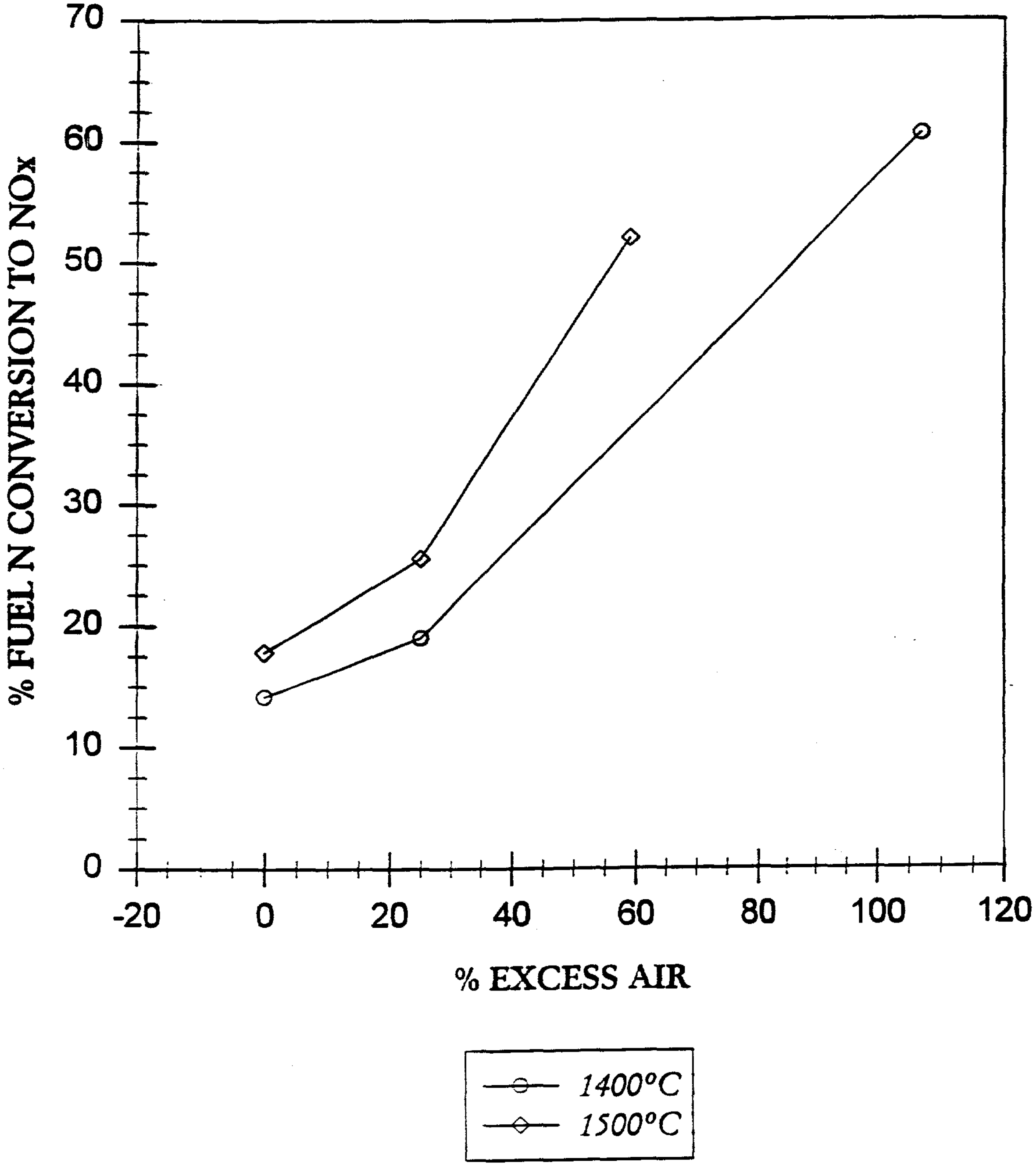


Figure 12 Effects of Excess Air and Temperature on NO_x Emissions for Wannian Anthracite



Combustion System Modeling

Introduction

The char combustion system pilot plant tests will be performed at the Foster Wheeler Combustion and Environmental Test Facility (CETF). The CETF furnace has been modeled for the HIPPS char burner application to predict the combustion characteristics inside the furnace and to help develop the burner design and flow arrangement before on-site testing. PCGC-3 has previously been used at Foster Wheeler to simulate the conventional pulverized coal-fired furnaces. Even though the PCGC-3 code was originally designed for simple coal combustion configurations, after some modifications, it is capable of modeling a more complicated furnace such as CETF, where both char and pulverized coal are burned. With careful design of the computational model and manipulation of certain parameters, good convergence has been reached. The detailed information about the model setup, data input and modeling results will be discussed in this report.

Model Setup

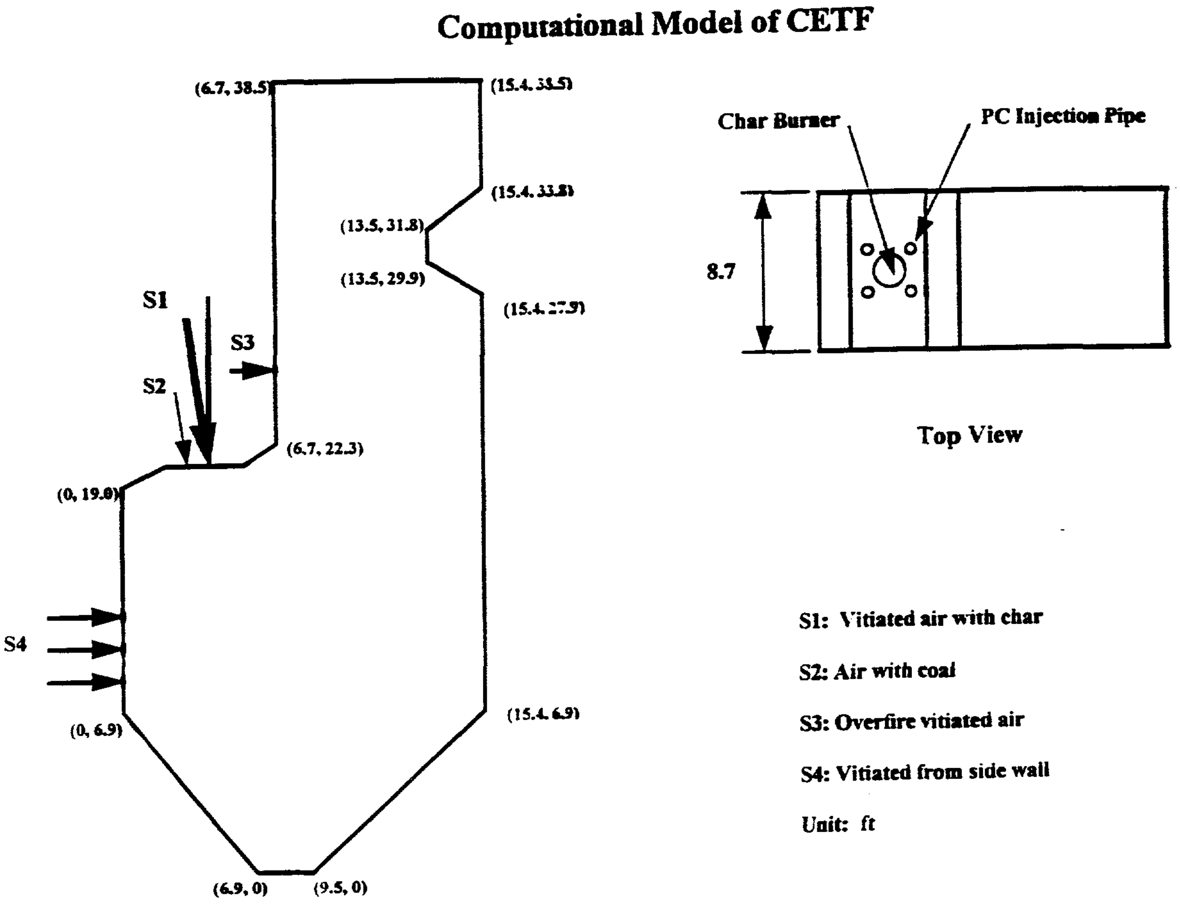
CETF furnace for HIPPS application will have one char burner located in the arch of the furnace. The burner will be designed to fire approximately 908 Kg/h (2000 lb/h) of char. In addition to the main char fired burner, the current design being analyzed has four ports near the char burner for injection of pulverized coal. A small percentage of raw coal may be required to stabilize the char flame. It is believed that the mixing between the char particles and the central vitiated air is minor due to the short distance. Therefore, the computational model neglects the particle movement inside the burner. In other words, the inlet cells for vitiated air in central part of the burner and those for vitiated air with char loading are located in the same plane. Dimensions of the entire furnace are shown in Figure 13. The computational block (grid) model for the furnace is shown in Figure 14. It contains 63,180 (60x39x27) cells. Finer grids were used near the burner, especially, near the injection ports for the pulverized coal. As shown in Figure 14, the model includes the entire furnace.

Boundary Conditions and Input Parameters

Compositions of inlet gases (air and vitiated air) are listed in Table 7. Moisture content in air was neglected. The vitiated air composition was predicted based on the performance of pyrolyzer and gas turbine. The argon content was small and lumped into nitrogen content. Char ultimate and proximate analysis data obtained at FWDC laboratory were used in the simulation. Proximate analysis of char and pulverized coal are listed in Table 8. Ash percentage in the char is about 30%. Ash was assumed as an inert material in the combustion process in PCGC-3. Therefore, the existence of CaS and its effect on char combustion was ignored. Ultimate analysis data are listed in Table 9. Five particle size bins were used in the simulation. Size distributions of these particles are shown in Table 10 (based on 80% through 200 mesh). Particle density of 700 kg/m^3 was estimated based on the tap density measured by Brigham Young University (BYU).

A wall emissivity of 0.4 was used, based on PCGC-3 validation of other furnaces. The water wall temperature was assumed to be 700 K, which was applied to the hopper and water wall above the arch. A temperature of 1400 K was used for the side wall and arch wall to simulate refractory lined surfaces.

Figure 13 CETF Char-fired Furnace Model



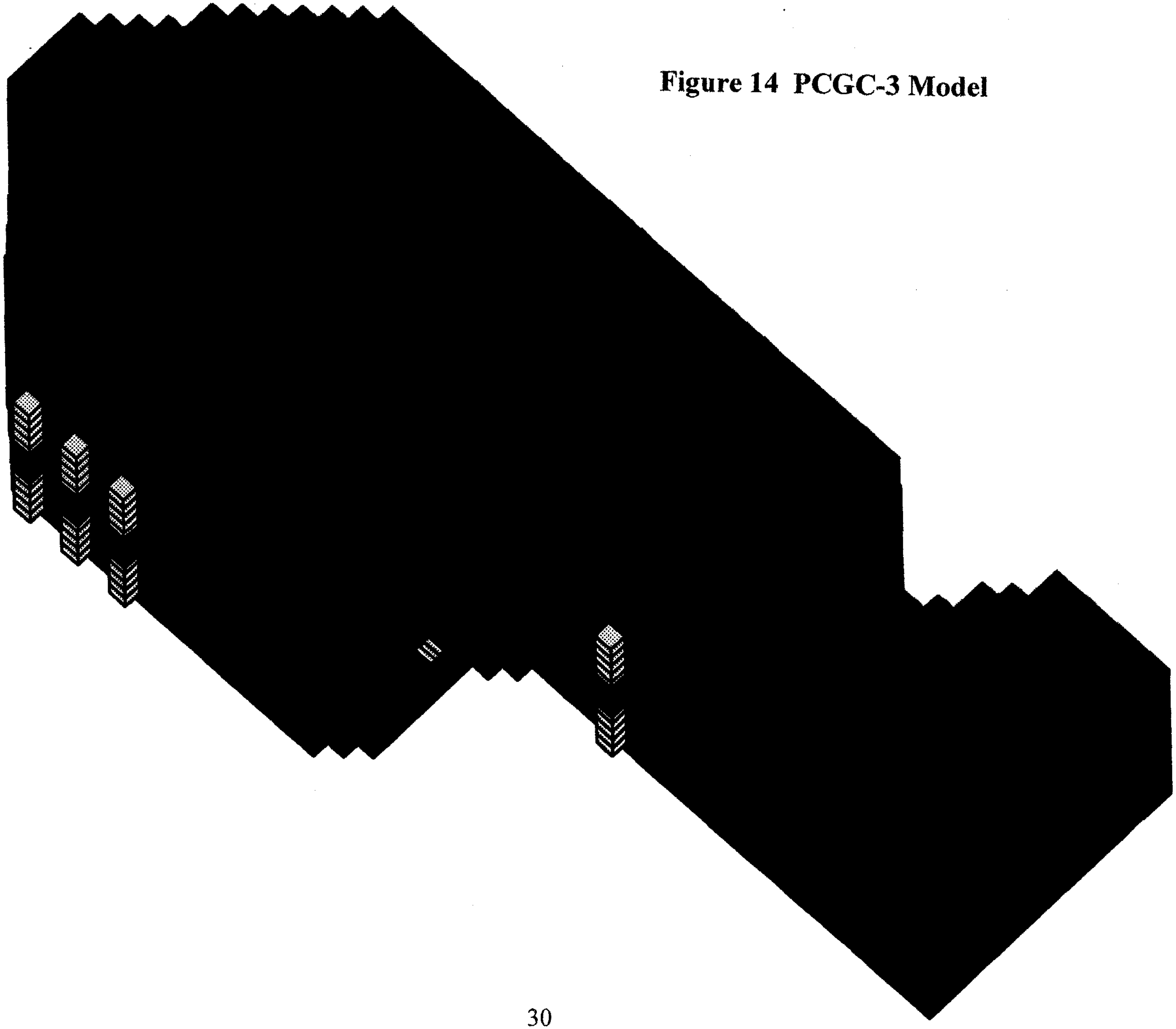


Figure 14 PCGC-3 Model

Table 7. Compositions of air and vitiated air used in simulation

Inlet Gas	O_2	N_2	H_2O	CO_2
Air	20.95%	79.02%	0%	0.03%
Vitiated Air	13.63%	74.32%	7.02%	5.03%

Table 8. Proximate analysis data of coal and char (as received basis)

Solid Fuel	Volatile Matter	Fixed Carbon	Ash
Char	1.30%	69.10%	29.60%
Coal	36.60%	54.90%	8.50%

Table 9. Ultimate analysis data used (dry ash free basis)

Element	C	H	O	N	S
Wt%	92.00%	0.60%	2.80%	2.00%	2.60%

Table 10. Size distribution of char/coal particles

Diameter (micron)	10	25	50	75	125
Wt%	40%	30%	10%	10%	10%

The default values for coal devolatilization kinetics in PCGC-3 were used. These default values are applicable to high-volatile bituminous coals as will be used as supporting fuel in CETF. For char oxidation, the current version of the code uses a first-order char oxidation model (with respect to partial pressure of oxygen on particle surface). The char oxidation rate at the external surface of an individual particle is expressed as:

$$r = \frac{dm_p}{dt} = -S_{ex}\frac{M_C}{R}p_{O_2}A\exp\left(-\frac{E}{RT}\right)$$

where, m_p is the mass of a char particle (kg), S_{ex} is the external surface area of the particle (m^2), p_{O_2} is the partial pressure of oxygen at particle surface (Pa), A is the pre-exponential factor (m/K-s), E is the activation energy (J/mol), R is gas constant (J/kg-K), T is particle temperature (K), and M_C is the molecular weight of carbon (kg/mol).

Partial pressure of oxygen is related to mole concentration [O_2] based on the equation of state for ideal gases.

$$p_{O_2} = [O_2]RT$$

Therefore, the char oxidation rate can also be expressed as:

$$r = -S_{ex}M_C[O_2]TA\exp\left(-\frac{E}{RT}\right)$$

Kinetic data listed in the PCGC-3 manual for a char from high-volatile bituminous-A coal was used. The pre-exponential factor (A) and the activation energy (E) used were 1.03 m/K-s and 7.49×10^4 J/mol, respectively. These values are not necessarily suitable for HIPPS char. Shrinking-core (constant density) char combustion mode was assumed. The heating value of the char was not specified in the input, instead, was calculated during the simulation based on Dulong's correlation.

In order to simulate the combustion, especially, the ignition of char correctly, accurate kinetic data for the oxidation of HIPPS char is needed. Reasonable kinetic data to be used in modeling should be obtained directly through char oxidation experiments. There are two kinds of experimental data available on HIPPS char, one from drop-tube tests conducted at FWDC and the other from flat flame burner test conducted by BYU. Modeling of drop-tube furnace using PCGC-3 code was tried in the hope that a reasonable set of kinetic data could be backed up by matching the calculated char burnout with the measured burnout. Unfortunately, the simulation of the drop tube furnace failed because

PCGC-3 was designed for turbulent combustion, while the flow inside the drop tube was laminar except near the gas entrance. Based on the report prepared by BYU on the flat flame char oxidation tests (also through personal communication with Dr. Thomas Fletcher at BYU), the reactivity of HIPPS char seems to be very similar to those of ordinary chars generated form high-volatile bituminous coals. The most dependable kinetic data for ordinary chars are those obtained at Sandia National Labs. However, these data were correlated to a rate expression with half order kinetics with respect to the partial pressure of oxygen, i.e.,

$$r = -S_{ex} p_{O_2}^{0.5} A \exp\left(-\frac{E}{RT}\right)$$

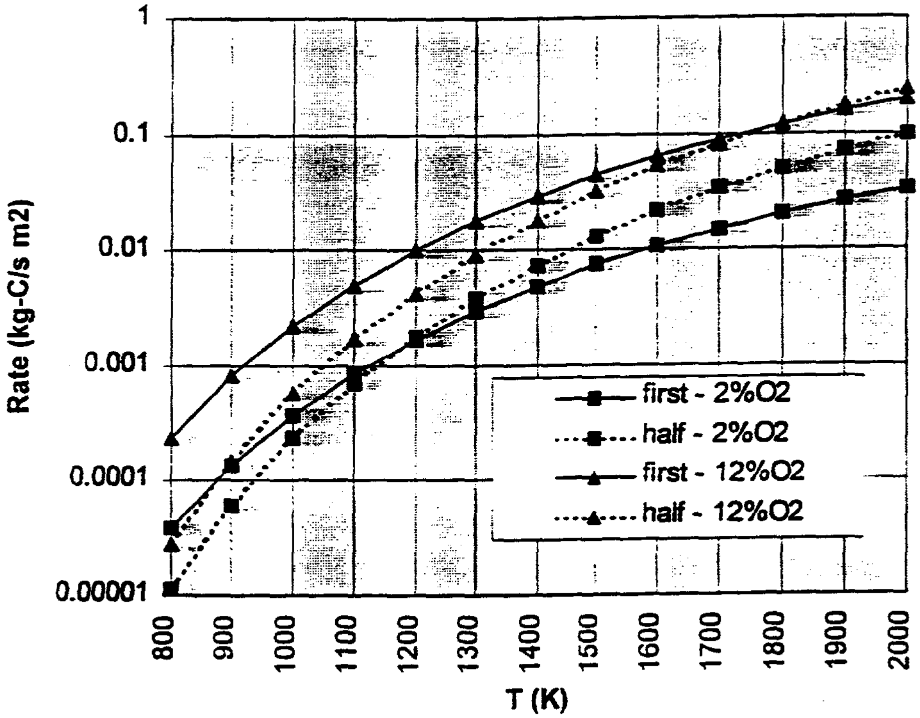
Based on a Sandia's report, the half-order char oxidation model may be considered to be more accurate than the first-order model. A comparison between the first order model used in this simulation and a half order model is shown in Figure 15. The A and E values used for the half order model are 290 kg-Carbon/m^2-s-atm$^{0.5}$ and 1.004×10^4 J/mol, respectively. These values were reported by Sandia Lab for a Pittsburgh high volatile bituminous coal. It needs to be mentioned that the reaction rates in Figure 15 were calculated based on the kinetic rate expressions shown above and the mass transfer effect on actual rate was not accounted for. It can be seen that at lower temperatures, the half-order model has lower oxidation rates than the first-order model. In other words, the first-order model will over predict the reaction rate during particle ignition. At high temperatures, the half-order model gives higher reaction rates than the first order model. Actually, at high temperatures, the reaction will be controlled by mass transfer or diffusion of O_2 towards the char surface, instead of by the reaction kinetics. Therefore, kinetic model is more important in predicting particle ignition or initial stage of char oxidation. We are currently working towards incorporating the latest (half-order) Sandia kinetic model into PCGC-3.

Results and Discussion

After about 20 hours of iteration, the case converged. The residual went down to 2.7 (or relative error of 5.0×10^{-4}). The energy imbalance went down to 0.4% with mass imbalance down to 0.0005%.

Detailed modeling results were visualized using GMS post-processor. Some plots are included in this report. Consumption of char for each particle size can be observed in the particle trajectory plot (Figure 16 through 18) with char mass fraction as the color scale. From Figure 16, it can be seen that the smallest particle (10 micron in diameter) is burned near the burner outlet. For 50 micron particles (see Figure 17), char oxidation goes to completion when the particles reach the lowest positions in their trajectories. The combustion of the 125 micron particles continues on their way upwards towards the exit (see Figure 18). Most of 125 micron particles get completely burned inside the furnace, while some of them still contain certain amount of char when exiting the furnace. The overall particle burnout is 99.5%. A plot of particle temperatures for 50 micron particles is shown in Figure 19. The maximum temperature is less than 1800 K. Particle movement for each particle

Figure 15 Comparison Between First-order and Half-order Char Oxidation Models



size forms a U-shaped particle trajectory as expected in arch-fired furnaces. Particles penetrate to certain distance downwards and then move upwards. Some particles hit the hopper wall. Particles also reach the back side of the wall, probably due to the high horizontal momentum. Based on the above observations, both vertical and horizontal velocities of vitiated air are quite high. To minimize the contact of particles with furnace wall, less gas flow velocities are suggested. Changing the firing angle may also help.

A cross section of XY plane (parallel to the left side wall of the furnace) was made to examine the distribution of gas temperature. Based on the gas temperature plot (Figure 20), maximum temperature around 1800 K is located below the char burner. The average exit gas temperature is 1050 K. The maximum gas temperature is lower than that in conventional coal-fired furnace, which is reasonable because CO_2 and H_2O contained in the vitiated air lower the flame temperature, even though the inlet gas temperature is much higher. The adiabatic flame temperature was calculated to be 1921 K based on total gas and particle feedings. The high ratio of furnace surface to furnace volume may also account for lower flame temperature and lower exit gas temperature.

Task 3 - Subsystem Test Unit Design

Subtask 3.1 - Pyrolyzer/Char Transport Test Design

The design of the Pyrolyzer/Char Transport Test (PCTT) has been completed. The FWDC Second-Generation PFB pilot plant in Livingston, NJ is being modified for these tests. Two test arrangements have been designed. The first to be tested will be a bubbling bed arrangement. After testing is completed on the bubbling bed arrangement, the pilot plant will be modified to a circulating bed arrangement, and more tests will be run. The test matrix has been discussed in the previous report [3]. Table 11 summarizes the parameters that will be varied. Procurement of equipment and modification of the pilot plant are in progress. This work is reported under Subtask 4.1.

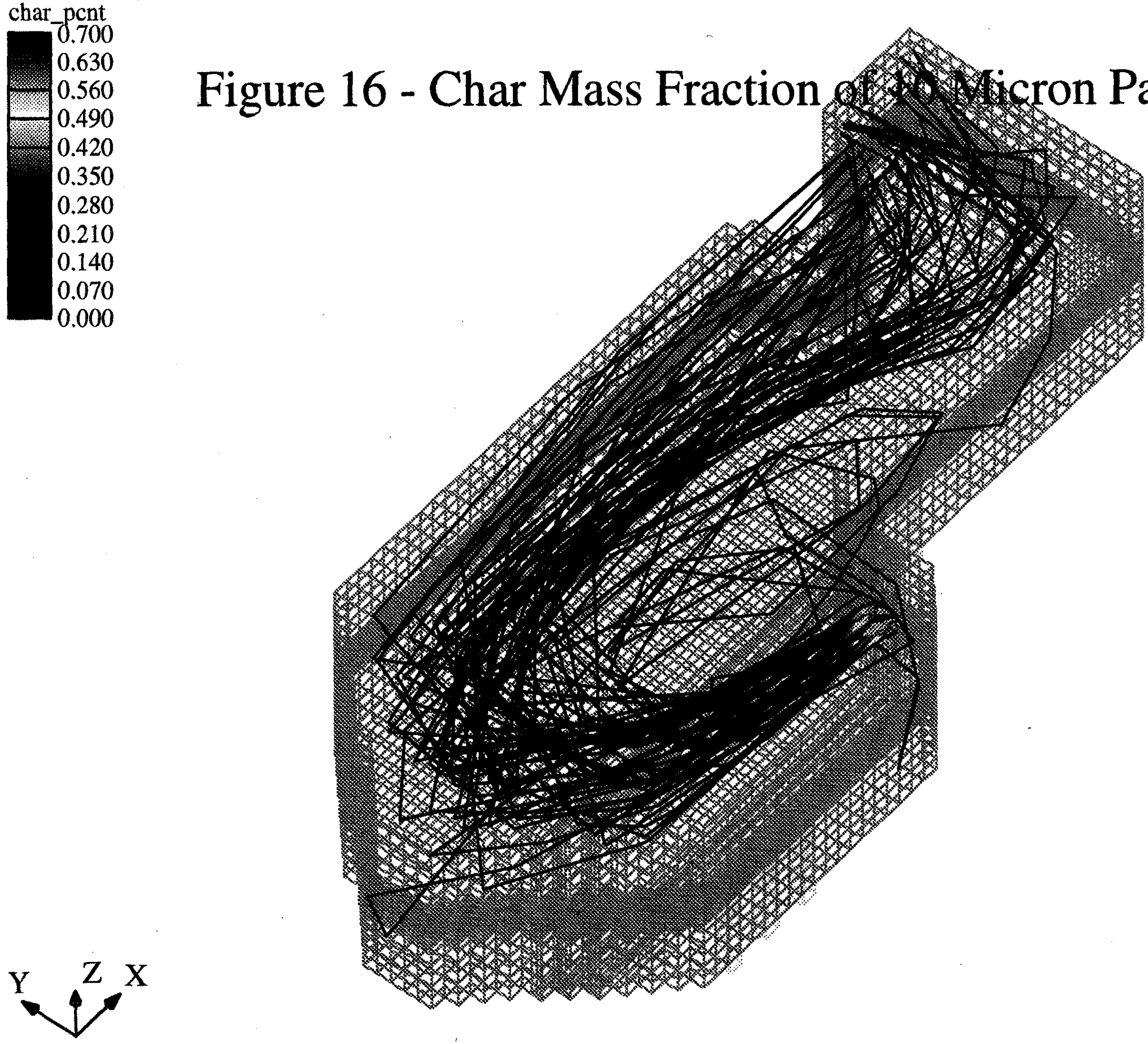


Figure 16 - Char Mass Fraction of 10 Micron Particles

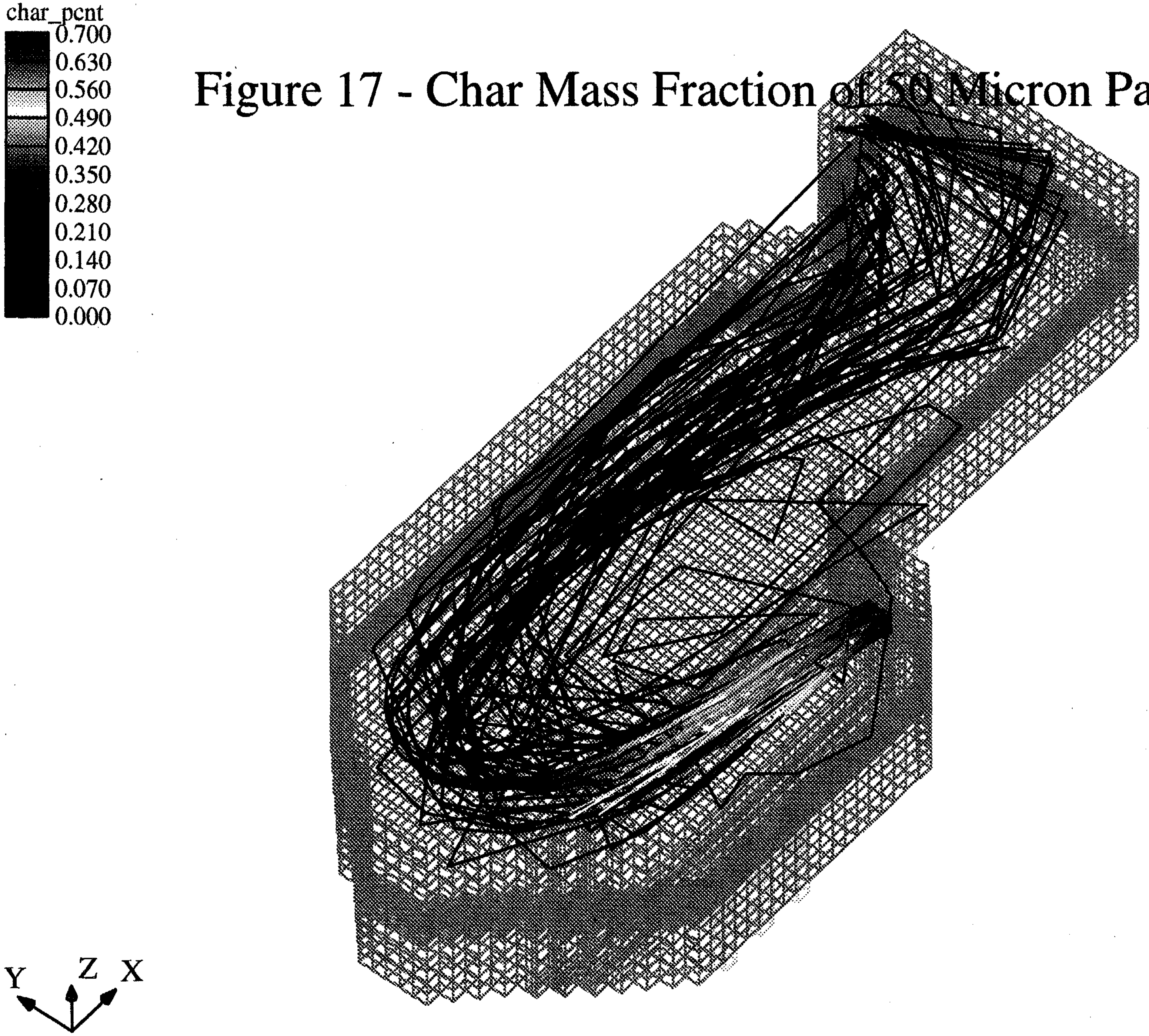


Figure 17 - Char Mass Fraction of 50 Micron Particles

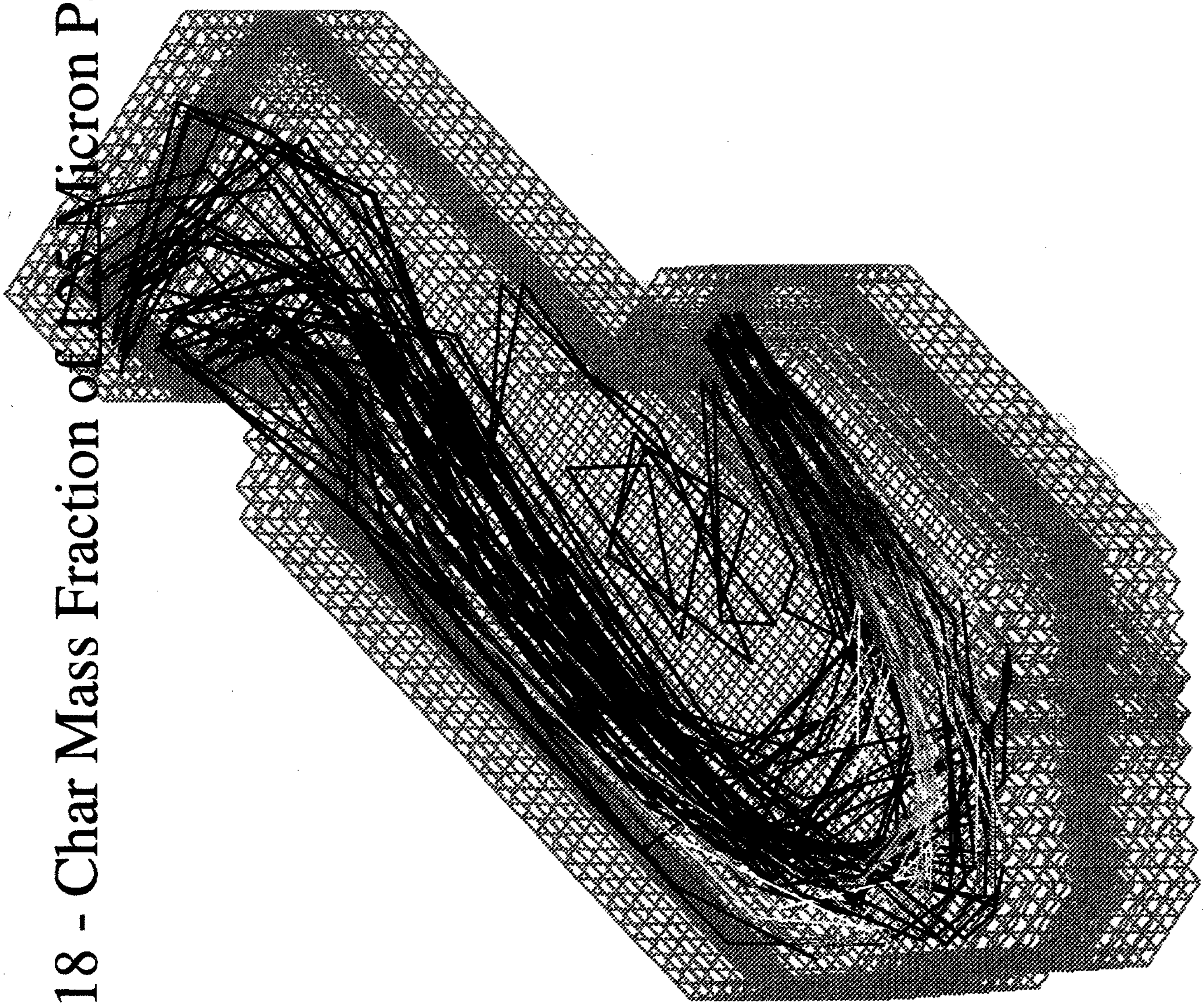
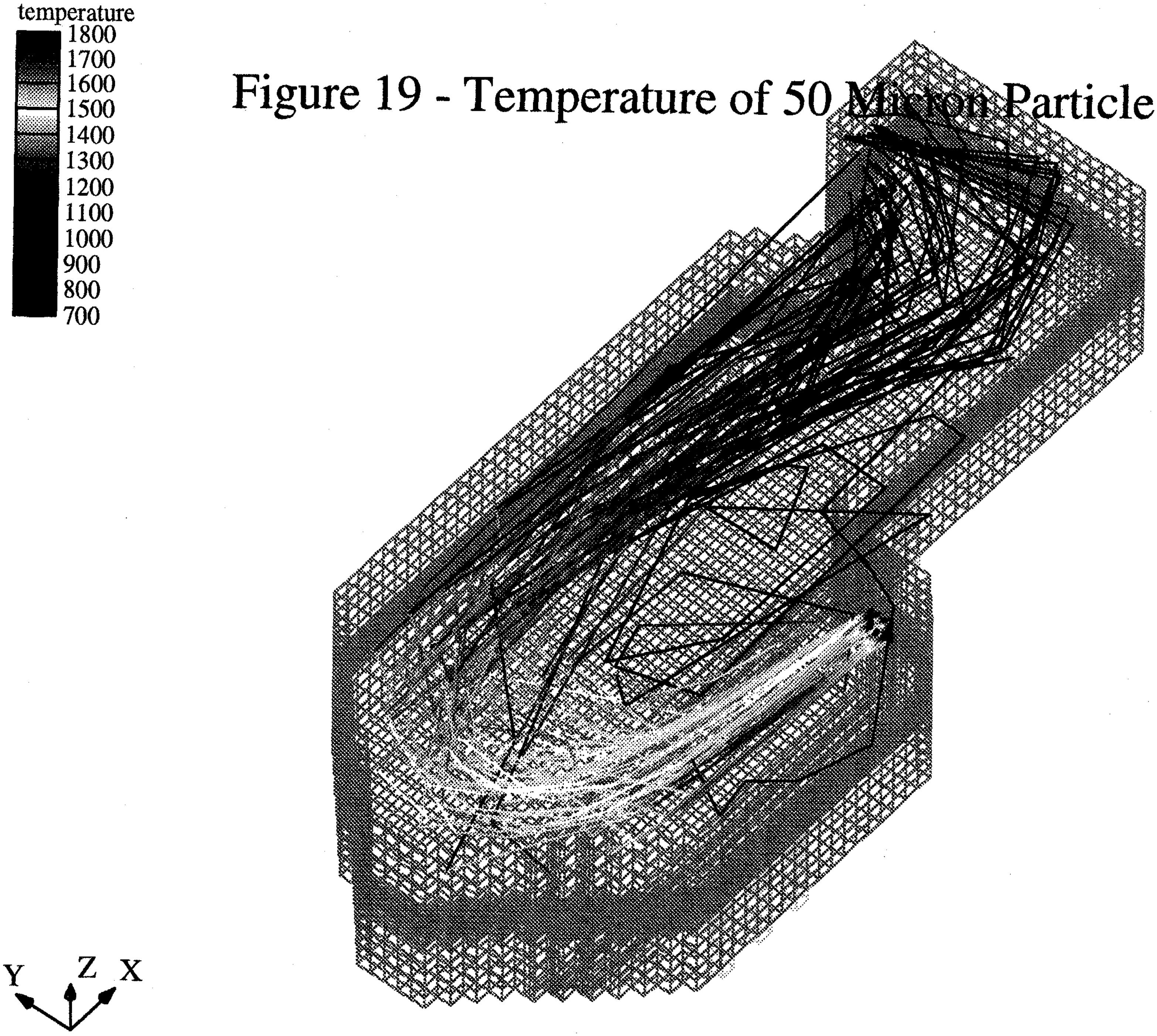


Figure 18 - Char Mass Fraction of 75 Micron Particles

Figure 19 - Temperature of 50 Micron Particles (K)



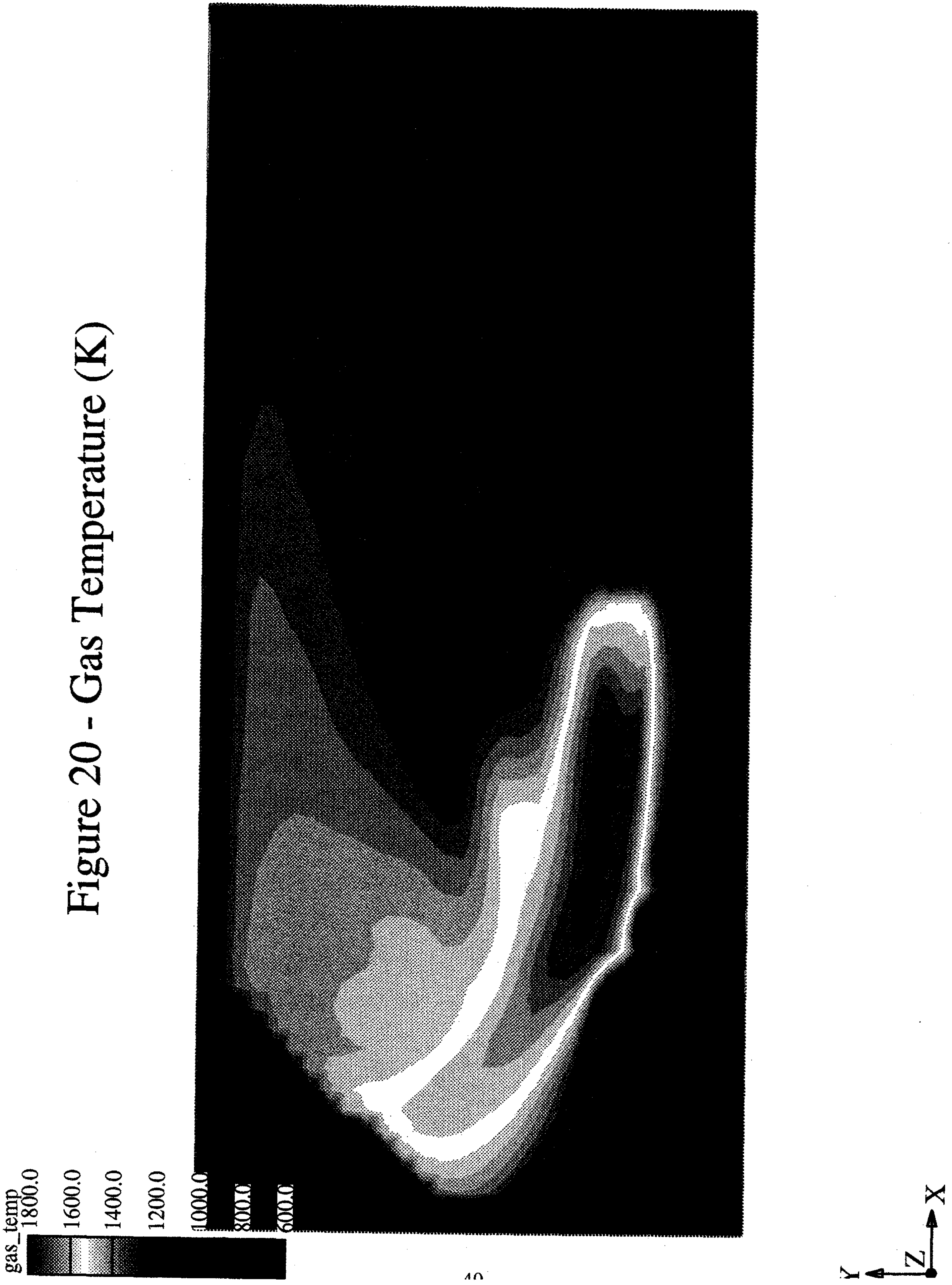


Figure 20 - Gas Temperature (K)

TABLE 11

PYROLYZER TEST MATRIX

RUN NO.	BED ARRANGEMENT	COAL SIZE	SORBENT SIZE	SAND	STEAM FLOW (Kg/h)	RISER VELOCITY (m/s)	CYCLONE DESIGN	PURPOSE
1	BUBBLING	C1	S1	NO	24.4	1.03	--	● Obtain design data for bubbling bed operation with initial coal size.
		C1	S1	NO	97.5	1.03	--	
		C1	S2	YES	24.4	1.03	--	
		C1	S2	YES	97.5	1.03	--	
2	BUBBLING	C2	S1	NO	24.4	1.03	--	● Obtain design data for bubbling bed operation with second coal size.
		C2	S1	NO	97.5	1.03	--	
		C2	S2	YES	24.4	1.03	--	
		C2	S2	YES	97.5	1.03	--	
3	CIRCULATING	C1	S1	NO	24.4	1.52	CY1	● Determine whether to design for sorbent carryover or sorbent separation. ● Check initial coal size with circulating bed.
		C1	S1	NO	24.4	2.74	CY1	
		C1	S2	YES	24.4	1.52	CY1	
		C1	S2	YES	24.4	2.74	CY1	
4	CIRCULATING	C3	TBD	TBD	24.4	1.52	CY1	● Obtain design data for circulating bed with initial cyclone design.
		C3	TBD	TBD	24.4	2.74	CY1	
		C3	TBD	TBD	24.4	TBD	CY1	
		C3	TBD	TBD	97.5	1.52	CY1	
		C3	TBD	TBD	97.5	2.74	CY1	
		C3	TBD	TBD	97.5	TBD	CY1	
5	CIRCULATING	TBD	TBD	TBD	TBD	1.52	CY2	● Obtain design data for circulating bed with second cyclone.
		TBD	TBD	TBD	TBD	2.13	CY2	
		TBD	TBD	TBD	TBD	2.74	CY2	
		TBD	TBD	TBD	TBD	3.65	CY2	
6	CIRCULATING	TBD	TBD	TBD	TBD	1.52	TBD	● To obtain data as required
		TBD	TBD	TBD	TBD	2.13	TBD	
		TBD	TBD	TBD	TBD	2.74	TBD	
		TBD	TBD	TBD	TBD	3.65	TBD	

Subtask 3.2 Char Combustion System Test Design

The FWEC arch-fired combustion system is now the base case system for char combustion in HIPPS. The concept is illustrated in Figure 21. The lower furnace has two arches where the burners are located. The burners fire down into the furnace, and combustion air is added in stages through the front and rear wall. This type of arrangement causes a long flame path where the air supply is gradually added to the fuel to avoid quenching. This approach also results in essentially a staged combustion which tends to minimize NO_x. In addition to the air staging, the geometry of the furnace promotes recirculation of hot gases from the upper furnace back into the flame. This situation is also a stabilizing influence on the flame and the flame temperature.

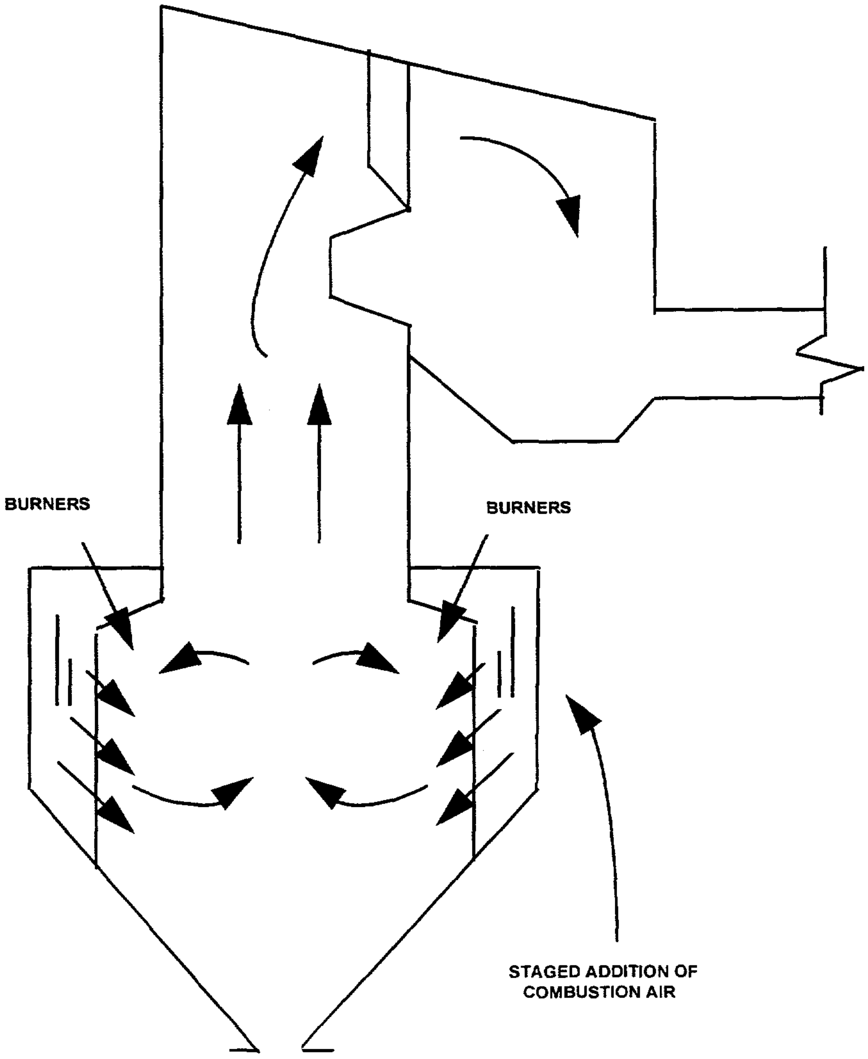
Combustion tests will be run at the Foster Wheeler Combustion and Environmental Test Facility (CETF) in Dansville, New York. This facility is used to test burners. It consists of a furnace and convection pass that was designed to simulate conditions in larger scale boilers. Under HIPPS conditions, the facility will be capable of approximately 30MMBtu/h heat input to the furnace. The furnace was originally built for arch-firing, but it was later converted to horizontal-firing. It will be converted back to arch-firing with a design that will facilitate changing back and forth between the two configurations.

The CETF needs to be modified in two areas in order to perform the required HIPPS testing. One area is the furnace/burner design, and the other is the process systems. The furnace needs to be modified to an arch-fired arrangement and a burner for char firing needs to be designed. The furnace design has been completed. The burner design is in progress. Char combustion information being developed in Subtask 2.4 is being used in the burner development.

The auxiliary or process systems at the CETF also need to be modified to simulate the HIPPS conditions. The char needs to be fed to the burner with a solids/gas ratio like that of HIPPS, and the combustion air needs to be of the oxygen content and temperature that results from the use of gas turbine exhaust as combustion air.

The process flow diagram for the CETF tests is shown in Figure 22. Instead of direct firing of fuel from the pulverizer; char, coal and sorbent will be stored in bins and fed from there to the burner. By decoupling the pulverizers from the fuel transport system, the transport conditions of the HIPPS plant can be more closely simulated. The combustion air will be heated with a duct burner, and tempered with recirculated flue gas. In this manner, both the temperature and the oxygen level of the Commercial Plant combustion air can be matched.

Figure 21 Arch Firing



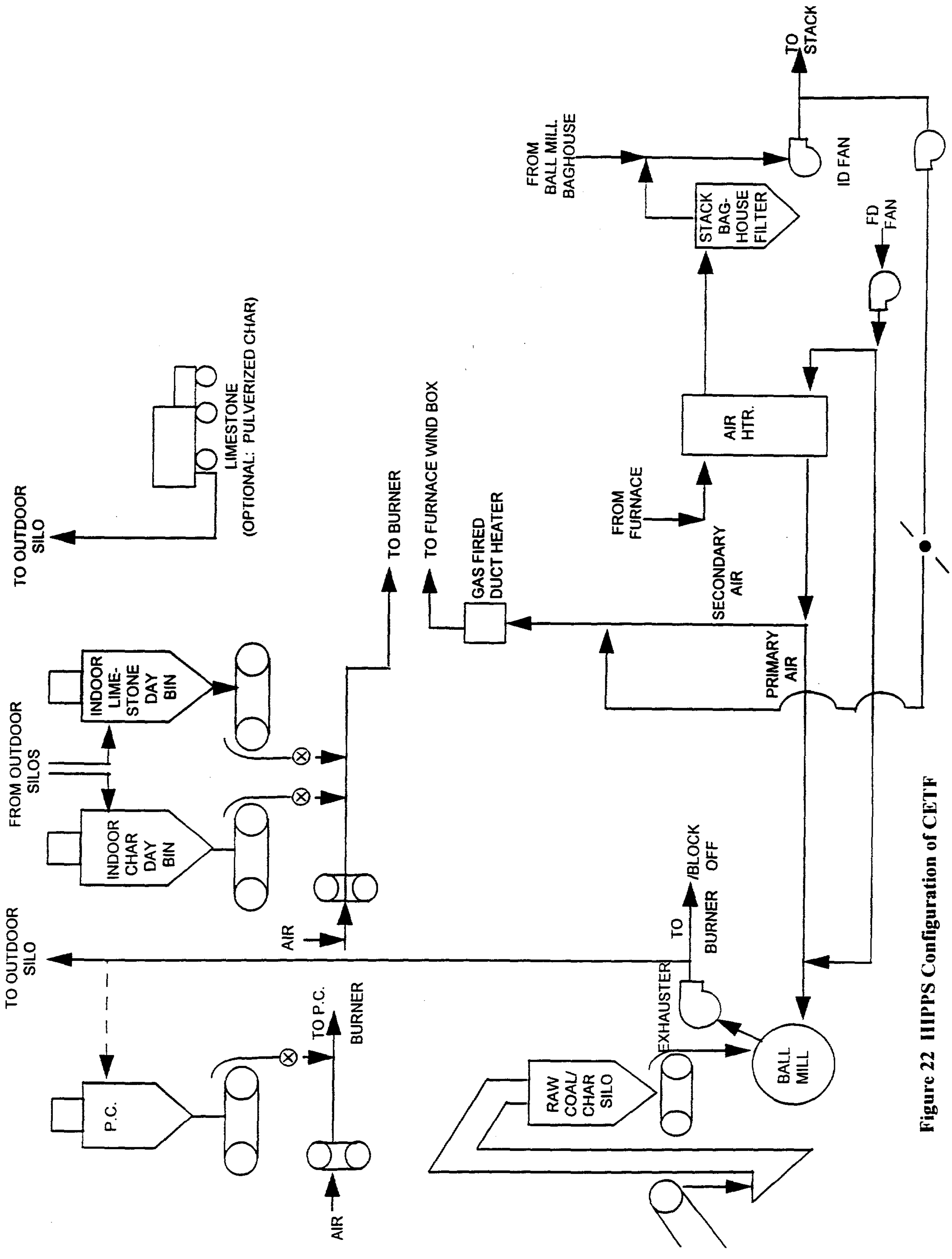


Figure 22 HIPPS Configuration of CETF

The char combustion system tests are scheduled to begin in October 1997. Most of the tests will be run with commercially produced char, but char generated in the PCTT will also be used to the extent that it is available.

Subtask 3.3 - Integrated System Test Design (IST)

FWDC, FWEC and UTSI personnel met at the UTSI Coal Fired Flow Facility (CFFF) primarily to update the IST process flow schematic and to discuss modification of the furnace for arch-firing. In general, it was decided to proceed with the design and construction of the IST on a system-by-system basis as design information becomes available. UTSI will be pulverizing the coal for the Livingston pyrolyzer tests, and so an upgrade of this system has already begun. A char transport system can be also be fabricated with mostly existing equipment, and this can be tested in 1997. Enough design information is available to design the furnace modification, and this design work is now proceeding. The critical path system for the IST will be the pyrolyzer system, and final design of this system cannot be done until the PCTT testing is done. A preliminary arrangement for the pyrolyzer system will be done in early 1997 and design of the support structure will start.

A boiler to supply high pressure steam to the pyrolyzer has been purchased. Installation will begin in the next Quarter. A pressurized seed injection system, previously used in discontinued DOE testing was examined by UTSI personnel for possible use as a sorbent feed system. It is feasible to use this system, and the procedure for transfer of this equipment to the DOE CFFF as surplus government property was initiated. Preliminary specifications are being prepared for a fuel gas incinerator (thermal oxidizer).

Task 4 - Subsystem Test Unit Construction

Subtask 4.1 - PCTT Construction

All equipment being purchased for the Livingston pilot plant modification has been ordered. The last equipment required for the bubbling bed tests is due in late October. Construction is in progress on this modification. Refractory repairs have been made in the pyrolyzer, and the solids drain was modified. The candle filter has been inspected and made ready for additional testing. All the safety valves that are being used have been sent out for recertification. Several of these valves required repair. Piping has been run for the new coal feeding system, and modifications have been made to the coal silo to accommodate the new bin vent that will be required. Wiring is being done for new equipment and as required by equipment relocation.

Subtask 4.2 - Char Combustion System Construction

Wall panels have been ordered to convert the furnace wall and windbox to arch-firing. Because of the high ash content of the HIPPS char, sootblowers will be required, and these have been purchased.

Subtask 4.3 - IST Construction

The coal processing system upgrade continued, as required because of deterioration of the CFFF coal system components and possible higher system operating pressure. Purchase Orders were issued for replacement coal system control valves and solenoid valves needed to provide coal system reliability. Many of these components were received this quarter. Repair and replacement of coal system electrical and control equipment was performed as needed for PCTT coal pulverization. The coal drying condenser system was refurbished as needed too, and a new bag filter exit rotary valve and motorized shaker system were installed. The planned coal system upgrade will not need to be completed further to pulverize coal for the PCTT, so system upgrade will be interrupted for this coal pulverization next Quarter.

The CFFF cryogenic system was also reactivated this Quarter since this system is needed to pulverize PCTT coal next Quarter.

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