


12-1-1997

Development of an Atmospheric Fluidized Bed Combustor (AFBC)

William Orndorff
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DEVELOPMENT OF AN ATMOSPHERIC FLUIDIZED
BED COMBUSTOR (AFBC)

A Thesis

Presented to

the Faculty of the Department of Chemistry

Western Kentucky University

Bowling Green, Kentucky

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

by

William Wren Orndorff

December 1997

DEVELOPMENT OF AN ATMOSPHERIC FLUIDIZED
BED COMBUSTOR (AFBC)

Date Recommended August 18, 1997

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ACKNOWLEDGMENTS

I would like to express my sincere thanks to the U.S. Department of Energy for my traineeship award of \$12,500, which enabled me to attend graduate school at Western Kentucky University. I appreciate Western Kentucky University for allowing me \$250 for the purchase of the IGOR PRO software, which was used several times for writing this thesis. I would also like to thank my advisor, Dr. Wei-Ping Pan, as well as the other chemistry faculty for their support during my study. I must also greatly acknowledge my wife and six children, who have sacrificed much during the last year. Without their support and help, I could not have continued.

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DEVELOPMENT OF AN ATMOSPHERIC FLUIDIZED
BED COMBUSTOR (AFBC)

William Wren Orndorff

December 1997

35 Pages

Directed by: Wei-Ping Pan, John T. Riley, and Charles Lee

Department of Chemistry

Western Kentucky University

The relatively recent interest in the U.S. in the development of atmospheric fluidized bed combustion (AFBC) has been preceded by two main factors. First of these is the ever present problem of acid rain and growing public support for cleaner burning fossil fuels. Second is the increasing demand on public landfills and subsequent need for burning of municipal solid waste. From these factors and their corresponding influences, Western Kentucky University has the impetus and has received the financial assistance necessary to build and develop a laboratory scale AFBC system. A brief history of the events leading to this development, as well as selected results from the last 12 months of this project are discussed.

I. INTRODUCTION

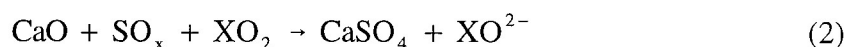
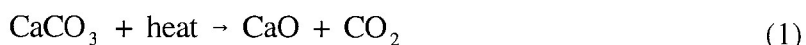
A. Atmospheric Fluidized Bed Combustion

Atmospheric fluidized bed combustion (AFBC) is the combination of fine ground bedding material (limestone or sand) and fine ground coal, blended together under forced combustion air. The air, which is driven up through the blend, causes this mixture to become suspended or fluidized, from which comes its name. It would not be erroneous to visualize this mixture as having the consistency of quick sand. How high this mixture is suspended over the forced air is a function of the velocity of the incoming combustion air.¹ Usually, in AFBC systems the combustion air is near atmospheric pressure inside the furnace and is the main driving force for carrying the light ashy material out of the combustor, where it is caught in a high temperature cyclone and in some cases recycled back into the furnace. The recycling is done primarily to increase combustion efficiency and utilization of the bedding material for sulfur capture, which will be described in more detail later.

When the combustor is operating smoothly, there is a continuous supply of coal and limestone being fed into the system at a rate of approximately 2 to 3 % of the total weight of the bed material. During normal operation the bed height is kept at a predetermined level; therefore it is necessary to remove a fraction of the bed periodically, and in some cases continuously, in order to obtain this objective. Bed height is a factor in both combustion and sulfur capture efficiency, due to longer residence times, thus proper bed management is essential for consistent firing conditions.

AFBC technology is commonly associated with the burning of low quality coal, and hence has lower operating temperatures relative to conventional coal fired power plants. This method is ideal for the burning of municipal solid waste (MSW), as well as

refuse derived fuels (RDF), especially when you consider the clean burning facet of AFBC technology. Even though the operating temperatures of atmospheric fluidized bed combustion are low, relative to conventional coal fired power plants, they are still sufficient to force the CaCO_3 (limestone) to be reduced to CaO which then acts as an absorbent for SO_x emissions, as well as various other undesirable gases. This reaction is the unique aspect of AFBC technology that allows this combustion technique to operate so cleanly. Reactions 1 and 2 refer to these reactions:



AFBC technology has been in commercial use worldwide for over fifty years, usually in smaller steam generating and petrochemical applications that are a fraction of the size of the typical U.S. coal fired power plants. The first AFBC system in the U.S. was built only 30 years ago, with serious projects beginning in the early 1980's.

B. Environmental Concerns Of Coal Combustion

Sulfur content in coal varies drastically with geographical locations. However, for comparison we can approximate the average sulfur content in coal to be 1 to 2.5%.² This amount may seem small or even insignificant at first glance. However, if we take a conservative 0.6% concentration multiplied by the number of tons consumed each year by the U.S. coal fired power plants (780 million short tons),³ we reach some extremely high levels of sulfur emission -- of approximately 4.7 million short tons. This problem is further exacerbated by the geographical location of many of our coal fired power plants and the prevailing southwesterly winds which can dump excessive amounts of undesirable emissions over a relatively small area. Couple this problem with a border nation, such as Canada or Mexico, and you have a recipe for an international problem with far reaching implications.

Acid precipitation is defined as rain or snow with pH values of less than 5.6.⁴ Rain as acidic as vinegar (pH 2.4) and lemon juice (pH 2.1) was recorded in 1974 (Pitlochry, Scotland) and 1964 (Northeast, U.S.), respectively.⁵ It is widely accepted that acid rain begins with NO_x and SO_x emissions, which react with moisture in the atmosphere, to form H₂SO₄ and HNO₃. Hence NO_x and SO_x gas levels are directly related to the pH of acid rain produced. Since coal fired power plants are among some of the highest emitters of NO_x and SO_x gases they are chiefly blamed for the acid rain dilemma. Depending on the geographical location, some estimates place as much as 60 to 70 % of the acid rain contribution on sulfur emissions.⁶

Sulfur in and by itself is not a toxic chemical. On the contrary, it is a vital element necessary for life. Uses of sulfur include fertilizer (50%), chemicals (20%), and insecticides (2%).⁷ However, sulfur is synonymous with acid rain and increased public awareness of the problems surrounding acid rain has facilitated the implementation of dozens of clean air laws. A brief time line of these acts, as they affected Jefferson County, Kentucky, is provided below:⁸

- 1970 Clean Air Act determines a limit on SO₂ emissions, treating the issue as a local problem;
- 1972 SO₂ limits are made for coal fired power plants in Jefferson County and Floyd County, Indiana;
- 1973 Louisville Gas and Electric Company installs a scrubber to help remove SO₂ from its coal fired power plants;
- 1976 The U.S. Environmental Protection Agency allows Public Service Indiana to operate their Gallagher power plant in New Albany without new pollution controls;

- 1979 Jefferson County encourages the EPA to control emissions from the Gallagher plant because they are a factor in Jefferson County's SO₂ problem;
- 1980 Federal law establishes program to compile the evidence which demonstrates that SO₂ gases are a significant factor in acid rain and that these gases can be carried over long distances;
- 1982 EPA rules that the SO₂ emissions from the Gallagher plant are not a significant factor in Jefferson County's air pollution;
- 1986 Since Jefferson County has not had a violation in three years, the EPA announces that the county does not have a SO₂ problem;
- 1987 Gallagher plant lowers its SO₂ emissions, however, its levels are still four times the amount allowed by Louisville Gas & Electric plants;
- 1990 Clean Air Act Amendments are passed, providing for the first comprehensive plan for reducing acid rain;
- 1992 Louisville Gas & Electric and Jefferson County agree to spend 38 million dollars on a project to upgrade scrubbers at two plants (Mill Creek and Cane Run);
- 1995 Production is off 30 percent in high-sulfur coal mines. Workers face widespread layoffs;
- 2000 Stricter emissions take effect.

From the above time line four noticeable events take place. First, air pollution is a regional problem, treating it as a local problem is futile and unsatisfactory. Second, removing sulfur from the smokestack is expensive. Third, Kentucky will be severely hard hit from the trickle down effect of thousands of coal miners being out of work. Fourth, the year 2000 looks bleak.

As was brought out in the above paragraph, removal of sulfur from the smokestacks is very expensive; however other methods exist to remove sulfur prior to

combustion, unfortunately some are more expensive. Studies made during the 1970's calculated the cost of chemically removing the sulfur prior to combustion at approximately 60% of the price of coal, which when applied to today's market would be over 25 dollars per ton, or 20 billion dollars on a yearly national scale.⁹ Optimum utilization of the AFBC system can result in up to 95% retention of the sulfur when operating at a Ca/S ratio of 2 to 3,¹⁰ thus making AFBC one of the best candidates for combustion of high sulfur coal.

C. Burning of Municipal Solid Waste

The attitude of the present U.S. population has been consumed with convenience. The undermining effect of this tone has placed increased demands upon manufacturers, as well as retailers, to devise and market "disposable" items. This trend is evident from the advent of disposable diapers, ink pens, razors, and even cameras, just to name a few. These types of items, however, place a tremendous burden upon our nation to dispose of them, especially, when you multiply this attitude by two hundred and fifty million. In 1980 every man, woman, and child in the U.S. generated over 2 kilograms of trash, which converts to over 200 million tons on a yearly basis, for the entire U.S.¹¹ Within the news section of almost any newspaper, you will find the growing problem of disposal of solid waste, almost no one wants a landfill located next to their neighborhood.

One possible remedy for this problem is the burning of municipal solid waste, since the "typical" solid waste contains approximately 5,000 Btu's per pound,¹² with some wastes containing over 16,000 Btu's per pound.¹³ Other advantages include:¹⁴

1. Incinerators require a small parcel of land, relative to landfills;
2. Incinerators can be located closer to centralized collection sites, thus reducing transportation costs;
3. Incinerators are not interrupted by inclement weather;
4. Residue from an incinerator is usually stable and inorganic;
5. Inconspicuous designs of incinerators could allow for placement near residential areas;

6. Incinerators can be geographically located near water sewage treatment plants, thus facilitating the burning of undesirable gases and drying and burning of sludge;
7. Incinerators can be less expensive than landfills;
8. Incinerators can burn almost any type of refuse;
9. Opportunity exists to capture some of the steam generated, as well as the recycling of the inorganic materials.

However, not all that glitters is gold. There are some serious side effects of burning municipal solid waste that can be extremely toxic to the environment. Among some of these emissions is formaldehyde, which can be generated at the rate of 0.021 to 0.0014 pounds per ton of refuse.¹⁵ Hydrogen chloride can also be produced, with variations between 400 and 700 ppm of dry flue gas.¹⁶ However, the most toxic gases produced during combustion of municipal solid waste are the dreaded “dioxins,” whose presence even in trace concentrations can still pose a significant health hazard. Current studies are underway within Western Kentucky University’s Chemistry Department to study the mechanism for formation of these chemicals, as well as the conditions which favor their production.

D. Western Kentucky University’s AFBC System

In early 1991, Western Kentucky University (WKU) under a proposal submitted by Drs. John T. Riley and Wei-Ping Pan, Department of Chemistry, received a grant for the establishment of a laboratory scale AFBC system. WKU’s AFBC system was designed to simulate the combustion environment of the Tennessee Valley Authority’s (TVA) 160-MWe AFBC Demonstration unit, which is located at TVA’s Shawnee Fossil Plant reservation near Paducah, Kentucky. TVA had originally built a 20-MWe AFBC pilot plant facility at Shawnee during the early 1980’s with operational testing beginning in May 1982. This 102 million dollar project allowed TVA to operate the pilot unit under

various conditions and with a variety of fuels until 1987. During this 5 year span, the pilot unit successfully logged over 20 thousand hours of operation.

TVA became interested in pursuing AFBC technology only after passage of the Clean Air Act in 1976,¹⁷ although studies performed on AFBC technology in the early 1970's demonstrated that this method was capable of burning low grade, high sulfur coal while being environmentally friendly and cost effective. The demonstration unit's construction was begun in February 1985 and completed in October 1988. During the time period from October 1988 to April 1992, the unit logged almost 17 thousand hours of generation, although the plant was besieged with approximately 100 shutdowns lasting from several days to several weeks.¹⁸ Currently, the unit operates on a load dispatch for the Shawnee plant.

One of the problems for the demonstration unit was premature heat exchanger tube failure. The heat exchanger tubes are the metallic tubes (usually made from either carbon steel or stainless steel) that act as a medium for transferring the heat of coal combustion to the water, which is subsequently super heated to steam and serves as the driving force for the turbines coupled to the electrical generators.

There are two main sources of wear for the tubes: corrosion and erosion. Erosion is the destruction or deterioration of metal due to the rubbing action of abrasive materials (such as coal or limestone). Corrosion is the destruction or deterioration of metal by direct chemical or electrochemical reaction with its environment.

Although construction for WKU's AFBC combustor began in late 1991, it was well into early 1995 before wide scale combustion experiments were taking place. This delay was due to a shortage of manpower and funds, which meant that most of the work fell upon the Ogden College Instrument Shop, whose manpower at that time was limited to two personnel.

II. EXPERIMENTAL

A. Combustor

The AFBC combustor, which is at the center of this research project, is currently located in the basement of the Science and Technology Hall in room 103a. The instrumentation that analyzes the various gases along with the combustor's computer control are located nearby in room 102. The combustor is approximately 4.9 meters in height with an outer diameter of 0.6 meters. The combustor's outer skin is made of plate metal. Therefore it was necessary to insulate the inside of the combustor with a ceramic material (refractory) in order to extend the life of the combustor, as well as lower the surface temperature of the combustor itself. This modification resulted in reducing the inner diameter to 0.3 meters, with a resultant volume of 0.3 cubic meters (after the wind box was accounted for). The combustor can be further detailed in 12 main areas, as illustrated in Figure 1.

1. Wind Box This section is represented by the lower part of the combustor, from the ground floor to 0.5 meters (above the floor). It is in this area that the air from the forced draft fan (FDF) enters the combustor and is subsequently forced through the setter plate.
2. Setter Plate This porous material represents the floor of the hot bed material. Its design allows for air (from the FDF) to be forced through, which results in a bubbling action within the bed.
3. Forced Draft Fan (FDF) This fan is responsible for providing the combustion air to the bed. The fan itself is a lobed (Roots-type) positive displacement blower, typical of those found on a Detroit Diesel engine. It

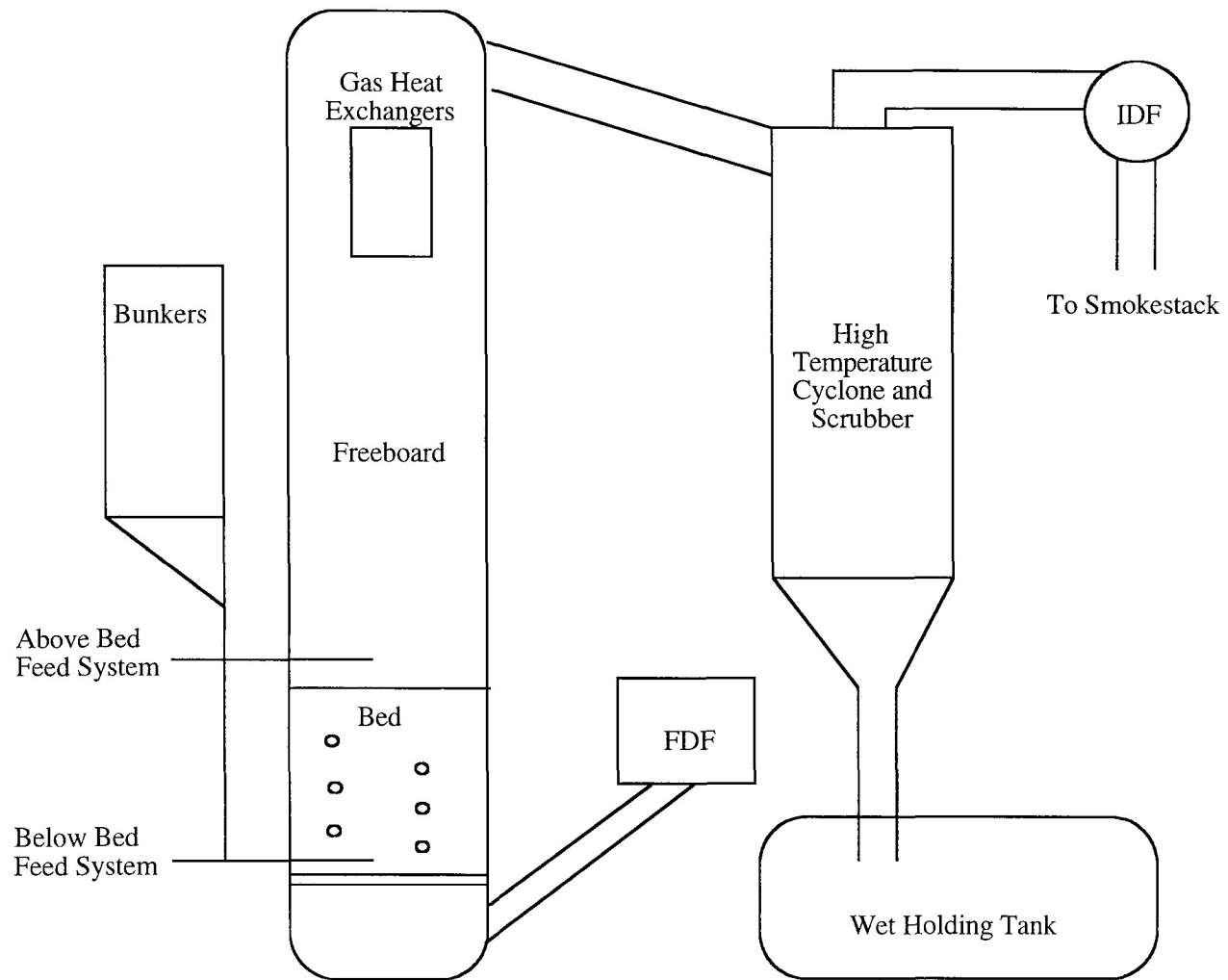


Figure 1. Western Kentucky University's atmospheric fluidized bed combustor

is powered by 5 horsepower electric motor, which is controlled by a Wood's variable electrical box, in order to deliver various flows of air.

4. Bed Area This portion of the combustor contains the majority of the combustor bed. The exact area is a function of air velocity, but it typically runs from the setter plate to a height of 1 meter.
5. Bed Heat Exchangers Six moveable tubes are located within the bed area. Typical operation involves setting the correct coal/lime feeds and air flows and then using the moveable tubes to adjust the bed temperature to the desired setting.
6. Freeboard This area runs from the top of the bed area to the top of the combustor. It is in this area that secondary air is introduced, which helps facilitate complete combustion.
7. Gas Heat Exchangers Sixty-six tubes are in fixed position for this segment of the combustor, and are located approximately 1 meter from the top.
8. Above Bed Feed System This feeding system is designed to help start the combustion process and for experiments in which the client desires an above bed feed.
9. Below Bed Feed System This feeding system is designed for use after the combustion process has been stabilized and the bed fluidized. This system is the primary delivery method during normal runs, since the feeding position allows for longer bed residence, and hence better combustion efficiency. The fuel is introduced under pressure by this system.
10. Bunkers These containers are used to store the fuels and bedding material during combustion runs. Typically, these vessels hold enough coal and limestone for 8 hours of operation.
11. Cyclone/Scrubber The hot gases from the combustor are allowed to enter this area where they are met with a wall of water (which keeps the cyclone

cool), which subsequently takes almost all solids to the bottom of the scrubber where a wet holding tank is waiting. Problems with formation of solids at the gas/water interface has been eliminated by drilling a small hole so that a rod can be inserted to scrape down any buildup.

12. Induced Draft Fan (IDF) The IDF helps ensure the positive and correct flow of gases from the combustor to the cyclone/scrubber and to the smokestack. This fan is also interfaced with a variable speed Wood's control box. Specifically, the fan was designed to insure that 1 to 2 inches of water pressure differential exists between the top of the combustor and the entrance to the cyclone/scrubber.

The combustor's operating parameters (air/water flow, coal/lime feed, bunker weights, temperatures, and pressures) are controlled and logged to file with a Zenith 150 MHz (Pentium processor) computer utilizing the LABTECH software version 3.0. During the combustion runs any needed changes in the parameters can easily be entered into the computer by accessing the correct control screen and making the necessary corrections on line.

B. Flue Gas Sampling System

The first combustion runs involved setting the desired coal/air ratio while using the lime feed to control the bed temperature. Needless to say, this procedure was unsatisfactory, since the operating conditions were frequently being changed. The problem was corrected by providing six moveable bed heat exchanger tubes. Currently during combustion runs, the desired coal/air ratio and temperature are attained and then maintained by inserting any combination of these tubes from zero to 20 inches inside the combustor.

Flue gas can be sampled from any one of four locations on the combustor. Thermocouples are provided at these access sites so that we can measure the temperature of the combustion gases at their respective place in the combustor. Information derived from this practice provides insight for reaction mechanisms and transition state energies.

Originally, flue gas was pulled through 80 feet of 1/16" TEFLON tubing and 21 connectors (or 21 possible sources of leaking), heated to 120°C. The logic behind using vacuum only was to prevent any possible adsorption of HCl or other gases from adsorbing onto the stainless steel components of a pump, prior to analysis by GC/FTIR and IC. However, this practice was a futile attempt, since the pressure differential between the two ends of the tubing was too large, resulting in widespread dilution of the flue gases due to leaking connectors. Hence, modification of the flue gas sampling system was in order and was accomplished by placing a laboratory size stainless steel pump approximately 30 centimeters from the combustor. Flue gas is now drawn from the combustor with only 8 connectors, which greatly reduces the amount of possible leaking sources, as well as diminishing the pressure differential between the combustor and the pump. Additionally, the gases were originally allowed to flow directly from the flue gas system directly into the FTIR cell, with subsequent passage through the GC. However, due to the high moisture concentrations (6 to 8%), which rapidly deteriorated the GC columns, this approach also proved to be unsatisfactory. The problem was corrected by installing for a moisture absorbent directly prior to the FTIR cell. Using this last modification made it necessary to move the IC collection to another probe while gathering CO₂ concentrations for the GC/FTIR. Figure 2 shows the layout of the old flue gas system and Figure 3 represents the new flue gas sampling system.

C. Fourier Transform Infrared (FTIR) Spectroscopy

Analysis of the flue gases is accomplished by first examining the gases by FTIR spectroscopy. The FTIR instrument operates upon the theory that, when the vibration frequency of the molecules under investigation matches the frequency of the scanning infrared light, there will be an absorption of energy by the molecules from the light. It is essential that for this interaction to take place; the molecule must possess a permanent dipole. Needless to say, this instrument is useless for measuring oxygen and nitrogen concentrations. The FTIR used in the lab was a Perkin Elmer model 16 PC, which is

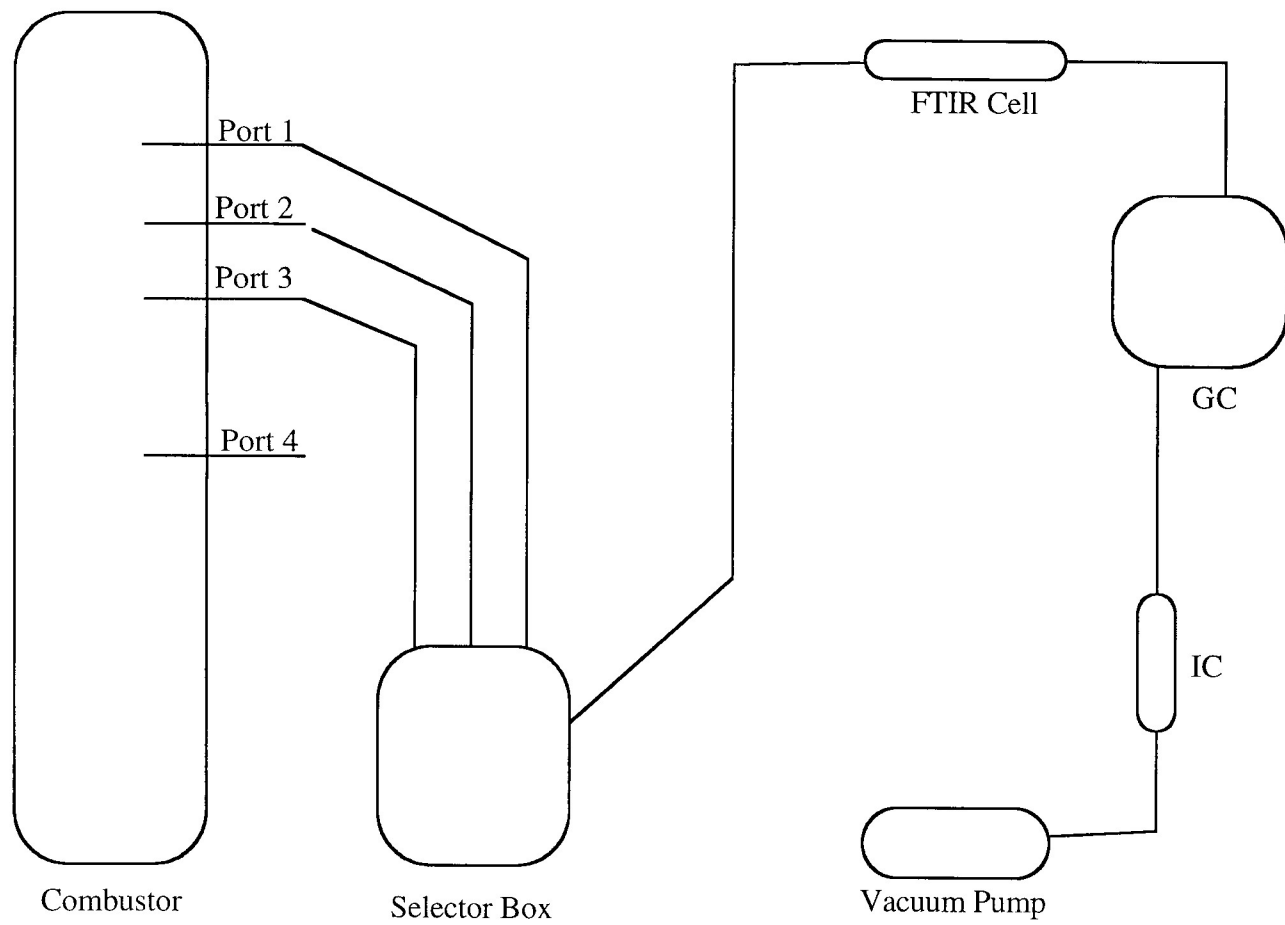


Figure 2. Old flue gas sampling system

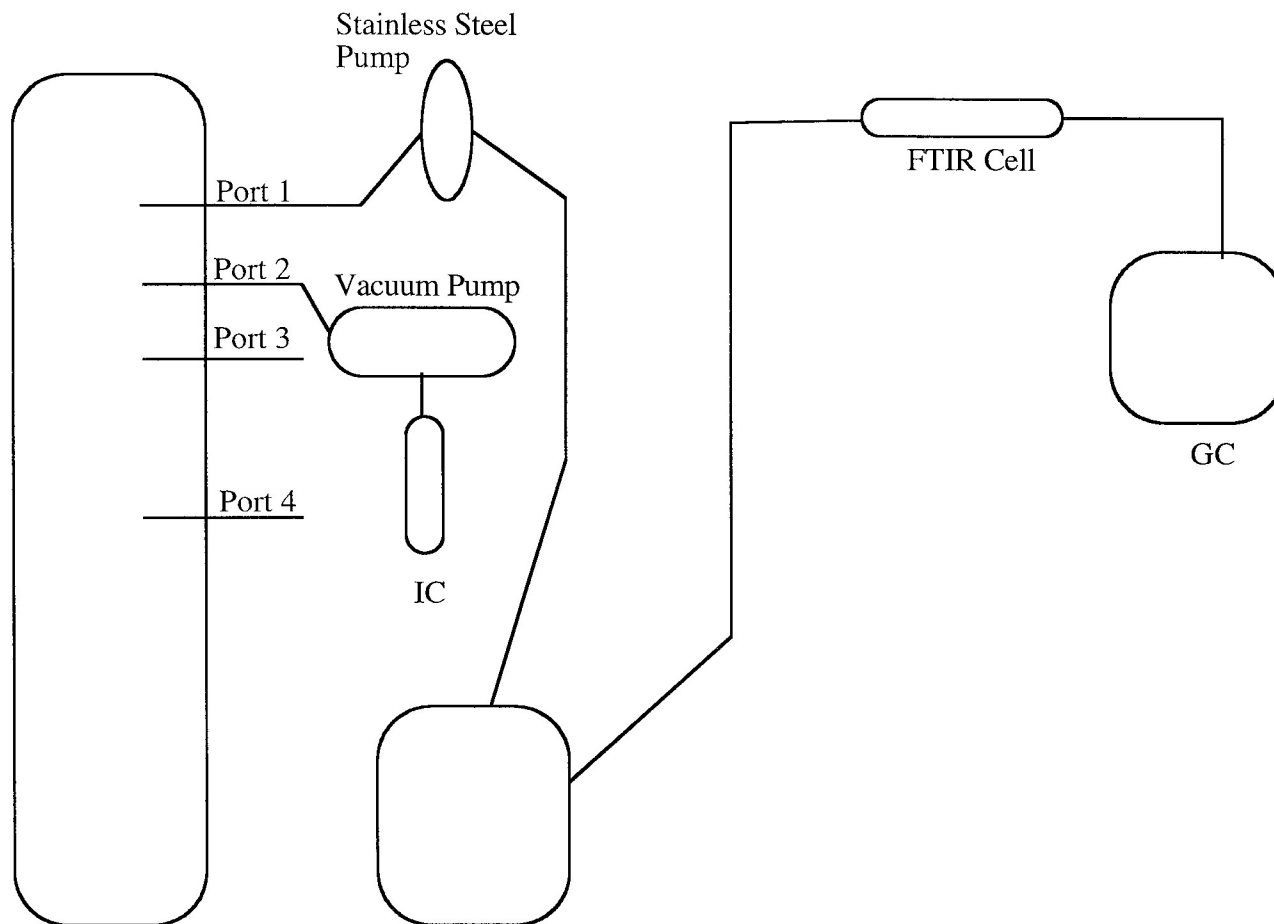


Figure 3. New flue gas sampling system

interfaced with a Digital DEC Station 316SX computer. The software used by this computer was the Infrared Data Manager (IRDM) version 3.5, which was supplied by Perkin Elmer. Using the OBEY micro language the computer was programmed to automatically scan every 15 minutes (or in most cases 6), calculate the area under a peak, and to save the file on both hard drive and diskette, with the most critical information being printed on the screen. This modification allowed the elimination of one operator. Before August 1995, it was essential to have one operator just to initiate the scans, calculate the area under the peak, and log the results. The FTIR spectrometer would normally be set to scan from 4400 to 450 wavenumbers and automatically calculate the area for 2400 to 2220 wavenumbers (CO_2), 2200 to 2040 wavenumbers (CO), and 1401 to 1303 wavenumbers (SO_2). Usually the instrument would take 16 scans and average the results for its final file. Figure 4 illustrates a typical FTIR spectrum.

D. Gas Chromatograph (GC)

The next instrument in the analysis of the flue gas is the Shimadzu GC-8A, which is equipped with a thermal conductivity detector. The GC columns allow for separation of the various gases under investigation, while the thermal conductivity detector uses a Wheatstone bridge configuration to capitalize on two phenomena of nature. First is that resistivity and hence resistance that can be approximated as a linear function over a wide dynamic range. Second is that each gas has its own specific thermal conductivity. Thus, the Wheatstone configuration allows a reference gas, such as argon, to flow over two of the filaments (or resistors) while the sample gases are flowed over the other two elements (or resistors). Because the sample gas cools the filament at a rate different from the reference, we have a difference in the resistors which we can quantify. Figure 5 illustrates this configuration. Since the difference in resistance is a function of the quantity and thermal conductivity of the sample gas, it was necessary to use the area normalization method. The specific operating conditions and column requirements are listed below:

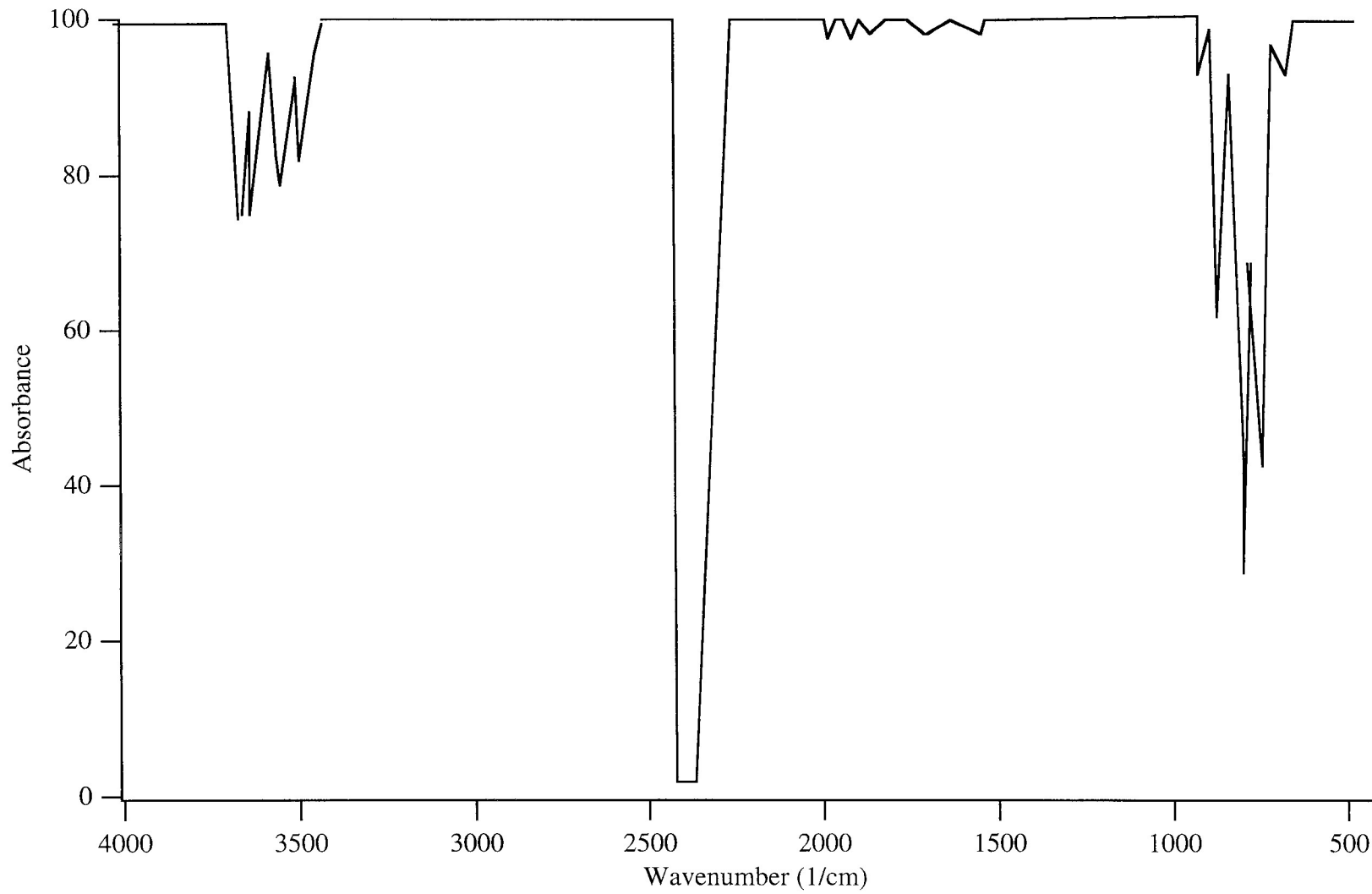


Figure 4. Typical FTIR Spectrum

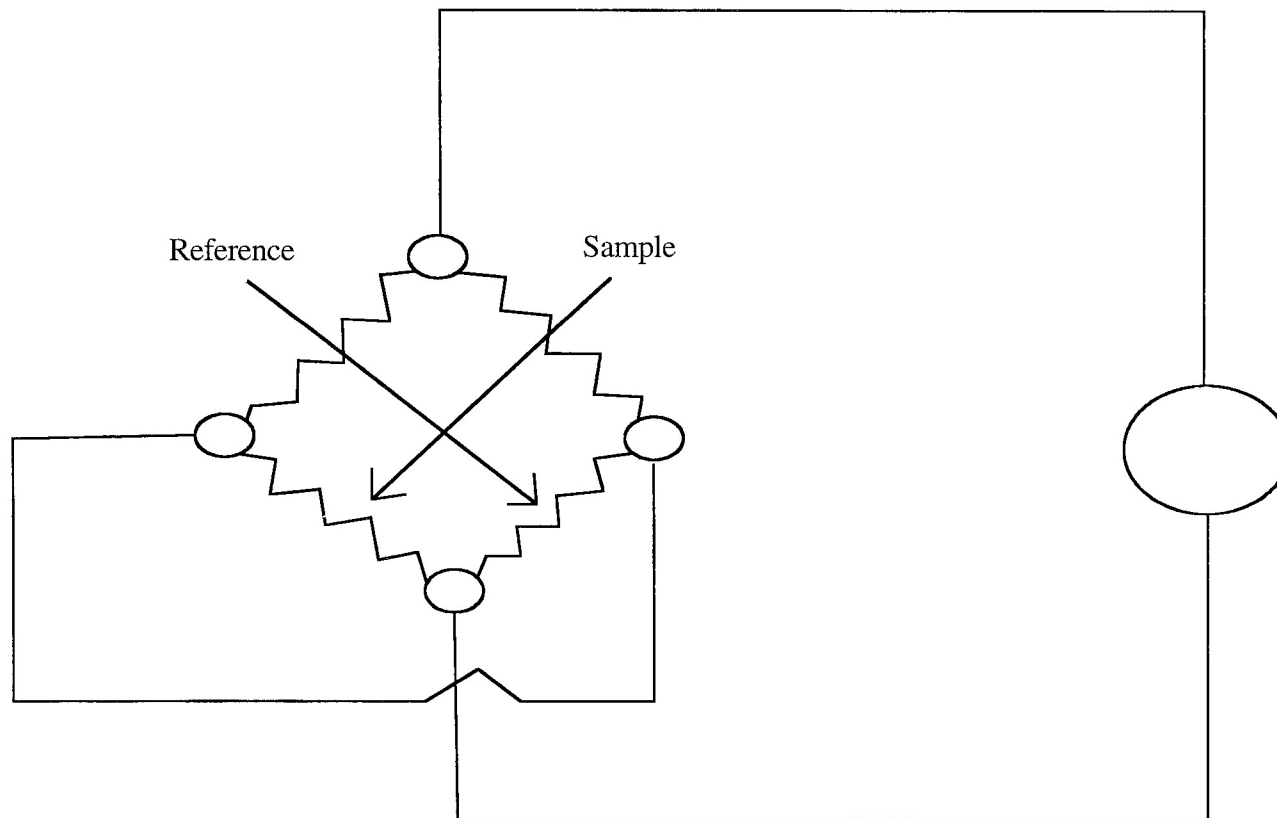


Figure 5. Wheatstone bridge configuration for thermal conductivity detector

Carrier Gas:	Argon
Injection/Detector Temperature:	110°C
Column Temperature:	70°C
Attenuation:	64
Polarity:	Positive
TCD Current:	70 mA
Primary Gas:	6.0 Kg/cm ²
Carrier Gas #2:	3.0 Kg/cm ²
Carrier Gas #1:	1.6 Kg/cm ²
Relay 4:	0.8 minutes
Sample Flow Rate:	Approximately 20 mL/min

The layout of the GC can be rather confusing; for ease of interpretation, the following annotation is used:

10 Port Valve:	Individual ports are denoted by 1p, 2p, ... 10p;
Injection Ports:	Denoted by Inj.#1 and Inj.#2;
TCD Exit Ports:	Denoted left or right.

The layout for the GC Column was as follows:

1p goes to entrance/exit flue gas line;
 2p goes to entrance/exit flue gas line;
 3p goes to 10p via 1/8" sample loop tubing;
 4p goes to Inj.#1;
 5p goes to 7p;
 via C-5000 991788L SN# 9433A
 3 meters X 1/8" X 0.085" SS p/w
 mole sieve 5A 60/80 mesh
 ALLTECH

6p goes to 9p;

via C-5000 991788L SN# 9432A
1 meter X 1/8" X 0.085" SS p/w
Porapak R 80/100 mesh
MAOT 250C
ALLTECH

8p goes to right TCD port;

via C-5000 991788L SN# 9431A
1 meter X 1/8" X 0.085" SS p/w
Porapak R 80/100 mesh
MAOT 250C
ALLTECH

and

0.5 meters X 1/8"
Shimlite Q
100/80 mesh

Inj.#1 goes to 4p;

Inj.#2 goes to left TCD port;

via 1 meter X 1/8"
Shimlite Q
100/180 mesh

The GC, which was interfaced to both the PRG-102A Integrator and the C-R6A Chromatopac was programmed using BASIC language to operate automatically every 18 minutes. The time program which is provided below, shows the operation of Relays 4, 5, and 6. Relay 4 controls the ten port operable valve, which facilitates the accurate flow of flue gas. Relay 5 controls the operation of the flue gas pump. Relay 6 controls the actuator valve, which allows for brief periods of purging for the flue gas sampling port. Figure 6

shows the current time program for the GC, while Figure 7 represents a typical GC chromatogram.

E. Ion Chromatograph (IC)

The final step in the analysis of the flue gas was the IC collection system. In this step the flue gas is passed over approximately 50 mL of a buffered solution mixed with 1 mL of concentrated hydrogen peroxide. The hydrogen peroxide oxidizes the SO_2 gases and forms sulfate ions, while the buffer solution takes the HCl gases and forms chloride ions. These ions are then readily detected with the IC instrument. The lab utilized the Shimadzu HIC-6A Ion Chromatograph, which utilized the Shimadzu CDD-6A Conductivity Detector and the Shimadzu LC-600 Liquid Chromatograph, all of which were interfaced with the Shimadzu CR501 Chromatopac. Figure 8 represents a typical IC chromatogram.

F. Calibration of the FTIR, GC, and IC Instruments

For most of the experiments, calibration of the GC and FTIR instruments was accomplished by flowing compressed air through the flue gas system for at least 30 minutes at 20 mL per minute. At the end of this time a background spectrum was gathered for the FTIR. This step was followed by using a standard 10% CO_2 gas with an inert carrier. Again the gas was allowed to flow for 30 minutes at 20 mL per minute, before any spectra were gathered. After the 30 minute waiting period, approximately 7 different spectra (which were spaced over 5 minutes apart) were gathered. This process was repeated again for the 15% and 20% CO_2 gases. During this period, it was essential to keep a consistent flow rate through the flue gas system during runs, since a higher flow rate would require higher pressures and thus change the concentration ($pV = nRT$) of the analyzed gases. For the FTIR, once all of the spectra had been obtained, the area was calculated for each peak of interest and the average value was determined for each concentration. Then a graph was made of FTIR Readings versus Concentration, using

```
LIST TIME.PRG
TIME PROGRAM FILE 1

0.01  PRINT DATE$,TIME;
0.07  RELAY 4 ON
1.13  RELAY 4 OFF
5     RELAY 5 OFF
5.1   RELAY 6 ON
5.3   RELAY 6 OFF
5.6   RELAY 5 ON
20    RELAY 5 OFF
20.1  RELAY 6 ON
20.3  RELAY 6 OFF
20.6  RELAY 5 ON
35    RELAY 5 OFF
35.1  RELAY 6 ON
35.3  RELAY 6 OFF
35.6  RELAY 5 ON
50.1  RELAY 6 ON
50.3  RELAY 6 OFF
50.6  RELAY 5 ON
60    START
```

Figure 6. Time Program for the Gas Chromatograph

96/08/06 13:29:37

0.165

1.19

2.11

1.65

2.45

4.328

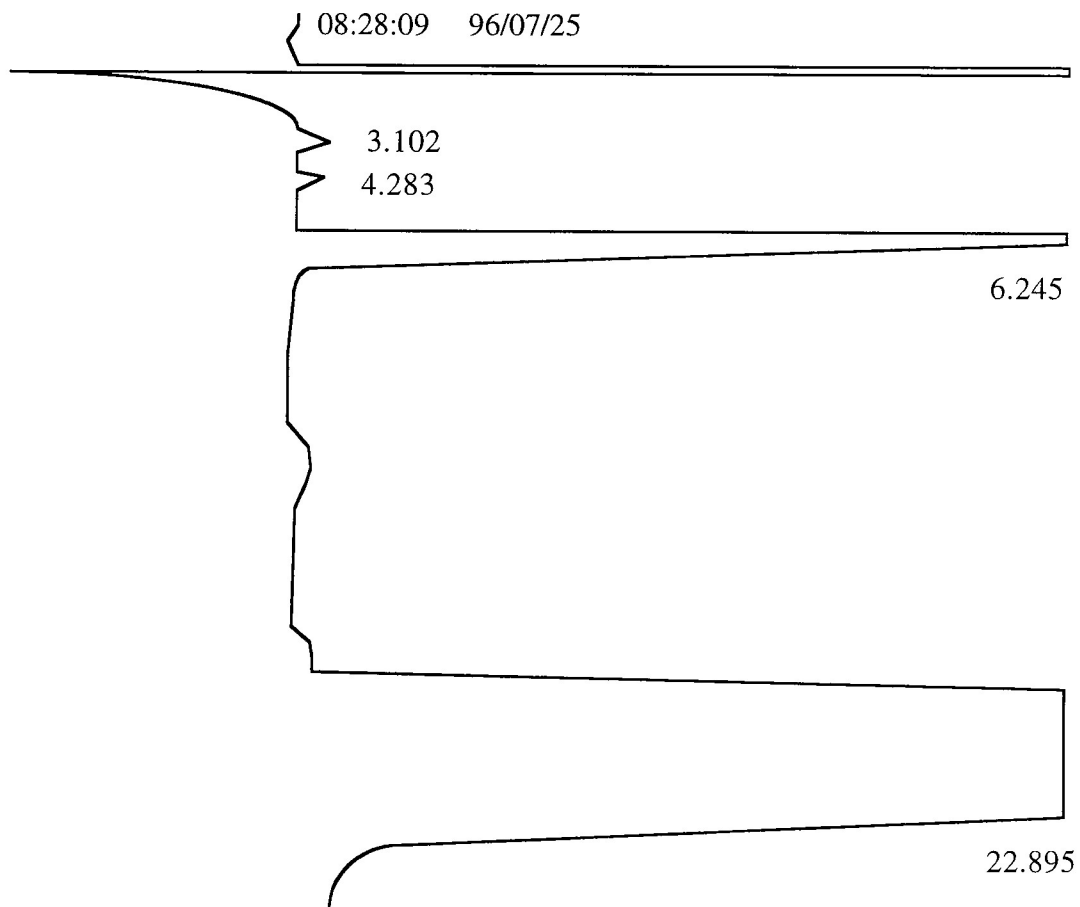
5.4

CHROMATOPAC C-R3A
 SAMPLE NO 2
 REPORT NO 3386

FILE 1
 METHOD 41

PKNO	TIME	AREA	MK	IDNO	CONC	NAME
1	0.165	5411			0.1866	
2	1.19	6172			0.2129	
3	1.65	408			0.0141	
4	2.11	3928	V		0.1355	
5	2.45	271403	V		9.3624	
6	4.328	294505	V		10.1593	
7	5.4	2317051	V		79.9292	
	TOTAL	2898878			100	

Figure 7. Typical GC Chromatograph



CHROMATOGRAM	6	MEMORIZED				
CR501 CHROMATOPAC						
CHANNEL NO	1	FILE	8			
SAMPLE NO	0	METHOD	61			
REPORT NO	34					
PKNO	TIME	AREA	MK	IDNO	CONC	NAME
1	3.102	879			0.0295	
2	4.283	2088			0.0701	
3	6.245	72314			2.4276	
4	22.89	2903551			97.4	

TOTAL					100	

Figure 8. Typical IC Chromatograph

zero concentration, as well as the 3 different concentrations as data points. Since absorbance is defined by a logarithmic function, specifically

$$\text{Absorbance} = - \log \left(\frac{\text{Intensity}_{\text{current}}}{\text{Intensity}_{\text{initial}}} \right)$$

therefore we would expect the graph to fit an exponential curve, which is exactly what we observe. Figure 9 is an illustration. For the GC, only the 15% data was necessary, since we used the area normalization method.¹⁹ IC calibration was performed by using two standards and fitting those areas under the curve to a simple point slope form equation.

G. Current Project

Western Kentucky University's (WKU) task in one particular project is to determine the effect of chloride corrosion on heat exchanger tube failure, if any. Further investigation includes the evolution of chloride during combustion and its kinetics and the interrelationship between chlorine, sulfur, and alkali species in combustion gases and boiler corrosion. Specifically, during Phase One eight metal samples (comprised of four different metals) will be placed inside WKU's combustor for 1000 hours and exposed to combustion gases similar to TVA's demonstration unit. The four metal samples chosen for this phase are carbon steel 1040 and stainless steels 304, 309, and 347. The various chemical and physical properties of these metals is provided in Tables 1 and 2.

Table 1. Coupon Composition

<u>Alloy</u>	<u>C</u>	<u>Cr</u>	<u>Cu</u>	<u>Fe</u>	<u>Mn</u>	<u>Mo</u>	<u>Ni</u>	<u>P</u>	<u>S</u>	<u>Si</u>
C1020	0.180	0.050	NR	Bal	0.450	0.010	0.020	0.008	0.005	0.024
SS304	0.05	18.39	0.41	Bal	1.84	0.36	8.11	0.032	0.001	0.46
SS309	0.058	28.28	0.090	Bal	1.78	0.140	13.41	0.017	0.011	0.440
SS347	0.045	18.03	0.14	Bal	1.20	0.17	9.79	0.018	0.014	0.52

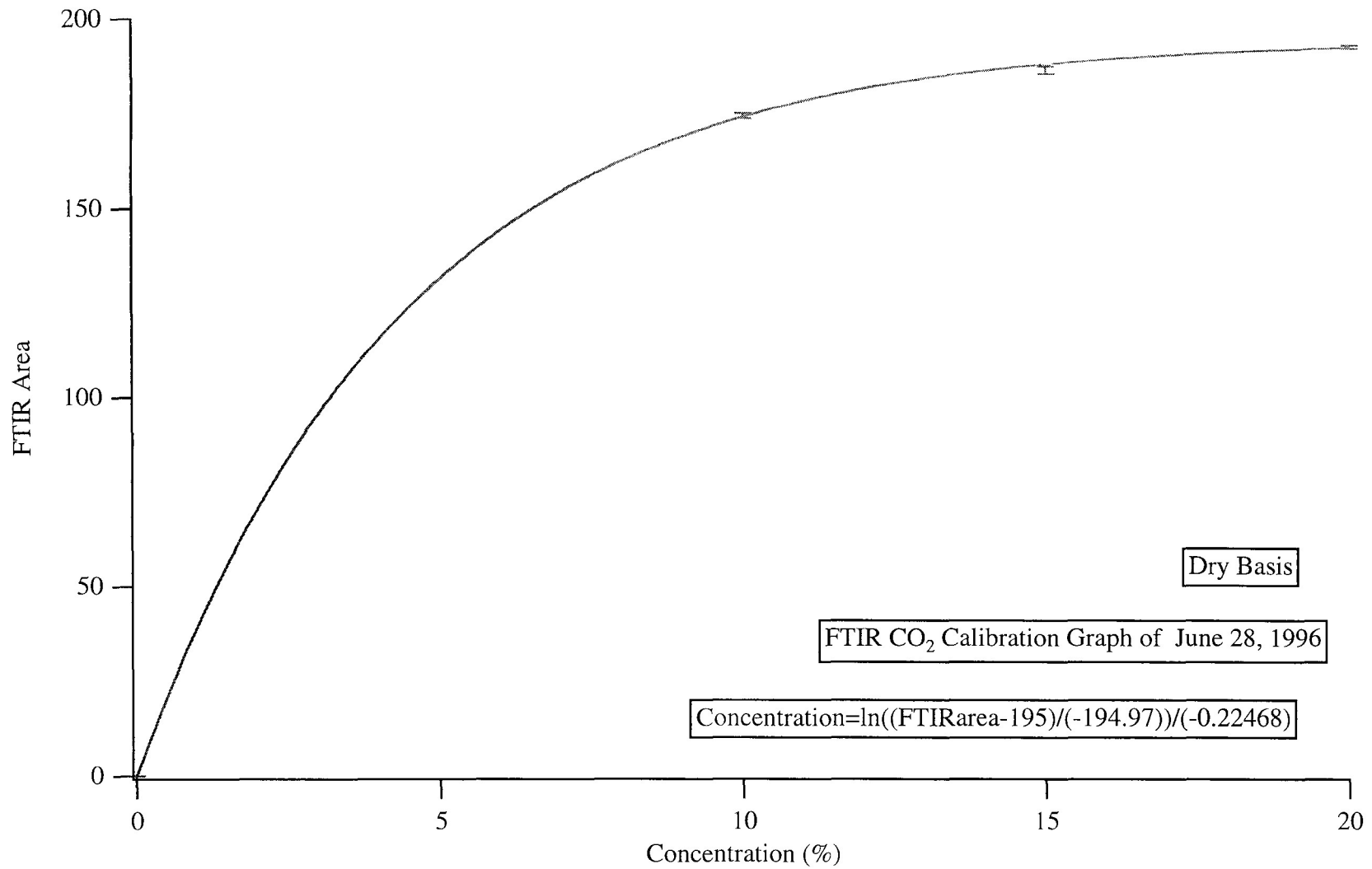


Figure 9. FTIR Calibration Graph

Table 2. Strength and Characteristics of Coupons

<u>Alloy</u>	<u>Tensile KSI</u>	<u>Yield KSI</u>	<u>Elong %</u>	<u>Hardness</u>
C1020	NR	NR	NR	NR
SS304	92500	42500	55	HRB 85
SS309	86.7	38.5	52.6	166
SS347	93.5	47.4	47	HRB 84

During Phase One of the project, the metal samples will be removed and weighed approximately every 250 hours in order to monitor the rate of weight loss. Combustion efficiency during this time should be between 97 and 98%. Combustion gases should also be approximately 15% CO₂, 5% O₂, and 80% N₂ with the operating temperature of the bed between 1470 to 1510 Fahrenheit. The coal used during this phase will possess a low chlorine and high sulfur content.

Phase Two will involve the placement of a second set of metal samples, identical in composition to those in Phase One, under identical combustion parameters, with the exception of the coal quality. In Phase Two, a high chlorine and high sulfur coal will be burned. Analysis at the end of these two phases will examine the differences in weight loss, for the metal samples, between Phase One and Phase Two. Results from these experiments should help quantify the effect of chlorine on boiler components corrosion, if any.

III. RESULTS AND DISCUSSION

Analysis of the data was initiated by copying the combustors operating parameters onto a diskette, which was subsequently downloaded onto a Macintosh computer utilizing IGOR PRO software (McSink V1.07 was used to strip line feeds and lines of text). This software allowed us to compare various operating parameters and their subsequent effect upon CO₂ concentration and combustion efficiency. Additional information could be obtained from noting whether the system was using the above bed feed or below bed feed system.

Combustion efficiency is a function of bed height/temperature, freeboard height/temperature, coal rank/type/size, combustor design, excess air and recycle ratio. During the combustion runs some of these variables (such as air flows and fuel feeds) could be changed and the effects noted. However, others such as combustor design could not be changed during a run.

Combustion efficiency can be calculated in a variety of ways. Typically, the rate of combustion and carbon content of the fuel are known, which leaves two unknown variables of unburned carbon and rate. Usually, for most combustors these two unknowns are known, or can at least be approximated, thus allowing simple calculation using the equation below:

$$\text{Combustion Efficiency} = \left(\frac{\frac{\text{Btu's}_{\text{in}}}{\text{per unit time}} - \frac{\text{Btu's}_{\text{out}}}{\text{per unit time}}}{\frac{\text{Btu's}_{\text{in}}}{\text{per unit time}}} \right) * 100$$

However, for the wet scrubber/cyclone that was used by our facility, the determination of the rate of unburned carbon was rather difficult. Therefore, two

alternative methods were developed. The first of these was to compare the carbon to ash ratios using the following equations:

$$\begin{aligned} \text{Combustion Efficiency} &= \left(\frac{\frac{\text{Carbon}_{in}}{\text{Ash}_{in}} - \frac{\text{Carbon}_{out}}{\text{Ash}_{out}}}{\frac{\text{Carbon}_{in}}{\text{Ash}_{in}}} \right) * 100 \\ &= \left(\frac{\frac{(\text{Coal Feed} * \% \text{Carbon})}{(\text{Coal Feed} * \% \text{Ash} + \text{Lime Feed} * \% \text{Ash})} - \frac{(\text{Fly ash} * \% \text{Carbon})}{(\text{Fly ash} * \% \text{Ash})}}{\frac{(\text{Coal Feed} * \% \text{Carbon})}{(\text{Coal Feed} * \% \text{Ash} + \text{Lime Feed} * \% \text{Ash})}} \right) * 100 \\ &= \left(1 - \left[\frac{(\text{Fly ash} * \% \text{Carbon}) (\text{Coal Feed} * \% \text{Ash}_{\text{coal}} + \text{Lime Feed} * \text{Ash}_{\text{lime}})}{[(\text{Fly ash} * \% \text{Ash}) (\text{Coal Feed} * \% \text{Carbon})]} \right] \right) * 100 \end{aligned}$$

The second of these methods was to compare the carbon-to-iron ratios using X-ray fluorescence. This method is preferred over the carbon-to-ash ratio, since particle sizes of the limestone and whether the feed system is below or above bed can severely affect the limestone content in the fly ash, and thus the combustion efficiency. One of the major drawbacks to analyzing the fly ash with the XRF method is that iron can easily escape our current filtration (pillow case) type collection system. The following equation is used for combustion efficiency:

$$\text{Combustion Efficiency} = \left(\frac{\frac{\text{Carbon}_{in}}{\text{Iron}_{in}} - \frac{\text{Carbon}_{out}}{\text{Iron}_{out}}}{\frac{\text{Carbon}_{in}}{\text{Iron}_{in}}} \right) * 100$$

Figure 10 demonstrates the correlation between bed temperature and combustion efficiency. Higher operating temperatures reflect the higher combustion efficiency, which is exactly what is expected from the literature.²⁰

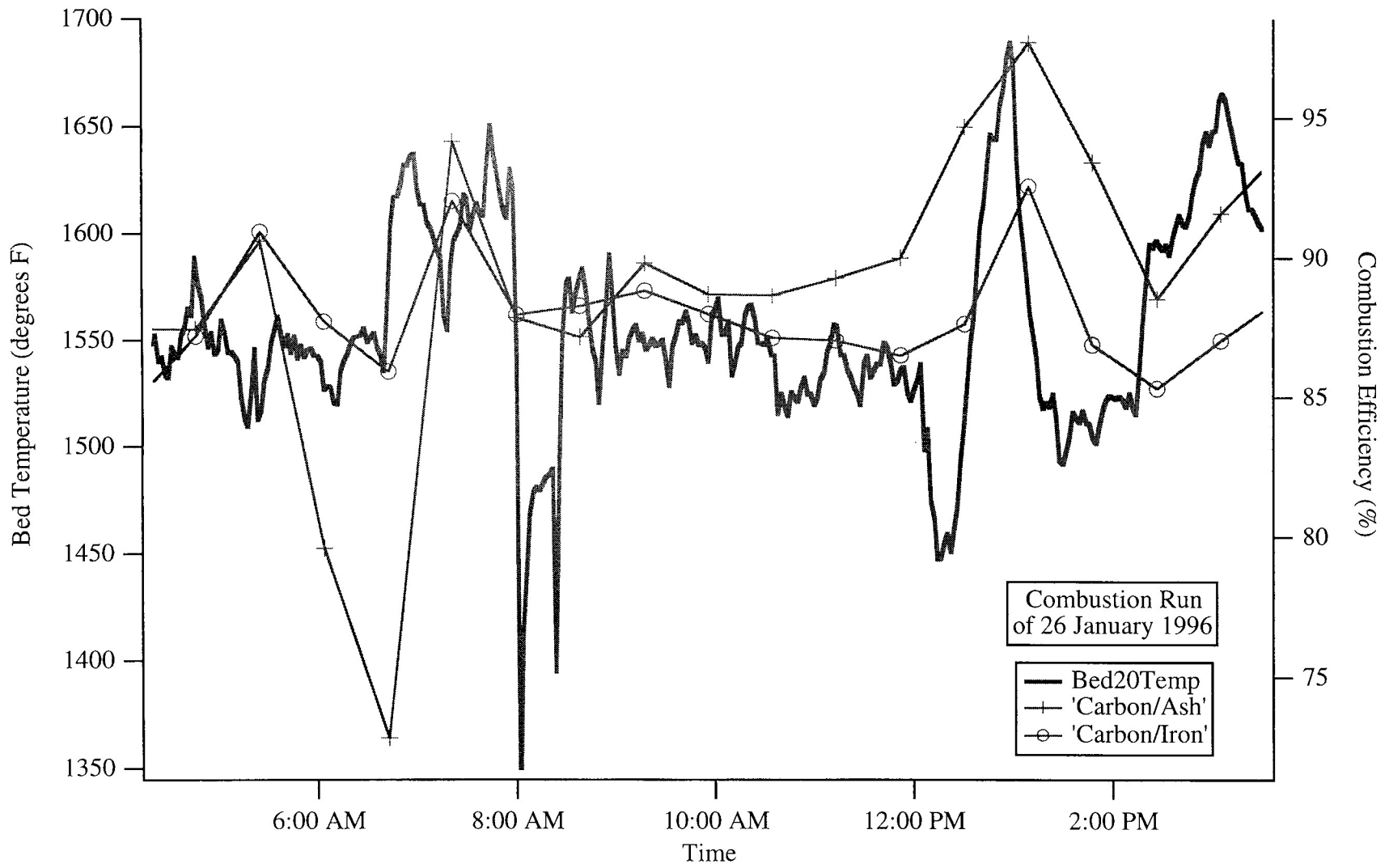


Figure 10. Graph of Bed Temperature and Combustion Efficiency

CO₂ concentration is a function of limestone feed (reduction of CaCO₃, which produces CO₂) and fuel/air ratio (combustion of carbon containing material). Factors that affect combustion efficiency would likewise affect the CO₂ concentration, which is exactly what was observed. Figure 11 demonstrates the correlation between CO₂ concentration and limestone feed and or bed height. During this particular experiment (26 January 1996) the coal and limestone feeds were held constant, while only the air flow rate was changed to maintain bed temperature. While part of the increase in CO₂ concentration is due to changes in the fuel/air ratio, a significant increase was due to differences in bed height.

Figure 12 displays the effect of operating temperature upon sulfur retention within the bed. When the temperature is too high, the formation of CaSO₄ is inhibited and the sulfur is emitted into the flue gas stream. Conversely, when the bed temperature is ideal, CaSO₄ is formed and sulfur is retained in the bed. From this figure and Figures 10 and 11, we can observe that increasing bed temperature will increase CO₂ concentration and combustion efficiency. However it will also decrease sulfur retention. Therefore, regardless of our short term goals, we must acknowledge that there is an upper operating limit for the AFBC process and that exceeding that limit will negate the whole purpose of using AFBC in the first place.

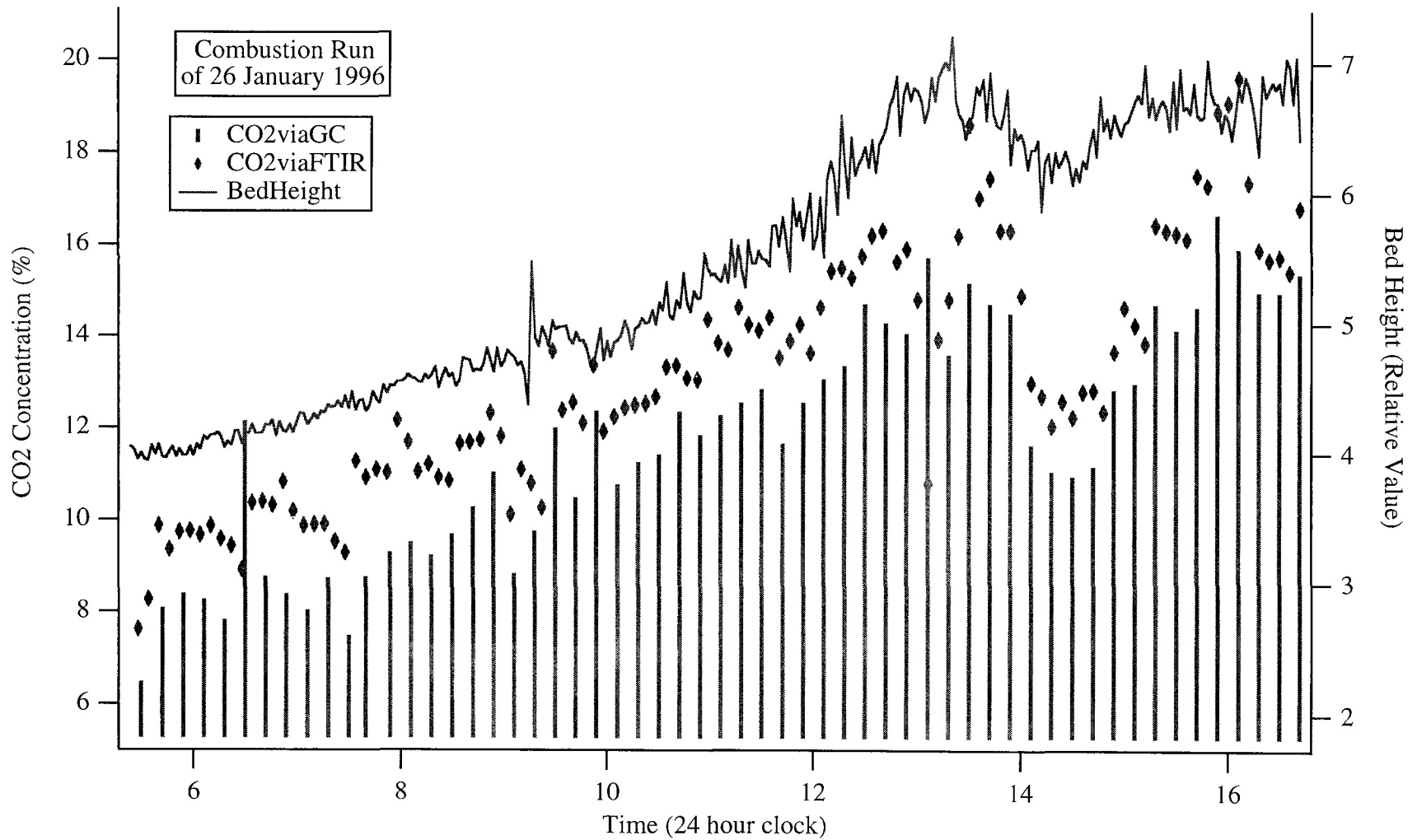


Figure 11. Graph of CO₂ Concentration and Bed Height

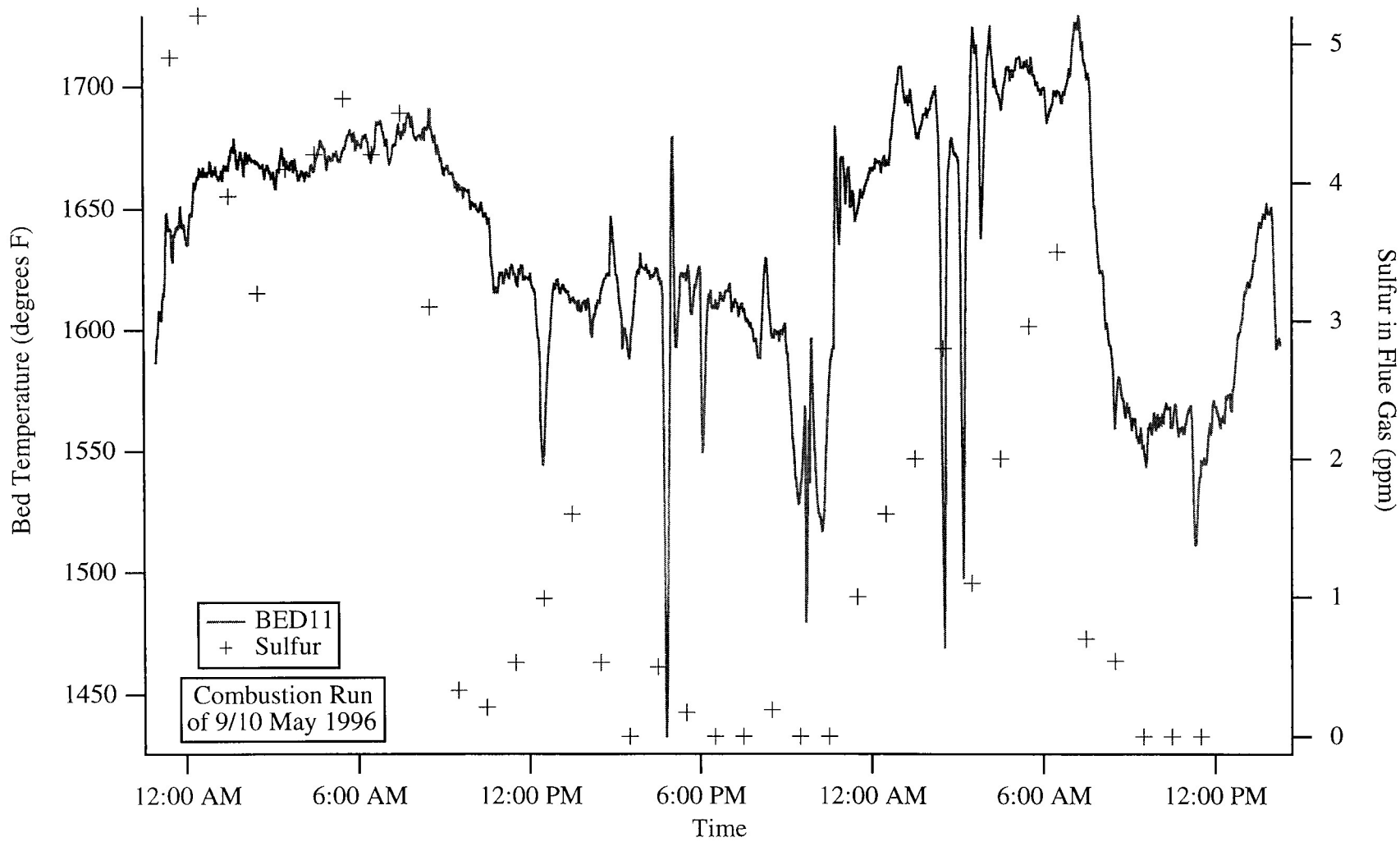


Figure 12. Graph of Bed Temperature and SO₂ Concentration

IV. CONCLUSIONS

Growing public concerns over acid rain and municipal solid waste problems have created an unusual environment, where the need for development of atmospheric fluidized bed combustion is near an all time high. The combustor developed by Western Kentucky University has demonstrated the ability to operate for extended periods of time and to produce results that are consistent and characteristic of world class research organizations. Projected opportunities using WKU's AFBC system offer strong possibilities of further utilization, with promise for improving the economic development of the Commonwealth of Kentucky as well as improving the quality of air and reducing the environmental hazards of coal fired power plants. AFBC techniques do, however, have operating limitations. Exceeding those parameters negates the whole purpose of using this method and the ideals for which it was developed.

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