COMBUSTION CHARACTERIZATION OF COAL-WATER SLURRY FUEL PREPARED FROM PLANT COAL AND RECOVERED COAL FINES

FINAL REPORT

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EXECUTIVE SUMMARY

In process of coal cleaning operations, a significant amount of coal is washed away as waste into the ponds. Clearly, such a large quantity of dumped coal fines has a detrimental effect on the environment. This investigation presents an innovative approach to recover and utilize waste coal fines from the preparation plant effluent streams and tailing ponds. Due to the large moisture content of the recovered coal fines, this study is focused on the utilization of coal fines in the coal-water slurry fuel (CWSF). The CWSF consists of 53.3 percent weight solids with a viscosity of less than 500 centipoise and 80-90% of solids passing 200 mesh. The 53.3 percent weight solids constitute a blend of 15% effluent recovered coal fines and 85% clean coal. It is our premise that a blend of plant coal and recovered waste coal fines can be used to produce a coal-water slurry fuel with the desired combustion characteristics required by the industry. In order to evaluate these characteristics the coal-water slurry fuel is fired in a test furnace at three firing rates (834,330 Btu/hr, 669,488 Btu/hr and 508,215 Btu/hr) with three different burner settings for each firing rate.

Combustion tests were conducted to determine the range of secondary air swirl required to maintain a stable combustion flame. Results obtained during the flame stability testing show no significant effect of swirl settings on Nox, SO2 and CO2 for three combustion tests (834, 330 Btu/hr, 669, 488 Btu/hr, 508, 215 Btu/hr). At each of the two higher firing rates, combustion was relatively complete regardless of swirl settings, therefore, burner setttings may be adjusted to provide a visually stable flame without concern for higher carbon in ash as a function of burner settings. The parameters affecting flame stability are mainly coal particle size, volatile matter, ash content and excess air. Tests conducted at three different locations (Top, Middle, Bottom) revealed that the gaseous concentrations such as Nox, SO2 and CO2 were a function of residence time for each of the firing rates. Effect of swirl settings on Nox for three firing rates were investigated. It was found that the variation of Nox concentrations with respect to the change in swirl numbers was significant. But, the variation of Nox Concentration with respect to firing rates was found to be consistent with the increase in firing rates. The flame stability was accessed by the visual observation of the flame with relation to the burner quarl.

X-ray fluorescence analyzer was used to analyze plant coal, recovered coal fines, slurry fuel and fly ash for major mineral oxides (SiO2, Al2O3, Fe2O3, SiO2 P2O5, CaO, MgO, Na2O and K_2O). Then, they were evaluated for elemental concentrations based on sulfur free and ash basis. The analysis indicated that silicon, aluminum and iron concentrate were found to be the most dominating elements. In essence, silicon had the highest concentration with the level of 50.9, 56.5, 50.1 and 51.1 (sulfur free basis) and 49.9, 54.6, 49.2 and 51.1 (ash basis) for plant coal, recovered coal fines, slurry fuel and fly ash respectively. A cyclone located at the end of the combustion run (EOR) was used to collect the bulk fly ash particles. The fly ash, slurry fuel and its feedstocks were analyzed for particle size distribution via Malvern laser diffraction analyzer. The fly ash particle size distribution revealed that 90% of particles by weight had a size less than 30 microns. The majority of particles by weight were found to be in the range of 15-20 microns.

The maximum percentage of the particles by weight, was found to be in the size range of 36 to 88 microns, 3 to 27 microns and 9 to 77 microns for plant coal, recovered coal fines and coal-water slurry respectively.

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Acronyms

AR	As-Received
ASTM	American Society for Testing Materials
ASME	American Society of Mechanical Engineers
Btu	British Thermal Unit
CTF	Combustion Test Facility
CWF	Coal-Water Fuel
CWS	Coal-Water Slurry
CWSF	Coal-Water Slurry Fuel
DOE	Department of Energy
EERC	Energy & Environmental Research Center
EPA	Environmental Protection Agency
ESP	Electrostatic Precipitator
FEGT	Furnace Exit GAS Temperature
HVT	High Velocity Thermocouple
IPRF	International Flame Research Foundation
PPM	Parts Per Million
XRD	X-ray Diffraction
XRF	X-ray Fluorescence

CHAPTER I

1.0 INTRODUCTION

Coal has been the most abundant and principal source of fuel and energy for years. Coal accounts for 31%, oil 38%, natural gas 20%, nuclear energy 4.5%, and hydroelectric energy 6.5% of the worlds energy supplies[1]. The use of coal has increased by several orders in magnitude, over years due to the growing demand of electric energy in several areas. Although coal is the least expensive and most abundant fuel, it has its own drawbacks such as storage and handling problems. The gaseous emissions emitted from the combustion of coal are the major air pollutants. As a result of advanced mining and coal preparation techniques, in addition to the abundance and low cost, large quantities of waste coal fines are disposed off into ponds. These coal fines pose a serious threat to the environment and human life. It is approximated that, about 3 billion standard tons of coal fines are rejected every year as waste during the coal cleaning process in the United States. An estimate by U.S. bureau of mines indicates, 174,000 acres of waste coal refuse disposal remain unreclaimed [2]. Many methods have been developed to recover coal fines from the effluent ponds. These recovered coal fines contain a large amount of moisture. Inspite of thorough dewatering process, the moisture content could be as high as 20-25% [3]. Due to this high percentage moisture, it is economical and advantageous to use these fines in the form of slurry fuel.

Coal-water slurry fuel is typically a mixture of coal and water containing approximately about 70% coal and 30% water by weight. Coal-water fuel is a potential clean alternative fuel due to the ease of transportation, storage, environmentally clean and can be burned in existing oil fired furnaces with minor modifications. Coal-water slurry fuel can be used in a wide variety of applications such as utility boilers, residential and small industrial furnaces. As coal being a major constituent in the coal-water slurry fuel, utilization of recovered coal fines in addition to the plant coal fines in the form of slurry can cause a substantial reduction in price, ease in transportation and help in the environmental clean up. Therefore an innovative approach is considered where 15 percent of the recovered coal fines are blended with 85 percent of the plant coal fines from the handling plants to prepare the coal-water slurry fuel with a viscosity less than 500cp. The recovered coal fines are expected to have different combustion characteristics due to its different chemical composition, oxidation level, particle size distribution and moisture content. The slurry fuel prepared from these fines will have unique combustion characteristics as well. Therefore experiments are performed at three different firing rates to study the various combustion characteristics of coal-water slurry fuel prepared from recovered coal fines.

1.1 GENERAL BACKGROUND

The United States consumes approximately 18 million barrels of petroleum a day, hence, domestic supplies of oil and natural gas are rapidly depleting [4]. The Annual Energy Outlook 1997 (AEO97) projects an increase in oil consumption whereas the oil prices will remain stable. In fact, AEO97 has projected that the wellhead prices for crude oil in the lower 48 States will fall by 0.8 percent a year in the low world oil price and to increase by 1.2 and 2.8 percent a year in the reference and high price cases. It also has been forecasted that the total petroleum product supplied ranges from 20.6 million on a low economic growth scenario and 23.6 million barrels a day of consumption for a high growth scenario, with the most recent consumption of 1995 at 17.7 million barrels a day [4]. AEO97 has determined that petroleum constitutes just under 40 percent of the United States' primary source of consumption.

According to AEO97, total coal production increased from 613 million tons (14.6 quadrillion Btu) in 1970 to 1,033 million tons (22.0 quadrillion Btu) in 1995. In fact, it has been projected by 2015 coal production will reach 1,268 million tons (26.5 quadrillion Btu) [4]. With the majority of this production to come from western mines, where their output has grown 10 percent a year from 45 million tons in 1970 to 489 million tons in 1995.

As a result, the current energy situation is a major national concern. Since these major sources of energy (crude oil and natural gas) are decreasing, alternative sources of energy have been explored, such as nuclear, fusion, solar, thermal, wind and fossil energy. Nuclear and fusion energy are still in the developmental stages and research expenditures are costly. Cost effective and environmentally safe energy sources are consistently being sought. Fossil fuels made out of coal are seriously being considered as the resource to meet the energy needs of the nation in the next century and to meet the continued need of energy with the continuous depletion of natural gas and oil.

1.1.1 Coal Reserves

Coal is located across the United States, thus, the most abundant source of bituminous coal is found in the eastern part of the country; whereas sub-bituminous coal and lignite are located in the West. Lignite forms of coal are mostly found in North Dakota and Montana, though, Texas and South Dakota are known to have significant amounts. The largest sub-bituminous coal deposits are in Montana, Wyoming and Alaska, significant amounts are also found in New Mexico and Colorado [5]. Essentially, bituminous coal is widely distributed among states; however anthracite coal is basically restricted to Pennsylvania. In the United States, both tonnage and heating value of coal are ranked in decreasing order for bituminous, sub-bituminous, lignite and anthracite coals. All coals are subjected to various process preparations for their prospective markets (heating, utility power generation, etc.); however cleaning of steam coal for utility use has been confined to the bituminous type.

Since there are environmental concerns, coal cannot be directly burned due to its high content of sulfur. The direct combustion of coal will result in SO_X emissions exceeding the Environmental Protection Agency (EPA) standards. Congress passed an Air Quality Act of 1963 which initiated an effort to clean up the nation's air quality at local, state and federal governmental levels. In 1970 the EPA and the Clean Air Act Amendments followed suit with the continued consciousness of standards in the reduction of sulfur dioxide emissions [5].

The regulations of sulfur dioxide was an incentive to find sulfur removal processes for coal. The following techniques were implemented for sulfur dioxide reductions in coal technology usage:

- flue gas desulfurization - removal of SO_2 from coal combustion gas
- physical coal cleaning - removal of pyritic sulfur from the coal prior to combustion
- chemical coal cleaning - removal of pyritic and organic sulfur from coal prior to combustion
- synthetic fuel production - conversion of coal into clean burning gaseous or liquid fuels
- fluidized bed combustion (burning coal in the presence of additives which remove sulfur as a mineral residue) [5].

1.1.2 Coal Cleaning

Washability of coal is a series of tests that determine the potential for improvement done to the quality of coal through physical coal cleaning. In order to determine the preparation methods and equipment needed to clean the coal, the preparation engineer must conduct physical and chemical tests to determine the washability data. The coal is divided into small samples by size, specific gravity, and distribution. They are then analyzed for moisture, ash, heating value, pyritic and total sulfur among other characteristics [5].

Washability data published by the U.S. Bureau of mines in R1 8118 reflects that, specific gravity separation are used frequently for the removal of ash from coal which can eliminate 25-55% of pyrite from U.S. coals. However, more advanced physical coal techniques may be able to remove 90% of the pyritic sulfur in coals. The amount of sulfur removal depends on the initial sulfur in raw coal, the ratio of pyritic sulfur to organic sulfur, the size distribution of the pyrite in the coal and the preparation methods used. When specific gravity separation methods are used, the desulfurization potential of the United States coals varies according to the coal regions and among coal beds within the same region [5].

It should be noted that coal cleaning is not one particular method or process but several of different operations that may be used sequentially or alternatively in various situations. A basic coal cleaning plant is designed on the basic properties of raw coal and a set of industry specifications for the clean coal product. Coal cleaning is a basic name for processes that remove inorganic and some organic impurities from coal. However, it does not alter the chemical nature of the coal itself. In short, a coal cleaning plant is a continuous process of technologies instead of one distinct process.

1.1.3 Coal Beneficiation

Coal beneficiation is a basic term that describes operations involved with the performed run-of-mine (ROM) coal to prepare it for specific end uses, such as feed to a coke oven, a coal-fired boiler or use in a coal conversion process. It is also referred to as coal preparation or coal cleaning. Essentially coal beneficiation is the entire range of operations that covers simple crushing, size classification operations to extensive chemical and micro-biological processes to render the ROM coal more suitable for end use [6].

Beneficiation provides significant means of reduction of sulfur and mineral content of several coals. Thus, providing a plausible and economic solution to the problem of burning high sulfur coals in an environmental conscious manner. Hence, the beneficiation of coal results in the following:

- lower transportation costs per unit of energy delivered,
- lower waste disposal costs at the user facility,
- improved coal handling capabilities,

- higher combustion efficiency in the furnace, as well as, reduced slagging in the furnace, which turns into reduced downtime for the furnace

Coal cleaning, drastically, reduces the amount of sulfur, sand, silicates and other materials in the coal which are harmful in the production and utilization of coal products. It also removes undesirable materials and improves the combustion efficiency. There are two types of cleaning processes used for the removal of sulfur and other materials from coal; one, physical coal cleaning (PCC) and two, chemical coal cleaning (CCC) [6].

Technologies became more advanced as a result of the strict guidelines set by EPA for the removal of sulfur at power plants. Therefore, new technological and what deemed uneconomical was explored as possible processes for sulfur removal.

In comparison to PCC, CCC has not had as long as a history in regards to its development in technology. Most CCC processes have been developed past bench scale [7]. Listed below are some of the CCC processes and their developers in parenthesis:

- Nitrogen oxides oxidation (KVB)
- Ferric sulfate oxidation (TRW)
- Oxygen oxidation (Kennecott)
- Air oxidation (Department of Energy)
- Chlorine oxidation (Jet Propulsion Laboratory)
- Hydrothermal (Batelle)
- Alkaline oxidation (Iowa State)
- Microwave (General Electric)
- Bacterial (Jet Propulsion Laboratory, Ohio State, and others)

There are many physical coal cleaning plants that can handle over 360 million metric tons of raw coal a year. The principal coal cleaning process used in the 1980's was oriented toward product standardization and ash reduction, with an increased concern toward sulfur reduction [6].

The methods of sulfur removal varies commercially and according to types of sulfur in the coal sample. PCC removes the pyritic sulfur and ash materials that have been practiced in the United States since 1890. These early operations consisted of belt washers, bumping tables, and other precursors to modern processes that were adapted from ore beneficiation practices to coal cleaning. The baum coal-washing machine was used for alternatively flooding and draining, a moving bed of coal was in commercial use in Europe before 1900, and was introduced to the States in 1928. Most methods that were used were gravity separation, in which "pure" coal has a lower specific gravity than the pyrite of the ash materials [8].

Within the last quarter of this century significant improvements have been made in the equipment used to clean coal. The leading method for cleaning is still based on gravity separation. As well, other processes use pre-treatment followed by physical separation. One example is chemical comminution followed by a physical sink-float separation of chemical pre-treatment with iron carbonyl followed by magnetic separation. CCC is a technology that is on the leading edge, more development will be required to lower the utilization costs and removal of sulfur with more accuracy [8].

1.1.4 Sulfur Types

It is important to clean coal prior to preparation and usage because of the strict emission standards that are set by the Environmental Protection Agency (EPA). Reduction of sulfur by physical cleaning techniques varies according to the distribution of the sulfur forms in the coal. Three general forms of sulfur are found in coal: organic, pyritic and sulfate sulfur. Organic sulfur is bonded chemically to the organic carbon of the coal and is only removed once the chemical bonds are broken. The amount of organic sulfur present designates the lowest limit which a coal can be cleaned with respect to sulfur removal by physical methods [9].

Mineral sulfur occurs in two forms, pyrite or marcasite; which are two dimorphous forms of ferrous disulfide, FeS_2. Pyrite and marcasite may have the same chemical composition, but each has its own unique crystalline form. Sulfide sulfur occurs in particles sizes 0.1 micron to 25 cm in diameter throughout the coal matrix. Pyrite is a dense mineral (4.5 g/cm^3) in comparison with bituminous coal (1.30 g/cm^3) and is water-insoluble; therefore, the best removal is by means of specific gravity separation [9].

Sulfate sulfur is usually present in the smallest amount, roughly around 0.1% or less by weight. It is usually water soluble, originates from in situ pyrite oxidation and may be removed by washing coal, i.e., physical cleaning [9].

There are many processes for chemical coal cleaning that are still under construction. Chemical cleaning is designed to remove up to 40% of organic sulfur, whereas physical cleaning removes about 50% of the pyrite sulfur. The actual removal depends on the washability of the coal, the unit processes used and the separating density [10].

Emissions regulations must be taken into serious consideration because the composition and properties of coal can vary widely even within a coal seam. In general, the sulfur content in coal varies; the average value for sulfur in coal can be used to determine how much sulfur must be removed to stay in compliance with a particular standard if long term averaging of the resultant SO_2 emission is allowed [10]. Overall coal cleaning plants employ the same philosophy; stepwise separations and beneficiation. The goal of all cleaning plants is the same, to treat (cleaning physically and or chemically) small, piece wise fractions of the incoming coal, and feed [10].

1.2 HISTORY AND DEVELOPMENT OF COAL-WATER FUEL

Coal-water slurries were originally intended to transport the coal and then dewatered for regular use. Due to some of the technology advancement in the field of particle size distribution effect and addition of chemical additives in the coal-water fuel, led to produce a stable highly loaded coal mixture with low viscosity. The first documented use of coal-water slurry dates back to 1891 when Wallace C. Andrews patented the concept and operated a test facility for the transport of coal [11]. The major advancements in slurry technology was in the late 1970's. Prior to that, Germany and USSR were the only countries where coal-water fuel combustion was active. Since 1970's research in the coal-water slurry combustion technology has been progressing rapidly and it is in a position where it can be fully commercialized.

The major developments in CWF combustion technology before 1970 has been reported by Marnell[12] and are listed in the Table 1.1. This table lists all the details regarding the type of fuel, water percentages, application, steam rate and plant location. Among the eight combustion tests listed six of them were performed in USSR and one each in Germany and USA.

From 1979 to 1985 some of the major CWM combustion trails done on the utility and industrial boilers in Japan, Spain, Sweden, United Kingdom and United States are presented by Daniel Beinstock and Oliver K. Foo[13]. Table 1.2. lists the details of test furnaces, test period, organization and the country where it was performed.

Table 1.1 Major Coal-Water Combustion Experiments up to 1970[5].

Fuel Type	%Water	Slurry Flow, Metric Ton/hr	Application	Steam Rate, Metric Ton/hr	Location
Coal beneficiation wastes	50	40	Power plant boiler	170	USSR
Coal beneficiation wastes	45	8	LMZ boiler	40	USSR
Coal beneficiation wastes	45	1.5	Spray above stoker fired LMZ boiler	0.6	USSR
Wet Coal	15-50	2	DKV Boiler	---	USSR
Coal-Water Mixture	40	2	Horizontal cyclone	---	USSR
Coal waste	40	1	Cyclone	---	USSR
Coal-Water Mixture	30	29	Twin cyclone boiler	220	USA
Coal-Water Mixture	40	20	Pulverized coal boiler	100	Germany

A review of industrial and utility-scale coal water fuel fired, demonstration projects was compiled by V. Rathi, M. Ramezan and J. winslow[11]. This report presents the history and development of the coal-water mixture fuel as demostrated by various authors from time to time.

Table 1.2 Some of the major CWM combustion trails done on the utility and industrial boilers from 1979 to 1985 [13].

Country	Organization	Test Furnace	Test Period
Japan	Babcock Hitachi K.K	80 x 10^6 Btu/hr test furnace	1982
	Electric Power Development Co. Ltd.	1.3-MW Btu/hr cylindrical test furnace	1982
Spain	UNSEA	4-MW test furnace	1983-1985
Sweden	AB Carbogel	Various prototype burners with capacities upto 3.5-MW have been tested	1979
United States	Atlantic Research	1.3 x 10^6 Btu/hr furnace at ARC, and 4.0 x 10^6 Btu/hr test furnace at Babcock & Wilcox Alliance Research Center	1979
	Slurry Tech, Inc.	4.0 x 10^6 Btu/hr test furnace at Babcock & Wilcox Alliance Research Center	1980
	Gulf & Western Industries, Inc.	80 x 10^6 Btu/hr test furnace at Combustion Engineering, Inc. 70 x 10^6 Btu/hr test furnace at Forney Eng. Co.	1982
United Kingdom	NEI International Combustion, Ltd.	5 x 10^6 Btu/hr test furnace	1982-1983

1.3 GENERATION OF WASTE COAL FINES

In the early years, due to the lack of advanced technology in the areas of mining, cleaning process and less environmental restrictions on the waste disposal resulted in large number of slurry ponds. A large quantity of coal which contains high percentage of coal content was rejected as waste and thus refuse piles were formed. These piles are very large in size and vary over a range of two hundred thousand to ten million tons[2]. After the advent of mechanical mining methods and advanced coal preparation method, large quantities of coal refuse was rejected to ponds and gob piles.

Figure1.1 shows the processing of the coal and how the waste coal fines are dumped into the waste land forming slurry ponds.

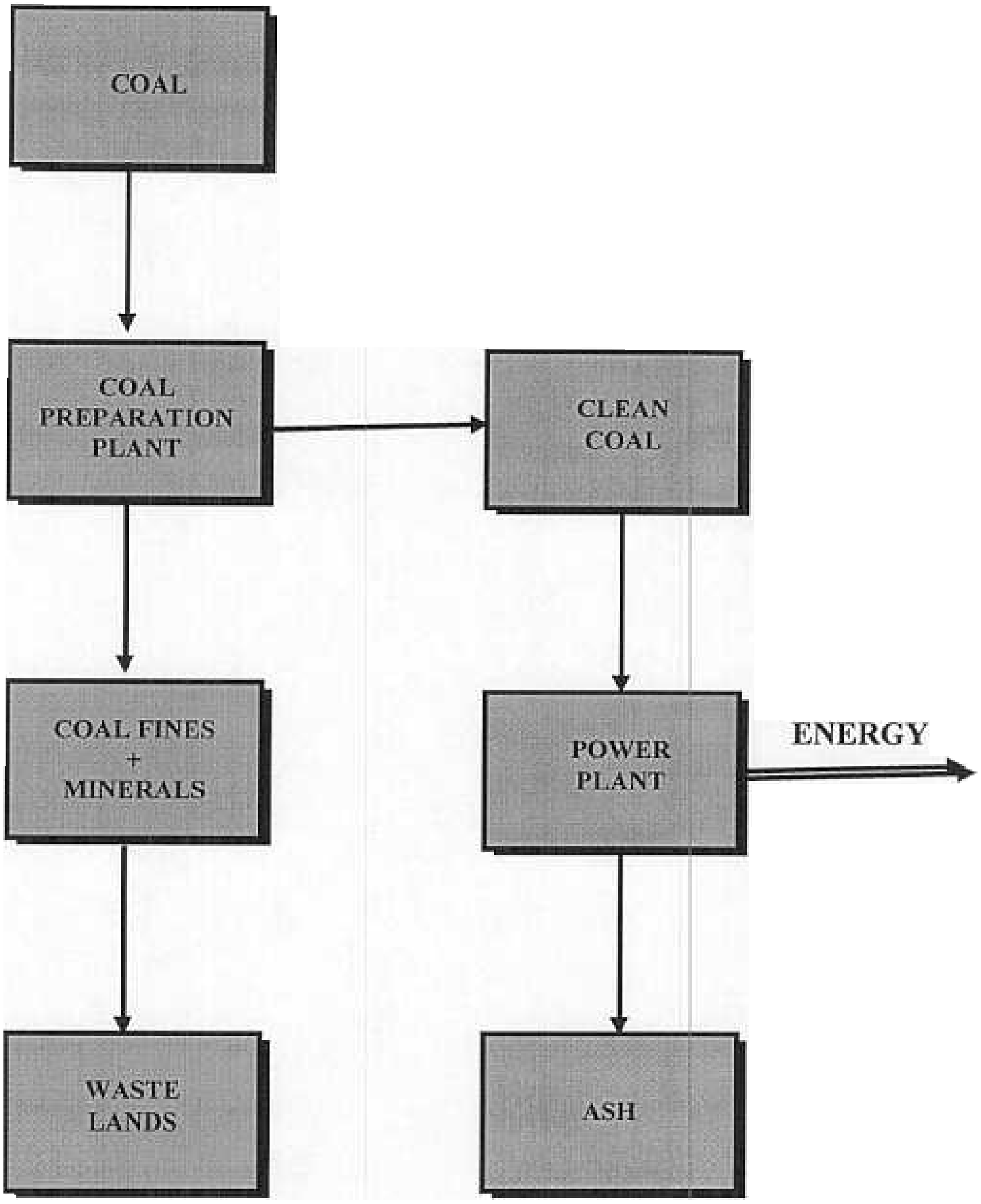


Figure 1.1 Coal preparation process

It is estimated that there are approximately 28,000 gob piles throughout the United States. According to the recent estimates, nearly 30% of the material from underground coal mining in U.S. is rejected on the surface as waste. This amount of almost (3 billion standard tons) of coarse and fine coal refuse is produced from the coal cleaning operations[14].

1.4 ENVIRONMENTAL PROBLEMS ASSOCIATED WITH THE WASTE COAL FINES

Disposal of mineral waste causes a very serious threat to the environment and human health. One of the most influential factor being the ground water pollution which effects the human life residing near these slurry ponds. The value of the land is depreciated greatly. In addition to ground water pollution the other environmental problems associated are acid formation, erosion and sedimental control. As refuse piles are easy to ignite, they cause air pollution by emitting the polluting gases such as nitrogen oxides and sulfur dioxides.

1.5 PROCESSING OF COAL FINES

The main objective in the processing of coal fines is to produce clean coal with high percentage of Btu, low sulfur and mineral matter with excellent combustion characteristics. As large amounts of coal require crushing, sizing and washing in order to remove the sulfur and mineral matter the coal fines produced during this process are disposed off as refuse due to the difficulty in transportation and storage. Hence the major sources of coal fines are from the refuse ponds and preparation plants. It is estimated by the Illinois Clean Coal Institute (ICCI) that the coal cleaning method developed by them could save $10 million in fine coal at an average coal preparation plant each year. The basic principle of physical cleaning is the utilization of relative density difference between the coal particles and other material suspended in some aqueous solution.

Some of the common physical coal cleaning processes listed by (Morrison,1982) are gravity separation technique, froth flotation, oil agglomeration, magnetic separation, electrostatic separation and column flotation. Selection of coal cleaning technology is influenced by the characteristics of coal such as ash content, surface chemistry and use of coal-water mixture. The most effective process would be the one by which high percentage of clean coal can be recovered with a minimum of sulfur and ash.

1.5.1 Oil-Agglomeration

In this process coal is cleaned by an addition of oil-based liquid to the suspension of the coal particles used to separate the clean coal [15]. The agglomerates of coal are removed by screening or flotation. It's been observed that the agitation of the mixture enhances the detachment of the mineral matter. This process is very efficient in handling extremely fine materials in the -200 mesh range and materials with considerable amounts of clay slime [16]. This process is more effective in ash reduction than sulfur reduction.

1.5.2 Froth Flotation

Froth flotation is a process used to separate minerals, suspended in liquids, by attaching them to the gas bubbles to provide selective levitation of the solid particles[17]. These bubbles get attached to the hydrophobias coal particles and cause them to float to the surfaces where they are collected. This process has been in use for long period and is extensively used in iron ores, coal , limestone, copper and many other minerals of similar chemical nature. Numerous modifications are done on this method over a period of time and in the process, one of the most promising technique known as column flotation was developed.

The major difference between the conventional flotation process and column froths is the addition of wash water at the top of the column and elimination of agitation mechanism hence saving on energy and maintenance costs[17]. An innovative method of adding a packing in the column is done by Michigan Technological University known as (MTU) static tube process is one of the most advanced physical froth flotation process for cleaning coal fines and is recognized as one of the leading technology recognized by the U.S. Department of energy based on the comparison of the interlaboratory comparison.

V. Choudhry et.al[18] conducted number of tests to recover a low-ash, low sulfur coal from preparation plant effluents using a packed column and to study its feasibility. This work was funded by the Illinois clean coal institute. This study included the effect of feed rate, pulp density, reagent dosage and the effect of machine variables such as pulp level in column, air and waste water rate. It has been found that high Btu can be recovered about 80-85% and the elimination of pyritic sulfur being 80% and the ash content reduced from 55-60% ash to 6-10%. Increase in wash water increased the overall performance and optimal pulp level was found to be 25cm below the feed entry point. The optimal air flow rate was found to be at 25 to 35 in/min.

1.5.3 Electrostatic Separation

The difference in conductivity or dielectric properties of coal and minerals, to maintain or dissipate an induced charge under dynamic conditions is utlilized in the electrostatic separation [16]. When coal is fed into the electrically ground rotor, the coal-rich dielectric particles remain attached to the rotor and can be removed later.

1.6 PREPARATION OF COAL-WATER SLURRY FUELS

The properties of coal has a significant effect on the characteristics of the coal-water slurry fuel. Important aspect in the preparation of the Coal-water slurry is to maximize the coal content of mixture. Particle size and viscosity play an important role in maximizing the coal content of the mixture. A decrease in particle size increases the surface area available for reaction and hence increases the rate of char burnout[1]. A minimum of 25% volatile matter(on dry basis) is preferred in the coals used for CWSF.

The rheological properties of CWS play a vital role in their storage, transportation, atomization and combustion. The fundamental understanding of the preparation and handling of the highly loaded CWS with low viscosity, desirable atomization and combustion properties are necessary in the commercialization of the CWS[3]. Solid concentration and the particle size are the two important hydraulic variables. Due to the variability in the characteristics such as the particle size distribution, shape of the particles, concentration of solids, surface chemistry of particles and dispersant used to stabilize the suspensions, the governing parameters have to be determined experimentally [12,13].

The value of volatile matter content is used as an indication of coal classification and ignitability and in general, high volatile matter content(approx. 30% or above) is desirable in coal firing as it enhances fuel ignition and flame stability[15].

The erosion of the boiler tubes is a function of the ash composition and ash content in the slurry fuel. several investigations (Borio, et al) have indicated that the potential for boiler pressure part erosion could be a significant load limiting factor, and would adversely affect the economics of CWF conversion in some case. Some of the significant properties for consideration in the preparation of coal-water fuel are listed below in Table 1.3.

Table 1.3 Significant properties of coal-water fuel [19].

Coal characteristic	Impact on CWM	Desired range[a]
Energy content	High energy content lowers handling and storage costs	13,000-15,000Btu/lb
Volatile content	Volatiles improve ignition and combustion	30% or higher
Ash content	High ash concentrations increase particulate emissions, combustor derating, and coal leaning costs	55% or lower
Ash chemistry	corrosive ash with low softening temperatures can cause combustor slagging or fouling and need for derating	Noncorrosive, low in sodium, high softening temperature
Sulfur content	High sulfur content increases SO_2 emissions and sulfur removal costs	1% or lower
Organic sulfur content	Organic sulfur can not be removed by physical cleaning	Low enough to ensure 1% total sulfur in CWMs
Surface chemistry	Governs the effectiveness and cost of additives and influence the choice of coal cleaning method	

[a]Range for clean dry coal before mixing with water. CWMs are limited to coals with characteristics within the ranges shown.

1.7 COMBUSTION MECHANISM OF COAL-WATER SLURRY

Combustion of the coal-water slurry is a complex mechanism and hence a number of studies have been performed over a wide range specifically on the single droplet and spray techniques in order to understand the different stages in the combustion of coal-water slurry.

A detailed description of the various stages in the combustion mechanism of the coal-water fuel droplet combustion as studied in a laminar flow reactor by two different experimental procedures is presented by Shun-won kang[20] as follows:

- Injection of the CWF droplet
- Drying of the CWF droplet

- Agglomeration and swelling during the coal plasticity period
- Localized ignition followed by the spread of ignition
- Volatile flame formation
- Rotation induced by volatile evolution
- Extinction of volatile flame and ignition of char
- Fragmentation both during devolatilization and char burnout
- Ash shedding and completion of char burnout

The major difference in the combustion of coal-water slurry and pulverized coal is the presence of water. The addition of water to the coal causes an ignition delay due to the evaporation phase. As the droplet size increases the combustion time increases and the flame temperature is low due to the presence of moisture. To increase the burning rates of the droplet coals having high volatile matter content is used. In order to overcome the large size of the droplet, very fine droplets are to be injected using an injector.

1.8 GASEOUS EMISSIONS

The future of the coal utilization depends totally on the global environmental concerns. The combustion of coal causes a number of gaseous emissions to be emitted into the atmosphere which are harmful to the environment. The major air pollutants being particulate and the oxides of nitrogen, sulfur, and carbon. Coal fired utility boilers account for about 65% of SO_x and 29% of NO_x emissions in United States. These emissions effect the environment by contributing to acid rain and green house effect. Therefore the control of these pollutants from entering into the atmosphere is very important for the future utilization of coal in any application.

1.8.1 Nitrogen Oxides Emissions

Nitrogen oxides are formed by the oxidation of nitrogen present in the organic coal structure. The nitrogen oxides basically is a combination of NO and NO_2, usually known as NO_x. The Nitrogen oxides when combined with oxygen and water produce acidic products, thereby contributing to the formation of acid rain[21].

$2N + O_2 \rightarrow 2NO$

$NO + H_2O \rightarrow HNO_2$

$2NO + O2 \rightarrow 2NO_2$

$NO_2 + H_2O \rightarrow HNO_3$

NO_x are produced by two primary mechanisms during the combustion . They are thermal NO and fuel NO, depending on the source from where the nitrogen is supplied. Thermal NO is the NOx formed during the reaction between oxygen and nitrogen in combustion envirinment at high temperatures. NO_x formed by the thermal NO is a function of N_2 and O_2 concentrations, temperature and time of exposure N_2 to O_2 at high temperatures(Laflesh, et.al. (1985)).

Fuel NO refers to the NO_x formed from organically bound fuel nitrogen. From the previous studies it has been observed that the NO_x formed by this process is independent of the temperature. The availability of oxygen is a major factor affecting the fuel bound nitrogen to NO_x. Due to the presence of nitrogen usually in the amount of .5 to 2% by weight in coal fuel NO is a major contributor of NO_x.

Reaction of nitrogen gases in the atmosphere have a several diverse environmental effects including the production of photochemical smog, contribution to the destruction of the ozone layer and green house effect.

1.8.2 Sulfur Dioxide Emissions

Sulfur dioxide is another harmful pollutant also contributes for the acid rain formation is produced by the oxidation of organic sulfur present in the coal [21]:

$S_{coal} + O_2 \rightarrow SO_2$

Sulfur dioxide when reacts with oxygen and water in atmosphere to produce sulfuric acid and contributes to the acid rain.

$2SO_2 + O_2 \rightarrow 2SO_3$

$SO_3 + H_2O \rightarrow H_2SO_4$

The sulfur basically exists as organic and inorganic sulfur. Organic coal is chemically bound to the hydrocarbon matrix of the coal while inorganic sulfur is mainly in the form of loose pyrite. The total sulfur content in U.S. coals range from 0.2% to 10% by weight, while majority in the range of 1.0 to 4.0 percent[22]. The organic sulfur content is usually below 2% while pyritic sulfur occurs in a wide range. The introduction of stringent emission restrictions has forced the coal-fired units to use various control techniques.

1.8.3 Carbon Dioxide Emissions

Carbon dioxide emitted from the coal combustion adds to the problem of green house effect. Carbon reacts with oxygen to produce either carbon monoxide or carbon dioxide. The only option of reducing the global CO_2 is by improving the efficiency of the power generation from the heat of combustion of fossil fuels. The carbon dioxides emissions from coal firing result in two to three times higher than the carbon dioxide emissions from natural gas fired plants. Carbon monoxide emissions in general are very low.

CHAPTER II

2.0 LITERATURE REVIEW

Number of oil fired facilities of various capacities were converted to fire coal-water slurry fuel. In order to maintain a stable flame and to keep the NO_x, SO_x and CO_2 emission below the standards set by EPA (Environmental Protection Agency), various changes in burner, atomizer and emission control equipment's were made. Some of the experiences, modifications and test results of previously performed work obtained from the literature are presented. The main emphasis being on the gaseous emissions of the test data.

Michael J. Rini, Patrick L. Jennings and Jon. G. McGowan [23] presented a development of an High Efficiency Advanced Coal Combustor (HEACC) for firing benificated coal fuels in industrial retrofit application. It was observed that the swirler diameter and type were the main parameters affecting the burner aerodynamics. The burner developed was able to maintain a stable flame and had a potential to reduce the NO_x through internal staging. In order to evaluate the carbon conversion efficiency, NO_x and SO_x emissions, fly ash composition and particle size distribution pilot scale($5x10^6$ Btu/hr) combustion tests were performed. The results indicated a high carbon conversion efficiency, and the NO_x emissions were in the range of 600-700 ppm with overfire air. Preheating of fuel to 220°F improve the spray quality and hence a better flame stability was observed. Full scale testing was conducted considering coal-water fuels and second test utilized a fine grind, dry pulverized coal of 21 micron mean particle size. An efficiency greater than 98% was achieved while firing CWS at an excess air level of 30-35%. NO_x emissions were lowered to approximately 20-25% with a reduction of excess air level to 20-25%

but at the expense of combustion efficiency. An efficiency of 98 to 99.9% was achieved while firing dry pulverized coal and NO_x levels were lowered to 340 to 375 ppm.
Sarma V. Pisupati et. al[24] discussed the combustion performance of an industrial boiler firing Super Clean Coal-Water Slurry (SCCWS) prepared from cleaned coal with less than 4.0 wt% ash and 1wt% sulfur for 500 hours. A decrease in temperature of about 127 °F at the center of the furnace was noticed when compared to firing natural gas alone. At the side wall of the boiler a reduction of 600 °F was reported as compared to firing natural gas which implies the concentration of combustion gases only in the central axis in case of slurry fuel combustion. Preheating the slurry and increasing the atomizing air from 148 to 190 psi did not have a significant effect on the combustion efficiency. With an increase in solids percentage from 59% to 62% the efficiency increased from 93.2% to 94.2%. Highest coal combustion efficiency was achieved at a spray angle of 65°. SO_2 emissions were in the range of 0.6 to 1.0 lb/MMBtu and NO_x emissions were in the range of 0.7 to 1.4 lb/MMBtu. A combustion efficiency of 95% was achieved by optimizing the operating parameters and making few minor modifications.

In order to compete with the fuel oil, G. Fynes et. al[25] emphasized on utilization of low cost coal fines. To achieve this goal high-ash waste fines from washery plants were utilized in the preparation of coal-water mixtures and the application limited to small capacity for feasibility. To disperse the organic and mineral matter components, an additive is added. 1 MW coal-water mixture burner is utilized and the flame characteristics, heat flux profiles and flame temperature distribution were studied under different firing conditions. In order to overcome the high viscosities formed due to the presence of high quality swelling clays a component dispersant has been used. The coal-water slurry fuel is fired in a 0.3 MW combustion test rig to produce a furnace exit gas temperature of approximately 1080 °C. The slurry fuel was fired at a fuel feed rate of 100 kg/hr at an excess air level of 25%. A stable flame was achieved with a combustion efficiency of 97.3% and a peak heat flux of 85Kw/m^2 was observed. From the results it is concluded that coal-water fuel prepared from the washery plant is stable, economical, clean and feasible.

To overcome the atomization and plugging problems of the atomizer tip as experienced in the ash fouling furnace at University of North Dakota Energy and Environmental Research Center (UNDEERC), Jay R. Gunderson et. al (1989)[26] considered a packed bed slurry combustor where atomization of the fuel was not needed. The main objective being, the utilization of coal-water slurry fuel for heating purposes, in residential and commercial applications. The air flow rate, packaging size and fuel density were identified as the major parameters affecting the maximum temperature attained and the rate of combustion. Addition of catalyst causes very few carbon monoxide emissions.

At Chatham Station 1 (12.5MWe) of the New Brunswick Electric Power Commission, Canada, FW/Forney CWF burner was used for the demonstration purpose[27]. 84% and 78% boiler efficiency was reported for oil fired and CWF fired furnaces respectively. At Chatam Station 2 (22.5MWe) ABB/CE burner system was used. carbon conversion efficiency in the range of 87-91% and boiler efficiency about 74-77% reported when firing CWF.

Ronald W. Breault and Anthony F. Litka[28] presented the development of an advanced CWF-fired combustor system for commercial-scale boiler and water heating applications to evaluate the economic and technical feasibility. An internal reactor with internal separation combustor is used for CWS combustion. At an heat input of 4 MMBtu a combustion efficiency of 99% was reported when firing without preheated air or fine atomization. To achieve a high carbon conversion efficiency centrifugal forces combined with staging is used. By dividing the combustion chamber into multiple zones by using partitions the axial flow of unburned coal particles over a certain size is retarded thereby causing increase in residence time and hence better carbon conversion. The particles passing through all the partitions are passed into the secondary combustion chamber where the char burnout is completed. Combustion test results of firing CWS at 1.25 to 5 MMBtu/hr indicate a combustion efficiency higher than 99% based on the baghouse ash carbon burnout. NO_x emissions were less than .38 lb/MMBtu and SO_x emissions were 1lb/MMBtu.

B. Mills et al[29] have presented the preparation and properties of Snamprogetti slurries of coal and petroleum coke. Also the combustion data obtained by firing dry pulverized coal, petroleum coke slurry and two other coal water slurries with different particle size are compared. The burner used was rated at 500 kg/hr of CWS. The results of carbon dioxide, oxygen, NO_x concentrations, temperature of flue gases and combustion air were recorded continuously and some of the comparisons are as listed below. The NO_x levels were 50-150 ppm, 100-200 ppm, 210-400 ppm, 250 ppm and CO2 levels were 500-800 ppm, 125-420 ppm, 85-180 ppm and 30-110 ppm for pulverized coal, CWS, CWS and petroleum coke slurry. Addition of extra refractory lining in the furnace represented excellent combustion efficiency and flame stability at 3:1 turndown without the use of support fuel. The combustion efficiencies were approximately 85%.

Test results obtained from the combustion of CWF in a 3 ton per hour oil-fired boiler is presented by D. C. Kim et al[30]. The main purpose of these tests were to improve the CWF combustion efficiency and hence, in the process, investigate the furnace temperature distribution , combustibility and ash characteristics. Castable lining on the furnace walls was applied as an effort to promote CWF combustion by raising the furnace temperature. Addition of the castable lining on the furnace wall increased the overall furnace temperature and flame was more stable. An increase of 100-150°C in the furnace exit temperature was noticed and therefore it can be said that the castable lining reduces the heat transfer effects to the furnace wall. An increase of 4 to 6% in combustion and boiler efficiency is observed when analyzed with respect to boiler load at 240°C air preheat temperature and 15% excess air. Excess air requirement was reduced with the addition of the castable linings.

Xinyu Cao et. al[31] performed experiments on an 60t/h double-drum natural circulation industrial boiler, to investigate the flame burning characteristics of coal-water slurry fuel. The characteristics studied include the measurement of temperature field, gas concentration field, burn-out rate, furnace emissivity and effective heat coefficient. An impact multistage atomizer with a flow rate about 1.7t/h atomizer was used. The solids loading of CWS being 61.95%. The temperatures, gas components and particle burnout rate of the flame from five different sections were recorded and analyzed. It was concluded that the maximum temperature of CWS flame was 200°C less than oil fired flame. The flame of CWS was longer than that of oil. At the time of volatile and coke burnout the temperatures were highest at a distance of 1 to 2.76m from burner exit. The burnout rate of fly ash in furnace rare was found to be 98.3%. The combustion reaction was most vigorous at a biggest radius which was 0.6 meters away from the central line of fire. Furnace emissivity for CWS and pulverized coal is 0.75 and 0.6 for oil. The effective heat coefficient was 0.57 near the furnace wall.

Yiannis A. Levendis and Ajay Atal[32] have performed experiments and calculations in order to understand the different stages of CWF combustion. The combustion behavior of the single CWF droplet(100-600μm in diameter) inside a high temperature furnace at a gas temperature of 1600K is monitored with a special pyrometer. These experiments were aimed at finding the combustion characteristics, obtain accurate flame temperatures and investigate the combustion rates. Burnout times and particulate/flame temperature data were measured using a ratio optical pyrometry and SEM microscopy was used to find the microstructure data. It was reported that the CWF particles burn with in two different phases one being volatile flame combustion and the other char oxidation. At a furnace temperature of 1250-1450K, the volatile combustion of these particles accounted for 20% of burnout time. At about 500K above the gas temperature char burns and volatiles burn at a few hundred degrees above the char.

The combustion test results of co-firing low solids coal-water slurry with conventional pulverized coal in a 32 mega watt pulverized coal boiler is discussed by Joseph J et. al[33]. The boiler consisted of 3 low NO_x burners supplied by the Energy & Environmental Research Corporation(EERC). Thirteen combustion tests were performed to evaluate the combustion performance of the boiler, effect of co-firing on gaseous emissions such as NO_x, SO_2 and CO_2 . An effort was also made to study the stability of the low solids CWS and evaluate the ability of boiler to meet the load demands. The tests were conducted to start with 5%, 10%, 20% and finally 40% Btu input from CWS. Test data were obtained for mid volatile and high volatile coals. The solid loadings in cases of mid volatile coals were 48% on the average. The SO_2 emissions for the mid volatile coal were in the range of 1400 ppm for both baseline and co-firing testing. The opacity was observed to be slightly lower during mid volatile tests. But in both cases it is below the regulatory limits in the range of 10%. The CO data were found to be fluctuating especially in case of high volatile coals. But on the average CO levels were within the EPA standard limits. But the fluctuations may be due to the interaction of slurry with pulverized coal flame causing some loss in combustion efficiency. A reduction of 15 to 20% NO_x was observed when co-firing low solids CWS.

Pilot scale combustion test were performed by R. V. Thambimuthu et al[34] to study the combustion and heat transfer characteristics of coal-water fuel, pulverized coal and No. 6

fuel oil. Three tests were performed on each fuel at 1, 3 and 5 percent excess oxygen, to investigate the effect of excess air and residence time on fuel conversion. A duel fuel gas/oil burner was used in the combustion and was installed at the inlet of the quarl. The fuels were fired at a nominal thermal input of 0.46 MW. A firing rate between 0.42 and 0.48 MW were noted in case of coal-water fuel and pulverized coal. The composition of coal-water fuel being 70 wt% coal, 29 wt% water and 1 wt% additives. The mean diameter of coal particles in CWF were 36μm with 86% less than 75μm. To encounter flame stability problems a narrow quarl was developed and used in firing all three fuels. From the visual observation it was noted that the pulverized coal and CWF flames expanded radially filling the discharge hole of the quarl, while flame obtained by oil fuel was smaller. It was observed that the fuel nitrogen content was lowest for No. 6 oil and highest for CWF, and a similar trend in the NOx measured is expected but from experimental measurement of the NOx, it was observed that NOx concentrations were less than those of pulverized coal, due to the lower flame temperatures. SO_2 concentrations were almost same in case of CWF and pulverized coal. The fuel burnout efficiency for oil was found to be the highest in the range of (99.7-99.9) and slightly less for pulverized coal(90.2-97.7) and lowest for CWF(84.0-95.3).

The combustion and fouling characteristics of the coal-water slurry fuels having high volatile content were evaluated in a 300KW multi-fuel test rig by A. Anjum at el[35]. An effort was made to measure the fouling rate, air preheat requirements, flame stability, turn-down ratios on benificated, unbenicificated and pulverized coal with different additives. Also, a comparison of the test data obtained from CWS and pulverized coal is done using a air-cooled fouling test section. The flue gas analysis in addition to the particle size distribution was listed.

The preparation and combustion of slurry fuel in a pilot scale industrial unit is discussed by J. M. Pasiel[36]. The combustion trials were conducted using 0-10 mm washery fines as feedstocks (I) Type 1/4 Gras des Cevennes containing 13% ash, (II) Type 1/2 Gras du Bousquet d'ord Slime containing 35% ash, other feedstocks were charcoal dust and a mixture of 1/4 Gras, petroleum pitch and water. The typical slurry specifications were 39.75 wt% water content, 60 wt% solids content, additives 0.25% and 1.25 t/m^3 density. The slurry flow rate was 800kg/hr. The particle sizes were in the range of 50% less than 35 microns. The slurry prepared was burned in a hot-walled combustion chamber equipped with a twin fluid atomizing burner. The atomized slurry, primary air and secondary air were injected axially into the combustion chamber without any swirling effect. It was observed that solids content greater than or equal to 67%, rapidly increased in viscosity, and particles exceeding 200 microns were produced, thereby declining the quality of the slurry. It was noted that the combustion was homogenous, stable and efficient producing high levels of CO_2 at low excess air. NO_x concentrations were in the range of 75 to 500 ppm at 6% of oxygen. This process was found to be effective for almost all types of coal, especially washing fines, charcoal dust and slimes with high ash content but required special equipment and therefore limited to industrial units of 5 to 35 MW capacity.

Initial coal-water fuel firing trials, from conversion of a 10MW oil fired boiler to fire CWM, fired was presented by A. Anjum and S. Winnard[37]. Four different slurries prepared from different methods of grinding, particle size distribution, parent coal and amount of additives were fired in the oil fired boiler converted to fire slurry. Percentage of ash in all the fuels were similar. The burner used is dual fuel rotary cup burner with separate guns for CWM and oil. The results of firing CWF at 50, 52, 61 and 48 kg/hr firing rate at excess oxygen levels of 3.6, 5.0, 6.0 and 2.6 respectively give a NO_x concentrations of 400, 200, 180 and 140 ppm respectively. SO_2 concentrations were 450, 500, 500, 240 and CO2 percentages being 14.2, 13.0 12.5 and 15.5 for firing rates of 50, 52, 61 and 48 kg/hr respectively.

M. Cioni et al[38] described the results obtained by firing CWF in a Santa Gilla #2 oil designed utility boiler. The boiler is tangential fired and equipped with 8 burners. The primary air consisting about 30% is subdivided to swirl through the quarl and also circulate circumferentially outside. Secondary air is injected above and below the quarl. The tests were performed on three different fuels, oil, CWF and CWF and oil mixture and comparisons were made. The concentrations of CO, CO_2, O_2, SO_2 & NO_x were obtained by taking samples with a probe inserted in the combustion chamber. Higher concentrations of NO_x and a lower concentrations of SO_2 is observed during CWF combustion compared to oil fired, mainly due to the difference in the composition of the fuels. Concentrations of NO_x were found to be 162, 150 and 305 ppm in oil, CWF/oil and CWF respectively. The temperature in the combustion chamber, when firing oil was found to be 100°C higher than firing CWF, but the heat flux distribution was found to be quite similar. The combustion efficiency at 50% load, in case of CWF was found to be 97.4%.

R. D Braun and R. I. Johnston[39] presented the utilization of CWF in a wet process cement kiln. 60 to 70% of the solid concentrations were used with coal size of 80% less than 75 μm. The CWF prepared was a mixture of western Canadian coals with added tailings. The typical CWF had a thermal value of 27,000 MJ/t, moisture 38.8%, ash 19.9%, volatile matter 28.1% and sulfur about 0.42%. About 85 to 88% of the total fuel was CWS. Natural gas about 3-5% was introduced below the flame to shorten the unburnt fuel and stabilize the flame. Vanes were set at an angle of 20° in CWF line in order to impart the swirl to the flame. Atomizer air was swirled by setting vanes at 30%. The objective of imparting the swirl was to increase the turbulence in the flame and hence increase the combustion rate. It was observed that utilizing the swirl vanes did not have significant effect on combustion. Imparting the swirl to the primary air also did not have a significant effect on combustion.

An effort was made to study the major burner design parameters influencing the combustion of CWF and found the optimum value of these parameters for different fuels. Test were performed on seven different types of fuel by S. Bortz et al[40]. The slurries were tested over a wide range of burner inputs and settings. A circular burner was used where the secondary air could be swirled with a continuously variable intensity by using a movable block swirler. In order to improve the ignition performance, four staging air ports were placed around the burner periphery. A long and a medium quarl were also tested during the experiments. Four different atomizers with different spray angles were used. The flame length was typically about 0.5m down stream of the quarl for unstaged condition and at staged conditions the length would be longer and more opaque. All seven slurries could be fired into 3/4 insulated furnace without gas support by optimizing the air rates and using 300° C. Burnout rates under these conditions for high and medium volatile coals were in the range of 95-99%. In general slurries made with high volatile coals and fine particle size distribution had a good ignition and high burnout rates.

CHAPTER III

3.0 EXPERIMENTAL EQUIPMENT AND PROCEDURES

3.1 EXPERIMENTAL EQUIPMENT

The combustion tests on coal-water slurry fuel were performed at the Energy and Environmental Research Center's (EERC) combustion test facility. This combustion test facility consists of a pilot scale combustion test unit with a furnace capacity of approximately 900,000 Btu/hr of slurry, firing at a rate between 80-150 lb. The setup consists of four major components, coal-water fuel feed system, combustion chamber, burner assembly and particulate control device. Figure 3.1 show the experimental setup of the test facility, consisting of a down fired combustion chamber to the left, control and display panel to the right and coal-water slurry fuel feed system in the middle. On the top are series of water cooled heat exchangers used to control the temperature of flue gases entering the electrostatic precipitator.

3.1.1 Coal-Water Slurry Fuel Feed System

The fuel feed system consists of a reservoir tank, where the slurry is stored with a mechanical agitator used to continuously stir the slurry in order to reduce the settling of the coal fines and maintain homogeneity. A pump is used to deliver the slurry fuel to an atomizer through a burner gun. The slurry is mixed with the atomizing air before entering the burner. Figure 3.2 shows a pump that will deliver the slurry to the burner, piping system and a cylindrical slurry storage tank with a mechanical agitator, which consists of blades to which a small motor is fitted to continuously rotate the blades inserted in the tank. The slurry feed rate is controlled through the pump. Figure 3.3 shows the transfer

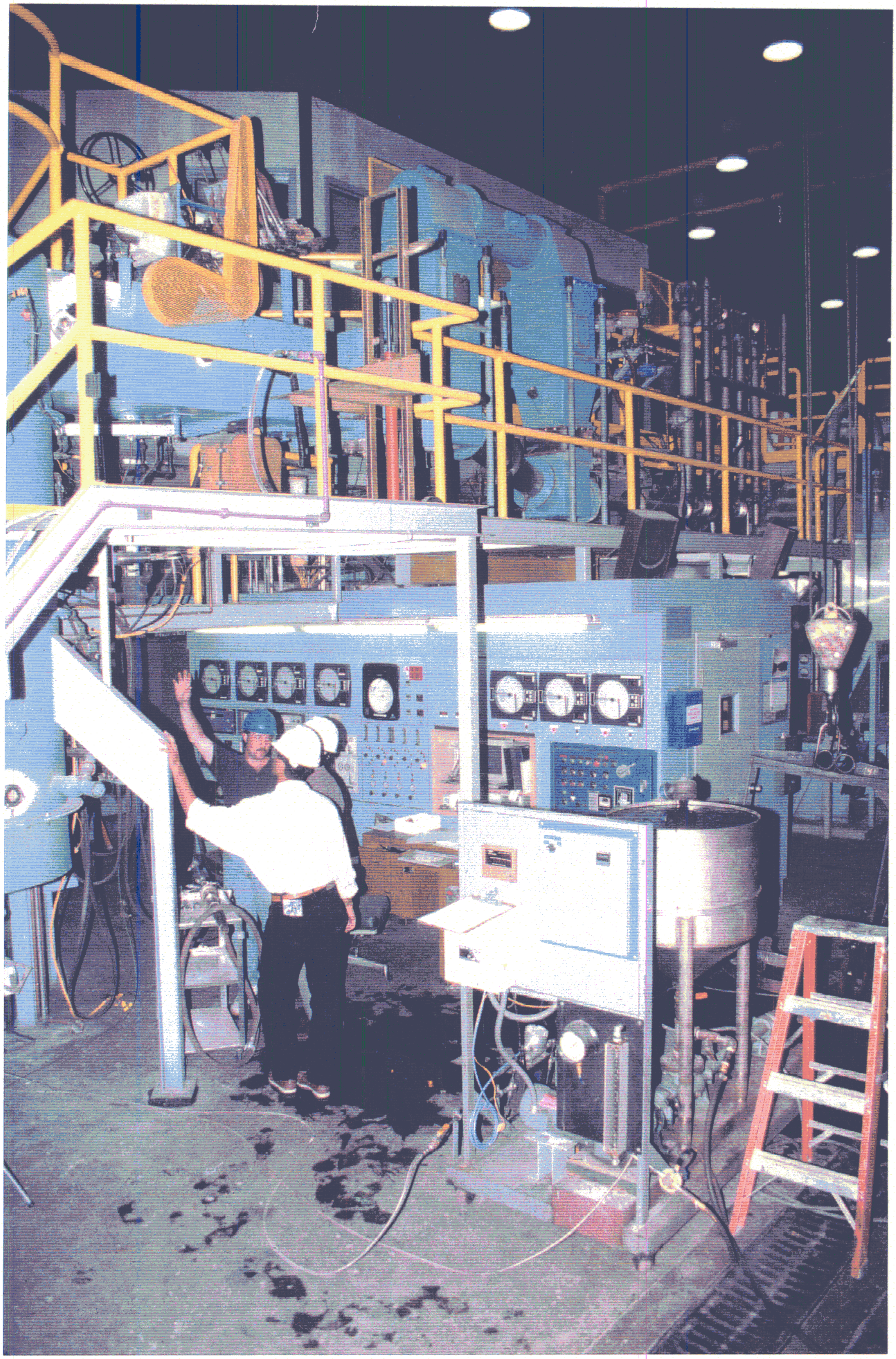


Figure 3.1 CWSF fired test unit and auxiliary systems

Figure 3.2 CWSF feed system

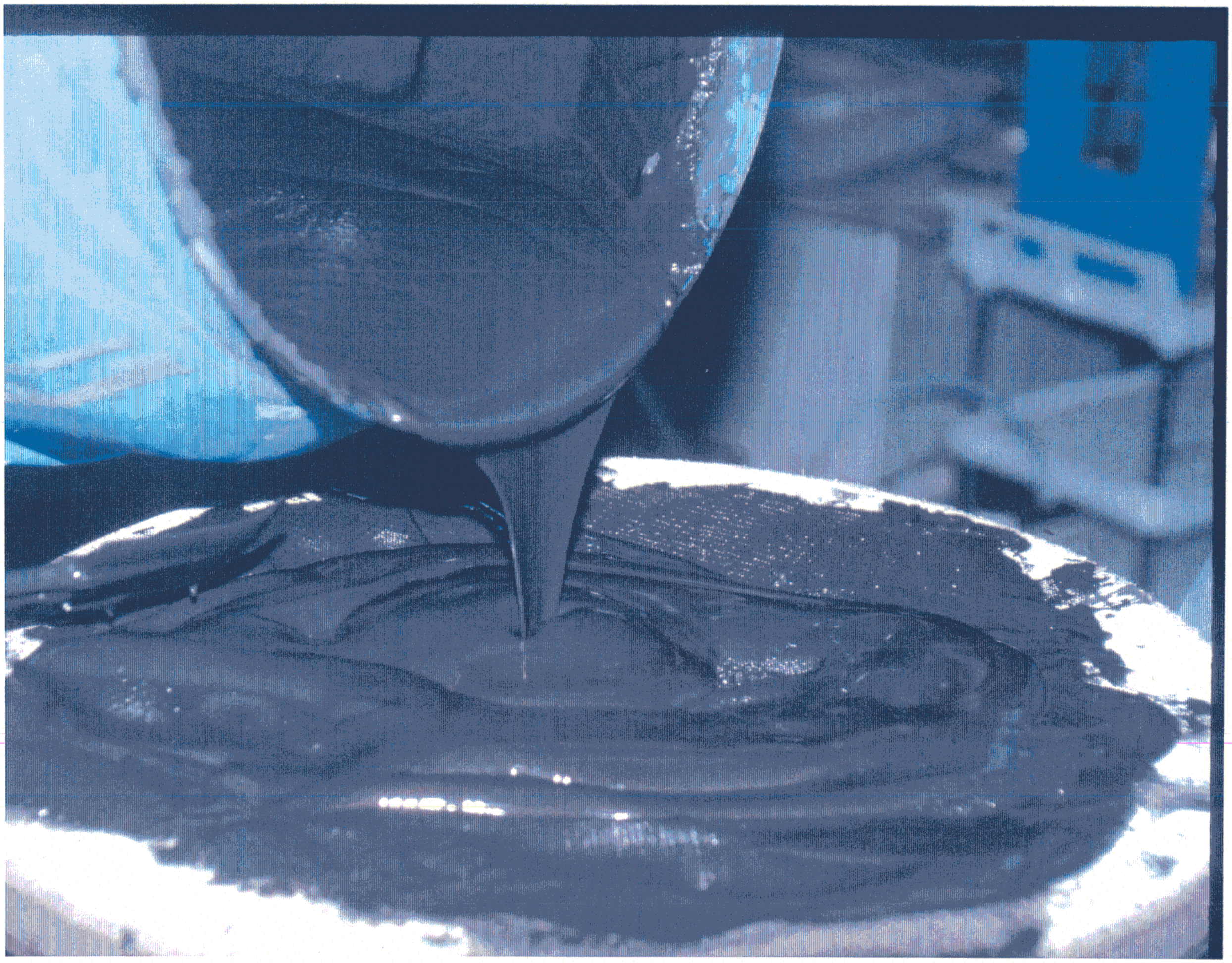


Figure 3.3 Transfer of coal-water slurry fuel from storage drum to the slurry tank

of slurry from a storage drum into the reservoir tank. A sieve is placed over the reservoir tank to eliminate the passing of solidified or improperly mixed fuel into the tank.

3.1.2 Combustion Chamber

The combustion chamber is an important part of the equipment and can be adjusted to conduct test runs either to fire coal-water slurry fuel or pulverized coal by making few minor changes. This combustion chamber is 30 inches in diameter, 8 feet high, and is refractory lined. Figure 3.4 shows the front view of the combustion test furnace used in the combustion of the coal-water slurry fuel. A port at the lower end of the combustion chamber is 23.5 inches from the quarl and is visible in the figure. Two other ports, in the middle and on the top of the chamber, are 44 and 66.5 inches from the quarl. They are used for inserting various probes to collect the gas samples, measure temperature of the flame and take photographs of the flame. From Figure 3.4, it can be observed that the bottom of the combustion chamber is fitted with an International Flame Research Foundation burner with adjustable secondary air swirl vanes. To the burner end, the slurry fuel and atomized air inlets are attached.

The top of the furnace exit consists of a 10 inch square duct, which is refractory lined, and is used to pass the flue gases out of the furnace. A vertical probe bank, designed to simulate superheater surfaces in convective pass of a utility boiler, is located in the duct The flue gases leaving the probe bank duct, passes through a series of water-cooled heat exchangers before being discharged through an electrostatic precipitator. A fouling probe bank at the furnace exit is used for inserting the test probes to collect the ash deposits.

3.1.3 Probes and Measuring Instruments Used in the Collection of the Data

A probe consisting of a high velocity S type thermocouple is used to measure the temperature of the flame. A stream of air is passed through the unit and the temperature

Figure 3.4 Lower port and burner assembly of the combustion test furnace

of the air exiting the probe is measured. This high velocity thermocouple probe is inserted at various ports along the combustion chamber in order to measure the temperatures of the flame.

A gas collecting probe is used to collect the flue gas from different locations of the combustion chamber to study the gaseous emissions such as NO_x, SO_2, CO_2 and O_2 present in the samples collected from different firing rates and varying swirl numbers. Figure 3.5 shows the gas collecting probe which is used to collect the flue gas from one of the port in the combustion chamber. The flue gas collected through the probe is analyzed for various gaseous emissions using a MISCO model gas analyzer as shown in Figure 3.6.

An online gas analyzer is used to measure the various gaseous emissions at the end of the combustion unit, to measure the various emissions from the flue gas for the total duration of the experiments, at an interval of 10 minutes. A data acquisition system is incorporated into the analyzer to store the emissions data. This data obtained is used in the analysis of the gaseous emissions.

A test probe is used to collect the ash samples from various locations of the combustion chamber. Figure 3.7 shows the ash collecting probe being removed from one of the ports in the combustion chamber. This sample is used in the computation of the carbon conversion efficiency by measuring the percentage of unburn carbon in ash.

Ash fouling test probes are used to collect the ash foulings. These ash fouling test probes are located at the top of the combustion chamber, with a hinged door at the top of the furnace to facilitate in cleaning and inspection processes. The three fouling probes made of type 304 stainless steel pipe of 1.66 inches outer diameter, and are cooled with

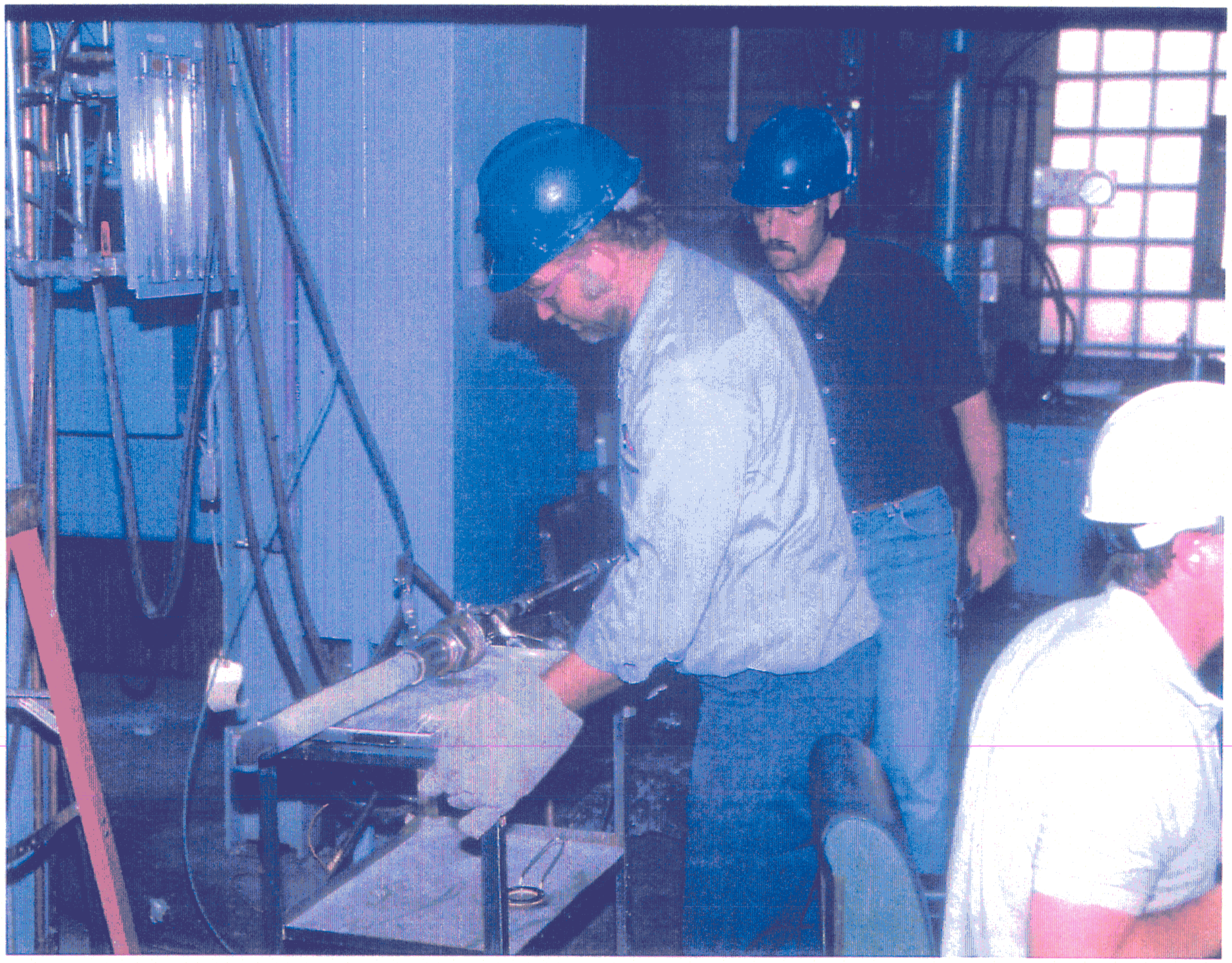


Figure 3.5 Probe used in the collection of gas sample

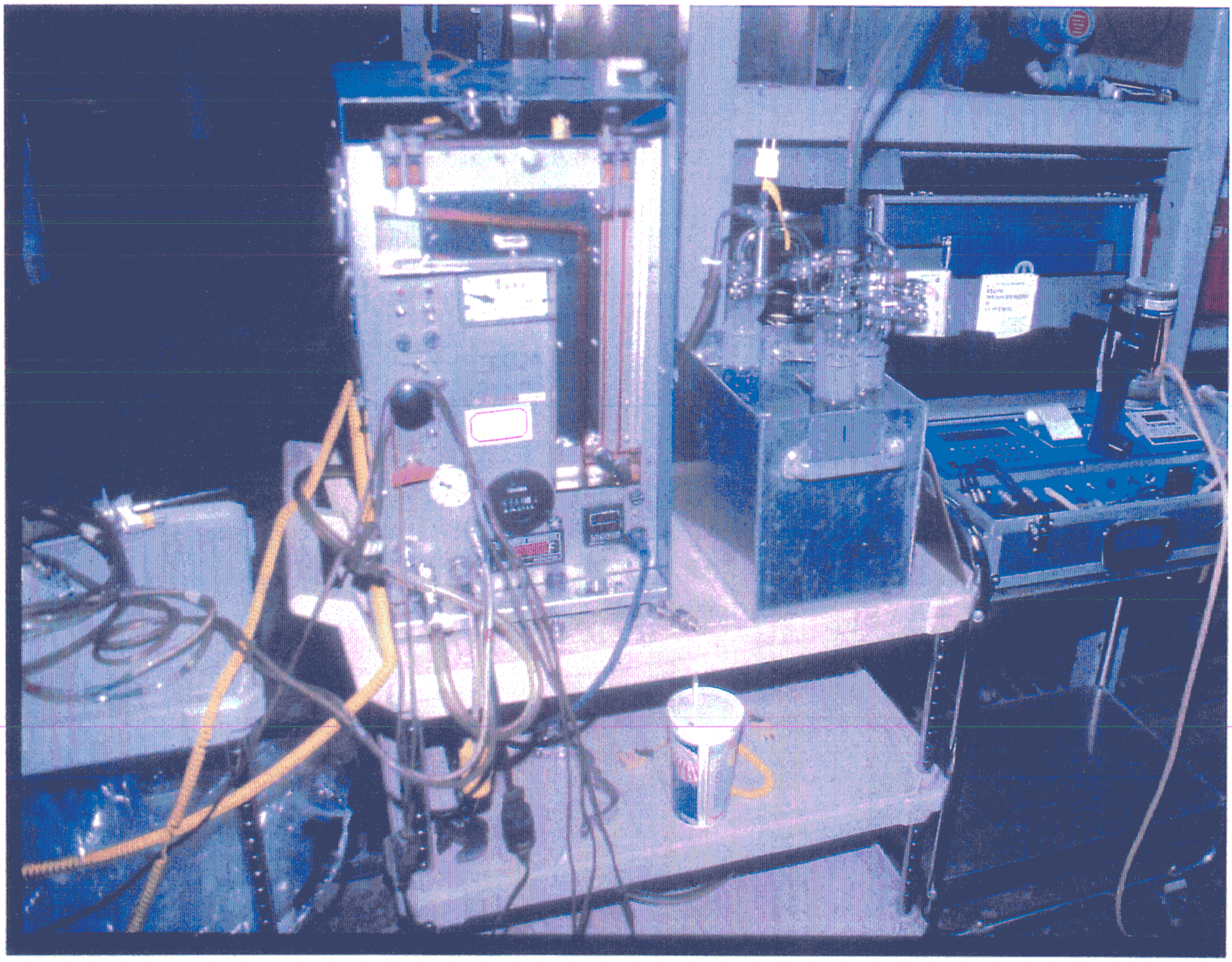


Figure 3.6 MISCO flue gas analyzer to measure the flue gas concentrations

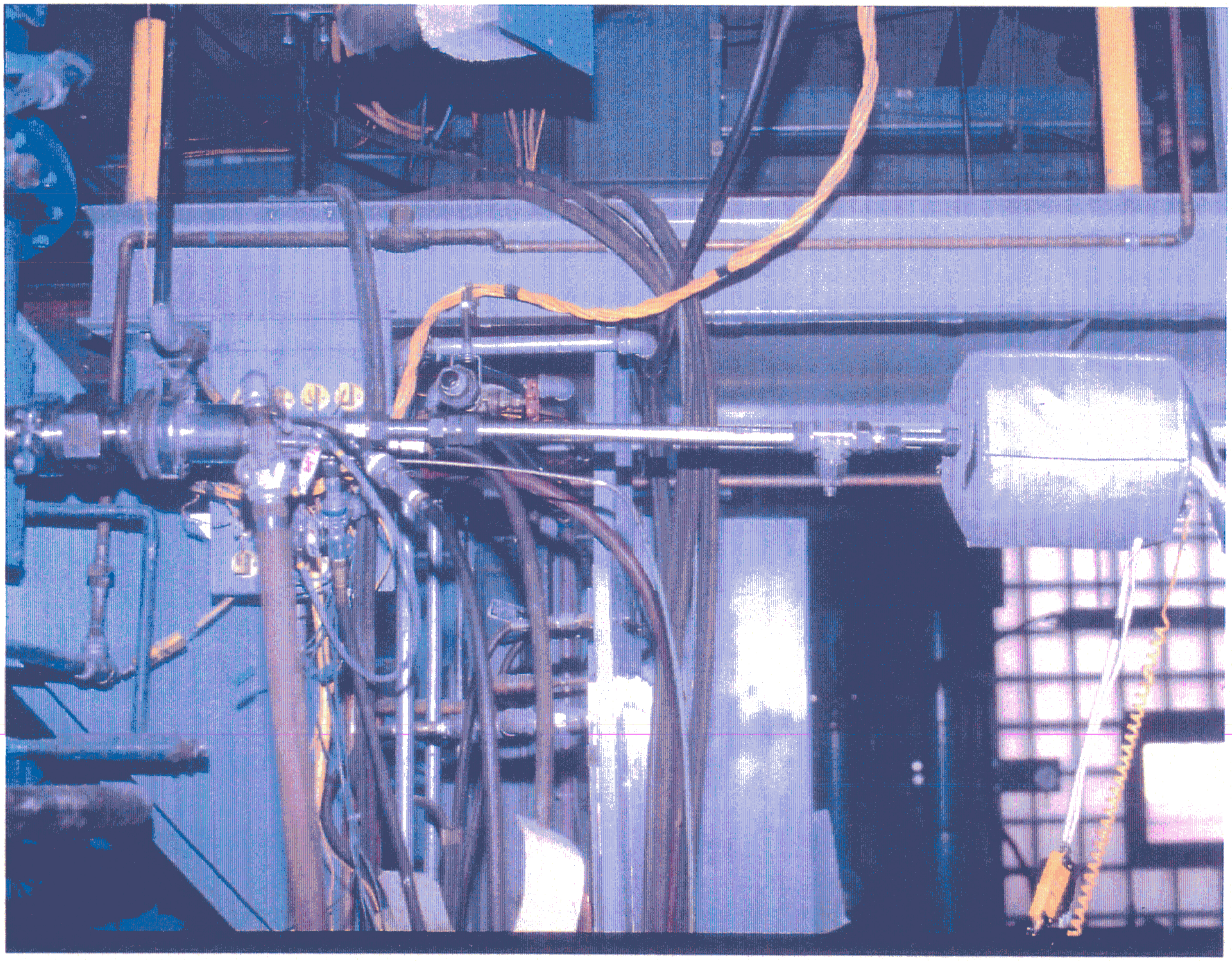


Figure 3.7 Probe to collect the ash from different locations

compressed air. Each probe is fitted with two thermocouples embedded in its upstream edge to measure metal temperature. Figure 3.8 shows the ash fouling probe bank with three probes and hinged door. One of the thermocouple, on each probe, is attached to a temperature recorder/controller that regulates the cooling air to the probe. Normally, the surface temperature of each probe is maintained at 1000^0F, while the gas temperature entering the probe bank is maintained at approximately 2000^0F. The ash foulings collected over a test period are analyzed for the chemical compositions.

Figures 3.9-3.12 which are detailed photos of the Ash Fouling Probe Bank, were removed immediately from the Test Furnace. Figure 3.9 is a distance view of test run AF-CTS-712 of the fouling probe bank that was removed from the chamber. To the left of the probe bank it can be seen the ash that was removed from in between the fouling probes in the sample tray. One can clearly see that the ash is strong in strength and clumped together in a large pile.

Figure 3.10 is a close view of the ash fouling of test run AF-CTS-712. The ash is dark in color on the top and gets extremely lighter as it gets closer to the hinged door. There are several small bubble type chunks that are protruding from the square accumulated ash.

Figure 3.11 is another close view of the ash fouling probe bank, however, this is test run number AF-CTS-713. The ash towards the top of the probes are much darker than the one viewed in test run AF-CTS-712. This ash does follow the same pattern as Figure 3.10 in that the shades get lighter as it is closer to the hinged door.

Figure 3.12 is another close view of the test run AF-CTS-714; there are bubble clumps, slightly larger on the square accumulation of ash on the hinged door. The ash color gets lighter as it gets closer to the door.

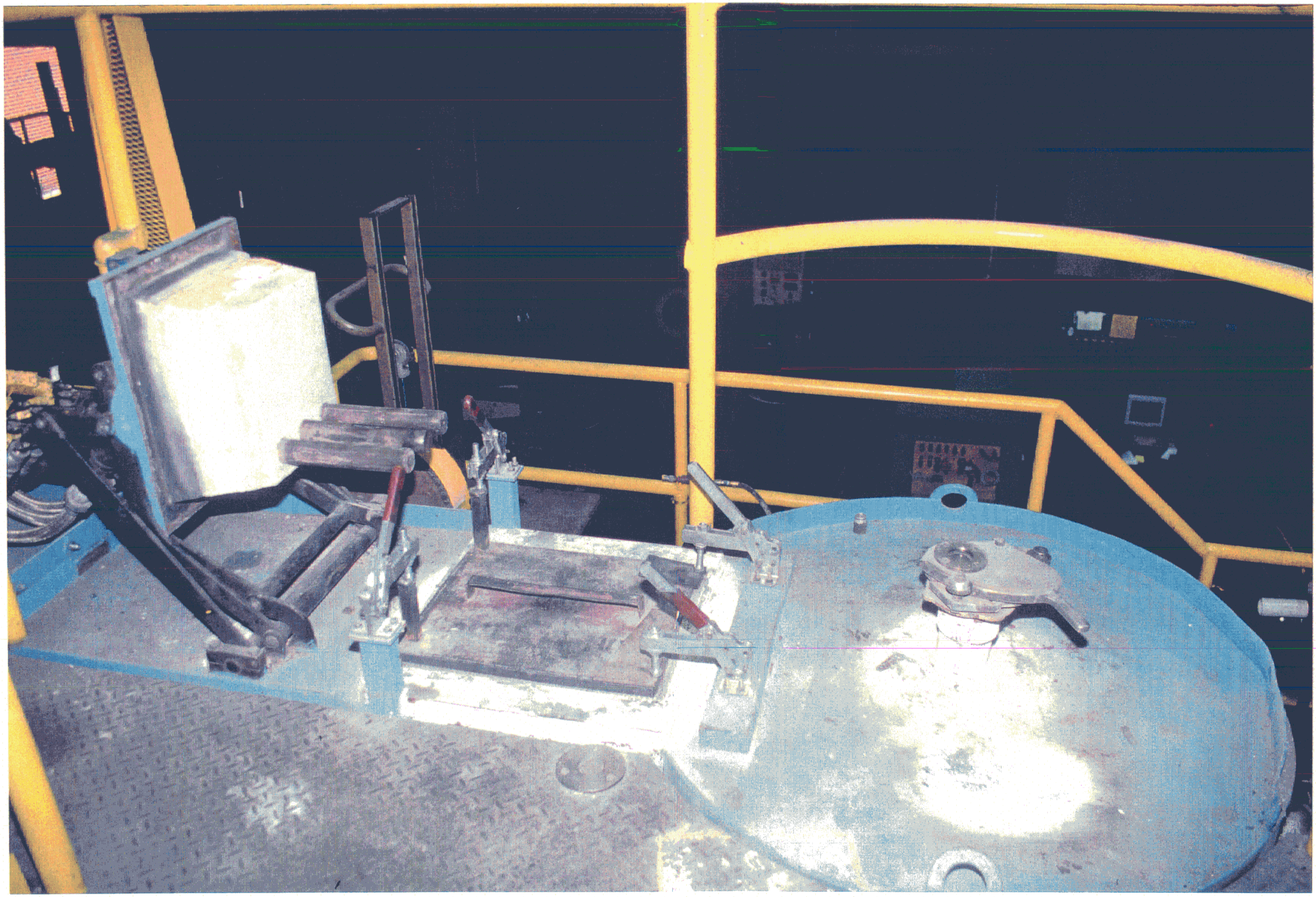


Figure 3.8 Ash fouling probe

Figure 3.9 Peripheral View of Probe Bank

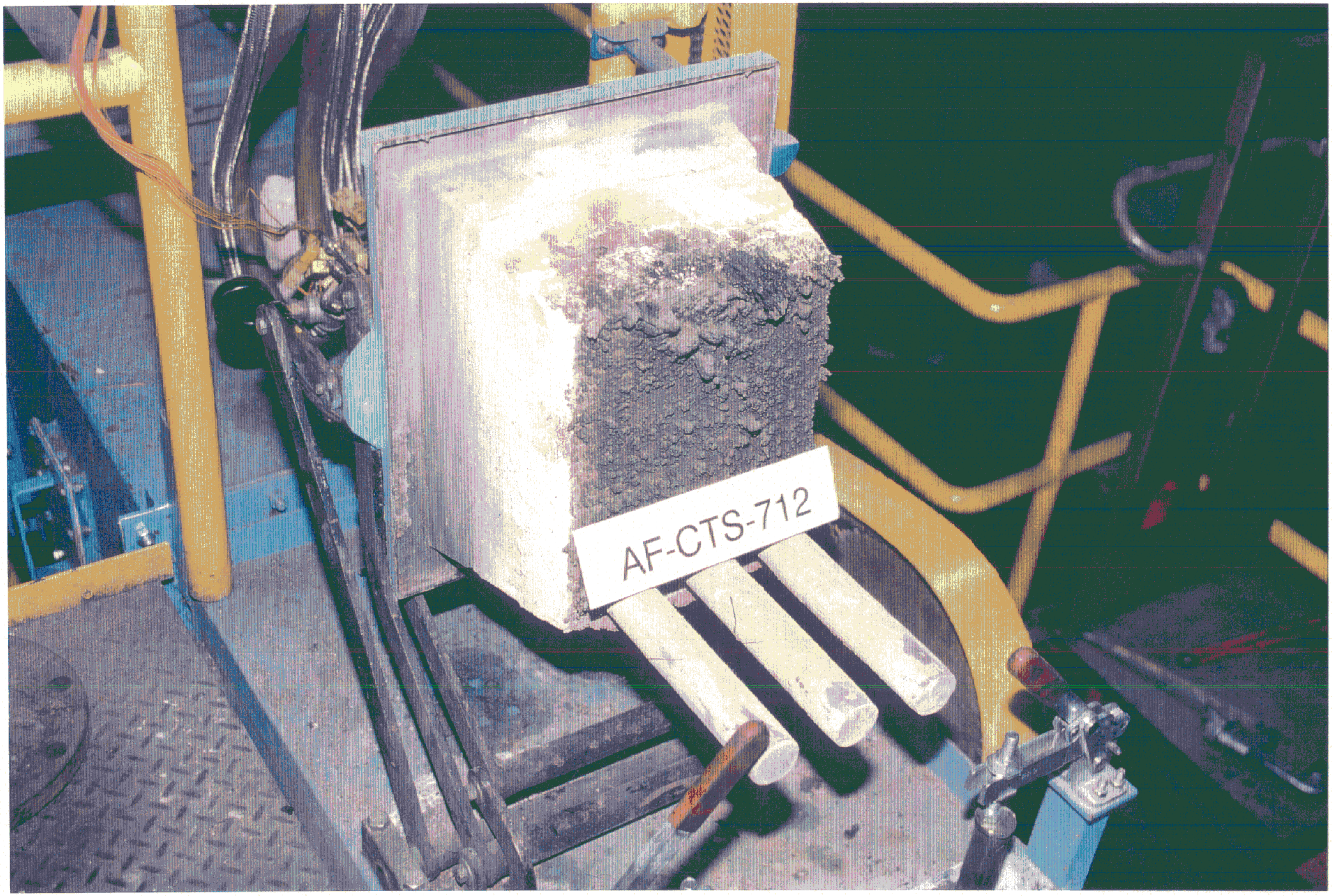


Figure 3.10 Close View of Ash Fouling Probe Bank (Test Run AF-CTS-712)

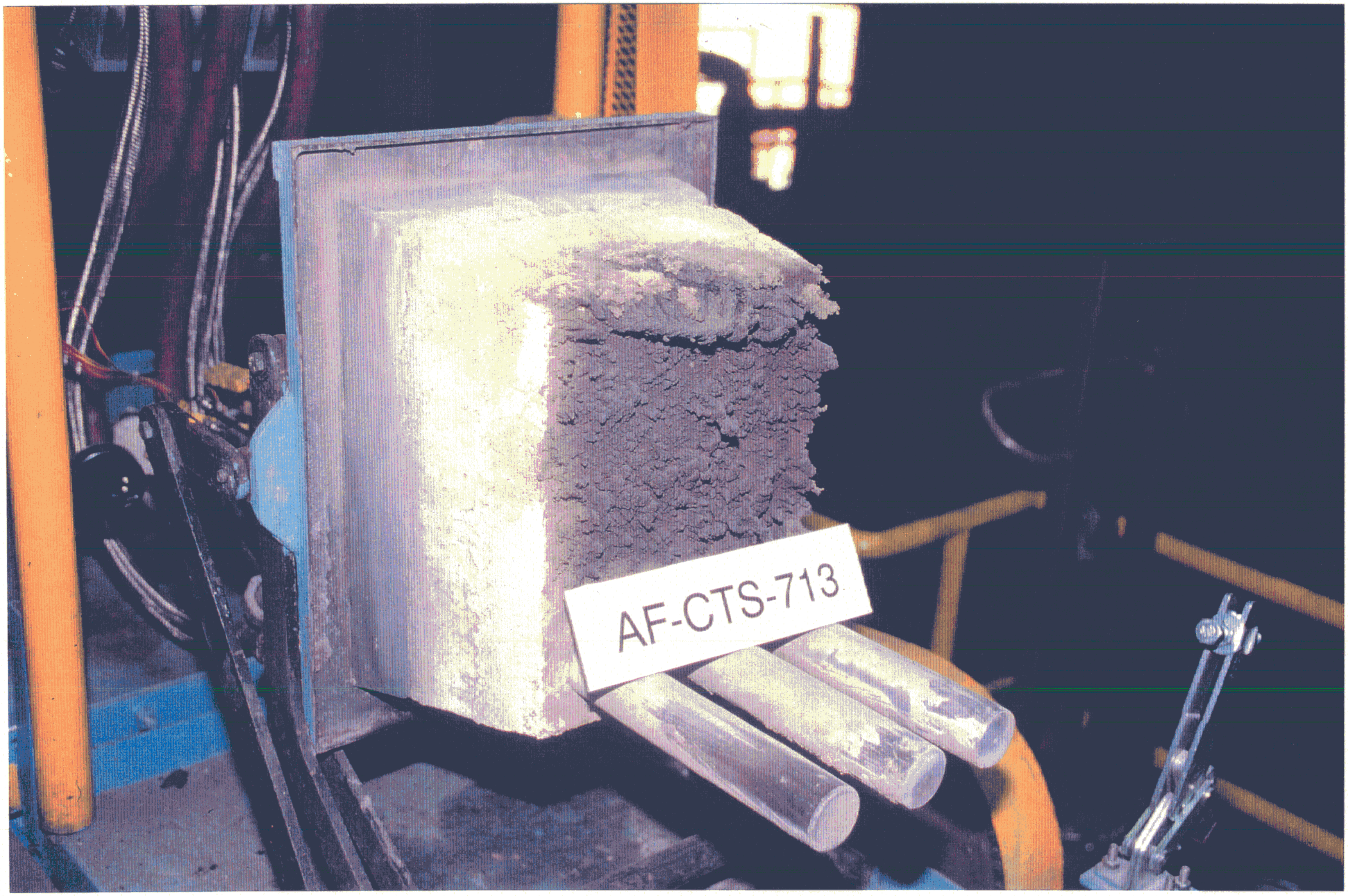


Figure 3.11 Close View of Ash Fouling Probe Bank (Test Run AF-CTS-713)

Figure 3.12 Close View of Ash Fouling Probe Bank (Test Run AF-CTS-714)

3.1.4 Burner and Atomizer Assembly

An International Flame Research Foundation (IFRF) type adjustable secondary air swirl generator is used to create an internal recirculation zone in the burner region. This adjustable swirl burner consist of two annular plates and two series of interlocking wedge shaped blocks, each attached to the plates. The two jets of blocks can form alternate radial and tangential flow channels, where the air flow splits into an equal number of radial and tangential streams which will combine further downstream into one swirling flow. Rotation of the movable plate, causes the radial channels to progressively close and cause tangential channels to open, increasing the angular momentum continuously between 0 and a maximum value. This maximum value depends on the total air flow rate and the geometry of the swirl generator. An internal recirculation zone is set up in case of strong swirl, due to the adverse axial pressure gradient, which is large enough to reverse the flow along the axis.

Heated primary air is mixed with the coal-water slurry before atomization and is carried out of the burner gun. The heated secondary air is introduced in an annular section surrounding the burner gun.

3.1.5 Particulate Control Devices

Baghouse is a large bank that collects fly ash both at the inlet and outlet of the pilot plant. An alternative type of equipment that collects ash; may also be used alone and or in conjunction with an electrostatic precipitator (ESP). Electrostatic precipitator (ESP) is located on the back of the pilot scale combustion system for particulate control. Essentially, this device collected bulk fly ash samples. It was operated at a constant inlet gas temperature (300-350°F) with voltage input regulated to the highest voltage possible without sparkover. Its performance is characterized by EPA Method 5 particulate samples at both the inlet and outlet. The fly ash collected from the ESP was subjected to laboratory analysis of resistivity as well as the American Society for Testing Materials (ASTM) analyses and advanced scanning electron microscope (SEM) analyses. Figure 3.13 is a picture of the baghouse and the (ESP) standing next to it. It is apparent that these two equipment are not small in size. The baghouse is on the right and stands two levels tall. Whereas the (ESP) is a level and a half tall and is located on the left. A small cyclone located at the end of run was used to collect fly ash samples that were analyzed for carbon content, the effect of burner settings and the load on carbon conversion. Figure 3.14 clearly displays the cyclone standing individually and Figure 3.15 is a photo of a technician and the graduate student from Prairie View A&M University examining the cyclone at the EERC test facility. On Figure 3.14 the cyclone is strongly tapped for support and has a bucket/sampling pail for collection of the ash.

3.2 EXPERIMENTAL PROCEDURES

3.2.1 Coal-Water Slurry Preparation

Coal samples consisting of about 1,850 lbs of 2″ X 0″ plant coal and 1,090 lbs of black water(pond) fines slurry were obtained from the Peabody Coal Company's Marrisa mines in Marrisa, Illinois. The as received (AR) plant coal contained a moisture of about 13.70% weight and was visible wet on the surface, therefore it was floor dried to remove the surface moisture to facilitate proper functioning of the equipment. The plant coal was then stage crushed to 1/4″ top size with a hammer-mill crusher, then pulverized to a nominal 80% passing 200-mesh and 100% passing 100-mesh. This combustion grind was prepared using a hammer-mill pulverizer/mechanical separator system. The as received (AR) pond fines slurry with 21.63 wt% solids content, were thermally dewatered, using a steam coil to evaporate water, to obtain 41.95 wt% solids content. The concentrated fine slurry was analyzed for particle size distribution via sieve and Malvern laser diffraction. Wet milling was performed on the coarse coal particles which otherwise would plug the CWF pumping and injection system. A sample of the milled fines slurry and plant coal

Figure 3.13 Baghouse and Electrostatic Precipitator

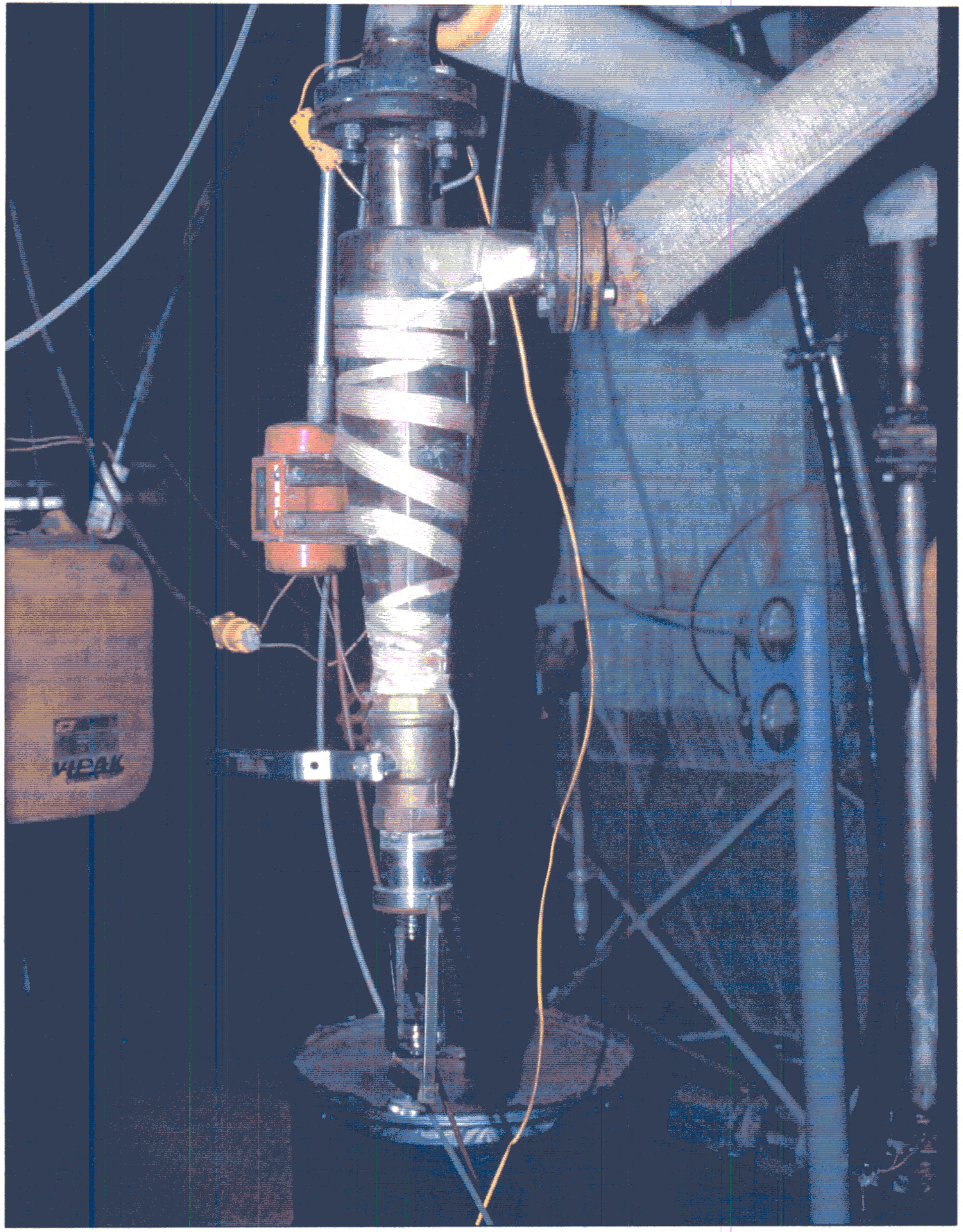


Figure 3.14 Cyclone

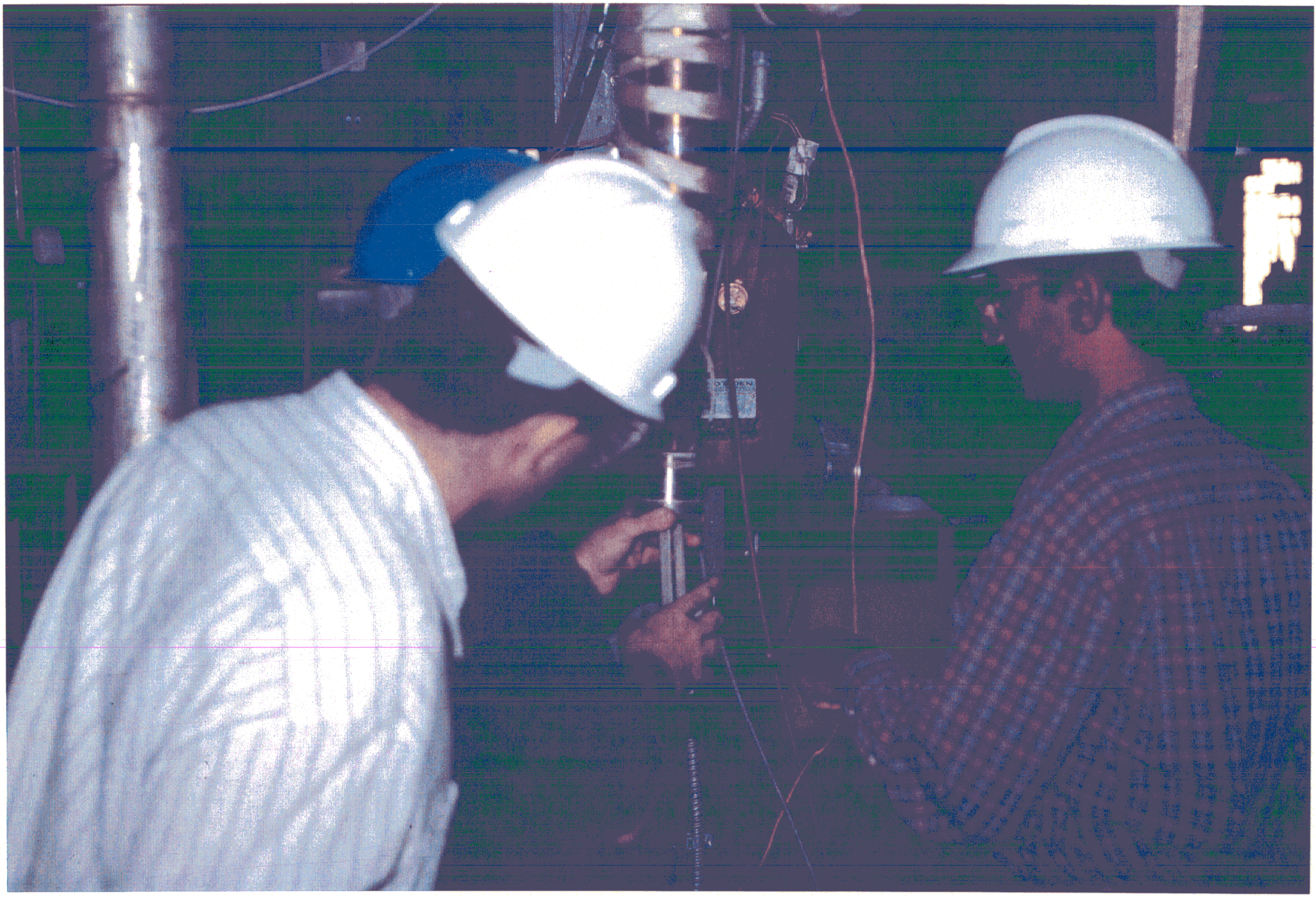
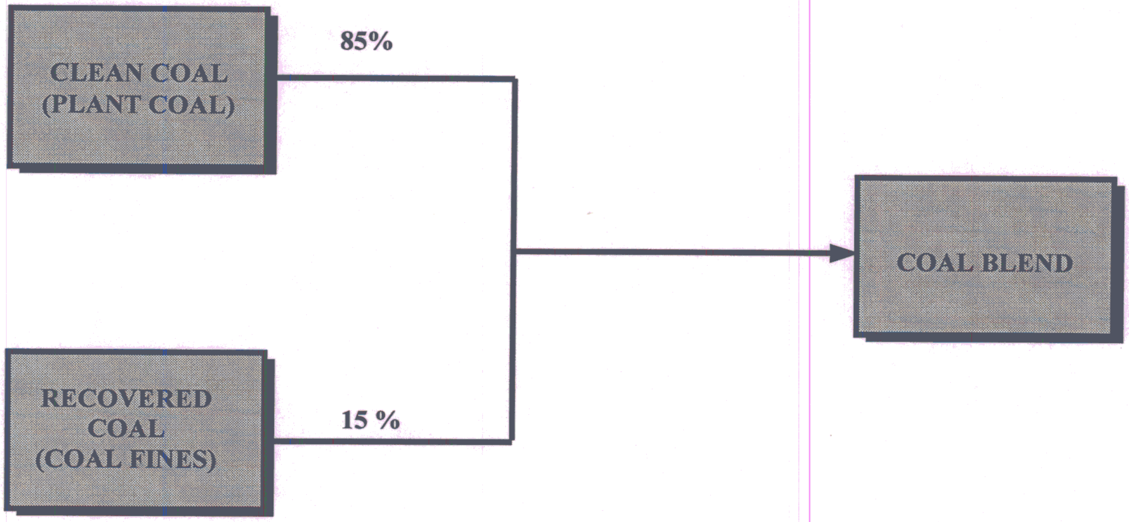


Figure 3.15 Inspection of Cyclone

were analyzed for proximate, ultimate and heating values. The wet milled fines were also analyzed for particle size distribution by Malvern laser diffraction analysis.



Blend Characteristics:

100 % Passing 100-mesh

80-90 % Passing 200-mesh

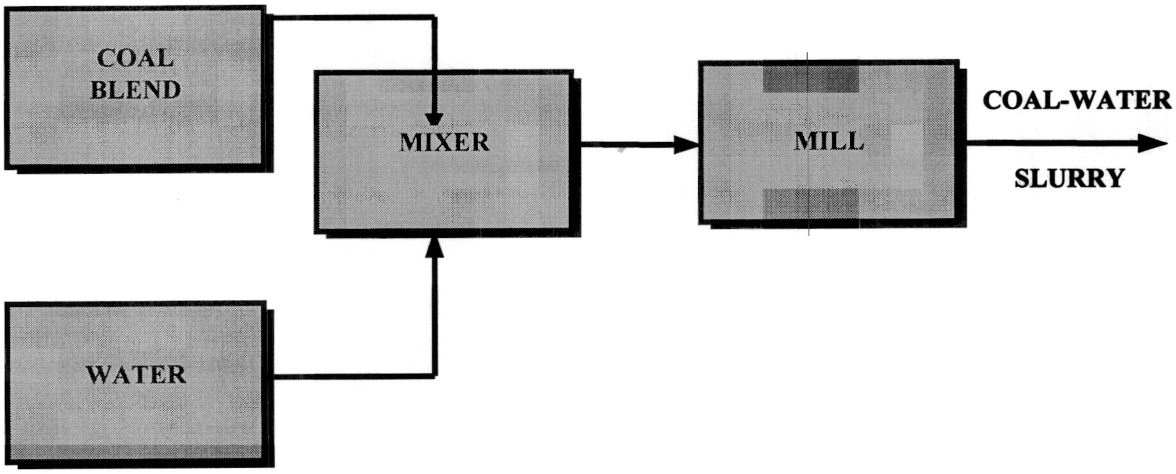
Figure 3.16 Preparation of Coal-Blend

Once the plant coal was pulverized to the required particle size and moisture content adjusted, these pulverized plant coal fines were mixed with wet milled fines in the ratio of 85/15 weight ratio, as presented in Figure 3.16, to form the blend.

The mass of CWF required for combustion testing was estimated from the ash-fouling furnace firing rate(s) and heating value(s) of the CWF. The pulverized plant coal and wet milled fines slurry were then mixed with the required amount of deionized water in a 500-gallon stirred tank. Figure 3.17 shows the process of preparing the coal-water slurry fuel from the blend of plant coal and coal fines. The slurry was then pumped into the barrels where minor adjustments of water content were made to achieve the desired viscosity. The final CWF, delivered to the combustion system, had a nominal solids content of 53.5 wt%. A sample of the as-fired CWF was analyzed for proximate, ultimate and heating values.

3.2.2 Combustion of Coal-Water Slurry

Prior to firing the CWS, the furnace was pre heated using natural gas. Pilot scale combustion tests were conducted to determine the range of secondary air swirl required to maintain a stable flame and a slurry feed rate. After the furnace reached a temperature of about 2000° F, coal-water slurry was introduced into the furnace. The coal-water slurry was fired at three different firing rates 834,330 Btu/hr, 669,488 Btu/hr and 508,214 Btu/hr and at three different swirl settings for each firing rate. Hence a total of nine tests were performed. Pilot-scale combustion tests were conducted to determine the range of secondary air swirl required to maintain a stable combustion flame. Secondary air swirl was used to stabilize the flame. Swirl is defined as the ratio of tangential momentum to axial momentum imparted to the secondary air by movable blocks internal to the burner and is used to set up an internal recirculation zone(IRZ). Application of swirl to the combustion



Slurry Specifications:

Maximum Particle size : $D_{max} = 200\ \mu m$

Mean Particle Diameter : $40 \leq D \leq 50\ \mu m$

Viscosity : $\mu \leq 500$ cp

Figure 3.17 Preparation of Coal-Water Slurry Fuel from the Blend

air causes the coal particles to be entrained in the IRZ thereby increasing the heating rate of the particles causing an increase in the release of volatiles and char combustion.

During the first test condition, CWS was fired at a rate of 834,330 Btu/hr with an excess air level of 20%, simulating a full load condition. The burner settings were adjusted to determine the point at which the flame separates from the burner, indicating flame instability, and the point at which the flame is fully contained within the burner quarl, indicating stable flame. The flame becomes more compact and intense as swirl is increased to an optimum level. Increasing swirl beyond the optimum level can cause the flame to be pulled into the burner region, causing combustion in the coal pipe and detoriating the burner parts due to exposure to intense heat of the flame. The burner settings were adjusted at 0.55, 0.40 and 0.20 swirl numbers. At each burner settings primary air flow, secondary air flow, furnace exit gas temperatures, furnace wall heat flux, and a full gas analysis of CO, CO_2, O_2, SO_2, and NO_x were recorded. Flame temperature was determined by a high-velocity thermocouple. These measurements provide an indication of the flame shape and intensity. Photographs of the flame at each burner settings are taken to provide a visual record of the flame. Formation of NOx can be affected by increasing the swirl beyond a certain point in the process of improving the flame stability and carbon conversion.

The burner is set at a constant swirl setting once the flame stability evaluation is done and the ash fouling test probes are inserted into the flue gas duct work. The surface metal temperature on each probe is maintained at approximately 1000 ^{0}F by regulating steam. The ash-fouling deposits were collected over the total test period. During this test period, particulate was extracted from three elevations of the furnace and analyzed for its carbon content. Flue gas concentrations of CO_2, O_2, SO_2, and NO_x were recorded using a MISCO portable gas analyzer at three different locations of the combustion chamber. The ash fouling probes are inserted into the probe bank at the top of furnace to collect the ash foulings. The fouling deposits collected after the test period are weighed and analyzed. Figure 3.18 shows the sample of ash foulings collected during a test run at 834,330 Btu/hr. An evaluation of the deposit strength and the compositions of the deposit are recorded. The flue gases passing out of the flue gas duct pass through a series of heat exchangers and then to an electrostatic precipitator where the bulk fly ash samples are collected. These samples are analyzed for carbon content, size distribution, and elemental oxide composition using x-ray fluorescence. The same test procedure is repeated to measure all the data for the other two firing rates and burner settings.

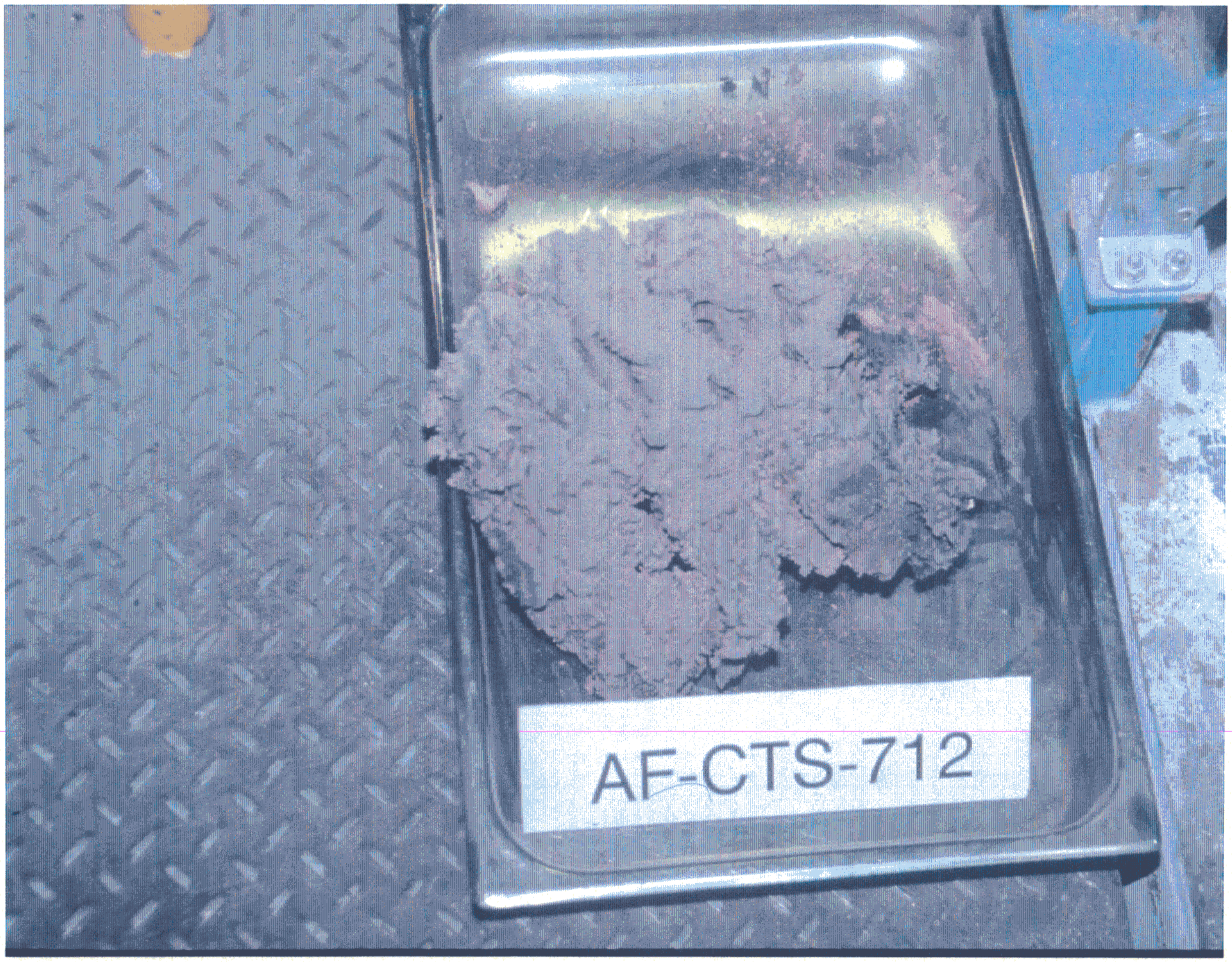


Figure 3.18 Sample of ash deposit collected during a test run at 834,330 Btu/hr

CHAPTER IV

4.0 RESULTS AND DISCUSSIONS

The chemical analysis of the CWSF, its feedstocks and combustion test data obtained at three firing rates are reported and discussed. The chemical analysis of the coal-water slurry fuel and its feedstocks involves the determination of proximate analysis, ultimate analysis, heating values and ash deposit compositions. The combustion data includes the results obtained from the flame stability tests, gas and ash samples collected from different locations of the combustion chamber, and gaseous emissions obtained over the total duration of the experiments.

The above mentioned data is used to evaluate the following conditions:

1. Effect of three different firing rates(834,330 Btu/hr, 669,488 Btu/hr and 508,215 Btu/hr) on the NO_x, SO_2, CO_2 and O_2.
2. Effect of varying the burner settings for each firing rate on gaseous emissions and percentage of carbon in ash.
3. LOI, residence time and flue gas compositions with respect to the top middle and bottom locations of the combustion chamber
4. Carbon conversion efficiency.

4.1 CHEMICAL ANALYSIS

The chemical analyses were performed on the plant coal, recovered coal fines, coal-water slurry fuel and ash deposits in order to have a through understanding of the combustion characteristics. Proximate analysis (moisture, ash, volatile matter and fixed carbon), ultimate analysis (carbon, hydrogen, nitrogen, sulfur, oxygen and ash) and heating values were analyzed for coal-water slurry fuel and its feedstocks. X-ray fluorescence analysis were performed on the ash deposits.

4.1.1 Proximate Analysis

The analysis were performed on the plant coal, recovered coal fines and coal-water slurry fuel using a Fisher coal analyzer. The moisture content was determined using the ASTM D3302-74 standard method and volatile matter determined by heating the dried sample to 950°C. The percentage of ash was determined by ASTM D3174-73 method. Figure 4.1 shows percentage by weight of as received moisture, volatile matter, fixed carbon and ash of coal-water slurry fuel and its feedstocks.

The volatile matter, fixed carbon and ash are moisture free. Figure 4.1 demonstrates that a high percentage of ash around 56.72 percentage is found in the case of recovered coal fines when compared to 12.71 and 19.75 percentage in the case of plant coal and coal-water slurry. This high percentage of ash was expected as these fines are recovered from the ponds that basically contains the rejected material after extracting the clean coal. High percentage of sulfur can have a detrimental effect on the combustion equipment and on the boiler tubes due to fouling and scaling. It can also be noted that the percentage of moisture in case of recovered coal fines is about 78.37 percent, which is very high when compared to the plant coal which is about 13.7 percent. This is due to the fact that recovered coal fines are the byproducts of clean coal that are washed away with water during the cleaning process.

Volatile matter is a very significant factor as it helps in the initial combustion of the fuel. Higher percentage of volatile matter is always desirable. Due to the presence of about 20.40 percent of carbon fixed in recovered coal fines, it is considered as apart of the blend in the fuel.

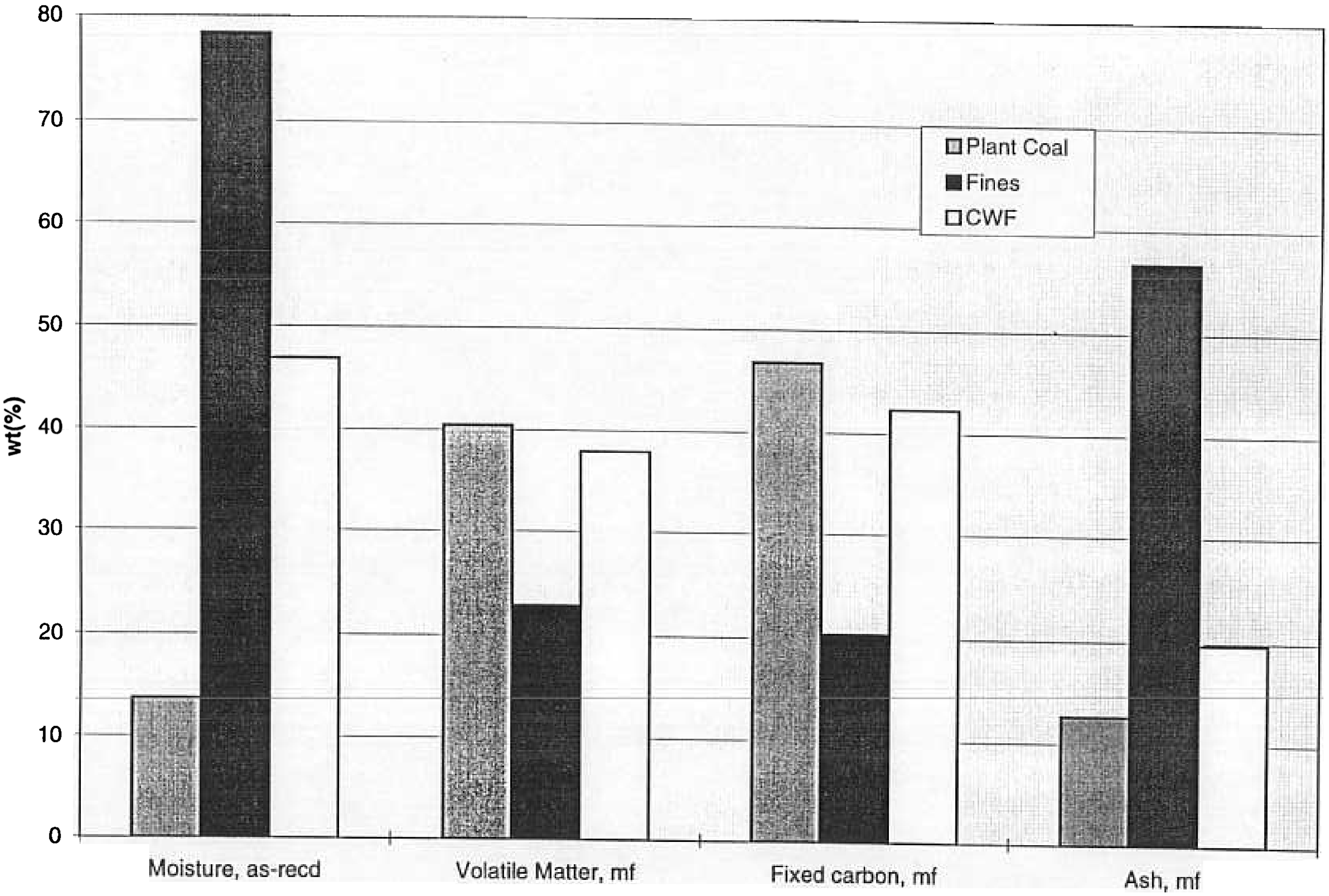


Figure 4.1 Proximate Aalysis of Coal-Water Fuel and Feedstocks

4.1.2 Ultimate Analysis

Ultimate analysis was performed on the plant coal, recovered coal fines and coal-water slurry using the standard ASTM methods to determine the carbon, hydrogen, nitrogen, sulfur, oxygen and ash contents. The carbon, hydrogen and nitrogen contents are determined using a LECO CHN-600 analyzer and LECO SC-132 sulfur analyzer are used to determine the sulfur percentage. Forms of sulfur are determined using ASTM-D2492-80 method. The important elements effecting the combustion and gaseous emissions are the carbon, nitrogen, sulfur and oxygen.

It is observed from Figure 4.2, that sulfur in cases of plant coal and recovered coal is high because the coal samples from Illinois area contain high sulfur. The sulfur content in coal-water fuel is about 1.84 percent of sulfur. The percentage of sulfur present in the fuel has a direct influence on the amount of sulfur dioxides being emitted during combustion. The nitrogen percentages are 1.24, 0.68 and 0.57 for plant coal, recovered coal fines and coal-water fuel respectively. The other gaseous emissions such as CO_2 and NO_x are dependent on other factors such as percentage of air input, temperature, swirl, etc, in addition to the percentage of carbon and nitrogen present in fuel.

In addition, details on particle size distribution of plant coal, recovered coal fines and coal-water slurry fuel are presented in reference[41].

4.1.3 Heating Values, Sulfur and Ash Input

Table 4.1 shows the heating values in Btu/lb for coal-water fuel and its feedstocks. It is seen that the recovered coal fines contain about 5,440 Btu/lb which can be utilized instead of being dumped into the ponds. Coal-water fuel prepared from the blend of plant coal and recovered coal fines contain 10,985 Btu/lb. Included in the Table 4.1 are the ash

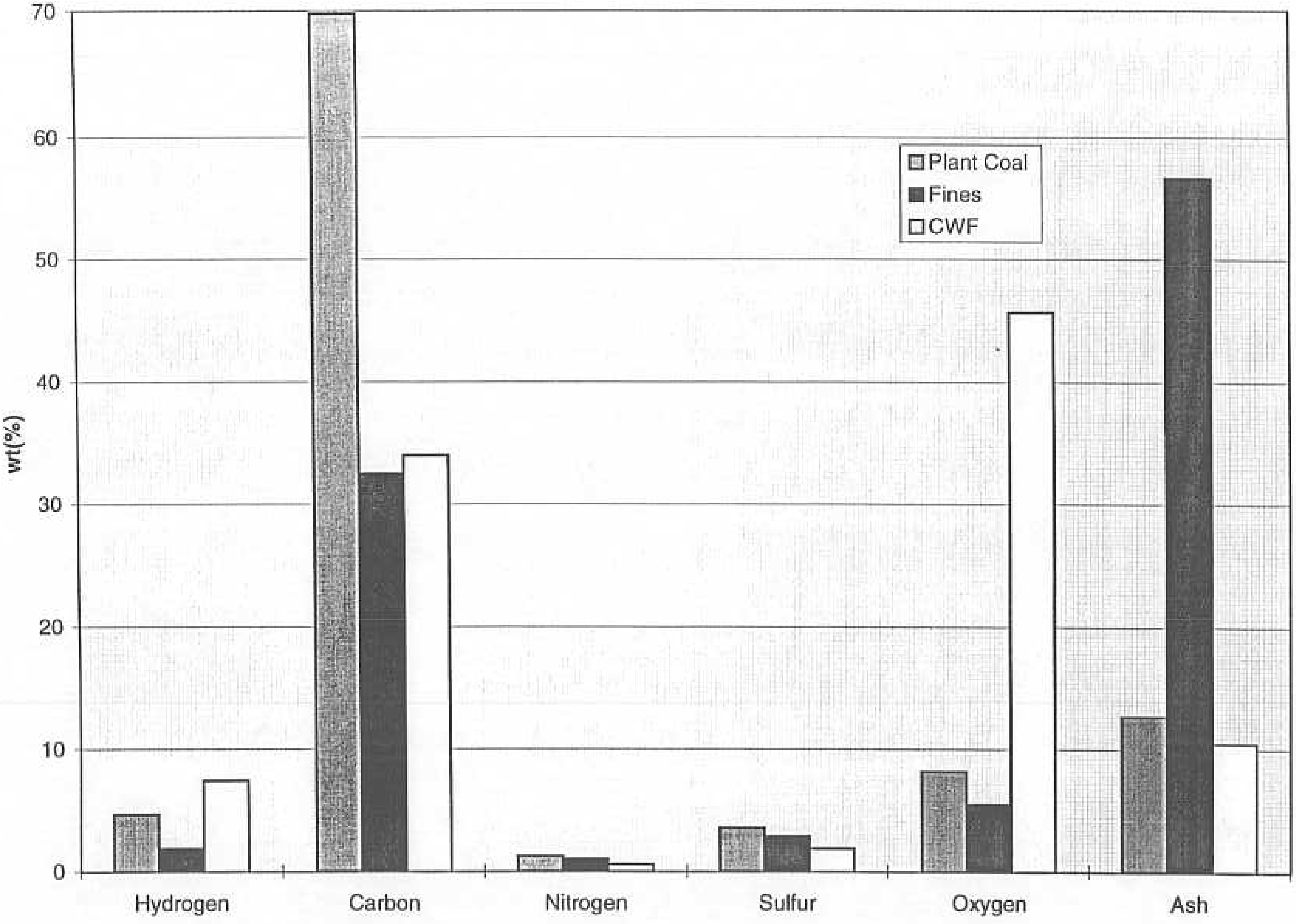


Figure 4.2 Ultimate Analysis of Coal-water Fuel and its Feedstocks

and sulfur input in lb/MMBtu for coal-water fuel and its feedstocks. It can be noted that the recovered coal fines have a very high amount of sulfur and ash input.

Table 4.1 Heating Value, Sulfur and Ash Input for Bituminous CWF and Feed Stocks

	Plant Coal	Recovered Coal Fines	Coal-Water Fuel
Heating Value, Btu/lb, mf	12,130	5,440	10,985
Sulfur Input, lb/MMBtu	6.69	47.93	6.30
Ash Input, lb/MMBtu	10.48	104.26	17.98

4.2 GASEOUS EMISSIONS AND FLAME STABILITY DATA ANALYSIS

4.2.1 Effect of Varying the Firing Rates(834,330 Btu/hr, 669,488 Btu/hr and 508,215 Btu/hr) on NO_x, SO_2, CO_2, O_2 with Excess Air.

NO_x is defined as the combination of NO and NO_2. The nitric oxides emitted during the combustion of coal is generally classified as thermal NO_x and fuel NO_x depending on the source from where the nitrogen is supplied. The NO_x emissions resulted from the combustion of CWS fuel at three different firing rates are recorded by an online gas analyzer for the total duration of the experiment. Figures 4.3, 4.4 and 4.5 represent the NO_x emissions at 834,330 Btu/hr, 669,488 Btu/hr and 508,215 Btu/hr firing rate respectively. It is seen from these figures, the NO_x emissions for each of the three firing rates were found to be less than 500 ppm, which is within the standard set by the EPA (250-500 ppm). On an average, over the total test run the NO_X emissions were found to be 460 ppm, 399 ppm and 240 ppm for 834,330 Btu/hr, 669,488 Btu/hr and 508,215 Btu/hr firing rates respectively[42]. An important observation made with respect to the firing rates is NO_x emissions were found to increase with the increase in the firing rate. This is due to the increase in fuel input which causes more nitrogen oxides when in

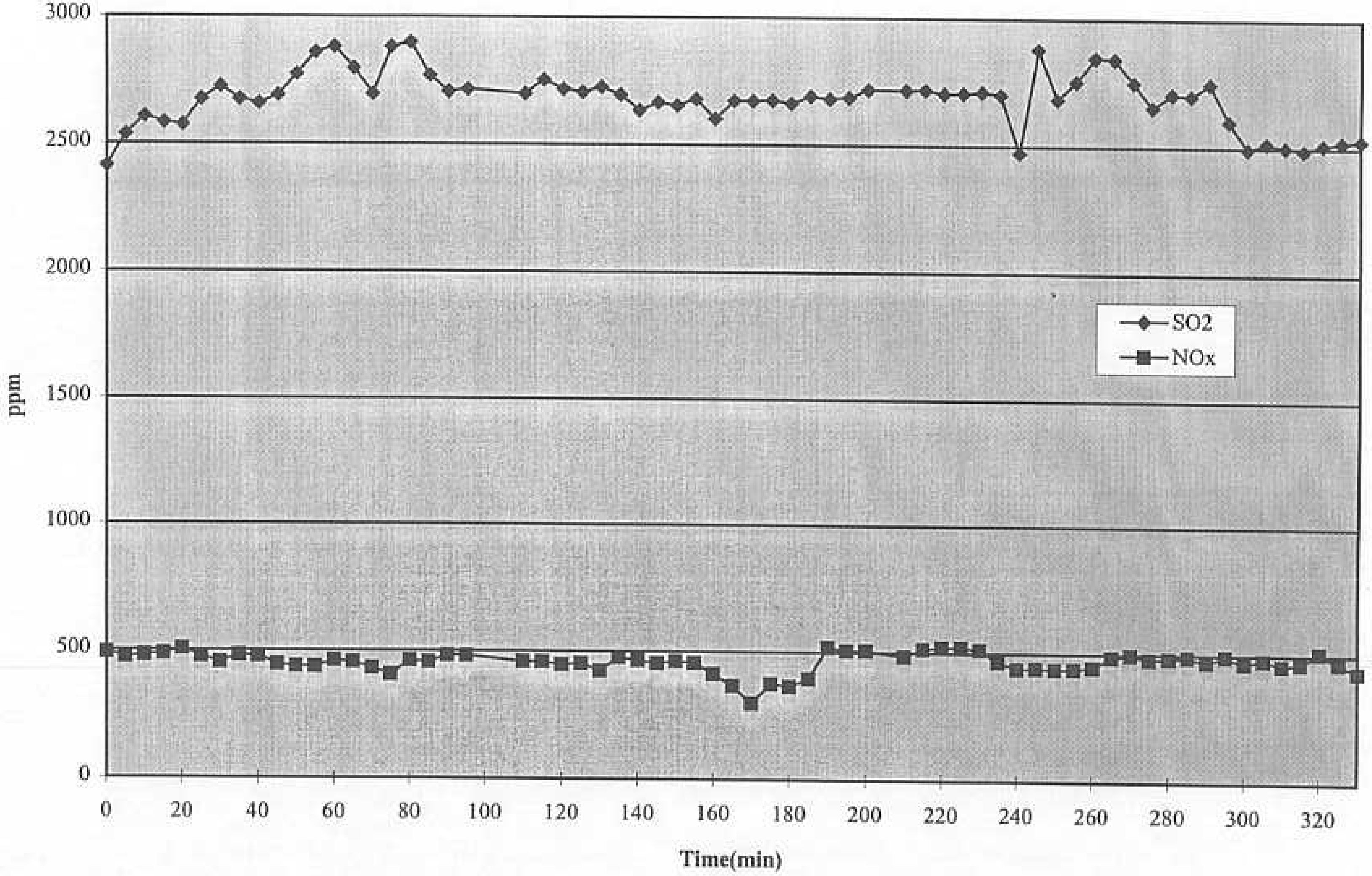


Figure 4.3. Concentrations of SO2 and NOx from flue gas during a test run at 834,330 Btu/hr

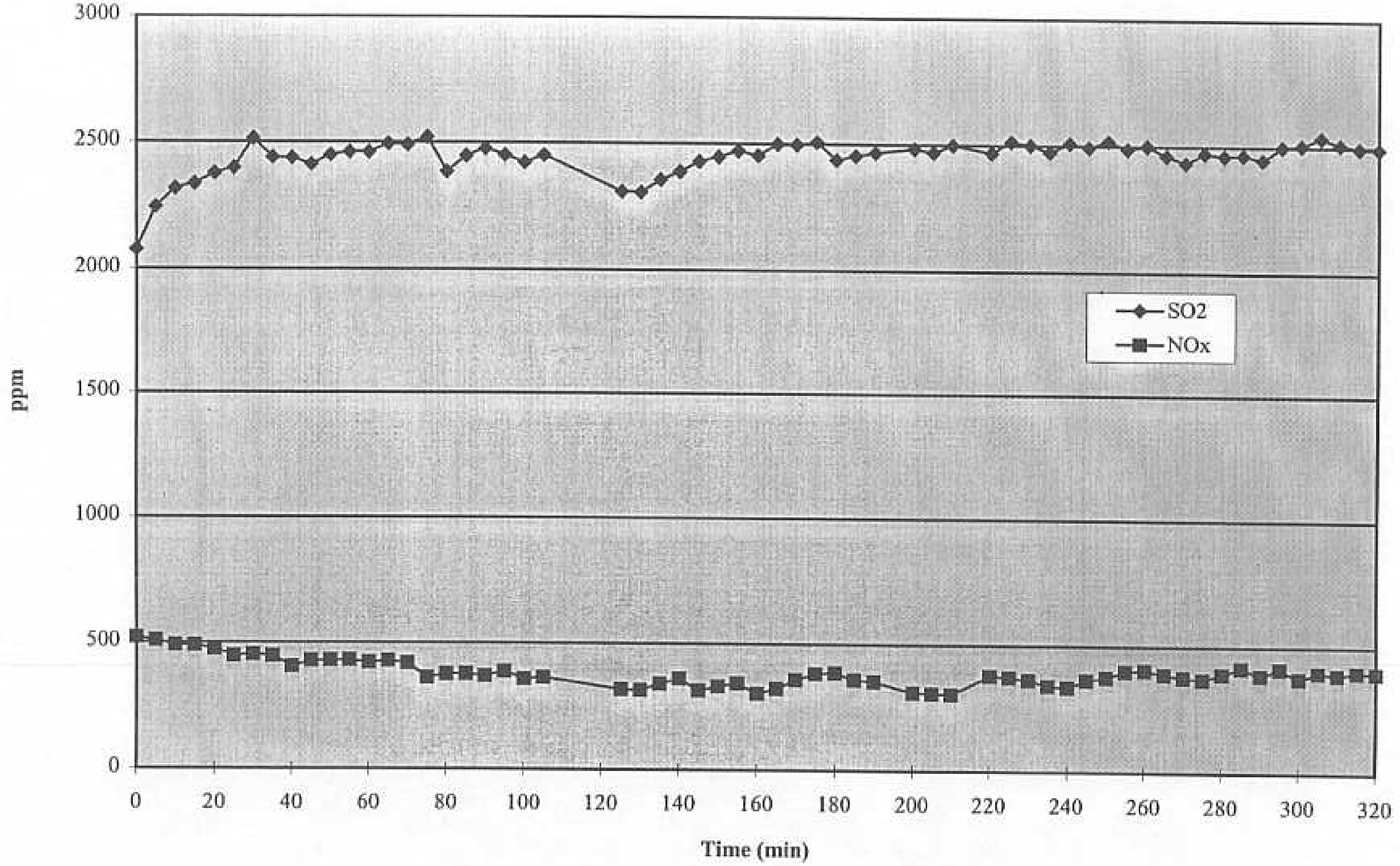


Figure 4.4 Concentrations of SO2 and NOx from the flue gas during a test run at 669,488 Btu/hr

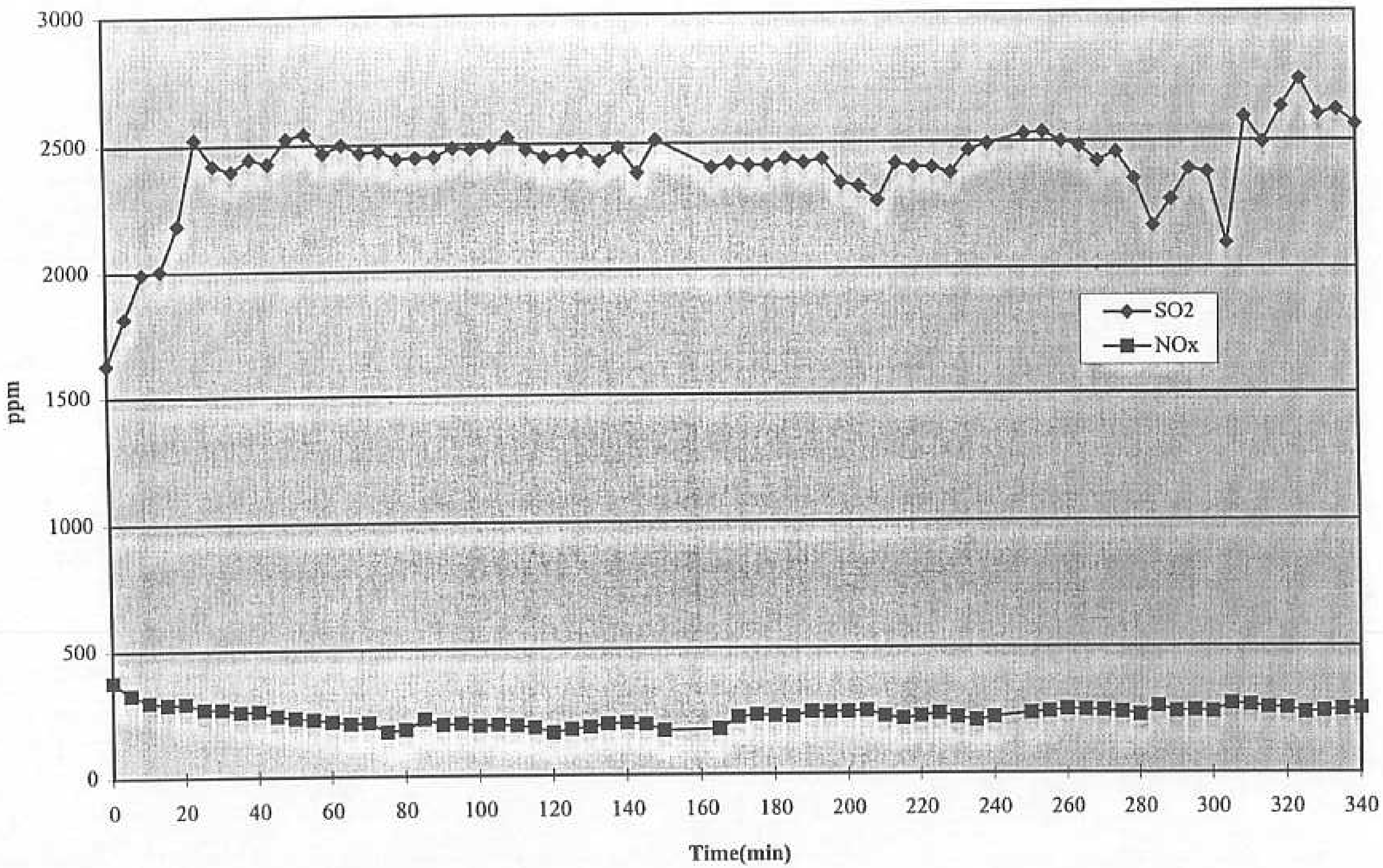


Figure 4.5 Concentrations of SO2 and NOx in the flue gas during a test run at 508,215 Btu/hr

contact with the air. Comparison of the NO_x emissions with the test results obtained from previously performed experiments by Shyam Singh et.al [43], involving the combustion of the blend of plant coal and recovered coal fines in the same proportions (85/15) shows a significant reduction of NO_x in case of CWS combustion. NO_x emissions of 827.7 ppm was recorded at a firing rate of 200,480 Btu/hr of coal blend combustion whereas, 240 ppm was noted for 508,215 Btu/hr firing rate of CWSF.

In addition, figures 4.3, 4.4 and 4.5 present the sulfur dioxide emissions obtained from the combustion of CWSF, at three different firing rates, over the total duration of the tests. The sulfur dioxide emissions were found to be in the range of 2000-3000 ppm for all three firing rates. Also, it is observed that as the firing rates increased, the SO_2 emissions also increased. Sulfur dioxide emissions are generally dependent on the amount of sulfur present in the fuel rather than the combustion properties. A high percentage of SO_2 emissions were observed for all three firing rates due to the presence of high sulfur in plant coal and recovered coal fines. From the ultimate analysis, the amount of sulfur in the CWSF was 1.84 wt%. A Comparison of the SO_2 emissions obtained from the combustion tests performed by Shyam Singh et.al[36] on blend (85% plant coal and 15% plant coal) revealed a lower SO_2 emissions for the blend combustion. SO2 emissions of 2041.9 ppm were listed at a firing rate of 200,480 Btu/hr for coal blend combustion, whereas, on an average 2500 ppm of SO_2 emissions were observed while firing CWSF at 508,215 Btu/hr firing rate. This increase in SO2 emissions was due to the high percentage of sulfur present in the CWSF.

Figures 4.6, 4.7 and 4.8 present the percentage of oxygen and carbon dioxide in the flue gas during the three tests at 834,330 Btu/hr, 669,488 Btu/hr and 508,215 Btu/hr respectively. It was found from the plots that the majority of oxygen emissions were in

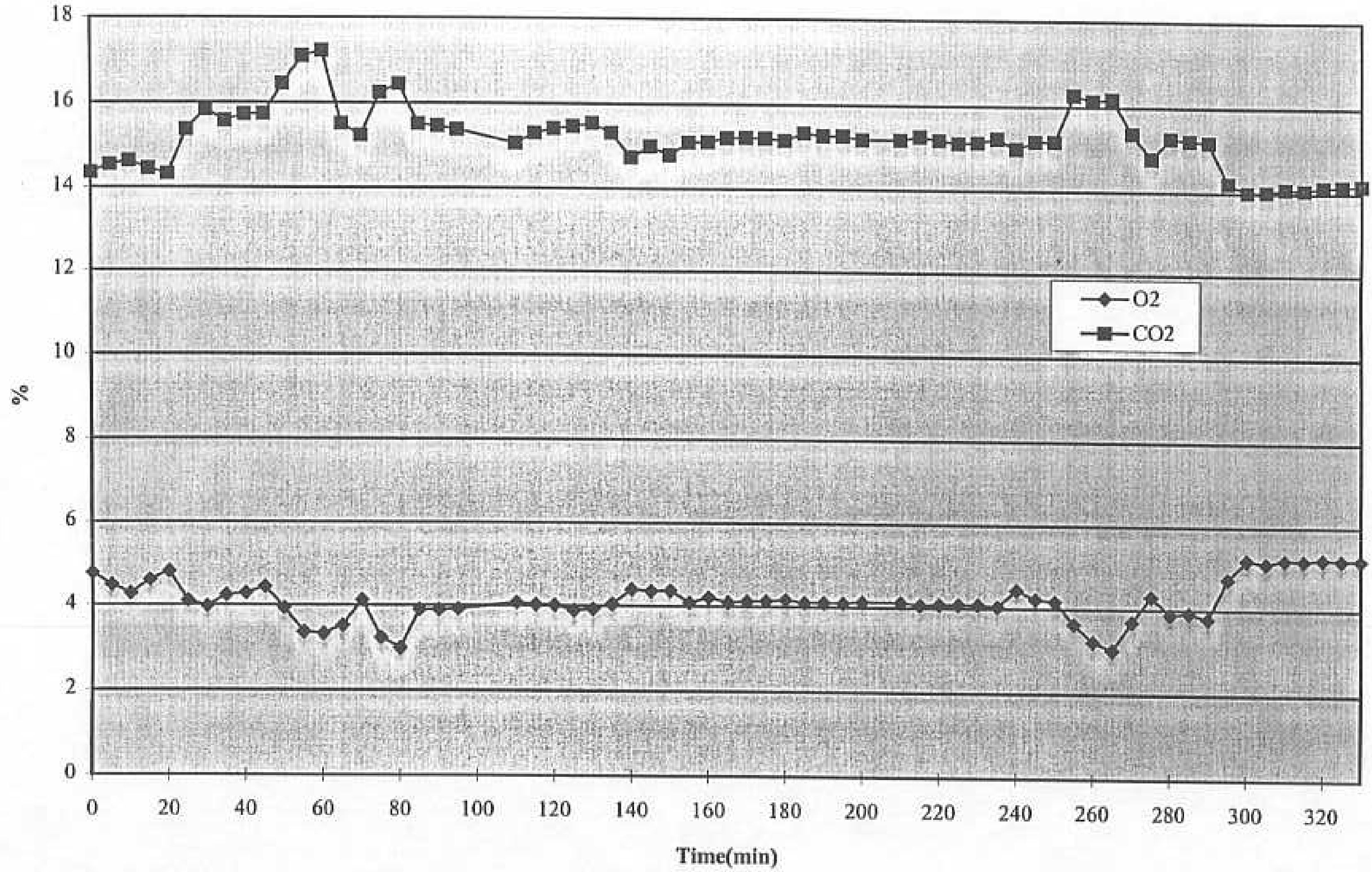


Figure 4.6. Concentrations of O2 and CO2 from the flue gas during a test run at 834,330 Btu/hr

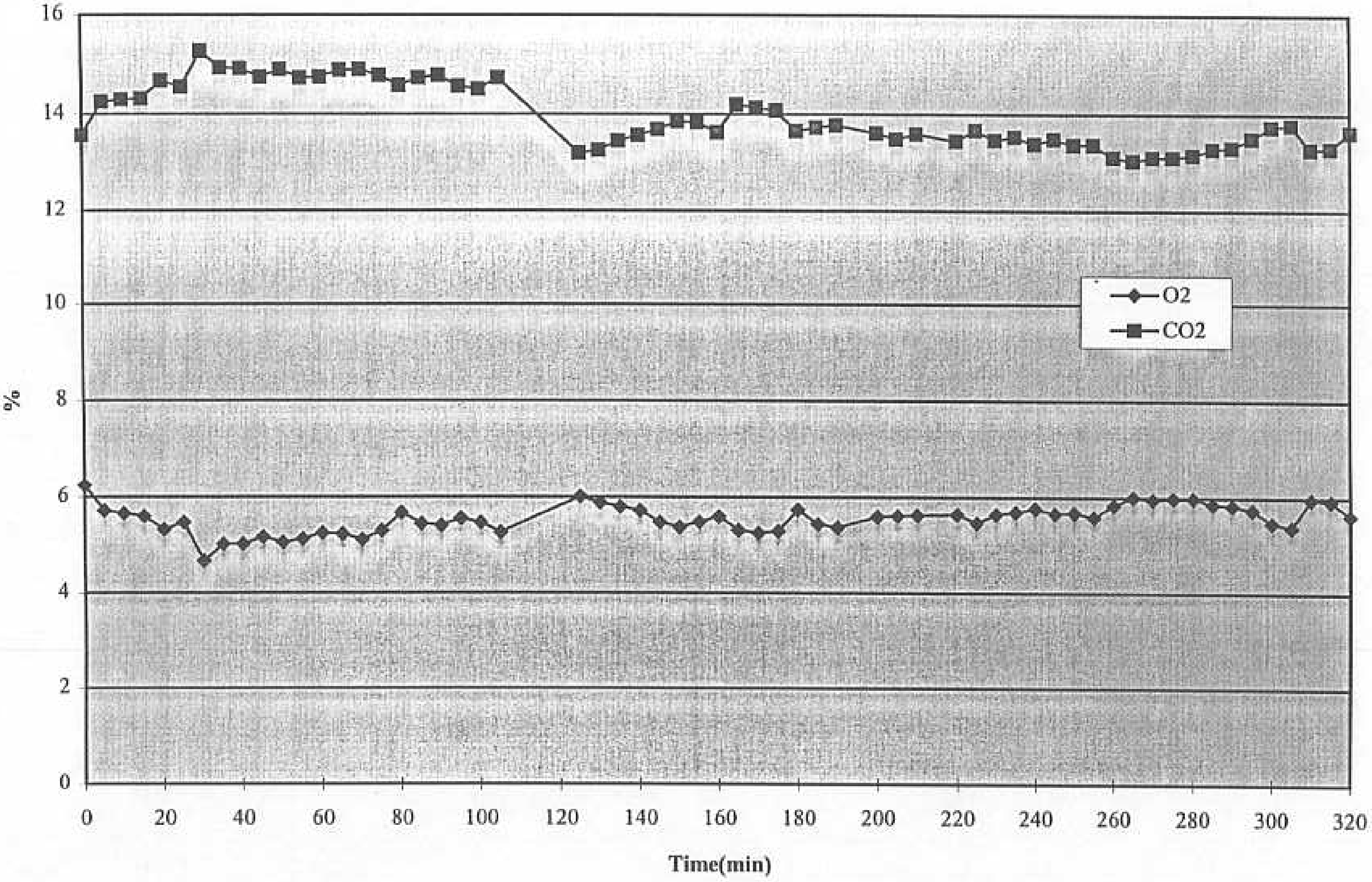


Figure 4.7 Concentrations of O2 and CO2 from the flue gas during a test run at 669,488 Btu/hr

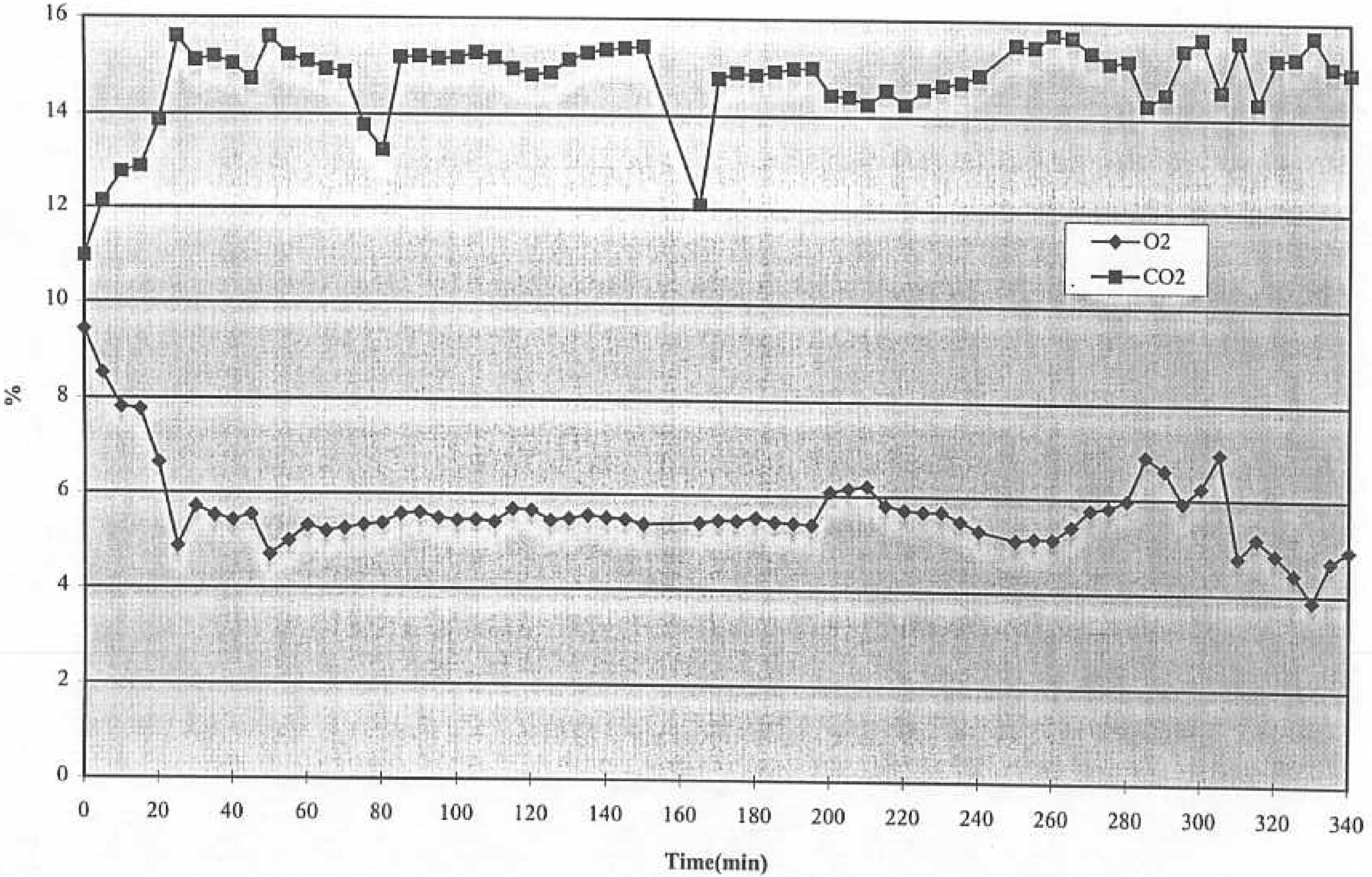


Figure 4.8 Concentrations of O2 and CO2 in the flue gas during a test run at 508,215Btu/hr

the range of 4 to 6 percent by weight. The carbon dioxide emissions were in the range of 13 to 17 percent by weight for all the three firing rates.

4.2.2 Effect of Swirl Settings on Gaseous Emissions and Various other Combustion Parameters.

Swirl is defined as the ratio of tangential momentum to axial momentum imparted to the secondary air stream. An important aspect of maintaining a stable flame in creating an internal recirculating zone within the flame, which allows for mixing of the combustion air and fuel. This phenomena can be implemented by creating a swirl. In order to allow the proper mixing of combustion air and fuel, an internal recirculation zone is set up to cause alternate paths of radial and tangential flow. Once the swirl was applied to the combustion air, the heating rate of coal particles were increased causing an increase in the release of volatiles and char combustion.

A flame is said to be stable when it is fully contained within the burner quarl. Flame stability is assessed by the visual observation of the flame in relation to the burner quarl as a function of secondary air and operating conditions.

The swirl setting when increased from a lower number to a higher number, the flame becomes more compact and intense upto a certain number which is considered to be optimum. Any further increase in the swirl number beyond the optimum level may cause the flame to be extracted into the burner region, exposing the burner components to the high intensity of heat, causing damage to the parts and possible combustion in the pipe.
Nitrogen oxide emissions could be effected by increasing the swirl in order to provide flame stability and higher carbon conversions. Excessive burner swirl can cause increased NO_x formation. Also, the position of flame front plays an important factor in NO_x formation[44].

Table 4.2 shows the flame stability test results obtained by varying the swirl number to 0.2, 0.4 and 0.55 for all three firing rates. The various parameters measured are

Table 4.2 Flame Stability Test Results

	Swirl Number	**Heat Input:** **834,330 Btu/hr** **Feed Rate :** **140.2 lb/hr** **Date: 8/02/95**	**Heat Input:** **669,488 Btu/hr** **Feed Rate :** **112.5 lb/hr** **Date: 8/03/95**	**Heat Input:** **508,215 Btu/hr** **Feed Rate :** **85.4lb/hr** **Date: 8/04/95**
CO2	0.55	16.5	16.8	14.9
%	0.4	17.9	17.6	15.3
	0.2	16.4	17.6	15.1
Nox	0.55	480	471	242
(ppm)	0.4	452	424	243
	0.2	442	424	256
SO2	0.55	2895	2807	2403
(ppm)	0.4	3191	2806	2665
	0.2	2943	2853	2498
C in Ash	0.55	2.83	2.2	3.36
%	0.4	1.68	1.62	3.92
	0.2	1.94	1.35	3.88
FEGT	0.55	2130	2136	1997
°F	0.4	2137	2129	2012
	0.2	2166	2132	2016
Furnace	0.55	2195	2195	2038
HVT	0.4	2117	2187	2002
Temp °F	0.2	2142	2180	1980
Primary	0.55	15.88	13.08	8.56
Air	0.4	16.10	12.08	8.44
Scfm	0.2	15.57	11.83	8.61
Secondary	0.55	118.62	100.43	69.65
Air	0.4	115.13	99.20	69.59
Scfm	0.2	116.30	100.49	69.96
Excess Air	0.55	17.78	21.95	22.15
%	0.4	15.49	19.55	18.56
	0.2	12.84	20.07	21.25

percentage of carbon in ash, FEGT (Furnace Exit Gas Temperature), Furnace HVT(High Velocity Thermocouple) temperature, primary air flow, secondary air flow excess air, and flue gas composition The FEGT was found to be in the range of 1990-2170 °F and furnace HVT temperature in the range of 2000-2200 °F. The lowest FEGT of 1997 °F was reported for a firing rate of 508,215 Btu/hr at a swirl setting of 0.5 and the highest FEGT being 2166 °F at a firing rate of 834,330 Btu/hr and 0.2 swirl setting. A trend in decrease of temperature was noticed as the firing rate was decreased. The primary air was in the range of 15-17 scfm and secondary air in the range of 115-119 scfm.

Figures 4.9 and 4.10 show the effect of NO_x and SO_2 emissions with respect to the swirl number at three test conditions(834,330 Btu/hr, 669,488 Btu/hr and 508,215 Btu/hr). A significant increase in the NO_x and SO_2 emissions were observed with an increase in the firing rate. At the lowest firing rate the Nox emissions were in the range of 240-250 ppm, and 420-480 ppm for highest firing rate. SO_2 emissions in the case of lowest firing rate were in the range of 2400-2700 ppm for lowest firing rate and 2800-3200 ppm for highest firing rate. It was observed that varying the swirl caused a very small variation on the gaseous emissions and there was no definite correlation in the data with respect to the change in swirl. Also, it was noticed that various other factors such as air flow, excess air and temperature influenced the gaseous emissions and hence, an inconsistency in the gaseous emission data was observed.

Percentage of carbon in ash signifies the amount of carbon that is not burnt. From this data the carbon conversion efficiency can be evaluated. Table 4.2 shows the percentage of carbon at each firing rate for different swirl numbers. The carbon conversion efficiencies were calculated for each swirl setting from the percentage of carbon in ash. It was found that the carbon conversion efficiency in all the cases irrespective of the swirl setting is found to be greater than 98 percent. Additionally, from Table 4.2 one can notice that the percent of carbon content in ash, at the lowest firing rate, is nearly twice the carbon content of the two higher firing rates.

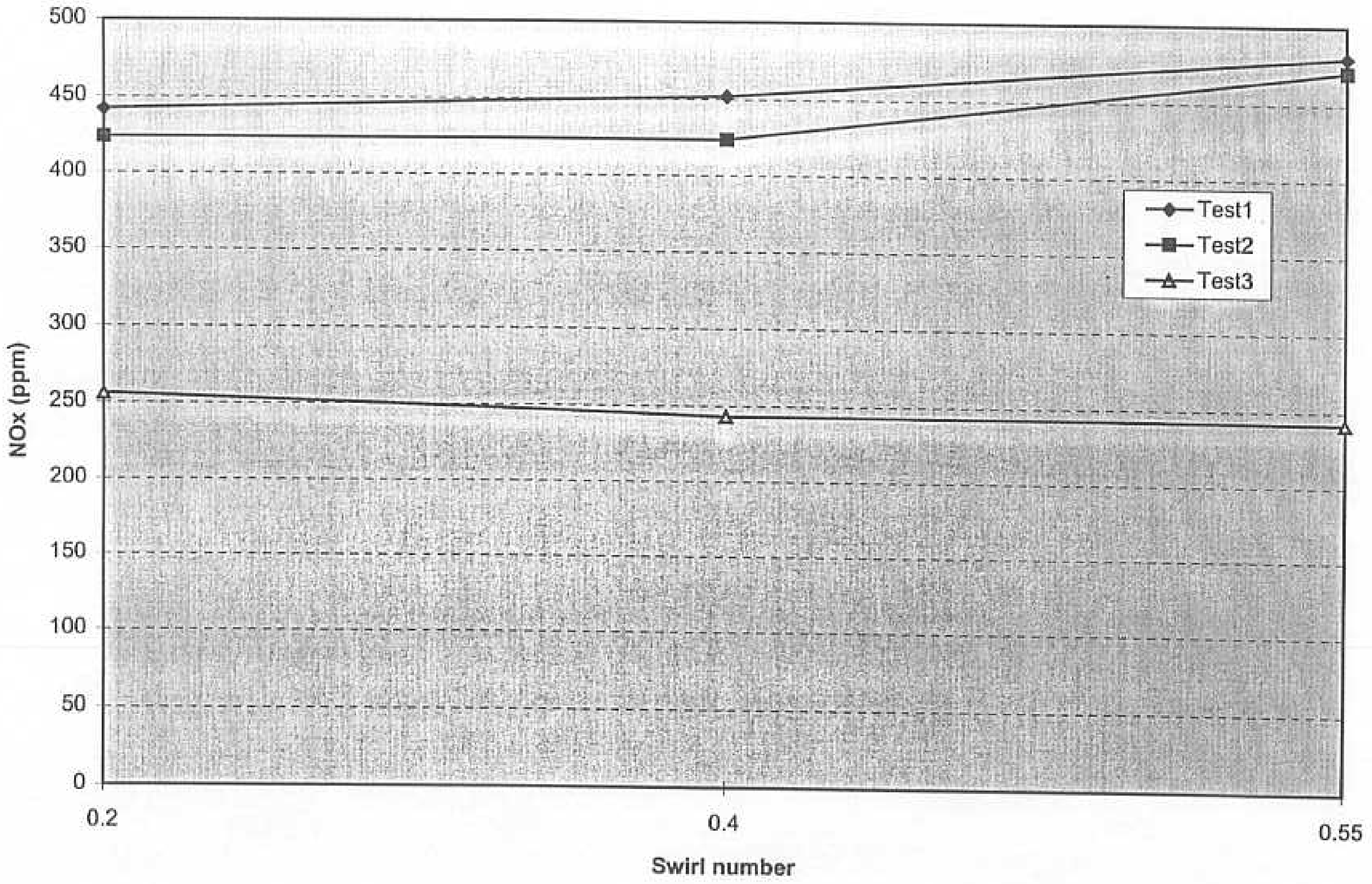


Figure 4.9 Effect of Swirl Setting on NOx at Three Firing Rates

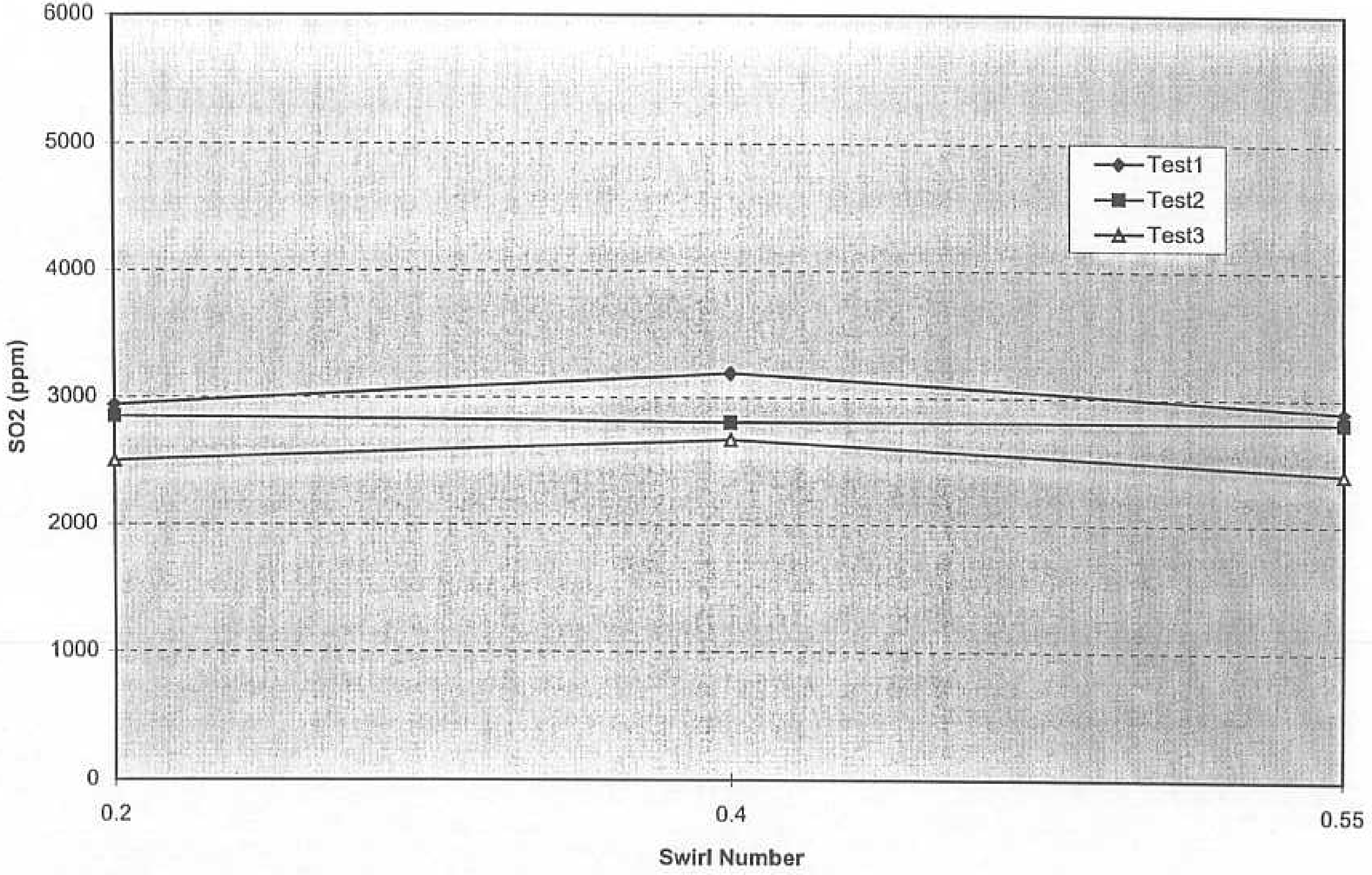


Figure 4.10 Effect of swirl setting on SO2 at three firing rates

Figures 4.11, 4.12 and 4.13 show the photographs of the flame at a swirl number of 0.2, 0.4 and 0.55 respectively, and at a firing rate of 834,330 Btu/hr. A higher swirl number indicates a higher tangential velocity component over the axial velocity component. Figure 4.11 represents a diffused flame and was not contained within the burner quarl. Figure 4.12 shows the flame at 0.40 swirl and was more compact, but Figure 4.13 which was adjusted at a swirl number of 0.55 was more stable than the other two burner settings. Although the flames were diffused, at this particular setting of 0.55 the flame was comparatively more compact and contained within the burner quarl, indicating a stable flame over the other two burner settings.

Figures 4.14 and 4.15 show the photographs of the flame at 0.55 swirl number for 669,488 Btu/hr and are taken within a minute difference. Figures 4.16 and 4.17 show the flame at 0.40 swirl number for a firing rate of 669,488 Btu/hr and are taken a minute apart. From the comparison of these two sets of figures, it is seen that the flame at 0.40 swirl number is found to be more compact and stable over the flame at 0.55 swirl number.

Figures 4.18 and 4.19 show the photographs of the flame at 0.80 and 0.55 swirl number for 508,215 Btu/hr. From these photographs it can be observed that the flame is totally diffused and very hard to visualize the stability of the flame. At a swirl setting of 0.55 the flame is more stable than at the 0.80 swirl setting.

4.2.3 Flue Gas Compositions and Various Parameters Measured at Bottom, Middle and Top Locations of the Combustion Chamber

Ash and flue gas samples from three different locations of the combustion chamber were collected for different firing rates. Table 4.3, 4.4 and 4.5 show the FEGT, gas volume, residence time, flue gas compositions, moisture percentages and loss on ignition data for three firing rates and at three different locations of the combustion chamber. The bottom, middle and top ports are 23.5, 44 and 66.5 inches from the burner quarl. From the tables, the following observations are made. The furnace exit gas temperatures did not vary significantly from the middle top and bottom locations for each firing rate. But a change in temperature with respect to the firing rate was observed. The temperatures increase

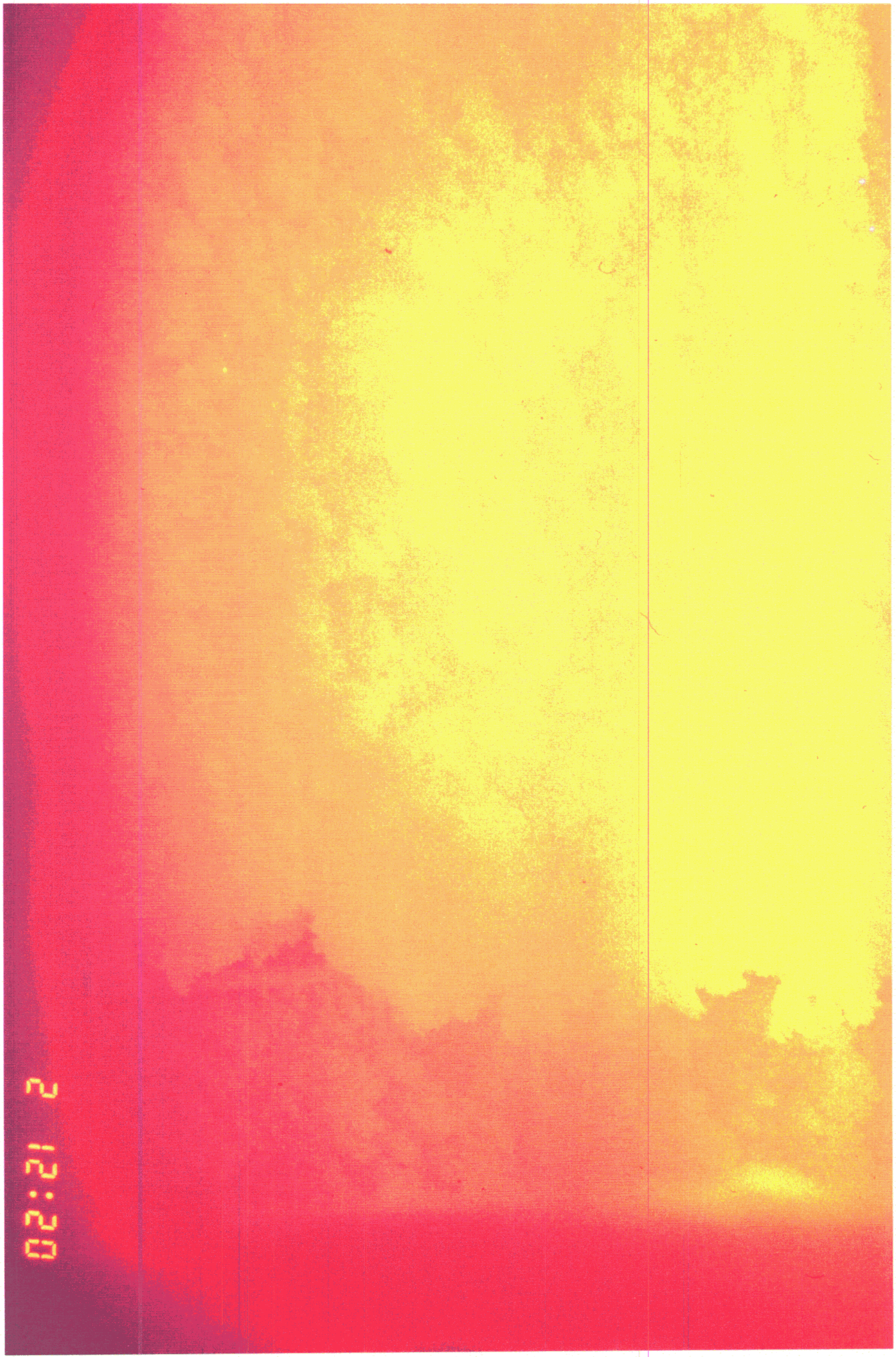


Figure 4.11 Flame at a firing rate of 834,330 Btu/hr adjusted to 0.2 swirl number

Figure 4.12 Flame at a firing rate of 834,330 Btu/hr adjusted to 0.4 swirl number

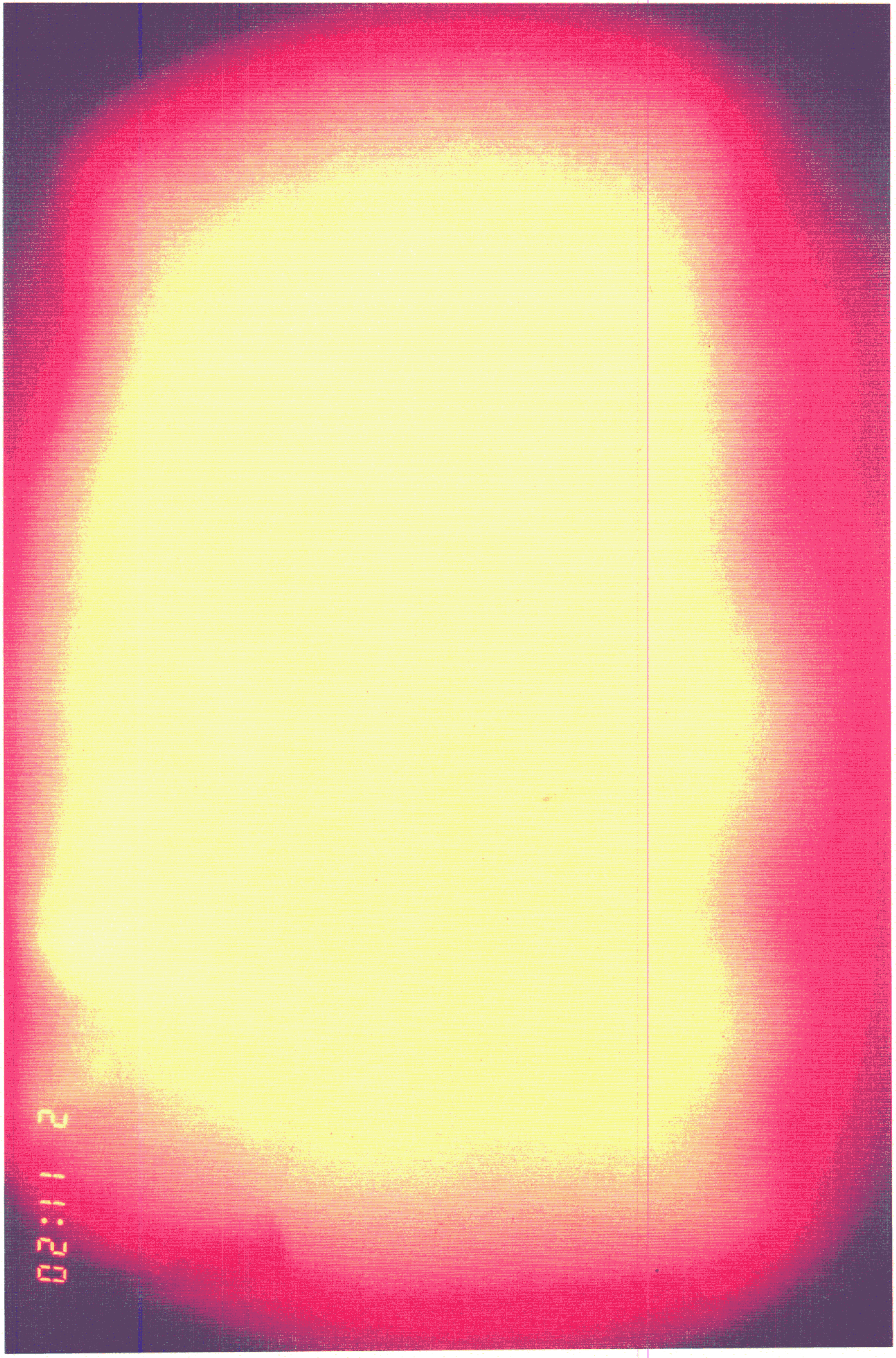


Figure 4.13 Flame at a firing rate of 834,330 Btu/hr adjusted to 0.55 swirl number

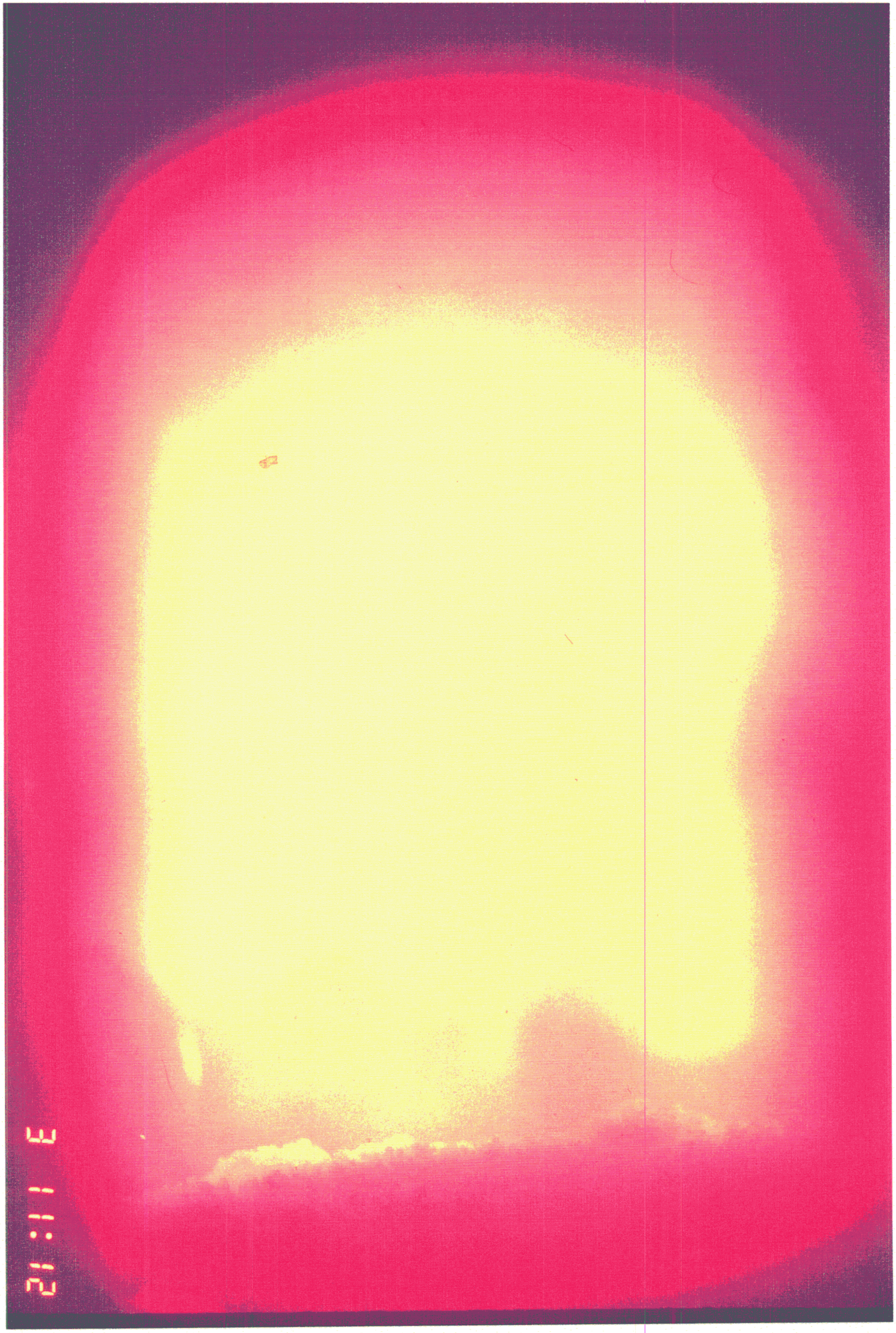


Figure 4.14 Flame at a firing rate of 669,488 Btu/hr adjusted 0.55 swirl number (11:12 hh:mm)

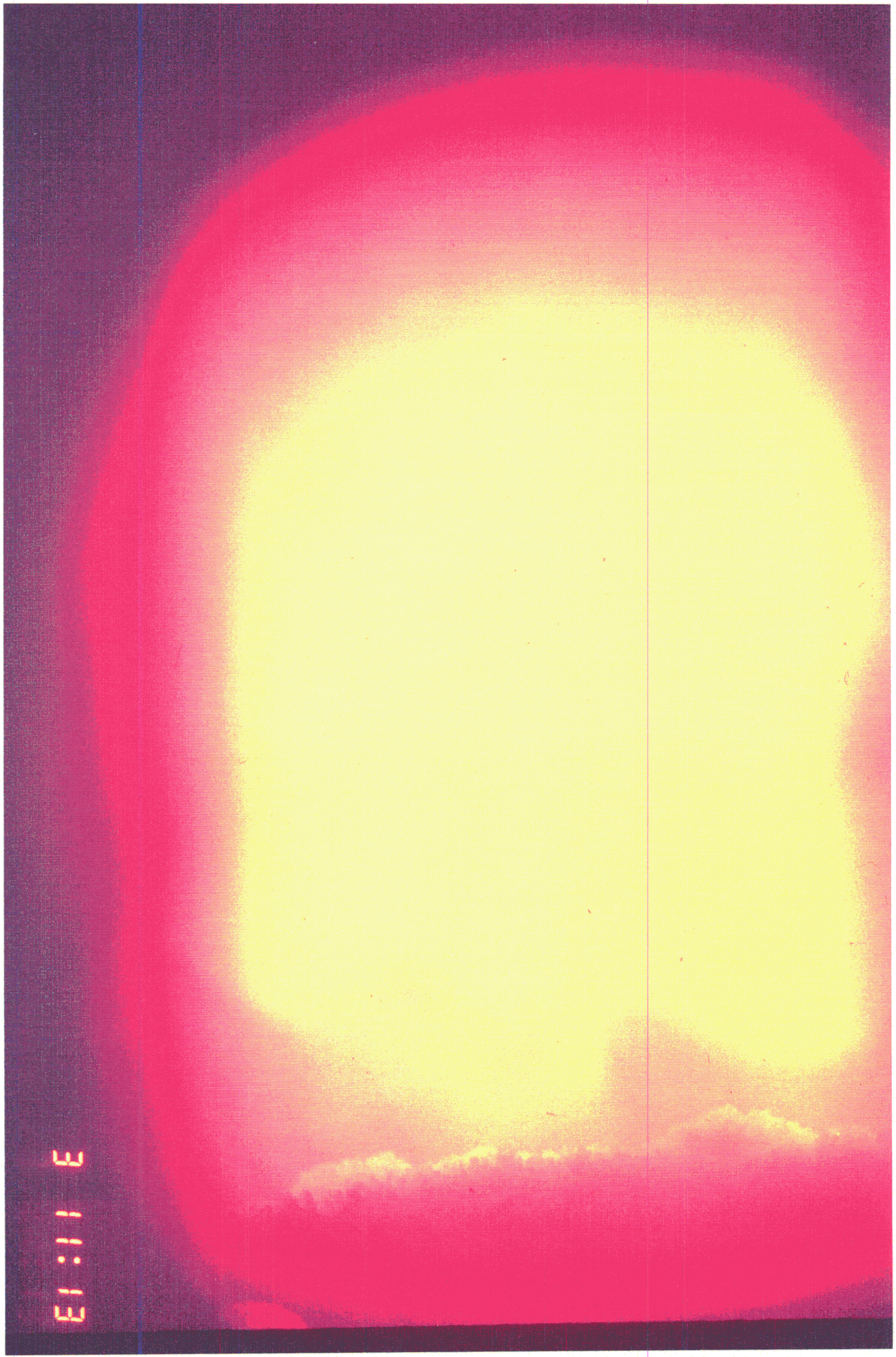


Figure 4.15 Flame at a firing rate of 669,488 Btu/hr adjusted to 0.55 swirl number (11:13 hh:mm)

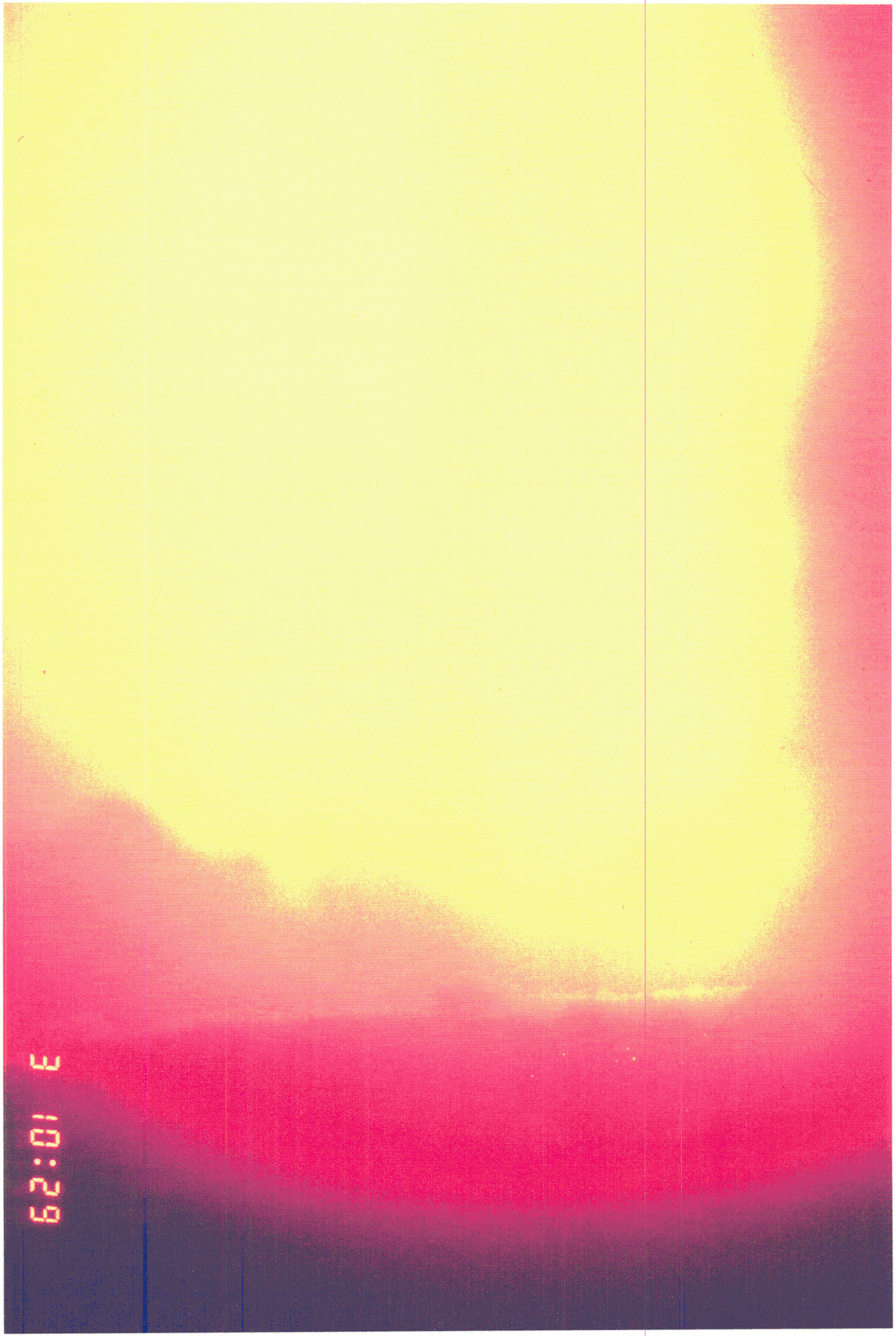


Figure 4.16 Flame at a firing rate of 669,488 Btu/hr adjusted to 0.4 swirl number (10:29 hh:mm)

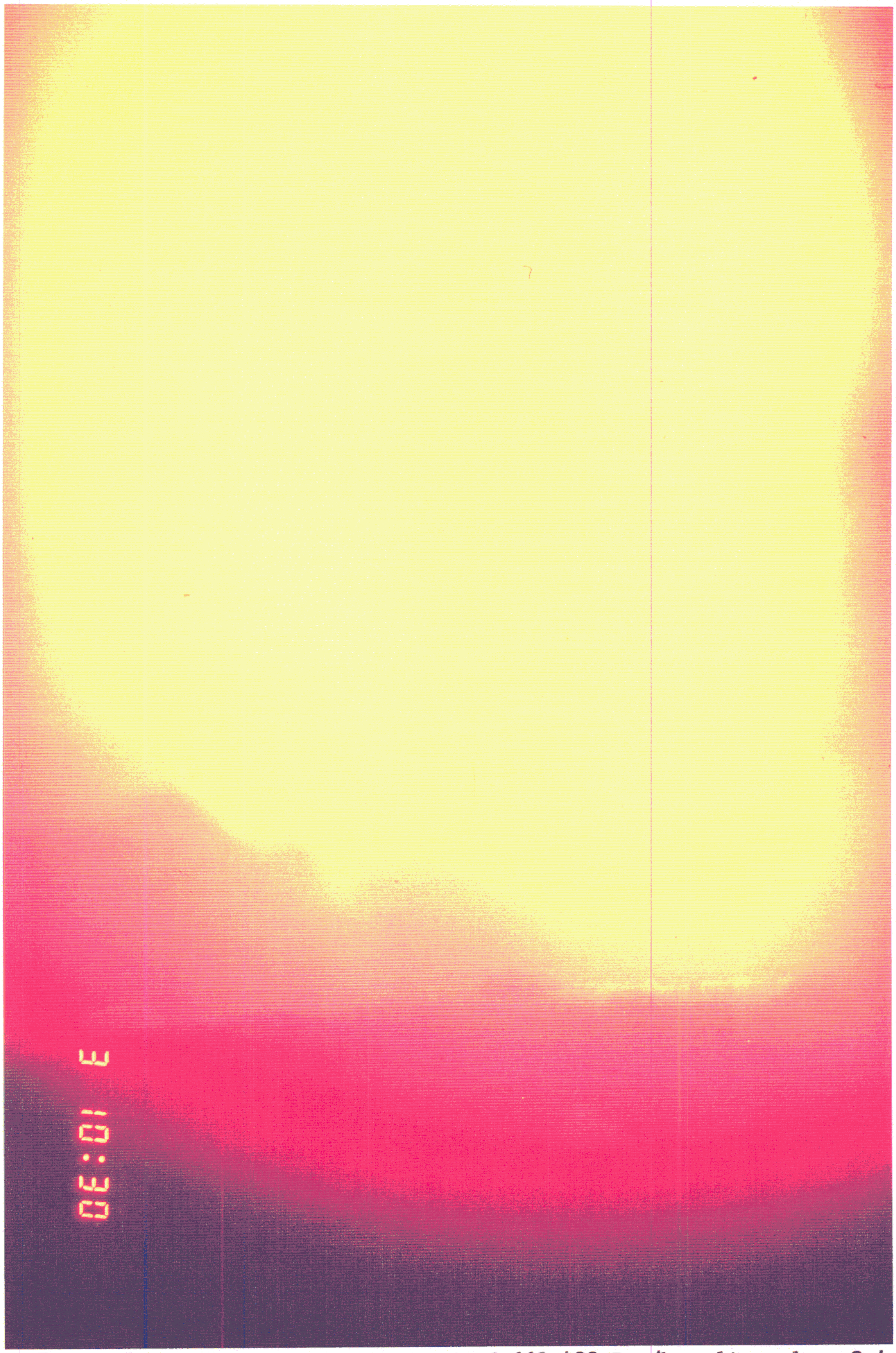


Figure 4.17 Flame at a firing rate of 669,488 Btu/hr adjusted to 0.4 swirl number (11:30 hh:mm)

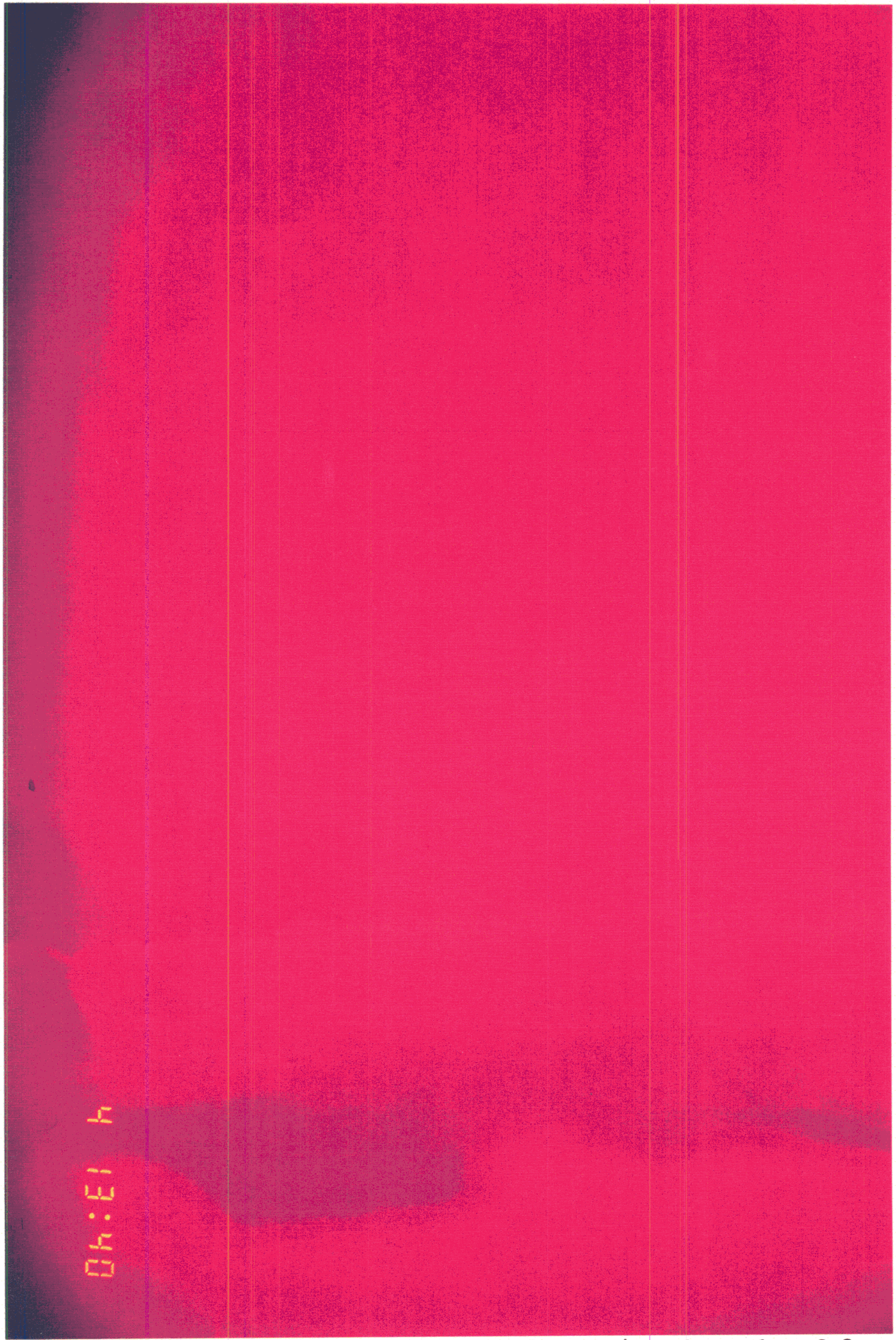


Figure 4.18 Flame at a firing rate of 508,215 Btu/hr adjusted to 0.8 swirl number

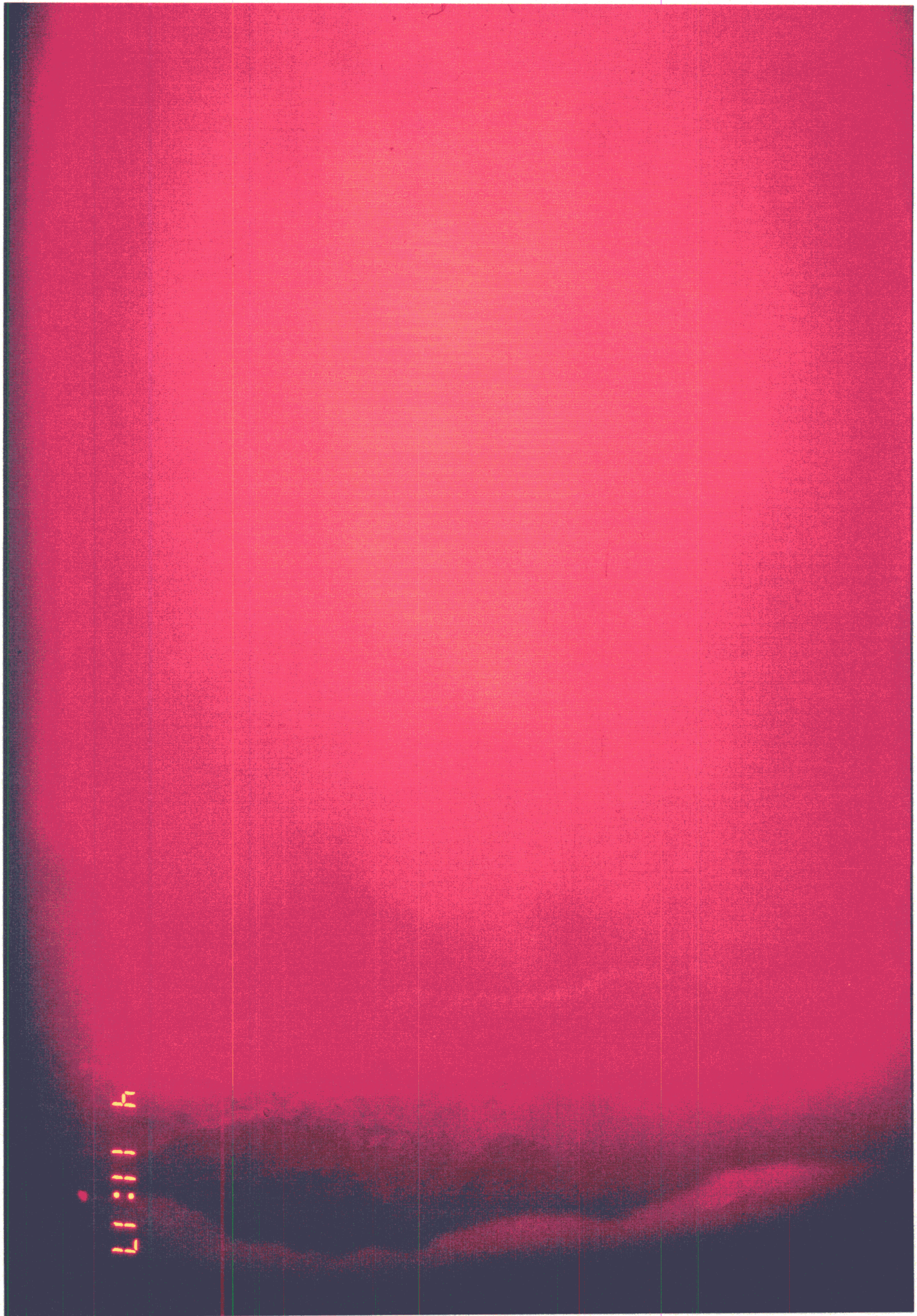


Figure 4.19 Flame at a firing rate of 508,215 Btu/hr adjusted to 0.55 swirl number

Table 4.3 Test results of flue gas compositions and various parameters measured at three different locations of the combustion chamber at 834,330 Btu/hr

Test 1 (AF-CTS-712)
Heat Input: 834,330 Btu/hr
Feed Rate : 140.2 lb/hr
Date: 8/02/95

Sampling Location	Bottom	Middle	Top
FEGT, °F	2153	2159	2191
Gas Volume, acfm	974.7	1019.8	963.1
Residence Time, sec	0.59	1.06	1.70
Flue Gas Composition			
O_2, % dry	2.72	3.65	2.444
CO_2, % dry	15.9	15.8	16.9
SO_2, ppm	2264	2818	3103
NO_x, ppm	458	468	481
Excess Air, %	14.75	21.06	13.19
Moisture, %	2.12	2.54	2.85
LOI, %	84.01	22.41	6.60

Table 4.4 Test results of flue gas compositions and various parameters measured at three different locations of the combustion chamber at 669,488 Btu/hr

Test 2 (AF-CTS-713)
Heat Input: 669,488 Btu/hr
Feed Rate : 112.5 lb/hr
Date: 8/03/95

Sampling Location	Bottom	Middle	Top
FEGT, °F	2070	2085	2087
Gas Volume, acfm	840.2	821.6	826.6
Residence Time, sec	0.68	1.32	1.98
Flue Gas Composition			
O_2, % dry	4.19	3.74	3.87
CO_2, % dry	14.5	14.9	14.9
SO_2, ppm	2479	2723	2846
NO_x, ppm	317	333	379
Excess Air, %	24.69	21.51	22.41
Moisture, %	1.92	1.27	0.00
LOI, %	84.76	17.02	2.33

Table 4.5 Test results of flue gas compositions and various parameters measured at three different locations of the combustion chamber at 508,215 Btu/hr

Test 3 (AF-CTS-714)
Heat Input: 508,215 Btu/hr
Feed Rate : 85.4lb/hr
Date: 8/04/95

Sampling Location	Bottom	Middle	Top
FEGT, °F	1961	1977	2002
Gas Volume, acfm	627.9	631.4	620.3
Residence Time, sec	0.91	1.71	2.64
Flue Gas Composition			
O_2, % dry	3.88	3.98	3.64
CO_2, % dry	14.7	15.0	15.2
SO_2, ppm	2488	2855	2864
NO_x, ppm	213	178	200
Excess Air, %	22.43	23.31	20.82
Moisture, %	1.20	1.28	0.33
LOI, %	84.93	19.03	3.65

with an increase in firing rate. The residence time is calculated by taking the volumetric flow rate divided by the cross-sectional area of the furnace multiplied by the distance to each port. It is seen that as the firing rate increases, more fuel is injected and as a result more gases are evolved, causing the gas to flow at a higher velocity and hence lower residence time. From Tables 4.3, 4.4 and 4.5 it is seen that the residence times are 0.59, 0.68 and 0.91 seconds for 140.2 lb/hr, 112.5 lb/hr and 85.4 lb/hr respectively at bottom location. Figure 4.20 shows the residence time with respect to the firing rates at different locations. NO_X concentrations are highest for top location followed by middle and bottom locations for the two higher firing rates. Sulfur dioxide concentrations are also observed to increase from bottom location to top location in all three firing rates. Oxygen percentage is found to be in the range of 2.5 to 4.5 and carbon dioxide is in the range of 14 to 17 percent for all the firing rates.

LOI indicates the percentage burnout of all the material collected. From Table 4.3 it can be seen that the burnout percentage was 84.84% at the bottom, 22.41% at the middle and 6.60% at the top of the combustion chamber for a firing rate of 834,330 lb/hr. It can be concluded that the majority of the fuel about 84% of the fuel is burnt at the bottom of the furnace. The excess air ranges from 13-22, 21-25 and 19-26 percent for firing rates of 834,330 Btu/hr, 669,488 Btu/hr and 508,215 Btu/hr respectively. The percentage of moisture decreases as the firing rate decreases. This is due to the fact that the residence time increases with decrease in the firing rate.

Figure 4.21 shows a sample of ash deposit collected during a test run of 669,488 Btu/hr. The details of the ash x-ray fluorescence analysis of the ash deposits, CWS and its feedstocks on a sulfur and ash free basis are presented in reference [45].

4.2.4 Carbon Conversion Efficiency

Percentage of carbon in ash signifies the amount of carbon that is not burnt. From this data the carbon conversion efficiency can be evaluated. Table 4.2 shows the percentage of carbon at each firing rate for different swirl numbers. The carbon conversion

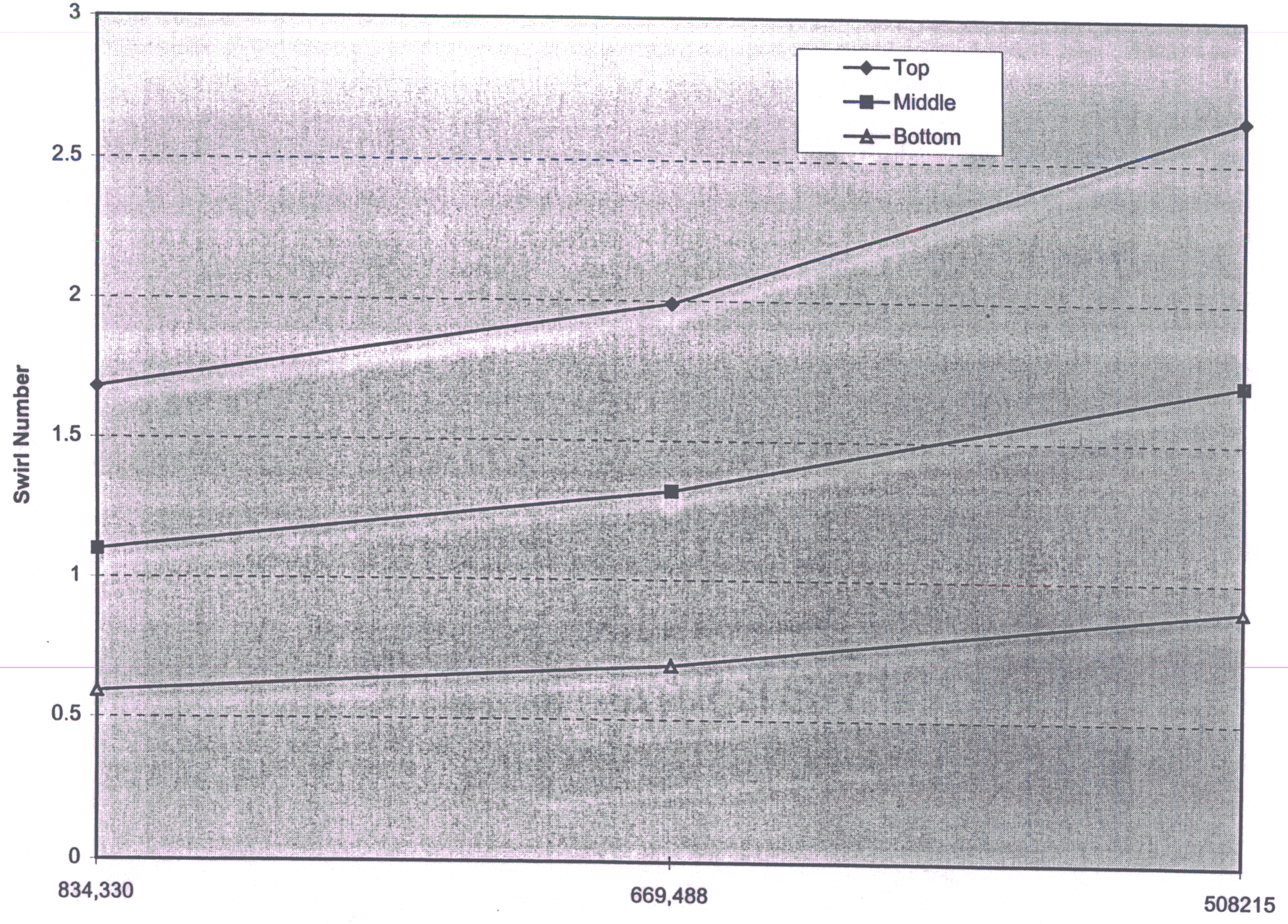


Figure 4.20 Residence time for different firing rates at different locations of the combustion chamber

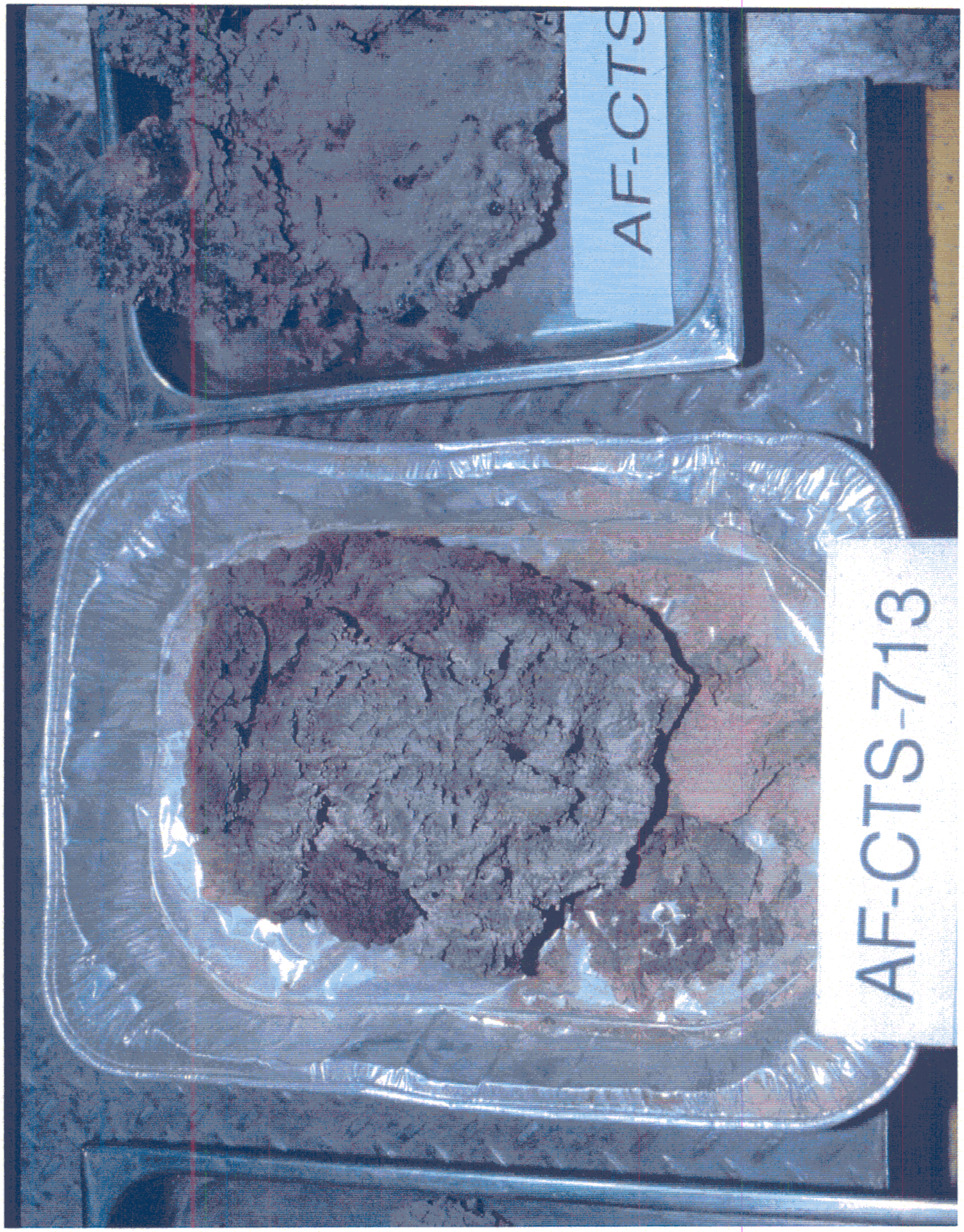


Figure 4.21 Sample of ash deposit collected during a test run at 669,488 Btu/hr

efficiencies are calculated for each swirl setting from the percentage of carbon in ash. It is seen that the carbon conversion efficiency in all the cases irrespective of the swirl setting is found to be greater than 98 percent. Also, from Table 4.2 it can be observed that the percentage of carbon content in ash at the lowest firing rate is nearly twice the carbon content of the two higher firing rates.

4.3 PARTICULATE ANALYSES

Tables 4.6 - 4.8 are the results of the particulate extraction tests that were conducted at firing rates of 834,330, 669,488, and 508,215 Btu/hr.

For the firing rate 834,330 Btu/hr, the values for carbon dioxide were greatest at the top of the burner at this firing rate. Therefore, this fuel has a high carbon content. This indicates good fuel efficiency. The values for NOx increased from bottom to top, however this was not the exact pattern. There was a slight variation in this pattern because of the large amount of excess air that was detected at the middle of the burner.

As well, these values for NOx were less than 500 ppm all three locations for firing rate of 834,330 Btu/hr, this is very much desired because the value falls within EPA standards and this fuel may be used in industry.

It can also be observed from Table 4.6 - 4.8 that the percent variations between O_2 and CO_2 are minimal at all three test runs. The level of NO_x in ppm for the middle location is less than the top and bottom.

For the firing rate of 669,488 Btu/hr, particulate extraction test results, it can be observed in Table 4.7 that the values for NOx very significantly lower than those in Table 4.6. With the largest value for NOx at 379 ppm which was extracted from top of the burner quarl at the end of the test run. This value fell well below the EPA standard of 500 ppm.

The SO_2 values for Table 4.7 were slightly higher than those in Table 4.6, these values vary any where from 2898 to as low as 2479, whereas in Table 4.6 the range was from 3103 to 2197. It can be seen in these charts that the pattern for these values were inconsistent. They did not steadily increase from top to bottom or reason for this inconsistency was because there was a significant amount of excess air in the burner quarl. The same inconsistent pattern occurred for the O_2 values.

In Table 4.8 the NO_X values were lower than both Tables 4.6 and 4.7, this is because the test was performed at a lower firing rate, 508,215 Btu/hr. The percent values of CO_2 remained relatively consistent between 14.4 to 15.2.

Table 4.6 - Particulate Extraction Test AF-CTS-712 at 140.2 lb/hr Feed Rate and 834,330 Btu/hr Firing Rate

Time	1311	1410	1522	1615	1644	1658
Sample Location	Bottom	Middle	Top	Top	Middle	Bottom
FEGT °F	2153	2153	2162	2191	2159	2155
Gas Vol, scfm	974.7	978.7	972.2	963.1	1019.8	1020.3
Residence Time, sec	0.59	1.10	1.68	1.70	1.06	0.56
Flue Gas Comp						
O_2, % dry	2.72	2.81	2.64	2.44	3.65	3.63
CO_2,% dry	15.9	15.9	16.7	16.9	15.8	16.2
SO_2, ppm	2264	2197	2213	3103	2818	2842
NO_x, ppm	458	383	473	481	468	451
Excess Air %	14.75	15.35	14.42	13.19	21.06	21.11
Moisture %	2.12	2.71	2.07	2.85	2.54	3.22
LOI, %	84.01	39.60	6.44	6.60	22.41	84.84

Table 4.7 - Particulate Extraction Test AF-CTS-713 at 112.5 lb/hr Feed Rate and 669,488 Btu/hr Firing Rate

Time	1205	1227	1257	1337	1414	1450
Sample Location	Bottom	Bottom	Middle	Middle	Top	Top
FEGT °F	2086	2070	2077	2085	2078	2087
Gas Vol, scfm	831.6	840.2	819.6	821.6	821.6	826.6
Residence Time, sec	0.69	0.68	1.32	1.32	1.99	1.98
Flue Gas Comp O_2, % dry	3.89	4.19	3.69	3.74	3.74	3.87
CO_2,% dry	16.9	14.5	15.0	14.9	15.1	14.9
SO_2, ppm	2815	2479	2898	2723	2863	2846
NO_x, ppm	362	317	324	333	347	379
Excess Air %	23.26	24.69	21.17	21.51	21.54	22.41
Moisture %	1.78	1.92	1.59	1.27	0.00	0.00
LOI, %	84.78	84.76	15.48	17.02	1.45	2.33

Table 4.8 - Particulate Extraction Test AF-CTS-714 at 85.4 lb/hr Feed Rate and 508,215 Btu/hr Firing Rate

Time	956	1027	1056	1128	1221	1243
Sample Location	Top	Top	Middle	Middle	Bottom	Bottom
FEGT ^{o}F	2002	1988	1977	1979	1957	1961
Gas Vol, scfm	616.8	620.3	631.4	619.8	641.4	627.9
Residence Time, sec	2.65	2.64	1.71	1.74	0.90	0.91
Flue Gas <u>Comp</u> O_2, % dry	3.53	3.64	3.98	3.60	4.30	3.88
CO_2,% dry	15.0	15.2	15.0	15.4	14.4	14.7
SO_2, ppm	2856	2864	2855	2860	2433	2488
NO_x, ppm	210	200	178	173	220	213
Excess Air %	19.9	20.82	23.31	20.60	25.57	22.43
Moisture %	0.00	0.33	1.28	1.83	1.91	1.20
LOI, %	1.25	3.65	19.03	28.50	84.89	84.93

4.4 PARTICLE SIZE DISTRIBUTION

Figures 4.22 through 4.26 show the particle size distribution for plant coal, recovered coal fines, coal-water slurry, ESP ash and fly ash respectively. As viewed from these figures, 90 percent of particles by weight have sizes less than 70 microns for plant coal, less than 20 microns for recovered coal fines, less than 77 microns for CWS, less than 36 microns for ESP ash less than 30 microns for fly ash. Additionally, majority of particles by weight have size range between 36 to 88 microns for plant coal, between 3 to 27 microns for recovered coal fines, between 9 to microns for CWS, between 7 to 27 microns for ESP ash and between

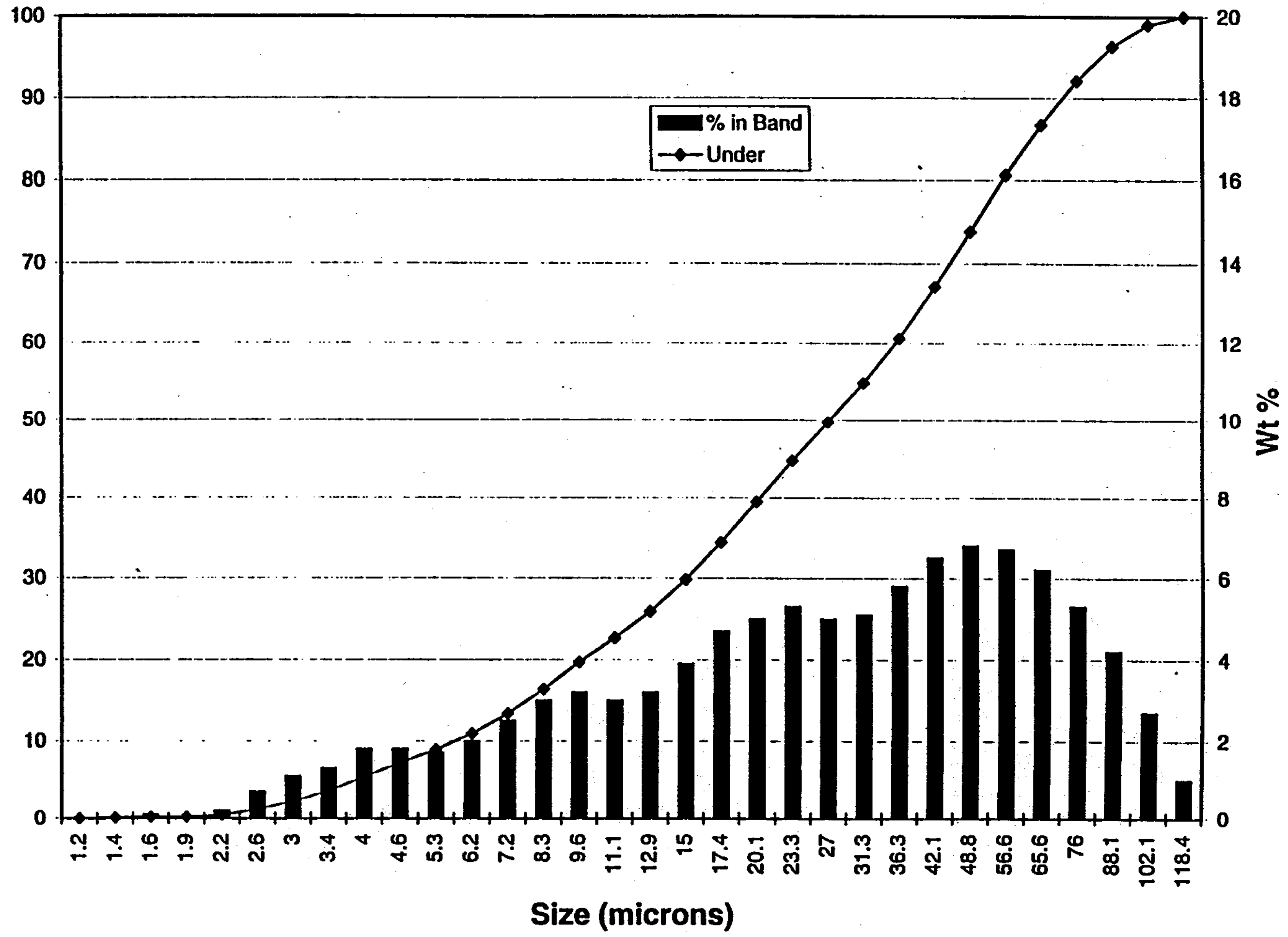


Figure4.22 Particle Size Distribution of Plant Coal

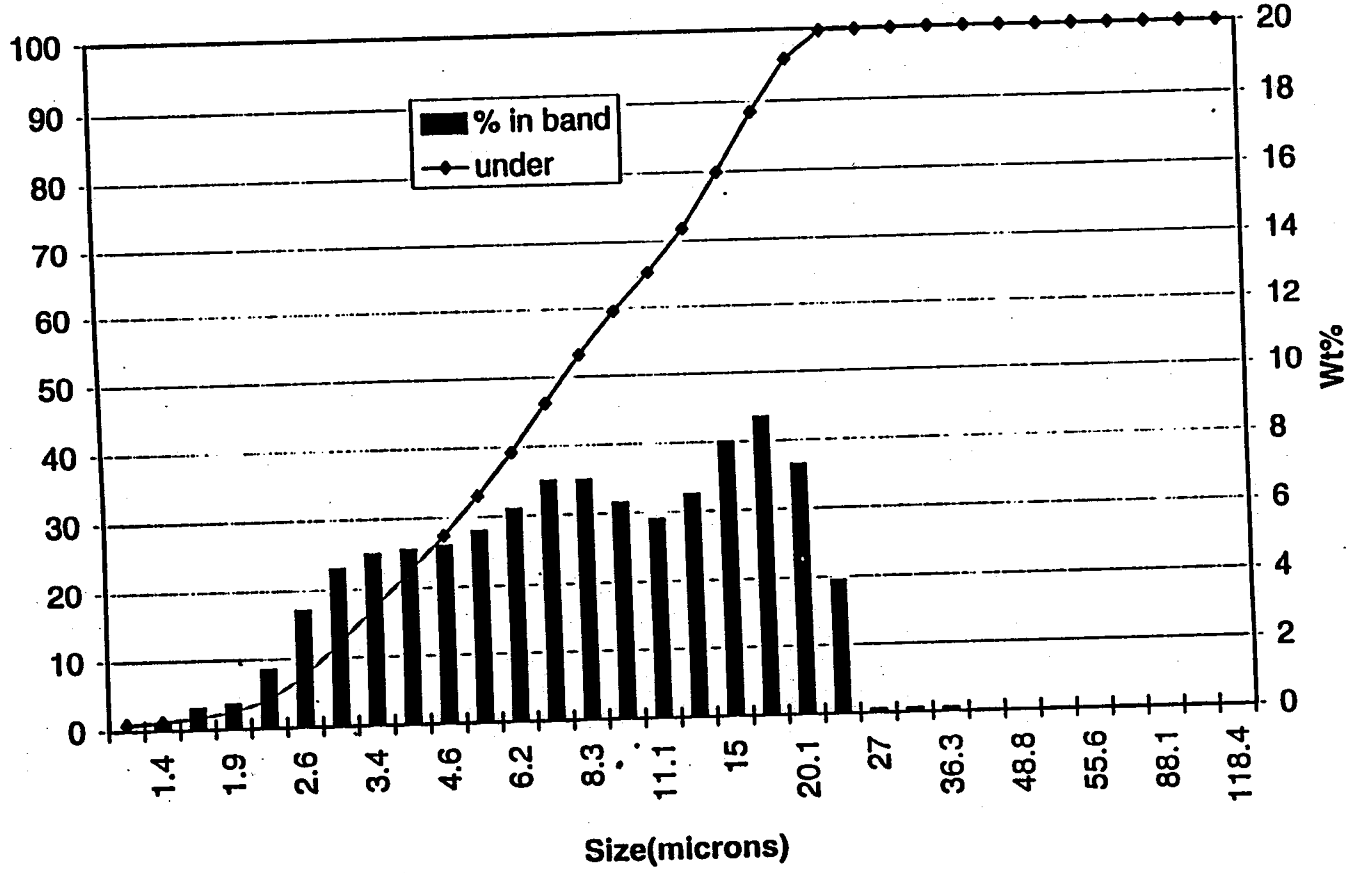


Figure 4.23 Particle Size Distribution of Recovered Coal Fines

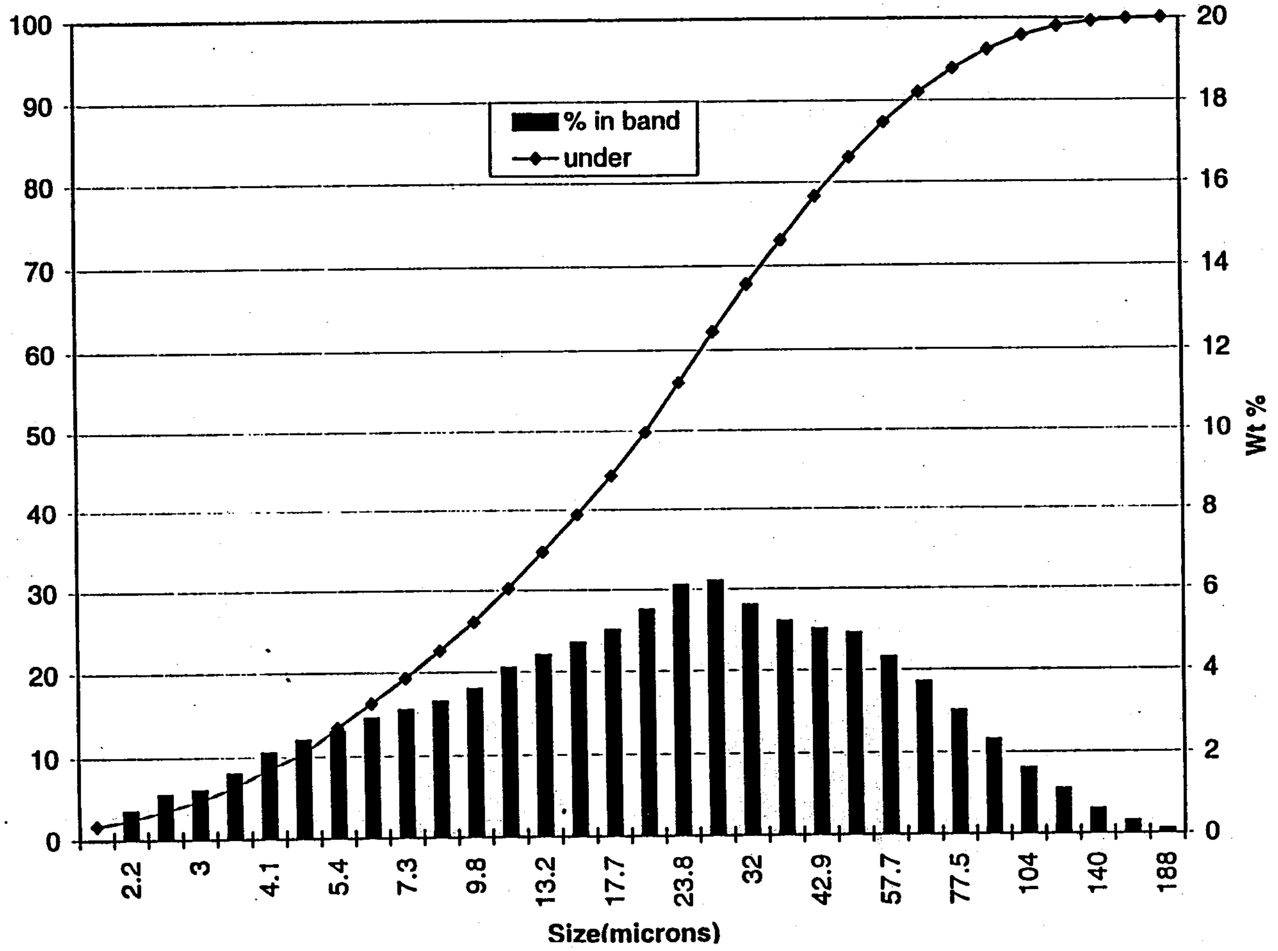


Figure4.24 Particle Size Distribution of CWS

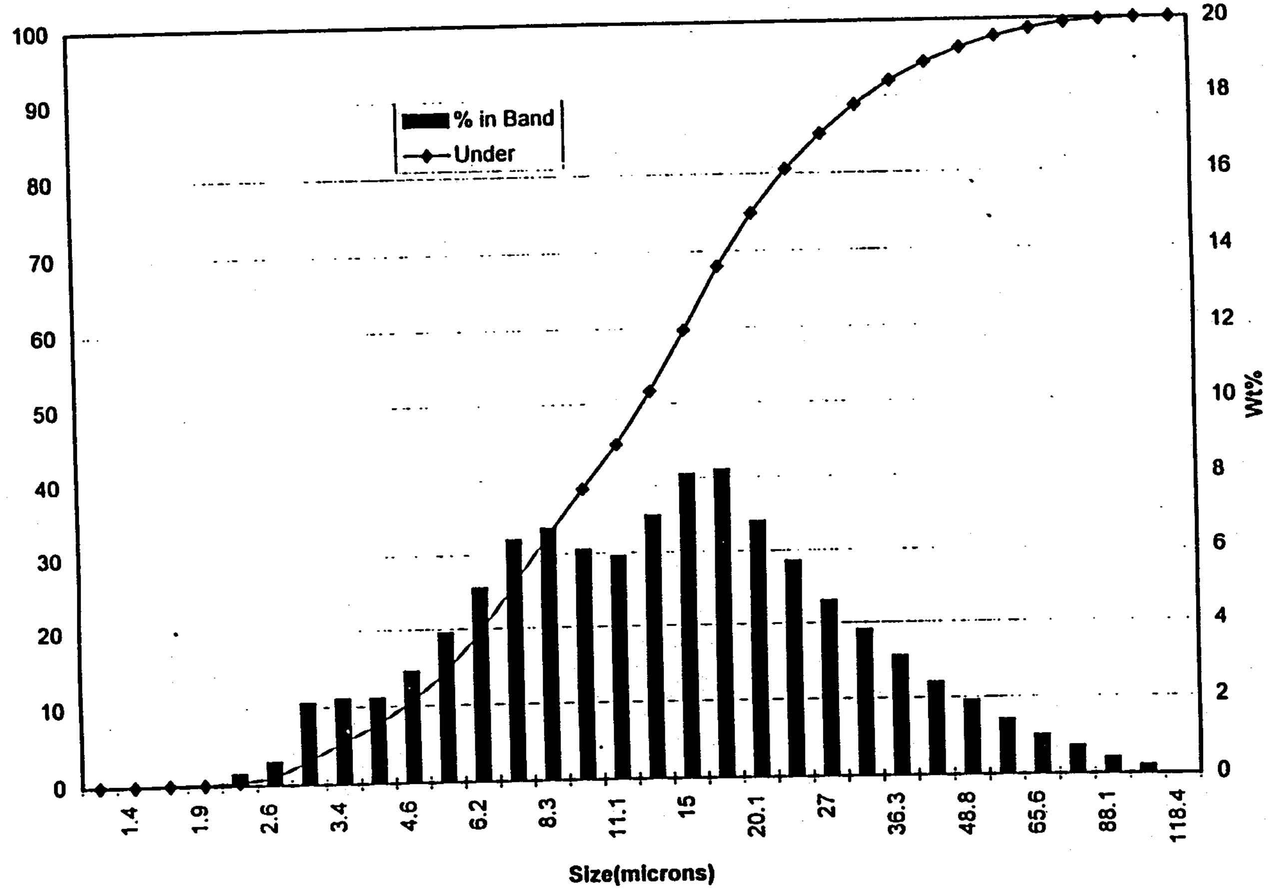


Figure 4.25 Particle Size Distribution of ESP Ash

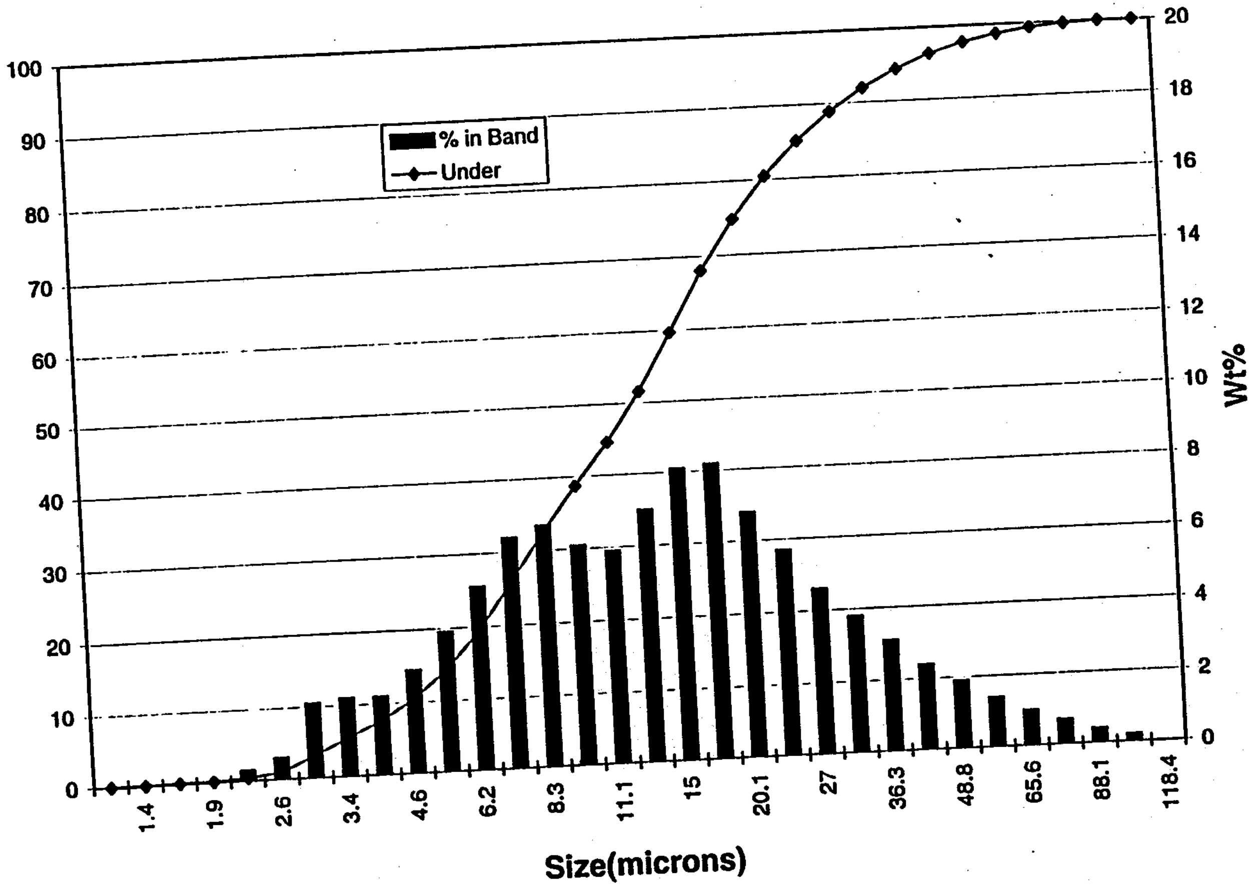


Figure 4.26 Particle Size Distribution of Fly Ash

4.4.1 Wet Sieve Analysis

The lowest value of particles, Table 4.9, were from the mesh 170 where the particle size was of the value of 250 microns, this was 18.29%. Where it was also 18.29% of the particles were greater than the screen size. The majority of the particles of the Peabody raw fines were greater than the 400 screen mesh, 45 microns.

Table 4.9 - Wet Sieve Analysis of Peabody Raw Fines, 41.08% Dry Solids

Screen Mesh	Size (Microns)	% On Screen	%> Screen Size
170	250	18.29	18.29
200	150	1.84	20.13
230	90	2.81	22.94
270	75	1.90	24.83
325	53	2.37	27.21
400	45	1.25	28.45

Table 4.10 - Wet Sieve Analysis of Peabody Fuel Barrel #1, 54.78% Dry Solids

Screen Mesh	Size (Microns)	% On Screen	%> Screen Size
100	150	2.15	2.15
140	106	3.19	5.34
170	90	1.50	6.83
200	75	2.62	9.46
270	53	8.04	17.50
325	45	3.76	21.26

It is apparent that the average particle sizes of the Peabody fuel, Table 4.10, falls on a mesh level of 200 with the particle sizes being of the value of 75 microns. The percent of particles on the screen at this value are larger than 9.46.

Table 4.11 - Wet Sieve Analysis of Peabody Composite Fines (Attrited) 38.38% Dry Solids

Screen Mesh	Size (Microns)	% On Screen	%> Screen Size
170	90	0.55	0.55
200	75	0.28	0.82
230	63	0.26	1.08
270	53	0.51	1.59
325	45	0.98	2.57
400	38	0.94	3.51

Looking at the wet sieve analysis of Peabody Composite Fines (attrited) Table 4.11, it is apparent that the majority of the particles passed through with 0.28% on mesh 200 and 0.51% on mesh 270.

4.4.2 Elemental Oxide Analysis

The recovered coal fines, Figure 4.27, are highest in silicon oxide content with a value of

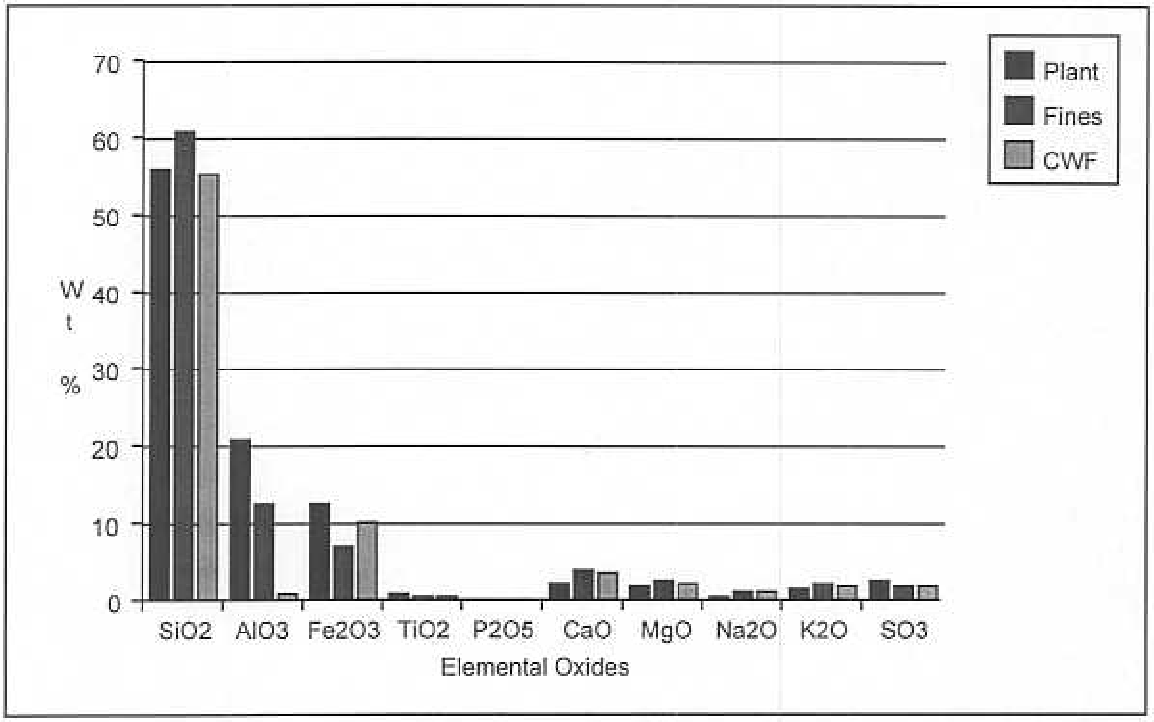


Figure 4.27 - Ash Composition Elemental Oxide Analysis of Bituminous CWF and Feedstocks on an Ash Basis

approximately 61% by weight; and is not surprising because they are obtained from the adjourning ponds from the coal cleaning operations. Plant coal follows closely behind at a value of 57% which therefore indicates that a significant amount of sand and silt has not been removed. The amount in the CWF is an even mixture of the two constituents, plant coal and recovered coal fines. Aluminum oxide and iron oxide follows significantly behind the silicon values.

The remaining elemental oxides, potassium, calcium, titanium, sulfur, magnesium and phosphorus are all marginal values. Which means that these values fell below 10% and do not make a significant impact on the fuel's efficiency.

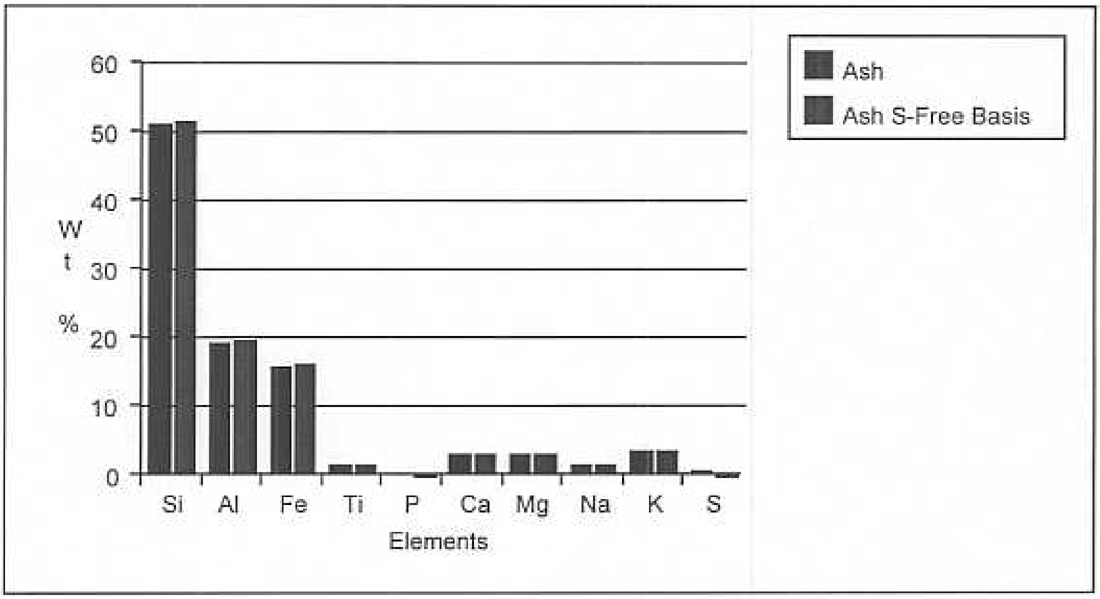


Figure 4.28 - XRF Analysis of ESP End-Of-Run Ash

The elements Si, Al and Fe, Figure 4.28, are the most present and abundant in particular in Si. These elements are unwanted because they tend to char and reduce the efficiency of fuel. These values of the ashes are consistent in regards to the Si content on both a Sulfur and Sulfur free basis.

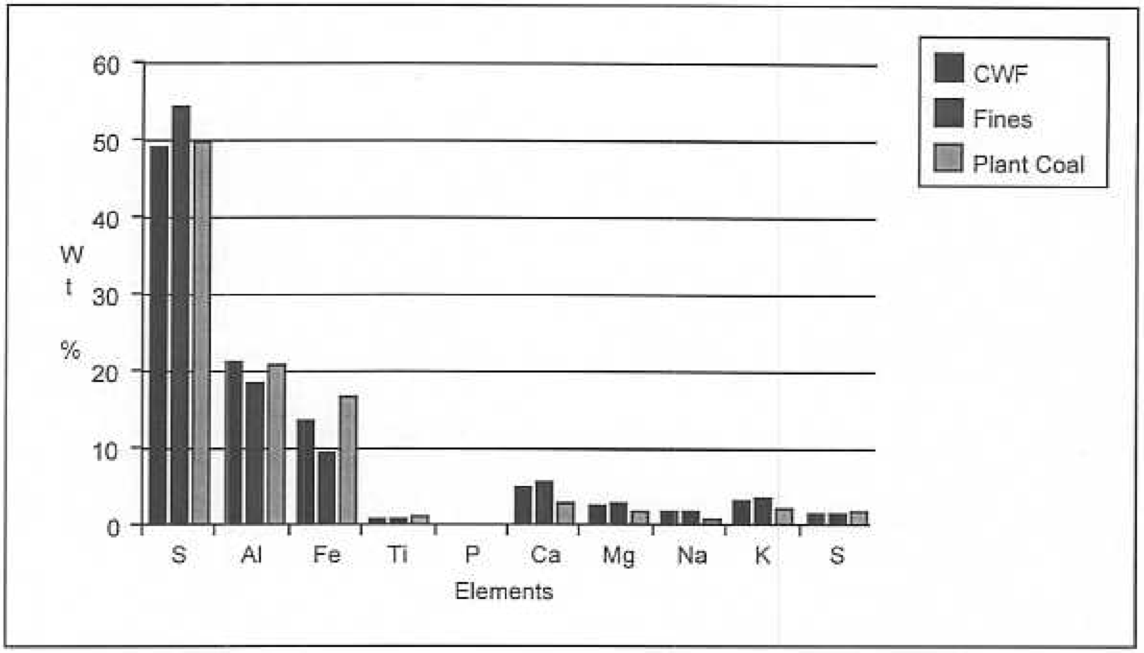


Figure 4.29 - XRF Analysis of Elements Bituminous CWF and Feedstocks on an Ash Free Basis

Looking at the elements alone in Figure 4.29, it can be seen that the highest concentrated elements fall within Si, Al and Fe, followed by Ca. These elements are undesirable because they reduce the overall efficiency of fuel when it is combusted.

4.5 ASH ANALYSIS

Elemental oxide deposit weight percentage composition values are displayed in Table 4.12. The ash fouling indicates that the fouling rate and deposit strengths increase with the firing rate, feed rate and furnace exit gas temperatures. The ash input rate was consistent (17.67) at all three firing rates. It can be observed that the values for SiO_2 remained constant at about 55% deposit composition by weight. Values for Na_2O decreased as the firing rates decreased. However, the values for Fe_2O_3 increased as the firing rates decreased, this is because there was not enough burning of the fuel. The same pattern can be observed of SO_3.

Figures 4.30-4.32 are detailed close up photos taken of the ash that was removed from the ash fouling probe bank for test runs AF-CTS-712, AF-CTS-713, and AF-CTS-714. Figure 4.30 is an ash sample from test run AF-CTS-712, the ash is a dusty gray color on the top with some slightly dark black color scattered about it. To the left of the pan a person can observe that there are some ash that is black and tends to appear light brown in color. This ash is clumped and stiff. There are various chunks clumped together about the sample tray.

Figure 4.31 is a photo of the ash taken from test run AF-CTS-713, has ash sample that is various colors. The range can be observed from light gray on the top to black that tends to look brown. This sample is also very stiff and is clumped the chunks are all large in size.

Figure 4.32 is a photo of the ash taken from test run AF-CTS-714, this photo also displays ash that is clumped together. However, the clump appears to be one big unit and there are two small units. The ash however it a charcoal color and is black and dark gray in color on the top of the sample.

Table 4.12 - Ash Fouling Probe Results

Test/Date	AF-CTS-712/8-2-95	AF-CTS-713/8-3-95	AF-CTS-714/8-4-95
Feed Rate, lb/hr	140.2	112.5	85.4
Firing Rate, Btu/hr	834,330	669,488	508,215
Length of Run, hrs	3.58	4.08	5.03
FEGT, ^{o}F	2,170	2,089	1,992
Probe Metal Temp. ^{o}F	996	1,004	978
Excess Air, %	14.01	21.39	21.20
Ash Input Rate, lb/MMBtu	17.97	17.97	17.97
Equivalent 5% Na_2O Ash Input, lb/MMBtu	4.67	4.67	4.67
Ash Fouling Probe Sinter Layer Wt.	971.4	839.8	608.3
Ash Specific Deposit Rate, g/kg-input ash	40.64	39.00	29.74
Deposit Strength	454	347	329
Sample Number	95-0912	95-0913	95-0914
Deposit Composition wt. %	834,330 firing rate	669,488 firing rate	508,215 firing rate
SiO_2	54.80	55.20	55.10
Al_2O_3	18.30	18.50	18.20
Fe_2O_3	13.40	13.50	14.60
TiO_2	0.90	0.90	0.90
P_2O_5	0.30	0.10	0.20
CaO	5.70	5.70	6.20
MgO	1.60	1.60	1.40
Na_2O	2.80	2.00	1.00
K_2O	2.40	2.40	2.50
SO_3	0.00	0.00	0.00
Total	100.20	99.90	100.10
SiO_2/Al_2O_3	2.99	2.98	3.03

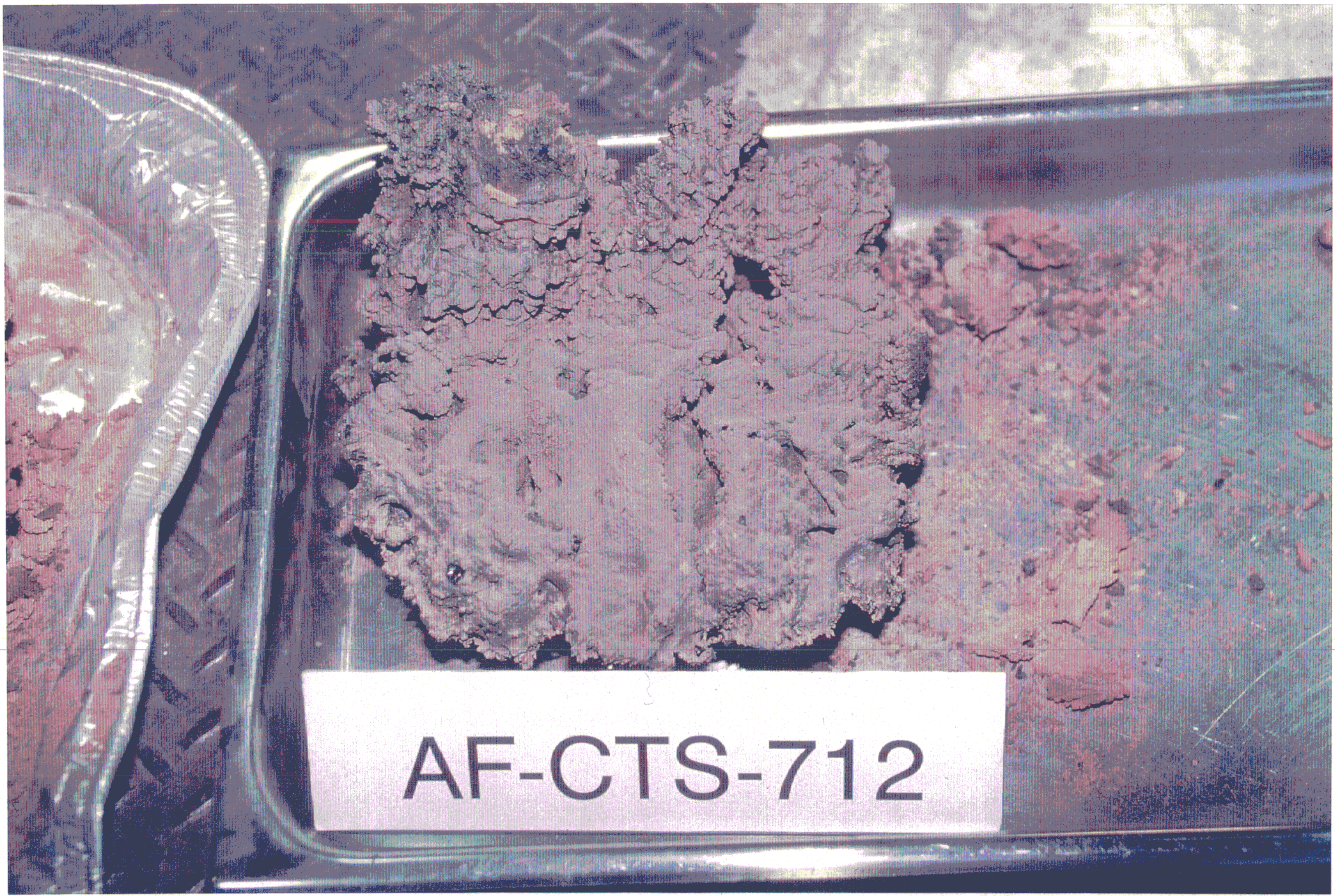


Figure 4.30 Photo of Ash Sample Test AF-CTS-712

Figure 4.31 Photo of Ash Sample Test AF-CTS-713

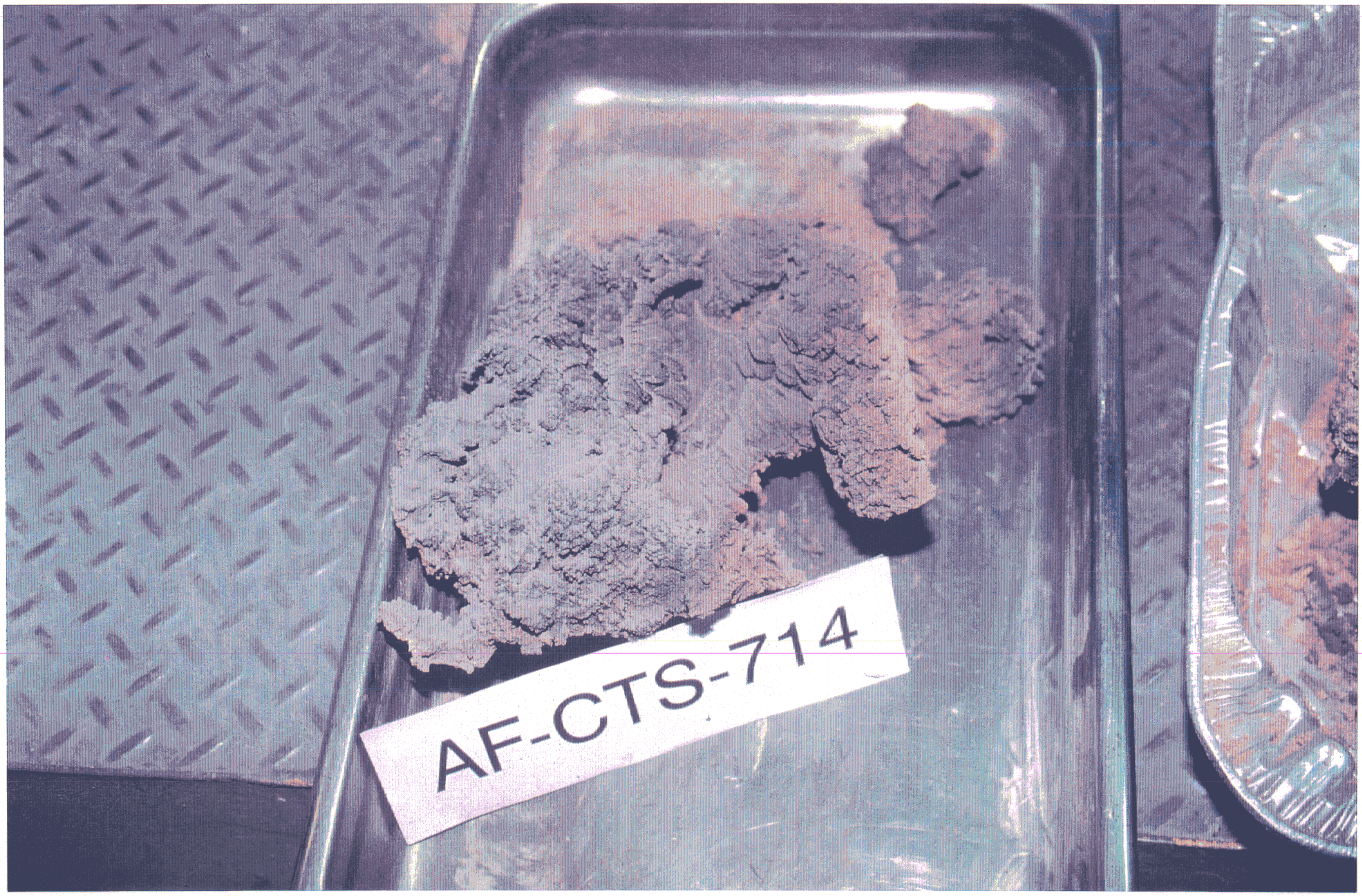


Figure 4.32 Photo of Ash Sample Test AF-CTS-714

CHAPTER V

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

The following conclusions are made from the combustion of coal-water slurry fuel:

- Coal-water slurry fuel was prepared for a blend of 85% plant coal and 15% recovered coal fines with solid content of 53.3 percent by weight. It had viscosity less than 500 cp and 90 percent of particles, by weight, had sizes less than 77 microns.

- Combustion tests were successfully performed over three firing rates (834,330 Btu/hr, 669,488 Btu/hr and 508,215 Btu/hr) at three different burner settings for each firing rate.

- Chemical analysis on plant coal, recovered coal fines and coal-water slurry fuel were performed. In the case of recovered coal fines, high ash (56.72 wt%) and sulfur (2.82 wt%) content were observed. The coal-water slurry fuel contained 10.49 wt% of ash and 1.84 wt% sulfur.

- The NO_x emissions were found to be in the range of 500 ppm for all three firing rates which were within the EPA standards. An increase in NO_x emissions from 460 ppm to 240 ppm (average for total duration of the experiments) was found with the increase in firing rate from 834,330 Btu/hr to 508,215 Btu/hr.

- Due to a higher percentage of sulfur in the recovered coal fines and plant coal, the SO_2 emissions were found to be in the range of 2000-3000 ppm for all firing rates.

- The oxygen concentrations were found to be in the range of 4 to 6 percent and carbon dioxide concentrations were found to be in the range of 13 to 17 percent by weight for all three firing rates.

- Combustion was nearly complete, regardless of burner settings, therefore burner settings were adjusted to provide a visually stable flame without concern for higher carbon content in ash as a function of burner settings.

- The burner settings did not have a significant effect on the gaseous emission

- The residence time is found to be higher at higher firing rates for all the locations. The gaseous emissions varied with respect to the location, but the variation was not very significant. The furnace exit temperatures were almost even through out the combustion chamber for each firing rate.

- The carbon conversion efficiency was found to be greater than 98 percent regardless of the swirl setting.

- The utilization of waste coal fines has an enormous impact on the environment by saving the land area previously reserved for effluent ponds.

5.2 RECOMMENDATIONS FOR FUTURE WORK

- Experiments should be conducted on coal-water slurry fuel, and on blend at the same firing rates and the same burner settings for a better comparison of the test data.

- Experiments should be performed with different proportions of the plant coal and recovered coal fines such as 80/20, 85/15 and 90/10 (plant coal/recovered coal fines).

- Swirl numbers should be varied over a wide range, and data should be obtained with respect to various swirl numbers to have through understanding of the flame stability.

- A full cost analysis on the preparation and combustion of the coal-water slurry fuel has to be investigated to find the economic advantage.

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APPENDIX-1

Emissions data obtained during a test run at 834,330 Btu/hr

Time(actual)	Time(min)	O2(%)	CO2(%)	SO2(ppm)	CO(ppm)	Nox(ppm)	EXCESS-AIR (%)	FUEL-INP(lb/hr)	FIR-CALC(Btu/hr)
11:12 AM	0	4.778	15.529	2735.71	0	491.211	20.204	126.03	750000
11:17 AM	5	4.489	15.793	2774.79	0	473.633	18.555	126.03	750000
11:22 AM	10	4.279	15.595	2843.18	0	480.469	17.463	126.03	750000
11:27 AM	15	4.607	15.529	2870.05	0	485.352	18.517	126.03	750000
11:31 AM	20	4.817	15.513	2796.77	0	504.883	21.872	126.03	750000
11:36 AM	25	4.108	16.831	2940.88	0	476.563	16.019	126.03	750000
11:41 AM	30	3.977	17.308	2928.67	0	452.148	15.705	126.03	750000
11:46 AM	35	4.24	17.059	2940.88	0	480.957	16.765	126.03	750000
11:51 AM	40	4.289	17.29	2957.98	0	478.027	16.49	126.03	750000
11:56 AM	45	4.441	17.542	2896.92	0	445.801	17.9	126.03	750000
12:01 PM	50	3.933	17.999	2967.75	0	437.012	14.981	126.03	750000
12:06 PM	55	3.361	18.259	3080.11	0	436.523	14.04	126.03	750000
12:11 PM	60	3.322	18.315	4052.27	0	460.938	14.02	126.03	750000
12:26 PM	65	3.522	16.657	2936	0	454.59	11.425	126.03	750000
12:31 PM	70	4.128	16.093	2948.21	0	432.129	15.02	126.03	750000
12:36 PM	75	3.229	16.57	2938.44	0	406.25	12.394	126.03	750000
12:41 PM	80	2.985	16.709	2975.08	0	460.938	11.433	126.03	750000
12:46 PM	85	3.898	16.093	2916.46	0	454.102	13.924	126.03	750000
12:51 PM	90	3.894	16.178	2896.92	0	482.91	13.478	126.03	750000
12:56 PM	95	3.913	16.127	2940.88	0	481.445	13.469	126.03	750000
1:16 PM	110	4.074	15.876	2264.28	0	458.008	14.753	126.03	750000
1:21 PM	115	4.03	15.842	2269.17	0	457.52	13.845	126.03	750000
1:26 PM	120	4.016	16.076	2266.73	0	446.777	13.921	126.03	750000
1:31 PM	125	3.889	16.195	2249.63	0	453.125	12.872	126.03	750000
1:36 PM	130	3.928	16.093	2357.1	0	423.828	12.582	126.03	750000
1:41 PM	135	4.05	15.959	2249.63	0	477.051	13.407	126.03	750000
1:46 PM	140	4.406	15.431	2110.4	0	464.355	17.191	126.03	750000
1:51 PM	145	4.362	14.251	2178.79	0	454.102	26.905	126.03	750000
1:56 PM	150	4.377	14.667	2169.02	0	461.914	21.667	126.03	750000
2:01 PM	155	4.089	14.839	2173.91	0	457.031	19.757	126.03	750000
2:06 PM	160	4.216	13.741	2203.22	0	412.598	30.063	126.03	750000
2:11 PM	165	4.099	11.424	2215.43	0	366.211	55.704	126.03	750000
2:16 PM	170	4.123	10.913	2195.89	0	297.852	67.464	126.03	750000
2:21 PM	175	4.138	12.628	2156.81	0	375	45.35	126.03	750000
2:26 PM	180	4.162	11.98	2176.35	0	364.258	55.315	126.03	750000
2:31 PM	185	4.108	13.565	2203.22	0	395.02	36.865	126.03	750000
2:41 PM	190	4.108	15.892	2166.58	0	520.508	16.063	126.03	750000
2:46 PM	195	4.099	15.926	2232.53	0	506.348	16.525	126.03	750000
2:51 PM	200	4.123	15.942	2222.76	0	507.324	16.171	126.03	750000
2:56 PM	210	4.118	16.06	2178.79	0	485.84	16.819	126.03	750000
3:01 PM	215	4.06	15.776	2230.09	0	514.648	14.389	126.03	750000

APPENDIX-1

Emissions data obtained during a test run at 834,330 Btu/hr

3:06 PM	220	4.079	16.043	2198.33	0	522.461	14.725	126.03	750000
3:10 PM	225	4.084	16.11	2276.5	0	522.461	14.582	126.03	750000
3:15 PM	230	4.089	16.622	2230.09	0	513.184	14.373	126.03	750000
3:20 PM	235	4.045	16.813	2195.89	0	467.285	14.004	126.03	750000
3:25 PM	240	4.446	16.779	754.763	0	439.453	14.88	126.03	750000
3:35 PM	245	4.226	16.744	2950.65	0	442.871	14.24	126.03	750000
3:40 PM	250	4.177	17.042	2975.08	0	439.941	13.924	126.03	750000
3:45 PM	255	3.635	17.633	2989.74	0	440.918	10.896	126.03	750000
3:50 PM	260	3.224	17.633	3048.36	0	446.777	10.339	126.03	750000
3:55 PM	265	3.029	17.362	3094.77	0	486.816	8.761	126.03	750000
4:00 PM	270	3.703	16.918	3045.92	0	496.094	10.354	126.03	750000
4:05 PM	275	4.309	17.13	3065.46	0	480.469	10.182	126.03	750000
4:10 PM	280	3.879	17.326	3106.98	0	483.398	7.161	126.03	750000
4:15 PM	285	3.918	17.742	3092.33	0	490.234	7.418	126.03	750000
4:20 PM	290	3.786	18.166	3148.51	0	471.68	5.578	126.03	750000
4:30 PM	295	4.748	15.809	2906.69	0	493.652	19.244	126.03	750000
4:35 PM	300	5.208	15.562	2818.75	0	466.309	21.169	126.03	750000
4:40 PM	305	5.129	15.677	2823.64	0	480.469	21.027	126.03	750000
4:45 PM	310	5.213	15.776	2816.31	0	459.961	20.987	126.03	750000
4:50 PM	315	5.203	15.992	2811.43	0	465.332	21.055	126.03	750000
4:55 PM	320	5.237	16.06	2838.3	0	509.766	21.364	126.03	750000
5:00 PM	325	5.217	16.127	2826.08	0	468.75	21.241	126.03	750000
5:05 PM	330	5.217	16.313	2857.84	0	433.594	20.977	126.03	750000

Emission data obtained during a test run at 669,488

Time(actual)	Time(min)	O2(%)	CO2%	SO2(ppm)	CO(ppm)	Nox(ppm)	EXCESS-AIR(%)	FUEL-INP (lb/hr)	FIR-CALC (Btu/hr)
10:22 AM	0	6.248	15.545	2576.94	0	520.508	30.188	105	624855
10:27 AM	5	5.716	15.992	2713.72	0	508.789	26.292	105	624855
10:32 AM	10	5.657	16.279	2769.9	0	490.723	24.764	105	624855
10:37 AM	15	5.598	16.45	2774.79	0	489.746	23.152	105	624855
10:42 AM	20	5.32	16.692	2811.43	0	475.098	22.083	105	624855
10:47 AM	25	5.467	16.779	2801.66	0	448.242	22.931	105	624855
10:52 AM	30	4.665	17.596	2874.93	0	453.613	16.831	105	624855
10:57 AM	35	5.012	17.272	2833.41	0	448.242	18.862	105	624855
11:02 AM	40	5.017	17.76	2808.98	0	405.762	19.247	105	624855
11:07 AM	45	5.164	17.578	2777.23	0	429.199	20.009	105	624855
11:12 AM	50	5.051	17.614	2806.54	0	430.176	19.487	105	624855
11:17 AM	55	5.125	17.506	2830.97	0	431.152	19.455	105	624855
11:22 AM	60	5.242	17.651	2838.3	0	421.875	20.139	105	624855
11:27 AM	65	5.227	17.47	2879.82	0	429.199	20.298	105	624855
11:32 AM	70	5.105	17.542	2840.74	0	419.922	19.784	105	624855
11:37 AM	75	5.296	17.87	2857.84	0	362.793	20.968	105	624855
11:42 AM	80	5.672	17.308	2743.03	0	376.465	22.932	105	624855
11:47 AM	85	5.442	17.578	2796.77	0	377.441	21.496	105	624855
11:52 AM	90	5.403	17.47	2826.08	0	368.652	21.167	105	624855
11:57 AM	95	5.554	17.308	2843.18	0	387.695	22.369	105	624855
12:02 PM	100	5.462	16.831	2835.85	0	358.887	23.897	105	624855
12:07 PM	105	5.261	16.883	2794.33	0	365.234	22.632	105	624855
12:27 PM	125	6.009	12.738	2496.33	0	318.359	36.173	105	624855
12:32 PM	130	5.882	12.18	2462.14	0	315.918	40.727	105	624855
12:37 PM	135	5.799	14.266	2613.58	0	341.309	8.384	105	624855
12:42 PM	140	5.721	14.651	2838.3	0	361.816	23.33	105	624855
12:47 PM	145	5.471	14.823	2845.62	0	315.43	21.219	105	624855
12:52 PM	150	5.369	14.95	2904.25	0	331.543	20.729	105	624855
12:57 PM	155	5.486	15.061	2904.25	0	343.75	21.046	105	624855
1:02 PM	160	5.594	15.205	2936	0	303.711	21.699	105	624855
1:07 PM	165	5.305	15.318	2931.11	0	324.219	20.315	105	624855
1:12 PM	170	5.252	15.302	2901.8	0	358.887	20.101	105	624855
1:17 PM	175	5.286	15.366	2914.02	0	382.813	20.225	105	624855
1:22 PM	180	5.735	14.745	2811.43	0	387.207	23.548	105	624855
1:27 PM	185	5.437	15.253	2835.85	0	359.375	21.678	105	624855
1:32 PM	190	5.364	14.543	2738.15	0	353.516	27.985	105	624855
1:37 PM	200	5.594	14.205	2681.97	0	310.547	30.919	105	624855
1:42 PM	205	5.613	13.697	2635.56	0	307.617	34.521	105	624855

Emission data obtained during test run at 669,488

1:46 PM	210	5.628	12.247	2498.77	0	304.688	50.363	105	624855
1:56 PM	220	5.642	15.045	2816.31	0	378.906	21.898	105	624855
2:01 PM	225	5.467	15.334	2860.28	0	373.535	19.971	105	624855
2:06 PM	230	5.642	15.125	2867.61	0	363.77	21.708	105	624855
2:11 PM	235	5.691	15.077	2838.3	0	340.82	21.264	105	624855
2:16 PM	240	5.765	15.125	2882.26	0	335.449	21.637	105	624855
2:21 PM	245	5.662	15.205	2848.07	0	363.77	20.914	105	624855
2:26 PM	250	5.677	15.141	2901.8	0	375.488	21.213	105	624855
2:31 PM	255	5.589	15.061	2855.39	0	400.391	20.693	105	624855
2:36 PM	260	5.838	14.886	2892.03	0	405.273	22.279	105	624855
2:41 PM	265	6.004	14.792	2835.85	0	389.648	22.646	105	624855
2:46 PM	270	5.96	14.966	2828.53	0	377.93	21.692	105	624855
2:51 PM	275	5.989	14.871	2872.49	0	369.629	22.892	105	624855
2:56 PM	280	5.989	15.061	2874.93	0	391.602	22.592	105	624855
3:01 PM	285	5.862	15.029	2911.57	0	416.992	21.606	105	624855
3:06 PM	290	5.833	15.302	2877.38	0	387.695	20.556	105	624855
3:11 PM	295	5.75	15.399	2938.44	0	414.063	20.025	105	624855
3:16 PM	300	5.471	15.71	2940.88	0	375.488	17.36	105	624855
3:21 PM	305	5.383	15.66	2936	0	399.414	17.579	105	624855
3:26 PM	310	5.97	15.334	2906.69	0	390.625	20.215	105	624855
3:31 PM	315	5.931	15.334	2894.48	0	401.367	19.867	105	624855
3:36 PM	320	5.628	15.892	2999.51	0	398.926	15.167	105	624855

Emissions data obtained during a test run at 508,215

11:53 AM	185	5.442	14.934	2542.74	0	224.121	20.34	85	505835
11:58 AM	190	5.418	14.997	2498.77	0	244.141	20.359	85	505835
12:03 PM	195	5.393	15.013	2532.97	0	242.188	20.224	85	505835
12:08 PM	200	6.092	14.45	2425.5	0	243.164	25.053	85	505835
12:13 PM	205	6.165	14.419	2432.82	0	246.094	25.845	85	505835
12:18 PM	210	6.219	14.266	2359.55	0	225.098	26.833	85	505835
12:23 PM	215	5.818	14.558	2506.1	0	215.332	24.3	85	505835
12:28 PM	220	5.716	14.266	2469.46	0	223.633	24.831	85	505835
12:33 PM	225	5.686	14.574	2454.81	0	234.375	22.79	85	505835
12:38 PM	230	5.686	14.667	2432.82	0	219.238	22.895	85	505835
12:43 PM	235	5.491	14.729	2542.74	0	206.543	21.974	85	505835
12:48 PM	240	5.291	14.886	2559.84	0	219.727	21.098	85	505835
12:58 PM	250	5.105	15.513	2586.71	0	235.352	16.492	85	505835
1:03 PM	255	5.144	15.48	2618.46	0	241.211	16.68	85	505835
1:08 PM	260	5.134	15.726	2567.17	0	249.023	15.96	85	505835
1:13 PM	265	5.403	15.677	2547.63	0	246.094	16.466	85	505835
1:18 PM	270	5.76	15.366	2506.1	0	243.652	19.6	85	505835
1:23 PM	275	5.809	15.157	2513.43	0	238.281	19.334	85	505835
1:28 PM	280	5.97	15.205	2427.94	0	227.051	20.142	85	505835
1:33 PM	285	6.903	14.297	2256.96	0	260.254	27.756	85	505835
1:38 PM	290	6.619	14.527	2369.32	0	239.746	25.006	85	505835
1:43 PM	295	5.931	15.431	2447.48	0	243.164	18.491	85	505835
1:48 PM	300	6.248	15.66	2420.61	0	238.281	16.139	85	505835
1:53 PM	305	6.961	14.589	2205.66	0	270.996	30.73	85	505835
1:58 PM	310	4.778	15.611	2650.22	0	264.16	16.907	85	505835
2:03 PM	315	5.178	14.342	2532.97	0	254.395	24.558	85	505835
2:08 PM	320	4.851	15.253	2681.97	0	252.93	17.907	85	505835
2:13 PM	325	4.446	15.285	2757.69	0	234.863	18.049	85	505835
2:18 PM	330	3.884	15.726	2669.76	0	239.258	16.186	85	505835
2:23 PM	335	4.709	15.093	2640.44	0	247.07	19.452	85	505835
2:28 PM	340	4.949	14.981	2594.04	0	251.465	20.564	85	505835

Emissions data obtained during a test run at 508,215

Time(actual)	Time(min)	O2(%)	CO2(%)	SO2(ppm)	CO(ppm)	Nox(ppm)	EXCESS-AIR(%)	FUEL-INP(lb/hr)	FIR-CALC Btu/hr)
8:49 AM	0	9.443	10.962	2054.22	0	376.953	69.289	85	505835
8:54 AM	5	8.525	12.14	2298.48	0	325.684	51.763	85	505835
8:59 AM	10	7.816	12.78	2462.14	0	296.875	44.628	85	505835
9:04 AM	15	7.772	12.892	2449.92	0	286.621	43.361	85	505835
9:09 AM	20	6.649	13.874	2606.25	0	290.039	33.157	85	505835
9:14 AM	25	4.875	15.611	2914.02	0	267.09	18.068	85	505835
9:19 AM	30	5.711	15.125	2828.53	0	266.113	23.128	85	505835
9:24 AM	35	5.525	15.205	2879.82	0	254.395	21.02	85	505835
9:29 AM	40	5.427	15.061	2879.82	0	258.301	22.629	85	505835
9:34 AM	45	5.54	14.745	2816.31	0	237.305	23.66	85	505835
9:39 AM	50	4.704	15.611	2879.82	0	229.98	17.467	85	505835
9:44 AM	55	4.993	15.237	2855.39	0	223.633	19.7	85	505835
9:49 AM	60	5.31	15.109	2838.3	0	213.867	20.357	85	505835
9:54 AM	65	5.203	14.95	2872.49	0	205.566	19.173	85	505835
9:59 AM	70	5.256	14.886	2857.84	0	209.961	20.43	85	505835
10:04 AM	75	5.325	13.785	2955.54	0	173.34	30.292	85	505835
10:09 AM	80	5.369	13.26	2769.9	0	181.152	36.399	85	505835
10:14 AM	85	5.569	15.189	2730.82	0	222.656	20.662	85	505835
10:19 AM	90	5.598	15.221	2840.74	0	200.195	21.025	85	505835
10:24 AM	95	5.491	15.173	2872.49	0	203.125	20.657	85	505835
10:29 AM	100	5.442	15.189	2879.82	0	195.313	20.768	85	505835
10:34 AM	105	5.452	15.302	2889.59	0	199.219	20.909	85	505835
10:39 AM	110	5.408	15.189	2914.02	0	195.801	21.051	85	505835
10:44 AM	115	5.686	14.966	2813.87	0	187.5	23.851	85	505835
10:49 AM	120	5.662	14.839	2852.95	0	166.016	23.768	85	505835
10:54 AM	125	5.447	14.886	2870.05	0	179.199	23.711	85	505835
10:59 AM	130	5.491	15.157	2843.18	0	188.477	22.442	85	505835
11:04 AM	135	5.559	15.302	2811.43	0	200.195	21.586	85	505835
11:08 AM	140	5.506	15.366	2855.39	0	203.125	21.036	85	505835
11:13 AM	145	5.476	15.399	2865.16	0	197.754	20.939	85	505835
11:18 AM	150	5.379	15.431	2860.28	0	173.34	20.596	85	505835
11:33 AM	165	5.413	12.1	2525.64	0	177.246	47.656	85	505835
11:38 AM	170	5.471	14.776	2489	0	223.633	21.417	85	505835
11:43 AM	175	5.457	14.902	2525.64	0	231.934	20.47	85	505835
11:48 AM	180	5.53	14.855	2484.12	0	228.027	21.088	85	505835