NITROGEN OXIDE FORMATION IN PULVERIZED COAL FLAMES

by

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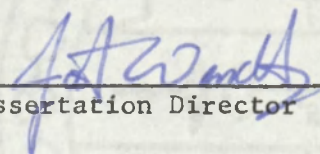
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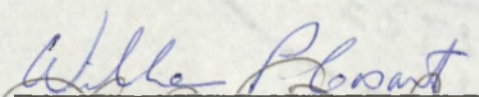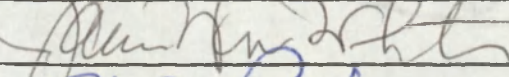
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performance at the final examination.

To my parents

for the sacrifices they made,

the encouragement they gave,

and the inspiration they are.

ACKNOWLEDGMENTS

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ABSTRACT

The combustion of pulverized coal leads to emissions of nitrogen oxides through both the fixation of atmospheric nitrogen (thermal NO_x) and the oxidation of chemically bound nitrogen in the fuel (fuel NO_x). The purpose of this research was to identify and investigate those factors which influence NO_x formation in self-sustaining, pulverized coal flames. The research concentrated on three specific areas which were found to constitute a major gap in the knowledge of NO_x formation in pulverized coal flames: the relative proportions of thermal and fuel NO_x formed in practice under normal operating conditions; the dependence of fuel nitrogen conversion on local oxygen concentration, flame temperature, and fuel composition; and the fraction of fuel nitrogen conversion resulting from volatile nitrogen oxidation.

The approach was experimental, utilizing a 6" x 76" refractory tunnel furnace to study 6 lb/hr, self-sustaining, pulverized coal flames. The flue gas was sampled with a water-cooled, stainless steel probe and continuously monitored for NO, CO, CO_2, O_2, and SO_2. Fuel NO was isolated by comparing the emissions from combustion with air to those from combustion in $Ar/O_2/CO_2$ under similar aerodynamic and thermal conditions. Special experiments involving ammonia and nitric oxide addition to the fuel stream produced data used to estimate the importance of char and volatile fuel nitrogen in producing fuel NO emissions.

The combustion characteristics of three bituminous coals (Colorado, Pittsburgh, and Western Kentucky), one sub-bituminous coal (Montana), and one coal char (FMC-COED) were investigated. Both the relatively slow fuel/air mixing characteristic of tangentially fired systems and the rapid mixing of wall-fired systems were simulated from an NO_x emission point of view.

It was found that fuel nitrogen oxidation is the primary source of NO emissions from pulverized coal flames. Variations in burner design, primary air, air preheat, swirl, and throat velocity did not alter that conclusion since, under all conditions examined, fuel NO contributed at least 75% of the total NO emissions.

Total and fuel NO emissions increase only slightly as the fuel nitrogen level increases because the percent conversion of fuel nitrogen decreases. Oxidation of chemically bound nitrogen is the primary NO formation mechanism regardless of coal composition or coal rank. Fuel nitrogen speciation, coal rank, and other composition variables are of second-order importance.

Furthermore, the results showed that fuel NO formation is insensitive to combustion zone temperature over a wide range typical of industrial practice. Thermal NO, however, exhibits an exponential temperature dependence. At low temperatures, the total NO emissions approach the (constant) fuel NO value, and the thermal NO asymptotically approaches zero. At extremely high temperatures, the fuel NO emissions undergo a dramatic increase, probably due to a radical change in the physical behavior of the coal particles as they are suddenly exposed to an extremely hot environment.

Early mixing of fuel and oxygen was the most important factor determining the ultimate fuel nitrogen conversion to NO. This large effect was due entirely to changes in the fraction of volatile nitrogen converted. Early mixing can be achieved by detaching the flame from the burner and it results in large increases in volatile NO. Oxidation of char nitrogen, however, is relatively insensitive to changes in early oxygen concentration or combustion hardware. Volatile NO, which constitutes the major portion of fuel NO under normal combustion conditions, is amenable to abatement by combustion modifications, but abatement of char NO may be extremely difficult. Thus, unless the char/volatile nitrogen distribution can be altered in the combustion process, there may exist a lower limit on the NO emission level which can be achieved through combustion modifications.

CHAPTER 1

BACKGROUND

1.1 Introduction

For several centuries man has relied on the combustion of coal

to provide one of his most fundamental needs, energy. In 1920, coal pro-

vided some 80 percent of the nation's energy, but by 1974 this dependence

had dropped to only 18 percent, largely because of economic, operational,

and environmental advantages associated with oil and natural gas. How-

ever, in recent months the steadily declining reserves of these fuels and

increased reliance on foreign sources have led to the realization that

domestic coal resources offer one of the principal means to achieve a

desirable level of energy self-sufficiency (U. S. Congress, 1975).

Ultimately, gasification and/or liquification may be the dominant coal

utilization processes; however, for at least the next twenty years, the

major utilization will be through direct combustion. It is, therefore,

important that technology be developed which allows combustion of the

national coal reserves in an environmentally acceptable manner.

Direct combustion of pulverized coal is a complicated physico-

chemical process involving both homogeneous and heterogeneous chemical

reaction; multicomponent mass transfer; and conductive, convective, and

radiative heat transfer. In addition to releasing energy, coal combus-

tion results in significant amounts of atmospheric pollutants, including

particulates, sulfur oxides (SO_x), and nitrogen oxides (NO_x). This work

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focuses on the abatement of nitrogen oxides by combustion modification, with special emphasis on the role of chemically bound nitrogen in the fuel. The overall goal was to identify and investigate those factors which are important in the formation of nitrogen oxides in self-sustaining, pulverized coal flames. Although little such information is presently available, the mechanisms of coal combustion and the formation of nitrogen oxides in "clean" systems (gaseous fuels) have both been extensively investigated and are reviewed in the following sections of this chapter. Insight into the physical and chemical processes involved in coal combustion is useful because they influence both the fate of nitrogen chemically bound in the coal and the formation of nitrogen oxides in general. Section 1.2 contains a detailed discussion of the pertinent combustion mechanisms and is arranged in the order in which a coal particle is believed to burn. Sections 1.3 and 1.4 review the current knowledge of nitrogen oxide formation mechanisms and highlight the current absence of information regarding pollutant formation from coal combustion.

1.2 Mechanisms of Coal Combustion

1.2.1 Overview

In most large, coal-fired process furnaces and boilers, pulverized coal is carried with air into a hot combustion chamber where the particles are heated at a rate of 10^4 °C/sec or more (Field et al., 1967). The coal particles are heated by radiation from the luminous flame and by the hot combustion gases which are recirculated into the combustion zone

(Beer, 1962). Almost immediately the particles decompose and react (Mentser et al., 1974), producing gases, termed "volatiles," which are a mixture of combustibles, carbon dioxide, and water vapor. The volatiles then burn homogeneously after which the remaining solid char slowly burns out heterogeneously. Thus, the combustion process is logically divided into three conceptual parts: 1) pyrolysis-volatile evolution, 2) volatile combustion, and 3) combustion of solid residue. Each is discussed in detail in the following sections because each part can potentially affect the fate of chemically bound nitrogen and the local combustion conditions. It should be noted, however, that while this conceptual division is desirable for discussion purposes the regimes of volatile evolution and combustion, and char burnout, both interact and partially overlap in actual flames. Furthermore, it is incorrect to think of coal as being composed of well-defined amounts of volatile matter and fixed carbon (Field et al., 1967). In fact, as Saji (1954) has shown, in certain jet flames substantial amounts of volatile matter may remain in the coal particles even after traveling through a major part of the furnace.

1.2.2 Pyrolysis (Volatile Evolution)

The rate of evolution and chemical composition of the volatile is strongly dependent on the composition of the original coal; however, coal is a very complex substance. In addition to wide variation in chemical composition, coals from different geographic locations often exhibit gross differences in physical behavior (Essenhigh, 1974) with regard to plastic behavior, melting, and swelling characteristics. Even samples from the same coal seam may exhibit variability in particle size and

shape due to irregular breakage or nonhomogeneity with regard to maceral and mineral distributions. Further, any given coal sample is a heterogeneous mixture of mineral species and a multitude of complex organic molecules whose structure is not well-established. Figure 1 shows the structure of two "typical" coal molecules proposed by Fuchs and Sandhoff (1942).

The dotted lines in Figure 1 indicate the points of initial bond rupture as proposed by Fuchs and Sandhoff. They used thermodynamic arguments to determine that, in the pyrolysis of coal, aliphatic carbon-carbon linkages break first, that carbon-hydrogen linkages are severed next (near 600°C), and that aromatic carbon-carbon linkages break last because of resonance stabilization. In the temperature range from 400 to 700°C, oxygen-containing complexes and other heterocyclic structures break off and, in the case of carbonization, these liberated radicals transform into more stable products, especially aldehydes which, in turn, decompose into nitrogen bases, phenols, hydrocarbons, carbon monoxide, water, and hydrogen. Finally, Fuchs and Sandhoff noted the existence of a straight-line relation between pyrolysis temperature and volatile yield.

The amount and composition of the volatiles are also dependent on the time/temperature history of the particle, i.e., the rate of temperature rise, the final temperature attained, and the duration of decomposition at that temperature. Unfortunately, there is a scarcity of data at heating rates typical of pulverized coal firing. Loison and Chauvin (1964) studied the pyrolysis products from seven coals of different rank and although their heating rate was somewhat low (10^3 °C/sec), and their

MOLECULE A — $C_{135}H_{97}O_9NS$
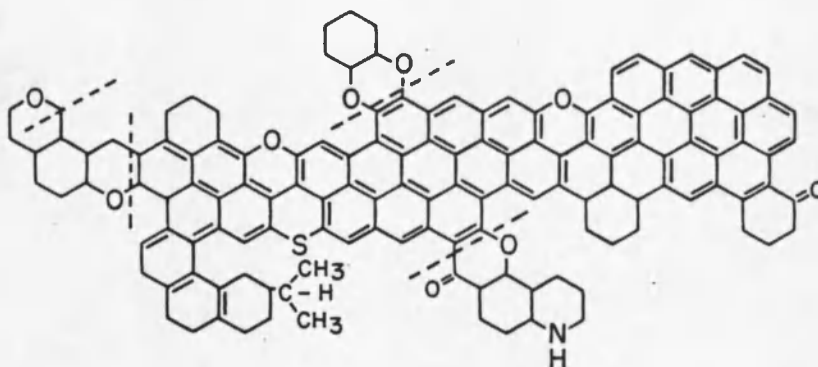
(DOTTED LINES INDICATE PROBABLE POINTS OF INITIAL SPLITTING.)

MOLECULE B — $C_{70}H_{41}O_6N$
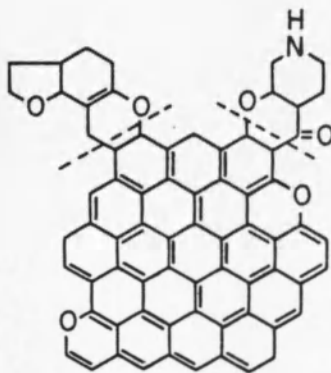
Figure 1. Representative coal molecules.

quench technique possibly ambiguous (Field et al., 1967), their data give an indication of volatile composition. They found that pyrolysis of a 31 weight percent volatile coal at 1500 °C/sec and to 1050°C resulted in 35 weight percent volatiles (measurement of volatiles is described in Chapter 4, Table 2). They analyzed the volatiles and found 72 percent condensable tars, 15 percent H_2, 5 percent CH_4, 4 percent CO, and 1 percent CO_2.

Mentser et al. (1974) devolatized four coals by pulse-heating at a rate of 8250 °C/sec. When a high volatile Pittsburgh bituminous was heated to 1000°C, a volatile yield of 36 percent was obtained. They also analyzed the volatiles (by mass spectroscopy) and found 53 percent condensable tars, 31 percent H_2, 6 percent CO, 6 percent CH_4, 3 percent C_2 to C_4, and 1 percent CO_2. Mentser et al. also found that as the pyrolysis temperature was increased above 1000°C the condensible tars decreased and CO increased (as did the total volatile yield).

Recent work by Blair, Bartok, and Wendt (1976) has shown that at high heating rates (up to 2 x 10^4 °C/sec), and high pyrolysis temperatures (1800°C), about 40 percent of the volatiles consisted of very high boiling point fractions, with the remainder consisting of CH_4, CO, CO_2, C_2H_2, C_2H_4, and C_2H_6. Furthermore, the species distribution in the volatiles was a strong function of coal composition and pyrolysis temperature, but not of heating rates when these were greater than 500 °C/sec.

Badzioch and Hawksley (1970) have determined the kinetics of pyrolysis for ten bituminous coals at temperatures up to 1000°C and heating rates to 5 x 10^4 °C/sec. Although they did not chemically analyze the volatile matter, they found the total amount of volatiles to

be sensitive to the heating rate; under rapid heating conditions, the yield of volatile products was 1.3 to 1.8 times higher than the difference in volatile matter between the proximate analysis of the coal and the char.

Anthony et al. (1975) have studied the rapid devolatization of Pittsburgh and Montana coals at temperatures up to 1100°C and heating rates to 10^4 °C/sec. Both coals devolatized so rapidly, even under inert conditions, that most of the weight loss occurred during heat-up (even in the cases with a 10^4 °C/sec heating ratio). For the Montana lignite, devolatization was found to be independent of pressure, heating rate, and particle size (50-1000 μm); but for the bituminous coal it increased with decreasing pressure, decreasing particle size, and, to a small extent, increasing heating rate. These workers also found that the kinetics and yields of the primary decomposition could be described by a set of independent first-order, parallel reactions represented by a Gaussian distribution of activation energies around a mean of 51 kcal/mole for the bituminous coal at elevated pressure. Again, no attempt was made to determine the actual volatile speciation.

Howard and Essenhigh (1967) experimentally investigated the pyrolysis of a Pittsburgh bituminous coal in an actual one-dimensional flame. These workers found that ignition occurs at a temperature of about 1100°C on the solid surface and it precedes significant volatile evolution. During the period of rapid volatile evolution (beginning soon after ignition), particles larger than about 65 microns are surrounded by a reaction zone which is removed from the solid surface, thus preventing heterogeneous reaction. Particles less than about 65 microns in size

(approximately half of the standard coal grind) simultaneously experience both rapid, gas phase volatile combustion and heterogeneous combustion. Finally, they noted that pyrolysis occurs as though the volatile matter exists as two different components, one evolved very rapidly and the other relatively slowly. The slowly evolving component appears to represent about 15 percent of the total volatile matter.

The evolution of nitrogeneous specie during coal pyrolysis has recently been investigated by Pohl and Sarofim (1975), Axworthy (1975), and Blair et al. (1976). This work is discussed in Section 1.4 in the context of NO formation mechanisms.

Thus, although a detailed mechanistic description of volatile evolution is not available, certain facts are discernible. Volatile evolution is dependent on fuel-composition and, under certain conditions, heating rate. The volatiles contain significant heavy condensibles in addition to the H_2, CH_4, C_2H_x, CO, and CO_2 which are probably evolved early.

1.2.3 Volatile Combustion

The volatiles themselves may burn in either of two regimes of combustion (Sternling and Wendt, 1972). In the first regime, the coal undergoes rapid heating, causing the release of large quantities of volatiles with a high velocity relative to the particle (in the limit, the particle may even rupture). In this case, the volatiles and oxygen are mixed, though imperfectly, prior to combustion and the burning occurs in turbulent flame fronts which can engulf clouds of particles. In this

regime, evolving nitrogen species may be rapidly oxidized by available oxygen if the local stoichiometry is fuel lean.

The second regime occurs when the rate of vaporization is slow enough to allow a diffusion flame to attach itself around or behind the particle (Lilley and Wendt, 1976). Here, most of the combustion occurs in a flame sheet surrounding the particle and its wake, this reaction environment being quite different from that of the premixed case. In particular, there are hot fuel-rich regions where precombustion pyrolysis can occur, and thus in the flame front the "fuel" may differ from the material fed into the furnace. Precombustion pyrolysis in fuel-rich zones may also enhance the formation of molecular nitrogen from the bound nitrogen specie.

Volatile combustion in this second regime is rapid. Field et al. (1967) have estimated that, for a mean volatile molecular weight of 100, it would take approximately 10 msec for the volatiles from a 50 μm particle to be consumed at 1000°C under conditions typical of the second regime.

Further clarification is needed to define which of these regimes of volatile combustion will be dominant for any particular coal or set of furnace conditions.

1.2.4 Char Burnout

The last regime of combustion is the char burnout regime (Sternling and Wendt, 1972) and although it may overlap with the volatile evolution and combustion to some degree (Howard and Essenhigh, 1967), it is clear that the char burnout is generally of much longer duration

(Mulcahy and Smith, 1969). Because of strong heating, the remnant of the coal particle containing the heavy ends is strongly pyrolyzed and converted into a char. While volatile combustion times are of the order of 10 msec, char burnout is generally greater than 300 msec.

Beer and Essenhigh (1960) were among the first to indicate the importance of both diffusion and reaction in this regime. Initially, the overall reaction process was viewed as three steps in sequence: transport of oxygen (and other reactants) to the surface of the particle, reaction with the surface, and transport of the products away. Clearly, the latter step is unlikely to be controlling (Field et al., 1967) because there is no evidence that the chemical reaction rate is inhibited by the presence of combustion products at temperatures above 1000°K and because the products will not significantly alter the diffusion rate of oxygen through what is largely inert diluent nitrogen. Howard and Essenhigh (1967) reported that during the initial rapid volatile evolution the heterogeneous combustion rate was suppressed; however, in general, they found the rate of heterogeneous reaction to be chemical reaction controlled.

Anson, Moles, and Street (1971) used high-speed, cine photography and microscopic analysis to study the structural changes of bituminous coal particles during rapid heating in air. They found that, in general, hollow spheres were formed and these burned both externally and internally at approximately constant diameter until, at an advanced stage, they fragmented. Smith (1971) studied the rate of reaction of size-graded fractions of petroleum coke, anthracite, and char from a swelling

bituminous coal. He also found constant density burning, but noted some particle shrinkage. His results suggested that combustion rates were limited by the combined effects of diffusion into the pores of the particles and by chemical reaction on the pore walls. Subsequently, Smith and Taylor (1972) made measurements on the structural properties of pulverized semi-anthracite particles at various stages of combustion. Their results showed that macropores developed during reaction and that the micropore volume was reduced. Smith and Taylor also determined that the system was only completely kinetically controlled for very small particles.

Mulcahy and Smith (1969) found that the char is primarily oxidized by O_2, not by CO_2 as had been previously suggested. They also suggested that surface reactions between carbon and OH radicals might be of importance. Ayling and Smith (1972) subsequently used two-wavelength radiation pyrometry to determine the temperatures of burning semi-anthracite particles. From their results they inferred that the combustion produced only carbon monoxide in the vicinity of the particles. This CO is then subsequently homogeneously oxidized to CO_2 somewhere in the particles' neighborhood (Field et al., 1967).

In summary, present data suggest that char burnout is slow relative to volatile combustion. Chemical interactions between char and volatile nitrogen specie are, therefore, not likely. High flame zone temperatures and larger combustion volumes may also be required for firing coal char directly in a coal system. Current information further suggests that the char burnout regime is characterized by heterogeneous

external and internal oxidation of carbon by oxygen to form carbon monoxide which is subsequently homogeneously oxidized to carbon dioxide. Thus, char nitrogen is likely to be evolved in a fuel-rich regime where conversion to N_2 may be favored. The marked difference between char burnout and volatile combustion strongly suggests it should be possible to alter NO emissions by changing the distribution of nitrogen between the char and volatile phases.

1.3 Thermal NO Formation

During the combustion of fossil fuels, nitrogen oxides are formed by the high temperature, thermal fixation of molecular oxygen and nitrogen present in the combustion air. NO is the favored oxide form because the residence time in most stationary combustion processes is too short for the oxidation of NO to NO_2, even though NO_2 is thermodynamically favored at lower temperatures (Bartok et al., 1964). NO, however, does oxidize in the atmosphere to NO_2, which is a primary participant in photochemical smog. NO resulting from the oxidation of atmospheric nitrogen, N_2, is defined as thermal NO.

To date, there has been no definitive work on thermal NO formation in pulverized coal flames because of the experimental complexities associated with feeding, stabilizing, and measuring of coal flames. However, considerable information has been obtained in premixed and diffusion flames with gaseous fuels and it is relevant to the homogeneous formation of thermal NO in coal flames.

For many years it was generally assumed that the thermal fixation of NO occurred according to the mechanism suggested by Zeldovich, Sadovnikov, and Frank-Kamenetskii (1947):

$$O + N_2 = NO + N$$

$$N + O_2 = NO + O$$

plus the reaction

$$N + OH = NO + H$$
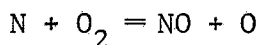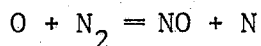
taken together with the assumption that the combustion reactions have equilibrated prior to the onset of nitric oxide formation. The data of Fenimore (1971), Harris et al. (1970), and others (Bowman, 1973; Pershing and Berkau, 1973) support this simplified picture for post combustion zone formation; however, Fenimore (1971) noted a substantial amount of "prompt" NO which formed very rapidly in the flame front of methane-air and ethylene-air flames and which could not be rationalized based on the extended Zeldovich mechanism with equilibrium radical concentrations. Prompt NO has subsequently been observed experimentally in gaseous systems by Bowman and Seery (1972), Bartok et al. (1972), Halstead and Munro (1971), Thompson, Beer, and Brown (1971), Lange (1971), Sarofim and Pohl (1973), Iverach, Basden, and Kirov (1973), Wendt and Ekmann (1975), and Malte and Pratt (1975).

At present there is still no general agreement about the mechanism for prompt NO production. Fenimore (1971) and Iverach et al. (1973) have attributed it to reactions other than those of Zeldovich. Other investigators (Marteney, 1970; Edelman and Economos, 1971; Bowman, 1971; DeSoete, 1972; Engleman et al., 1973) have suggested prompt NO is

the consequence of nonequilibrium radical concentrations in the vicinity of the combustion zone. Thompson et al. (1971) and Sarofim and Pohl (1973) used a partial equilibrium to predict radical concentrations and, subsequently, NO concentrations successfully. More recently, Mitchell and Sarofim (1975), Malte and Pratt (1975), and Bowman (1975) have experimentally observed "super equilibrium" radical concentrations; however, even the measured concentrations were not sufficient to explain the NO formation in methane/air combustion (Malte and Pratt, 1975) and in propane/air combustion (Takagi et al., 1975). In addition, Cernansky and Sawyer (1975), Shoffstall (1975), and Merryman and Levy (1975) have observed the existence of significant NO_2, particularly on the fuel-rich side of gas flames. To date, however, neither prompt NO or NO_2 has been explicitly measured in pulverized coal flames.

In summary, thermal NO formation in gaseous flames occurs through the extended Zeldovich mechanism and the same is believed likely for coal flames. This means that thermal NO is largely formed through a relatively slow, very temperature-dependent reaction, where the resultant thermal NO emissions are likely to depend on the time-temperature history throughout the entire length of a combustor. With light hydrocarbons, the Zeldovich mechanism is also almost certainly coupled to the hydrocarbon chemistry indirectly via the nonequilibrium radical concentrations and is probably coupled directly via some type of Fenimore reaction (CN). With coal, the situation is far more complex. Fenimore type reactions may be significant because of the large number of hydrocarbon radicals present. The

importance of nonequilibrium O and OH concentrations is unclear because

of the uncertainty regarding the controlling combustion regime.

1.4 Fuel NO Formation

1.4.1 Importance of Fuel NO

For many years it was assumed that NO was formed only by high

temperature fixation of atmospheric nitrogen and oxygen; recent experi-

mental studies, however, have indicated that the conversion of bound

nitrogen in the fuel to NO is potentially of equal or greater importance

in the formation of NO_x during coal and residual oil combustion. In an

early EPA (NAPCA) evaluation of fuel additives in a small experimental

furnace, Martin, Pershing, and Berkau (1971) noted that certain nitrogen-

containing additives, notably various amines and nitrates, increased NO_x

emissions through approximately 50 percent conversion of the nitrogen in

the additive to NO.

To date, there has been no definitive study on the absolute impor-

tance of fuel nitrogen conversion in self-sustaining pulverized coal

flames, but considerable related information is available. As shown in

Table 1, a number of good experimental studies have been conducted on the

addition of typical nitrogeneous compounds to flat, laboratory flames.

The data in Table 1 indicate that fuel nitrogen is a large potential

source of NO emissions and that the oxidation of many nitrogen-containing

compounds to NO is rapid, occurring on a time-scale comparable to that of

the combustion reactions (Bowman, 1973). For example, Axworthy (1975)

found that above a stoichiometric ratio of 0.8 more than 50% of the inlet

nitrogen appeared as NO in the exhaust.

Table 1. Studies on the addition of nitrogeneous compounds to flat, laboratory flames.

Investigator	Fuel	N compounds
Shaw and Thomas (1968)	CO	pyridines, amines, cyanides
Wendt and Sternling (1974)	CH_4	NH_3
Axworthy (1975)	CH_4	HCN, NH_3, NO
DeSoete (1975)	CH_4, C_2H_4	C_2N_2, NH_3, NO
Sarofim et al. (1975)	CH_4	NH_3, NO, pyridine, methylamine
Sawyer (1975)	C_3H_8	C_2N_2, NH_3, NO
Haynes, Iverach, and Kirov (1975)	C_2H_2, C_2H_4, C_3H_8, CH_4, H_2	CN species, NO, NH
Merryman and Levy (1975)	CH_4	methylamine, pyridine, piperidine

Sternling and Wendt (1972) have considered the fate of chemically bound nitrogen and point out that the situation is more complex than suggested by the gaseous combustion studies just described. They note that, in addition to fuel NO from the gas phase combustion of volatiles, there exists the potential for significant "char NO" if a substantial portion of the original coal nitrogen remains in the coal particle until the char burnout regime. Recent experimental work by Pohl and Sarofim (1975) and Blair et al. (1976) has shown that significant amounts of nitrogen (about 70% at 1750°C) may remain in the char after devolatilization and detailed analytical modeling of the char burnout regime (Wendt and Schulze, 1976) demonstrated that NO from this source could be potentially significant.

Several investigators have attempted to infer the importance of fuel nitrogen conversion in practical systems by investigating the emissions from distillate and residual oils doped with typical nitrogen compounds. Turner, Andrews, and Siegmund (1972) measured NO emissions from a package boiler burning oils doped with twenty nitrogen additives and measured 40 to 80% conversions under normal operating conditions. Martin and Berkau (1972) used a small experimental furnace to determine the amount of NO produced from burning a distillate oil doped with pyridine, quinoline, and piperidine; conversions ranged from 20 to 70 percent. Appleton and Heywood (1973) studied the NO formation from kerosene doped with pyridine in a one-dimensional spray combustor. With rapid initial mixing, they obtained almost complete conversion of the bound nitrogen to NO. Pershing, Martin, and Berkau (1975) burned a low sulfur residual oil in argon/oxygen and thereby inferred that

approximately half of the total NO measured under normal combustion conditions was the result of fuel nitrogen oxidation.

The most definitive work on fuel NO from coal combustion has been carried out in low temperature fluid bed combustors and may not, therefore, be directly applicable to pulverized coal flames. Jonke et al. (1969) observed 580 ppm NO while operating a 1300°C coal-fired fluid bed with both N_2/O_2 and Ar/O_2. This corresponds to approximately 25 percent fuel nitrogen conversion and suggests that the emissions are essentially all fuel NO (at 1300°K). Recent work by Pereira et al. (1975) confirmed the importance of fuel NO (relative to thermal NO) in fluid bed combustors and disclosed that above 800°C the NO formed from volatile combustion became the main NO source.

At present, the only information on the importance of fuel nitrogen conversion in actual self-sustaining pulverized coal flames is indirect. Based on a study of the influence of burner parameters on NO formation, Heap, Lowes, and Walmsley (1973) postulated that fuel NO accounts for the major portion of the NO_x formed in wall-fired units. Dykema and Hall (1975) conducted a statistical analysis of NO emissions from field units and estimated that, for a "typical" wall-fired boiler, 500 ppm of the 580 total ppm (3% O_2) NO result from fuel nitrogen. Habelt and Howell (1976) used field emission data and a thermal NO model to conclude that in coal-fired tangential boilers fuel nitrogen conversions were very low (10 percent at 15 percent excess air). Pershing et al. (1975) partially verified the initial hypothesis of Heap by burning pulverized coal in both air and argon/oxygen. This work was not

absolutely definitive, however, because of the increased temperature

associated with argon/oxygen flames. Thus, while the potential of fuel

nitrogen conversion as a major NO source is well-established, its actual

importance (relative to thermal NO) has not yet been defined. Further,

as described in the following three sections, its dependence on combus-

tion parameters is largely unknown. This is of particular importance

because control technology, which has been shown to be extremely effective

in controlling thermal NO formation in natural gas flames, may actually

increase emissions from coal-fired boilers because it increases fuel NO.

1.4.2 Oxygen Dependence

Available evidence indicates that increased oxygen availability

results in increased fuel nitrogen conversion. Figure 2 is a composite

plot of the work of Bartok et al. (1972), Wendt and Sternling (1974),

Axworthy (1975), and Sarofim et al. (1975) on the addition of nitrogen

additives (NH_3, HCN, $(CN)_2$, and NO) to jet-stirred combustors and flat

flames. The data indicate that, in premixed systems, nearly quantitative

conversion to NO is achieved at conditions typical of most furnaces and

boilers (stoichiometric ratio of 1.1 to 1.4). Substoichiometric condi-

tions (< 1.0), however, resulted in significantly reduced conversions.

Appleton and Heywood (1973) found that, in an actual combustor, imperfect

fuel-air mixing causes inhomogeneities and, consequently, the average

fuel nitrogen conversion is determined by local stoichiometry. Their

data indicated that imperfect mixing results in lower fuel nitrogen con-

versions and a much smaller dependence on overall stoichiometry than sug-

gested by the premixed experiments. The data of Martin and Berkau (1972),
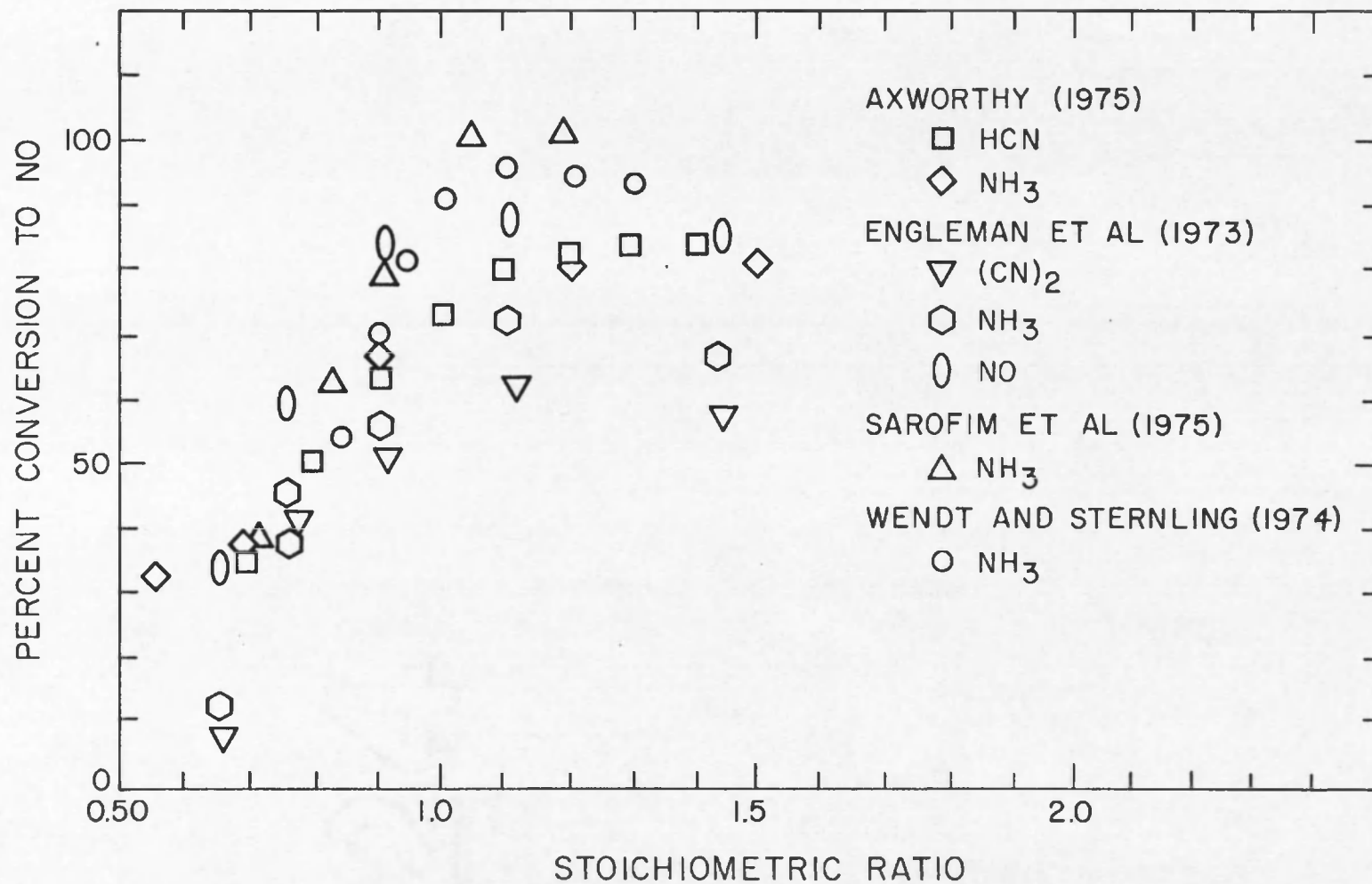
Figure 2. Effect of oxygen and speciation on fuel nitrogen conversion.

and Turner et al. (1972) further demonstrate the importance of local
oxygen concentration in fuel NO production during oil combustion. No
direct measurements on the oxygen dependence of fuel NO formation have
been made in coal-fired systems. The dependence is potentially complex
if NO formation from both char and volatile nitrogen is significant
because each could exhibit a different oxygen dependence due to differ-
ences in combustion regime.

1.4.3 Composition Dependence

Considerable data are available on the influence of nitrogen
compound type on conversion based on studies with prototype compounds.
As Figure 2 indicates, there is only a very slight dependence on compound
type based on premixed gaseous experiments with species which may be
typical of volatile nitrogen compounds. This supports the hypothesis of
Flagan, Galant, and Appleton (1974) that the formation of NO from organic
fuel nitrogen can be represented by a rate-constrained, partial equilib-
rium. Data on oil flames show a similar insensitivity to speciation.
Martin and Berkau (1972), investigating both unsaturated single-ring and
saturated multi-ring nitrogen compounds, observed only a slight effect of
composition on fuel nitrogen conversion in distillate oil flames. Turner
et al. (1972) tested 20 different nitrogen-containing additives,
including 1°, 2°, and 3° amines and heterocyclics with similar results.

At present, no direct evidence on the influence of composition on
conversion is available for coal systems. Nitrogen speciation in coal
may be significant because it may determine whether the nitrogen is
evolved with the volatiles or remains in the char. As previously

discussed, these regimes are significantly different and hence the fate of nitrogen specie is likewise different. Overall coal composition could dramatically affect the physical properties (e.g., swelling and plastic behavior) of the coal and hence the combustion characteristics and fuel nitrogen conversion. Coal particles which rupture due to high volatile evolution rates for example could potentially result in very high fuel nitrogen conversions.

In addition to speciation, the amount of nitrogen chemically bound in the fuel is believed to be important and indirect evidence suggests that nitrogen conversion to NO decreases with increasing nitrogen content. This has been predicted based on theoretical analysis of the diffusion character of the flame (Sternling and Wendt, 1974) and experimentally observed for prototype nitrogen compounds (Martin and Berkau, 1972; Turner et al., 1972). Habelt and Howell (1976) reported total NO emission data from full-scale tangential boilers firing coals with 0.6 to 2.1 wt percent fuel nitrogen. Their data show only a small increase (15 percent/1 percent N), suggesting a small effect of compound type and decreased conversion with increased nitrogen content (if fuel NO is assumed to be significant in tangential firing).

1.4.4 Temperature Dependence

At present, there is no definitive data on the influence of flame temperature on fuel nitrogen conversion and the indirect evidence is limited and inconclusive. Based on a theoretical analysis of the char burnout regime, Wendt and Schulze (1976) predict a weak temperature dependence. DeSoete (1975) measured a small effect of temperature on the

oxidation of $(CN)_2$ and NH_3 in premixed hydrocarbon flames. However, Heap, Tyson, and Lowes (1975) report a significant influence of air pre-heat and wall temperature on total NO emissions from actual pulverized coal flames. They attributed this either to thermal NO formation (which is known to be extremely temperature sensitive) or to the influence of heating range on the fate of coal nitrogen compounds. Pohl and Sarofim (1975) reported that the nitrogen content in the char decreased with increasing exposure time and temperature. At very high temperatures, certain coals may have an increased tendency to rupture, causing a dramatic increase in fuel nitrogen conversion.

In summary, the fundamental, experimental, and analytical results to date demonstrate the _potential_ of substantial fuel NO formation, both from gas phase oxidation of volatile nitrogen species and from combined homogeneous/heterogeneous oxidation of char nitrogen. Unfortunately, however, uncertainties in the controlling kinetic mechanisms, fundamental rate constants, and actual char burnout environment do not allow defini-tive quantitative results to be predicted. Pilot-scale testing has demonstrated the importance of fuel nitrogen in oil combustion and fluid bed studies suggest its importance with coal. Indirect information from pilot- and full-scale, pulverized coal testing is inconclusive. Thus, at present, there is no definitive data available on the absolute importance of fuel nitrogen conversion in pulverized coal-fired furnaces and boilers.

Further, the influence of operating variables is uncertain because the dependence of conversion to NO on oxygen concentration, coal composition, and flame temperature is not known. Control technology

cannot be confidently applied because of this overall lack of general

understanding of the controlling pollutant formation processes.

CHAPTER 2

SCOPE

The overall objective of this work was to identify and investigate those factors which are important in the formation of nitrogen oxides in self-sustaining, pulverized coal flames. The research concentrated on three specific areas which were found to constitute a major gap in the knowledge of NO_x formation in pulverized coal flames:

1. What are the relative proportions of thermal and fuel NO_x formed under normal operating conditions?

2. How does fuel nitrogen conversion depend on local oxygen concentration, flame temperature, and fuel composition?

3. If fuel nitrogen conversion is significant, what fraction is the result of volatile nitrogen oxidation and how do hardware and combustion parameters alter this fraction?

The approach was basically experimental, utilizing a laboratory combustor to study self-sustaining, pulverized coal flames in detail. As described in Chapter 1, past work had been largely confined to fundamental investigations of potentially important phenomena and full-scale field testing. This study provided a bridge between these extremes by utilizing an experimental system which was large enough to stabilize a self-sustaining flame under industrial combustion conditions, yet small enough that the controlling phenomena could be identified.

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Because of the aerodynamic and physicochemical complexities of the coal combustion process, a useful and still rigorous theoretical analysis of pollutant formation from coal flames is not currently feasible. Rather, it was felt that a valuable contribution to the overall understanding of the problem could be made using a combination of fundamental analysis, empiricism, and special experimentation. In this way, a quantitative understanding of the overall mechanisms of NO_x formation in actual coal flames could be obtained and utilized both to provide general insight applicable to pollution control in practical combustion systems and to identify those areas which require further investigation through basic studies.

CHAPTER 3

COMBUSTION FACILITY

3.1 Design Criteria

The combustion facility was designed to meet the following criteria which were developed based on the research objectives and past operating experience:

1. The furnace had to contain the salient features of real combustion hardware so that the results would be acceptable in the industrial community; i.e., it had to be capable of burning 75 percent minus 200 mesh coal* in a swirling turbulent diffusion flame with inlet air velocities near 100 ft/sec and about 600°F preheat.

2. It had to be large enough to allow utilization of proven screw feeding technology and to insure that the flame would be self-sustaining. However, it also had to be small enough that synthetic oxidizer atmospheres could be applied at reasonable cost using standard pressured cylinders.

3. The combustion chamber had to be vertical so that the coal feeder could be mounted directly above it and feeding problems, therefore, minimized.

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*Industrial installations normally pulverize their coal so that approximately 75 percent of the particles will pass through a 200 mesh screen.

4. The facility had to be flexible. In addition to a variety of pulverized coals, it had to be suitable for studying the combustion of residual oils, solid (pulverized) wastes, low Btu gas, crude oil, char, oil shale, etc.

5. It had to be versatile so that only minor modifications were required to convert it from the classical tunnel chamber to alternate configurations.

The design described in the following sections was developed from these criteria. It is similar to that used by Howard and Essenhigh (1966), but has a higher initial combustion intensity.

3.2 Furnace

The experimental furnace is illustrated in Figure 3. The vertical combustion chamber is 76" long and 6" in diameter inside. The overall outer diameter is approximately 27". In the lower half of the furnace, the walls consist of an outer steel shell, 1/4" of roll board insulation, 8" of Harbison-Walker Lightweight 26 insulating castable (2600°F max. service temperature) and 2" of Harbison-Walker Castolast G 3200°F castable refractory. In the upper half of the furnace, the walls consist of 6" of insulating castable and 4" of the high temperature Castolast G. This casting pattern was used so that the furnace would be capable of withstanding very hot combustion conditions (coal in argon/oxygen) and yet have minimal heat loss. Appendix A describes the heat transfer calculations which were used to determine the casting pattern.
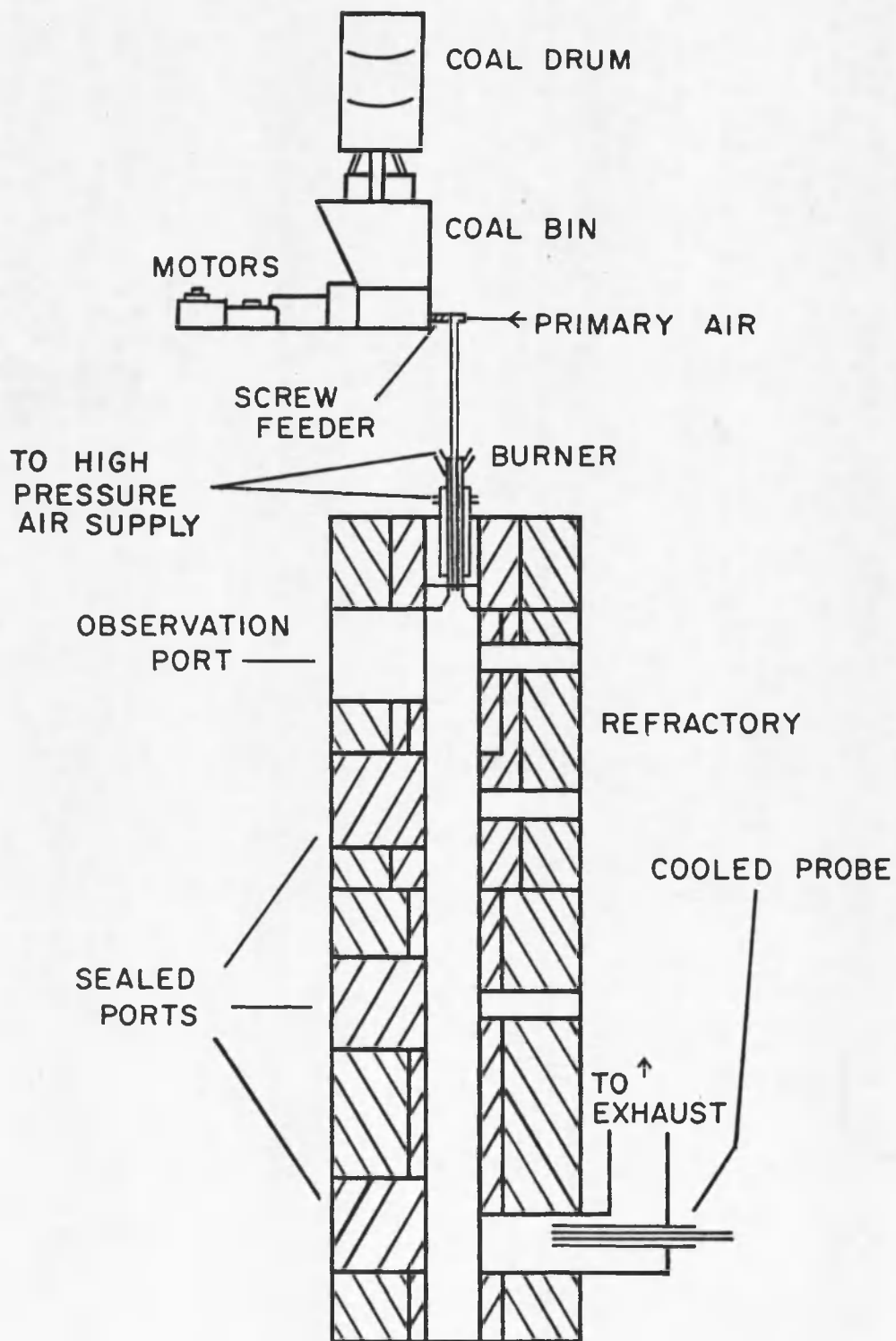
Figure 3. Experimental furnace.

At the full load firing rate of 85,000 Btu/hr (6.6 lbs coal/hr), the cylindrical combustion chamber provides a nominal residence time of approximately one second. This firing rate corresponds to a maximum combustion intensity (heat release per unit volume) of about 68,000 Btu/hr/ft^3 and is somewhat higher than was originally planned. Initial experimentation revealed, however, that the flame was more stable and symmetric at this higher firing rate, probably because of a more uniform coal feed and a higher upper zone wall temperature.

There are four 6" wide x 10" long observation ports and three 2" diameter ports spaced down the length of the furnace for flame photography, visual observation, and optical wall temperature measurements.

Fuel and air enter the combustion chamber at the top via a water-cooled burner described in detail below. The combustion gases leave the furnace through a 6" diameter exhaust port and flow through approximately forty feet of air and water double pipe heat exchangers. After the exchangers, the flue has a temperature of less than 300°F and is exhausted into a flume duct.

To start the system up initially, an 18" Eclipse extended pilot is used. The pilot is positioned in a horizontal port in the refractory about 5" below the top of the furnace. It normally extends approximately halfway through the refractory wall and is a long, internally spark ignited pilot burner. During ignition, power is turned on to the ignitor and the pilot air and gas valves opened in sequence. The gas is ignited by the electric spark after which the power to the ignitor is turned off. The pilot produces a long, horizontal flame directly across the outlet of

the main burner. When the gas flow to the fuel injector in the main burner (main gas) is then started, it ignites immediately and the pilot air and gas are then turned off. Once the furnace walls are above approximately 1900°F, the main gas is turned off and the coal flow begun. The coal flame ignites directly via radiation and convection from the walls.

3.3 Multifuel Burner

The specially designed water-cooled burner is illustrated in Figure 4. It has separate axial and swirl air inlets and is similar to that used in previous studies by Pershing et al. (1975). The axial air enters through two 1/2" angled ports into the center pipe. Swirl air enters a vaned swirl chamber via two tangential ports 180 degrees opposed and passes through eight 0.100" curved swirl vanes as shown in Figure 5. The inside diameter of the burner itself is 1.38"; however, several burner inserts were prepared so that the secondary air velocity (axial) could be maintained at 60 ft/sec for a variety of mass flows, air pre-heats, etc. (Thus, when the inlet air temperature was increased from 530°R to 1060°R, the burner throat area could also be doubled to maintain a constant velocity.) The burner throat is water-cooled and the exit is fitted with a 30 degree refractory (Castolast G) quarl that has an L/D ratio of 1. The top of the burner has a removable collar designed to accept a variety of fuel injectors for natural gas, fuel oils, and pulverized coals.

FUEL INJECTOR

AXIAL AIR
INLET

SWIRL AIR
INLET

COOLING
WATER
INLET

SWIRL
VANES

REFRACTORY
QUARL
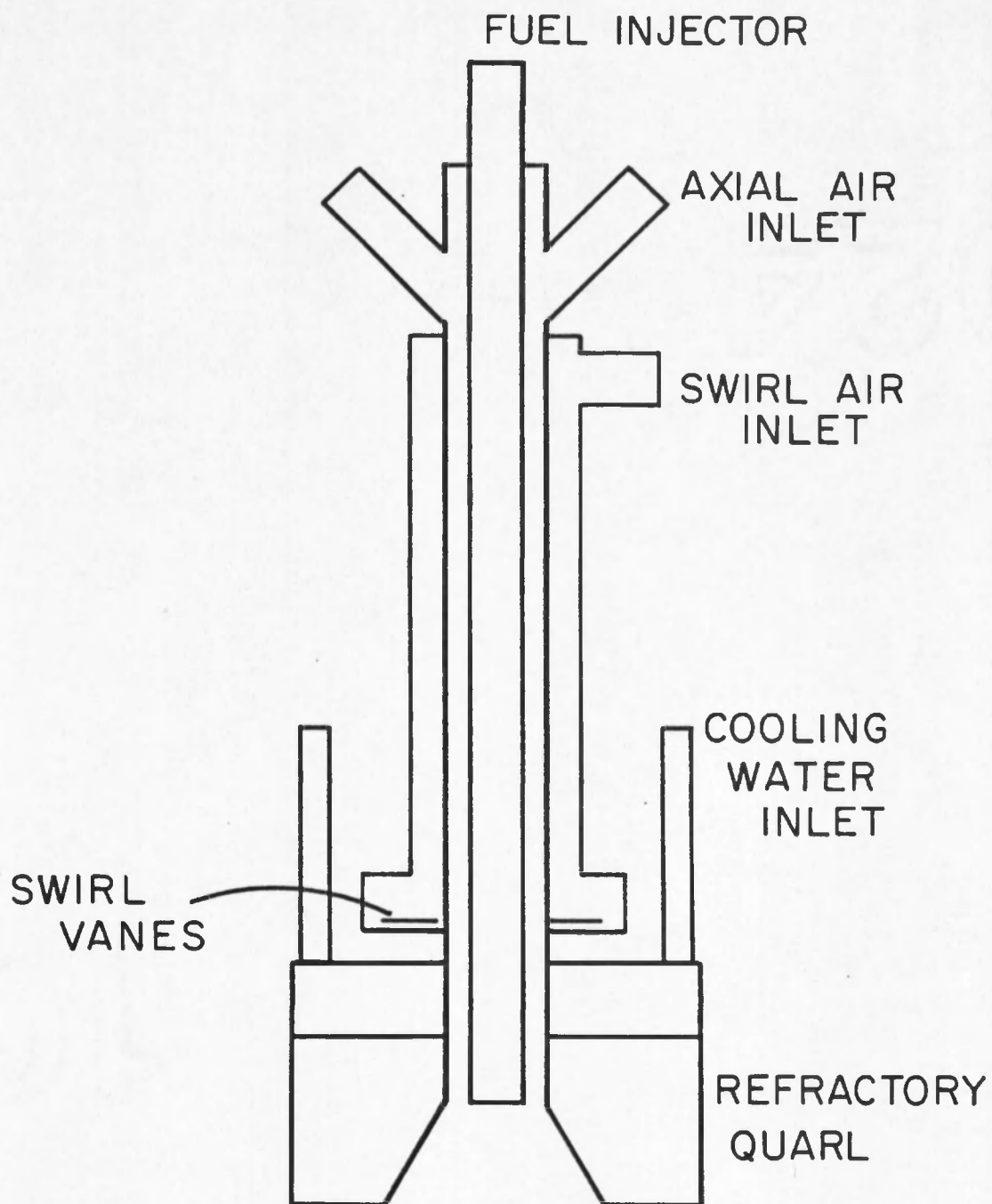
Figure 4. Multifuel burner.

8 VANES
1/8" THICK
0.100" TALL
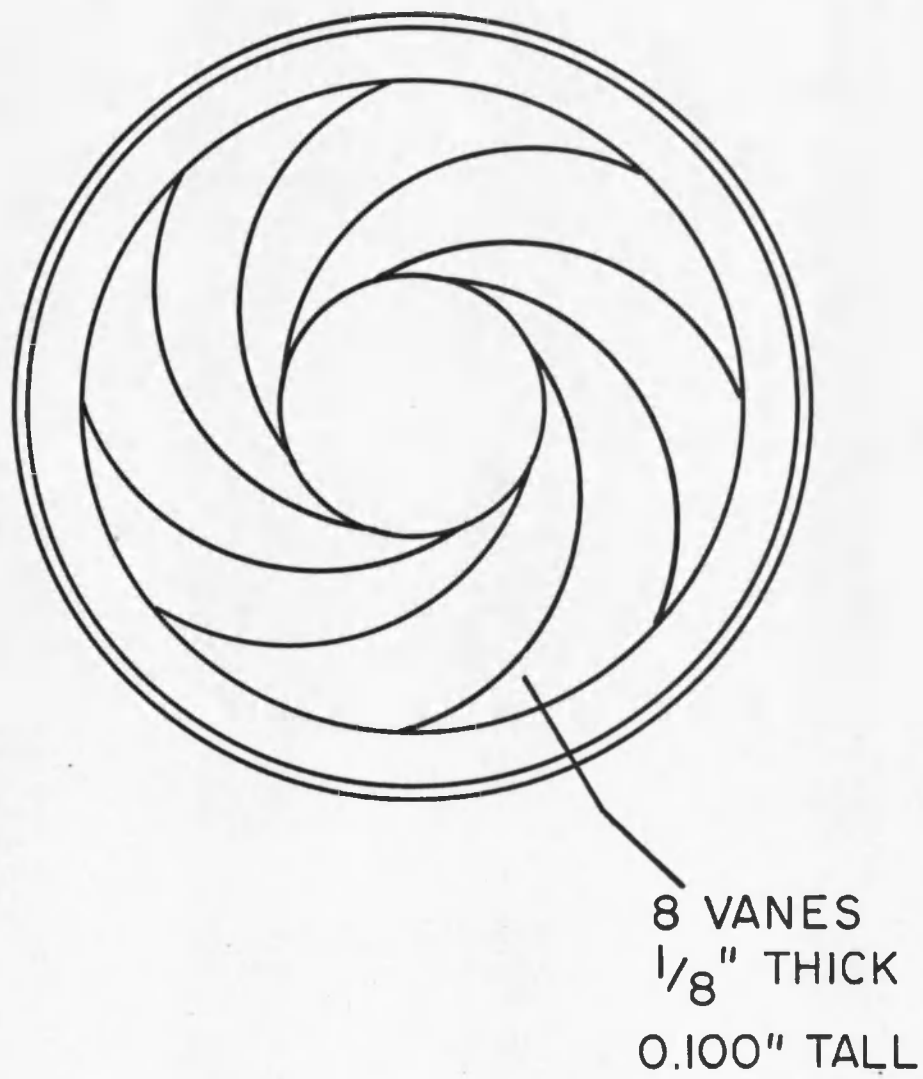
Figure 5. Swirl vanes.

3.4 Fuel Injectors

The fuel injectors used in this study are shown in Figure 6.
Both injectors were fabricated from 3/4" stainless steel tubes with
welded end plugs. The first contains three 11/64" holes angled to dis-
tribute the coal away from the axis of the furnace and is characterized
as a rapid mixing injector because it produces a short bulbous flame. It
was designed to be similar to the "coal spreader" system employed in many
commerical systems (Armento and Sage, 1975). The second injector con-
tains a single, 19/64" center hole with an area equal to that of the
three holes in the divergent injector. It produces relatively slow
mixing between the primary and secondary air streams and hence gives a
long, very thin flame. The two injectors are, thus, somewhat representa-
tive of two different classes of coal combustion equipment -- one with
intense mixing common in wall-fired units, the other with slow mixing
common in tangentially fired units (Habelt and Howell, 1976).

3.5 Air Supply System

The air supply system for the furnace is shown in Figure 7. Under
normal operating conditions, a 100 psig air compressor provides the
combustion air. After being filtered and partially dried, the air goes
through two high volume regulators where the pressure is stepped down to
approximately 30 psig. For special tests, the air is enriched or replaced
with varying amounts of carbon dioxide (CO_2), argon (Ar), and/or oxygen
(O_2), all of which are supplied from 250 cubic feet high pressure
cylinders. In each case there is an appropriate two-stage high volume

DIVERGENT   AXIAL
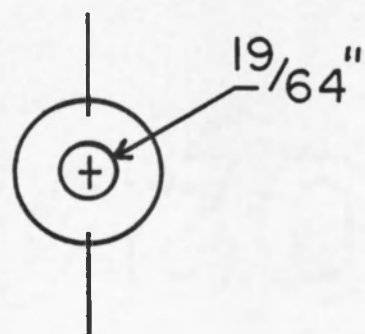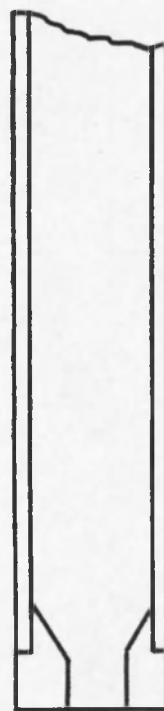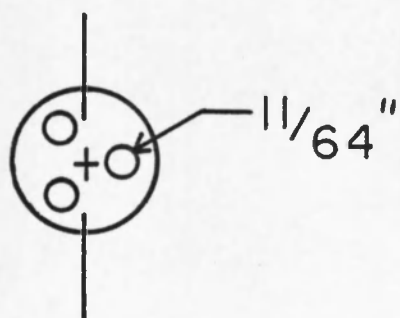
Figure 6.   Fuel injectors.
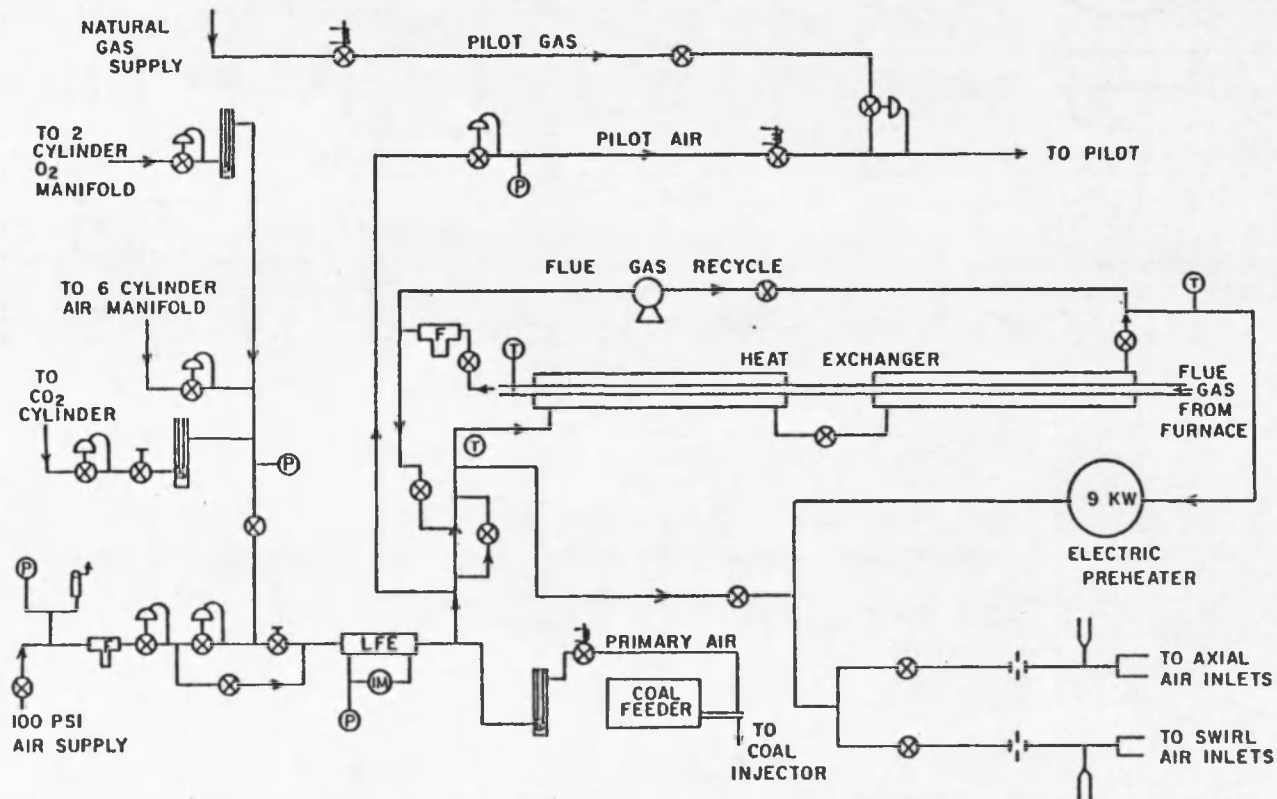
Figure 7. Air supply system.

regulator to step the pressure down to approximately 50 psig and a needle valve for fine control.

Once the pressure has been reduced, the air (or artificial oxidizer mixture) goes through a 3/4" micro-needle valve, for total flow control, and a laminar flow element. The pressure drop across the laminar flow element is measured by a 10" H_2O inclined manometer. In this way a relatively accurate measurement of the inlet oxidizer flow is obtained. Next, the air is split into three separate streams: the pilot air, the primary air, and the secondary air. On startup the pilot air goes through a regulator to step the pressure down to 10" H_2O and then to an Eclipse blast pilot mixer where it is combined with the pilot gas stream. Once the main flame has been ignited, the pilot air is shut off.

The primary air stream is used to transport the coal from the screw feeder to the burner. The flow is controlled by a needle valve and is metered with a calibrated rotameter. The primary air system also contains a solenoid valve which closes automatically after a flame-out. At present, the primary air is not preheated prior to the burner.

After the pilot and primary air streams are split off, the remaining flow goes to the preheating system. Here, the temperature is raised from 70°F to the desired level. This is accomplished by first passing it through the shell side of a double pipe heat exchanger. (The inner pipe contains the hot combustion gases from the furnace.) In this exchanger the air is preheated to approximately 300°F. The final preheating and temperature control is accomplished with a 9 Kw Chromalox

circulation heater. The heater was constructed with a 304 stainless steel shell and incoloy elements so preheats up to 1000°F can be obtained.

When desired, filtered flue gas can be recycled from the outlet of the heat exchanger (~200°F) and added into the secondary air stream via an ejector prior to the heat exchanger or via a pump just prior to the electric preheater. In both cases the recirculated gases go through the electric preheater and enter the burner at the same temperature as the secondary air. Recirculation of flue gases is common industrial practice, and has been shown to be an effective NO_x abatement measure for gas-fired flames.

Once the secondary air has the desired temperature and composition, it is split into axial and swirl air streams. The flow in each line is controlled with a high temperature globe valve and metered with a calibrated orifice. Two .036" exposed bead iron-constantan thermocouples just prior to the burner inlets are used both for estimating the temperature of each stream and for the input to the proportional temperature controller on the electric preheater.

3.6 Fuel Delivery System

The coal delivery system was designed to be totally enclosed to minimize dust and safety problems. First the coal is loaded into small steel barrels (18" dia x 36" high) outside the facility. The barrels are then closed, brought inside, and positioned above the feeder. After the appropriate connections are tightened, gate valves on the bottom of the barrels are opened and the coal flows into the feeder hopper.

The pulverized coal is metered with a twin-screw Acrison Model 105 feeder and the flow rate controlled with a mechanical variable speed drive. Detailed coal flow calibrations are in Appendix B. Flow problems were minimized by mounting the entire feeding system directly above the burner. Based on past experience and visual observation of the flow from the feeder, it was initially felt that coal pulsing was going to be a major problem. In an attempt to overcome this, a variety of in-line mixing schemes were tried. Ultimately, however, the best approach proved to be a direct, vertical connection from the feeder to the fuel injector (no mixing device). Flow uniformity was further improved by operating the feeder at maximum rpm and by introducing the primary air as a high velocity air jet just opposite the screw outlet.

Natural gas is used for bringing the furnace up to temperature and maintaining thermal equilibrium when coal is not being fired. In order to obtain a stable lite-off on coal, it is necessary that the wall temperature in the upper section of the furnace be above about 1900°F.

3.7 Safety/Control System

The furnace is equipped with an electrical interlock safety system to insure both safe startup and proper shut down in case of a variety of operational problems. The system was designed so that the facility could be operated without an attendant for long periods of time (nights, weekends, etc.) and thereby maintain thermal steady state. It monitors the outlet temperature and flow of the various cooling loops to insure system integrity. In the event of a poor or unstable flame for any reason it automatically shuts off all fuel flow. The system also

monitors the inlet air and in the event of a compressor failure shuts down both the furnace and electric air preheater (to protect the incoloy elements from overheating).

Before power is available for startup and operation, the following electrical switches must be closed:

1. Low pressure limit switch on the combustion air.

2. Remote shutdown toggle switch.

3. High temperature limit on the burner cooling water.

4. High temperature limit on the window cooling water.

5. Flow switch on the main cooling water.

6. Main power switch.

7. High temperature limit with sensor positioned above burner.

8. High temperature limit on flue cooling water.

Once these switches are all closed (as indicated by a series of green lights on the control panel), startup can be initiated. The natural gas system consists of the following control components:

1. Total gas solenoid valve (Maxon) which requires manual opening after it is activated electronically.

2. Pilot gas ball valve.

3. Pilot air solenoid valve-interlocked with the ignition transformer so that ignition cannot be attempted without pilot air flow.

4. Main gas control valve.

5. Main gas solenoid valve.

6. Ignition switch and high voltage transformer.

The coal delivery system has a similar set of control components:

1. Main coal feeder switch.

2. Primary air solenoid valve.

3. Coal feeder start relay and push-button.

For both fuels, the systems are designed so that in the event of a shut-down for any reason the operator must manually either reopen the gas valve or push the feeder start button again before the fuel flow will begin.

The coal, main gas, and pilot gas flames are all monitored by a Honeywell ultraviolet flame detector. In the event of a flame-out (or very poor flame), this flame detector shuts the system down. Details of the startup procedure are contained in Appendix C.

3.8 Analytical System

The analytical system was designed so that continuous monitoring of NO, NO_2, CO, CO_2, O_2, and SO_2 could be achieved. Figure 8 shows a schematic of the sampling and analysis system. The flue gas is withdrawn from the stack through a 3/8" water-cooled stainless steel probe. During the initial shakedown testing, the water-cooled stainless steel probe was compared with both cooled and uncooled quartz probes. No difference in the measured NO was noted, even with CO and unburned carbon present. It should be noted, however, that the flue gas has cooled to below 1000°F at the point of sampling and there is always at least 0.5% oxygen present in the sample.

Sample conditioning consists of a refrigerated dryer (water con-denser), two glass wool filters, a 60μ stainless steel filter (50°F), a
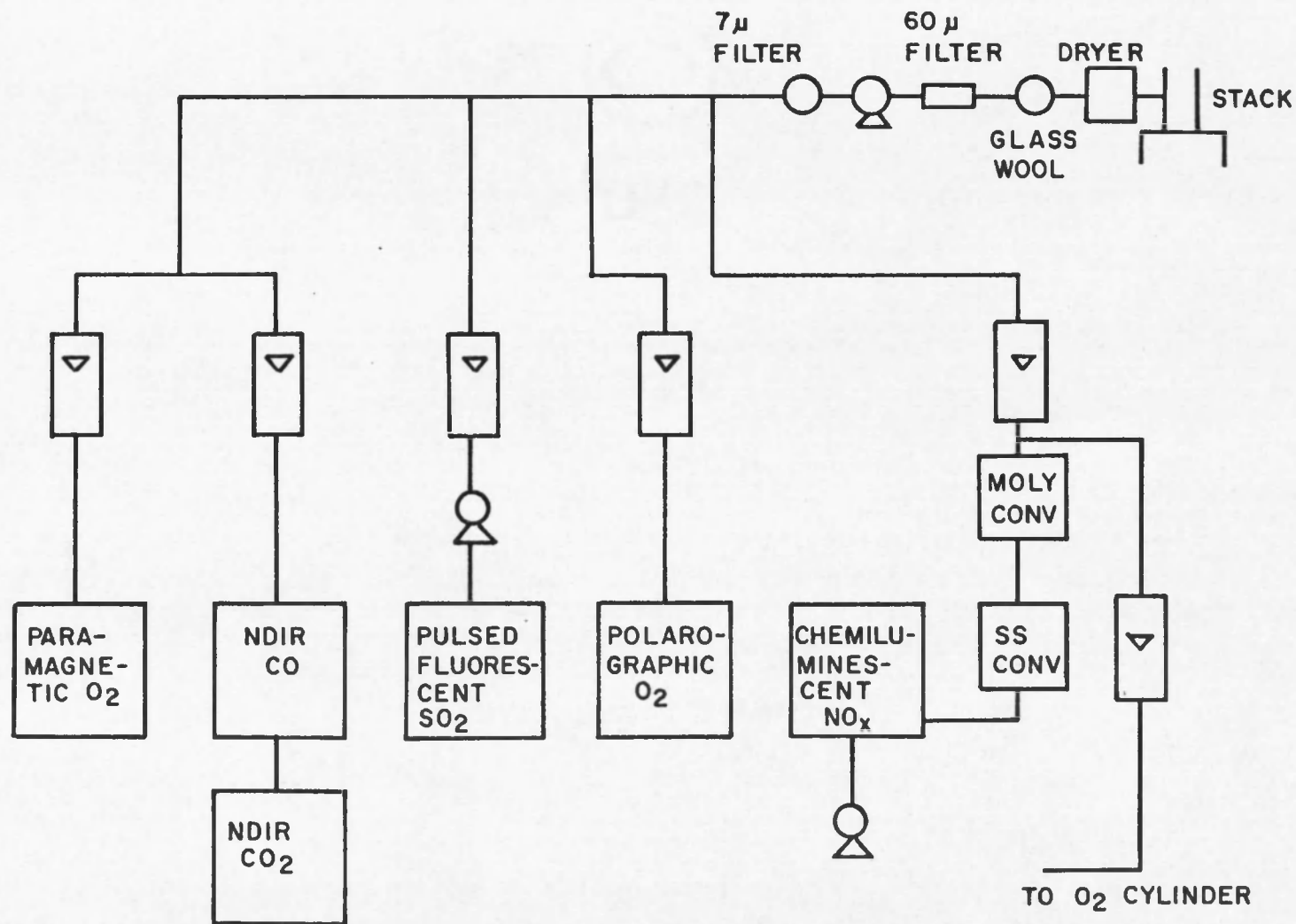
Figure 8. Analytical system.

stainless/Teflon sampling pump, and a 7µ stainless filter. All sample lines are 1/4" Teflon and all fittings 316 stainless steel.

The analysis system consists of the following equipment:

1. Beckman Model F3 Paramagnetic Oxygen Analyzer.

2. Beckman Model 864 Nondispersive Infrared CO Analyzer.

3. Beckman Model 864 Nondispersive Infrared CO_2 Analyzer.

4. Thermo Electron Model 40 Pulsed Fluorescent SO_2 Analyzer.

5. Beckman Model 715 Polarographic Oxygen Analyzer.

6. Thermo Electron Model 10AR Chemiluminescent NO-NO_x Analyzer with Model 300 Molybdenum Convertor.

All instruments are calibrated with zero and span gas at least every three hours. Details regarding the zero and span gases are contained in Appendix B.

CHAPTER 4

PRESENTATION OF RESULTS

4.1 Description of Results

This investigation examined the combustion of four pulverized coals, a pulverized coal char, and natural gas at a total of over 500 combustion conditions. The next seven chapters contain both the experimental results and the ensuing discussion on each topic where the topics are itemized according to the phenomena investigated. Each chapter deals with a single phenomenological area and closes with a summary of this investigation's contributions to the understanding of that particular topic.

Appendix D contains a complete tabulation of the experimental results for each fuel tested. In general, for each test condition, Appendix D contains the metered fuel and oxidizer inputs, the oxidizer composition and temperature, and the outlet flue gas composition, including NO, SO_2, CO, CO_2, and O_2 concentrations.

4.2 Fuel Analyses

The composition of the solid fuels used in this study are given in Table 2. (These data are based on the chemical analysis results from an independent laboratory.) The Colorado coal is the same coal used by Armento and Sage (1975). The Colorado, Pittsburgh No. 8, and Western Kentucky are all medium volatile bituminous coals, while the

Table 2. Pulverized fuel compositions.

	Colorado	Pittsburgh #8	Western Kentucky	Montana-Powder River Region	FMC coal char
Ultimate analysis (%, dry)					
C	73.1	77.2	73.0	67.2	72.8
H	5.1	5.2	5.0	4.4	0.9
N	1.16	1.19	1.40	1.10	.99
S	1.1	2.6	3.1	0.9	3.5
O	9.7	5.9	9.3	14.0	.7
Ash	9.8	7.9	8.2	11.7	21.2
Heating value (Btu/lb, wet)	12,400	13,700	12,450	8,900	
Proximate analysis (%, wet)					
Volatile*	38.9	37.0	36.1	30.5	3.6
Fixed carbon	52.6	54.0	51.2	39.0	73.8
Moisture	3.3	1.2	4.8	21.2	1.8
Ash	8.9	7.8	7.8	9.2	20.8

*As determined by the ASTM volatile analysis procedure in which the weight loss due to pyrolysis at 950°C for more than 3 minutes is measured.

Montana-Powder River Region coal is a sub-bituminous containing signifi-
cant moisture. The coal char originated from the FMC-COED coal gasifica-
tion process. Unfortunately, nothing is known about the composition of
the parent coal.

Figure 9 shows the particle size distribution of the solid fuels
used in this study. The coals were all pulverized prior to shipment to
Arizona. The coal char was received partially pulverized and was ground
to the appropriate mesh size with a rotating plate mill.

Figure 10 is a cumulative size distribution plot and indicates
that while all of the coals were pulverized to the normal industrial
standard of approximately 75 percent minus 200 mesh, the Colorado coal
contained somewhat less fines than the others. The "pulverized char" was
only 50 percent minus 200 mesh, but it did contain approximately as many
fines as the coals. The unpulverized char (as received) was only 25
percent minus 200 mesh.

The natural gas was commercial grade with approximately 90 per-
cent CH_4, 2 percent N_2, 6.5 percent ethane, and the balance higher
hydrocarbons.

4.3 Definition of Terms

Before considering the actual experimental results, it is impor-
tant to explicitly define the terminology used. Stoichiometric ratio
(SR) is the ratio of the inlet oxygen to the amount of oxygen needed to
completely burn the fuel to CO_2 and H_2O. Hence, a stoichiometric ratio
greater than 1.0 is fuel lean, while one less than 1.0 is fuel rich.
Excess air is the industrial term for defining the stoichiometric ratio;
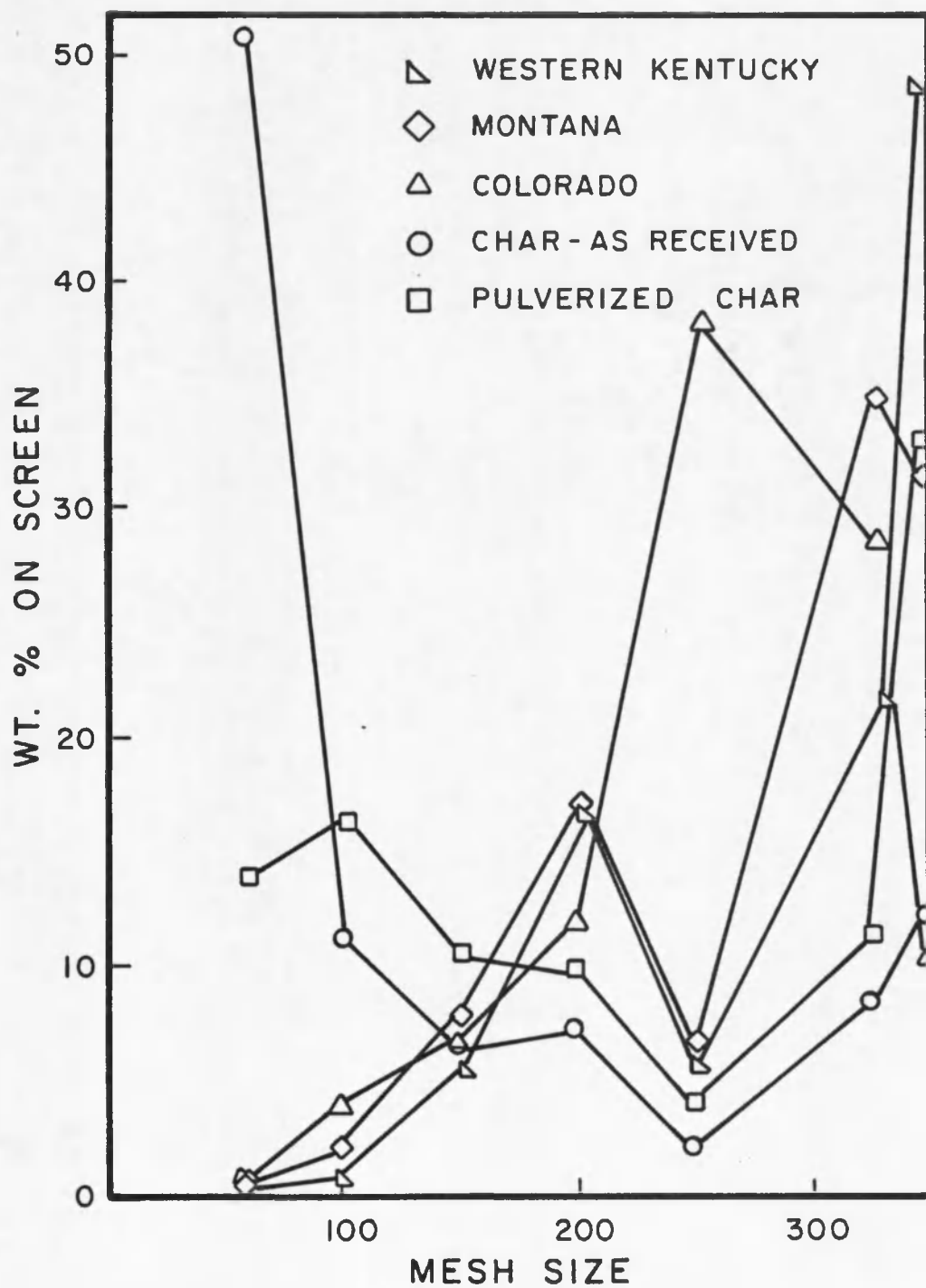
Figure 9. Particle size distribution.
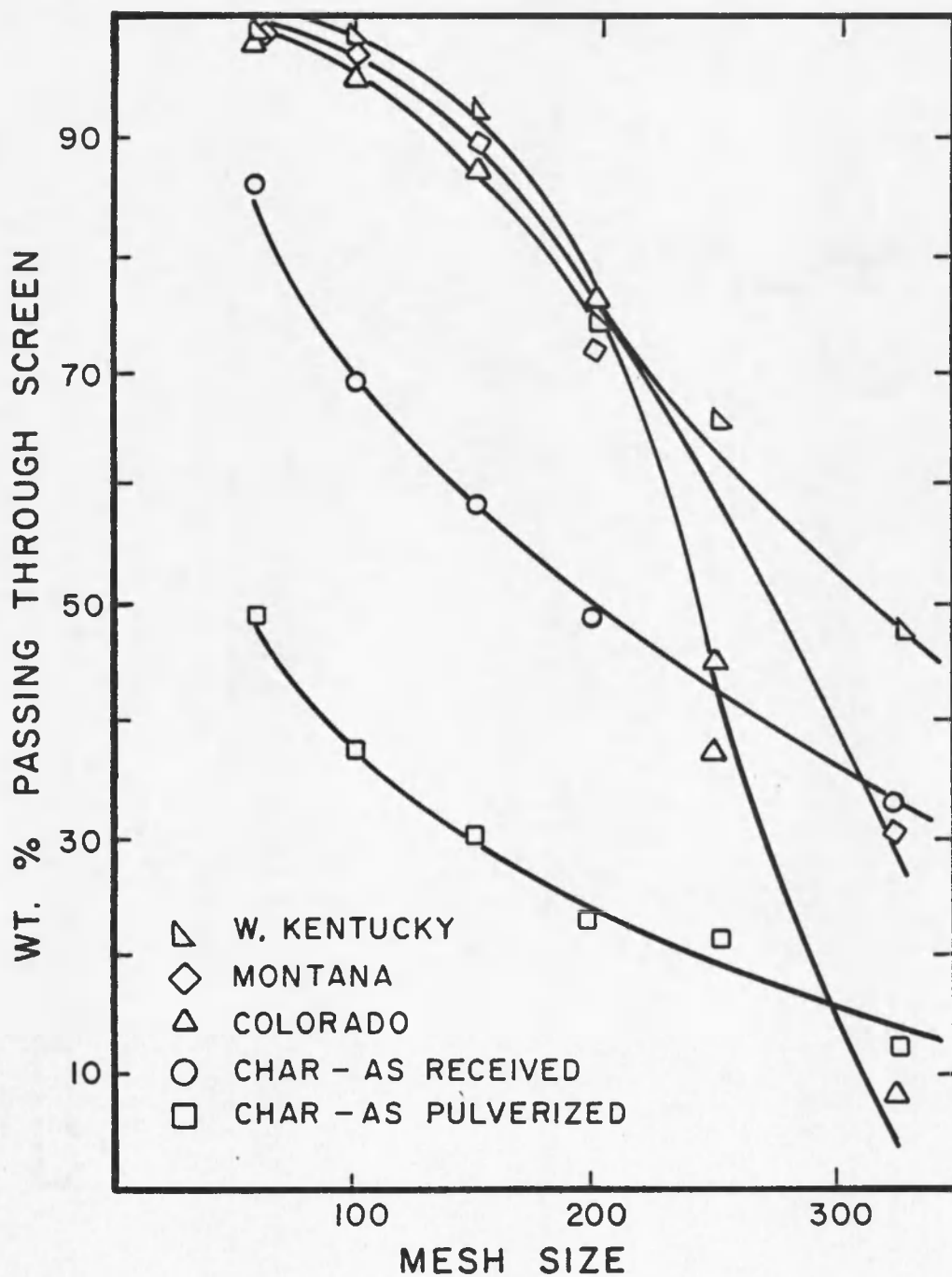
Figure 10.   Cumulative particle size distribution.

it is a measure of the amount of inlet oxygen which is in excess of that required for complete combustion and is equal to (SR - 1.0)*100%.

In general, all of the emission data, unless otherwise noted, are reduced to stoichiometric conditions (STOICHI), i.e., they are corrected for dilution by excess combustion air. In particular, the NO emission data (PPM NO, STOICHI) are presented as parts per million NO, by volume, dry, reduced to stoichiometric.

Primary air is that air used to transport the pulverized coal from the screw feeder to the furnace. As such, it is premixed with the coal prior to the burner and enters the combustion chamber through the fuel injector. Primary percentage and primary stoichiometry refer to the percent of the stoichiometric air requirement which is used as primary air.

Secondary air is that air not premixed with the coal prior to the burner. As previously described, it enters the combustion chamber through axial ports or tangential swirl vanes in the burner. The percent swirl is defined as the ratio of the volumetric flow of air introduced through the swirl vanes to the total secondary air volumetric flow rate (swirl plus axial) times one hundred percent.

Air preheat refers to the temperature of the secondary air. The primary air is not preheated prior to the burner.

The secondary air velocity is the axial velocity component of the total secondary air in the burner throat. Note that the axial velocity does not vary with the swirl percentage because it is based on the total secondary air going through the burner throat.

Flue gas recirculation (FGR) is defined as:

$$\frac{\text{std. ft}^3 \text{ recirculated}}{\text{std. ft}^3 \text{ inlet air} + \text{std. ft}^3 \text{ recirculated}} \text{ x } 100\% \qquad (4\text{-}1)$$

and is only added to the secondary air.

Finally, inlet "air," secondary "air," etc. are used in a general sense to refer to the incoming oxidizer streams. At the baseline conditions, the oxidizer streams are truly air (21% O_2, 79% N_2) from the high pressure air compressor. However, as noted later, during certain tests, the inlet "air" was really a synthetic oxidizer containing O_2, N_2, or Ar, and perhaps CO_2, NO, or NH_3. Oxygen enrichment refers specifically to tests in which pure oxygen was added to the compressed room air to increase the inlet oxygen percentage. Ar/O_2/CO_2 replacement refers to tests in which the compressed room air was completely shut off and the furnace operated with a synthetic oxidizer containing argon, oxygen, and perhaps carbon dioxide.

CHAPTER 5

FACILITY VALIDATION

5.1 Reproducibility

To establish the reproducibility of the experimental data, ten sets of data were taken at "identical" combustion conditions over a six-month period. The "baseline" operating conditions for the Western Kentucky coal were used for these tests because they are most representative of industrial practice. Baseline conditions are: full load, 5.9 lb coal/hr; 44% swirl; 650°F secondary air preheat; 14% primary air; 60 ft/sec secondary air velocity; and divergent coal injector. Figure 11 shows these results as a function of stoichiometric ratio and indicates that reproducibility is good, approximately ± 6% in the range of interest (SR = 1.1 to 1.2). Unless otherwise noted, these data were used directly to establish the error bars shown in subsequent figures. Due to the complexity of many of the figures, error bars are explicitly shown only when required for proper interpretation of the results.

CO emissions were also measured during these tests and, in general, they were at or below the detection limit of the analyzer (400 ppm). The low CO levels and the good agreement obtained between the O_2 and CO_2 analysis and the measured fuel and air inputs indicate that the coal was being completely burned under the baseline conditions. Below about 7% excess air, however, the CO emissions start to increase and by 2% excess there was approximately 0.5% CO in the flue.
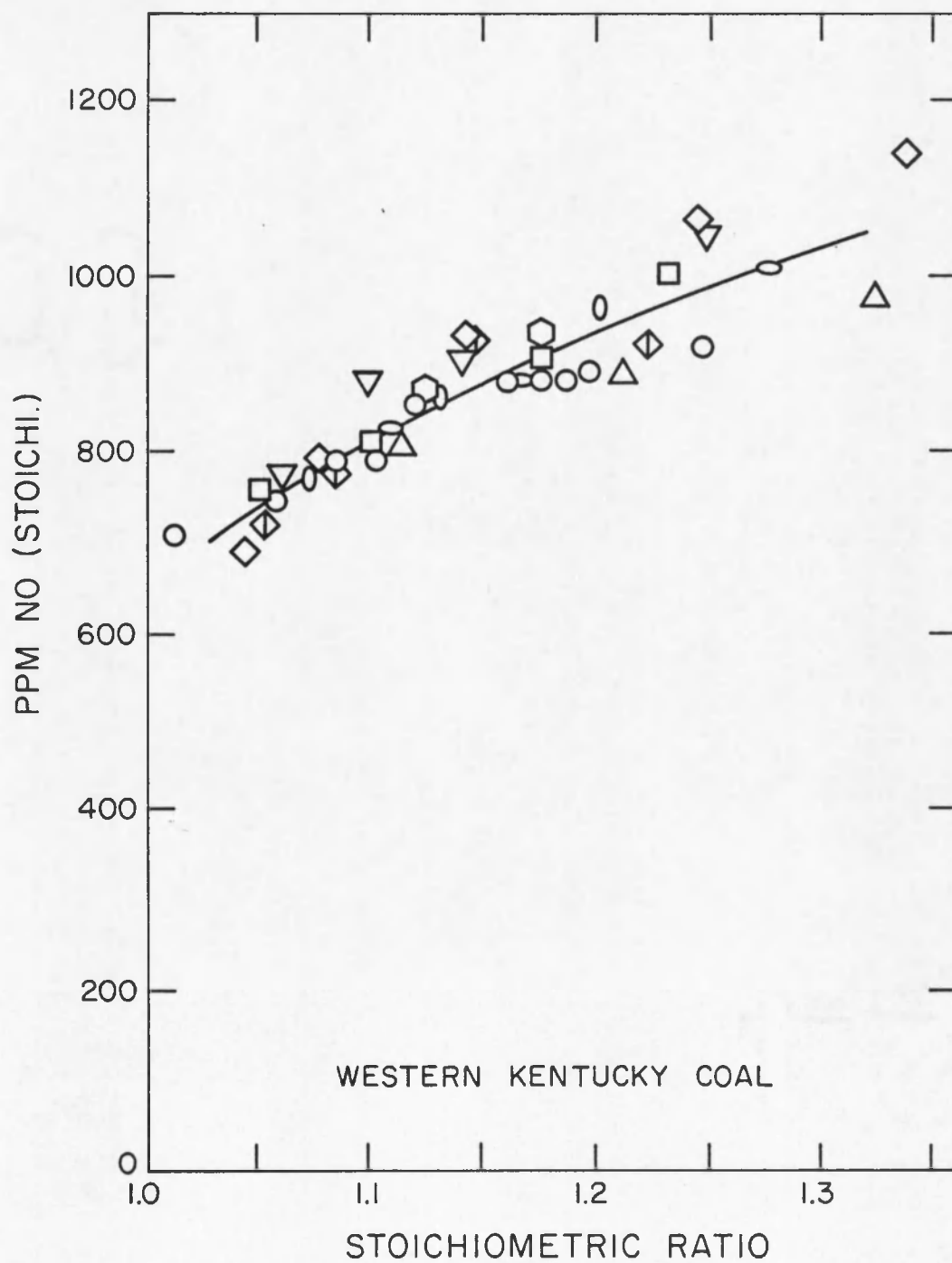
Figure 11. Baseline data reproducibility. -- Western Kentucky coal, divergent injector, 650°F preheat.

NO_2 measurements were made at a limited number of conditions. Levels ranged from 5 to 25 ppm (STOICHI) and were, in general, less than 5% of the total NO_x emission.

5.2 Simulation of Wall Firing

The burner/fuel injector systems used in this investigation were designed to simulate the initial coal/air mixing characteristics of wall-fired and tangentially fired watertube boilers since they represent more than 75 percent of the coal-fired units (Mason and Shimizu, 1974). In a wall-fired unit, the burners are mounted in arrays on either the front wall or on both the front and back wall (horizontally opposed firing). The burners typically employ a "coal spreader" in the end of the fuel tube to provide rapid initial mixing and hence flame stability, and flame attachment. The coal spreader is an impeller with circular vanes set at a 45-degree angle of divergence from the centerline to disperse the coal radially into the secondary air stream. The divergent fuel injector used in this investigation was designed to provide a similar radial velocity component.

Figure 12 shows the baseline data for the Colorado and Western Kentucky coals with the divergent injector plotted with field test results from nine wall-fired utility boilers (Crawford, Manny and Bartok, 1974; Crawford et al., 1975). (Note that the NO emission data have been converted to a 3 percent O_2 basis since this is the usual point of reference for field testing results.) Figure 12 indicates that, while there is considerable variation in actual field emission levels, the data
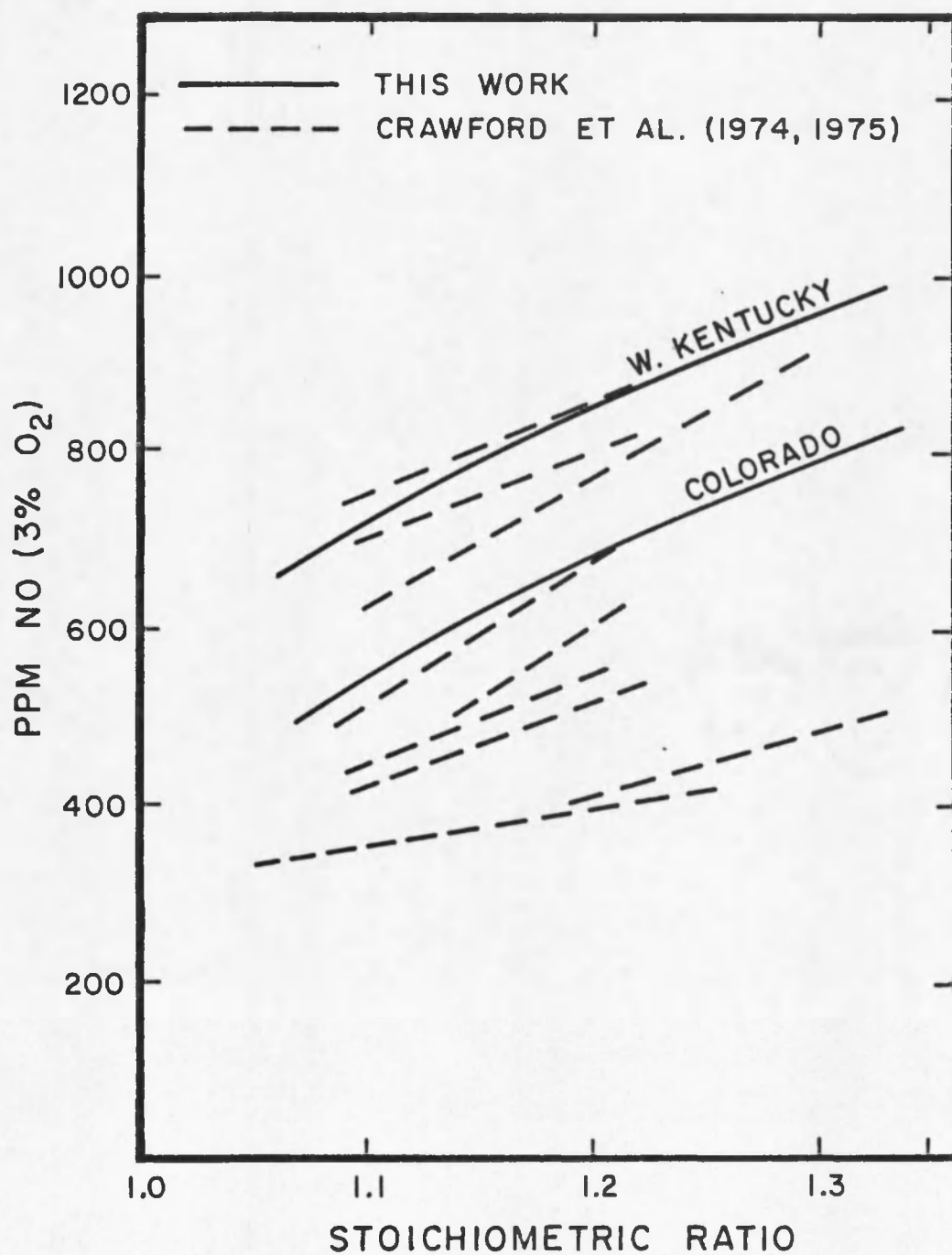
Figure 12.   Comparison with field data (wall firing).

reported herein on an 85,000 Btu/hr laboratory furnace with a divergent injector are consistent in both magnitude and trend with full-scale data.

5.3 Simulation of Tangential Firing

In a tangentially fired watertube boiler, the fuel and air enter the firebox through rectangular ducts in the corners of the furnace. The bulk of the combustion occurs in a rotating "fireball" in the center of the furnace chamber. (This is in marked contrast to a wall-fired unit where there are individual flames attached to each burner.) Figure 13 presents the baseline data for the Western Kentucky coal with the axial fuel injector along with the field test results (Crawford et al., 1974; Crawford et al., 1975; Lachapelle, 1976) on six tangentially fired field boilers. The axial fuel injector was designed to produce the relatively slow mixing between the primary air/coal stream and the secondary air stream which is characteristic of tangentially fired units. As Figure 13 indicates, the data obtained in this study have the proper excess air dependence although the absolute emission levels are slightly higher than those obtained from most field units. Thus, it appears that the axial fuel injection system may provide a viable methodology for subscale simulation of NO_x formation in a slowly mixed boiler.

In summary, the initial results demonstrated that it was possible to obtain reproducible data on NO_x formation in a small, self-sustaining pulverized coal flame and that with appropriate fluid dynamic changes the system could simulate the NO_x formation trends for each of the two major classes of full-scale combustion equipment.
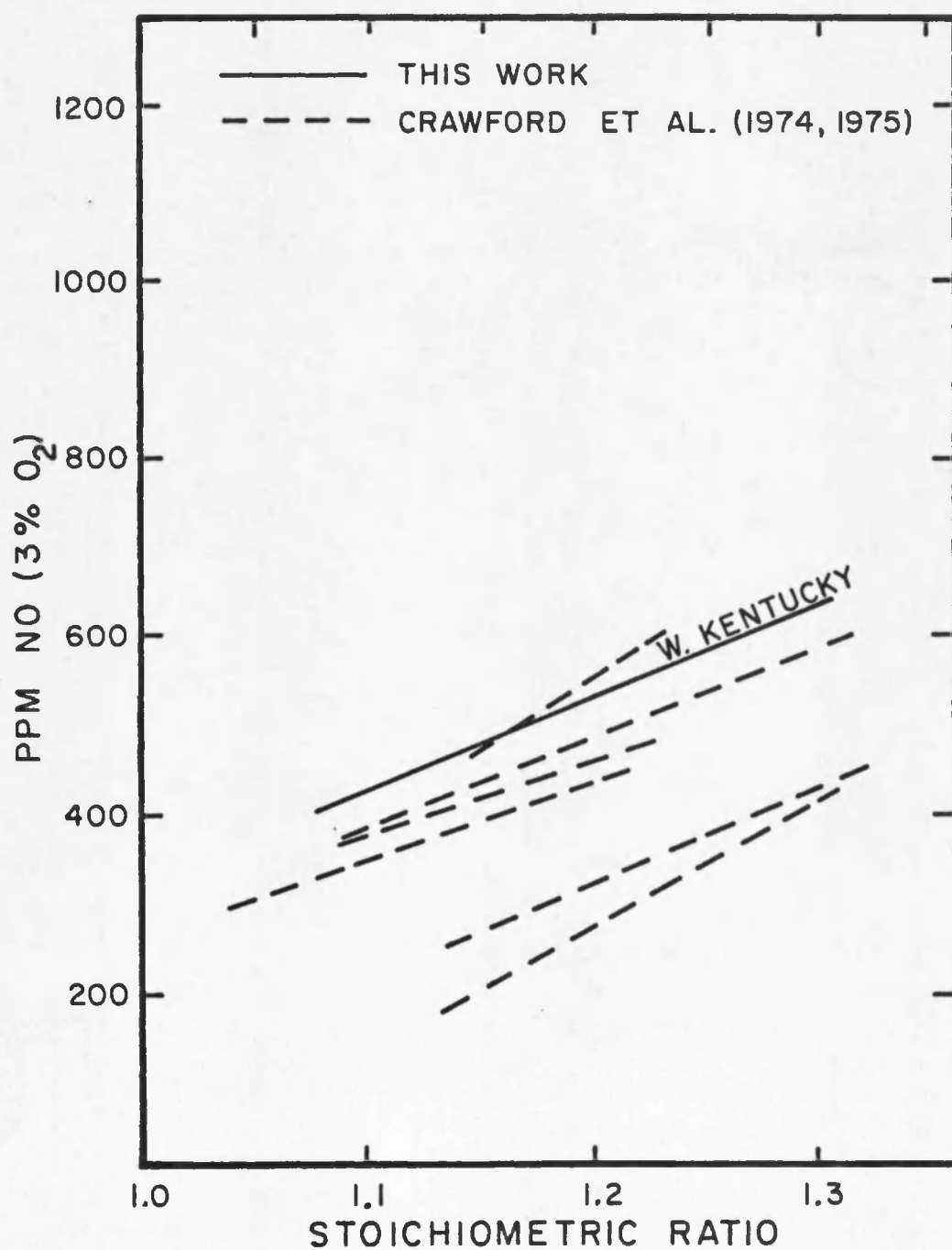
Figure 13. Comparison with field data (tangential firing).

CHAPTER 6

IMPORTANCE OF FUEL NITROGEN

6.1 Methodology Evaluation

By comparing the NO emissions at a particular set of operating conditions to those from the same fuel burning in an atmosphere containing no N_2, it is, in principle, possible to establish the fuel NO emissions and, by difference, the thermal NO emissions. In previous studies, an Ar/O_2 atmosphere has been used (Jonke et al., 1969; Pereira et al., 1975; Pershing et al., 1975); however, replacement of N_2 with Ar results in a theoretical flame temperature increase of approximately 400°F. Therefore, in this study, a synthetic oxidizer atmosphere containing 21% O_2, 18% CO_2, and the balance Ar, was used. Figure 14 indicates, in addition to being free of N_2, the $Ar/O_2/CO_2$ atmosphere allows matching of theoretical flame temperature between the air and $Ar/O_2/CO_2$ cases. (For a detailed discussion of the theoretical flame temperature calculations see Appendix E.)

The $Ar/O_2/CO_2$ replacement method does, however, suffer from at least three potential weaknesses:

1. Addition of CO_2 could have a chemical effect and, hence, change the NO kinetics.

2. Since the Ar, O_2, and CO_2 are commercial grade, they could contain significant impurities (e.g., N_2 or NO) which would invalidate the results.

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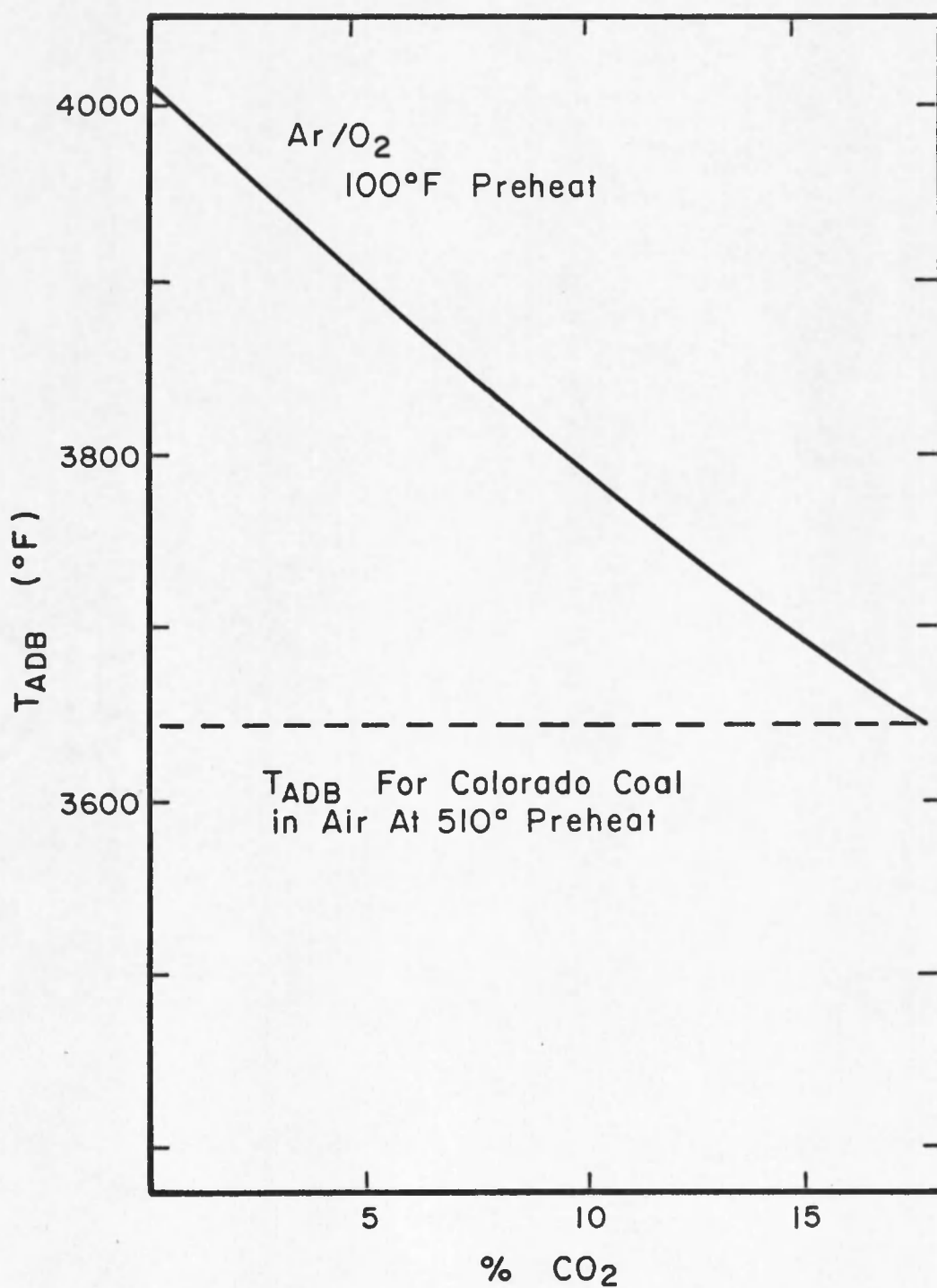
Figure 14. Theoretical flame temperatures for air and $Ar/O_2/CO_2$ systems.

3. If the furnace were not either leak tight or under positive
   pressure everywhere, there could be significant N_2 present from
   the room air.

To evaluate the first of these potential problems, a test series
was conducted in which theoretical flame temperature was maintained
constant with and without 18% CO_2 in the inlet air. Figure 15 shows these
results and demonstrates that the presence of small amounts of CO_2 in the
inlet air does not have any chemical effect on NO formation.

To evaluate the possibility of contamination of the Ar, O_2, and
CO_2, and to demonstrate that there were no air leaks in the system, tests
were run with 2-propanol and distillate oil. Under all conditions the
emissions with $Ar/O_2/CO_2$ were less than 12 ppm, the bulk of which is
probably due to the nearly complete oxidation of the small amount of fuel
nitrogen in the distillate oil (Martin and Berkau, 1972). Thus, it
appears that $Ar/O_2/CO_2$ replacement is a valid methodology for determining
fuel NO emissions.

6.2 Determination of Fuel NO

Data on fuel and thermal NO emissions as a function of stoichio-
metric ratio are shown in Figure 16 for the Western Kentucky coal with
both the divergent (rapid mixing) and axial (slow mixing) fuel injectors.
In each case, the upper line represents the emissions from the coal
burning in air (total NO) and the lower line the emissions from the coal
burning in $Ar/O_2/CO_2$ (fuel NO). Thermal NO is defined as the difference
between total NO and fuel NO, on the assumption that thermal fixation of
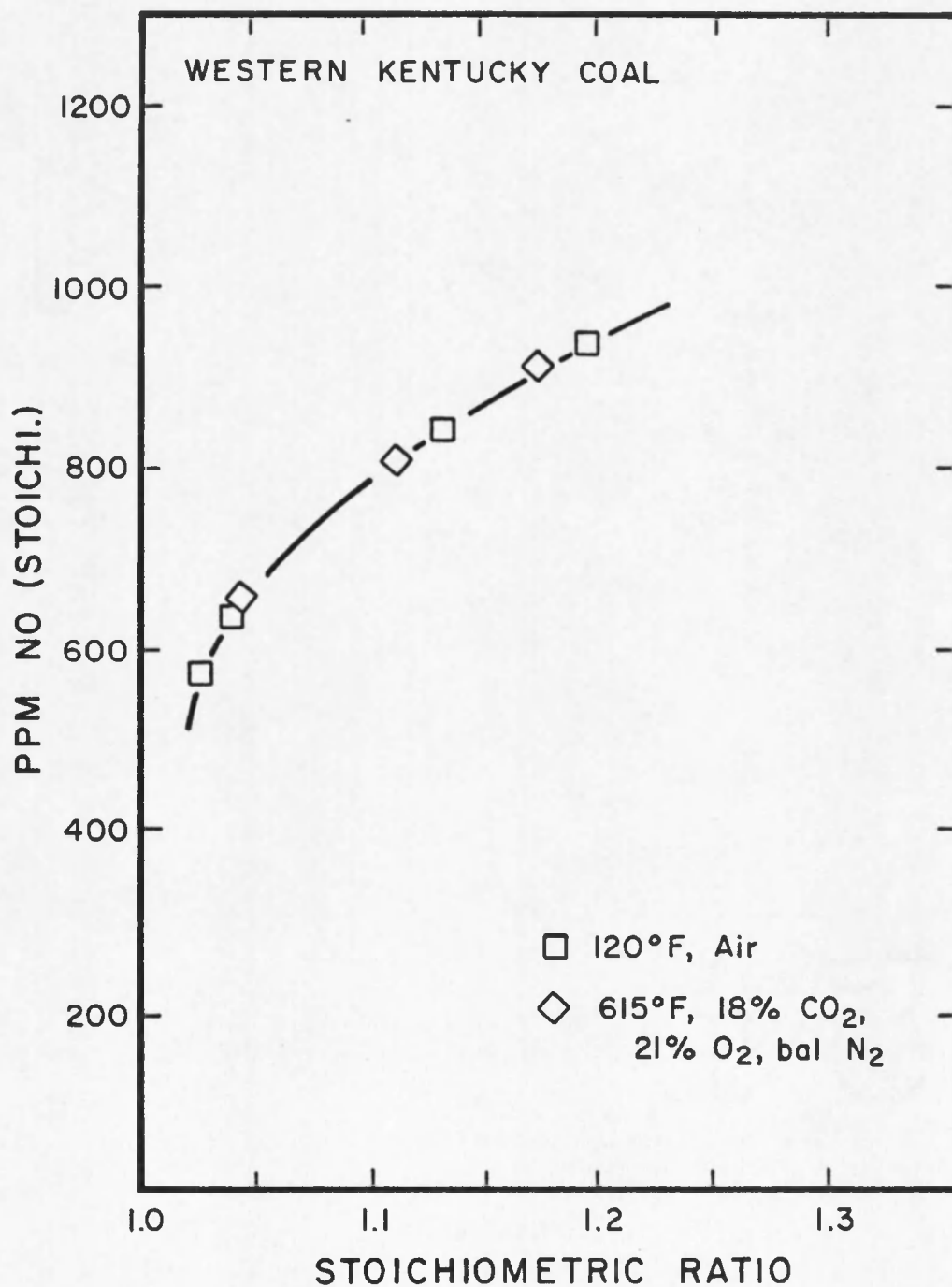
Figure 15. Absence of chemical effect due to CO_2 addition (constant
theoretical flame temperature). -- Western Kentucky coal,
divergent injector.
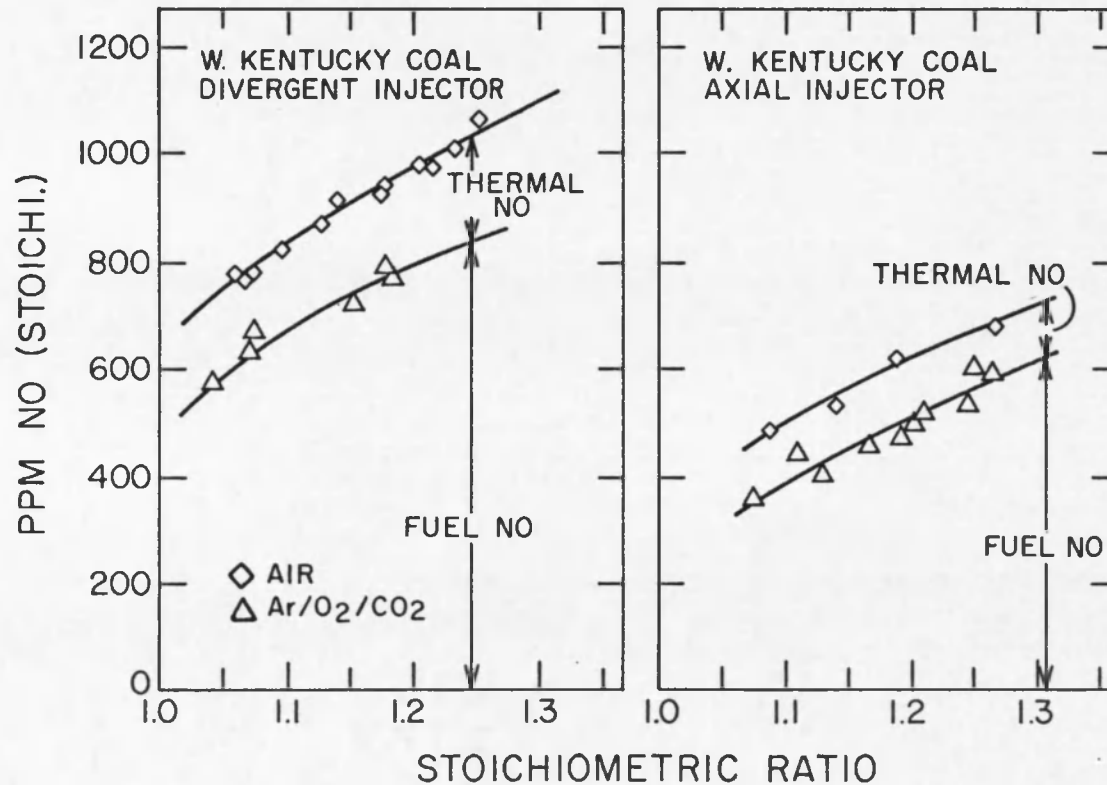
Figure 16. Thermal and fuel NO emissions. -- Western Kentucky coal, 650°F preheat.

atmospheric nitrogen does not inhibit fuel nitrogen conversion. (This is justifiable because of significant differences in the relative time scales. Fuel nitrogen oxidation is believed to occur concurrent with the hydrocarbon oxidation and hence prior to thermal NO formation.) The divergent injector data (650°F preheat, 45% swirl, 14% primary air, and 70 ft/sec throat velocity) clearly show that under these conditions over 80% of the total NO resulted from the oxidation of bound nitrogen in the fuel. Variations in primary air percentage, secondary air swirl, and burner throat velocity did not change this finding, and under all conditions examined, fuel NO contributed at least 75% of the total NO emissions (Pershing and Wendt, 1975).

Data from the single hole axial injector (650°F preheat, 45% swirl, 8% primary air) show that slow mixing significantly reduced total NO emissions. This is in agreement with pilot data (Heap et al., 1975) and field data on tangentially fired units (Crawford et al., 1975). However, it is clear that this reduction was due to a decrease in fuel NO emissions which again comprised approximately 80% of the total.

Decreased early mixing between secondary air and nitrogenous volatiles is probably the reason fuel nitrogen conversion is significantly lower with the axial injector than with the divergent injector. It has been postulated that in the axial case the flame sheet shields a substantial portion of the coal particles from the secondary air stream (Heap et al., 1973; Wendt and Sternling, 1974). This would cause the evolution of volatile nitrogen specie to occur in a fuel rich environment and hence favor the formation of N_2 over NO.

In summary, the data on fuel NO indicated that although slow mixing, as in tangentially fired systems, gives lower total NO emissions, the dominant NO producing mechanism in all cases was still through fuel nitrogen oxidation.

CHAPTER 7

COAL COMPOSITION

7.1 Total and Fuel NO

The four pulverized coals tested during this investigation repre-
sent a cross-section of chemical and physical properties. Ultimate
analyses are given in Table 2 (Chapter 4). The Colorado, Pittsburgh, and
Western Kentucky are bituminous coals with heating values over 12,000
Btu/lb; the Montana coal is a sub-bituminous with a heating value of
8,900 Btu/lb. The Colorado, Pittsburgh, and Montana have statistically
identical fuel nitrogen contents of 1.3 ± 0.05 percent (dry, ash free),
representative of many United States coals, while the Western Kentucky
coal is a relatively high nitrogen coal (1.52 percent). Thus, in addi-
tion to considering the effect of total nitrogen percentage, this work
focussed on the effect of coal rank for coals with the same nitrogen con-
tent. It is to be expected that coal rank will affect the physical and
chemical processes likely to occur during volatization and combustion.
The importance of total sulfur content was also considered; the Pittsburgh
and Western Kentucky are high sulfur (> 2.5 percent) eastern coals, while
the Colorado and Montana are western coals with only approximately one
percent sulfur.

Figure 17 summarizes the baseline total, fuel, and (by differ-
ence) thermal NO emission data for the divergent injector with all four
coals. In each case, the fuel flow was maintained at approximately

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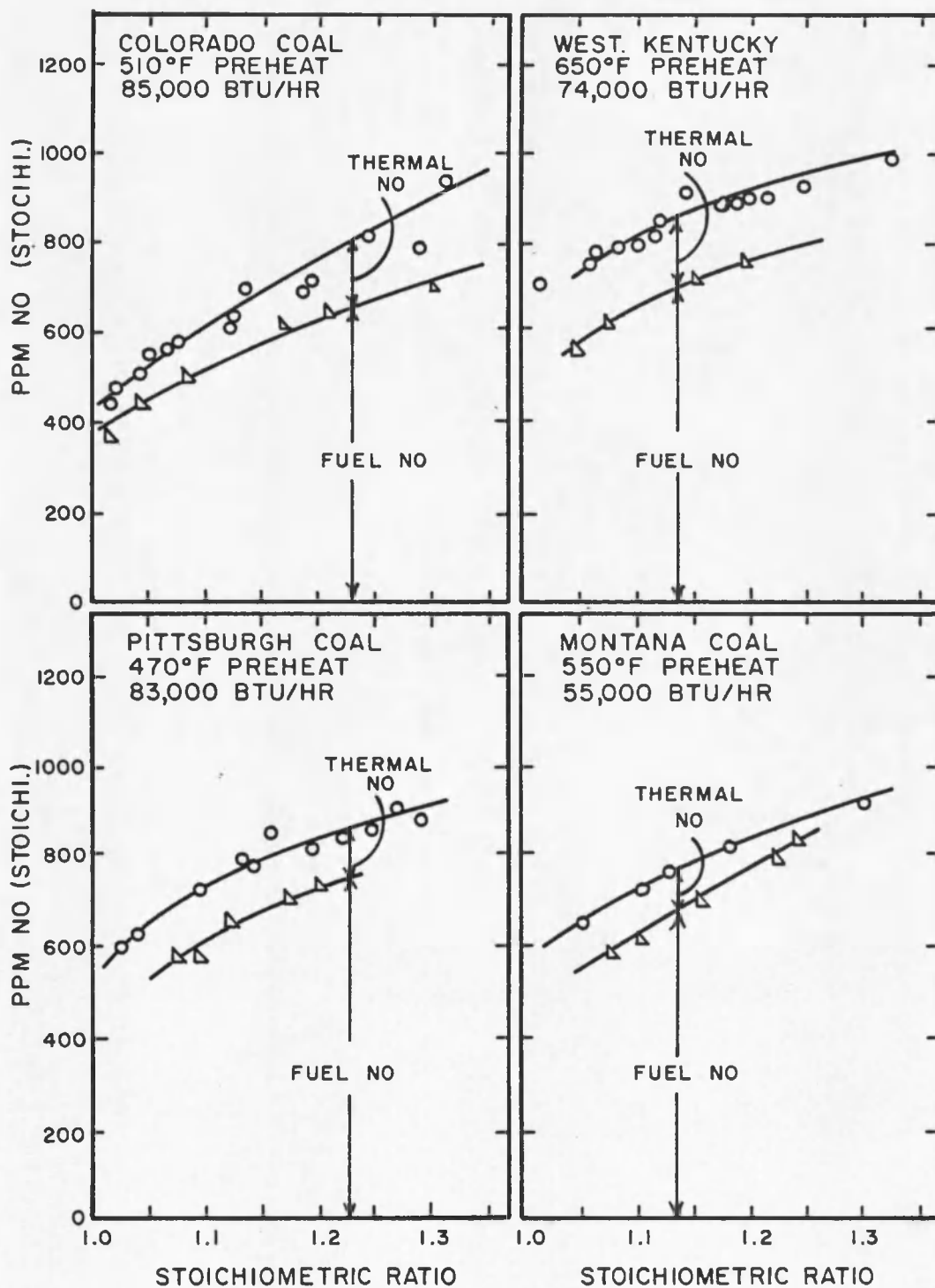
Figure 17. Effect of coal composition on thermal and fuel NO (divergent injector).

6.2 lbs/hr, the primary air at 14 percent of stoichiometric, the second-
ary air swirl at 44 percent, and the air preheat at its maximum. The
upper curve in each plot is data obtained while burning the coal with air
(total NO emissions) and the lower curve is with $Ar/O_2/CO_2$ (fuel NO
emissions). Over 75 percent of the total NO emissions are the result of
fuel nitrogen oxidation for each of the four coals tested.

Figure 18 is the analogous plot for the axial fuel injector with
the Western Kentucky and Montana coals. (The Colorado and Pittsburgh
coals were not tested with the axial injector because its conception and
fabrication occurred subsequent to their testing.) Again the results
indicate that the importance of fuel NO is not diminished by change of
coal composition.

Figure 19 is a composite plot of the divergent injector data on
the three bituminous coals at a constant set of operating conditions:
520°F secondary air preheat, SR = 1.15, 44 percent swirl, full load
(80,600 ± 4,300 Btu/hr gross heat input), and 14 percent primary air.
The data indicate that at these equivalent operating conditions, both
the total and fuel NO emissions increase only slightly as fuel nitrogen
increases. This is particularly surprising because the coals are known
to have significantly different chemical and physical properties and
because they exhibited different combustion characteristics. For
example, the Pittsburgh coal is a coking coal; many of the particles melt
upon heating and a fused carbonaceous residue and ash forms cenospheres
during combustion. The Pittsburgh coal flames were also generally less
stable than the Colorado or Western Kentucky flames; i.e., the number of
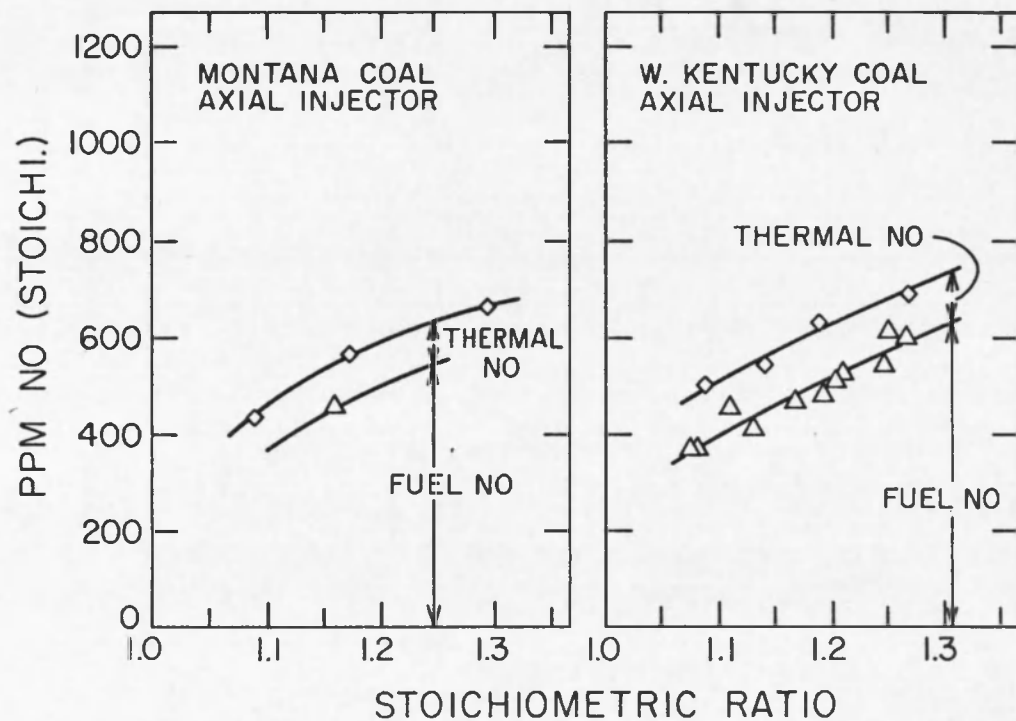
Figure 18. Effect of coal composition on thermal and fuel NO (axial injector).
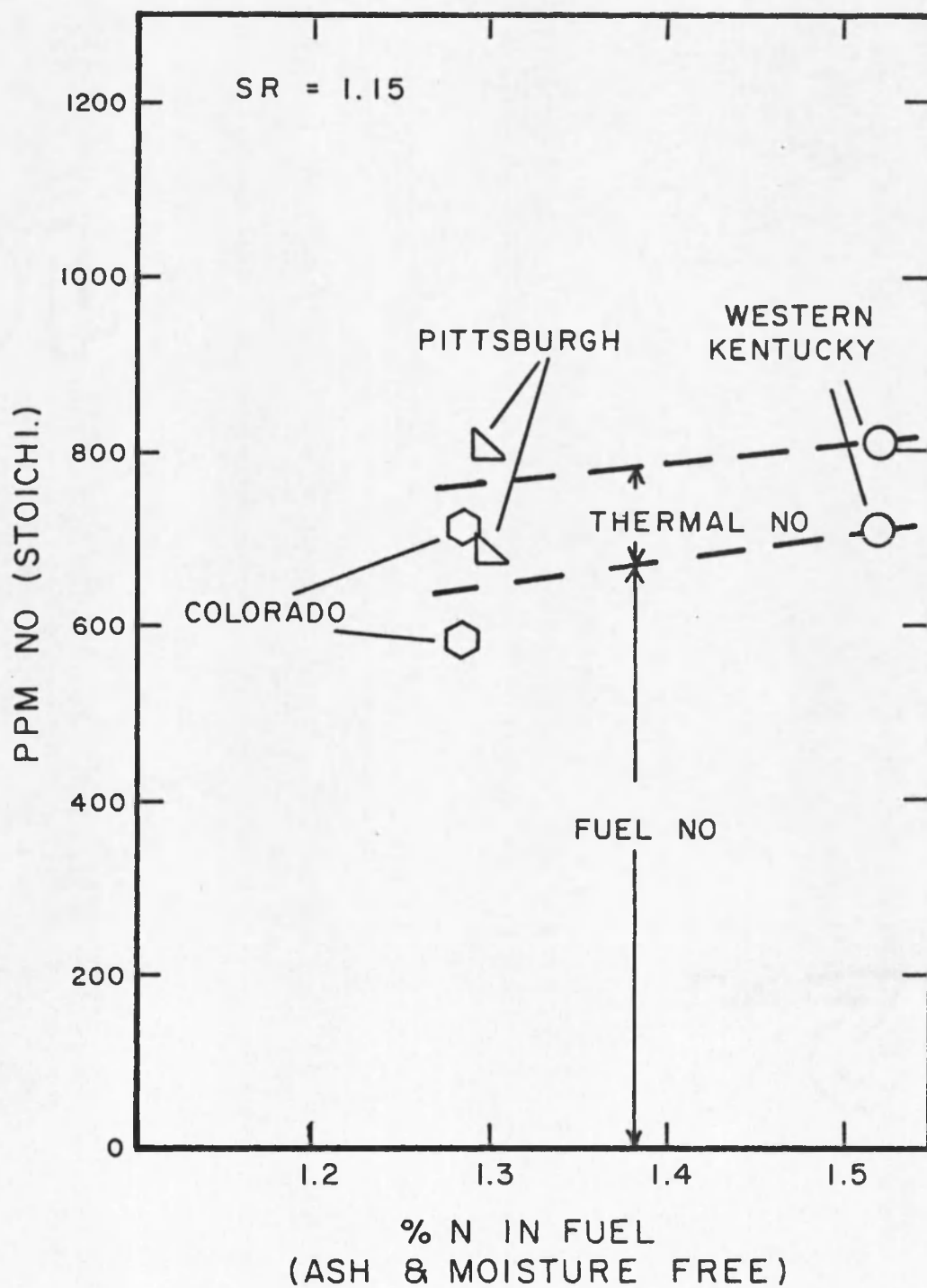
Figure 19. Effect of fuel nitrogen content (bituminous coals). --
Divergent injector, SR = 1.15, 520°F preheat.

test conditions where a self-sustaining, attached flame could be achieved
was much smaller for the Pittsburgh coal.

Figure 20 is a composite plot of the divergent injector data
obtained with the Montana sub-bituminous coal compared to that from
Western Kentucky coal. All of the data in Figure 20 were obtained with
the divergent injector, a stoichiometric ratio of 1.15, approximately
550°F secondary air preheat, 14 percent primary stoichiometry, 44 percent
swirl, and 75 percent load (55,000 Btu/hr) because this was the maximum
heat input the coal feeder system could deliver with the Montana coal
(due to the large amount of ash and moisture). The emissions again
varied only slightly with increasing fuel nitrogen content, even though
the combustion characteristics changed dramatically. The band of stable
operating conditions was much reduced in the case of the Montana coal,
perhaps because of its large moisture content (21 percent).

The lack of a first-order effect by the composition parameters on
total and fuel NO formation supports a recent observation by Blair et al.
(1976) that volatile nitrogen evolution during particle pyrolysis is not
a strong function of coal composition, even though the total mass
volatized varies widely from one coal to another. It is also consistent
with the hypothesis of Flagan et al. (1974) that volatile fuel nitrogen
conversion may be controlled by a rate-constrained partial equilibrium
and, hence, relatively independent of speciation.

7.2 Fuel NO Conversion

Figure 21 is a composite plot of the fuel nitrogen conversion (to
NO) data for the divergent fuel injector with each of the four coals at
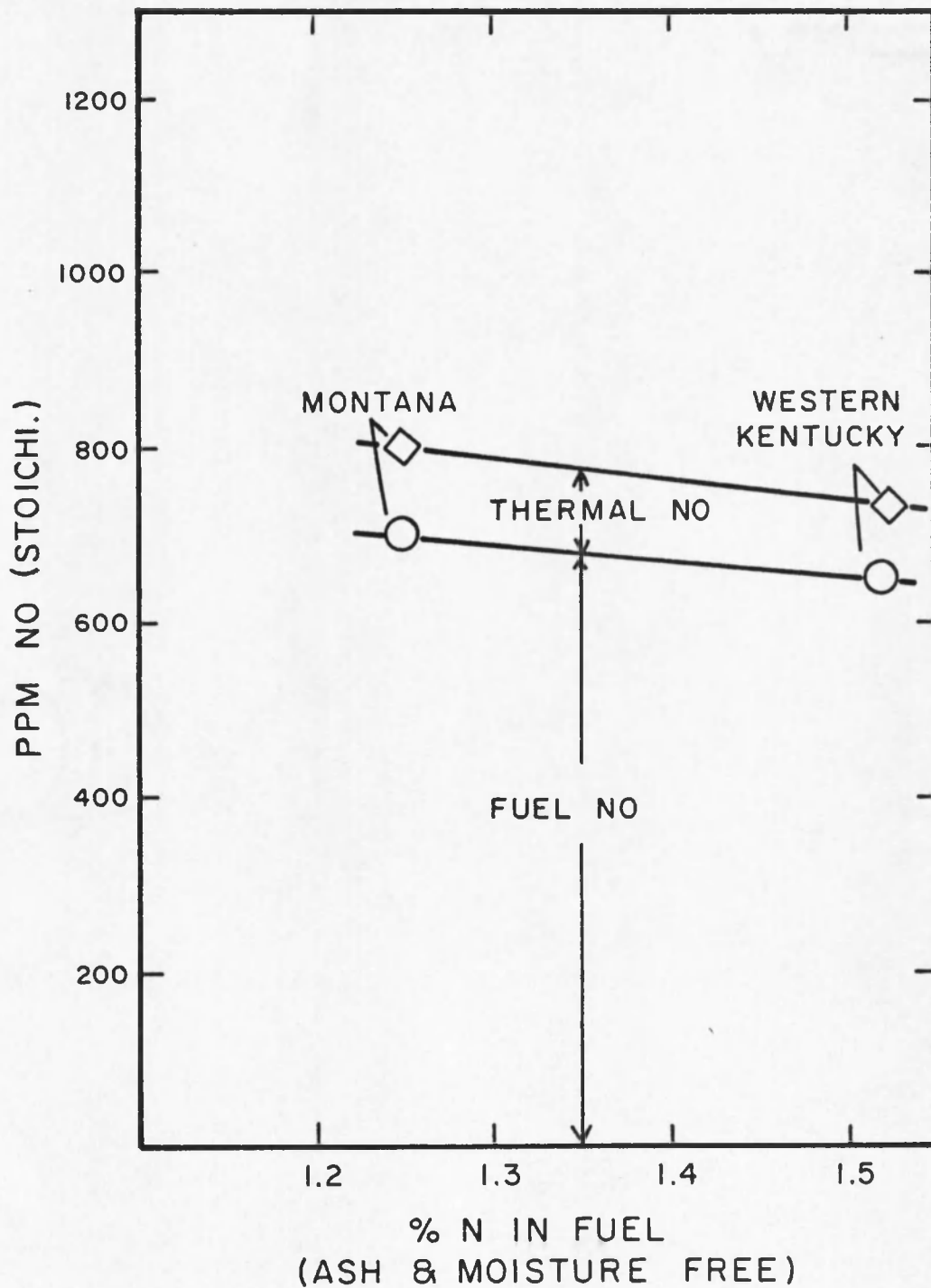
Figure 20. Effect of coal rank. -- Divergent injector, SR = 1.15, 75% load.
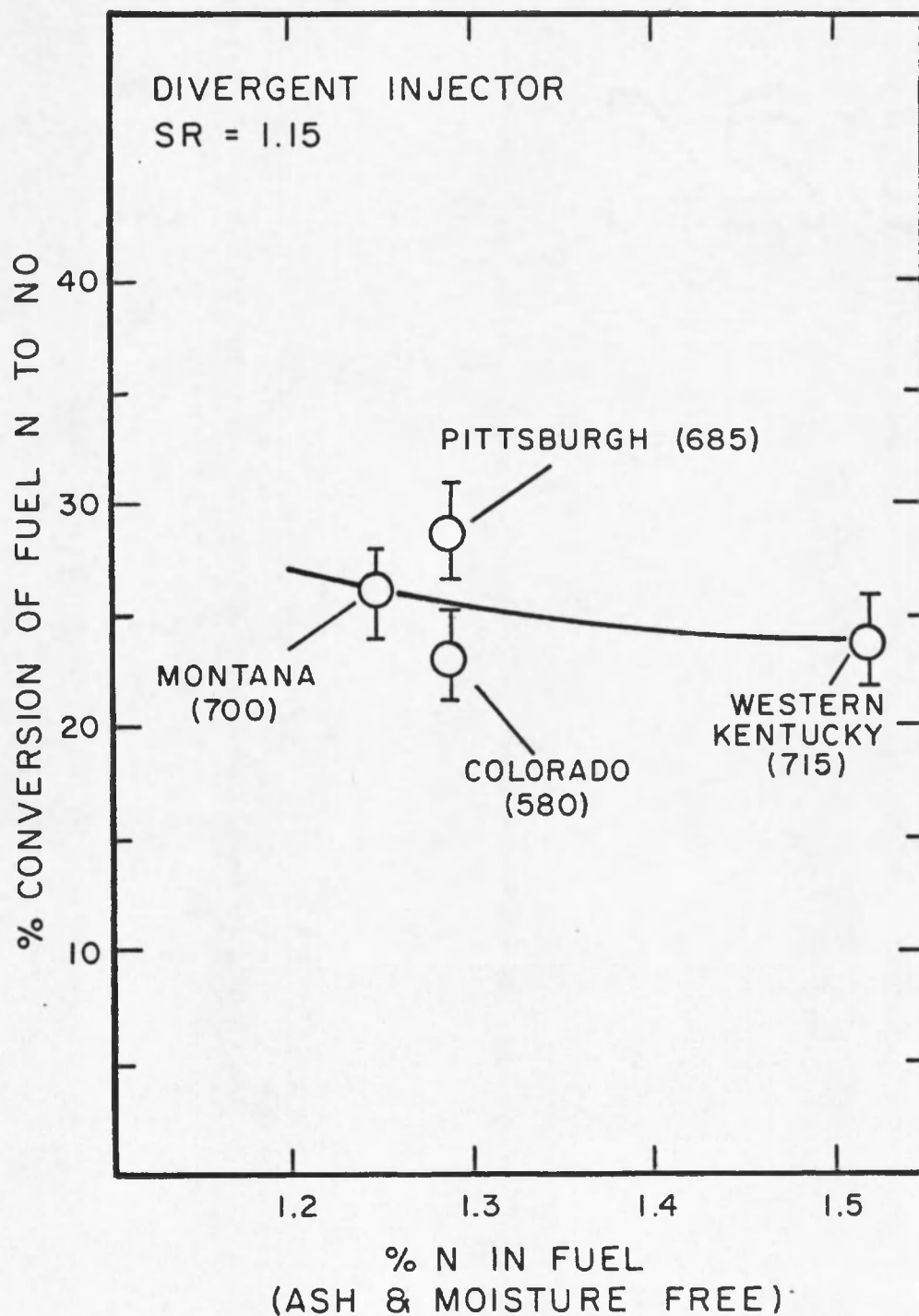
Figure 21. Effect of coal composition on fuel nitrogen conversion. --
Divergent injector, SR = 1.15.

SR = 1.15, 44 percent swirl, 520°F secondary air preheat and 14 percent primary stoichiometry. (The number associated with each point is the actual fuel NO emission in ppm (STOICHI) from which the conversion was calculated.) As noted in the previous section, the data indicate that none of the composition parameters has a first-order effect on NO emissions. The maximum difference in fuel NO emissions is 135 ppm (Western Kentucky vs. Colorado) which is less than half of the 290 ppm difference between divergent and axial injector fuel NO emissions (Western Kentucky coal). This indicates that hardware changes are more important than coal composition changes. (See Chapters 6 and 11 for discussions on fuel injector effects.)

As Figure 21 indicates, the reason the fuel NO emissions do not change significantly as nitrogen content increases is that the corresponding percentage conversion decreases simultaneously. In addition, to relate the fuel nitrogen conversion to the actual ppm emission level, one must consider not only the fuel nitrogen content, but also the total fuel composition (particularly the carbon/hydrogen/ash ratio). For the four coal tests, the baseline conversions ranged from twenty-three percent to twenty-eight percent and this is in good agreement with calculations from field results (Habelt and Howell, 1976; Dykema and Hall, 1975) and with recent definitive fundamental studies by Pohl and Sarofim (1975).

Figure 21 also shows two second-order effects which should be noted. First, it indicates that fuel nitrogen conversion (and hence fuel NO) is dependent, albeit only slightly, on composition parameters other than total fuel nitrogen content. The Pittsburgh and Colorado are both

bituminous coals with 1.29 percent fuel nitrogen. The difference in fuel nitrogen conversion (which is outside experimental error bounds) must, therefore, be attributed to composition parameters other than total nitrogen content and coal rank. The decreased conversion with the Colorado coal could be the result of its low sulfur content since sulfur oxidation has been shown to enhance fuel NO formation in oil flames (Wendt and Corley, 1976). It might also be the result of small differences in the nitrogen speciation, the physical behavior of the coals, or the particle size distribution.

Secondly, the Colorado and Montana are both western, low-sulfur coals with nearly equal fuel nitrogen contents. Comparison of their conversions indicates that coal rank also appears to have a small influence on fuel NO emissions.

7.3 Summary

The experimental results from the four coals lead to the following general conclusions:

1. Fuel nitrogen oxidation is the primary NO formation mechanism in pulverized coal combustion regardless of chemical composition or rank of the coal.

2. Total and fuel NO emissions are only slightly dependent upon composition parameters. The wide variation in emissions from actual field units cannot be attributed to differences in fuels.

3. Total and fuel NO emissions increase only slightly as the fuel nitrogen level increases because the percent conversion of fuel N to NO simultaneously decreases.

4. Composition parameters other than total nitrogen content (e.g.,
    sulfur content, nitrogen speciation, etc.) may be of second-order
    significance when comparing various coals.

5. Coal rank has a major effect on combustion characteristics but
    a second-order effect on either total or fuel NO emissions.

CHAPTER 8

TEMPERATURE DEPENDENCE

8.1 Preliminaries

A variety of experimental tests were conducted to investigate the overall temperature dependence of both the thermal and fuel NO formation mechanisms. Four separate methods were used to change the local flame temperature without altering the overall stoichiometry, swirl, primary air flow rate or load:

1. Reducing secondary air preheat.

2. Recirculating flue gas.

3. Partially replacing the N_2 (or Ar) with CO_2.

4. Slightly enriching the inlet air with O_2.

Burner sleeves were available to ensure that inlet velocities and, therefore, flow patterns could also be approximately matched, but our preliminary tests (Pershing and Wendt, 1975) indicated that they were not required since small variations in secondary air velocity had negligible effect on NO emissions.

8.2 Air Preheat

Figure 22 shows the results of reducing the secondary air preheat from 660°F to 110°F with the divergent injector and Western Kentucky coal. The NO emissions decreased by about 200 ppm to approximately the level previously determined to be the fuel NO (dotted line). This type
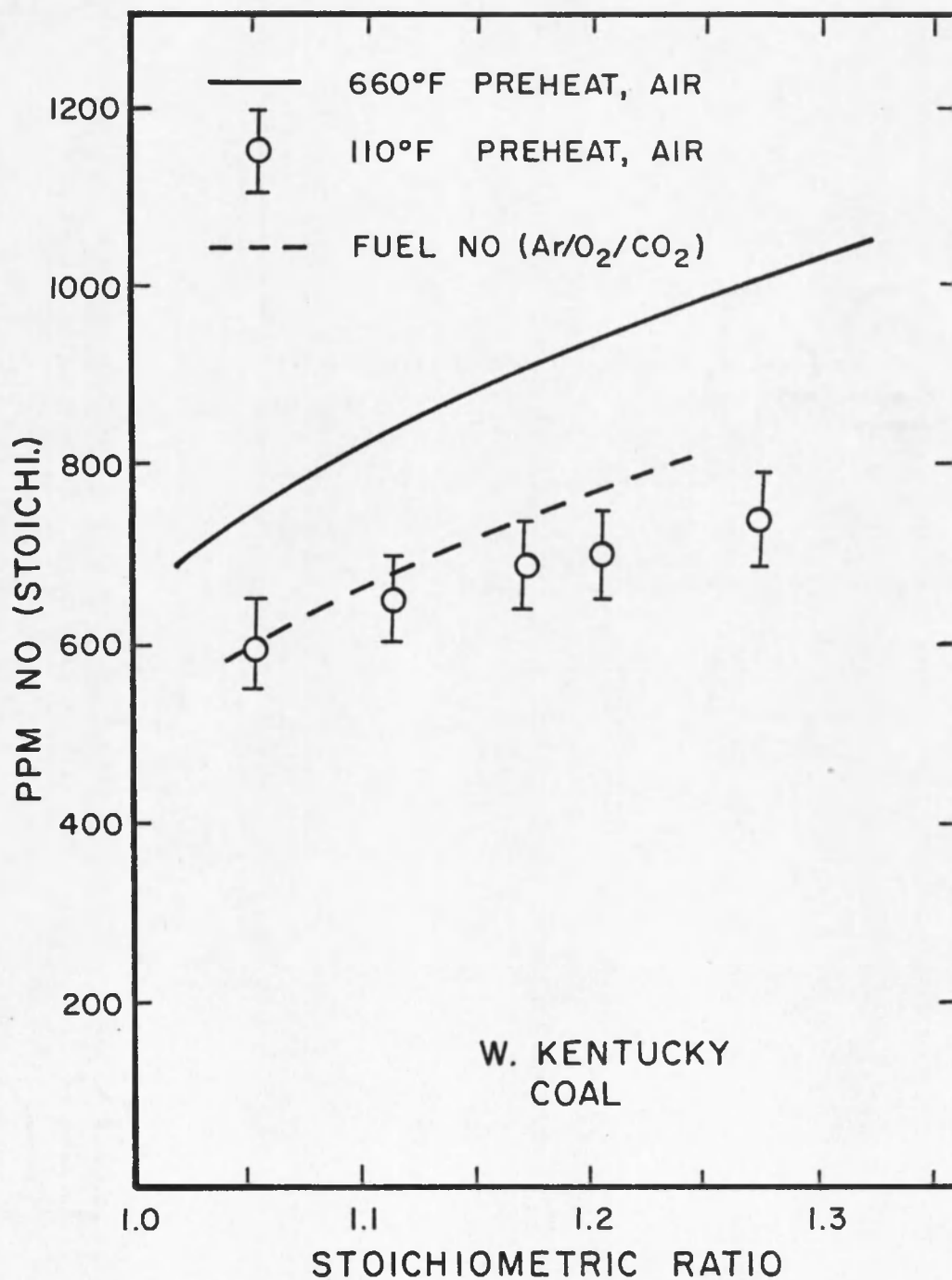
Figure 22. Effect of secondary air preheat on total NO emissions. -- Western Kentucky coal, divergent injector.

testing was not successful with the other coals due to combustion instabilities at the low preheat condition, again demonstrating the influence of fuel composition on combustion characteristics.

8.3 Flue Gas Recirculation

Recycling of combustion products (FGR) from the boiler exhaust back into the main combustion chamber is a common industrial technique to achieve superheat temperature control and reduce NO emissions from gas and oil firing. Figure 23 shows the data obtained in this work when various amounts of flue gas were recycled to the furnace while burning the Western Kentucky coal with the divergent injector. Even with large quantities of flue gas recirculation it was not possible to reduce the total NO emissions below the fuel NO level, within experimental error.

Similar testing with the Colorado and Pittsburgh coals resulted in even smaller reductions. With the Colorado coal, 12 percent FGR resulted in a 3.5 percent decrease in total NO emissions and with the Pittsburgh coal 14 percent FGR gave a 9.6 percent decrease (at a stoichiometric ratio of 1.15). Flue gas recirculation was not attempted with the Montana coal due to anticipated combustion instabilities.

8.4 Oxidant Heat Capacity

Figure 24 shows data taken during the combustion of the Colorado coal with varying amounts of CO_2 in the inlet air. The heat capacity of the inlet air was increased by replacing a portion of the nitrogen (di-atomic) with CO_2 (tri-atomic); in all cases, the inlet oxygen was maintained at 21%. (Of all the temperature variation methods,
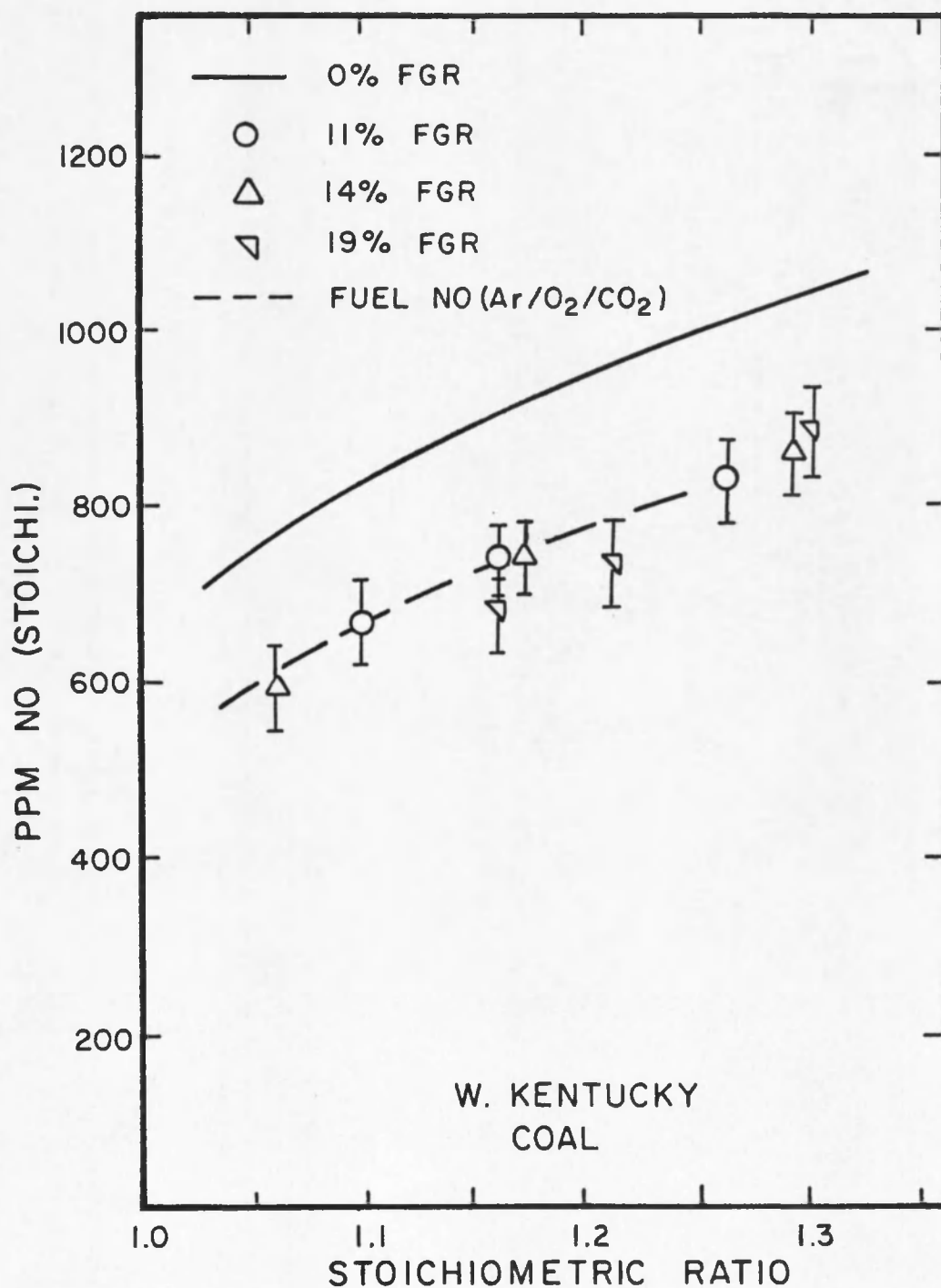
Figure 23. Effect of flue gas recirculation on total NO. -- Western
Kentucky coal, divergent injector, 700°F preheat.
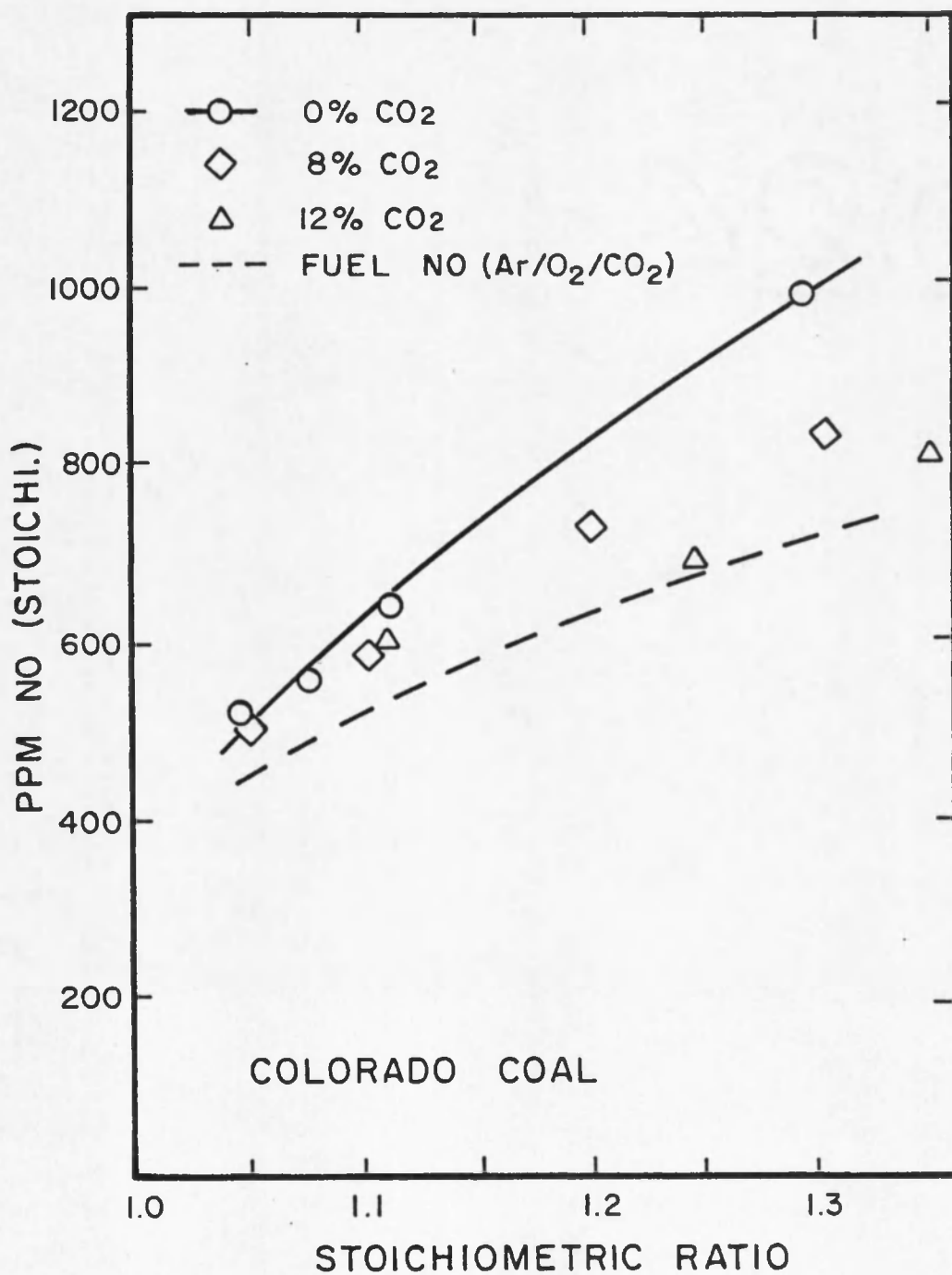
Figure 24. Effect of oxidizer specific heat on total NO. -- Colorado coal, divergent injector, 520°F preheat.

replacement of N_2 by CO_2 is perhaps the best because it does not change either the mass or volumetric flow rate of the oxidizer significantly.) As Figure 24 indicates, decreasing the flame temperature by increasing the oxidizer specific heat again reduces the NO emissions toward the fuel NO level.

8.5 Composite

In attempting to correlate the results of the flame temperature studies, a single temperature parameter was needed. No actual temperature measurements were attempted because of the difficulty in measuring in the hot, corrosive, particle laden environment. Furthermore, the pulverized coal flames examined in this study were turbulent diffusion flames with large internal temperature gradients and turbulent fluctuations. Since they were, therefore, characterized by temperatures which were functions of both spatial position and time, the adiabatic flame temperature was chosen as the parameter correlating flame temperature. Clearly, the actual peak temperatures were significantly lower.

Figure 25 shows the results for the divergent injector with the Western Kentucky and Colorado coals. All of the data are for a stoichiometric ratio of 1.15 and care was taken to minimize purely aerodynamic variations. The numbers associated with the data points refer to Table 3 which describes how each condition was achieved. In general, it was not possible to obtain data at exactly 1.15 stoichiometric air; therefore, the points in Figure 25 are nearly all interpolated values.

Total NO emissions increased exponentially with theoretical flame temperature, but at low temperatures they approached the (constant) fuel
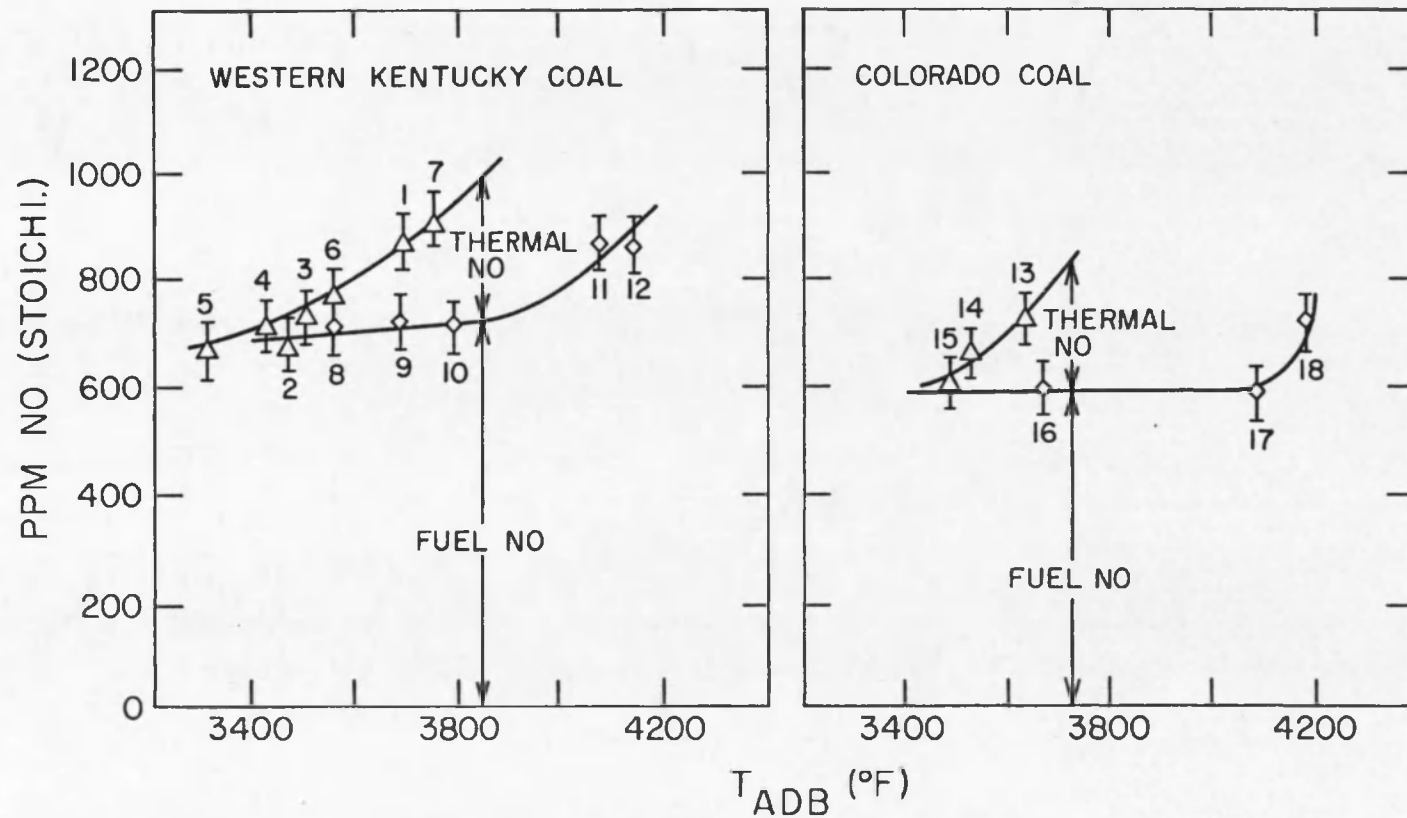
Figure 25. Temperature dependence of thermal and fuel NO. -- Western Kentucky and Colorado coals, divergent injector, SR = 1.15).

Table 3. Experimental conditions (Figure 25).

Western Kentucky Coal

1	666°F preheat (baseline) air
2	110°F preheat air
3	690°F preheat air with 10.6% FGR
4	685°F preheat air with 14.1% FGR
5	705°F preheat air with 19.0% FGR
6	690°F preheat 21% O_2, 11.6% CO_2 in N_2
7	540°F preheat 22.6% O_2 in N_2
8	110°F preheat 19.3% O_2, 16.0% CO_2 in Ar
9	110°F preheat 21.3% O_2, 18.7% CO_2 in Ar
10	110°F preheat 21.4% O_2, 11.4% CO_2 in Ar
11	475°F preheat 21% O_2 in Ar
12	435°F preheat 23.0% O_2 in Ar

Colorado Coal

13	505°F preheat air
14	515°F preheat 20.9% O_2, 7.7% CO_2 in N_2
15	530°F preheat 20.7% O_2, 11.8% CO_2 in N_2
16	215°F preheat 21% O_2, 18.7% CO_2 in Ar
17	475°F preheat 21% O_2 in Ar
18	481°F preheat 23.8% O_2 in Ar

NO value and the thermal NO asymptotically approached zero. Furthermore, within the accuracy of the experiment, the emissions were not dependent on the method for reducing temperature. Therefore, so long as the fluid dynamics remain unchanged, flue gas recirculation (or any temperature reduction technique) will only decrease the thermal NO formation and is, hence, of somewhat limited value for pollutant (NO_x) control with pulverized coal. This had been suggested previously by Pershing, Brown, and Berkau (1973), and by Armento and Sage (1975), based on pilot scale data. The ineffectiveness of FGR for NO_x control of pulverized coal firing was recently demonstrated on a full-scale unit by Thompson (1976).

As Figure 25 indicates, fuel NO emissions were found to be remarkably insensitive to temperature over a wide range applicable to present combustion technology. For the Pittsburgh coal, only two temperatures were tested, but the fuel NO was essentially identical -- 685 ppm at both 3820°F and 4080°F (SR = 1.15). As shown in Figure 25, fuel NO from the Western Kentucky coal was nearly constant between 3600°F and 3900°F. For the Colorado coal, fuel NO emissions were essentially constant over a theoretical temperature range of 3600°F through 4100°F and a wall temperature (measured by optical pyrometer) range of 1850°F through 2150°F. Further, this insensitivity to temperature appears to be independent of the excess air level, as shown in Figure 26.

At very high temperatures, however, fuel NO emissions from the Colorado and Western Kentucky coals underwent a significant increase, and this was observed to occur at a slightly different temperature for each coal. This sudden increase in fuel NO emissions may be the result of a
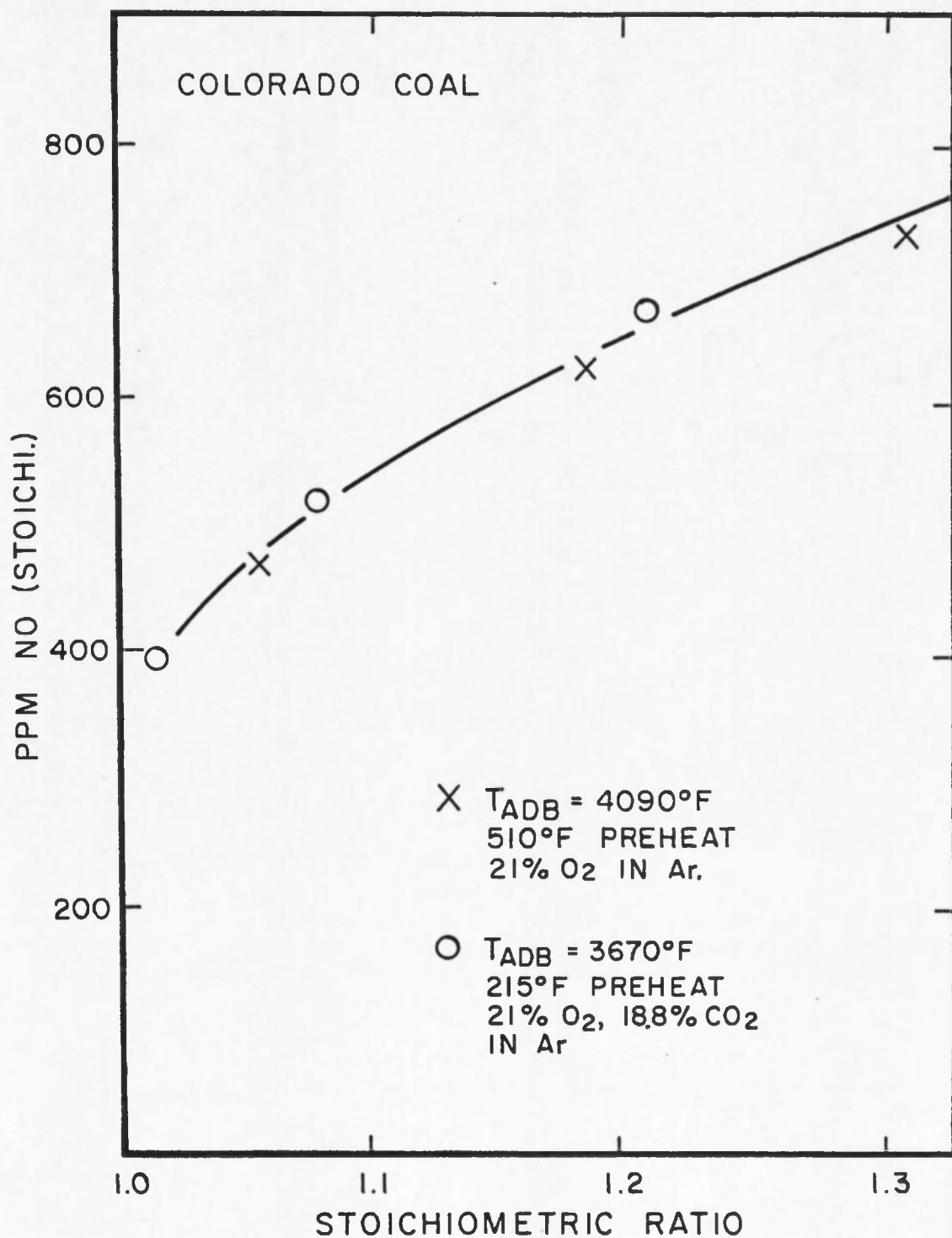
Figure 26. Temperature insensitivity of fuel NO formation. -- Colorado coal, divergent injector.

marked change in the physical behavior of the coal particles. For example, the volatile evolution rate may have become large enough to cause a significant fraction of the particles to rupture, thus exposing fresh nitrogen volatiles to secondary air.

Emissions from the Pittsburgh coal did not increase prior to the highest condition (4080°F). The Montana coal did not allow investigation at the temperature extremes due to combustion instabilities which were believed to be related to the large moisture content.

Figure 27 is a plot of the thermal NO measured for natural gas with that measured for the various coal flames. (Thermal NO was defined to be the difference between total NO and fuel NO, as determined with Ar/O_2CO_2.) The data indicate that the thermal NO values for coal are in line with those obtained for gas, in this combustor, for the same injectors and under similar aerodynamic and thermal conditions. This indicates that interactions between fuel and thermal NO are not of first-order importance and it suggests that the controlling thermal mechanism may be similar to that in gas flames. It also provides an inexpensive means for estimating thermal NO formation in larger units.

8.6 Summary

In summary, the temperature experimentation revealed that:

1. Fuel NO formation is relatively insensitive to flame temperature over a wide range of practical interest.

2. Thermal NO formation in coal flames behaves similarly to NO formation in natural gas flames under similar conditions.
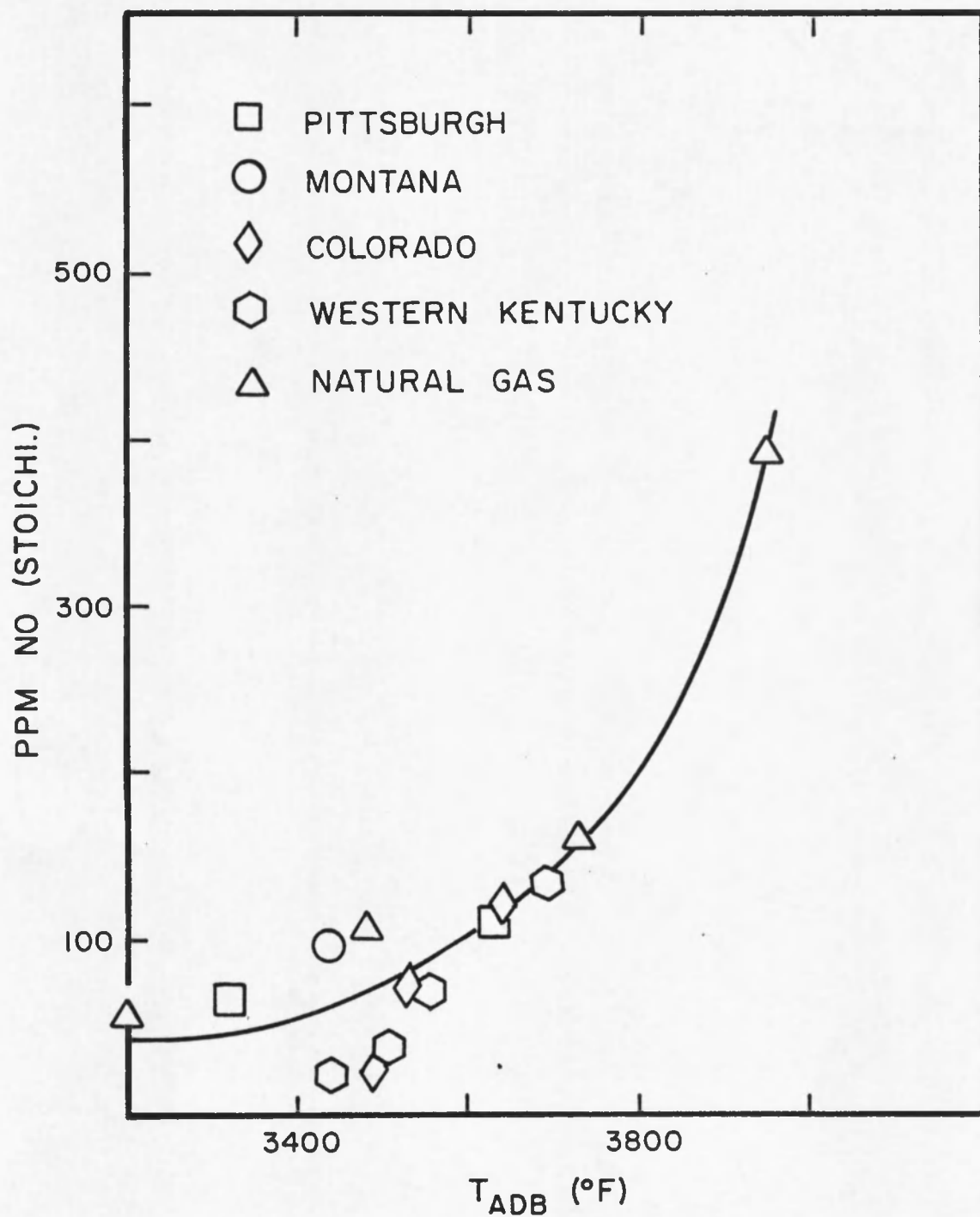
Figure 27. Thermal NO emissions from coal and natural gas. -- Divergent injector, SR = 1.15.

3. All temperature reduction schemes have approximately the same
    small effect on total NO emissions in that only the thermal NO
    is reduced.

It appears that without changes in aerodynamics and mixing there
is very little opportunity to lower total NO emissions below the (con-
stant) fuel NO level and still maintain stable flames.

At extreme temperatures, it is clearly possible to significantly
increase fuel NO formation. This might be due to particle heating rate
changes due to high initial heat fluxes to the particle, or to a second,
high temperature mechanism for fuel nitrogen oxidation to NO.

CHAPTER 9

INFLUENCE OF LOCAL OXYGEN CONCENTRATION

9.1 Introduction

Previous fundamental research on prototype fuel nitrogen com-
pounds (Chapter 1) has shown that in premixed gaseous systems approxi-
mately 100 percent conversion of fuel nitrogen to NO occurs under fuel
lean conditions (local SR $\geq$ 1.0). If the local stoichiometry becomes
fuel rich (SR < 1.0), however, the conversion will decrease dramatically.
Similar data are not presently available for pulverized coal flames
because a practical combustion system contains a distribution of local
stoichiometrics due to imperfect fuel/air mixing. Consequently, a series
of experiments was conducted in an effort to infer the dependence of both
fuel and thermal NO formation on local oxygen concentration. In addi-
tion, the experimentation was designed to help define the cause of cer-
tain effects which were thought to be due to hardware.

In general, the local stoichiometry distribution can potentially
be altered by changing the oxygen input to a particular region and by
altering the primary/secondary mixing. In this work, local stoichiometry
was changed by changing:

1. Overall excess air.

2. Primary air flow rate.

3. Primary oxygen concentration.

4. Secondary air swirl.

5. Flame stabilization and ignition times.

6. Inlet oxygen percentage.

Unfortunately, in no case was it possible to alter only local stoichiometry in a direct fashion. Further, detailed analyses of turbulent mixing and combustion fluid dynamics were beyond the scope of this work; rather, the work attempted to address specific questions and hypotheses with a view to interpreting large-scale data and defining areas of future research.

9.2 Overall Stoichiometry

As was noted in Chapter 5 (Figure 11), NO emissions increased significantly as the overall combustion stoichiometry (excess air) was increased. Further, as Figure 17 indicates, both total and fuel NO increased with increased combustion air for all four coals tested. This dependence has been previously observed by others in pilot-scale studies (Armento and Sage, 1975; Heap et al., 1975; Pershing et al., 1975) and in full-scale field tests (Crawford et al., 1974; Dykema and Hall, 1975; Lachapelle, 1976). Increased combustion stoichiometry is believed to increase local oxygen concentrations and, hence, favor the formation of both thermal and fuel NO. It is clear, however, that due to mixing limitations the actual local stoichiometry in the pyrolysis and combustion zones is much more fuel rich than the overall stoichiometry would suggest. If this were not so, then fuel nitrogen conversions would tend toward 100 percent as noted in Figure 2 based on premixed data.

9.3 Fuel NO Correlation

Figure 28 is a composite plot of all of the divergent injector fuel NO data versus stoichiometric ratio. All four coals exhibited the same excess air dependence and the actual fuel NO emission levels for the Pittsburgh, Western Kentucky, and Montana coals were essentially identical measured either on a dry, corrected volumetric basis or as emission factors (0.82 ± 0.02 lbs $NO_2/10^6$ Btu at 15% excess air). As the lower line in Figure 28 indicates, the Colorado coal gave slightly lower fuel NO emissions.

To quantify the stoichiometric ratio dependence, the concept of a dimensionless emission coefficient, ψ, was introduced. It was defined to be the ratio of the NO emissions measured at a particular stoichiometry to those measured at 15 percent excess air:

$$\psi \equiv \frac{\text{ppm NO (STOICHI)}}{\text{ppm NO (STOICHI) @ SR} = 1.15} \qquad (9\text{-}1)$$

The stoichiometric ratio 1.15 was selected as the reference point because it was approximately midway between the normal testing limits (SR = 1.02 to 1.3). Figure 29 is a composite of all the baseline fuel NO emission data from the four coals and the coal char (to be discussed in Chapter 10) in terms of the dimensionless emission coefficient, ψ. These data were all obtained at approximately 550°F preheat and the baseline primary air for each injector: 14 percent of stoichiometric with the divergent injector and 8 percent of stoichiometric with the axial injector. Between SR = 1.02 and 1.28, the data can be characterized by the linear equation
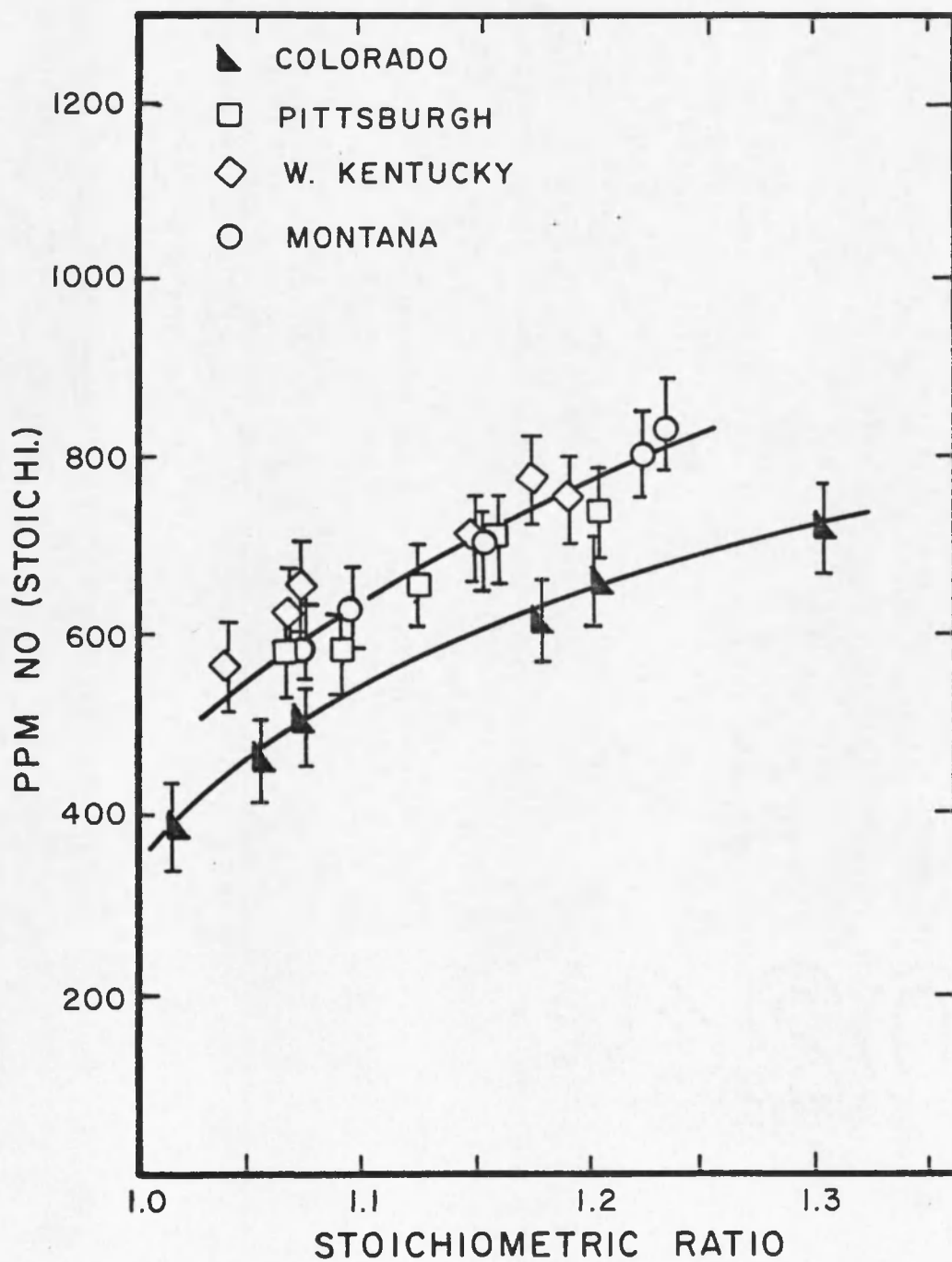
Figure 28. Fuel NO vs. stoichiometric air. -- All coals, divergent injector.
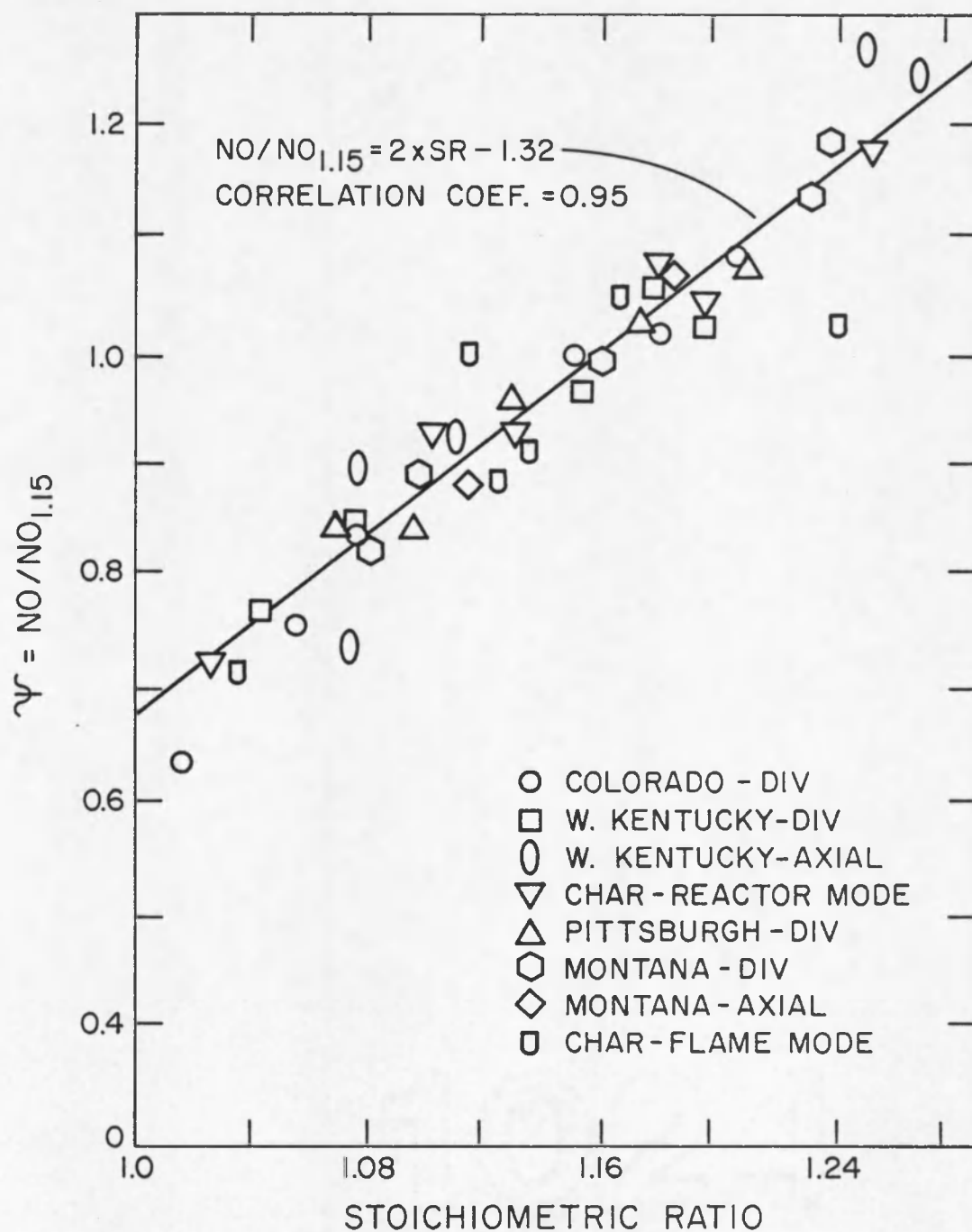
Figure 29. Correlation of fuel NO emissions with stoichiometric ratio.

$$\psi \equiv \frac{NO}{NO_{1.15}} = 2*SR - 1.32 \tag{9-2}$$

with a statistical correlation coefficient of 0.95. This demonstrates that the oxygen dependence can be decoupled from hardware and composition parameters.

9.4 Primary Air Flow Rate

Of particular interest in the area of local oxygen studies was the role of "early oxygen," that oxygen which is intimately mixed with the coal during volatile combustion. It may be the result of external premixing prior to the furnace (primary air), early mixing (primary/secondary interactions within 1 to 2 burner diameters) or primary entrainment prior to ignition. The early oxygen is present during the evolution of fresh nitrogen volatiles (0.5 to 5 msec) and, hence, could have a significant influence on volatile NO.

In the first early oxygen test series, the flow rate of primary air was varied while the total fuel and air flows (and hence stoichiometric ratio) were held constant. Figure 30 shows the results of these tests with the Western Kentucky coal for both the divergent and axial fuel injectors. In each case the upper line is data obtained in air (total NO) and the lower line is data from combustion in $Ar/O_2/CO_2$ (fuel NO). As the primary air flow rate is increased, the primary velocity increases and ultimately the flame lifts off the injector and stabilizes at some point downstream (due to the hot refractory walls). For example, with the axial injector and 14 percent primary air, the flame was stabilized (luminous zone begins) approximately 9 1/2" below the injector.
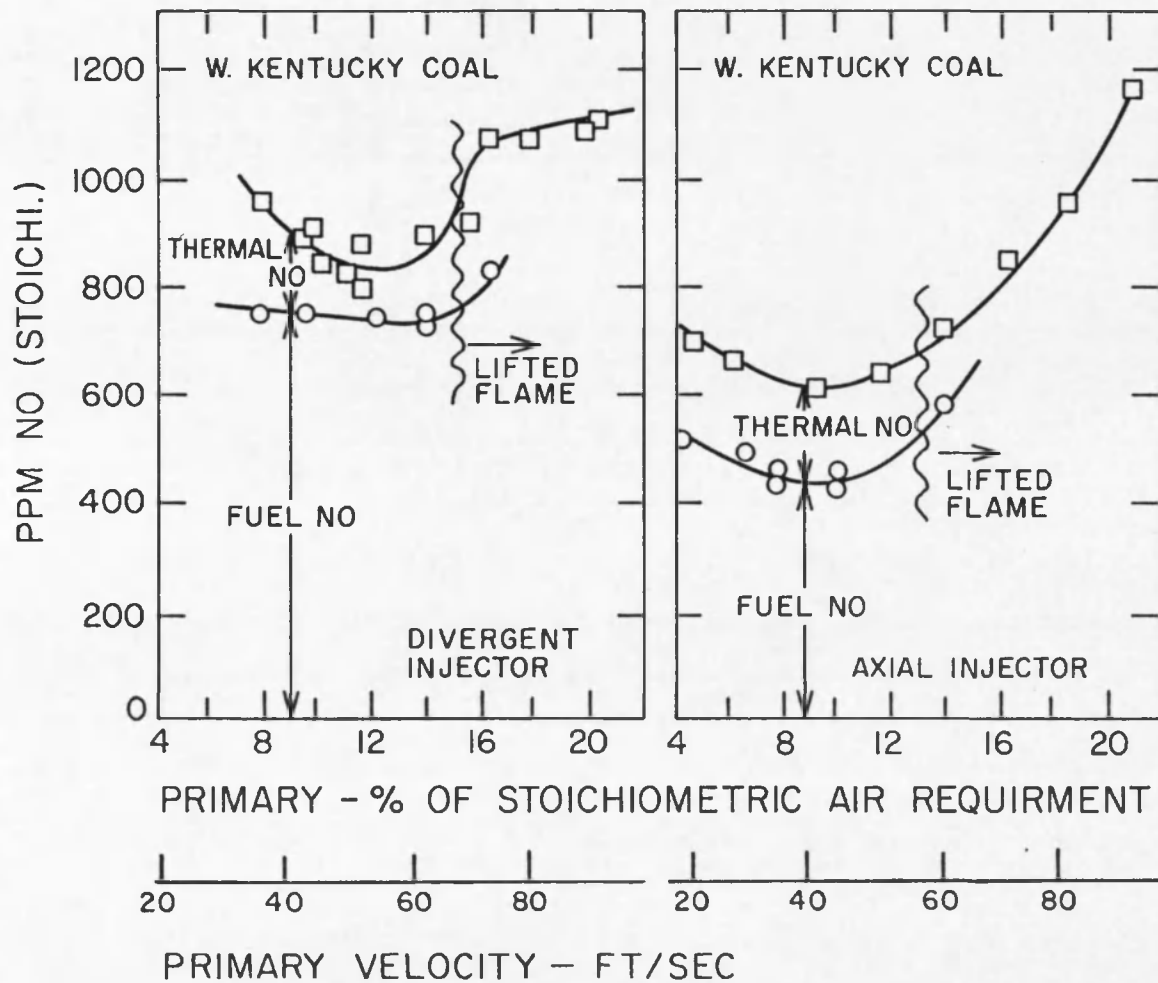
Figure 30. Effect of primary air flow rate. -- Western Kentucky coal, SR = 1.15, 600°F preheat.

It has been postulated (Heap et al., 1973), based on total NO emission data, that the increase in NO emissions associated with flame detachment is due to increased early mixing prior to ignition. The results shown in Figure 30 indicate that the increase is due to increased fuel NO and this further substantiates the hypothesis of Heap because oxidation of fuel nitrogen in prototype compounds is extremely stoichiometry sensitive. It must be noted, however, that flame detachment also dramatically alters the particle heating rate and, hence, potentially both the amount and evolution history of the nitrogen volatile. (This is discussed further in Chapter 11.)

At low primary air flow rates, visual observation of the flames revealed that the swirl character of the secondary air appeared to dominate the fluid dynamics. The coal jet(s) lost their integrity almost immediately and the coal appeared to be burning in a large, swirling bushy flame. Thus, the increased total and fuel NO emissions at low primary flow rates may have been due to early mixing but of another type -- swirl induced.

9.5 Primary Oxygen

Direct interpretation of primary air flow rate data is difficult because an increase in primary air flow rate has at least four potential effects:

1. For a fixed fuel injector size, it increases the primary air velocity.

2. It increases the primary stoichiometry (ratio of air/fuel in the primary jet).

3. It may significantly alter the primary/secondary mixing.

4. When it causes the flame to lift off, the particle heating rate and pyrolysis time are significantly altered.

To definitively test the hypothesis that the increased NO formation at high primary air flow rates was the result of increased early oxygen, a special test series was conducted in which the early oxygen was altered directly and singularly (other relevant parameters were held constant). In these tests with the Western Kentucky coal, the primary stoichiometry was varied from 0 to 20 percent of the stoichiometric oxygen requirement by adding either CO_2 or pure O_2 to the primary stream. At the 0% condition, the coal was being conveyed by pure CO_2. In all cases, the volumetric flow (and hence primary jet velocity) was maintained constant at 1.8 SCFM (62 ft/sec) to minimize changes in the flame fluid dynamics. The preheat and stoichiometric ratio were also held constant at 580°F and 1.15, respectively.

Figure 31 shows the results of these early oxygen tests compared directly with the previously discussed data obtained by varying the flow rate for both fuel injectors. The data indicate that with the divergent injector primary oxygen has little effect on total NO emissions below approximately 15 percent of the stoichiometric air requirement. Thus, this amount of primary air is being used for early hydrocarbon combustion and not volatile nitrogen oxidation. The significant NO emission, even with a pure CO_2 primary, is a reflection of the divergent fuel injector design which causes the coal to come into rapid contact with the secondary air.
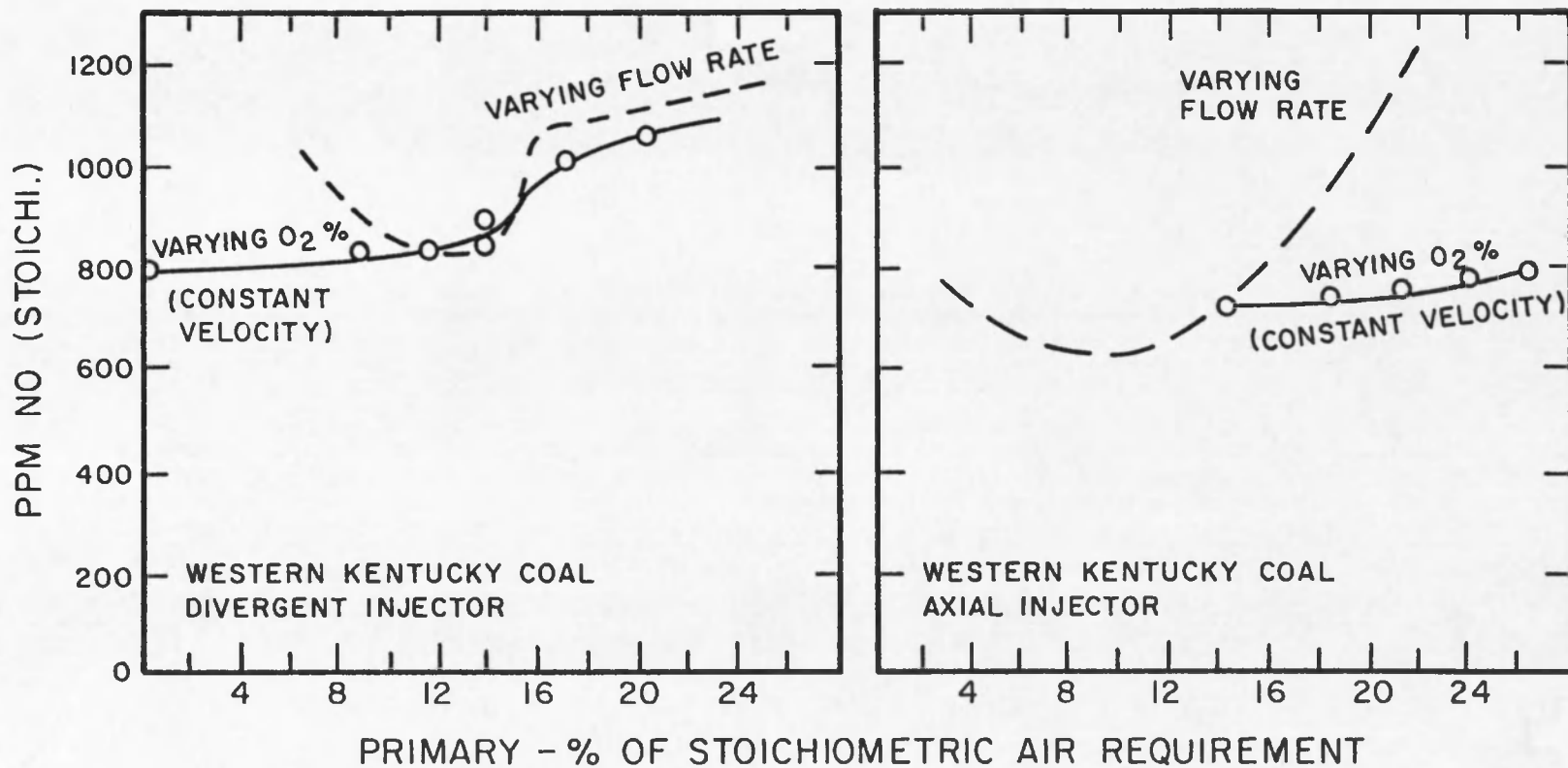
Figure 31.   Effect of primary stoichiometry. -- Western Kentucky coal, SR = 1.15, 580°F
preheat.

In contrast to NO emissions, however, flame stability and ignition characteristics were significantly affected by decreasing the inlet O_2 concentration in the primary air. This supports the hypothesis of Blair et al. (1976) that those very early volatiles necessary for ignition do not contain appreciable fuel N ultimately converted to NO; however, the subsequent volatiles, evolved during mixing with secondary air, do contain appreciable fuel N of which a portion is converted to NO.

For the axial injector (lower graph), the primary oxygen concentration was varied from 21 volume percent (air) to 40 volume percent by adding pure oxygen to the primary stream. This resulted in an increase in the primary stoichiometry from 14 to 26 percent, but since the primary flow rate was maintained constant, there was no change in the primary velocity. (The overall stoichiometry was also held constant at SR = 1.15 by decreasing the secondary air flow.) As Figure 31 indicates, this had relatively little effect on total no emissions. These data imply that either the early oxygen hypothesis is incorrect or the early non-nitrogen volatiles require more than 26 percent of the stoichiometric air for combustion.

In summary, these test results do not definitively establish the role of early oxygen. It appears that much of the volatile nitrogen is being evolved late in the volatization process and the conversion of this nitrogen is strongly dependent on the amount of oxygen available. However, further testing under well-defined fluid dynamic conditions is required to provide complete understanding of this phenomena.

9.6 Role of Early Mixing

In the process of conducting the experimental studies for this program, significant changes in the primary/secondary mixing were achieved by two other means. While the effects were not considered in detail because they were outside the scope of the program, they are note-worthy because they provide additional proof that early mixing must be retarded to minimize NO emissions.

Figure 32 shows the effect of secondary air swirl on total NO emissions for the Pittsburgh and Western Kentucky coals. In both cases, dramatic increases in NO emissions were observed when the swirl was reduced to the point where the flame was no longer stable on the fuel injector, again demonstrating the importance of early mixing.

Figure 33 shows that reducing the secondary air preheat from 510°F to 155°F had a very unusual effect on the NO emissions from the Colorado coal. Above approximately 25% excess air, the emissions decreased slightly as the temperature was lowered. This is consistent with the data reported in earlier sections on the other coals and with the data of Armento and Sage (1975) and Heap et al. (1975). At the lower excess air levels, the 155°F preheat data are considerably higher than the baseline case and it was noted visually that the "flame" was completely detached from the burner, in which case ignition took place at some distance down in the cylindrical chamber. This may have occurred because at the low excess air levels and low air preheat, devolatization was insufficient to maintain a stable, attached flame. The apparent increase in NO emissions is, therefore, probably due to a major change
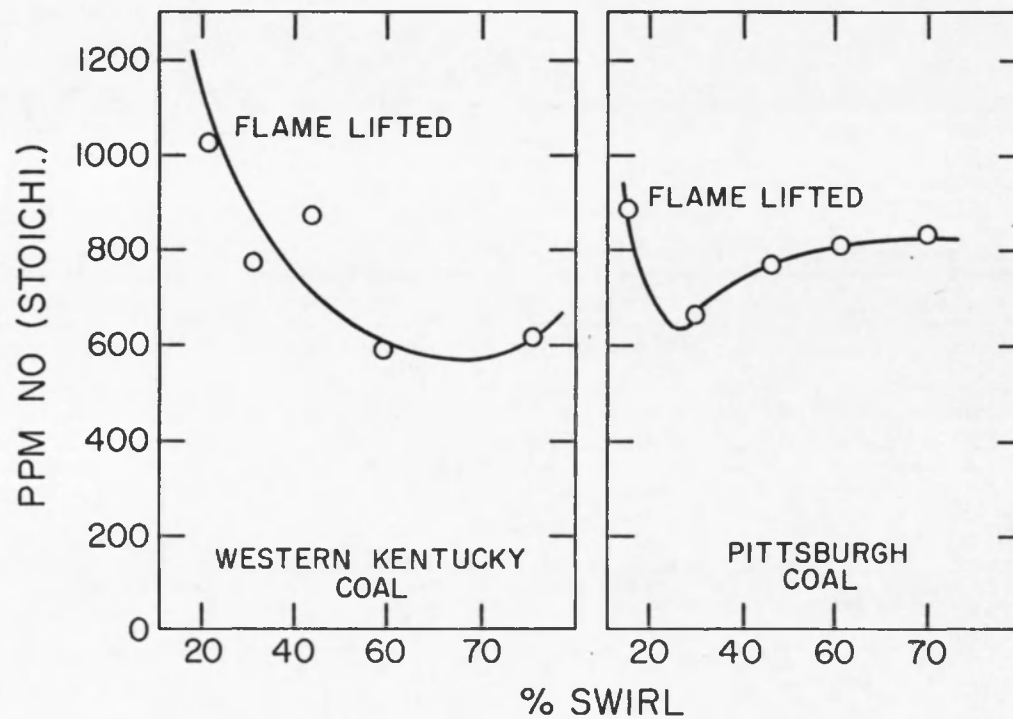
Figure 32. Effect of secondary air swirl. -- Pittsburgh and Western Kentucky coals, divergent injector, SR = 1.15.
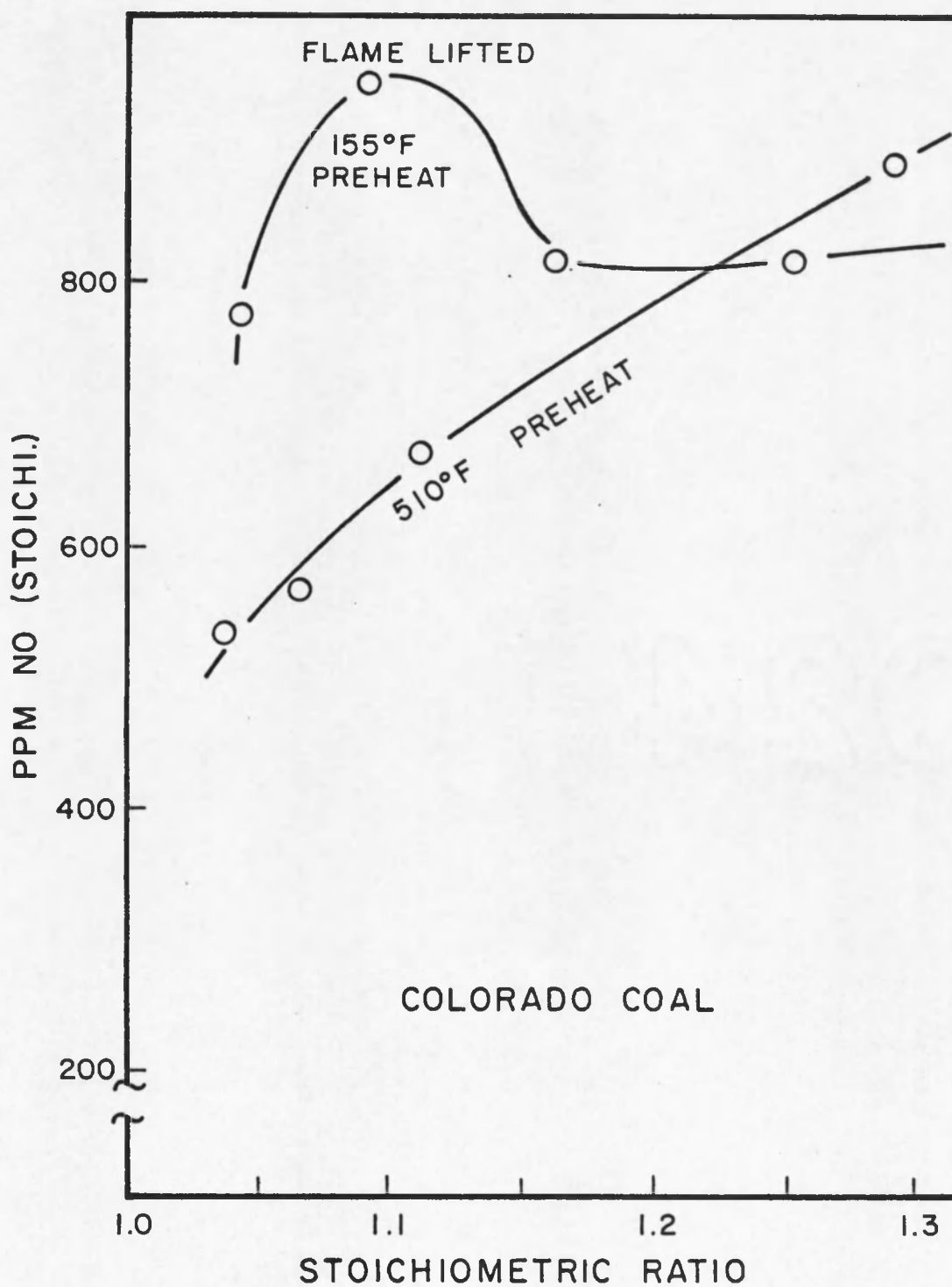
Figure 33. Aerodynamic effect of air preheat. -- Colorado coal,
            divergent injector.

associated with flame detachment rather than the decreased air preheat temperature.

Figure 34 shows the total NO emissions as a function of stoichiometric ratio for both attached and lifted Western Kentucky coal flames. Again, the significantly different character of the lifted flame may be due to the order of magnitude increase in particle heating time or to entrainment of considerable secondary air prior to combustion. Resolution of this question will require further research in a system with well-defined fluid dynamics.

9.7 Inlet Oxygen

In an effort to extend the total and fuel NO temperature studies beyond the preheating ability of the experimental systems, tests were conducted where the oxygen concentration in the inlet air was enriched with pure oxygen. Figure 35 is a composite of the results obtained at SR = 1.15 for Western Kentucky coal with the divergent injector. The data obtained with both air and Ar/O_2 are shown with that from the other temperature studies. (Table 4 describes the experimental conditions in detail.) With air, the flame color changed from the typical yellow-orange to almost white as the inlet oxygen concentration was increased from 21 to 30 percent. The skin temperature of the furnace also rose and, ultimately, a fuel injector tip was melted. Thus, there can be little doubt that the bulk flame zone temperature did increase as theoretically predicted.

In these tests the primary air flow rate and overall stoichiometric ratio were held constant; therefore, the primary stoichiometry
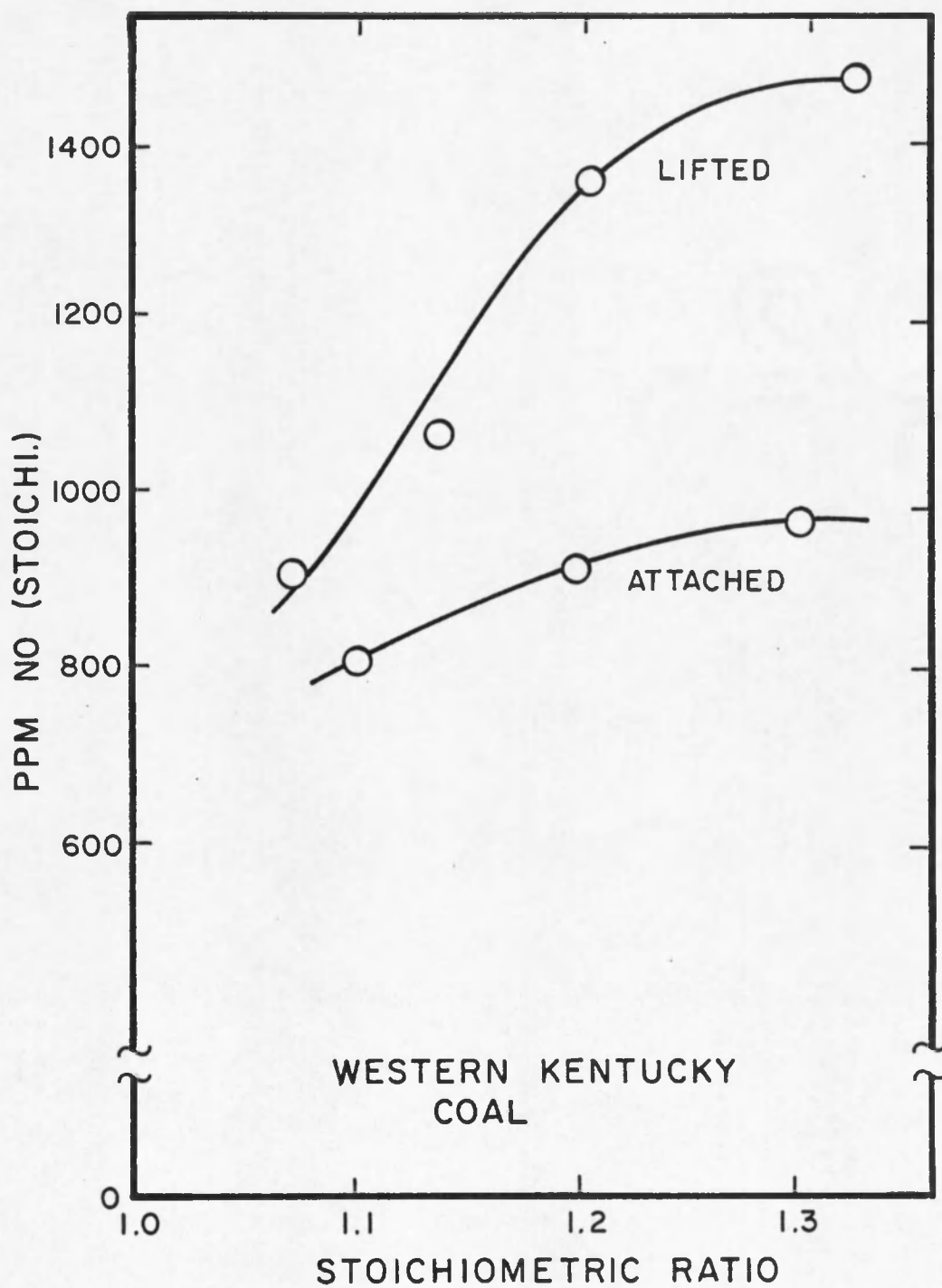
Figure 34. Comparison of lifted and attached flames. -- Western
Kentucky coal, divergent injector.
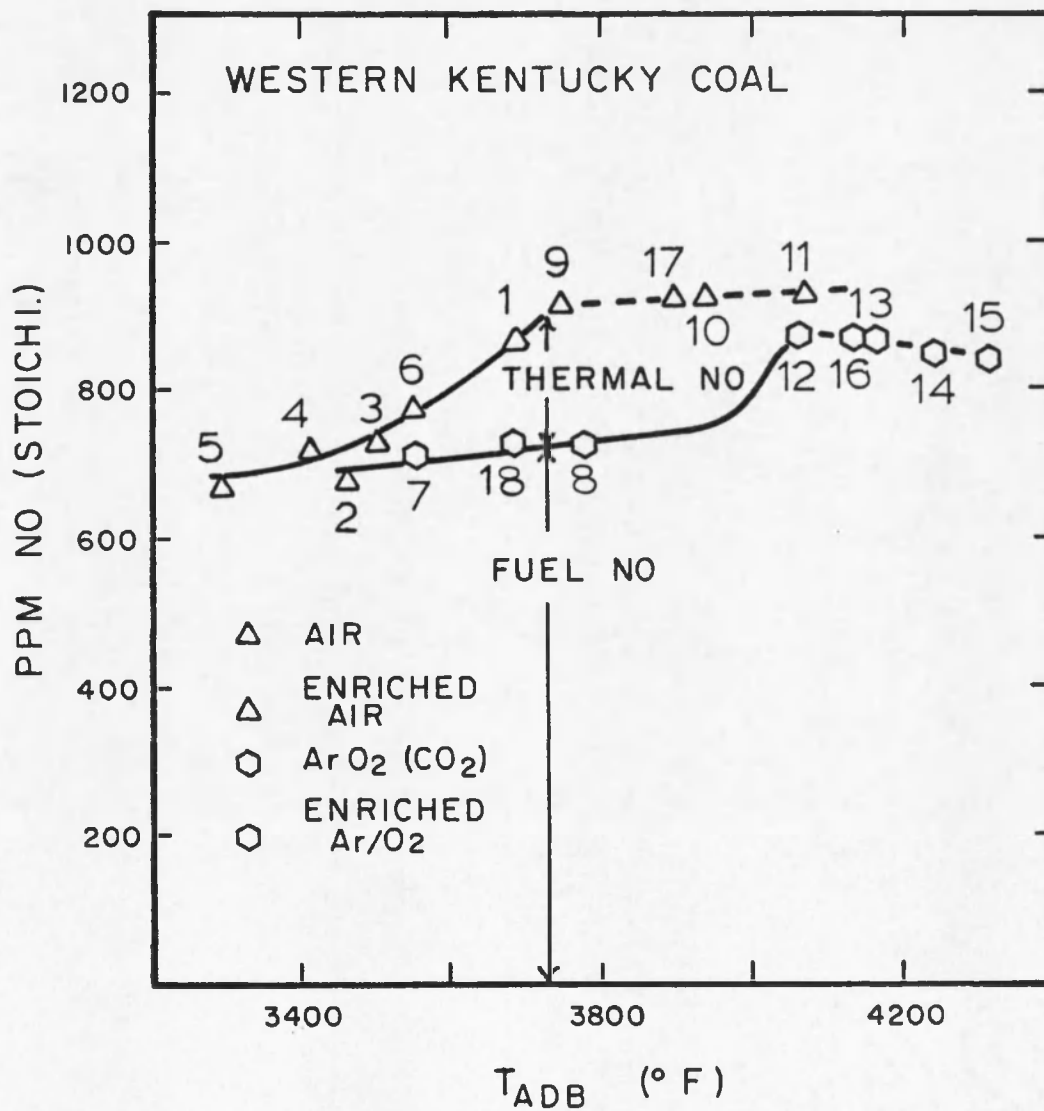
Figure 35. Effect of temperature increase by oxygen enrichment. --
Western Kentucky coal, divergent injector, SR = 1.15.

Table 4. Experimental conditions (Figure 35). -- All data are for 15% excess air, Western Kentucky coal, and the three hole divergent injector.

Point No.	Conditions
1	(Baseline) 660°F preheat 21% O_2 in N_2 (air)
2	110°F preheat 21% O_2 in N_2
3	690°F preheat 10.6% FGR
4	685°F preheat 14.1% FGR
5	705°F preheat 19.0% FGR
6	690°F preheat 21% O_2, 11.6% CO_2 in N_2
7	110°F preheat 19.3% O_2, 16.0% CO_2 in Ar
8	110°F preheat 21.4% O_2, 11.4% CO_2 in Ar
9	540°F preheat 22.6% O_2 in N_2
10	540°F preheat 25.8% O_2 in N_2
11	535°F preheat 28.8% O_2 in N_2
12	475°F preheat 21% O_2 in Ar
13	475°F preheat 24.1% O_2 in Ar
14	485°F preheat 26.7% O_2 in Ar

Table 4--Continued.

Point No.	Conditions
15	450°F preheat 29.9% O_2 in Ar
16	435°F preheat 23.0% O_2 in Ar
17	550°F preheat 24.9% O_2 in N_2
18	110°F preheat 21.3% O_2, 18.6% CO_2 in Ar

increased with the inlet oxygen concentration. Yet even though temperature and primary stoichiometry increased significantly, both thermal and fuel NO emissions remained relatively constant. This was particularly surprising in view of the fact that thermal NO was shown to increase with temperature (Chapter 8) and fuel NO was shown to increase with increasing primary stoichiometry. Assuming these previous conclusions are correct, it must be concluded that the combination of increased oxygen partial pressure and elevated temperature also somehow enhance the formation of N_2 from nitrogen specie, thus cancelling the other effects.

To confirm the existence of this phenomena, extensive tests were conducted at a variety of stoichiometrics with both enriched air and Ar/O_2 as the oxidizer. Figures 36 and 37 show these results on total and fuel NO emissions, respectively. Again, all the data were for the Western Kentucky coal with the divergent injector and constant primary air flow rate. As before, both total and fuel NO emissions were relatively insensitive to inlet oxygen concentration. Further testing with well-defined fluid dynamic conditions is needed to provide complete understanding of this phenomena.

9.8 Summary

The local oxygen studies confirmed the observation of other investigators that increasing the overall excess air increases the total NO emissions. Special testing, however, revealed the following new results:

1. Fuel NO emissions can be linearly correlated using a dimensionless emission coefficient for all fuels and injectors tested.
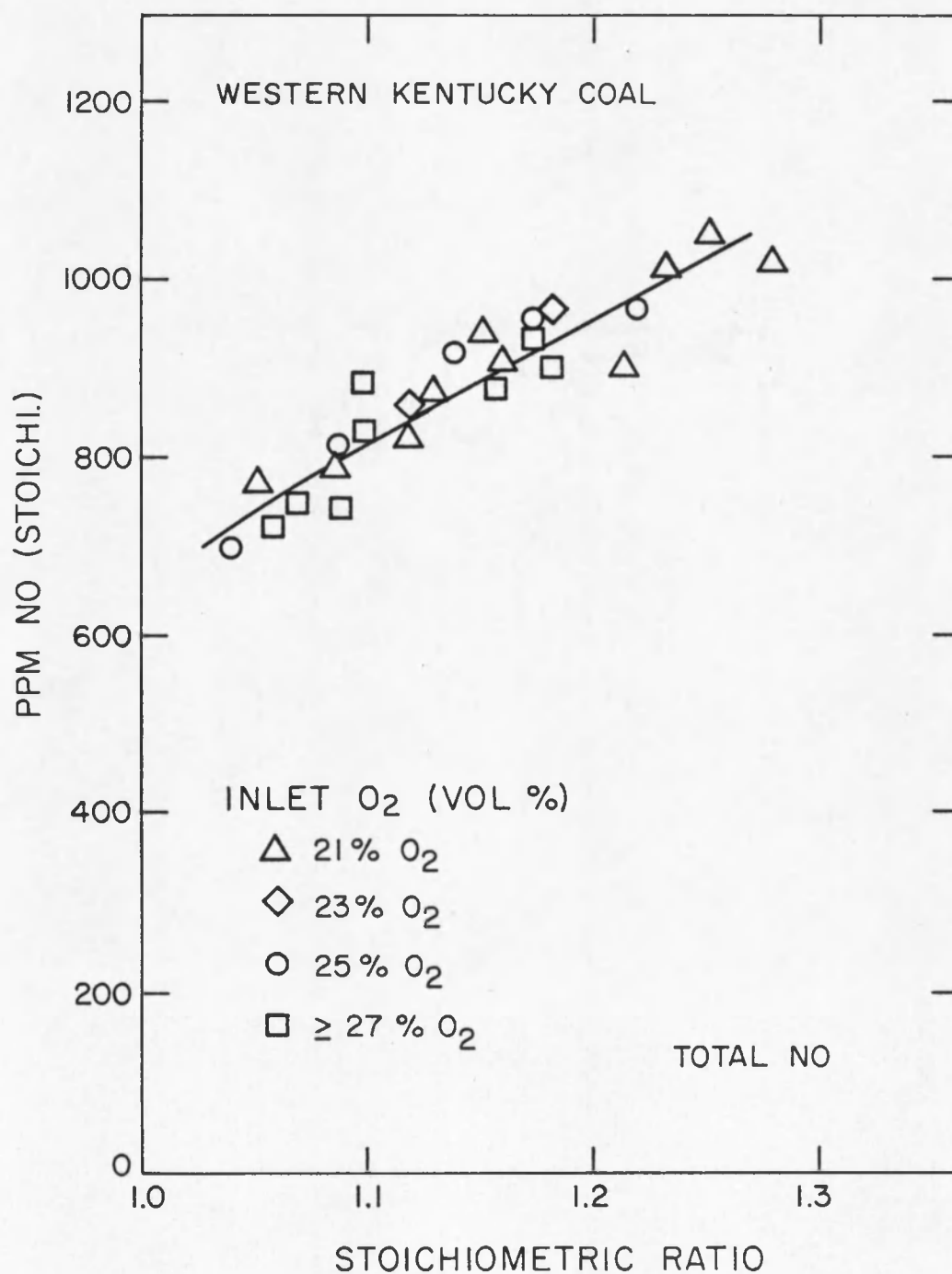
Figure 36. Effect of inlet oxygen concentration on total NO emissions. -- Western Kentucky coal, divergent injector.
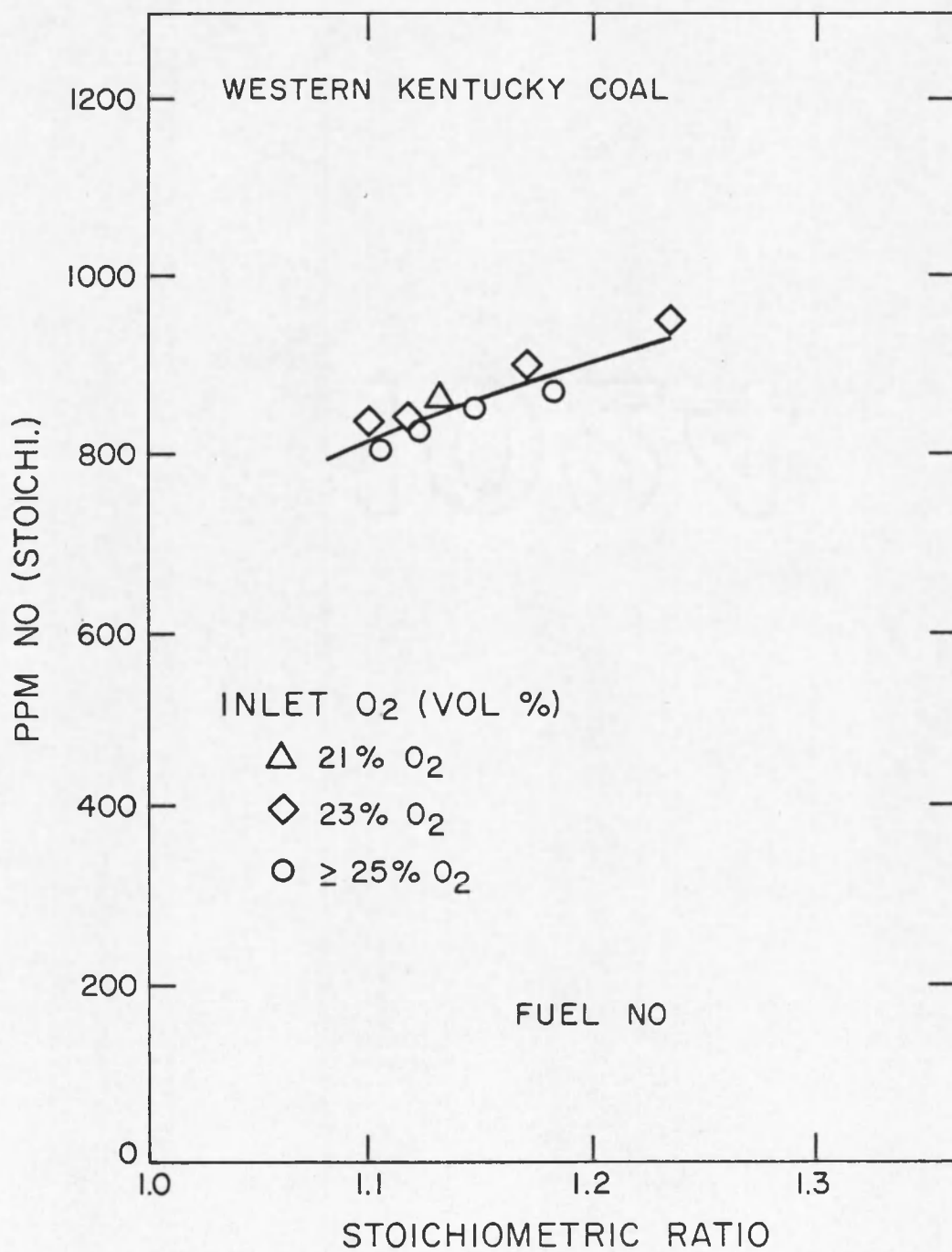
Figure 37. Effect of inlet oxygen concentration on fuel NO emissions. --
Western Kentucky coal, divergent injector.

Thus, the stoichiometry dependence can be decoupled from the hardware and composition parameters.

2. Below a certain level, further reduction of primary oxygen has little effect on NO emissions but dramatically reduces ignition stability. Thus, the early volatiles may not contain a significant amount of the volatile nitrogen ultimately converted to NO.

3. Increased early mixing, particularly as a result of flame detachment, dramatically increases both total and fuel NO emissions. This is probably the result of increased early oxygen availability, although this was not definitively confirmed.

4. Enrichment of the combustion air with pure oxygen has only a slight effect on either thermal or fuel NO emissions. This phenomena is not well understood at the present time and needs further research.

CHAPTER 10

COAL CHAR COMBUSTION

10.1 Char NO Emissions

Combustion of FMC coal char was studied to establish the combustion/pollution characteristics and to provide input for estimating the importance of char NO formation during pulverized coal combustion. Although this char was the result of a high temperature gasification process and contained only 3.6 percent volatiles, it cannot be assumed to be identical to the char produced in an actual pulverized coal flame because of differences in heating rate, pyrolysis time, and quenching effects. Hence, the testing was designed to provide general understanding of the char combustion process and pollutant forming characteristics rather than extensive emissions data. For example, the char was burned in two modes:

1. The flame mode, in which a turbulent diffusion flame was attached to the injector with the help of a small quantity of methane (21% of the total heat release) in the primary "air" and in which methane simulated nitrogen free volatiles.

2. The reactor mode, in which pure char without methane, burned far from the injector and which simulated the char burnout regime of coal after all volatiles had been consumed and after significant mixing had taken place.

These two modes of char combustion spanned probable conditions during the char burnout regime of pulverized coal combustion, and helped determine

the effect of mixing and of "shielding" by residual volatiles (Wendt and Sternling, 1974) on fuel nitrogen conversion to make char NO.

The flame mode was achieved using the axial fuel injector; an open 3/4" stainless steel tube was used as the fuel injector in the reactor mode. The data (corrected for dilution by methane combustion products*) are shown in Figure 38. These results indicate that essentially all the NO emissions result from fuel nitrogen oxidation; for both modes, the data from combustion in Ar/O_2 were coincident with those in air.

The data also revealed that the influence of combustion mode was relatively small; reactor mode emissions were only 100 ppm higher than those in the flame mode. The combustion characteristics of the two modes were markedly different, however. Visual observation indicated that in the flame mode combustion was essentially complete within 4 to 6 burner diameters from the fuel injector, while in the reactor mode the particles burned alone (rather than in a flame sheet) and ignition often occurred farther than 10 burner diameters from the fuel injector. Thus, particle heating rate and pyrolysis times appear to have little effect on char NO formation.

Figure 39 shows the char data replotted with data taken under similar combustion conditions with the Western Kentucky coal. Since the combustion mode has a major effect with coal and yet little effect with

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*In tests where methane was added to the primary air, the char emission data were corrected for dilution by the CO_2 present as a result of the methane combustion and by the N_2 in the air used for the methane combustion.
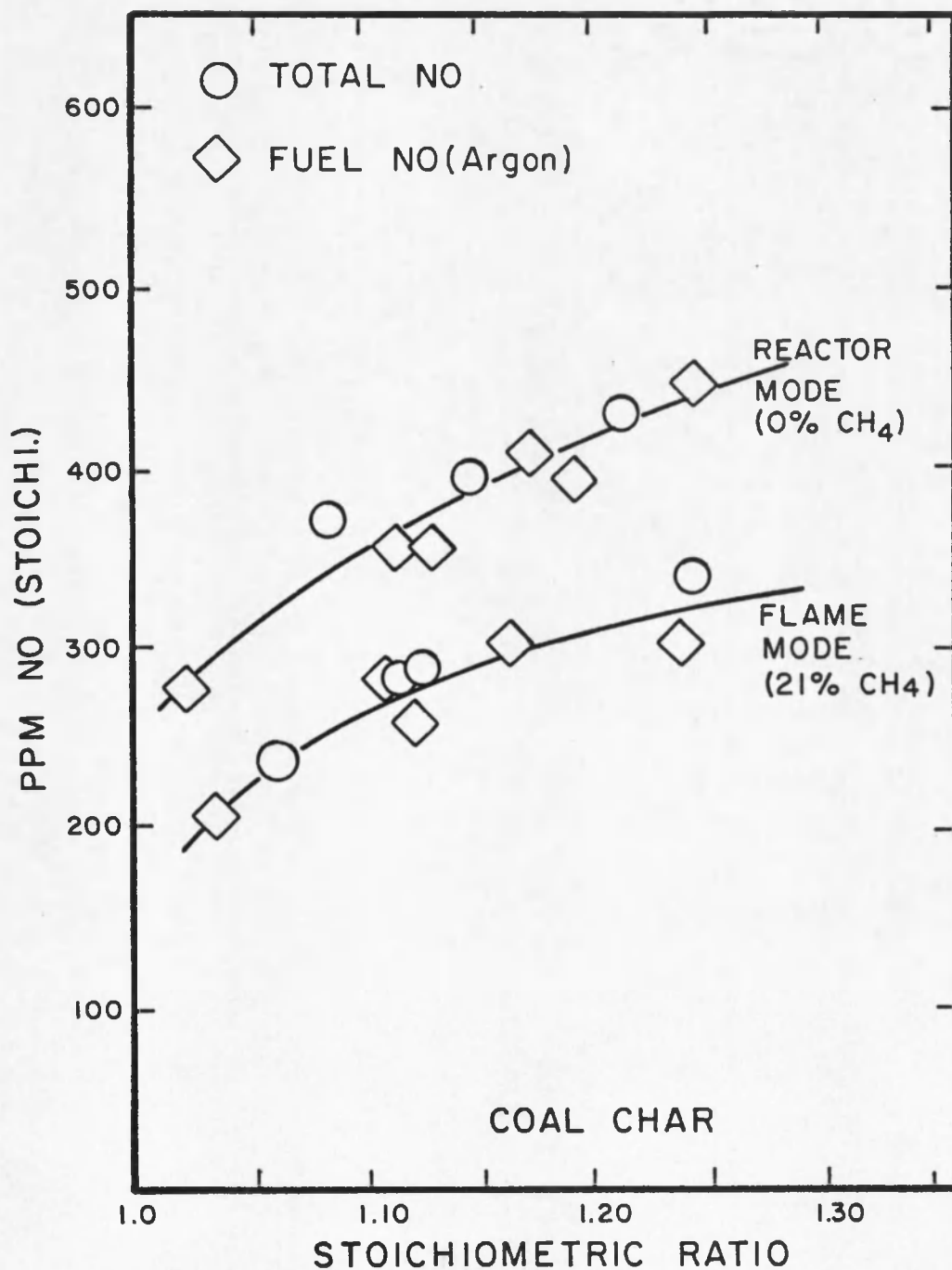
Figure 38.   Total NO and fuel NO emissions from coal char. -- Axial injectors, 550°F preheat.
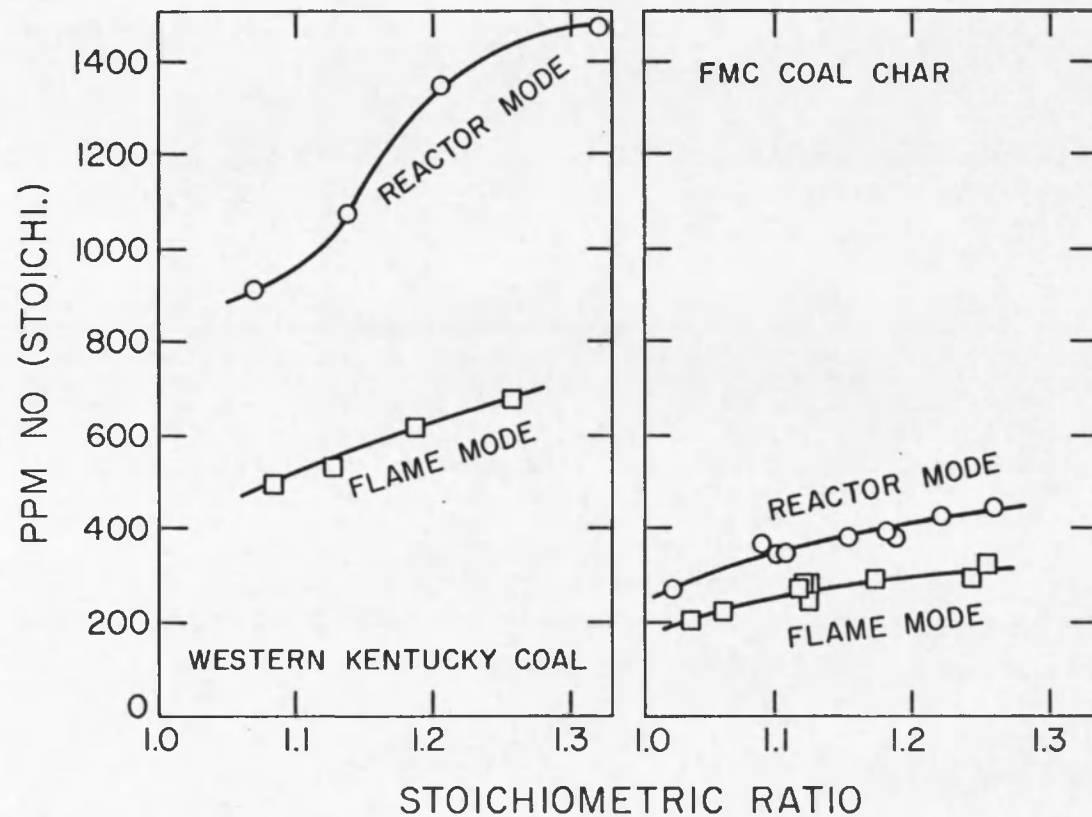
Figure 39. Comparison of combustion mode, Western Kentucky coal vs. FMC coal char.

coal char, the difference must be associated with volatile NO formation. (This effect is discussed in detail in Chapter 11.)

10.2   Influence of Flame Temperature

Figure 40 presents data taken on fuel NO emissions at various combustion temperatures for both the reactor and flame mode. Here, temperature variations were achieved by altering the heat capacity and oxygen content of the oxidizer. In char, as with coal, the oxidation of fuel nitrogen was unchanged over a broad temperature range. Further, since the emissions were essentially all fuel NO, total emissions would probably also be insensitive to temperature (in marked contrast to coal combustion).

10.3   Char Nitrogen Conversion

Figure 41 shows the fuel nitrogen conversions in both modes of char combustion compared to that of the Pittsburgh coal which has approximately the same amount of fuel nitrogen. Char conversions were approximately half that of the corresponding coal which again alludes to the importance of volatile NO formation. Although the absolute increase in char NO with increasing stoichiometry is less than that of a corresponding coal, the relative increase is essentially identical and can hence be correlated with the coal results (see Figure 29, Chapter 8).

10.4   Summary

Figure 42 summarizes all the conversion data for the four coals and the char (in the flame mode). These data again illustrate the two most significant conclusions from the char studies, that:
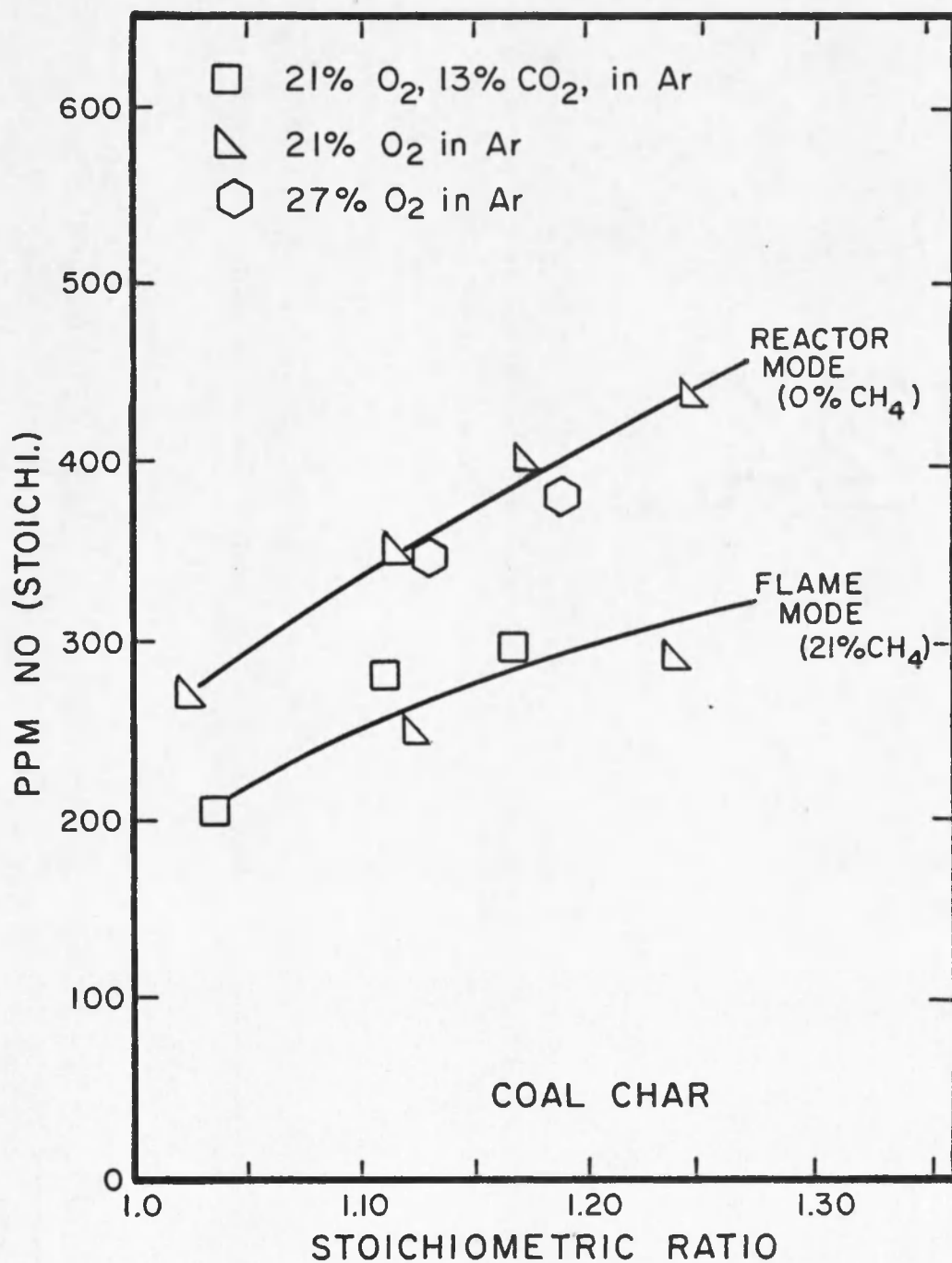
Figure 40.   Influence of combustion temperature on fuel NO emissions from coal char. -- Axial injectors, 550°F preheat.
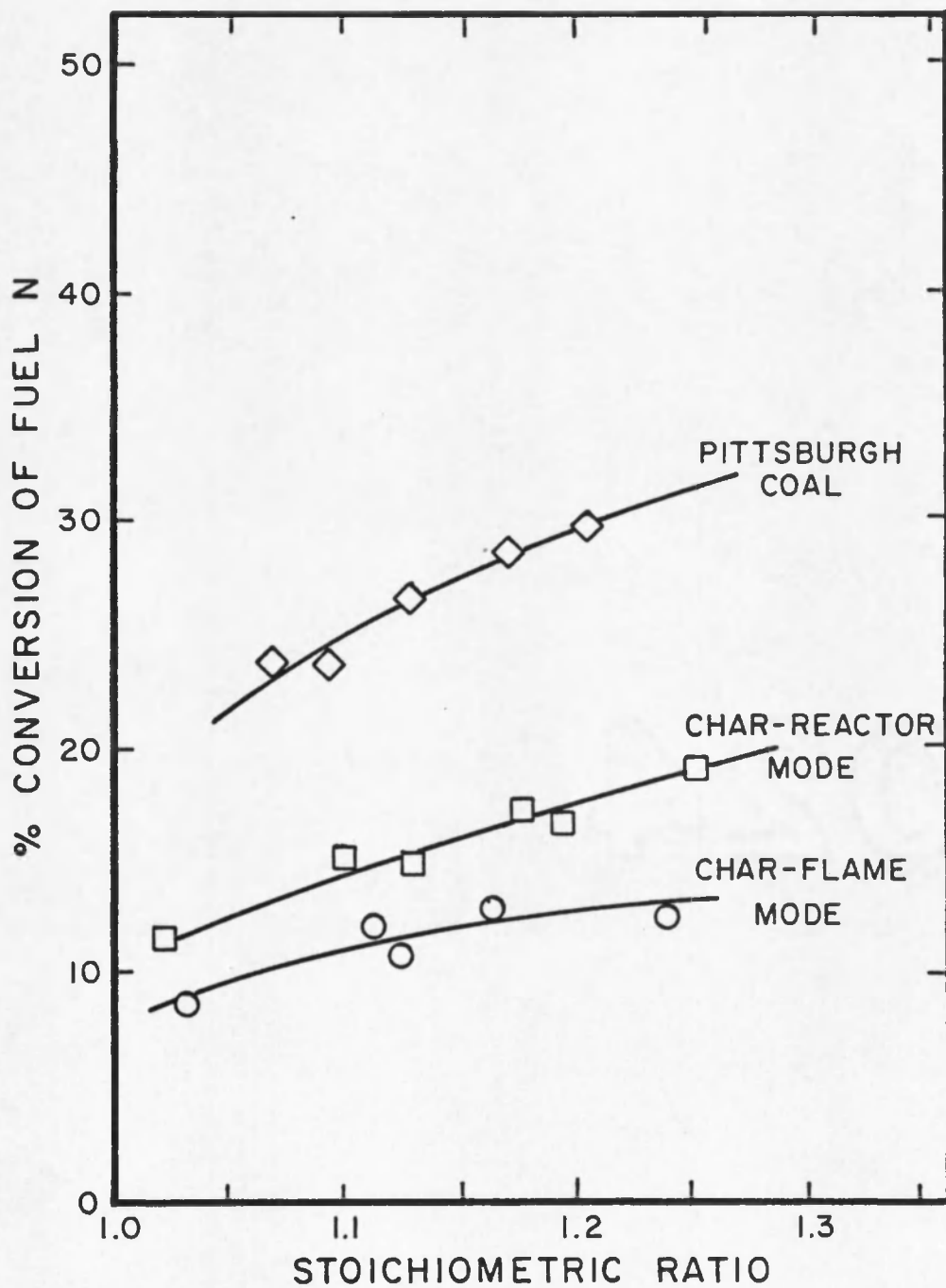
Figure 41. Stoichiometry dependence of coal and coal char.
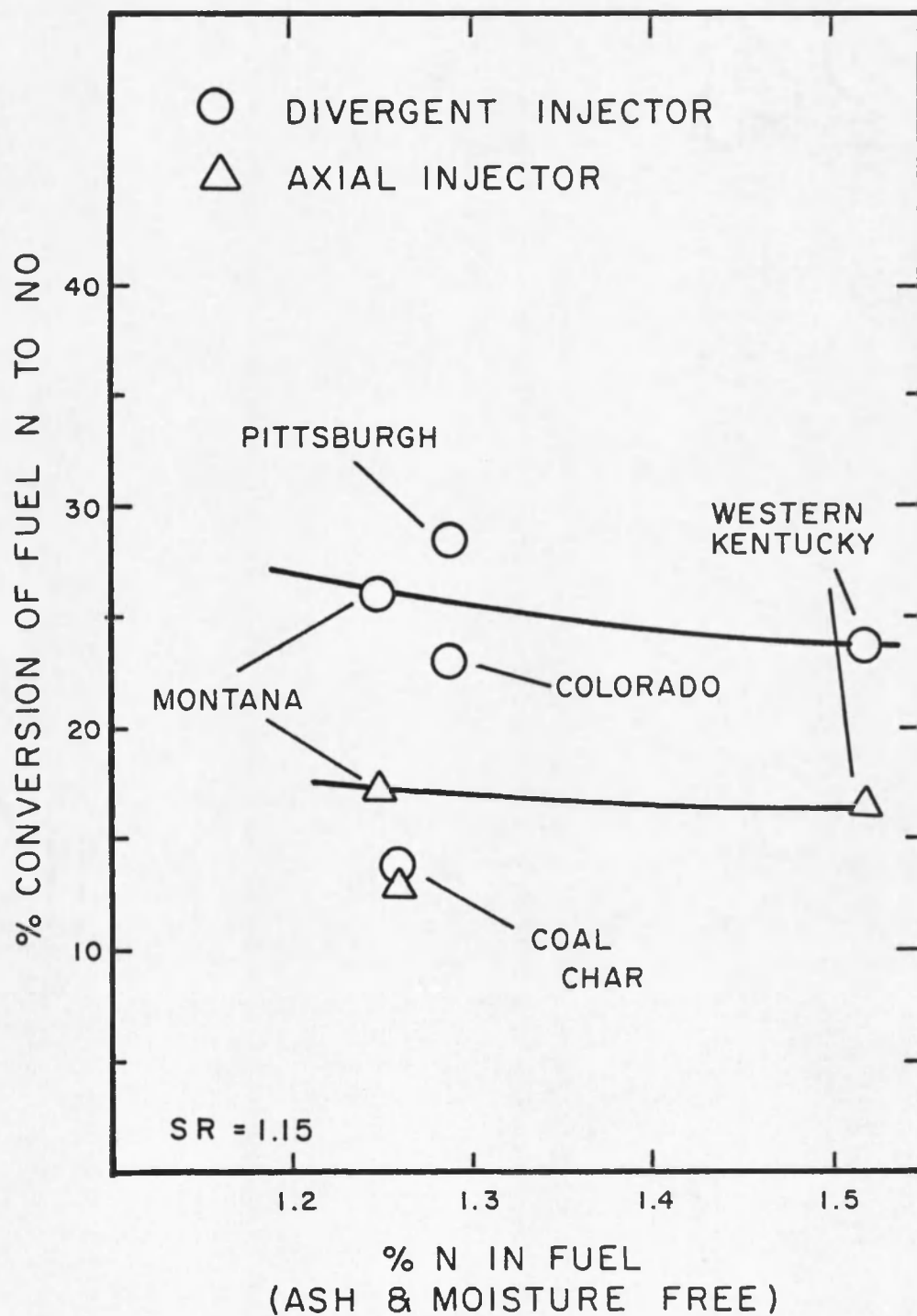
Figure 42. Fuel nitrogen conversion in coal and coal char flames. --
SR = 1.15.

1. Char nitrogen conversions are approximately half those of coal.

2. Char NO is relatively insensitive to changes in fuel injector (or burner) design.

CHAPTER 11

DETERMINATION OF THE FATE OF FUEL NITROGEN

IN PULVERIZED COAL FLAMES

11.1   Introduction

An analysis of the fate of fuel nitrogen in self-sustaining, pul-
verized coal flames was conducted. The analysis used empirically gen-
erated information, material balances, and results from special
experiments to:

1.   Deduce the relative importance of NO produced from the char (char

     NO) and NO produced from the volatiles (volatile NO) in self-

     sustaining flames.

2.   Deduce the effect of combustion modifications on the distribution

     of the nitrogen specie between the char and volatile phases

     (char/volatile split) and on the resulting conversions to char

     and volatile NO.

Described in the sections following are the combined theoretical
and experimental basis for the semi-empirical model developed, the
assumptions entailed therein, and the resulting predictions. It should
be emphasized that the model consists of a data analysis procedure
requiring specific experimental inputs. The fundamentals of fuel NO
formation and pulverized coal combustion are not sufficiently well
understood to allow a more predictive and rigorous theoretical analysis.

11.2 Theory

11.2.1 Unknowns

As discussed in Chapter 1, the combustion of pulverized coal particles can be visualized as the combination of two (partially overlapping) phenomenological parts: volatile combustion and char burnout. This conceptual picture was extended to explicitly include the nitrogen specie and used as the foundation for the analysis. Since volatile combustion times are of the order of 10 msec, while char burnout generally requires more than 300 msec, it was further assumed that the homogeneous conversion of nitrogen specie evolved with the coal volatiles is not chemically coupled to the conversion of char nitrogen to NO during the char burnout regime.

For any set of combustion conditions the parameters of interest are:

1. Weights:

   w_v = weight of volatiles evolved (DMMF*).

   w_c = weight of char (DMMF).

   w_t = initial weight of coal (DMMF).

2. Weight fractions:

   y_v = weight fraction nitrogen in volatiles.

   y_c = weight fraction nitrogen in char.

   y_t = weight fraction nitrogen in original coal.

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*DMMF refers to the dry, mineral matter (ash) free basis of the weights and weight fractions.

3. Fractional conversions of N to NO:

x_v = fractional conversion of volatile N to NO.

x_c = fractional conversion of char N to NO.

x_t = overall fractional conversion of fuel N to fuel NO.

The total weight fraction nitrogen (y_t) was obtained directly from the chemical analysis of the fuel. Likewise, the overall mean conversion of fuel nitrogen to NO (x_t) was calculated from the measured emission level in $Ar/O_2/CO_2$ (fuel NO) and the fuel composition. Finally, the calculations were per unit weight of original coal, i.e., $w_t = 1.0$.

11.2.2 Balance Equations

The relevant parameters were related by three mass balance equations:

1. Total mass balance:

$$w_v + w_c = w_t \qquad\qquad (11\text{-}1)$$

2. Nitrogen mass balance:

$$y_v w_v + y_c w_c = y_t w_t \qquad\qquad (11\text{-}2)$$

3. NO mass balance:

$$x_v y_v w_v + x_c y_c w_c = x_t y_t w_t \qquad\qquad (11\text{-}3)$$

and by empirical relations, described in detail in the following section.

11.2.3 Empirical Relations

Blair et al. (1976) have studied the rapid heating and pyrolysis of pulverized coals on an electrically heated platinum ribbon. Figure 43 shows the results these workers obtained with the same Western Kentucky
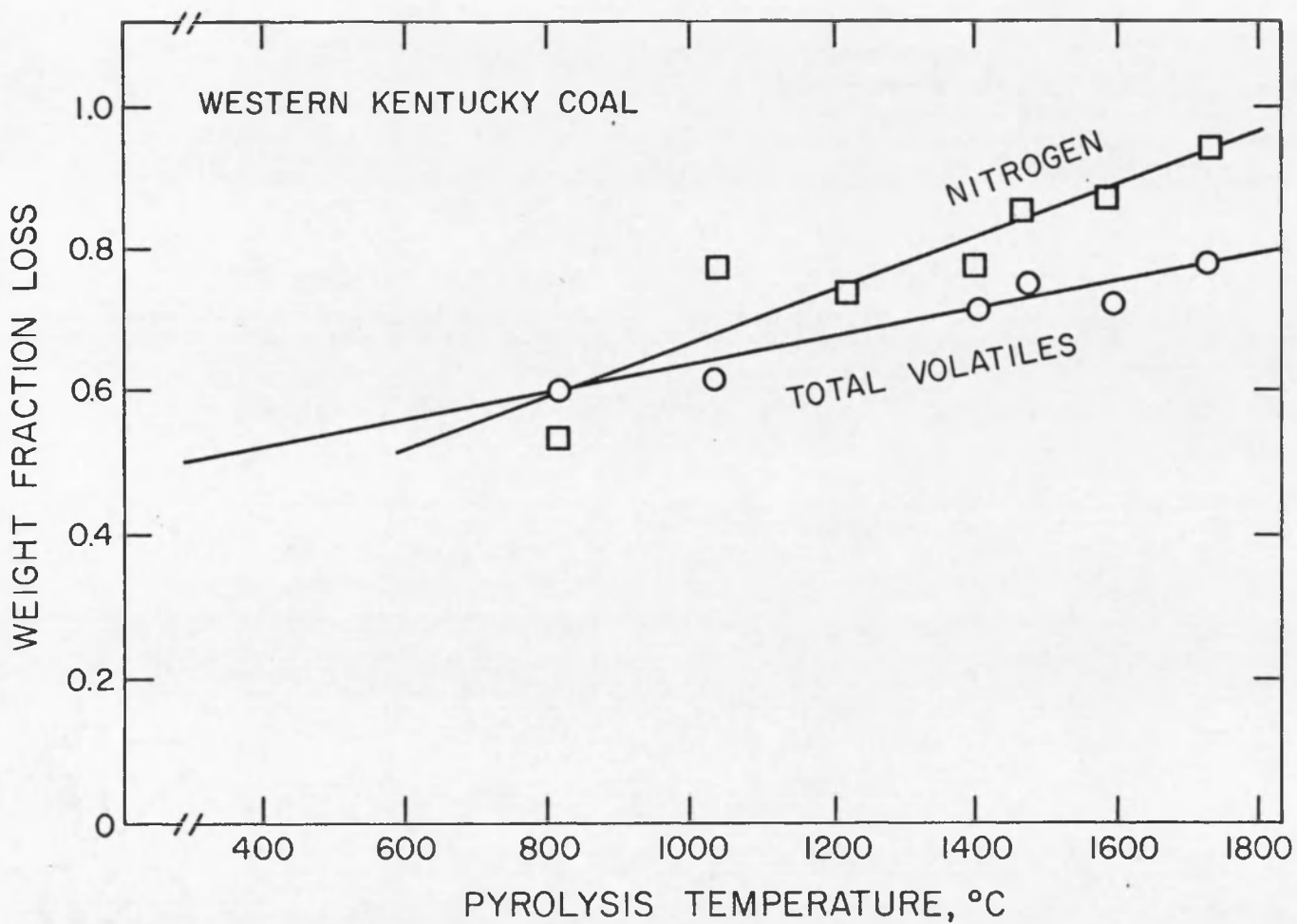
Figure 43. Volatile evolution as a function of pyrolysis temperature, Western Kentucky coal. -- Courtesy of D. W. Blair, Exxon Research and Engineering, Linden, New Jersey.

coal used in the work reported herein (Blair, 1976). For ultimate

pyrolysis temperatures between 800 and 1800°C, both the total volatile

fraction (w_v/w_t) and the nitrogen volatile fraction ($y_v w_v/y_t w_t$) were

found to be approximately linear with temperature. Since the effective

pyrolysis temperature in the actual coal flame was not known, the

linearized equations for these data were combined into a simple equation

relating nitrogen volatiles to total volatiles:

$$\frac{y_v w_v}{y_t w_t} = 1.92\ w_v - 0.559 \tag{11-4}$$

Pohl and Sarofim (1975) reported that heating rate, in addition to final

pyrolysis temperature, alters the amount of volatiles produced. Blair

et al. (1976) found only a slight dependence of volatile yield on heating

rate. In addition, quantitative data relating heating rate to overall

combustion parameters are not available. Therefore, for the purposes of

this analysis, it was assumed that the heating rate dependence (if any)

does not alter the relative proportions of nitrogen and total volatiles,

i.e., that selective distillation does not occur.

The experimental char results (Chapter 10) were used to develop

an empirical equation for the conversion of char nitrogen to NO:

$$x_c = (2.0*SR - 1.32)*(\frac{1}{1 + \beta_c y_c}) \tag{11-5}$$

The stoichiometry dependence was based on the linear correlation of the

fuel NO emissions from the char and the four coals with overall stoichio-

metry independent of fuel nitrogen content (Chapter 9). It was also

assumed that over a small range of char nitrogen contents the char con-

version dependence on nitrogen level could be correlated with a single

coefficient, β_c, which was calculated directly from the coal char data. The reciprocal/sum dependence was selected to be consistent with the experimental evidence on total conversion limits (Martin and Berkau, 1972) and is similar to that recommended by Fenimore (1972). If the rate limiting step is second order in NO, equation 11-5 becomes an exact representation. No hardware dependence was included in equation 11-5 because the experimental char results (Chapter 10) demonstrated that the influence of burner parameters on char NO formation was slight.

An empirical equation for the volatile conversion was also developed and again the reciprocal/sum form was used:

$$x_V = \frac{1}{1 + \beta_V y_V} \qquad (11\text{-}6)$$

but in this case the conversion is strongly coupled to both the burner/injector design and the overall stoichiometry in addition to the nitrogen level (Chapter 10). Although homogeneous combustion data on typical nitrogen compounds (e.g., Haynes et al., 1975) further emphasize the significance of local stoichiometry, quantitative information on the dependence in actual pulverized coal flames is not available. Therefore, both hardware and stoichiometry effects were implicitly included in the conversion coefficient, β_V, by experimentally determining it at each test condition.

11.3 Experiments

Experimental data were obtained to quantify the conversion of volatile nitrogen to NO in an actual pulverized coal flame environment. "Typical" volatile nitrogen compounds were added to the primary air/coal

stream just prior to the fuel injector. At present, there is no general agreement on volatile nitrogen speciation. Axworthy (1975) found significant amounts of HCN were evolved during pyrolysis. Blair et al. (1976) found the nitrogen was evolved late in the devolatization process as heavy organics although these are almost certainly further pyrolyzed before oxidation. Fundamental data discussed in Chapter 1 indicate that the dependence of conversion on speciation is small. NH_3 and NO were, therefore, chosen as representative specie which were commercially available and could be metered accurately. In addition, NO was believed to represent an upper limit on volatile nitrogen conversion. Both gases were CP grade from high pressure cylinders. Flow was metered with a pre-calibrated rotameter (see Appendix B) and maintained at a rate corresponding to 300 ppm (STOICHI) in the flue with total N to NO conversion.

At each test condition, NO emission data were taken with and without the additive. The difference was then attributed to the incremental increase in volatile nitrogen content; however, the volatile conversion could not be calculated directly because in either case the total amount of volatile nitrogen was unknown. Instead, the entire system of mass balance and empirical equations was solved for both the base and additive cases in a coupled manner with the assumption that the incremental amount of volatile nitrogen added did not alter the char/volatile split or the char conversion. Appendix F contains the numerical details of the solution procedure and the actual computer code which was used.

11.4 Assumptions

Thus, an analysis procedure to determine the fate of fuel nitrogen in the Western Kentucky coal was developed using mass balance equations and empirical relationships. For each set of combustion conditions two experimental tests were required (base and base + additive) to provide the required inputs to the model:

1. Fuel flow rate and composition.

2. Fuel NO emissions.

3. Additive flow rate and composition.

4. Increase in emissions due to the nitrogen additive.

5. Stoichiometric ratio.

The analysis procedure then predicted:

1. Char and volatile NO.

2. Overall char/volatile split.

3. Distribution of nitrogen between the volatiles and char.

The assumptions inherent in the analysis are as follows:

1. The conversion (or retention) of NH_3 and NO is representative of the conversion of volatile nitrogen specie to NO in the same environment.

2. The overall pyrolysis data of Blair (1976) are applicable at all conditions examined.

3. Volatile NO and char NO do not directly interact.

4. Addition of NH_3 or NO does not alter the char-volatile split.

5. The coal char results are representative of actual high temperature char burnout.

6. Char and volatile conversions can be fitted with $(1 + \beta_i y_i)^{-1}$

over a·small range of nitrogen contents.

The justification for each assumption has been discussed in the previous sections. As noted, the absence of detailed volatile evolution and combustion data makes assumptions 1 and 2 the most questionable.

11.5   Results

11.5.1 Baseline Conditions

The results of the char/volatile modeling are presented and discussed below and on the following pages. In general, two types of results are presented. First, the ppm NO (STOICHI), which were calculated to result from the oxidation of fuel nitrogen evolved with the volatiles (volatile NO) and of fuel nitrogen remaining in the char (char NO), are presented. Since each analytical prediction of the char and volatile NO is the direct result of two experimental measurements (the fuel NO and the conversion of the typical volatile additive) at the particular condition, the analytical predictions are shown as points on the figures. The scatter in these points is a direct result of experimental scatter.

Secondly, the analytical predictions of the weight fraction of the original coal which is evolved as volatiles and the weight fraction of the original nitrogen which is contained in these volatiles are presented. Again, these are computed results based on the corresponding experimental inputs.

All of the raw experimental results on which these two types of calculations were based are contained in Appendix D.

Figure 44 shows the analytical results for the Western Kentucky coal with the divergent injector at the baseline conditions. Experimental data were obtained with both NO and NH_3 as the "typical" volatile nitrogen compounds, but as Figure 44 indicates variations in compound type had little effect on the predicted amounts of char and volatile NO. This is consistent with laboratory (Axworthy, 1975) and pilot (Martin and Berkau, 1972; Turner et al., 1972) data and further confirms that volatile conversions are insensitive to nitrogen speciation. It also supports the small dependence of total NO emissions on coal composition. Furthermore, the conversion of the added NH_3 to NO was small (10 to 20 percent), indicating that the system did not behave as "premixed" in the sense of pre-mixing NH_3 and primary air alone. This was probably because early volatile hydrocarbons were evolved rapidly, prior to NH_3 oxidation. The low conversions of NH_3 thus help justify the contention that NH_3 behaves as coal nitrogen volatiles entering the flame front to be oxidized.

Three replicate test series were conducted on separate days to establish both the reproducibility of the experimental inputs and the sensitivity of the calculations. As Figure 44 shows, the results were quite acceptable. (NO was used for the replicate and most subsequent testing because of fouling problems with the NH_3 rotameter.)

The slight increase in char NO with increasing overall stoichiometry was built into the model (by the empirical fit of the experimental char results); however, the analysis predicts a relatively strong increase in volatile NO with increasing stoichiometry. This demonstrates the importance of keeping the coal and secondary air partially separated
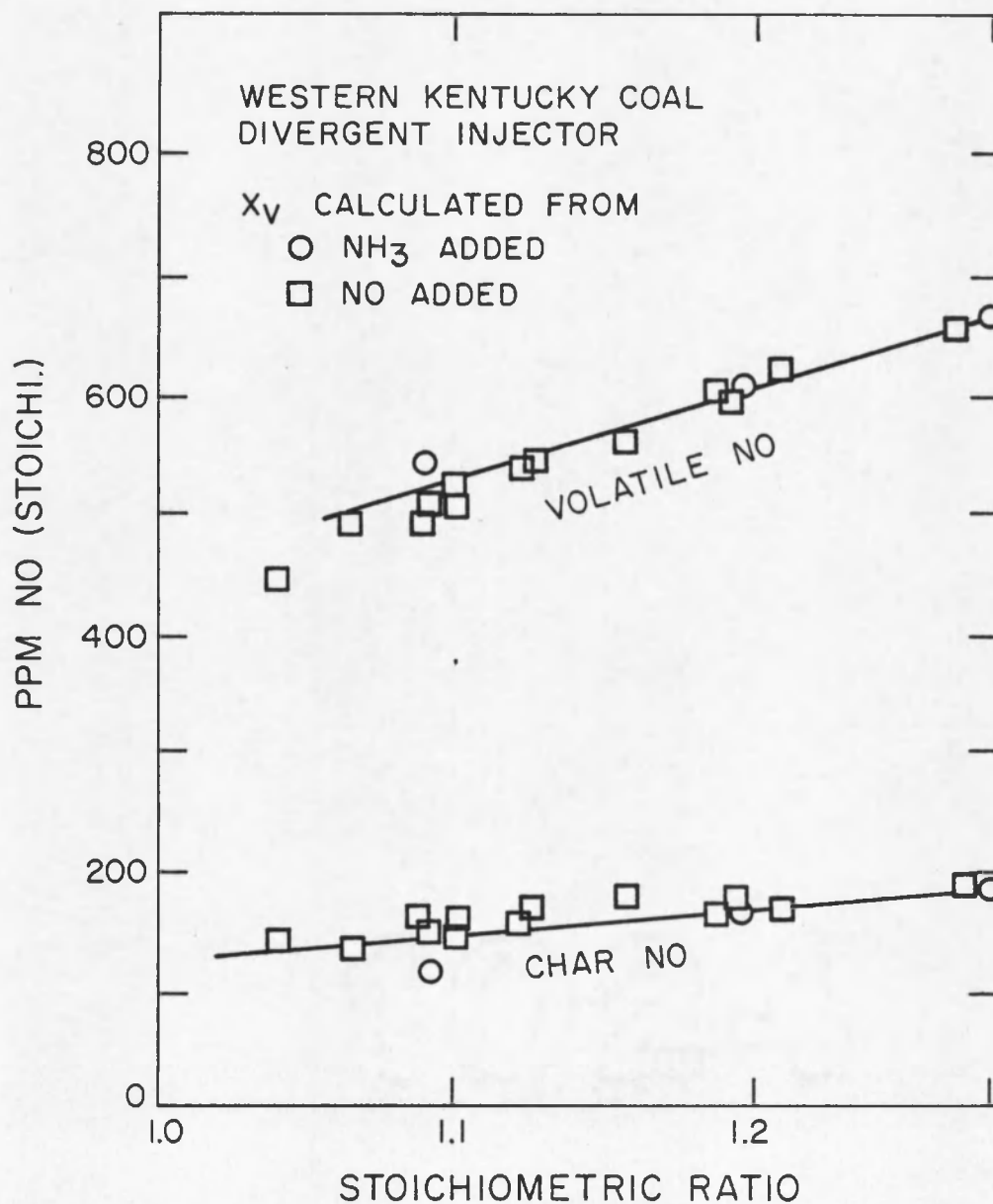
Figure 44. Char and volatile NO predictions (baseline conditions). --
Western Kentucky coal, divergent injector, 600°F preheat.

during the volatile combustion to achieve low NO emissions. The strong

dependence on overall stoichiometry also suggests that the reaction(s)

controlling volatile NO formation are slow relative to the combustion

reactions.

Figure 45 presents the analytical predictions on the mass frac-

tion of the original coal evolved as volatiles during the combustion pro-

cess (char/volatile split) and the mass fraction of the original fuel

nitrogen which was evolved with the volatiles (nitrogen volatiles). Both

appear to be independent of the additive used to estimate volatile con-

versions. The predictions indicate that almost 60 percent of the total

nitrogen remains with the solid phase; thus confirming the original

hypothesis of Sternling and Wendt (1972) regarding the potential impor-

tance of the char burnout regime. Both total and nitrogen volatiles

increased with increasing excess air. This could be due to increased

combustion rates at the higher stoichiometrics which result in increased

pyrolysis temperatures and hence more volatile nitrogen evolution.

11.5.2 Oxygen Enrichment

Enrichment of the combustion air with pure oxygen substantially

increased the flame temperature and primary oxygen, but resulted in little

change in either fuel or thermal NO (Chapter 9). In an effort to clarify

this phenomena, an experimental char/volatile test series was conducted

and the resulting analytical predictions are shown in Figures 46 and 47.

(The error bars in Figure 47 are based on the experimentally induced

scatter observed in the replicate tests at this condition as shown in

Figure 45.) Oxygen enrichment had little effect on either the predicted
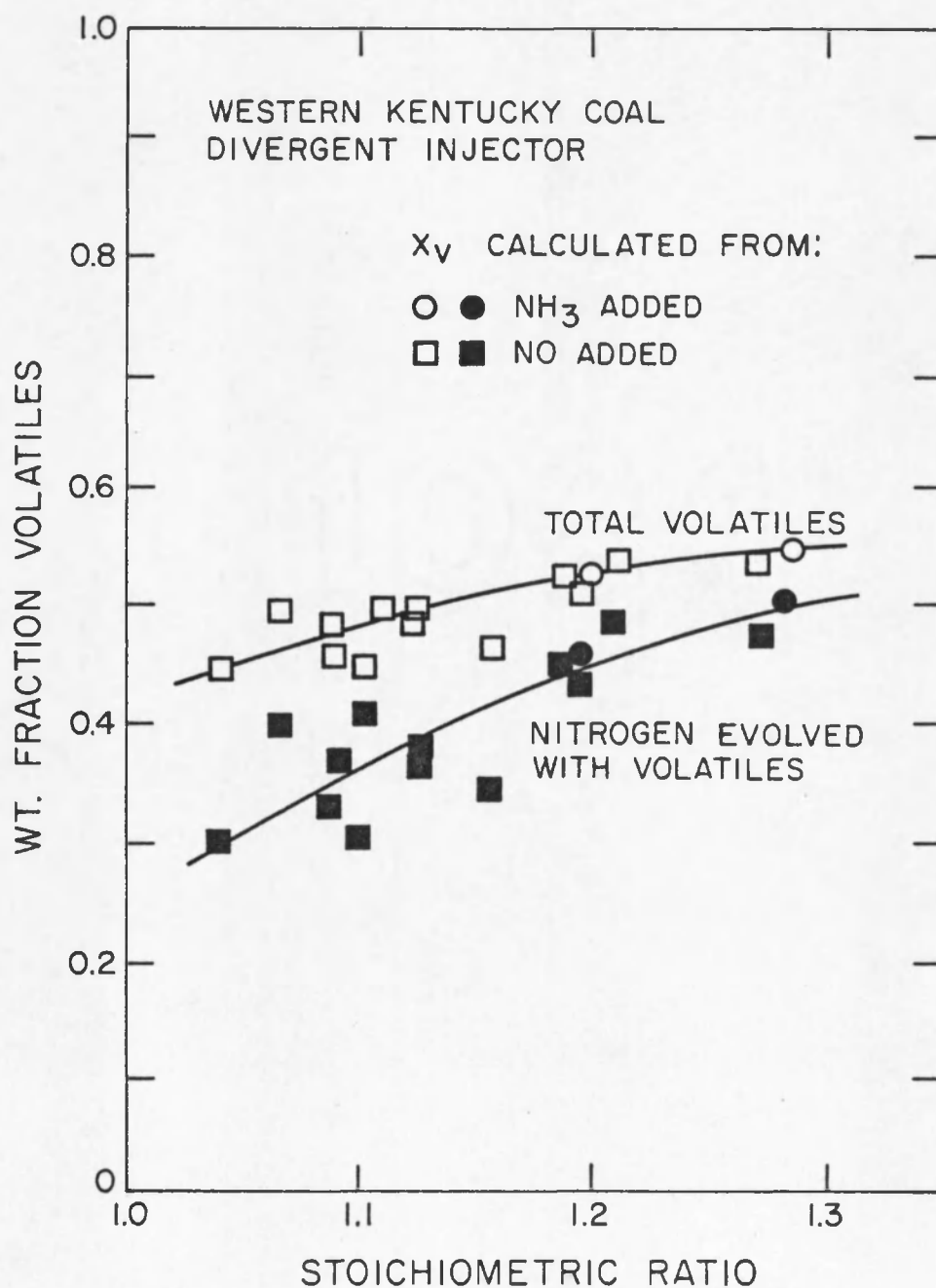
Figure 45.   Volatile split predictions (baseline conditions). --
Western Kentucky coal, divergent injector, 600°F preheat.
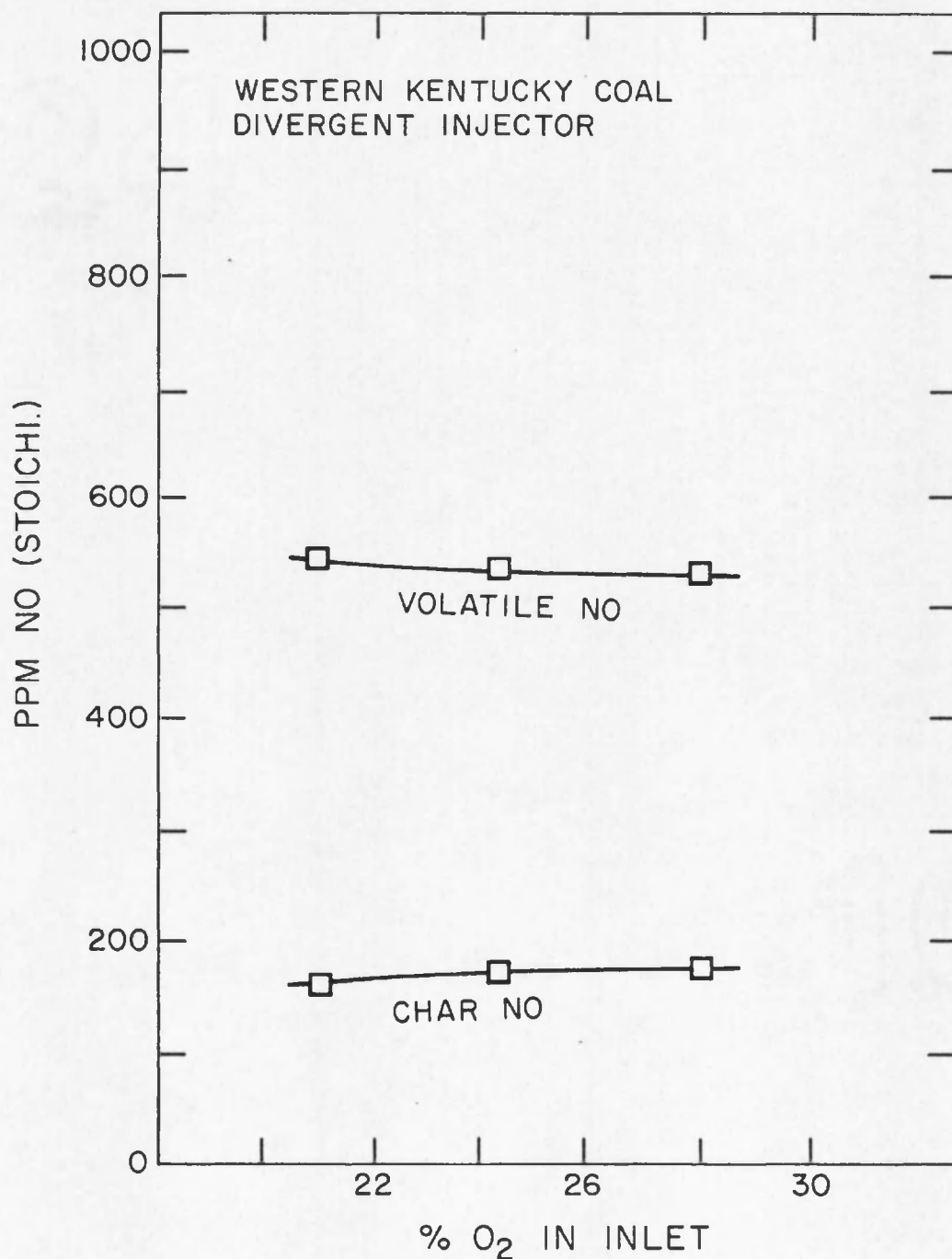
Figure 46.   Effect of oxygen enrichment on predicted char and volatile
            NO. -- Western Kentucky coal, divergent injector, SR = 1.13,
            575°F preheat.
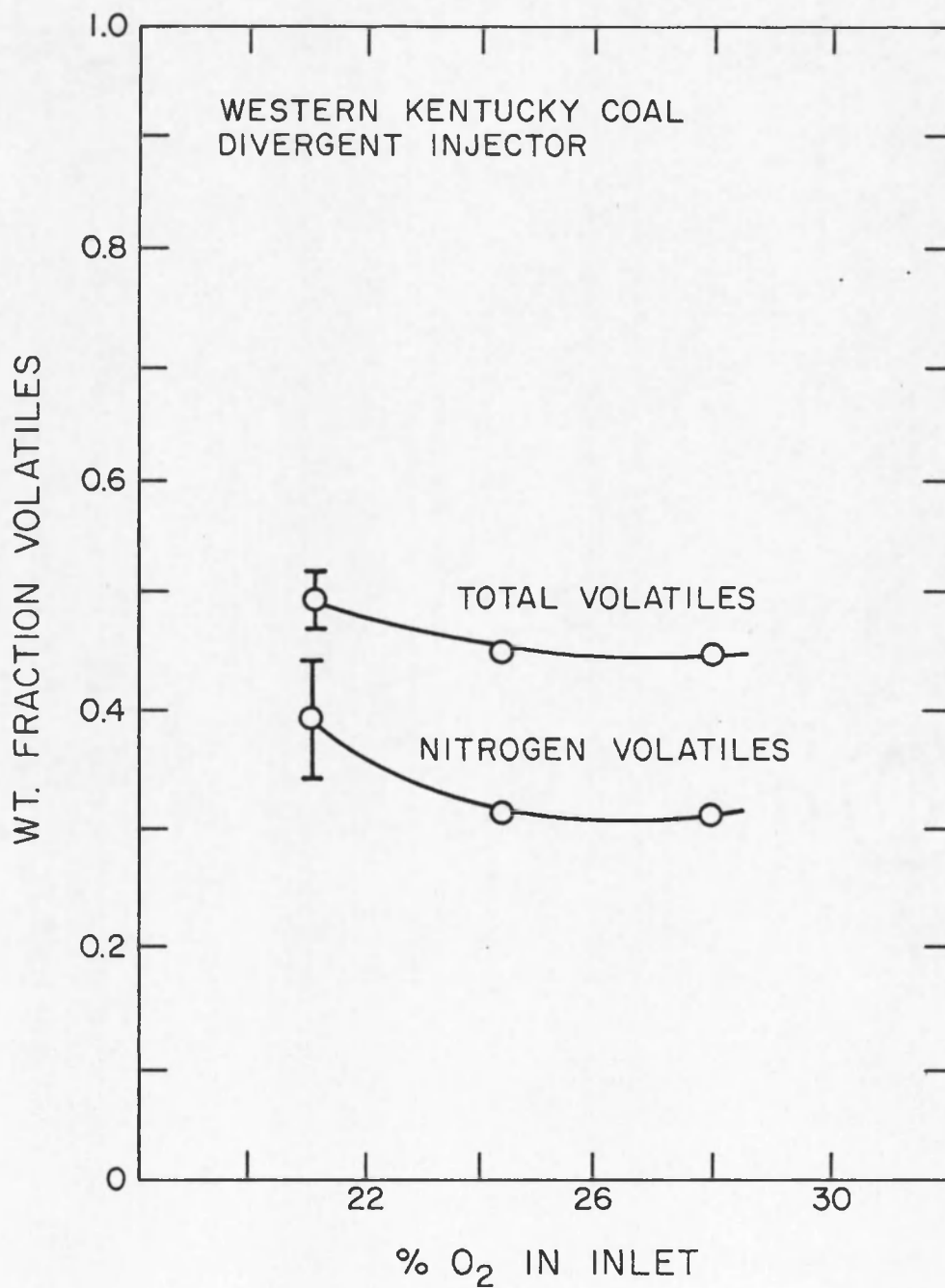
Figure 47. Effect of oxygen enrichment on predicted volatile split. --
Western Kentucky coal, divergent injector, SR = 1.13, 575°F
preheat.

char and volatile NO or on the amount of total and nitrogen volatiles.
Since the fuel NO is known to increase with increased primary oxygen (and
this is almost certainly due to an increase in volatile NO), it must be
concluded that increasing both primary and secondary oxygen (which
results in a significant temperature rise) either increases the rate of
N_2 formation or induces a fluid dynamic change which tends to compensate
the effect of increased primary oxygen.

11.5.3 Flame Temperature

Figures 48 and 49 show the analytical predictions resulting from
a test series in which the flame temperature was increased by decreasing
the heat capacity and increasing the oxygen content of the oxidizer.
Only a slight dependence of volatile NO and volatile nitrogen evolution
on temperature was predicted, an apparent contradiction to the pyrolysis
and heating rate data of Pohl and Sarofim (1975) and Blair et al. (1976).
To investigate this further, a particular condition was selected (SR =
1.20, 650°F preheat), experimental emission measurements obtained, and a
volatile conversion coefficient, β_v, calculated. The char/volatile split
was then arbitrarily varied with the conversion coefficient held constant.
The char/volatile split was directly related to an increase in pyrolysis
temperature using the data of Blair (1976) and the analytical results are
shown in Figure 50. An extreme change in pyrolysis temperature is
required to produce a significant change in fuel NO emissions. As
Figure 51 indicates, this is because although the nitrogen volatiles are
predicted to increase dramatically with increasing temperature, the vola-
tile conversion is simultaneously decreasing. Hence, changes in local
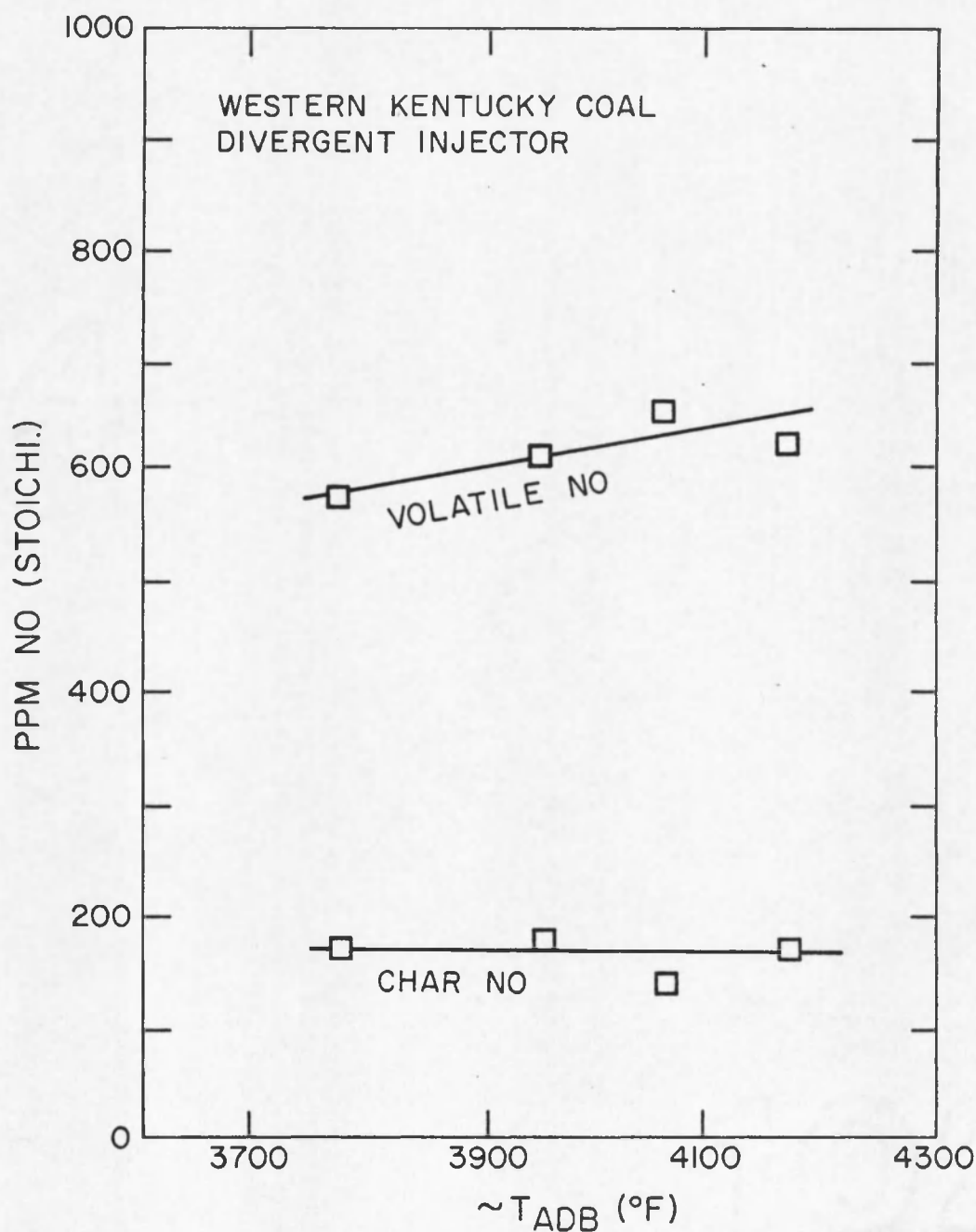
Figure 48.   Effect of flame temperature on predicted char and volatile
NO. -- Western Kentucky coal, divergent injector, SR = 1.17.
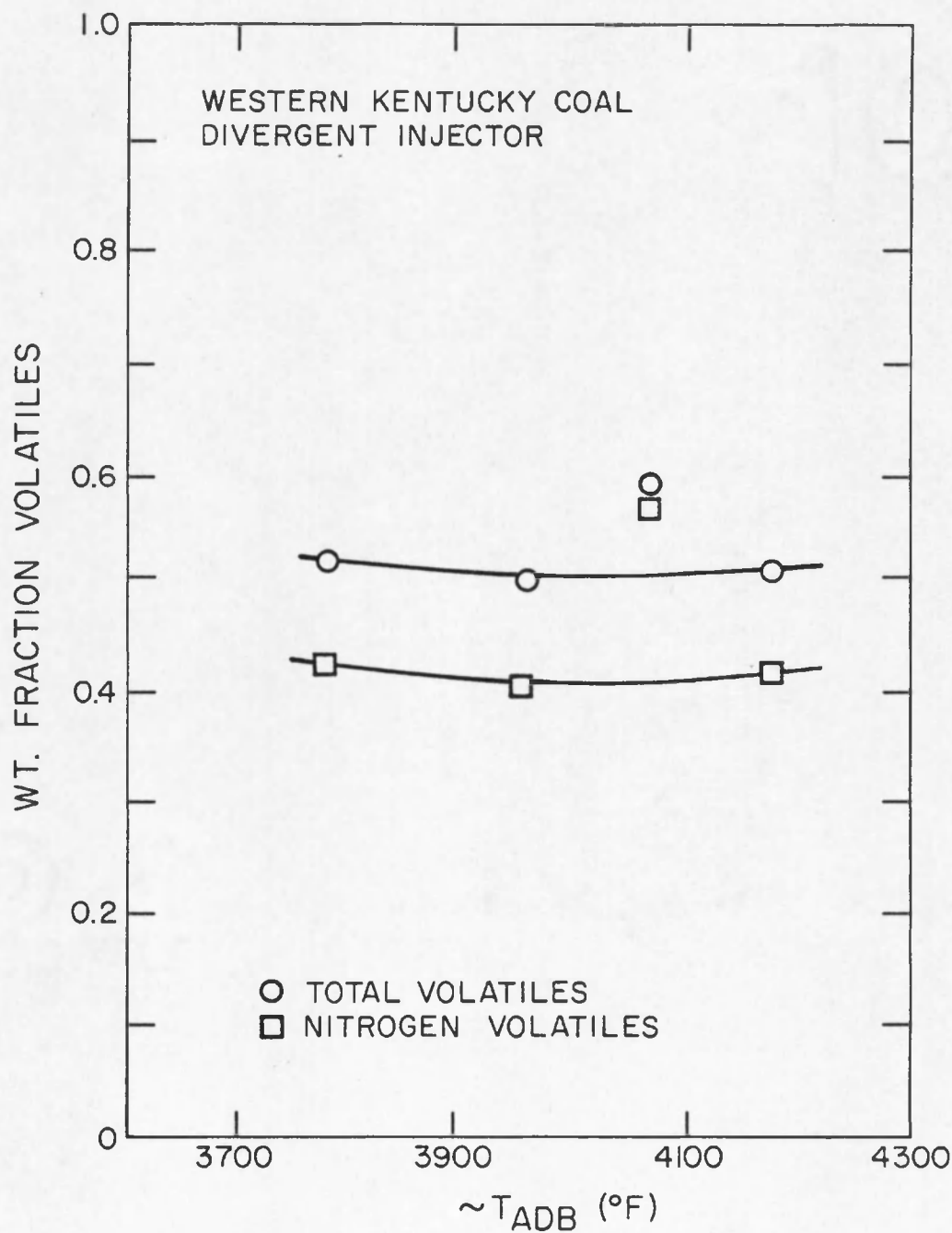
Figure 49. Effect of flame temperature on predicted volatile split. --
Western Kentucky coal, divergent injector, SR = 1.17.
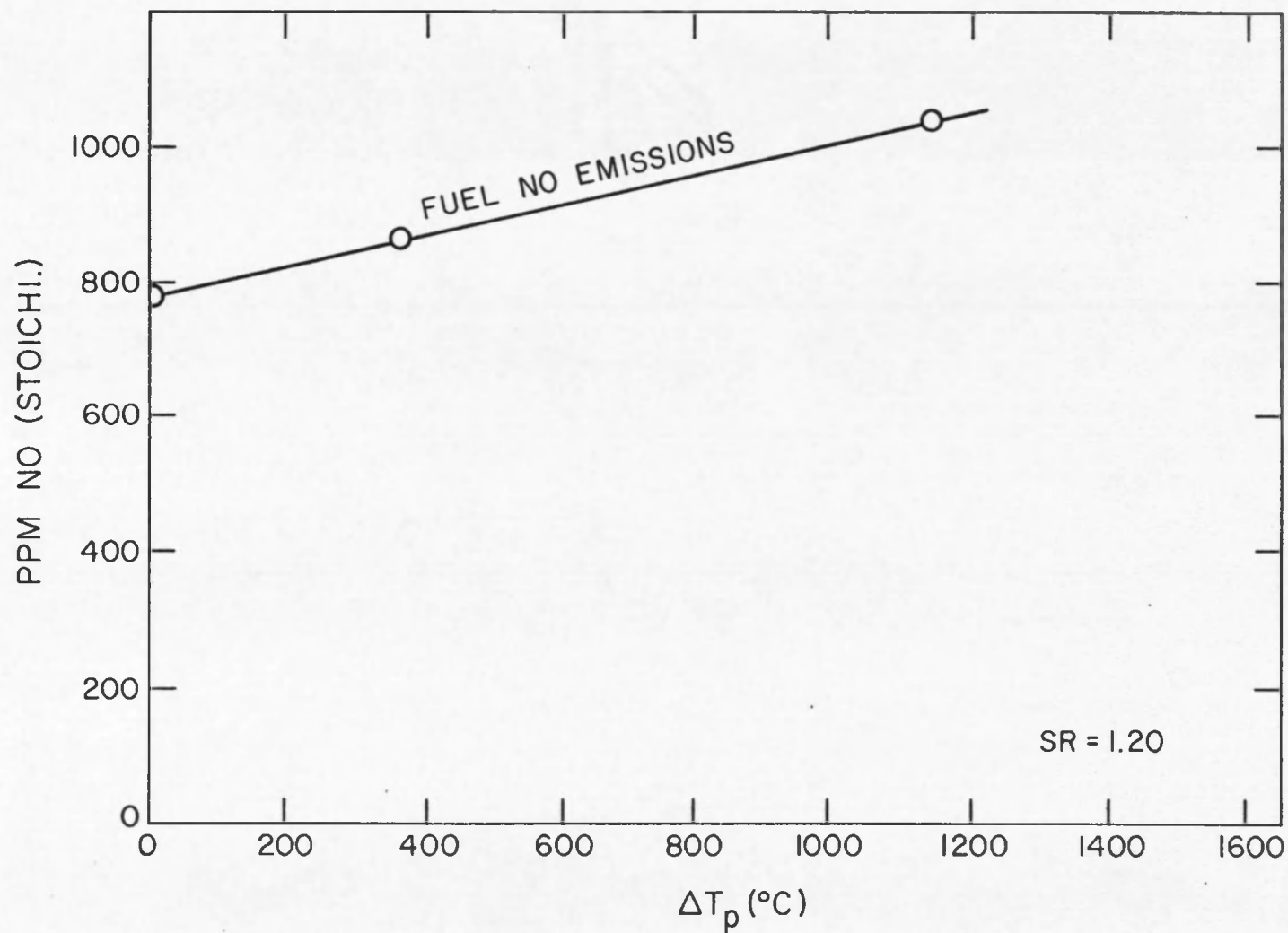
Figure 50. Projected increase in fuel NO emissions due to increased pyrolysis temperature. -- Western Kentucky coal, divergent injector, SR = 1.20.
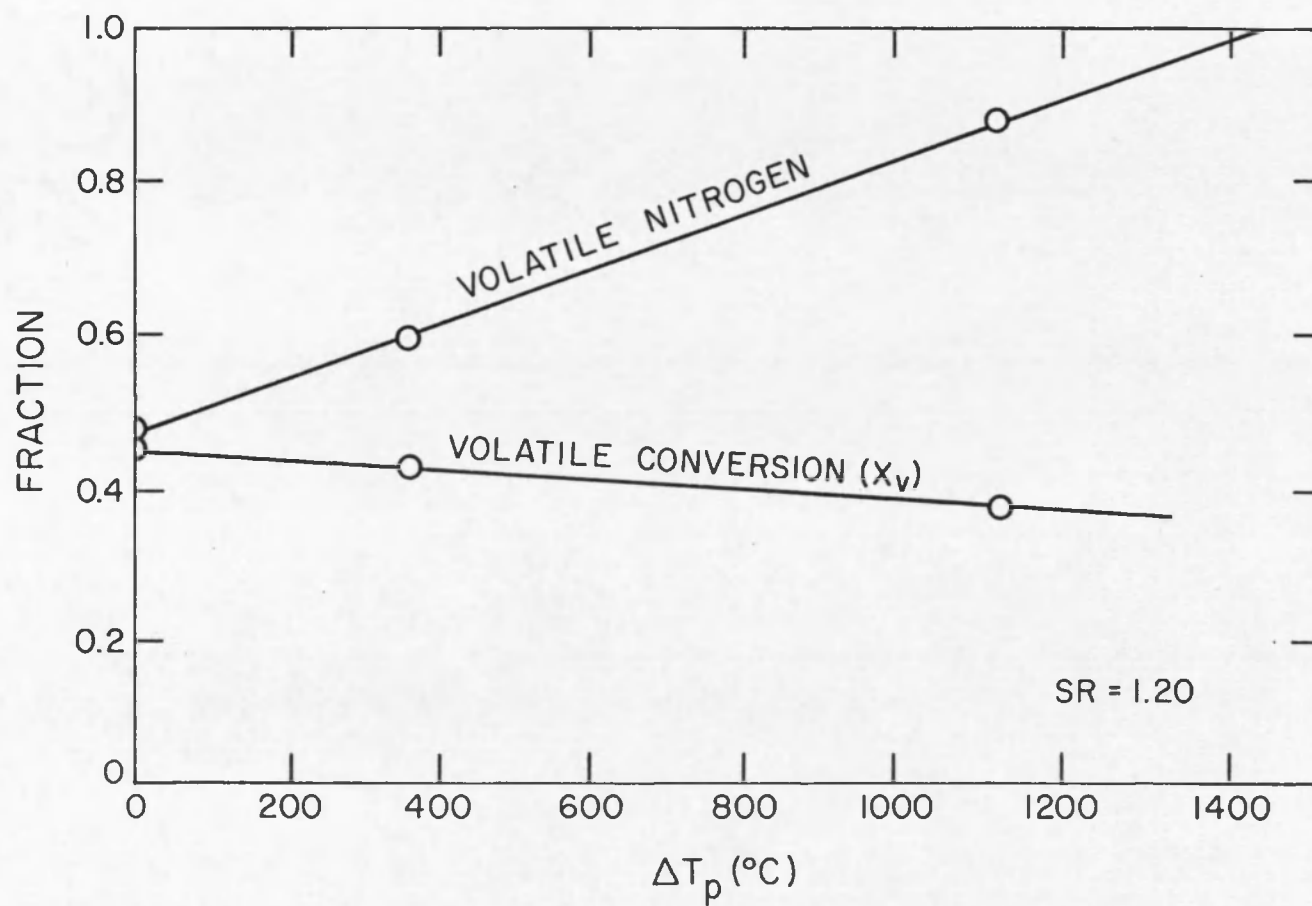
Figure 51. Projected effects of increased pyrolysis temperature. -- Western Kentucky coal, divergent injector, SR = 1.20.

combustion temperature which can be reasonably achieved in a full-scale or pilot-scale unit (500°F maximum) should have only a slight effect on fuel NO emissions (as was observed in this study). Further, to have an impact on volatile NO, control technology must dramatically alter particle heating and pyrolysis temperatures via fluid dynamic changes; overall temperature reduction methods such as flue gas recirculation are not likely to be effective.

11.5.4 Lifted Flames

Figure 52 shows the predicted effect of flame detachment on char and volatile NO, based on an experimental test series with lifted flames. Detachment has only a slight effect on char NO which is consistent with the experimental data on char combustion (Chapter 10). However, volatile NO emissions increase dramatically when the flame lifts off, probably because of increased local oxygen availability.

Figure 53 shows the total and nitrogen volatile fractions for lifted flames. Approximately 60 percent of the original nitrogen is evolved with the volatiles if the flame is detached. This is in contrast to approximately 40 percent in the attached case (Figure 45). The increased volatile evolution must be attributed to the dramatically increased particle heating prior to ignition (see Figure 43). The lack of stoichiometry dependence further supports the hypothesis that considerable premixing occurs prior to ignition.
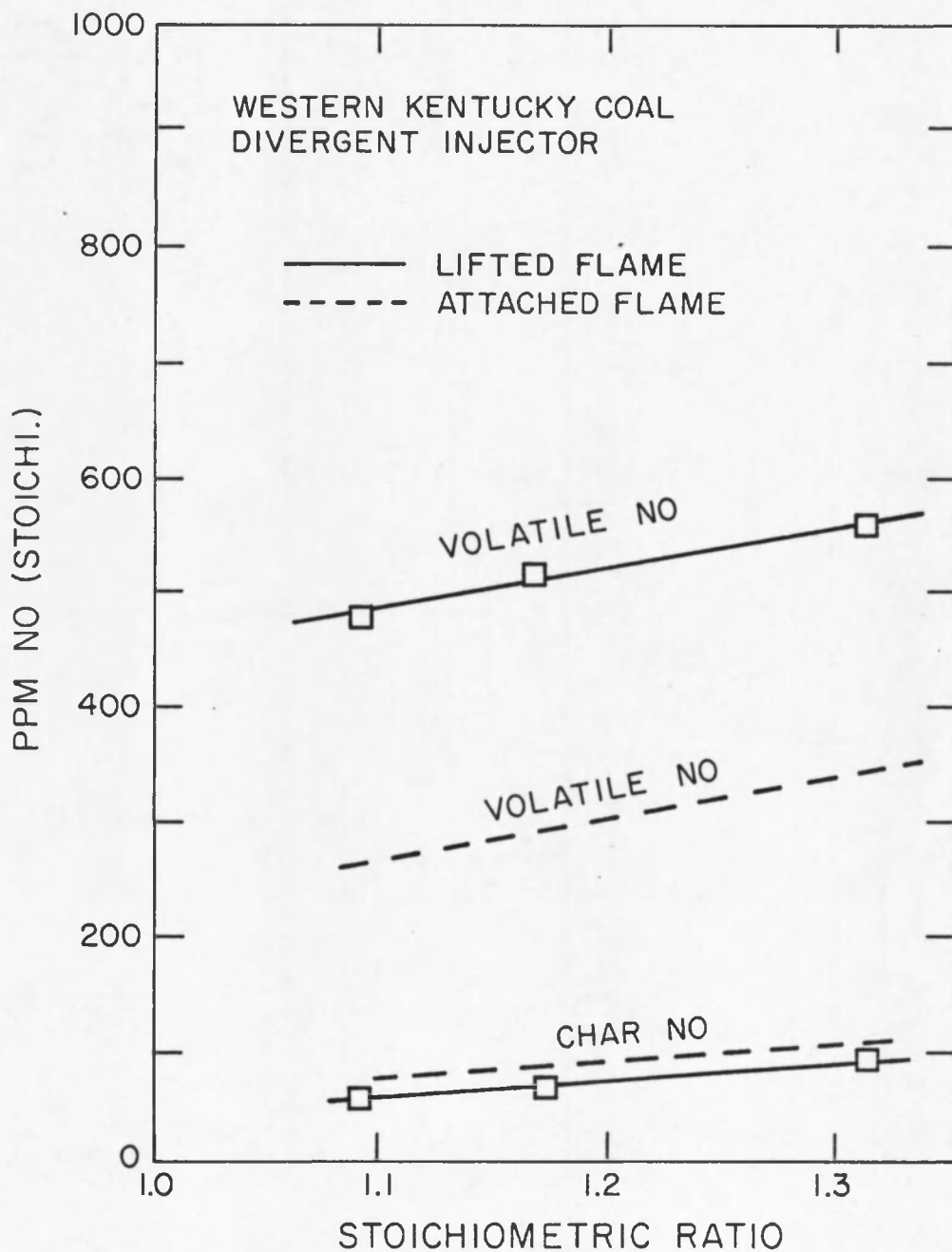
Figure 52. Effect of flame detachment on predicted char and volatile NO. -- Western Kentucky coal, divergent injector, 450°F preheat.
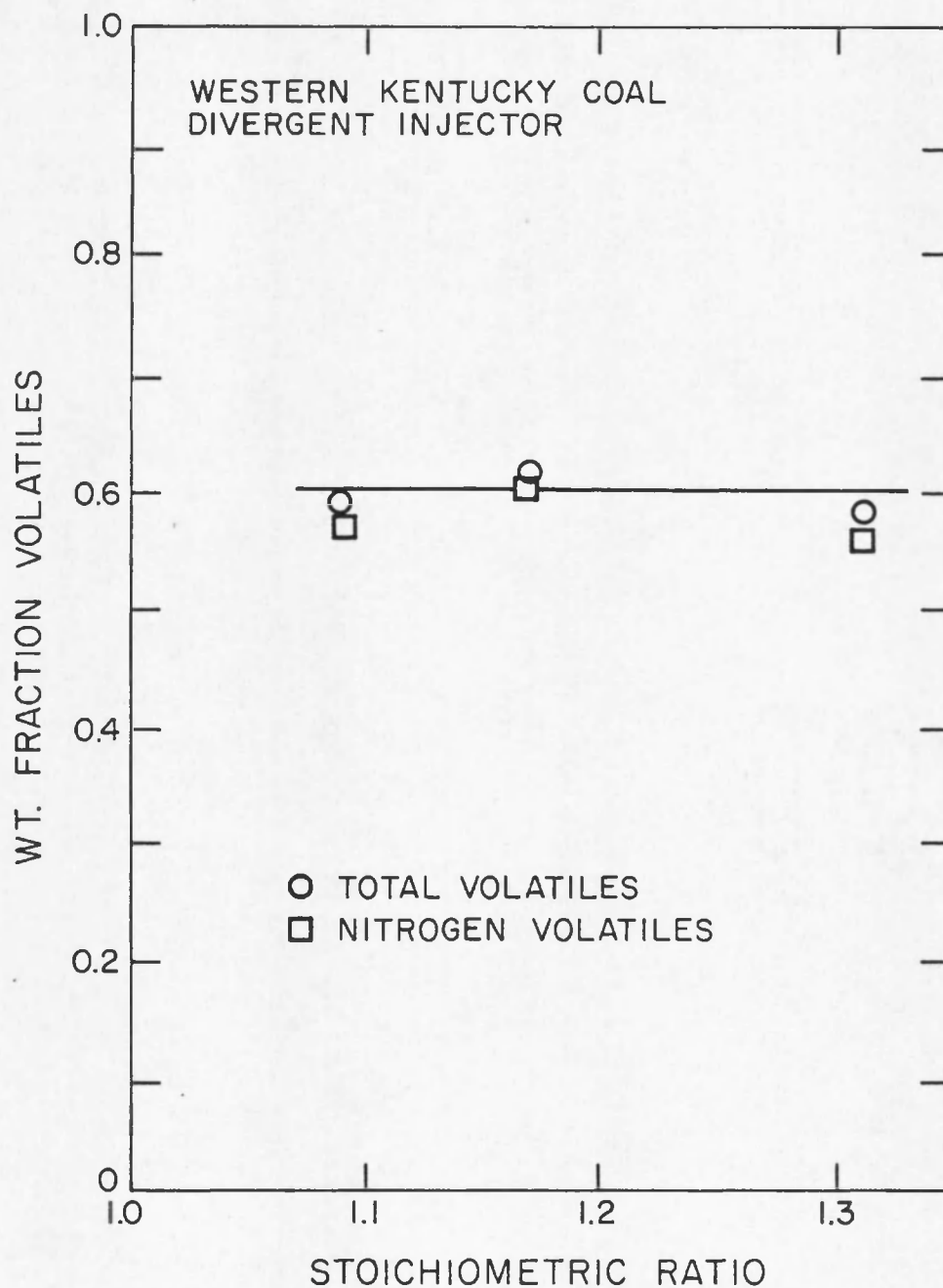
Figure 53. Effect of flame detachment on predicted volatile split. --
Western Kentucky coal, divergent injector, 450°F preheat.

11.5.5 Primary Air

Figures 54 and 55 show the predicted effect of primary air flow with the axial injector, based on an experimental char/volatile test series. As in previous data, primary stoichiometry and mixing had little effect on char NO; however, increased primary air flow dramatically increased volatile NO. This probably results from higher local oxygen concentrations.

Figure 55 indicates that the nitrogen volatiles increase dramatically with flame detachment. It is believed that this is due to a much longer particle heating time prior to ignition which causes a larger volatile nitrogen yield. The fact that the volatile nitrogen yield increases faster than the total volatiles again supports the hypothesis that much of the nitrogen is contained in the heavier volatile fractions which evolve last. Both the char/volatile NO predictions and the total and nitrogen volatile results further demonstrate the strong sensitivity of the volatile NO mechanism to early mixing.

11.6 Summary

The following conclusions were reached based on the char/volatile calculations:

1. At combustion conditions typical of pulverized coal systems, approximately half of both the coal and the fuel nitrogen are evolved as volatiles. The emissions for the Western Kentucky coal at SR = 1.15 are:
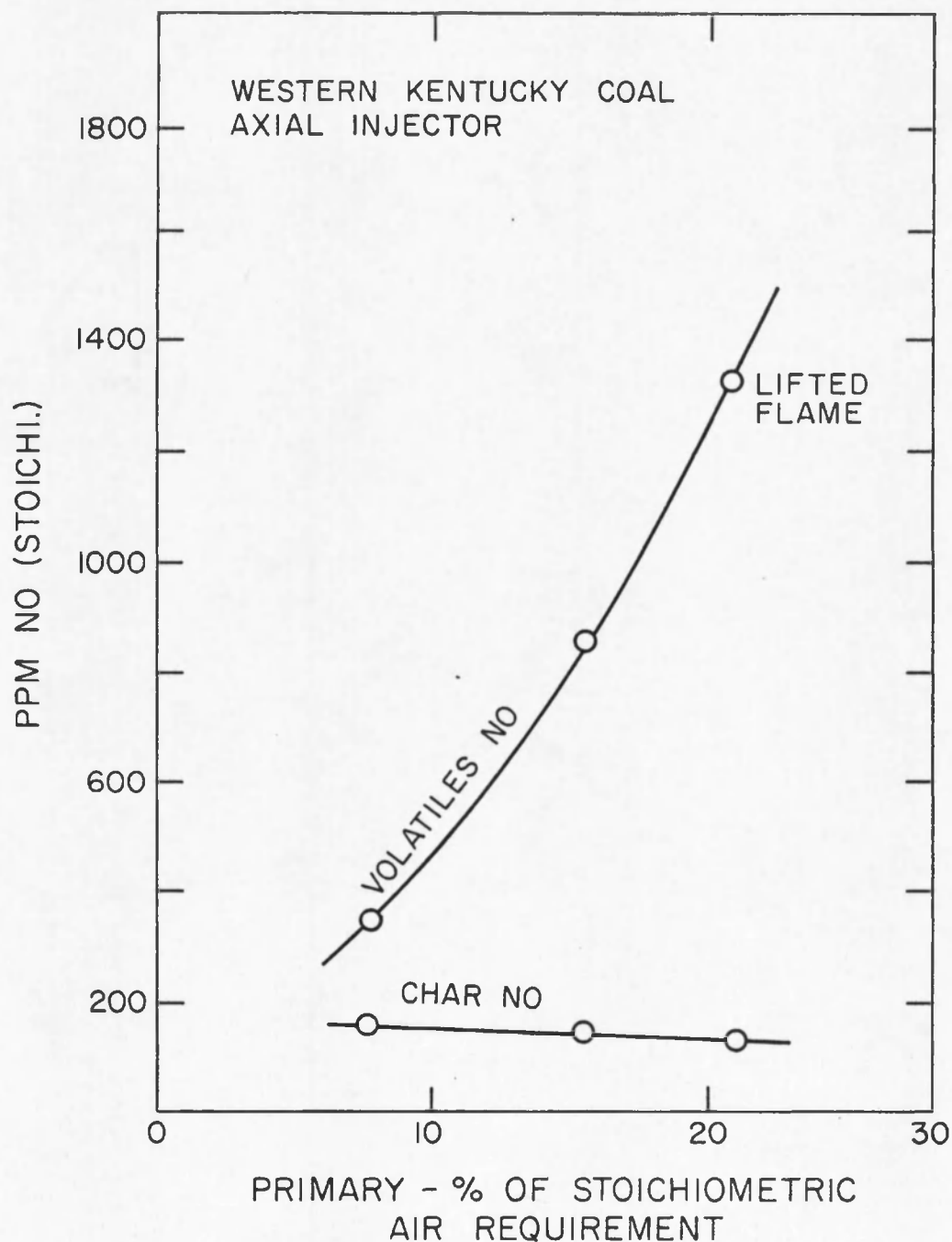
Figure 54. Effect of primary air flow rate on predicted char and volatile NO. -- Western Kentucky coal, axial injector, SR = 1.15, 575°F preheat.
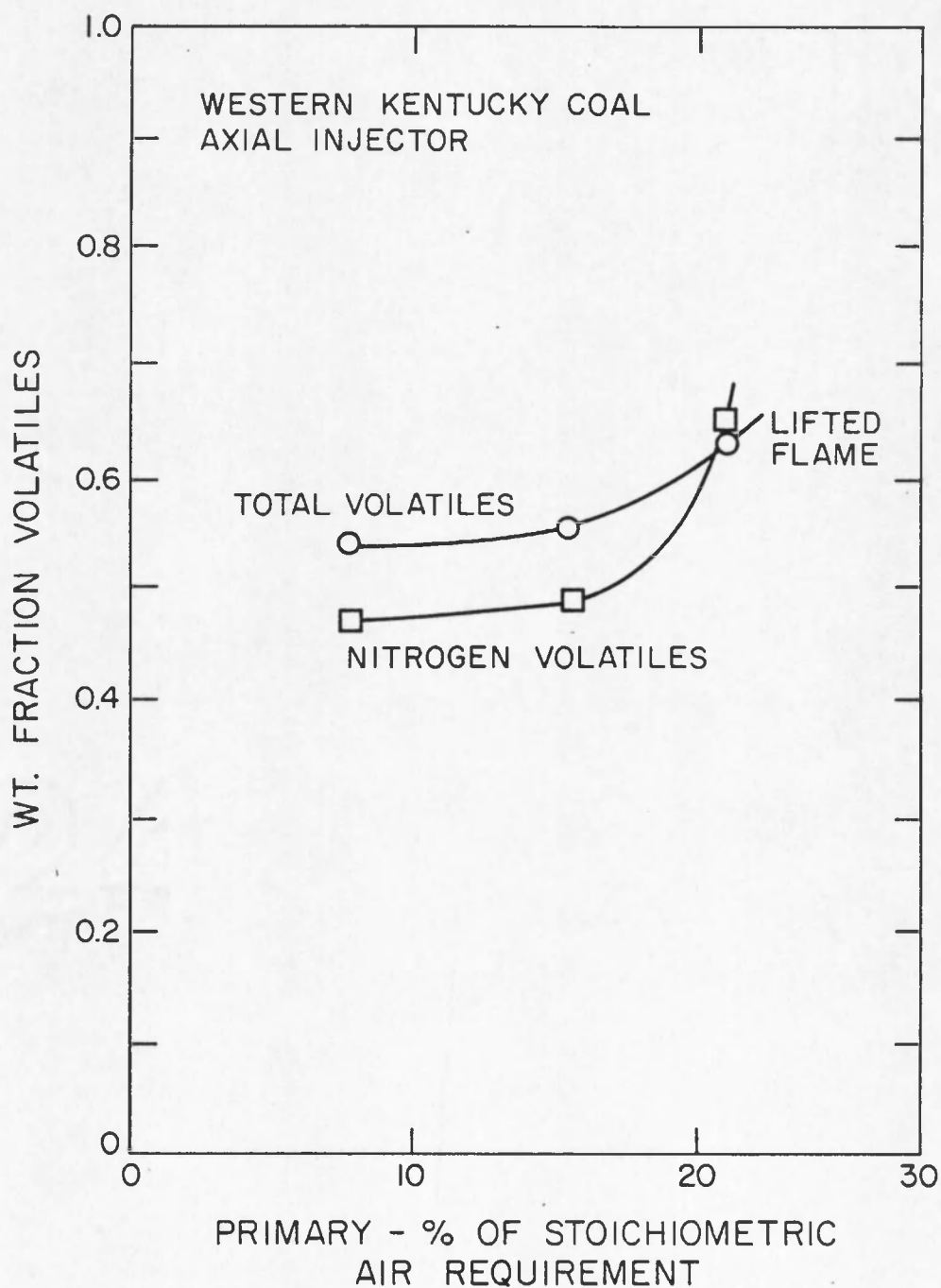
Figure 55.   Effect of primary air flow rate on predicted volatile split.
-- Western Kentucky coal, axial injector, SR = 1.15, 575°F
preheat.

	Rapidly mixed systems (divergent)	Slowly mixed systems (axial)
char NO*	160 ppm	155
volatile NO*	570	295
thermal NO	180	115
total NO emissions	910	565

2. Char and volatile NO emissions are relatively insensitive to changes in inlet oxygen concentration and flame temperature.

3. Volatile NO emissions can be significantly increased by increasing primary air flow, detaching the flame, or increasing the stoichiometric ratio. Slowing the early coal/secondary air mixing decreased volatile NO.

4. Char NO emissions appear to be relatively insensitive to changes in combustion parameters.

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*Based on the semi-empirical analysis.

CHAPTER 12

CONCLUSIONS

It is possible to produce a self-sustaining pulverized coal flame on a laboratory scale (6 lbs/hr of coal) with a refractory furnace. With minor burner modifications both the relatively slow fuel/air mixing characteristics of tangentially fired systems and the rapid mixing of wall-fired systems can be simulated from an NO_x emission point of view. Thus, NO_x formation and coal combustion studies conducted in a well-controlled laboratory system have general applicability to industrial systems.

In pulverized coal combustion, nitrogen oxides result from both the thermal fixation of atmospheric nitrogen and the oxidation of nitrogen chemically bound in the fuel, although the latter is by far the more important source under all normal combustion conditions. Both the volatile and char phases contain a significant fraction of the fuel nitrogen; however, volatile nitrogen conversion to NO far exceeds char nitrogen conversion because the former occurs homogeneously in the presence of considerable oxygen while the latter occurs heterogeneously, within or near the particle. Thus, to attain significant emission reductions, control technology must be directed at controlling fuel NO and in particular volatile NO.

Based on experimental test results from four coals, total and fuel NO emissions increase only slightly as the fuel nitrogen level

increases because the percent conversion of fuel nitrogen decreases. Oxidation of chemically bound nitrogen is the primary NO formation mechanism regardless of composition or coal rank. Nitrogen speciation is not of first-order importance and, hence, the variation in emission performance of field units is not likely the result of fuel composition variations, but rather differences in combustion hardware and operating parameters.

Fuel NO formation is remarkably insensitive to combustion zone temperature over a wide range typical of industrial practice. Increased temperature results in increased volatile nitrogen but this is almost compensated by a decrease in volatile nitrogen conversion. Thus, abatement technology which has been shown to dramatically reduce NO emissions from natural gas-fired systems through reduced local combustion temperatures (e.g., flue gas recirculation, water injection, increased heat removal, etc.) will not be cost-effective for pulverized coal units.

Both total and fuel NO emissions increase with increasing excess air because volatile nitrogen conversion exhibits a strong excess oxygen dependence. In contrast, char NO formation is only a weak function of overall excess air. Fuel NO emissions correlate linearity with overall stoichiometry if a dimensionless emission coefficient is used. Thus, the stoichiometry dependence can be decoupled from the fluid dynamic and fuel composition parameters.

Below a threshhold level, further reduction of primary oxygen has little effect on NO emissions, indicating that early volatiles do not contain significant volatile nitrogen. Increased primary oxygen and/or

early mixing between the fuel and air, particularly as a result of flame detachment, dramatically increase the volatile NO formation and hence the fuel NO. Oxidation of char nitrogen, however, is relatively insensitive to changes in early oxygen concentration or combustion hardware. Thus, the most effective method of controlling NO emissions from pulverized fuel firing is to reduce the initial oxygen availability, either through aerodynamic staging or external two-stage combustion. Volatile NO appears amenable to abatement by combustion modifications but abatement of char NO may be extremely difficult. Thus, unless the char/volatile split can be altered, there may exist a lower limit on the emission level which can be achieved via combustion modifications.

Finally, thermal NO formation in pulverized coal flames behaves similarly to NO formation in gas flames under similar conditions. It increases with increasing excess air and flame temperature, but it is relatively insensitive to fuel composition. Abatement can be accomplished through classical temperature reduction methods; however, since thermal NO is never more than 20 to 30 percent of the total emission level, the maximum reduction in total emissions is correspondingly low.

CHAPTER 13

RECOMMENDATIONS FOR FUTURE WORK

The results of this investigation provide numerous suggestions
for future work, both fundamental and more applied. Three general areas
are particularly worthy of note:

1. Mechanisms of fuel NO formation. This investigation definitively
   established the importance of the fuel NO mechanism and its
   dependence on combustion zone temperature, coal composition and
   rank, and excess oxygen. It also demonstrated the significance
   of char and volatile NO formation, but the mechanistic details
   are still lacking. For example, what are the reactions con-
   trolling volatile NO formation? Can N_2 formation be enhanced?
   What actual flame conditions are required to significantly alter
   the char/volatile split? Can essentially all of the nitrogen be
   driven off with the volatiles?

2. Investigation of two-stage combustion. This work demonstrated
   that the only effective means of controlling fuel and hence total
   NO emissions was by early separation of the fuel from the combus-
   tion air. Definitive work is needed to establish, under care-
   fully controlled conditions, how long the separation must be, how
   rich the stoichiometry should be, and what the optimal tempera-
   ture is. These are of particular interest because the present

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study revealed the existence of a char NO component which appears to not be amenable to control through combustion modifications.

3. <u>Influence of early oxygen</u>. This investigation established that increased early mixing, particularly as the result of flame detachment, resulted in markedly increased fuel and total NO emissions. While the effect is believed to be the result of early oxygen, this was not definitively established. In addition, enrichment of the combustion air with pure oxygen gave results which could not be definitely explained. Thus, these phenomena require further investigation under well-defined fluid dynamic conditions.

APPENDIX A

WALL TEMPERATURE ANALYSIS

A.1 Introduction

The walls of the experimental furnace were designed based on consideration of the following overall criteria:

1. The furnace was to be used to study, among other things, the combustion of coal in preheated, enriched argon/oxygen which has a theoretical flame temperature in excess of 4100°F. The walls, therefore, had to be capable of withstanding inner surface temperatures of approximately 3000°F (based on past experience).

2. The furnace had to be capable of supporting a self-sustaining, pulverized coal flame and, therefore, it was necessary to minimize heat losses to the maximum extent reasonable. 18,000 Btu/hr was established as the upper limit acceptable. (Total heat input was designed to be 50,000 to 60,000 Btu/hr.)

3. The steel shell temperature had to be less than 250°F to preclude the possibility of serious personal injury. Past experience had shown that small furnace modifications were often required during operation and during the course of these alterations it was impossible to avoid accidentally touching the furnace shell.

Due to the complexity of these design requirements, a mathematical model for wall heat transfer was developed and used to evaluate

various wall thicknesses and refractory casting patterns. The following
sections describe the analysis method, the specific equations and assump-
tions, and the actual computer code (KATHY.FOR) which were used. It
should be noted that the model was developed as a design tool, not a
detailed analysis procedure and hence only first-order effects were
considered.

A.2 Derivation of Equations

Preliminary calculations revealed that a composite wall structure
was necessary to achieve the design criteria just described. Thus, the
inner wall was specified as a high temperature, high density, castable
refractory capable of withstanding sustained surface temperatures of
3200°F. This was backed by a low density, medium temperature, insulating
castable refractory with a low thermal conductivity. Finally, a low
temperature asbestos "rollboard" was placed between the insulating
refractory and the steel shell to minimize thermal expansion problems.
The thickness of each layer and the temperature capability of the
insulating castable were defined based on the model results.

Figure A-1 shows a conceptual picture of the composite furnace
wall and defines much of the notation used in the theoretical development
which follows (a complete listing of nomenclature is contained in section
A.4). Since the inside of the furnace had a 12:1 length to diameter
ratio, and was essentially axi-symmetric, the heat transfer was approxi-
mated as being one-dimensional (radial). As indicated in Figure A-1, the
furnace was divided into horizontal slabs of height ΔZ.
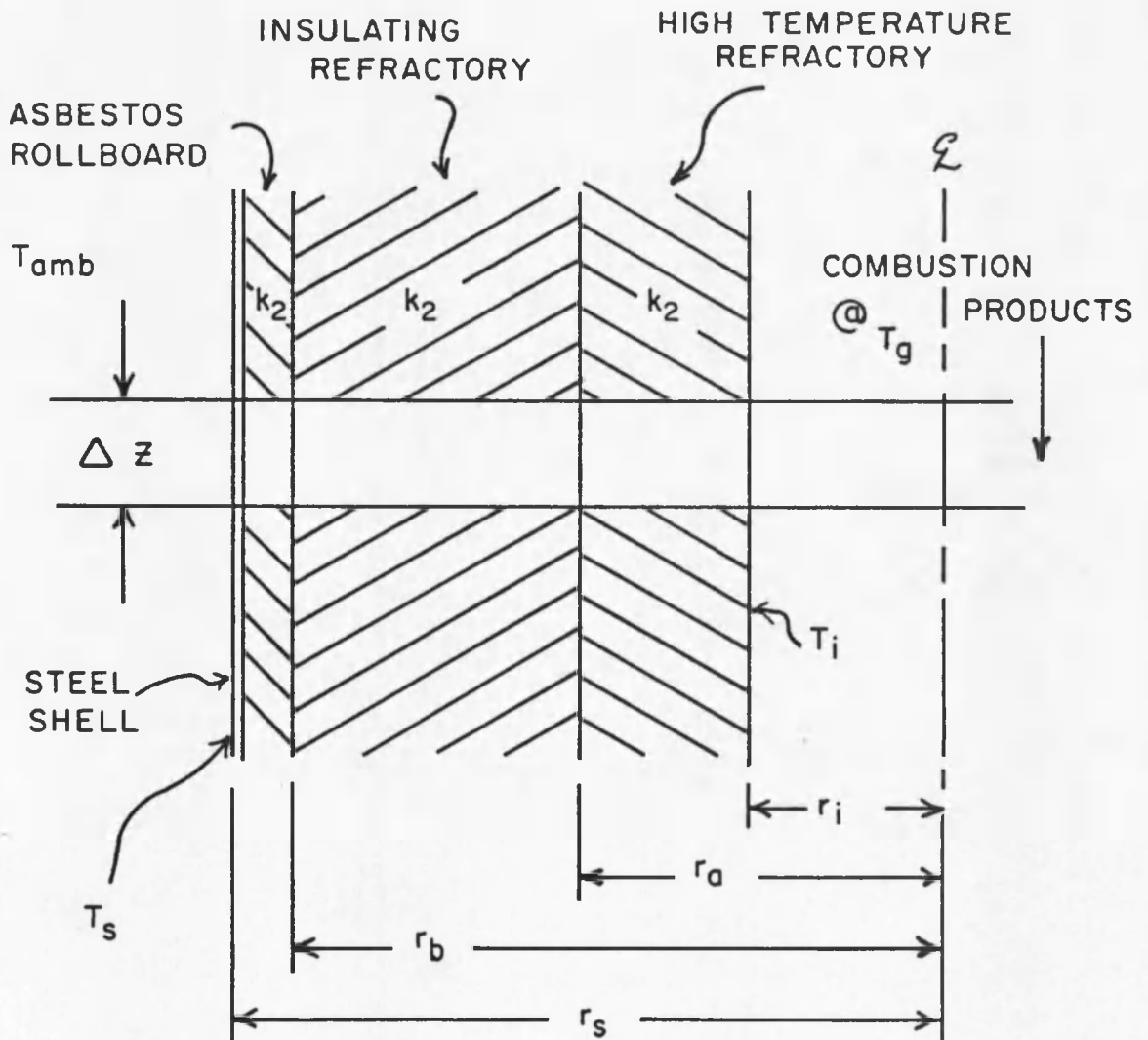
Figure A-1. Conceptual diagram of the composite furnace wall.

At steady state, the heat conduction, Q_j, through the jth composite wall increment with height ΔZ, is given by:

$$Q_j = 2\pi\Delta Z r_i q_i = \frac{2\pi\Delta Z(T_i - T_s)}{\left(\dfrac{\ln r_a/r_i}{k_1} + \dfrac{\ln r_b/r_a}{k_2} + \dfrac{\ln r_s/r_b}{k_3}\right)} \tag{A-1}$$

where Q_j is the total heat being transferred out of the jth furnace zone by conduction through the composite wall and where q_i is the heat flux at the inner surface. The thickness associated with the steel shell was neglected in the model because it added only a negligible heat transfer resistance due to the high thermal conductivity of the steel.

The heat transfer between the jth section of the outer steel wall and the ambient room air consisted of convective and radiative contributions, both of which were significant. The convective portion, Qc, was related to the surface and ambient temperatures (Ts and Tamb) by the equation:

$$Qc = h_s (2\pi r_s \Delta Z)(T_s - T_{amb}) \tag{A-2}$$

The heat transfer coefficient, h_s, was estimated using an empirical correlation suggested by McAdams (1954) for heat transfer by free convection from a long cylinder:

$$Nu = \frac{2 r_s h_s}{k_{au}} \equiv 0.5(GrPr)^{1/4} \tag{A-3}$$

The radiative heat transfer from the jth section of the outer steel shell was calculated using the equation:

$$Qr = \sigma(2\pi r_s \Delta Z) F_{12}(e_s T_s^4 - a_s T_{amb}^4) \tag{A-4}$$

where σ is the Stefan-Boltzmann constant and F_{12} is the view factor (1.0 because the cylinder is essentially completely surrounded by the ambient air). The emissivity, e_s, and the absorptivity, a_s, of the outer steel shell were both taken equal to 0.93 in accordance with the data of Hottel in Bird, Stewart, and Lightfoot (1960).

The total heat transfer from the jth section of the steel shell had to equal the sum of the radiative and convective contributions:

$$Q_j = Qr + Qc \tag{A-5}$$

It also had to equal the rate of heat transfer through the composite wall; hence, the previous equations were combined to give:

$$\frac{2\pi\Delta Z(Ti - Ts)}{(\dfrac{\ln r_a/r_i}{k_1} + \dfrac{\ln r_b/r_a}{k_2} + \dfrac{\ln r_s/r_b}{k_3})} = \{h_s(2\pi r_s\Delta Z)(Ts - Tamb)$$

$$+ \sigma(2\pi r_s\Delta Z)(e_s Ts^4 - a_s Tamb^4)\} \tag{A-6}$$

Note that once a particular casting pattern and set of refractory materials were specified only Ts and Ti were unknown in equation A-6.

Unfortunately, the heat transfer from the flame zone to the inner refractory surface was considerably more complicated due to steep internal temperature gradients, the presence of coal and soot particles, and an unknown flow field. The inner surface heat transfer was, therefore, estimated using an empirical, power-law model:

$$Q_j = h_i(2\pi r_i\Delta Z)(Tg^\alpha - Ti^\alpha) \tag{A-7}$$

where h_i is an empirical heat transfer coefficient determined experimentally and α is the power-law constant. Based on past experience with furnaces of this type, it was known that at the furnace top (zone 1) the

inner surface temperature would be approximately 2800°F for a coal flame with a theoretical flame temperature of 3400°F. These data were used to empirically estimate h_i. In general, the power-law constant, α, was taken to be four on the assumption that radiation from the flame and opposing walls controlled the surface temperature of the refractory. In a limited number of case studies, α was set equal to one to establish the influence of convective heat transfer control.

Finally, the gas temperatures of adjacent zones were related through a simple enthalpy balance:

$$Q_j = wC_p(Tg_j - Tg_{j+1}) \tag{A-8}$$

where w is the mass flow rate of the flue gas and Tg_{j+1} is the flue gas temperature entering the j+1 zone. Direct radiative exchange between the two zones was not explicitly included in this design calculation.

A.3 Solution Procedure

The equations just described were solved using a single pass, forward marching procedure to calculate the five unknown temperatures (Tg, Ti, Ta, Tb, and Ts) and the heat loss, Q_j, for each zone. Combustion was assumed to occur instantaneously in the first zone and, hence, the flue gas temperature in zone 1 was taken to be the theoretical flame temperature (which was input). The wall temperature in zone 1 was also input along with the power law constant, α.

The calculation procedure for the first zone was slightly different than for the subsequent zones because the refractory surface temperature was known (based on past experimental measurements). First, equation A-6 was solved for Ts, the outer steel shell temperature in

zone 1, using the specified inner wall temperature and the input dimensions and thermal conductivities. Since the equation could not easily be explicitly solved for Ts, it was solved numerically using the reducing interval method. Next, equation A-1 was used to calculate the heat transfer from zone 1 through the composite wall. The flue gas temperature entering zone 2 was then calculated using the enthalpy equation, A-8. Finally, the inside heat transfer coefficient, h_i, was estimated by applying equation A-7 to zone 1 where h_i was then the only unknown. This value of the inside heat transfer coefficient was then used for all the subsequent zones.

The solution procedure for zones 2 to N was as follows. The inlet flue gas temperature in the jth zone, Tg_j, was known from the enthalpy balance on the previous zone. Equations A-1, A-2, A-4, A-5, and A-7 were combined algebraically to give:

$$\{ \frac{h_s r_s}{h_i r_i} (Ts - Tamb) + \frac{\sigma r_s}{h_i r_i} (e_s Ts^4 - a_s Tamb^4) \} + \{ h_s r_s AR(Ts - Tamb)$$

$$+ \sigma r_s AR(e_s Ts^4 - a_s Tamb^4) + Ts \}^{\alpha} = Tg^{\alpha} \qquad (A-9)$$

where

$$AR = \frac{\ln r_a/r_i}{k_1} + \frac{\ln r_b/r_a}{k_2} + \frac{\ln r_s/r_b}{k_3}$$

and where both the heat flow, Q_j, and the inner surface temperature, Ti, have been eliminated. Equation A-9 was solved for the only unknown, Ts, the steel shell temperature in the jth zone; solution was again by the reducing interval method. Once Ts was known, equations A-2, A-4, and A-5 were solved for Q_j and equation A-1 was solved for Ti. Finally, equation

A-8 was solved for the temperature in the j+1 zone and the entire process repeated.

At the conclusion of the entire calculation procedure, the total heat loss and average steel shell temperature were calculated.

A.4   Nomenclature

Table A-1 describes the principal nomenclature used both in developing the equations and in the actual computer code. Unless otherwise noted, the internal program dimensions are as follows:

$$length = feet$$

$$temperature = degrees\ Rankine$$

$$time = hours$$

$$energy = Btus$$

A.5   KATHY.FOR Computer Code

The following pages contain a complete listing of the Fortran computer program KATHY.FOR which was used to solve the wall temperature equations. It was written in an interactive format and was run on a DEC-10 timesharing system. The user specifies:

1. The inside furnace diameter, the thickness of both refractory layers, and the asbestos thickness, all in inches.

2. The theoretical flame temperature, the ambient air temperature, and the inner refractory temperature (zone 1), in degrees F.

3. The flue gas power law constant.

The program then calculates and prints out:

1. The entire temperature field in degrees F.

2. The heat loss for each zone in Btu/hr.

Table A-1. Notation for wall temperature analysis.

Algebraic Representation	Computer Code	Definition
e	E	emissivity of steel shell = 0.93
Gr	GR	Grashof number for free convection
h_i	HI	empirical heat transfer coefficient for inner surface
h_s	H	convective heat transfer coefficient
k_{air}	KA	thermal conductivity of ambient air
k_1	K1	thermal conductivity of high temperature refractory
k_2	K2	thermal conductivity of insulating refractory
k_3	K3	thermal conductivity of asbestos rollboard
Nu	NU	Nusselt number for heat transfer
Pr	PR	Prandtl number
Q_j	Q(J)	rate of heat transfer through jth section of composite wall
Qc	QC	rate of convective heat transfer from steel shell
--	QCONR	Qc + Qr
Qr	QR	rate of radiative heat transfer from steel shell
q_i	--	heat transfer flux at inner surface

Table A-1--Continued.

Algebraic Representation	Computer Code	Definition
r_a	RA	radius to outside of high temperature refractory
r_b	RB	radius to outside of insulating refractory
r_i	RI	inner radius of furnace (.25 ft)
r_s	RS	outer radius of furnace shell
T	T	kth estimate of the steel shell temperature in jth zone
ΔT	DELT	temperature step size
Ta	TA(J)	temperature of outside of high temperature refractory
Tamb	TAMB	temperature of ambient air around furnace
Tb	TB(J)	temperature at outside of insulating refractory.
Tg	TG(J)	flue gas temperature in jth zone
Ti	TI(J)	temperature of inner refractory surface in jth zone
Ts	TS(J)	steel shell temperature in jth zone
Z	Z(J)	distance from furnace top of jth zone
ΔZ	DELL	height of differential element
α	NP	power-law constant = 4 for radiative control
σ	SIGMA	Stefan-Boltzmann constant

```
C
C
C
      DIMENSION TG(10),TI(10),TA(10),TB(10),
    X TS(10),Q(10),Z(10)
      REAL K1,K2,K3
C
C
C
C     THIS PROGRAM CALCULATES THE HEAT LOSS AND REFRACTORY
C     TEMPERATURE DISTRIBUTION FOR A CYLINDRICAL COMBUSTOR
C
C
C     DATA INPUT
C
C
100   CONTINUE
      TYPE 110
110   FORMAT (//,' ENTER IN DIA, REF 1 TH,  REF 2, ASBESTOS
    X TH IN IN. ')
      ACCEPT 112, XID,R1T,R2T,R3T
112   FORMAT (4F)
      IF ( XID .EQ. 0.0) GO TO 999
      RI = XID/2./12.
      RA = RI + R1T/12.
      RB = RA + R2T/12.
      RS = RB + R3T/12.
      TYPE 120
120   FORMAT (' ENTER TADB,TAMB,TSUR,DUM IN DEG F')
      ACCEPT 112, TADB,TAMB,TI(1),DUM
      TG(1) = TADB + 460.
```

```
              TAMB = TAMB + 460.
              TI(1) = TI(1) + 460.
              TYPE 130
130           FORMAT (' ENTER FLUE GAS COOL LAW POWER-REAL NO')
              ACCEPT 132,XNP
132           FORMAT (1F)
              NP = IFIX(XNP)
C
C
C             BEGINNING OF CALCULATIONS FOR ZONE 1
C             TEMPERATURES ARE IN DEG R, LENGTHS IN FT,
C              TIME IN HOURS, AND ENERGY IN BTUS
C
C
200           CONTINUE
              NPT = 10
              D = RS*2.
              K1 = 16.0/12.
              K2 = 3.0/12.
              K3 = 0.4
              E = 0.93
              SIGMA = 0.1712E-08
              PI = 3.1416
              ARA = RA/RI
              ARB = RB/RA
              ARC = RS/RB
              AR = ALOG(ARA)/K1+ALOG(ARB)/K2+ALOG(ARC)/K3
              T = TAMB + 5.0
```

```
              DELT =  100.0
C
C             ITERATIVE CALCULATION OF STEEL SHELL TEMP
C
250           CONTINUE
              CALL HCOEF(T,TAMB,  D,H)
C             H IS THE HEAT  TRANSFER COEFFICIENT FOR
C             FREE CONVECTION COOLING OF THE STEEL SHELL
260           CONTINUE
C             CAUTION, THESE Q'S ARE PER UNIT LENGTH (DELL=1)
              QR = PI*D*SIGMA*E*(T**4-TAMB**4)
              QC = H*PI*D*(T-TAMB)
C             QR IS THE RADIATIVE HEAT LOSS
C             QC IS THE CONVECTIVE HEAT LOSS
              QCONR = QR + QC
              QK = 2.0*PI*(TI(1) -T)/AR
              IF ( QK .LT. QCONR) GO TO 290
              T = T + DELT
              GO TO 250
290           CONTINUE
              T = T - DELT
              DELT = DELT / 10.
              IF ( DELT .GT. 5.0) GO TO 260
C             TS(1) IS THE STEEL SHELL TEMP
C             IN ZONE 1
300           CONTINUE
C
C             SETTING UP THE NON UNIFORM LENGTH GRID
C
              DO 310 I=1,NPT
              Z(I) =72./12.*FLOAT(I)  **2/FLOAT(NPT)**2
310           CONTINUE
```

```
          DELL = Z(1) -0.0
          Q(1) = 2.0*PI*DELL*(TI(1)-TS(1))/AR
C         Q(1) IS THE HEAT LOSS FROM ZONE 1 IN BTU PER HR
          TG(2) = TG(1) - Q(1)/54.4/0.3
          ROQO = Q(1)/2.0/PI/DELL
          TA(1) = TI(1) -ROQO*ALOG(ARA)/K1
          TB(1) = TA(1) - ROQO*ALOG(ARB)/K2
          TYPE 320
320       FORMAT (//,'Z',5X,'TG',6X,'TI',4X,'TA',6X,'TB',
     X    6X,'TS',8X,'Q',//)
          HI = Q(1)/(PI*D*DELL)/(TG(1)**NP-TI(1)**NP)
          QS = Q(1)
          TSS = TS(1)*DELL
C
C
C
C         BEGINNING OF CALCULATION FOR ZONES 2
C         TO NPT
C
C
          XQ1 = 0.0
          XQ2 = 0.0
400       CONTINUE



          NX = NPT + 1
          DO 499 I = 2,NX
          J = I -1
          VZ = Z(J)*12
          VTG = TG(J) -460
          VTI = TI(J) - 460.
          VTA = TA (J) -460.
```

```
        VTB = TB (J)  -  460.
        VTS = TS (J)  -  460.
        VQ = Q (J)
        TYPE 410,VZ,VTG,VTI,VTA,VTB,VTS,VQ
410     FORMAT(F5.1,5F7.0,F10.0)
        IF ( I .EQ. NX) GO TO 499
        DELL = Z (I) -Z (J)
        T = TAMB + 5.0
        DELT = 100.
C       ITERATIVE CALCULATION OF STEEL SHELL TEMP
420     CONTINUE
        CALL HCOEF(T, TAMB, D,H)
430     CONTINUE
        XXL = PI*D*DELL
        QR = XXL*SIGMA*E*(T**4-TAMB**4)
        QC = XXL*H*(T-TAMB)
        QCONR = QR + QC
        F = QCONR
        CA = HI*XXL
        CB = 2.0*PI*DELL/AR
        RNP = 1.0/FLOAT (NP)
        XTG = (F/CA +(F/CB+T)**NP)**RNP
        IF ( I .NE. 8) GO TO 460
        IF ( DUM .EQ. 1.0) GO TO 600
460     CONTINUE
        IF( XTG .GT. TG (I) ) GO TO 470
        T = T + DELT
        GO TO 420
```

```
470       CONTINUE
          T = T - DELT
          DELT = DELT/10.
          IF ( DELT .GT. 0.5) GO TO 430
          TS(I) = T
          Q(I) = QCONR
          TI(I) = TS(I) + Q(I)*AR/(2.0*PI*DELL)
          TA(I) = TI(I) - ROQO*ALOG(ARA)/K1
          TB(I) = TA(I) - ROQO*ALOG(ARB)/K2
          K = I + 1
          TG(K) = TG(I) -Q(I)/54.4/0.3
          QS = QS + Q(I)
          TSS = TSS + TS(I)*DELL
          XQ1 = CA*(TG(I)**NP-TI(I)**NP)
          XQ2 = CB*(TG(I)-TS(I))
499       CONTINUE
          TSA = TSS*12./72. - 460.
          TYPE 520, QS
520       FORMAT(/,' THE TOTAL HEAT LOSS IS',F8.0,'BTU/HR')
          TYPE 530, TSA




530       FORMAT(/,' THE AVE SHELL TEMP IS', F6.1,' DEG F')
          GO TO 100
600       CONTINUE
          TYPE 610,D,HI,H,QR,QC,CA,AR,CB,DELL,T,XTG
610       FORMAT  (/, 5E11.4,/,4E11.4,/2E11.4)
          GO TO 460
999       CONTINUE
          STOP
          END
```

```fortran
      SUBROUTINE HCOEF( T , TA, D,H)
      REAL MU,KA,NU
C     THIS SUBROUTINE CALCULATES THE HEAT TRANSFER
C     COEFFICIENT FOR A VERTICAL CYLINDER
C     DUE TO FREE CONVECTIVE COOLING
C
      MU = 0.046
      CP = 0.241
      G = 4.17E08
      KA = 0.0152
      TF = (T +TA)/2.0
      DT = T - TA
      RHO = 0.0808*492./TF
      B = 1.0/TF
      GR = D*D*D*RHO*RHO*G*B*DT/MU/MU
      PR = CP*MU/KA
      NU = 0.5*(GR*PR)**0.25
      H = NU*KA/D
C     H HAS UNITS OF BTU/(HT-SQ FT-DEG R)
      RETURN
      END
```

3. The total heat loss through the refractory walls in Btu/hr.

4. The average steel shell temperature in degrees F.

No instability or convergence problems were encountered with the program, even with a highly non-uniform grid. This was probably a result of the essential simplicity of the calculations and the excellent stability of the numerical method.

A.6 Discussion of Results

Figure A-2 shows a set of typical temperature profile results. This represents a normal bituminous coal/air flame combusting in the 6" x 72" furnace with composite walls containing 4" of Harbison-Walker Castolast G 3200°F castable refractory, 7" of Harbison-Walker Lightweight 26 insulating castable refractory and 1" of asbestos rollboard. The data indicate that for this case both refractories are operating well below their maximum temperature capabilities, but the average steel shell temperature (246°F) and total heat loss (18,800 Btu/hr) are only marginally acceptable.

Figure A-3 shows the effect of increasing the thickness of the insulating refractory and indicates that beyond approximately 8" a substantial increase in refractory thickness is required to achieve any significant reduction in either total heat loss or steel shell temperature. Therefore, 8" was established as an upper limit on the insulating refractory thickness.

Figure A-4 indicates that the high temperature refractory thickness has little effect on either heat loss or shell temperature. Tripling
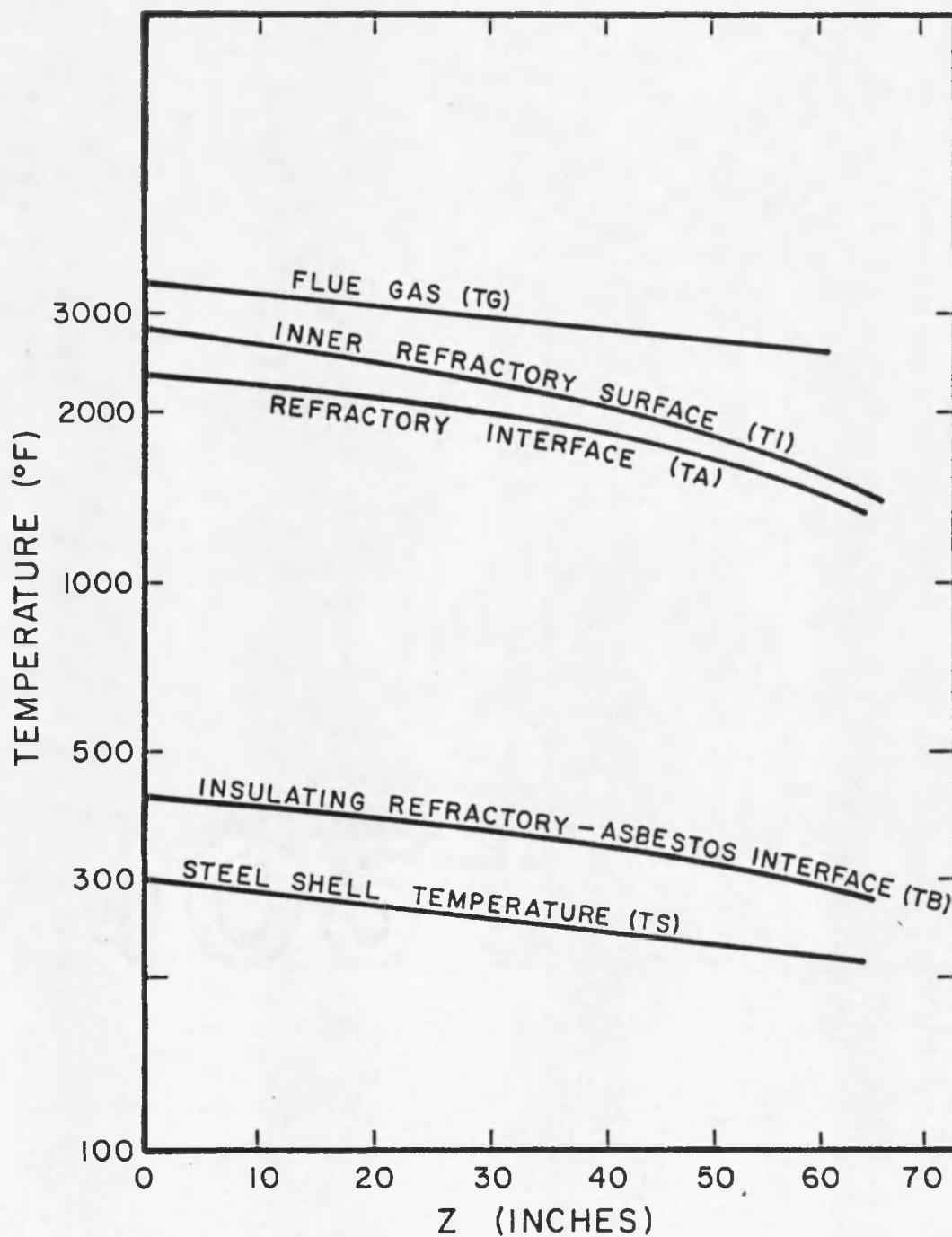
Figure A-2.   Temperature profiles. -- 4" Castolast G, 7" LWC-26,
              1" asbestos; radiation control.
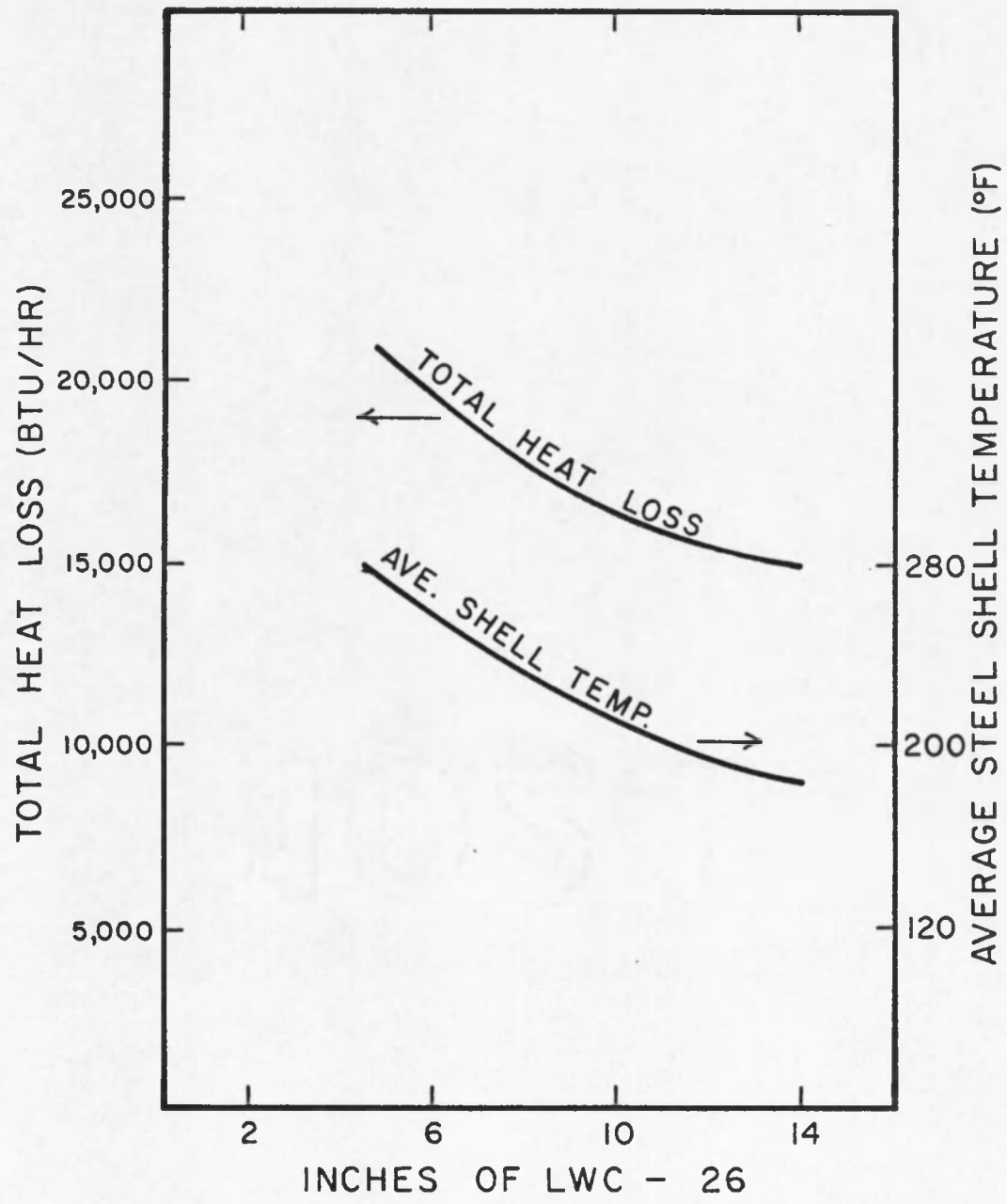
Figure A-3. Influence of insulating refractory thickness. -- 4"
Castolast G, 1" asbestos; radiation control.
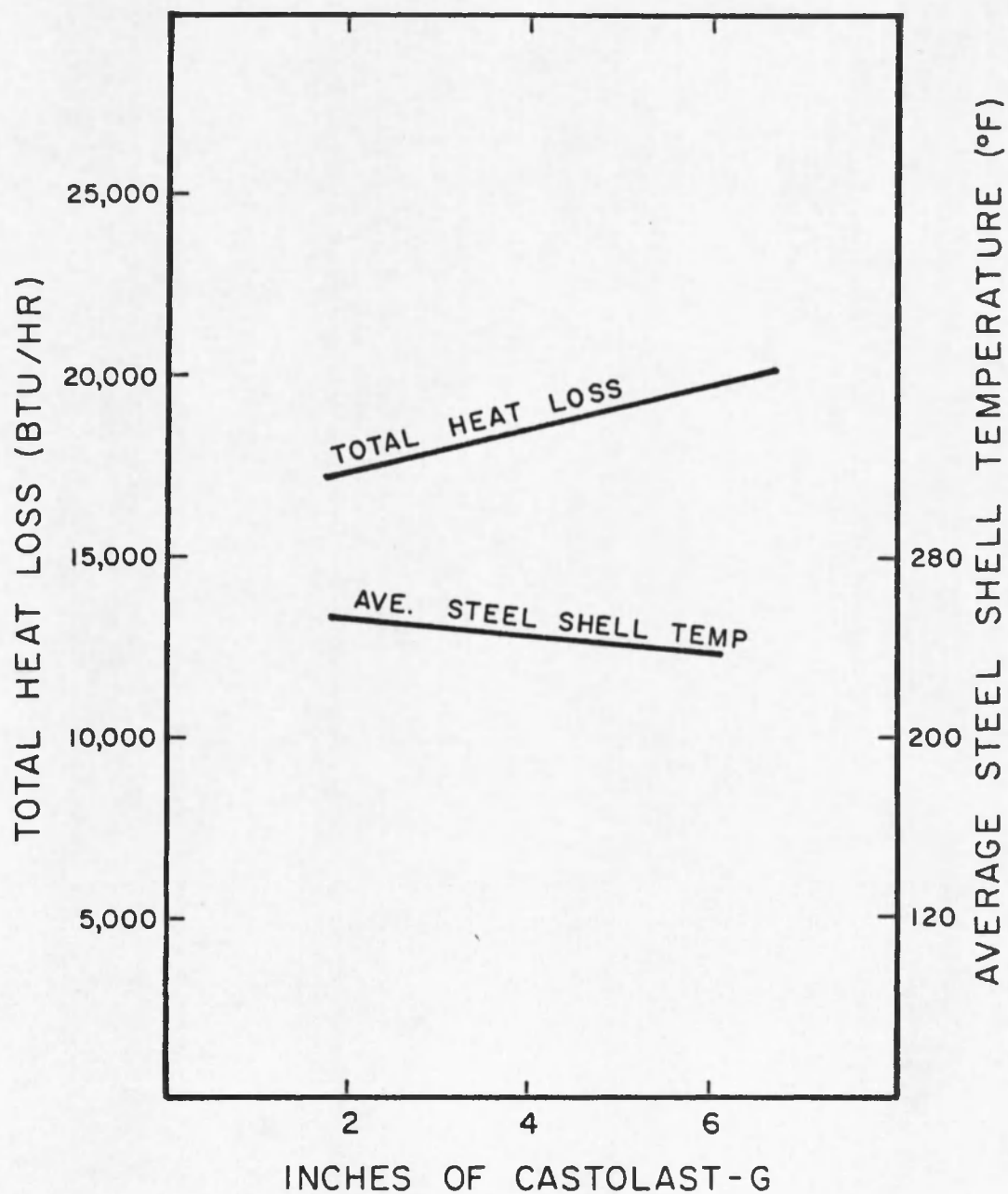
Figure A-4. Influence of high temperature refractory thickness. --
7" LWC-26, 1" asbestos; radiation control.

the thickness from 2" to 6" only reduces the average steel shell tempera-
ture 13 degrees F. Closer examination of the analysis, however, reveals
that if only 2" of high temperature refractory are used then the upper
portion of the insulating refractory is operating at 2550°F. Since the
service limit of this material is 2600°F, the condition was judged
unacceptable, and 4" of high temperature specified for the upper half of
the furnace.

The influence of the inside power-law constant, α, was also
studied and as the data below indicate it has little practical effect on
the design considerations. (However, this does not in any sense imply
that it is insignificant in a scientific analysis of the heat transfer in
a furnace.)

Power Law	Average Shell Temperature (°F)	Total Heat Loss (Btu/hr)
$\alpha = 4$ (radiation control)	246	18,800
$\alpha = 1$ (convection control)	265	21,400

In summary, the computer analysis indicated that the upper half
of the furnace should contain 4" of the high temperature refractory while
the lower half only needed 2". The thickness of the insulating refrac-
tory was defined to be 6" and 8", respectively, to balance the high
temperature refractory.

APPENDIX B

CALIBRATION DATA

B.1 Analyzers

The continuous, flue gas analyzers were zeroed and spanned at least every three hours. The zero gas was nitrogen supplied by a local vendor. The calibration gases were from Matheson Gas Products with the following specifications:

638 ppm NO in N_2, certified standard

1.82% CO in N_2, certified standard

12.42% CO_2 in N_2, certified standard

4.32% O_2 in N_2, certified standard

2413 ppm SO_2 in N_2, certified standard

The same NO calibration gas was used throughout the testing.

B.2 Screw Feeder

Figures B-1 through B-4 show the coal feeder calibration data for the Colorado, Western Kentucky, and Montana coals and the FMC coal char, respectively. These data were obtained by disconnecting the primary air lines and weighing the amount of coal delivered by the screw feeder in a specified period of time (usually 2 minutes). In general, the feeder gave a linear response which was reproducible to within ± 1.4 percent as shown in Figure B-4.
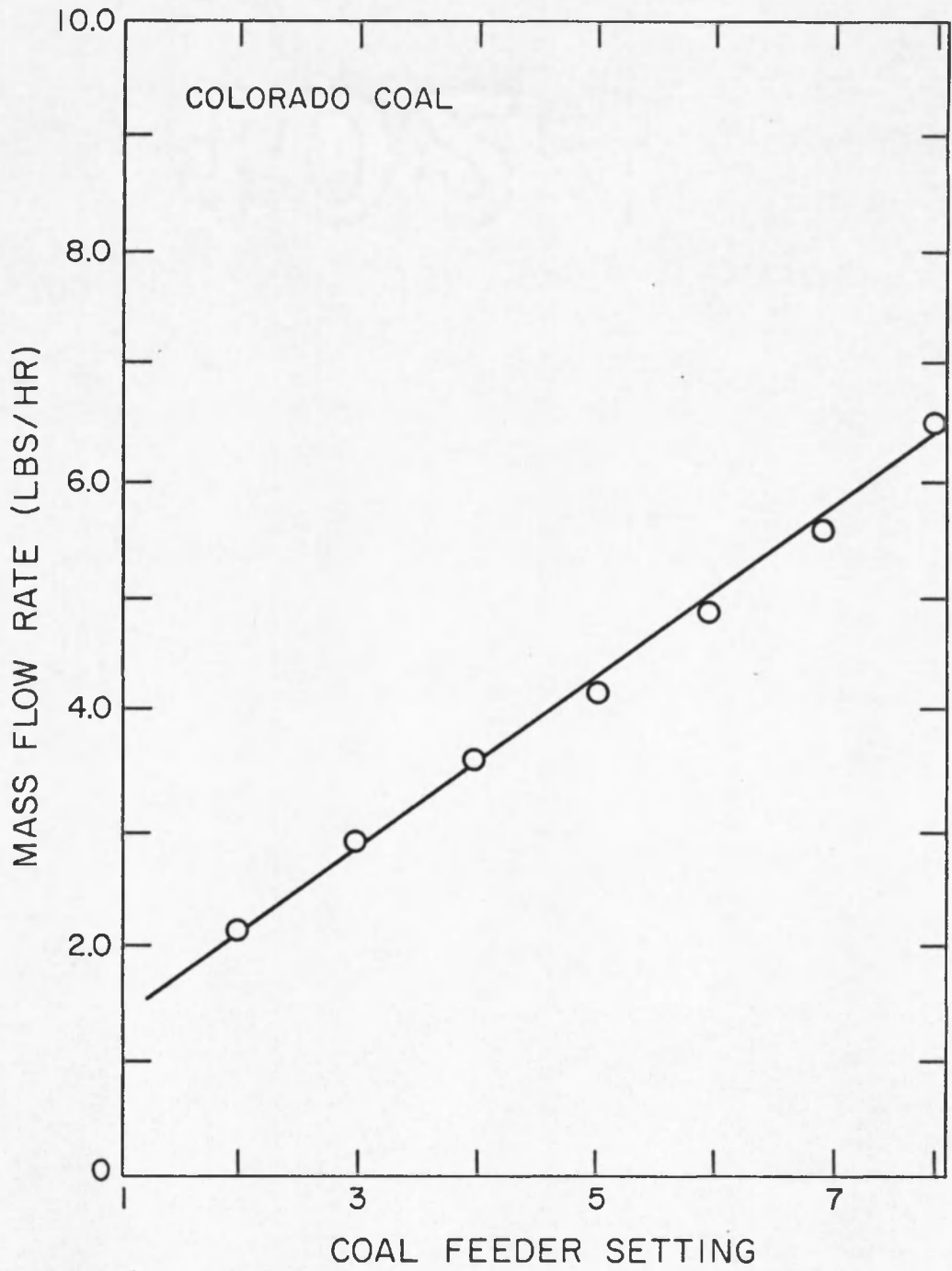
Figure B-1.   Feeder calibration, Colorado coal.
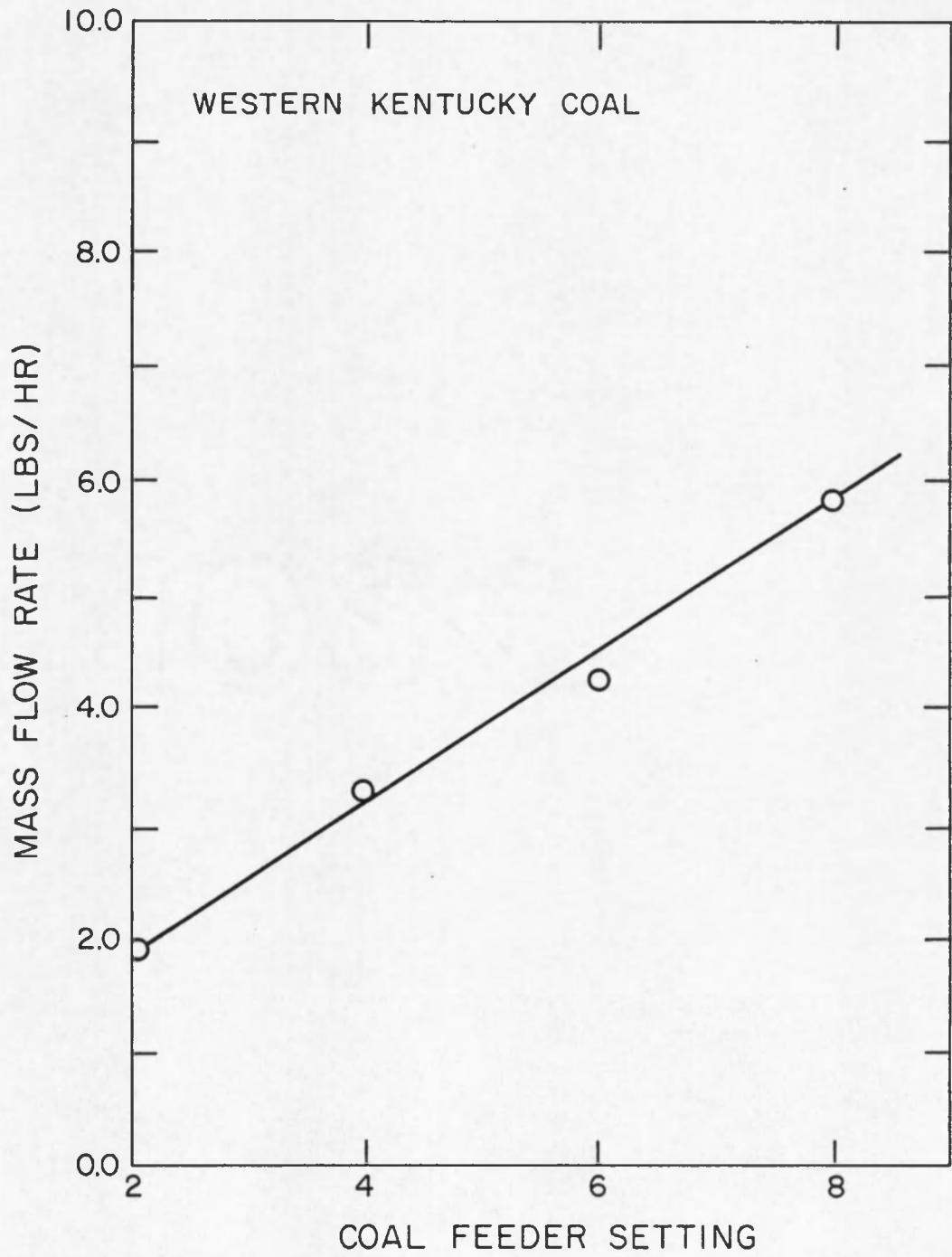
Figure B-2.   Feeder calibration, Western Kentucky coal.
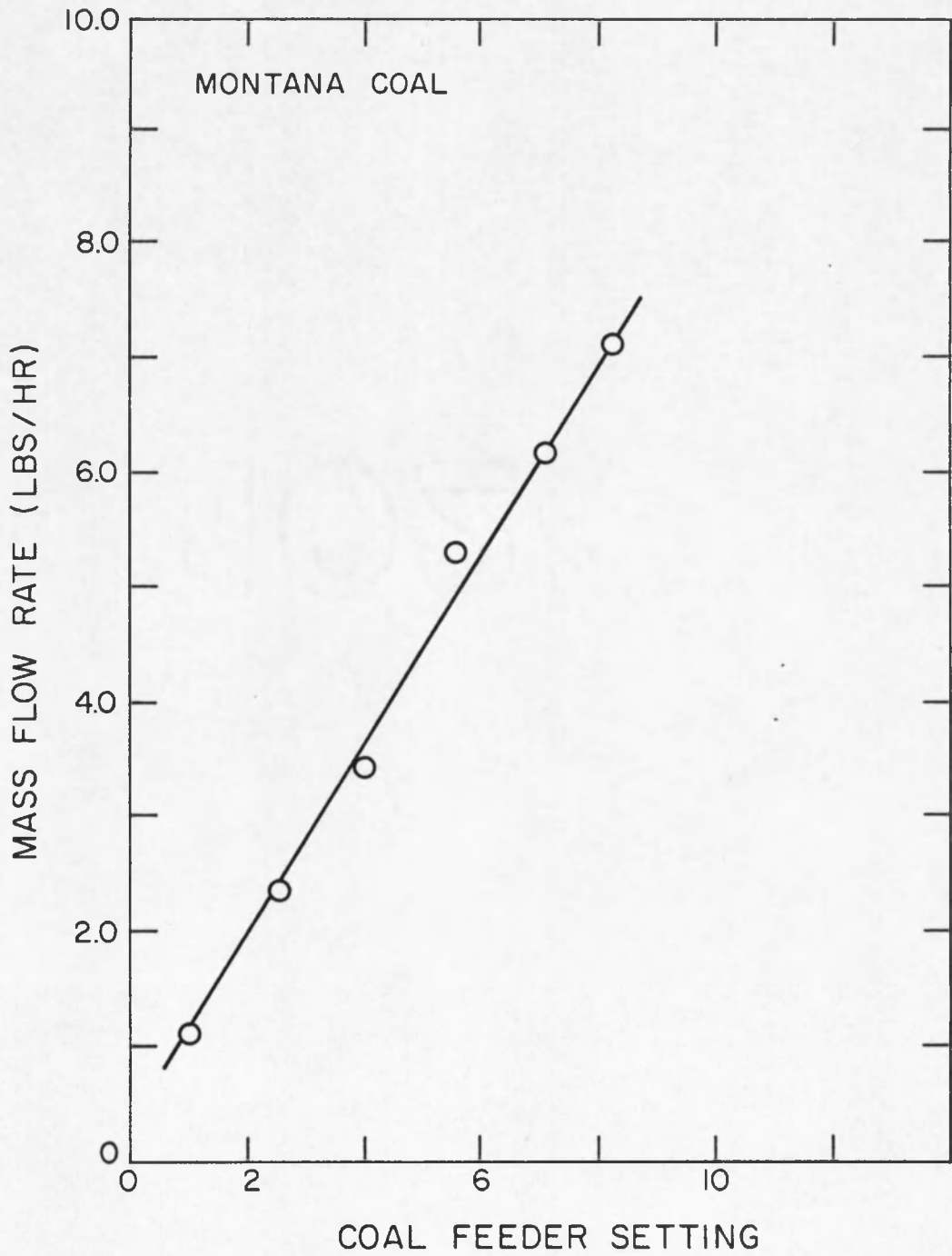
Figure B-3. Feeder calibration, Montana coal.
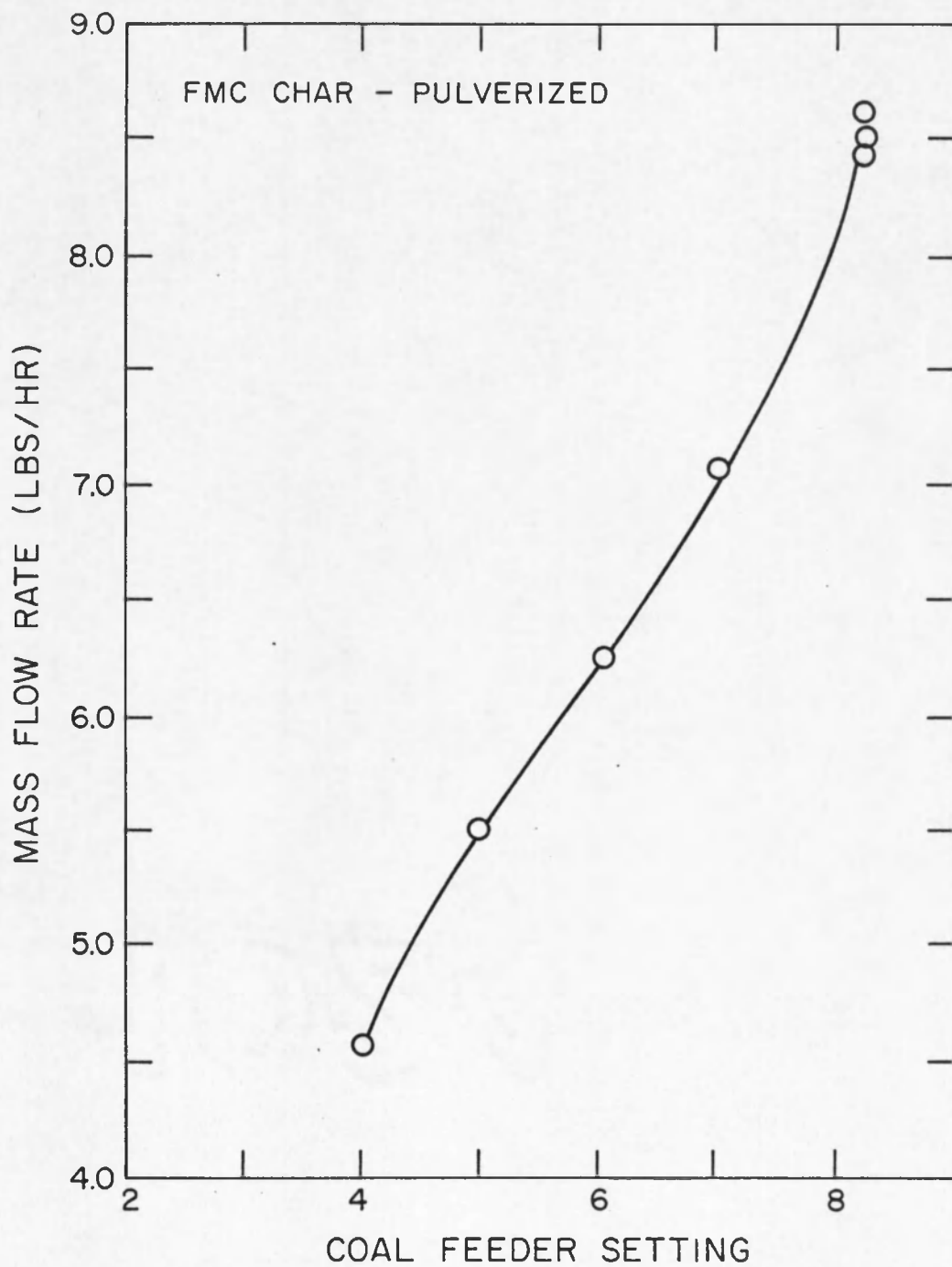
Figure B-4. Feeder calibration, FMC char.

Initially, there was concern that the flow of the primary air past the end of the screw might alter the calibration of the coal feeder under actual operating conditions; however, no evidence of this was observed. Three independent measures of the inlet air flow rate were made at each test condition. Below are the results for a typical baseline test point with the Colorado coal (1-11/05-4):

Method of calculation	ft^3 of inlet air
Coal flow + O_2 flue analysis	14.54
Metered air flow-laminar flow element	15.79
Coal flow + CO_2 flue analysis	14.78

This agreement ($\pm$ 5%) is well within the accuracy of the measurements and confirms the overall system calibrations.

B.3   Volatile Additive Rotameter

The NH_3 and NO which were added to the primary air as "typical" volatile compounds (Chapter 11) were metered with a 150 mm Brooks rotameter. Figures B-5 and B-6 show the calibration data obtained with this rotameter for each gas. These data were obtained by passing the test gas through the rotameter to the bottom of a burette which contained a small amount of soap solution. The gas produced bubbles whose rise time was measured. Each data point was the average of at least three separate tests; the reproducibility was approximately $\pm$ 6 percent.
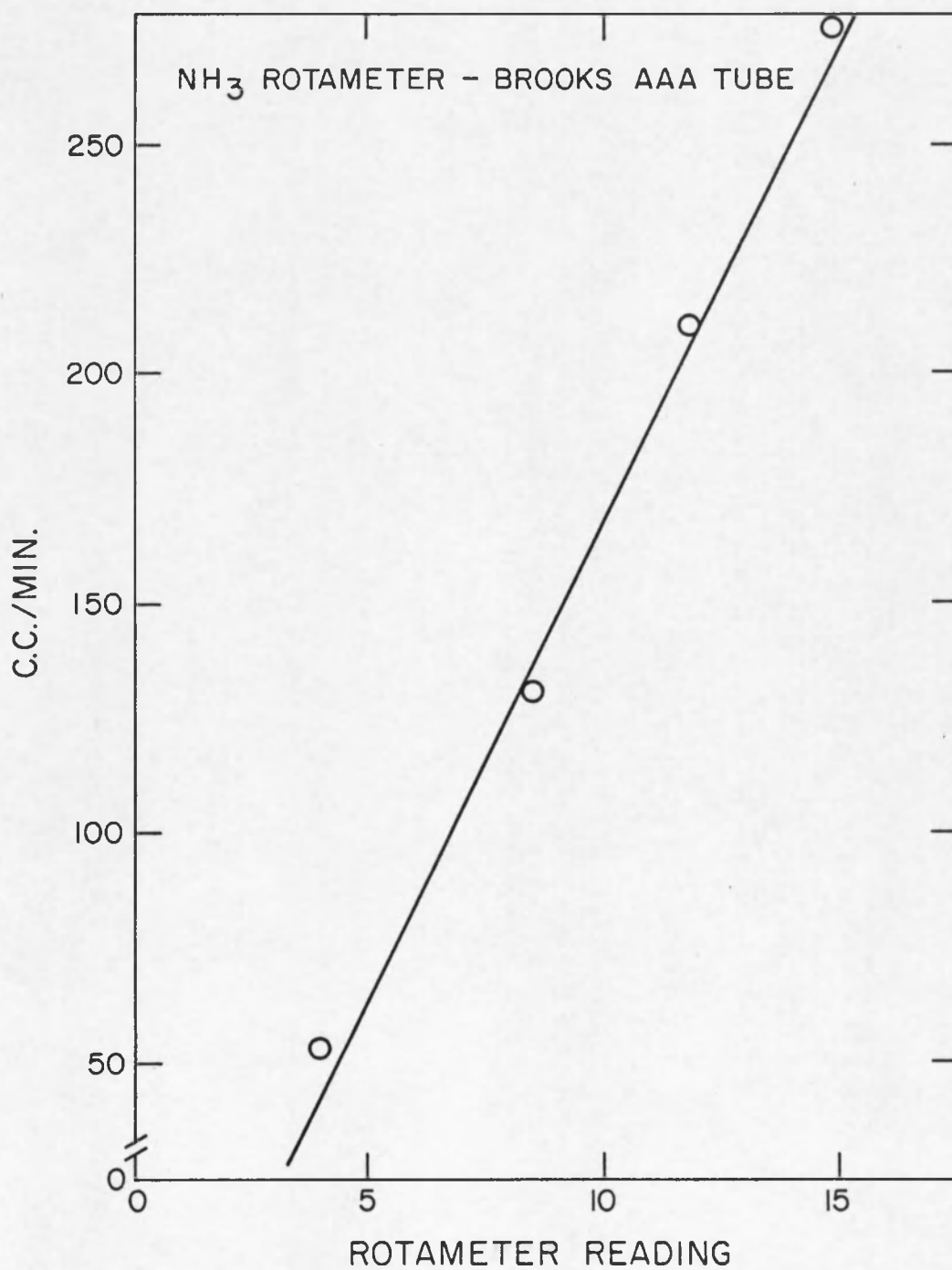
Figure B-5. Rotameter calibration, NH_3.
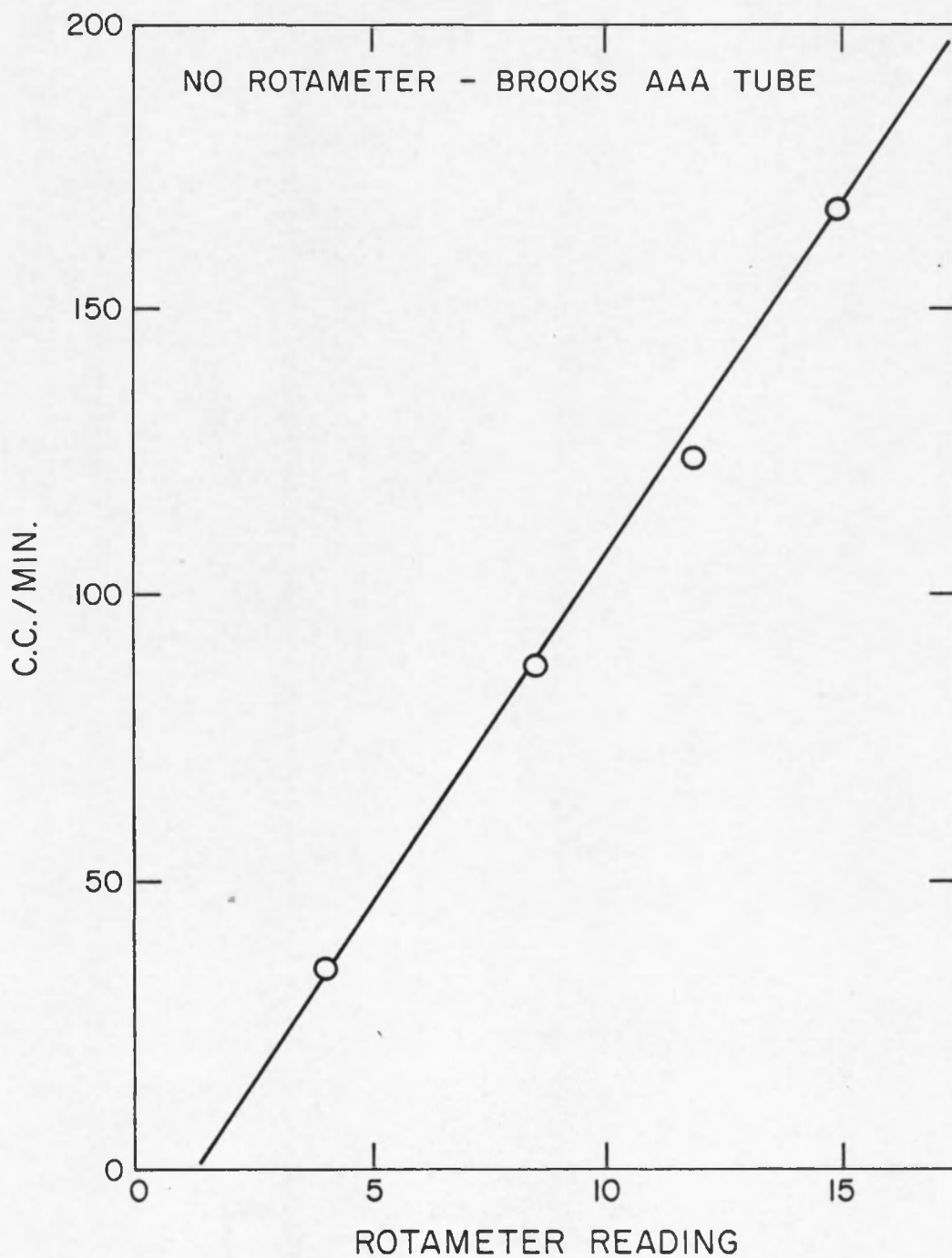
Figure B-6.   Rotameter calibration, NO.

APPENDIX C

OPERATING PROCEDURES

C.1   Furnace Warmup

On initial start-up from a cold condition it was necessary to
preheat the furnace by firing natural gas for at least 72 hours before
any coal testing was started. The natural gas was fired at approximately
the full load (coal) condition of 85,000 Btu/hr. This allowed the fur-
nace to come to thermal steady state and resulted in an inside wall
temperature of approximately 1900°F as measured with an optical pyrometer.
Due to the length of the warmup period and the detrimental effects of
thermal cycling on the refractory, the furnace was normally fired on gas
when coal testing was not in progress; total shut-down occurred only
during extended vacation periods and major system modifications.

The actual start-up procedure consisted of several distinct
parts. First, air, heated to 600°F by the electric preheater, was passed
through the furnace for approximately four hours to slowly bring the
refractory temperature to over 300°F. Next, the pilot flame was ignited
with the electric spark ignitor. The main gas flame was then ignited
directly from the pilot flame after which the latter was turned off.

The following detailed start-up procedure was prepared for
starting the furnace up from a cold condition. The valve numbers refer
to Figure C-1.
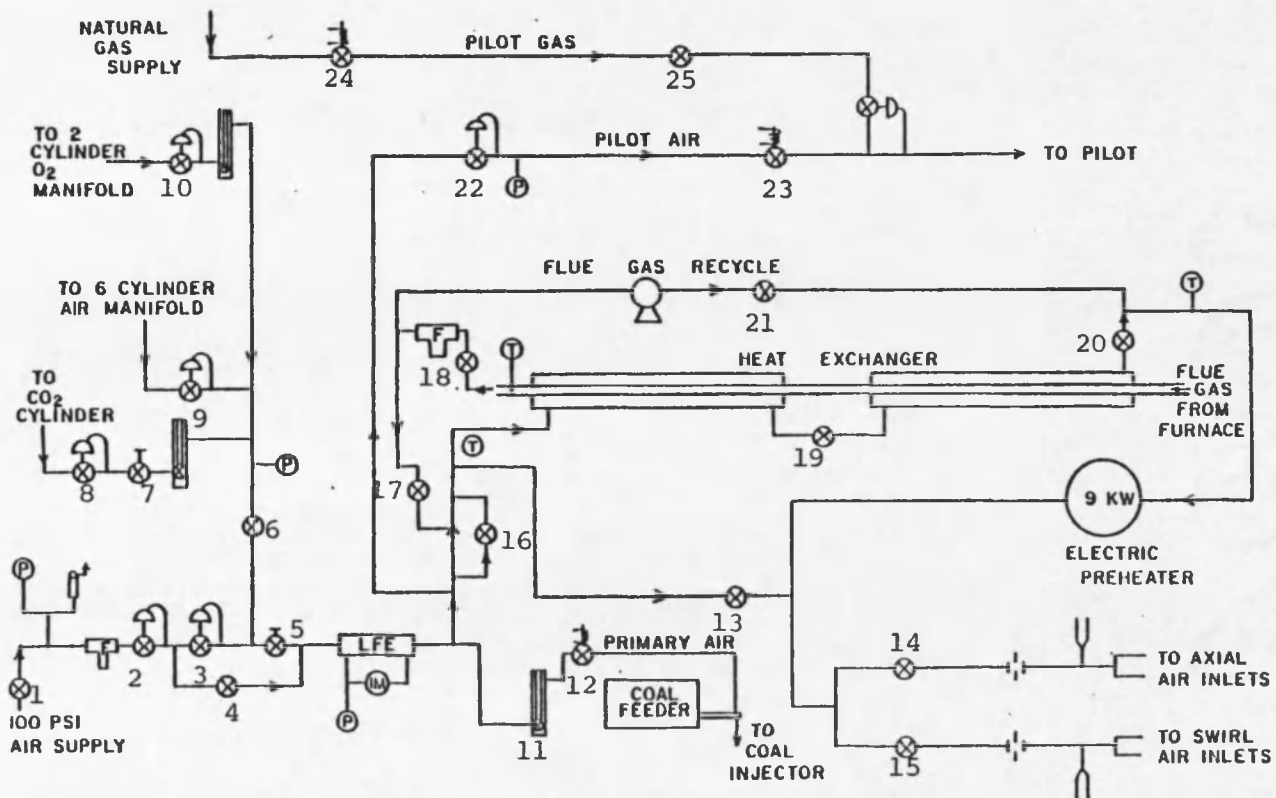
Figure C-1. Plumbing layout.

C.1.1 Initial Warmup

1. Turn air compressor on.

2. Check to be sure the flue gas draft fan is on.

3. Drain water traps.

4. Open high pressure air valve (#1).

5. Check high temperature limit switch on preheater.

6. Turn main power switch on.

7. Open secondary air control valve (#5) to give approximately 15 SCFM.

8. Turn on cooling water.

9. Set preheater controller at 600°F.

C.1.2 Pilot Ignition

1. Turn preheater off.

2. Make sure main gas valves are closed.

3. Check all cooling water streams.

4. Open pilot gas valve (#25).

5. Turn on pilot air (solenoid #23).

6. Turn Maxon gas valve switch on (solenoid #24). Gas flow will not start until valve 24 is also engaged manually.

7. Depress spark ignitor button.

8. Cock and open Maxon gas valve manually. Release ignition button.

9. Open shutter on quartz window and visually inspect the flame.

10. If pilot flame is unstable or ignition does not occur, reduce secondary air flow and, if necessary, readjust pilot air pressure regulator (#22) (8 oz/in^2 is optimum).

C.1.3 Main Flame Ignition

1. Turn on main gas switch (solenoid valve).

2. Open natural gas control valve and adjust flow to proper setting.

3. Adjust secondary air flow to proper level.

4. Visually inspect flame.

5. Close pilot gas ball valve (#25).

6. Switch off pilot air (solenoid #23).

7. Adjust preheater controller to desired set point.

8. Check flue oxygen level with polarographic oxygen analyzer. 2 to 3 percent excess oxygen is desirable.

9. Close window shutter.

10. Check all cooling water streams.

11. Check flame signal strength. If necessary, adjust axial and swirl air valves (#14 and #15) to give a stronger signal.

Three main types of problems were encountered during furnace warmup. The first was the condensation of water in the early portions of the heat exchanger because the entire system was totally cold. To overcome this, the initial warmup step with preheated air was added to the procedure.

Periodically, problems were encountered with the pilot system due to deposition of ash in the pilot port and the high temperature corrosion of the outer pilot tube. Initially, these were solved by cleaning the pilot tip. Ultimately, after approximately 6 months of operation, it was necessary to install a new pilot.

Sporadic problems were encountered in the ultraviolet flame detector system. Ash and slag would deposit in the detector port, partially blocking the UV rays and causing a weak flame signal. The problem was solved by increasing the axial air, thus lengthening the flame and increasing the UV emissions in the field of view of the detector.

C.2 Transition to Coal

The following detailed procedure was used for switching from natural gas to coal.

C.2.1 Preliminaries

1. Drain oil/water trap.

2. Clean out the appropriate coal injector.

3. Install full cylinders of Ar/O_2 and/or CO_2 if required.

4. Load coal into small barrel outside building.

5. Seal barrel and mount above coal feeder. Open gate valve on bottom of barrel and fill feeder hopper.

6. Remove barrel and seal hopper top.

C.2.2 Transition

1. Switch off main and Maxon gas valves.

2. Manually shut off main gas control valve.

3. Set preheater controller to 70°F.

4. Close secondary air control valve (#5).

5. Clean quartz observation window. Replace gas injector with appropriate coal injector.

6. Adjust secondary air control valve (#5) to give desired flow.

7. Check swirl and axial air valves (#14 and #15). Both should be completely open.

8. Adjust preheater controller to desired set point. Check high temperature limit reset.

9. Lock out flame safety system.

10. Turn on coal feeder switch.

11. Turn off primary air solenoid (#12).

12. Adjust primary air control valve (#11) to give desired flow rate.

13. Push coal feeder start button.

14. Visually inspect flame and, if necessary, adjust coal injector alignment to achieve symmetrical flame.

During the eight months of experimental testing on coal, a multitude of operational problems were encountered and the three most significant are discussed below. The difficulty of conducting coal combustion studies (compared to natural gas) cannot be over-emphasized; however, no unsolvable problems were met. Initially, it was anticipated (based on past experience) that pulsing of the coal feed would be a major problem. In an attempt to overcome this, a variety of inline mixing devices were tried. Ultimately, the best scheme proved to be a direct connection between the feeder and the burner in conjunction with a high velocity primary air jet which was positioned opposite the screw outlet and which sweeps the coal uniformly off the screw.

Periodically, both the bottom of the furnace and the heat exchangers would become blocked with fly ash. Ultimately, this situation

was improved by enlarging the flue system and by regular, bi-weekly cleaning of the furnace bottom from below.

Even with the improved coal feeding system, sporadic coal pulses would occur and momentarily extinguish the flame. When this occurred, the flame safety system would automatically shut the entire furnace down and, hence, interrupt the run. Experience showed that there was nothing dangerous about a momentary flame lapse because the walls were hot enough to directly ignite the coal particles once the pulse was past. Therefore, the flame safety system was ultimately bypassed during periods of data gathering to avoid unnecessary interruptions.

C.3 Overnight Operation

The following detailed procedure was used for switching back to natural gas from coal during periods when coal testing was not in progress:

1. Push coal feeder stop button.

2. Close primary air control valve (#11).

3. Close secondary air control valve (#5).

4. Turn coal feeder switch off.

5. Replace coal injector with gas injector.

6. Adjust secondary air control valve (#11) to give 15 SCFM.

7. Check furnace pressure. If 5" H_2O or greater, shut off secondary air and clean furnace flue.

8. Start up main gas flame as previously described.

9. Set preheater controller to temperature to be run in the next test series.

10. Check flame signal and cooling water streams.

C.4 Furnace Shutdown

To shut the furnace down for an extended period of time, one merely turns off the main power switch, closes the high pressure air valve, and all natural gas valves. The cooling water is not turned off for at least four days to insure that all portions of the furnace have had adequate time to cool down.

APPENDIX D

TABULATION OF EXPERIMENTAL DATA

D.1 Colorado Coal

The experimental data which were obtained during the Colorado coal combustion studies are tabulated on the following pages. In general, the following parameters were recorded:

1. Fuel flow in lbs per hour based on the calibration of the screw feeder (Appendix B).

2. Total air flow in standard cubic feet per minute (70°F). This was measured with a laminar flow element and an inclined manometer.

3. Percent swirl based on differential pressure readings across matched orifices in the swirl and axial air lines.

4. Secondary air preheat temperature (°F) based on thermocouple measurements of the swirl and axial air temperatures just prior to the burner inlets.

5. Primary air flow rate in standard cubic feet per minute (70°F). For the Colorado coal these numbers can only be considered approximate values due to a leak in the primary air system which was discovered after the conclusion of the tests.

6. Inlet O_2 concentration. This refers to the percent oxygen in the inlet combustion air. A value of 21 implies the oxidizer was compressed air and was assumed to contain 21 percent oxygen. Any

other value implies the oxygen concentration was experimentally measured using the paramagnetic oxygen analyzer.

7. Inlet CO_2 concentration based on direct measurement of the inlet air with the NDIR CO_2 analyzer.

8. The balance of the oxidizer composition, either N_2 or Ar.

9. Percent FGR, i.e., the amount of flue gas being recirculated according to equation 4-1.

10. O_2 concentration as measured by both a polarographic analyzer (polar) and a paramagnetic analyzer (para).

11. The stoichiometric ratio (SR) as determined from the paramagnetic oxygen reading if available, and from the polarographic reading if not.

12. The percent CO and CO_2 concentrations in the flue gas based on direct measurement by NDIR analyzers.

13. NO emissions as measured by the chemiluminescent analyzer.

14. NO emissions in ppm, by volume, dry, reduced to stoichiometric.

15. SO_2 emissions in ppm, by volume, dry, reduced to stoichiometric based on the flue gas analysis by the pulsed-fluorescent analyzer.

Fuel: Colorado Coal   Date: 11/05   Injector: Divergent

INLET PARAMETERS							
Run No.	1	2	3	4	5	6	7
Fuel flow, #/hr	6.6	6.6	6.6	6.6	6.6	6.6	6.6
Air flow, SCFM	20.7	24.3	17.4	15.9	18.4	19.0	20.0
% swirl	30	30	30	30	30	30	30
Sec. air preheat, °F	515	530	510	490	495	505	505
Pri. air flow, SCFM	2.8	2.8	2.8	2.8	2.8	2.8	3.45
Inlet O_2, %	21	21	21	21	21	21	21
Inlet CO_2, %	--	--	--	--	--	--	--
Balance	N_2	N_2	N_2	N_2	N_2	N_2	N_2
% FGR	--	--	--	--	--	--	--
FLUE MEASUREMENTS							
% O_2, polar	3.40	6.50	1.10	0.20	1.45	2.10	1.75
% O_2, para.	3.60	6.25	1.30	0.45	1.50	2.45	2.00
S.R. by O_2	1.194	1.421	1.062	1.021	1.072	1.124	1.099
% CO	.02	0.0	.12	.51	.04	.04	.04
% CO_2	15.0	12.2	17.6	17.9	17.2	16.2	16.8
NO, as meas., ppm	540	595	535	485	550	560	740
NO, 0% EA, ppm	772	847	570	496	592	634	818
SO_2, as meas., ppm	--	--	--	--	--	--	--

COMMENTS: 1-7 reduced swirl.

Fuel: Colorado Coal   Date: 11/05   Injector: Divergent

INLET PARAMETERS							
Run No.	8	9	10	11	12	13	
Fuel flow, #/hr	6.6	6.6	6.6	6.6	6.6	6.6	
Air flow, SCFM	22.0	20.0	19.0	20.0	20.4	20.6	
% swirl	31	31	30	31	31	42	
Sec. air preheat, °F	520	510	510	500	500	555	
Pri. air flow, SCFM	3.5	2.1	2.1	--	2.8	2.8	
Inlet O_2, %	21	21	21	21	21	21	
Inlet CO_2, %	--	--	--	--	--	--	
Balance	N_2	N_2	N_2	N_2	N_2	N_2	
% FGR	--	--	--	--	--	--	
FLUE MEASUREMENTS							
% O_2, polar	3.70	2.40	1.60	--	3.40	3.35	
% O_2, para.	4.20	2.75	2.10	--	3.50	3.40	
S.R. by O_2	1.235	1.141	1.104	--	1.188	1.181	
% CO	.02	.03	.04	.02	.01	.02	
% CO_2	14.8	15.4	16.2	16.8	14.8	15.4	
NO, as meas., ppm	820	510	445	--	620	630	
NO, 0% EA, ppm	1025	587	494	--	744	752	
SO_2, as meas., ppm	--	--	--	--	--	--	

COMMENTS: 8-13 reduced swirl.

Fuel: Colorado Coal   Date: 11/04   Injector: Divergent

INLET PARAMETERS							
Run No.	4	5	6	7	8	10	11
Fuel flow, #/hr	6.6	6.6	6.6	6.6	6.6	6.6	6.6
Air flow, SCFM	--	--	23.2	27.4	22.8	21.3	23.5
% swirl	--	--	34	35	33	33	33
Sec. air preheat, °F	--	--	505	510	490	470	475
Pri. air flow, SCFM	--	--	2.8	2.85	2.8	2.8	2.8
Inlet O_2, %	21	21	21	21	21	21	21
Inlet CO_2, %	--	--	--	--	--	--	--
Balance	N_2	N_2	N_2	N_2	N_2	N_2	N_2
% FGR	--	--	--	--	--	--	--

FLUE MEASUREMENTS							
% O_2, polar	0.55	0.85	2.25	4.5	1.85	0.7	2.1
% O_2, para.	0.45	1.0	2.50	5.0	2.1	0.8	2.4
S.R. by O_2	1.021	1.047	1.127	1.293	1.104	--	--
% CO	--	0.27	0.04	0.02	0.04	0.21	0.04
% CO_2	--	17.9	16.46	14.5	17.18	18.32	16.82
NO, as meas., ppm	460	490	580	615	510	--	--
NO, 0% EA, ppm	470	515	655	795	565	--	--
SO_2, as meas., ppm	--	--	--	--	--	--	--

COMMENTS: 4-11 baseline conditions.

Fuel: Colorado Coal   Date: 11/13   Injector: Divergent

INLET PARAMETERS							
Run No.	1	2	3	4	5	6	7
Fuel flow, #/hr	6.6	6.6	6.6	6.6	6.6	6.6	6.6
Air flow, SCFM	15.0	17.4	19.0	20.5	22.6	17.8	19.8
% swirl	65	63	66	66	66	33	34
Sec. air preheat, °F	485	475	480	485	490	495	490
Pri. air flow, SCFM	2.8	2.8	2.8	2.8	2.8	2.8	2.8
Inlet O_2, %	21	21	21	21	21	21	21
Inlet CO_2, %	--	--	--	--	--	--	--
Balance	N_2	N_2	N_2	N_2	N_2	N_2	N_2
% FGR	--	--	--	--	--	--	--
FLUE MEASUREMENTS							
% O_2, polar	--	0.8	2.3	3.4	5.0	1.8	3.75
% O_2, para.	--	1.0	2.4	3.4	4.9	2.0	3.8
S.R. by O_2	--	1.047	1.121	1.181	1.284	1.099	1.207
% CO	0.41	0.04	0.03	0.02	0	0.01	0
% CO_2	17.54	18.32	16.82	15.78	14.5	17.54	15.78
NO, as meas., ppm	--	495	615	680	750	580	615
NO, 0% EA, ppm	--	520	690	805	965	635	740
SO_2, as meas., ppm	--	--	1200	1140	1030	1310	1150

COMMENTS: 1-5 increased burner swirl.
           6-7 decreased burner swirl.

Fuel: Colorado Coal   Date: 11/13   Injector: Divergent

INLET PARAMETERS							
Run No.	8	9					
Fuel flow, #/hr	6.6	6.6					
Air flow, SCFM	22.5	17.2					
% swirl	34	35					
Sec. air preheat, °F	500	480					
Pri. air flow, SCFM	2.8	2.8					
Inlet O_2, %	21	21					
Inlet CO_2, %	--	--					
Balance	N_2	N_2					
% FGR	--	--					

FLUE MEASUREMENTS							
% O_2, polar	6.75	1.55					
% O_2, para.	6.75	1.45					
S.R. by O_2	1.444	1.070					
% CO	0.0	0.02					
% CO_2	12.48	17.9					
NO, as meas., ppm	610	545					
NO, 0% EA, ppm	880	585					
SO_2, as meas., ppm	950	1400					

COMMENTS: 8-9 decreased burner swirl.

Fuel: Colorado Coal   Date: 11/17   Injector: Divergent

INLET PARAMETERS							
Run No.	1	2	3	4	5	6	7
Fuel flow, #/hr	6.6	6.6	6.6	6.6	6.6	6.6	6.6
Air flow, SCFM	16.8	19.2	21.2	18.9	16.3	14.2	14.0
% swirl	45	45	46	45	46	45	46
Sec. air preheat, °F	495	495	505	500	490	480	465
Pri. air flow, SCFM	2.8	2.8	2.8	2.8	2.8	2.74	2.8
Inlet O_2, %	21	21	21	21	21	21	21
Inlet CO_2, %	--	--	--	--	--	--	--
Balance	N_2	N_2	N_2	N_2	N_2	N_2	N_2
% FGR	--	--	--	--	--	--	--

FLUE MEASUREMENTS							
% O_2, polar	0.50	1.85	3.9	--	--	--	--
% O_2, para.	0.75	2.15	4.3	4.75	2.55	--	0.25
S.R. by O_2	1.035	1.107	1.242	1.274	1.130	--	1.011
% CO	0.12	0.02	0.01	0.02	0.02	0.56	1.20
% CO_2	19.16	17.54	15.3	17.18	20.0	>20.0	>20.0
NO, as meas., ppm	6.25	765	820	950	900	--	370
NO, 0% EA, ppm	645	845	1020	1210	1015	--	375
SO_2, as meas., ppm	1600	1400	1250	1300	1500	--	--

COMMENTS: 1-7 baseline conditions, deleted.

Fuel: Colorado Coal   Date: 11/17   Injector: Divergent

INLET PARAMETERS							
Run No.	8	9	10	11			
Fuel flow, #/hr	6.6	6.6	6.6	6.6.			
Air flow, SCFM	15.7	19.7	15.0	18.0			
% swirl	45	46	45	46			
Sec. air preheat, °F	475	505	445	460			
Pri. air flow, SCFM	2.8	2.8	2.56	2.56			
Inlet O_2, %	21	21	21	21			
Inlet CO_2, %	--	--	--	--			
Balance	N_2	N_2	N_2	N_2			
% FGR	--	--	--	--			
FLUE MEASUREMENTS							
% O_2, polar	--	--	--	--			
% O_2, para.	0.70	3.95	0.95	3.65			
S.R. by O_2	1.032	1.217	1.044	1.197			
% CO	0.12	0.01	0.12	0.02			
% CO_2	>20.0	17.3	>20.0	17.3			
NO, as meas., ppm	820	1075	825	980			
NO, 0% EA, ppm	845	1310	860	1175			
SO_2, as meas., ppm	1650	1280	1700	1300			

COMMENTS: 8-11 baseline conditions, deleted.

Fuel: Colorado Coal   Date: 11/18   Injector: Divergent

INLET PARAMETERS							
Run No.	1	2	3	4			
Fuel flow, #/hr	6.6	6.6	6.6	6.6			
Air flow, SCFM	17.1	19.1	22.2	17.7			
% swirl	45	45	45	45			
Sec. air preheat, °F	503	506	513	506			
Pri. air flow, SCFM	2.8	2.8	2.8	2.8			
Inlet O_2, %	21	21	21	21			
Inlet CO_2, %	--	--	--	--			
Balance	N_2	N_2	N_2	N_2			
% FGR	--	--	--	--			
FLUE MEASUREMENTS							
% O_2, polar	.85	2.0	4.5	1.15			
% O_2, para.	.90	2.25	5.0	1.4			
S.R. by O_2	1.042	1.113	1.293	1.067			
% CO	0.23	0.06	0.02	0.16			
% CO_2	16.82	16.1	13.3	16.82			
NO, as meas., ppm	510	600	690	530			
NO, 0% EA, ppm	535	670	905	570			
SO_2, as meas., ppm	1500	1220	1000	1410			

COMMENTS: 1-4 baseline conditions.

Fuel: Colorado Coal   Date: 11/18   Injector: Divergent

INLET PARAMETERS							
Run No.	5	6	7	8			
Fuel flow, #/hr	6.6	6.6	6.6	6.6			
Air flow, SCFM	14.7	16.8	20.8	18.7			
% swirl	46	46	46	46			
Sec. air preheat, °F	105	92	90	90			
Pri. air flow, SCFM	2.8	2.8	2.56	2.56			
Inlet O_2, %	23.0	23.0	23.0	23.0			
Inlet CO_2, %	--	--	--	--			
Balance	N_2	N_2	N_2	N_2			
% FGR	--	--	--	--			
FLUE MEASUREMENTS							
% O_2, polar	0.65	1.10	4.5	2.95			
% O_2, para.	--	--	--	--			
S.R. by O_2	1.023	1.049	1.237	1.143			
% CO	0.56	0.09	0.02	0.04			
% CO_2	19.16	19.16	15.78	17.54			
NO, as meas., ppm	310	480	650	600			
NO, 0% EA, ppm	290	460	740	630			
SO_2, as meas., ppm	1520	1450	1100	1250			

COMMENTS: 5-8 23% O_2 in N_2

Fuel: Colorado Coal   Date: 11/19   Injector: Divergent

INLET PARAMETERS							
Run No.	1	2	3	4	5	6	7
Fuel flow, #/hr	6.6	6.6	6.6	6.6	6.6	6.6	6.6
Air flow, SCFM	16.3	18.7	23.2	17.8	20.8	--	--
% swirl	45	45	46	45	45	46	46
Sec. air preheat, $^{\circ}$F	501	506	515	506	511	428	471
Pri. air flow, SCFM	2.56	2.56	2.56	2.56	2.56	2.43	2.43
Inlet O_2, %	23.1	23.0	23.0	23.1	23.1	20.4	20.3
Inlet CO_2, %	--	--	--	--	--	--	--
Balance	N_2	N_2	N_2	N_2	N_2	Ar	Ar
% FGR	--	--	--	--	--	--	--
FLUE MEASUREMENTS							
% O_2, polar	1.15	2.6	6.25	1.8	4.05	4.1	2.4
% O_2, para.	--	--	--	--	--	--	--
S.R. by O_2	1.051	1.124	1.364	1.082	1.208	1.228	1.121
% CO	0.28	0.07	0.02	0.06	0.02	0.02	0.03
% CO_2	19.58	17.9	13.9	18.74	16.46	11.96	13.0
NO, as meas., ppm	585	730	795	680	790	630	460
NO, 0% EA, ppm	560	750	995	670	870	810	540
SO_2, as meas., ppm	1300	1200	920	1280	1100	1050	1300

COMMENTS: 1-5 23% O_2 in N_2.
6-7 21% O_2 in Ar.

Fuel: Colorado Coal   Date: 11/19   Injector: Divergent

INLET PARAMETERS							
Run No.	8	9	10	11	12		
Fuel flow, #/hr	6.6	6.6	6.6	6.6	6.6		
Air flow, SCFM	--	--	--	--	--		
% swirl	45	46	46	46	46		
Sec. air preheat, °F	470	470	470	475	490		
Pri. air flow, SCFM	2.43	2.43	2.78	2.78	2.78		
Inlet O_2, %	20.0	19.8	20.8	21.0	21.0		
Inlet CO_2, %	--	--	--	--	--		
Balance	Ar	Ar	Ar	Ar	Ar		
% FGR	--	--	--	--	--		
FLUE MEASUREMENTS							
% O_2, polar	1.7	0.75	1.15	3.35	5.15		
% O_2, para.	--	--	--	--	--		
S.R. by O_2	1.083	1.035	1.054	1.178	1.305		
% CO	0.07	0.28	0.18	0.02	0.0		
% CO_2	13.6	11.44	15.46	13.3	11.96		
NO, as meas., ppm	415	375	440	520	555		
NO, 0% EA, ppm	475	415	470	620	735		
SO_2, as meas., ppm	1500	1650	1580	1250	1050		

COMMENTS: 8-9 21% O_2 in Ar.
           10-12 21% O_2 in Ar.

Fuel: Colorado Coal   Date: 11/22   Injector: Divergent

INLET PARAMETERS							
Run No.	4	5	6	7	8	9	10
Fuel flow, #/hr	6.6	6.6	6.6	6.6	6.6	6.6	6.6
Air flow, SCFM	18.0	19.1	22.1	19.1	21.4	--	--
% swirl	45	45	46	45	45	45	45
Sec. air preheat, °F	490	520	540	520	515	225	215
Pri. air flow, SCFM	2.8	2.8	2.8	2.8	2.8	2.43	2.43
Inlet O_2, %	21	21	21	21	21	21.2	21.1
Inlet CO_2, %	--	--	--	--	--	19.2	18.6
Balance	N_2	N_2	N_2	N_2	N_2	Ar	Ar
% FGR	--	--	--	--	--	--	--

FLUE MEASUREMENTS							
% O_2, polar	0.9	1.9	4.15	1.25	3.05	6.5	3.8
% O_2, para.	--	--	--	--	--	--	--
S.R. by O_2	1.042	1.093	1.231	1.059	1.159	1.420	1.207
% CO	--	--	--	--	--	--	--
% CO_2	--	--	--	--	--	--	--
NO, as meas., ppm	525	530	600	550	590	585	550
NO, 0% EA, ppm	--	--	--	--	685	830	665
SO_2, as meas., ppm	1350	900	680	1050	900	820	980

COMMENTS: 4-8 baseline conditions.
          9-10 Ar/O_2/CO_2.

Fuel: Colorado Coal   Date: 11/22   Injector: Divergent

INLET PARAMETERS							
Run No.	11	12	13	14	15	16	
Fuel flow, #/hr	6.6	6.6	6.6	6.6	6.6	6.6	
Air flow, SCFM	--	--	19.1	20.4	21.8	19.02	
% swirl	45	45	45	45	46	45	
Sec. air preheat, °F	205	200	205	205	205	205	
Pri. air flow, SCFM	2.45	2.43	2.8	2.8	2.8	2.8	
Inlet O_2, %	21.3	21.2	21	21	21	21	
Inlet CO_2, %	18.6	18.6	--	--	--	--	
Balance	Ar	Ar	N_2	N_2	N_2	N_2	
% FGR	--	--	--	--	--	--	
FLUE MEASUREMENTS							
% O_2, polar	1.6	0.33	0.8	2.35	3.85	0.9	
% O_2, para.	--	--	0.9	2.48	4.05	1.05	
S.R. by O_2	1.077	1.015	1.042	1.126	1.224	1.049	
% CO	--	--	.07	.04	.04	.07	
% CO_2	--	--	18.3	16.6	14.9	18.3	
NO, as meas., ppm	475	385	605	650	660	635	
NO, 0% EA, ppm	510	390	--	--	--	670	
SO_2, as meas., ppm	1200	1420	1390	1240	1100	1350	

COMMENTS: 11-12 Ar/O_2/CO_2.
            13-16 Reduced air preheat.

Fuel: Colorado Coal   Date: 11/24   Injector: Divergent

INLET PARAMETERS							
Run No.	1	2	3	4	5	6	
Fuel flow, #/hr	6.6	6.6	6.6	6.6	6.6	6.6	
Air flow, SCFM	19.0	20.6	22.9	2.50	15.0	15.0	
% swirl	46	46	46	46	46	46	
Sec. air preheat, °F	510	515	515	520	515	515	
Pri. air flow, SCFM	2.8	2.8	2.8	2.8	2.8	2.8	
Inlet O_2, %	20.9	20.9	20.9	21	19.2	19.6	
Inlet CO_2, %	8.0	7.8	7.6	8.0	--	--	
Balance	N_2	N_2	N_2	N_2	N_2	N_2	
% FGR	--	--	--	--	--	--	
FLUE MEASUREMENTS							
% O_2, polar	1.35	2.1	3.7	5.2	1.8	2.8	
% O_2, para.	--	--	--	--	--	--	
S.R. by O_2	1.064	1.104	1.200	1.309	1.088	1.144	
% CO	--	--	--	--	0.04	0.07	
% CO_2	--	--	--	--	--	--	
NO, as meas., ppm	485	435	610	635	550	620	
NO, 0% EA, ppm	515	590	730	830	600	710	
SO_2, as meas., ppm	950	1000	1000	910	1250	1150	

COMMENTS: 1-4 CO_2 addition to inlet air.
          5-6 FGR shakedown.

Fuel: Colorado Coal   Date: 11/26   Injector: Divergent

INLET PARAMETERS							
Run No.	1	2	3	4	5	6	7
Fuel flow, #/hr	6.6	6.6	6.6	6.6	6.6	6.6	6.6
Air flow, SCFM	17.5	19.2	19.8	20.7	22.2	23.0	26.0
% swirl	46	45	46	46	46	46	45
Sec. air preheat, °F	150	155	155	155	160	165	170
Pri. air flow, SCFM	2.8	2.8	2.8	2.8	2.8	2.8	2.8
Inlet O_2, %	21	21	21	21	21	21	21
Inlet CO_2, %	--	--	--	--	--	--	--
Balance	N_2	N_2	N_2	N_2	N_2	N_2	N_2
% FGR	--	--	--	--	--	--	--
FLUE MEASUREMENTS							
% O_2, polar	1.2	6.3	2.2	3.45	4.1	4.9	5.5
% O_2, para.	0.95	5.6	1.85	3.1	4.45	5.5	6.35
S.R. by O_2	1.044	1.341	1.091	1.162	1.252	1.333	1.407
% CO	0.06	0.05	0.04	0.02	0.02	0.01	0.02
% CO_2	17.7	12.74	17.18	--	15.3	13.7	12.85
NO, as meas., ppm	740	505	870	700	650	625	610
NO, 0% EA, ppm	775	675	950	815	815	835	860
SO_2, as meas., ppm	--	--	1250	1200	1130	1050	975

COMMENTS: 1-7 reduced air preheat.

Fuel: Colorado Coal   Date: 11/26   Injector: Divergent

INLET PARAMETERS							
Run No.	8	9	10	11	12		
Fuel flow, #/hr	6.6	6.6	6.6	6.6	6.6		
Air flow, SCFM	28.0	17.0	20.6	22.2	17.2		
% swirl	46	45	48	45	45		
Sec. air preheat, °F	175	515	510	510	505		
Pri. air flow, SCFM	2.8	2.8	2.8	2.8	2.8		
Inlet O_2, %	21	18.0	18.8	19.2	19.8		
Inlet CO_2, %	--	--	--	--	--		
Balance	N_2	N_2	N_2	N_2	N_2		
% FGR	--	15.2	12.4	11.4	8.6		
FLUE MEASUREMENTS							
% O_2, polar	6.3	1.2	3.25	5.2	7.0		
% O_2, para.	7.35	--	--	--	--		
S.R. by O_2	1.505	1.057	1.172	1.309	1.469		
% CO	0.02	0.06	--	0.03	0.04		
% CO_2	11.96	18.32	--	13.3	11.44		
NO, as meas., ppm	610	530	640	640	610		
NO, 0% EA, ppm	920	560	750	840	895		
SO_2, as meas., ppm	--	1050	850	740	950		

COMMENTS: 8 reduced air preheat.
           9-12 FGR.

Fuel: Colorado Coal   Date: 11/24   Injector: Divergent

INLET PARAMETERS							
Run No.	1	2	3	4	5	6	7
Fuel flow, #/hr	6.6	6.6	6.6	6.6	6.6	6.6	6.6
Air flow, SCFM	19.6	21.3	20.9	21.0	21.3	22.3	22.8
% swirl	45	45	45	45	45	46	45
Sec. air preheat, °F	525	530	535	530	535	540	550
Pri. air flow, SCFM	2.8	2.77	2.76	2.82	2.8	·2.8	2.8
Inlet O_2, %	21	21	21	21	18.5	18.75	19.0
Inlet CO_2, %	--	--	--	--	--	--	--·
Balance	N_2	N_2	N_2	N_2	N_2	N_2	N_2
% FGR	--	--	--	--	13.1	12.5	11.6
FLUE MEASUREMENTS							
% O_2, polar	--	1.95	--	1.95	1.9	3.05	3.8
% O_2, para.	--	2.2	--	--	--	--	--
S.R. by O_2	--	--	--	1.096	1.093	1.159	1.207
% CO	--	0.11	--	0.10	0.04	0.03	0.03
% CO_2	--	16.82	--	16.95	16.95	15.78	14.82
NO, as meas., ppm	--	--	--	585	555	615	640
NO, 0% EA, ppm	--	--	--	640	605	715	770
SO_2, as meas., ppm	--	1280	--	1250	1130	1080	1020

COMMENTS: 1-3 shakedown.
        4 baseline conditions.
        5-7 FGR.

Fuel: Colorado Coal   Date: 11/24   Injector: Divergent

INLET PARAMETERS							
Run No.	8	9	10	11	12	13	14
Fuel flow, #/hr	6.6	6.6	6.6	6.6	6.6	6.6	6.6
Air flow, SCFM	22.6	21.8	24.5	27.2	22.2	16.2	18.6
% swirl	45	45	45	46	45	45	45
Sec. air preheat, °F	540	540	540	550	525	500	510
Pri. air flow, SCFM	2.82	2.82	2.8	2.8	2.8	2.4	2.4
Inlet O_2, %	21.0	20.7	20.9	20.8	20.5	24.9	--
Inlet CO_2, %	--	13.3	12.8	12.2	13.0	--	--
Balance	N_2	N_2	N_2	N_2	N_2	N_2	N_2
% FGR	--	--	--	--	--	--	--
FLUE MEASUREMENTS							
% O_2, polar	3.9	2.05	4.3	5.7	2.2	1.1	--
% O_2, para.	--	--	--	--	--	--	--
S.R. by O_2	1.214	1.101	1.241	1.349	1.110	1.043	--
% CO	0.02	--	--	--	--	--	--
% CO_2	14.82	--	--	--	--	--	--
NO, as meas., ppm	680	580	560	595	540	650	740
NO, 0% EA, ppm	825	640	695	805	600	575	--
SO_2, as meas., ppm	1110	1000	900	800	950	1550	--

COMMENTS: 8 baseline conditions.
9-12 CO_2 addition.
13-14 25% O_2.

Fuel: Colorado Coal   Date: 11/29   Injector: Divergent

INLET PARAMETERS							
Run No.	15	16	17	18	19	20	21
Fuel flow, #/hr	6.6	6.6	6.6	6.6	6.6	6.6	6.6
Air flow, SCFM	18.3	21.4	17.9	20.4	22.4	--	--
% swirl	45	45	45	45	46	46	46
Sec. air preheat, $^\circ$F	501	521	511	516	528	421	451
Pri. air flow, SCFM	2.42	2.42	2.56	2.56	2.56	2.45	3.13
Inlet O_2, %	25.0	24.6	23.1	22.9	23.0	21.0	20.5
Inlet CO_2, %	--	--	--	--	--	--	--
Balance	N_2	N_2	N_2	N_2	N_2	Ar	Ar
% FGR	--	--	--	--	--	--	--
FLUE MEASUREMENTS							
% O_2, polar	3.05	5.9	1.15	3.4	5.5	2.8	2.5
% O_2, para.	--	--	--	--	--	--	--
S.R. by O_2	1.130	1.289	1.051	1.168	1.306	1.144	1.127
% CO	0.07	0.02	0.07	0.02	0.02	0.04	0.04
% CO_2	20+	18.3	20+	17.1	14.9	14.5	14.8
NO, as meas., ppm	720	770	600	700	755	470	655
NO, 0% EA, ppm	690	865	575	755	905	540	764
SO_2, as meas., ppm	1320	1140	1480	1250	1060	1670	1670

COMMENTS: 15-16 25% O_2 in N .
            17-19 23% O_2 in N .
            20-21 Ar/O_2.

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Fuel: Colorado Coal   Date: 11/29   Injector: Divergent

INLET PARAMETERS							
Run No.	22	23	24	25	26		
Fuel flow, #/hr	6.6	6.6	6.6	6.6	6.6		
Air flow, SCFM	23.1	27.7	27.3	23.9	21.4		
% swirl	46	46	65	46	46		
Sec. air preheat, °F	461	501	508	492	481		
Pri. air flow, SCFM	3.61	2.42	2.48	2.43	2.43		
Inlet O_2, %	20.2	20.9	20.9	23.4	23.8		
Inlet CO_2, %	--	--	--	--	--		
Balance	Ar	Ar	Ar	Ar	Ar		
% FGR	--	--	--	--	--		
FLUE MEASUREMENTS							
% O_2, polar	2.7	4.4	3.9	4.4	3.3		
% O_2, para.	--	--	--	--	--		
S.R. by O_2	1.138	1.230	1.198	1.230	1.163		
% CO	0.06	0.04	0.04	0.06	0.06		
% CO_2	14.8	13.0	13.0	15.1	17.1		
NO, as meas., ppm	980	610	620	660	715		
NO, 0% EA, ppm	1175	775	765	730	735		
SO_2, as meas., ppm	1800	1380	1400	1480	1620		

COMMENTS: 22-26 Ar/O_2.

D.2 Pittsburgh Coal

The experimental data which were obtained during the Pittsburgh coal combustion studies are tabulated on the following pages. In general, the parameters which were recorded are the same as those discussed for the Colorado coal (Section D.1). The primary flow rate data should only be considered approximate because of a leak which was discovered in the primary air system after the conclusion of the Pittsburgh coal testing.

Fuel: Pittsburgh Coal   Date: 12/3   Injector: Divergent

INLET PARAMETERS							
Run No.	1	2	3	4	5	6	7
Fuel flow, #/hr	--	--	--	--	--	--	--
Air flow, SCFM	19.7	20.0	21.9	22.9	21.0	18.6	16.1
% swirl	45	46	46	45	46	45	45
Sec. air preheat, °F	475	475	470	490	480	470	465
Pri. air flow, SCFM	2.8	2.8	2.8	2.8	2.8	2.8	2.8
Inlet O_2, %	21	21	21	21	21	21	21
Inlet CO_2, %	--	--	--	--	--	--	--
Balance	N_2	N_2	N_2	N_2	N_2	N_2	N_2
% FGR	--	--	--	--	--	--	--
FLUE MEASUREMENTS							
% O_2, polar	1.75	2.15	3.8	5.25	3.75	1.5	0.55
% O_2, para.	2.1	1.95	3.65	5.0	3.55	1.4	0.55
S.R. by O_2	1.105	1.097	1.199	1.296	1.193	1.068	1.025
% CO	0.06	0.06	0.02	0.02	0.03	0.06	0.09
% CO_2	17.18	17.9	16.46	13.6	15.46	17.54	18.74
NO, as meas., ppm	585	680	685	690	670	640	590
NO, 0% EA, ppm	645	745	820	895	800	685	605
SO_2, as meas., ppm	1250	1300	1150	1050	1030	1200	1300

COMMENTS: 1-7 baseline conditions.

Fuel: Pittsburgh Coal   Date: 12/3   Injector: Divergent

INLET PARAMETERS							
Run No.	8	9	10	11	12	13	14
Fuel flow, #/hr	--	--	--	--	--	--	--
Air flow, SCFM	20.0	22.4	17.2	19.0	19.6	21.1	22.0
% swirl	47	46	46	45	45	45	46
Sec. air preheat, °F	470	480	465	465	465	480	490
Pri. air flow, SCFM	2.8	2.8	2.8	2.8	2.8	2.8	2.8
Inlet O_2, %	21	21	21	21	21	21	21
Inlet CO_2, %	--	--	--	--	--	--	--
Balance	N_2	N_2	N_2	N_2	N_2	N_2	N_2
% FGR	--	--	--	--	--	--	--
FLUE MEASUREMENTS							
% O_2, polar	3.25	4.9	0.65	2.50	2.85	4.50	6.5
% O_2, para.	3.15	4.75	0.65	2.55	2.8	4.35	6.25
S.R. by O_2	1.167	1.277	1.030	1.131	1.146	1.248	1.402
% CO	0.01	0.0	0.05	0.01	0.02	0.02	0.01
% CO_2	16.1	14.5	18.74	16.82	16.46	14.82	12.74
NO, as meas., ppm	735	710	620	710	690	700	670
NO, 0% EA, ppm	860	910	640	805	790	870	940
SO_2, as meas., ppm	1050	960	1280	1100	1050	1100	910

COMMENTS: 8-14 baseline conditions.

Fuel: Pittsburgh Coal   Date: 12/3   Injector: Divergent

INLET PARAMETERS							
Run No.	15	16					
Fuel flow, #/hr	--	--					
Air flow, SCFM	19.5	--					
% swirl	45	--					
Sec. air preheat, °F	485	--					
Pri. air flow, SCFM	2.4	2.4					
Inlet O_2, %	21	21					
Inlet CO_2, %	--	--					
Balance	N_2	N_2					
% FGR	--	--					
FLUE MEASUREMENTS							
% O_2, polar	4.25	2.70					
% O_2, para.	4.3	2.75					
S.R. by O_2	1.244	1.143					
% CO	0.01	--					
% CO_2	15.14	--					
NO, as meas., ppm	700	720					
NO, 0% EA, ppm	870	820					
SO_2, as meas., ppm	1030	--					

COMMENTS: 15-16 reduced primary air flow.

Fuel: Pittsburgh Coal   Date: 12/8   Injector: Divergent

INLET PARAMETERS							
Run No.	1	2	3	4	5	6	7
Fuel flow, #/hr	--	--	--	--	--	--	--
Air flow, SCFM	23.0	22.5	20.0	19.8	22.2	22.2	22.1
% swirl	46	31	30	16	15	45	62
Sec. air preheat, °F	495	495	490	500	500	470	470
Pri. air flow, SCFM	2.8	2.8	2.8	2.8	2.8	2.8	2.8
Inlet O_2, %	21	21	21	21	21	21	21
Inlet CO_2, %	--	--	--	--	--	--	--
Balance	N_2	N_2	N_2	N_2	N_2	N_2	N_2
% FGR	--	--	--	--	--	--	--
FLUE MEASUREMENTS							
% O_2, polar	2.8	3.0	1.35	1.5	3.25	2.75	2.65
% O_2, para.	3.0	3.35	1.5	1.7	3.6	3.05	2.9
S.R. by O_2	1.158	1.180	1.073	1.083	1.196	1.161	1.152
% CO	0.06	0.02	0.03	0.02	0.02	0.02	0.02
% CO_2	16.46	15.46	17.54	17.9	15.46	16.1	16.1
NO, as meas., ppm	660	575	560	720	780	660	690
NO, 0% EA, ppm	765	680	600	780	935	765	795
SO_2, as meas., ppm	--	1110	1300	1350	1100	1280	1300

COMMENTS: 1-7 effect of swirl.

Fuel: Pittsburgh Coal   Date: 12/8   Injector: Divergent

INLET PARAMETERS							
Run No.	8	9	10	11	12	13	14
Fuel flow, #/hr	--	--	--	--	--	--	--
Air flow, SCFM	22.3	20.7	22.3	21.0	20.8	19.4	--
% swirl	79	45	45	45	44	45	46
Sec. air preheat, °F	485	475	470	465	465	455	470
Pri. air flow, SCFM	2.8	2.8	3.1	4.1	>4.2	4.15	2.43
Inlet O_2, %	21	21	21	21	21	21	21.0
Inlet CO_2, %	--	--	--	--	--	--	15.8
Balance	N_2	N_2	N_2	N_2	N_2	N_2	Ar
% FGR	--	--	--	--	--	--	--

FLUE MEASUREMENTS							
% O_2, polar	2.60	2.70	2.75	3.15	3.35	1.35	1.45
% O_2, para.	2.85	3.05	3.10	3.55	3.80	1.55	--
S.R. by O_2	1.149	1.161	1.164	1.193	1.209	1.076	1.070
% CO	0.01	0.02	0.02	0.01	0.01	0.02	--
% CO_2	16.46	16.1	16.46	15.46	15.78	17.35	--
NO, as meas., ppm	700	670	720	885	880	790	550
NO, 0% EA, ppm	805	780	840	1055	1065	840	590
SO_2, as meas., ppm	1300	1300	1300	1300	1200	1380	1300

COMMENTS: 8 effect of swirl.
        9-10 baseline conditions.
        11-14 effect of primary air flow.
        11,12 lifted flames.

Fuel: Pittsburgh Coal   Date: 12/8   Injector: Divergent

INLET PARAMETERS							
Run No.	15	16	17				
Fuel flow, #/hr	--	--	--				
Air flow, SCFM	--	--	--				
% swirl	46	46	45				
Sec. air preheat, °F	480	470	470				
Pri. air flow, SCFM	2.43	2.35	2.35				
Inlet O_2, %	20.75	24.75	24.75				
Inlet CO_2, %	15.8	--	--				
Balance	Ar	N_2	N_2				
% FGR	--	--	--				
FLUE MEASUREMENTS							
% O_2, polar	3.25	3.4	2.0				
% O_2, para.	--	--	--				
S.R. by O_2	1.173	1.183	1.100				
% CO	--	--	--				
% CO_2	--	--	--				
NO, as meas., ppm	595	685	615				
NO, 0% EA, ppm	715	670	565				
SO_2, as meas., ppm	1170	--	1450				

COMMENTS: 15 Ar/O_2/CO_2.
          16-17 oxygen enrichment.

Fuel: Pittsburgh Coal   Date: 12/17   Injector: Divergent

INLET PARAMETERS							
Run No.	1	2	3	4	5	6	7
Fuel flow, #/hr	--	--	--	--	--	--	--
Air flow, SCFM	20.5	19.4	18.2	19.2	20.7	19.4	18.4
% swirl	37	36	36	36	36	36	37
Sec. air preheat, °F	480	480	480	485	295	480	470
Pri. air flow, SCFM	2.8	2.8	2.8	2.8	2.8	2.8	2.8
Inlet O_2, %	21	21	21	21	21	21	21
Inlet CO_2, %	--	--	--	--	--	--	--
Balance	N_2	N_2	N_2	N_2	N_2	N_2	N_2
% FGR	--	--	--	--	--	--	--
FLUE MEASUREMENTS							
% O_2, polar	3.95	2.70	1.55	2.85	--	3.6	--
% O_2, para.	4.05	2.65	1.50	2.9	--	3.65	1.9
S.R. by O_2	1.226	1.137	1.073	1.152	--	1.199	1.094
% CO	0.02	0.05	0.08	0.03	0.02	0.05	0.20
% CO_2	14.82	16.1	17.35	15.55	14.2	15.3	17.18
NO, as meas., ppm	560	560	500	580	--	710	685
NO, 0% EA, ppm	685	635	535	670	--	850	750
SO_2, as meas., ppm	1100	1250	1350	1250	1150	1300	1450

COMMENTS: 1-5 shakedown.
           6-7 reduced swirl, injector raised 1/4".

Fuel: Pittsburgh Coal   Date: 12/17   Injector: Divergent

INLET PARAMETERS							
Run No.	8	9	10	11	12		
Fuel flow, #/hr	--	--	--	--	--		
Air flow, SCFM	18.9	18.6	18.6	17.3	18.1		
% swirl	36	36	37	36	37		
Sec. air preheat, °F	485	490	490	480	485		
Pri. air flow, SCFM	2.8	2.8	2.8	2.8	2.8		
Inlet O_2, %	21.0	21	21	21	21		
Inlet CO_2, %	8.4	--	--	--	--		
Balance	N_2	N_2	N_2	N_2	N_2		
% FGR	--	13.2	14.1	14.9	14.0		
FLUE MEASUREMENTS							
% O_2, polar	3.5	4.0	2.95	1.6	3.5		
% O_2, para.	--	--	--	--	--		
S.R. by O_2	--	1.223	1.155	1.078	1.189		
% CO	--	0.07	0.07	0.14	0.06		
% CO_2	--	14.9	15.9	17.6	15.0		
NO, as meas., ppm	680	660	690	615	655		
NO, 0% EA, ppm	815	807	797	663	779		
SO_2, as meas., ppm	1170	1120	1190	1280	1180		

COMMENTS: 8-12 reduced swirl, injector raised.
            9-12 FGR.

Fuel: Pittsburgh Coal   Date: 12/18   Injector: Divergent

INLET PARAMETERS							
Run No.	1	2	3	4	5	6	7
Fuel flow, #/hr	--	--	--	--	--	--	--
Air flow, SCFM	20.5	21.3	19.1	20.1	21.1	20.2	18.8
% swirl	38	39	36	38	38	46	45
Sec. air preheat, °F	495	490	470	470	480	475	465
Pri. air flow, SCFM	2.8	2.8	2.8	2.8	2.8	2.8	2.8
Inlet O_2, %	21	21	21	21	21	21	21
Inlet CO_2, %	--	--	--	--	--	--	--
Balance	N_2	N_2	N_2	N_2	N_2	N_2	N_2
% FGR	--	--	--	--	--	--	--
FLUE MEASUREMENTS							
% O_2, polar	3.2	4.75	1.55	2.60	3.75	2.85	1.25
% O_2, para.	3.0	4.65	1.35	2.45	3.7	2.75	1.1
S.R. by O_2	1.158	1.269	1.065	1.125	1.203	1.143	1.052
% CO	0.09	0.04	0.18	0.04	0.02	0.02	0.30
% CO_2	16.1	14.5	17.9	16.1	15.14	16.46	17.9
NO, as meas., ppm	620	670	525	610	640	695	510
NO, 0% EA, ppm	720	850	560	685	770	795	580
SO_2, as meas., ppm	1400	1250	1500	1390	1290	1320	1500

COMMENTS: 1-5 warm-up.
           6-7 baseline conditions.

Fuel: Pittsburgh Coal   Date: 12/18   Injector: Divergent

INLET PARAMETERS							
Run No.	8	9	10				
Fuel flow, #/hr	--	--	--				
Air flow, SCFM	17.3	16.9	--				
% swirl	45	45	--				
Sec. air preheat, °F	460	--	--				
Pri. air flow, SCFM	2.5	2.5	2.5				
Inlet O_2, %	25	25	24.6				
Inlet CO_2, %	--	--	--				
Balance	N_2	N_2	N_2				
% FGR	--	--	--				

FLUE MEASUREMENTS							
% O_2, polar	3.75	3.0	2.75				
% O_2, para.	--	--	--				
S.R. by O_2	1.166	1.128	1.119				
% CO	0.04	0.05	--				
% CO_2	20.0	>20.0	--				
NO, as meas., ppm	810	780	720				
NO, 0% EA, ppm	795	737	690				
SO_2, as meas., ppm	1400	--	--				

COMMENTS: 8-10 oxygen enrichment.

Fuel: Pittsburgh Coal   Date: 12/19   Injector: Divergent

INLET PARAMETERS							
Run No.	1	2	3	4	5		
Fuel flow, #/hr	--	--	--	--	--		
Air flow, SCFM	17.2	17.9	19.6	19.5	21.0		
% swirl	45	45	48	46	46		
Sec. air preheat, °F	480	480	490	490	495		
Pri. air flow, SCFM	2.5	2.5	2.8	2.8	2.8		
Inlet O_2, %	24.8	24.85	20.85	20.85	20.85		
Inlet CO_2, %	--	--	--	--	--		
Balance	N_2	N_2	N_2	N_2	N_2		
% FGR	--	--	--	--	--		

FLUE MEASUREMENTS							
% O_2, polar	2.05	3.55	2.25	2.9	3.9		
% O_2, para.	--	--	--	--	--		
S.R. by O_2	1.085	1.157	1.114	1.152	1.216		
% CO	0.44	0.04	0.09	0.07	0.04		
% CO_2	>20.0	19.8	16.8	16.0	15.0		
NO, as meas., ppm	690	750	585	620	600		
NO, 0% EA, ppm	635	735	650	715	730		
SO_2, as meas., ppm	1700	1600	1490	1400	1050		

COMMENTS:

Fuel: Pittsburgh Coal   Date: 12/19   Injector: Divergent

INLET PARAMETERS							
Run No.	6	7	8				
Fuel flow, #/hr	--	--	--				
Air flow, SCFM	--	--	--				
% swirl	45	--	--				
Sec. air preheat, °F	460	--	--				
Pri. air flow, SCFM	2.43	2.43	2.43				
Inlet O_2, %	20.8	20.5	20.3				
Inlet CO_2, %	--	--	--				
Balance	Ar	Ar	Ar				
% FGR	--	--	--				
FLUE MEASUREMENTS							
% O_2, polar	1.9	2.45	3.65				
% O_2, para.	--	--	--				
S.R. by O_2	1.095	1.129	1.208				
% CO	0.14	0.04	--				
% CO_2	15.0	12.8	--				
NO, as meas., ppm	530	570	590				
NO, 0% EA, ppm	590	665	745				
SO_2, as meas., ppm	1600	1560	--				

COMMENTS: 6-8 Ar/O_2.

D.3 Western Kentucky Coal

The following pages contain a complete tabulation of the experimental data obtained during the Western Kentucky coal combustion studies. In general, the parameters are the same as those discussed in Section D.1 with the following exceptions:

1. The air flow entry refers only to the amount of secondary air. It no longer includes the primary air as in the previous sections.

2. The primary air flow rates are correct.

3. The inlet oxygen refers to the oxygen concentration in both the primary and secondary streams unless the primary oxygen concentration is listed separately in which case the inlet O_2 entry refers to the secondary alone.

4. There is a second data sheet associated with each test in the char/volatile series where NO or NH_3 was added. This second sheet shows the additive and the rotameter reading with the corresponding flow rate. It also shows the point at which the additive was introduced:

   pa = primary air stream just prior to the fuel injector (normal position),

   p = stainless steel water-cooled probe at the beginning of the flue duct,

   and the point at which the flue gas sample was withdrawn:

   p = stainless steel water-cooled probe at the beginning of the flue duct (normal position),

s = stainless steel tube at the end of the flue duct (approximately 30 ft downstream of the probe).

The emission data are also listed on this second sheet in ppm (STOICHI). The measured NO is the base plus additive case. The base (without additive) case emission is a directly adjacent test. Conversion is based on the metered additive flow rate.

Fuel: Western Kentucky Coal　　　Date: 1/20　　　Injector: Divergent

INLET PARAMETERS							
Run No.	1	2	3	4	5	6	7
Fuel flow, #/hr	5.9	5.9	5.9	5.9	5.9	5.9	5.9
Air flow, SCFM	13.9	12.9	12.3	13.4	14.3	14.5	12.7
% swirl	45	45	45	45	45	45	45
Sec. air preheat, °F	655	645	645	640	640	645	640
Pri. air flow, SCFM	2.15	2.15	2.15	2.15	2.15	2.15	2.8
Inlet O_2, %	21	21	21	21	21	21	21
Inlet CO_2, %	--	--	--	--	--	--	--
Balance	N_2	N_2	N_2	N_2	N_2	N_2	N_2
% FGR	--	--	--	--	--	--	--

FLUE MEASUREMENTS							
% O_2, polar	2.70	1.55	0.95	--	--	--	1.90
% O_2, para.	2.85	1.70	0.95	--	--	--	2.05
S.R. by O_2	1.148	1.083	1.045	--	--	--	1.102
% CO	0	0.01	0.03	0.02	0	0.01	0.01
% CO_2	16.1	17.4	18.1	16.5	14.8	16.8	15.1
NO, as meas., ppm	785	740	675	--	--	--	720
NO, 0% EA, ppm	910	805	710	--	--	--	800
SO_2, as meas., ppm	1520	1650	1710	1580	--	1400	1600

COMMENTS:　1-6 shakedown testing.
　　　　　　7 baseline conditions.

Fuel: Western Kentucky Coal   Date: 1/20   Injector: Divergent

INLET PARAMETERS							
Run No.	8	9	10	11	12	13	14
Fuel flow, #/hr	5.9	5.9	5.9	5.9	5.9	5.9	5.9
Air flow, SCFM	14.0	14.5	17.0	13.4	12.8	11.9	11.5
% swirl	45	47	45	45	45	45	45
Sec. air preheat, °F	650	660	690	670	655	650	640
Pri. air flow, SCFM	2.8	2.8	2.8	2.8	2.8	2.8	2.8
Inlet O_2, %	21	21	21	21	21	21	21
Inlet CO_2, %	--	--	--	--	--	--	--
Balance	N_2	N_2	N_2	N_2	N_2	N_2	N_2
% FGR	--	--	--	--	--	--	--
FLUE MEASUREMENTS							
% O_2, polar	3.25	3.75	6.0	3.55	2.65	1.8	1.3
% O_2, para.	3.65	4.35	6.3	3.3	2.4	1.7	1.2
S.R. by O_2	1.198	1.246	1.403	1.175	1.121	1.083	1.057
% CO	0	0	0.01	0.01	0	0.02	0.01
% CO_2	15.14	14.82	12.74	15.78	16.82	17.2	17.9
NO, as meas., ppm	740	730	720	750	760	730	710
NO, 0% EA, ppm	895	920	1030	890	860	795	753
SO_2, as meas., ppm	1460	1400	1290	1500	1580	1670	1700

COMMENTS: 8-14 baseline testing.

Fuel: Western Kentucky Coal   Date: 1/20   Injector: Divergent

INLET PARAMETERS							
Run No.	15	16	17	18	19	20	21
Fuel flow, #/hr	5.9	5.9	5.9	5.9	5.9	5.9	5.9
Air flow, SCFM	10.6	13.3	12.5	13.6	13.5	10.4	9.9
% swirl	44	45	32	32	25	19	44
Sec. air preheat, °F	625	640	645	655	670	660	570
Pri. air flow, SCFM	2.8	2.8	2.8	2.8	2.8	2.8	2.8
Inlet O_2, %	21	21	21	21	21	21	21
Inlet CO_2, %	--	--	--	--	--	--	--
Balance	N_2	N_2	N_2	N_2	N_2	N_2	N_2
% FGR	--	--	--	--	--	--	--

FLUE MEASUREMENTS							
% O_2, polar	0.3	3.5	3.1	4.55	4.4	1.7	1.2
% O_2, para.	0.25	3.5	3.05	4.55	4.5	1.7	1.05
S.R. by O_2	1.011	1.188	1.160	1.260	1.256	1.083	1.049
% CO	0.12	0.03	0.01	0.02	0	0.02	0.01
% CO_2	18.74	15.78	16.1	14.5	14.1	17.9	17.9
NO, as meas., ppm	560	740	680	720	880	880	645
NO, 0% EA, ppm	565	890	795	920	1120	966	680
SO_2, as meas., ppm	1830	1500	1500	1410	1420	1600	1550

COMMENTS: 15-16 baseline conditions.
        17-21 effect of swirl.
        19,20 lifted flames.

Fuel: Western Kentucky Coal   Date: 1/20   Injector: Divergent

INLET PARAMETERS							
Run No.	22	23					
Fuel flow, #/hr	5.9	5.9					
Air flow, SCFM	11.4	11.2					
% swirl	60	93					
Sec. air preheat, °F	590	615					
Pri. air flow, SCFM	2.8	2.8					
Inlet O_2, %	21	21					
Inlet CO_2, %	--	--					
Balance	N_2	N_2					
% FGR	--	--					

FLUE MEASUREMENTS							
% O_2, polar	3.2	3.4					
% O_2, para.	3.0	3.3					
S.R. by O_2	1.157	1.175					
% CO	0.02	0.02					
% CO_2	16.1	15.8					
NO, as meas., ppm	810	740					
NO, 0% EA, ppm	946	879					
SO_2, as meas., ppm	1560	1570					

COMMENTS: 22-23 effect of swirl.

Fuel: Western Kentucky Coal   Date: 1/21   Injector: Divergent

INLET PARAMETERS							
Run No.	1	2	3	4	5	6	7
Fuel flow, #/hr	5.9	5.9	5.9	5.9	5.9	5.9	5.9
Air flow, SCFM	12.5	13.5	14.8	16.3	18.1	15.0	--
% swirl	43	43	44	44	44	43	44
Sec. air preheat, °F	110	110	110	110	115	120	110
Pri. air flow, SCFM	2.8	2.8	2.8	2.8	2.8	2.8	2.43
Inlet O_2, %	21	21	21	21	21	21	21.7
Inlet CO_2, %	--	--	--	--	--	--	11.3
Balance	N_2	N_2	N_2	N_2	N_2	N_2	Ar
% FGR	--	--	--	--	--	--	--
FLUE MEASUREMENTS							
% O_2, polar	1.30	2.45	3.65	5.0	7.1	3.9	1.55
% O_2, para.	1.15	2.25	3.25	4.75	6.9	3.75	--
S.R. by O_2	1.054	1.113	1.172	1.275	1.460	1.204	1.072
% CO	0.07	0.01	0.0	0.0	0.0	0.0	--
% CO_2	18.3	17.0	16.2	14.0	12.1	14.6	--
NO, as meas., ppm	565	580	580	570	540	570	600
NO, 0% EA, ppm	600	650	685	740	805	695	625
SO_2, as meas., ppm	1670	1570	1490	1320	1160	1400	1710

COMMENTS: 1-6 NO air preheat.
          7 Ar/O_2/CO_2.

Fuel: Western Kentucky Coal   Date: 1/21   Injector: Divergent

INLET PARAMETERS							
Run No.	8	9	10	11	12	13	14
Fuel flow, #/hr	5.9	5.9	5.9	5.9	5.9	5.9	5.9
Air flow, SCFM	15.8	18.6	15.5	14.2	17.4	17.5	17.9
% swirl	44	44	22	23	44	44	44
Sec. air preheat, °F	110	110	110	110	110	110	110
Pri. air flow, SCFM	2.43	2.43	2.43	2.43	2.43	1.91	2.87
Inlet O_2, %	21.4	21.1	21.5	21.5	19.3	19.3	19.7
Inlet CO_2, %	11.4	11.3	10.8	10.6	16.1	15.8	16.1
Balance	Ar	Ar	Ar	Ar	Ar	Ar	Ar
% FGR	--	--	--	--	--	--	--
FLUE MEASUREMENTS							
% O_2, polar	3.0	6.3	3.55	1.95	3.2	3.5	3.4
% O_2, para.	--	--	--	--	--	--	--
S.R. by O_2	1.152	1.397	1.185	1.093	1.186	1.207	1.195
% CO	--	--	--	--	--	--	--
% CO_2	--	--	--	--	--	--	--
NO, as meas., ppm	630	620	955	930	580	550	675
NO, 0% EA, ppm	718	879	1115	995	760	730	870
SO_2, as meas., ppm	1550	1320	1520	1620	1350	1280	1330

COMMENTS: 8-14 Ar/O_2/CO_2.
            10,11 lifted flames.

Fuel: Western Kentucky Coal   Date: 1/21   Injector: Divergent

INLET PARAMETERS							
Run No.	15						
Fuel flow, #/hr	5.9						
Air flow, SCFM	14.3						
% swirl	44						
Sec. air preheat, °F	110						
Pri. air flow, SCFM	2.43						
Inlet O_2, %	18.9						
Inlet CO_2, %	16.1						
Balance	Ar						
% FGR	--						
FLUE MEASUREMENTS							
% O_2, polar	0.87						
% O_2, para.	--						
S.R. by O_2	1.043						
% CO	--						
% CO_2	--						
NO, as meas., ppm	515						
NO, 0% EA, ppm	568						
SO_2, as meas., ppm	1415						

COMMENTS: 15 Ar/O_2/CO_2.

Fuel: Western Kentucky Coal   Date: 1/22   Injector: Divergent

INLET PARAMETERS							
Run No.	1	2	3	4	5	6	7
Fuel flow, #/hr	5.9	5.9	5.9	5.9	5.9	5.9	5.9
Air flow, SCFM	12.6	13.4	14.0	15.9	14.0	12.9	12.3
% swirl	44	44	44	44	44	44	44
Sec. air preheat, °F	635	645	675	685	590	600	615
Pri. air flow, SCFM	2.8	2.8	2.8	2.8	2.8	2.8	2.8
Inlet O_2, %	21	21	21	21	21	21	21
Inlet CO_2, %	--	--	--	--	--	--	--
Balance	N_2	N_2	N_2	N_2	N_2	N_2	N_2
% FGR	--	--	--	--	--	--	--
FLUE MEASUREMENTS							
% O_2, polar	1.1	1.6	2.5	4.25	3.05	1.8	1.3
% O_2, para.	1.1	1.6	2.6	4.45	3.25	1.9	1.4
S.R. by O_2	1.052	1.078	1.133	1.253	1.172	1.094	1.067
% CO	0.04	0.03	0.02	0.01	0.01	0.02	0.01
% CO_2	17.5	17.1	16.1	14.3	15.4	16.8	17.3
NO, as meas., ppm	510	570	610	640	630	615	600
NO, 0% EA, ppm	540	620	695	815	745	675	645
SO_2, as meas., ppm	1800	1800	1730	1500	1650	1750	1820

COMMENTS: 1-7 warm-up.

Fuel: Western Kentucky Coal   Date: 1/22   Injector: Divergent

INLET PARAMETERS							
Run No.	8	9	10	11	12	13	14
Fuel flow, #/hr	5.9	5.9	5.9	5.9	5.9	5.9	5.9
Air flow, SCFM	15.0	14.9	13.1	13.5	15.9	12.0	12.1
% swirl	44	44	44	44	44	44	44
Sec. air preheat, °F	645	695	685	665	675	660	675
Pri. air flow, SCFM	2.8	2.8	2.8	2.8	2.8	2.8	2.8
Inlet O_2, %	21	20.75	21.0	--	21	21	17.75
Inlet CO_2, %	--	13.0	10.2	15.8	--	--	3.8
Balance	N_2	N_2	N_2	N_2	N_2	N_2	N_2
% FGR	--	--	--	--	--	--	16.4
FLUE MEASUREMENTS							
% O_2, polar	4.0	3.85	2.5	2.6	4.5	1.15	1.25
% O_2, para.	4.25	--	--	--	4.9	1.3	--
S.R. by O_2	1.239	1.213	1.126	--	1.286	1.062	1.060
% CO	0.01	--	--	--	0.01	0.02	--
% CO_2	14.5	--	--	--	14.0	17.0	--
NO, as meas., ppm	640	650	670	700	705	655	555
NO, 0% EA, ppm	804	808	760	--	921	700	590
SO_2, as meas., ppm	1570	1250	1420	1650	1500	1800	1600

COMMENTS: 8 warm-up.
            9-11 CO_2 addition.
            14 FGR.

Fuel: Western Kentucky Coal   Date: 1/22   Injector: Divergent

INLET PARAMETERS							
Run No.	15	16	17	18	19	20	21
Fuel flow, #/hr	5.9	5.9	5.9	5.9	5.9	5.9	5.9
Air flow, SCFM	14.0	16.3	15.0	12.9	12.0	13.3	12.6
% swirl	45	44	44	44	44	44	44
Sec. air preheat, °F	675	685	705	715	710	705	675
Pri. air flow, SCFM	2.8	2.8	2.8	2.8	2.8	2.8	2.8
Inlet O_2, %	18.5	19.0	18.1	17.75	17.6	19.1	18.75
Inlet CO_2, %	2.0	1.2	2.4	2.6	2.8	1.8	2.0
Balance	N_2	N_2	N_2	N_2	N_2	N_2	N_2
% FGR	14.1	12.5	18.2	19.0	19.0	10.6	11.8

FLUE MEASUREMENTS							
% O_2, polar	3.25	5.0	5.1	3.85	3.05	3.05	2.0
% O_2, para.	--	--	--	--	--	--	--
S.R. by O_2	1.172	1.294	1.302	1.211	1.160	1.160	1.099
% CO	--	--	--	--	--	--	--
% CO_2	--	--	--	--	--	--	--
NO, as meas., ppm	625	650	630	600	580	625	605
NO, 0% EA, ppm	740	855	835	735	680	730	670
SO_2, as meas., ppm	1440	1300	1200	1360	1450	1500	--

COMMENTS: 15-21 FGR.

Fuel: Western Kentucky Coal   Date: 1/22   Injector: Divergent

INLET PARAMETERS							
Run No.	22	23	24	25	26		
Fuel flow, #/hr	5.9	5.9	5.9	5.9	5.9		
Air flow, SCFM	14.7	13.2	11.6	14.6	16.5		
% swirl	45	45	44	44	45		
Sec. air preheat, °F	690	675	650	665	675		
Pri. air flow, SCFM	2.8	2.8	2.8	2.8	2.8		
Inlet O_2, %	19.25	21	21	21	21		
Inlet CO_2, %	--	--	--	--	--		
Balance	N_2	N_2	N_2	N_2	N_2		
% FGR	10.7	--	--	--	--		

FLUE MEASUREMENTS							
% O_2, polar	4.6	3.35	2.05	4.85	6.25		
% O_2, para.	--	3.9	2.35	5.4	7.1		
S.R. by O_2	1.264	1.214	1.118	1.326	1.480		
% CO	--	0.01	0.0	0.01	0.0		
% CO_2	--	14.82	16.6	13.3	11.9		
NO, as meas., ppm	640	730	730	730	710		
NO, 0% EA, ppm	820	895	820	985	1075		
SO_2, as meas., ppm	1500	1600	1790	1490	1310		

COMMENTS: 22 FGR.
          23-26 baseline conditions.

Fuel: Western Kentucky Coal   Date: 1/23   Injector: Divergent

INLET PARAMETERS							
Run No.	1	2	3	4	5	6	7
Fuel flow, #/hr	5.9	5.9	5.9	5.9	5.9	5.9	5.9
Air flow, SCFM	14.4	13.1	16.2	14.0	15.0	14.4	13.4
% swirl	44	44	44	44	44	46	44
Sec. air preheat, °F	665	675	675	675	675	675	675
Pri. air flow, SCFM	2.8	2.8	2.8	2.2	2.2	3.4	3.4
Inlet O_2, %	21	21	21	21	21	21	21
Inlet CO_2, %	--	--	--	--	--	--	--
Balance	N_2	N_2	N_2	N_2	N_2	N_2	N_2
% FGR	--	--	--	--	--	--	--
FLUE MEASUREMENTS							
% O_2, polar	2.75	1.35	4.45	2.43	3.3	3.45	2.6
% O_2, para.	2.75	1.25	4.4	2.35	3.2	3.45	2.55
S.R. by O_2	1.142	1.060	1.249	1.118	1.169	1.185	1.130
% CO	0.02	0.03	0.0	0.01	0.0	0.0	0.0
% CO_2	16.4	18.1	14.9	17.1	15.6	15.9	16.8
NO, as meas., ppm	795	735	835	660	710	1060	1030
NO, 0% EA, ppm	915	780	1060	740	840	1270	1175
SO_2, as meas., ppm	1560	1710	1400	1630	1550	1500	1580

COMMENTS: 1-3 baseline conditions.
           4-7 effect of primary air flow.

Fuel: Western Kentucky Coal   Date: 1/23   Injector: Divergent

INLET PARAMETERS							
Run No.	8	9	10	11	12	13	14
Fuel flow, #/hr	5.9	5.9	5.9	5.9	5.9	5.9	5.9
Air flow, SCFM	13.4	15.2	11.8	10.6	13.1	11.2	10.2
% swirl	44	44	44	43	43	41	41
Sec. air preheat, °F	665	675	655	655	655	645	630
Pri. air flow, SCFM	4.05	4.0	4.0	4.0	2.8	2.4	2.4
Inlet O_2, %	21	21	21	21	21	24.5	--
Inlet CO_2, %	--	--	--	--	--	--	--
Balance	N_2	N_2	N_2	N_2	N_2	N_2	N_2
% FGR	--	--	--	--	--	--	--
FLUE MEASUREMENTS							
% O_2, polar	3.77	5.1	2.67	1.50	2.05	2.8	--
% O_2, para.	3.75	5.1	2.65	1.45	--	--	--
S.R. by O_2	1.204	1.302	1.136	1.070	1.102	1.120	--
% CO	0.0	0.0	0.01	--	--	0.01	0.07
% CO_2	15.4	13.8	16.6	--	--	--	>20.0
NO, as meas., ppm	1120	1120	1025	910	795	755	--
NO, 0% EA, ppm	1365	1480	1170	980	882	727	--
SO_2, as meas., ppm	1510	1350	1530	--	--	1800	1980

COMMENTS: 8-11 effect of primary air, lifted.
12 baseline conditions.
13-14 oxygen enrichment.

Fuel: Western Kentucky Coal   Date: 1/23   Injector: Divergent

INLET PARAMETERS							
Run No.	15	16	17				
Fuel flow, #/hr	5.9	5.9	5.9				
Air flow, SCFM	10.8	12.9	10.9				
% swirl	42	44	43				
Sec. air preheat, °F	615	650	640				
Pri. air flow, SCFM	2.4	2.4	2.4				
Inlet O_2, %	24.1	24.6	23.9				
Inlet CO_2, %	--	--	--				
Balance	N_2	N_2	N_2				
% FGR	--	--	--				

FLUE MEASUREMENTS							
% O_2, polar	1.85	5.25	2.65				
% O_2, para.	--	--	--				
S.R. by O_2	--	--	--				
% CO	--	0.01	0				
% CO_2	>20.0	17.5	19.6				
NO, as meas., ppm	695	810	750				
NO, 0% EA, ppm	650	875	740				
SO_2, as meas., ppm	1870	1600	1800				

COMMENTS: 15-17 oxygen enrichment.

Fuel: Western Kentucky Coal   Date: 2/12   Injector: Divergent

INLET PARAMETERS							
Run No.	1	2	3	4	5	6	7
Fuel flow, #/hr	5.9	5.9	5.9	5.9	5.9	5.9	5.9
Air flow, SCFM	11.4	13.2	14.8	14.0	13.9	15.4	14.9
% swirl	44	44	44	43	43	44	44
Sec. air preheat, °F	636	646	673	664	661	673	666
Pri. air flow, SCFM	1.8	1.8	1.8	1.8	1.5	1.5	1.5
Inlet O_2, %	21	21	21	21	21	21	21
Inlet CO_2, %	--	--	--	--	--	--	--
Balance	N_2	N_2	N_2	N_2	N_2	N_2	N_2
% FGR	--	--	--	--	--	--	--
FLUE MEASUREMENTS							
% O_2, polar	1.55	2.1	4.05	3.25	3.25	4.55	4.25
% O_2, para.	1.45	2.0	4.15	3.3	3.35	4.6	4.5
S.R. by O_2	1.069	1.098	1.230	1.174	1.177	1.262	1.255
% CO	0.05	0.04	0.03	0.03	0.03	0.02	0.04
% CO_2	17.18	16.82	15.3	15.46	15.78	14.2	14.82
NO, as meas., ppm	710	740	810	780	650	665	700
NO, 0% EA, ppm	765	820	1010	925	775	850	890
SO_2, as meas., ppm	1280	1360	1400	1000	1000	910	890

COMMENTS: 1-4 baseline conditions.
5-8 reduced primary air.

Fuel: Western Kentucky Coal   Date: 2/12   Injector: Divergent

INLET PARAMETERS								
Run No.	8							
Fuel flow, #/hr	5.9							
Air flow, SCFM	11.8							
% swirl	44							
Sec. air preheat, °F	638							
Pri. air flow, SCFM	1.5							
Inlet O_2, %	21							
Inlet CO_2, %	--							
Balance	N_2							
% FGR	--							
FLUE MEASUREMENTS								
% O_2, polar	1.4							
% O_2, para.	1.4							
S.R. by O_2	1.067							
% CO	0.05							
% CO_2	17.54							
NO, as meas., ppm	600							
NO, O% EA, ppm	645							
SO_2, as meas., ppm	1140							

COMMENTS: 8 reduced primary air flow.

Fuel: Western Kentucky Coal　　　Date: 2/12　　　Injector: Axial

INLET PARAMETERS							
Run No.	9	10	11	12	13		
Fuel flow, #/hr	5.9	5.9	5.9	5.9	5.9		
Air flow, SCFM	15.4	17.0	18.0	18.4	16.3		
% swirl	44	44	44	45	45		
Sec. air preheat, °F	496	474	536	566	576		
Pri. air flow, SCFM	1.0	1.0	1.0	1.25	1.25		
Inlet O_2, %	21	21	21	21	21		
Inlet CO_2, %	--	--	--	--	--		
Balance	N_2	N_2	N_2	N_2	N_2		
% FGR	--	--	--	--	--		
FLUE MEASUREMENTS							
% O_2, polar	1.95	3.0	5.15	4.0	2.15		
% O_2, para.	--	--	--	--	--		
S.R. by O_2	1.096	1.156	1.303	1.220	1.107		
% CO	0.11	0.07	0.06	0.04	0.06		
% CO_2	16.82	15.46	13.0	14.2	16.46		
NO, as meas., ppm	380	430	480	500	405		
NO, 0% EA, ppm	420	500	635	620	450		
SO_2, as meas., ppm	1600	1300	900	1000	1100		

COMMENTS: 9-11 baseline conditions.
　　　　　12-13 increased primary air, lifted flames.

Fuel: Western Kentucky Coal   Date: 2/19   Injector: Axial

INLET PARAMETERS							
Run No.	1	2	3	4	5	6	7
Fuel flow, #/hr	5.9	5.9	5.9	5.9	5.9	5.9	5.9
Air flow, SCFM	15.2	15.8	17.1	17.3	16.0	--	--
% swirl	51	51	51	53	50	54	53
Sec. air preheat, °F	85	90	95	100	100	100	100
Pri. air flow, SCFM	1.0	1.0	1.0	1.0	1.5	0.87	0.87
Inlet O_2, %	21	21	21	21	21	19.7	19.1
Inlet CO_2, %	--	--	--	--	--	15.9	15.5
Balance	N_2	N_2	N_2	N_2	N_2	Ar	Ar
% FGR	--	--	--	--	--	--	--
		·					

FLUE MEASUREMENTS							
% O_2, polar	1.55	1.80	2.45	3.45	--	1.45	2.0
% O_2, para.	1.35	1.45	2.4	3.4	2.0	--	--
S.R. by O_2	1.064	1.069	1.121	1.180	1.098	1.074	1.110
% CO	0.14	0.07	0.06	0.06	0.06	--	--
% CO_2	18.0	16.8	16.46	14.82	16.6	--	--
NO, as meas., ppm	300	340	360	410	360	315	365
NO, 0% EA, ppm	320	365	405	490	400	360	450
SO_2, as meas., ppm	1840	1850	1650	1500	1700	1780	1600

COMMENTS: 1-5 reduced air preheat.
           4-5 increased primary air.
           5 lifted flame.

Fuel: Western Kentucky Coal   Date: 2/19   Injector: Axial

INLET PARAMETERS							
Run No.	8	9					
Fuel flow, #/hr	5.9	5.9					
Air flow, SCFM	--	--					
% swirl	53	53					
Sec. air preheat, °F	100	100					
Pri. air flow, SCFM	0.87	0.87					
Inlet O_2, %	19.7	18.9					
Inlet CO_2, %	0.2	8.2					
Balance	Ar	Ar					
% FGR	--	--					

FLUE MEASUREMENTS							
% O_2, polar	4.15	4.2					
% O_2, para.	--	--					
S.R. by O_2	1.250	1.268					
% CO	--	--					
% CO_2	--	--					
NO, as meas., ppm	455	425					
NO, 0% EA, ppm	615	605					
SO_2, as meas., ppm	1750	1200					

COMMENTS:

Fuel: Western Kentucky Coal   Date: 2/20   Injector: Divergent

INLET PARAMETERS							
Run No.	5	6	7				
Fuel flow, #/hr	5.9	5.9	5.9				
Air flow, SCFM	11.0	12.2	13.2				
% swirl	45	44	44				
Sec. air preheat, °F	500	525	548				
Pri. air flow, SCFM	1.8	1.8	1.8				
Inlet O_2, %	25.5	25.2	24.9				
Inlet CO_2, %	--	--	--				
Balance	N_2	N_2	N_2				
% FGR	--	--	--				

FLUE MEASUREMENTS							
% O_2, polar	1.05	2.3	3.45				
% O_2, para.	--	--	--				
S.R. by O_2	1.040	1.093	1.149				
% CO	0.07	0.09	0.03				
% CO_2	>20.0	>20.0	19.58				
NO, as meas., ppm	815	890	940				
NO, 0% EA, ppm	700	815	920				
SO_2, as meas., ppm	2450	1750	1600				

COMMENTS: (1-4 natural gas data).
          5-7 oxygen enrichment.

Fuel: Western Kentucky Coal   Date: 2/20   Injector: Divergent

INLET PARAMETERS							
Run No.	8	9	10	11	12	13	14
Fuel flow, #/hr	5.9	5.9	5.9	5.9	5.9	5.9	5.9
Air flow, SCFM	14.4	15.2	11.1	10.1	9.8	11.8	10.7
% swirl	45	44	44	44	44	44	44
Sec. air preheat, °F	563	598	578	558	542	550	547
Pri. air flow, SCFM	1.8	1.8	1.8	1.8	1.8	1.3	1.3
Inlet O_2, %	24.6	24.8	29.0	29.4	29.5	28.6	28.8
Inlet CO_2, %	--	--	--	--	--	--	--
Balance	N_2	N_2	N_2	N_2	N_2	N_2	N_2
% FGR	--	--	--	--	--	--	--
FLUE MEASUREMENTS							
% O_2, polar	3.9	4.75	4.0	2.6	2.05	3.75	2.35
% O_2, para.	--	--	--	--	--	--	--
S.R. by O_2	1.175	1.220	1.148	1.090	1.069	1.139	1.082
% CO	0.04	0.04	0.03	0.06	0.07	0.04	--
% CO_2	19.16	17.9	>20.0	>20.0	>20.0	>20.0	>20.0
NO, as meas., ppm	940	920	1040	950	955	815	775
NO, 0% EA, ppm	955	965	875	745	730	690	615
SO_2, as meas., ppm	1500	1450	1700	1850	1900	1700	1880

COMMENTS: 8-14 oxygen enrichment.
10 NO_x = 890 ppm, 0% EA.

Fuel: Western Kentucky Coal   Date: 2/20   Injector: Divergent

INLET PARAMETERS							
Run No.	15	16	17	18	19	20	21
Fuel flow, #/hr	5.9	5.9	5.9	5.9	5.9	5.9	5.9
Air flow, SCFM	--	9.7	10.6	9.54	9.47	9.54	8.9
% swirl	--	44	44	44	44	44	44
Sec. air preheat, °F	--	550	558	528	538	530	520
Pri. air flow, SCFM	1.8	1.8	1.3	1.3	1.3	1.3	1.8
Inlet O_2, %	30.0	30.5	30.0	30.5	28.8	29.2	29.4
Inlet CO_2, %	--	--	--	--	--	--	--
Balance	N_2	N_2	N_2	N_2	N_2	N_2	N_2
% FGR	--	--	--	--	--	--	--
FLUE MEASUREMENTS							
% O_2, polar	4.70	2.95	4.05	2.5	0.95	1.2	2.15
% O_2, para.	--	--	--	--	--	--	--
S.R. by O_2	1.171	1.099	1.144	1.082	1.032	1.040	1.073
% CO	--	0.06	0.03	0.06	0.13	0.06	0.06
% CO_2	--	>20.0	>20.0	>20.0	>20.0	>20.0	>20.0
NO, as meas., ppm	1130	1160	900	870	735	770	970
NO, 0% EA, ppm	940	885	730	655	555	575	750
SO_2, as meas., ppm	--	1710	1800	1900	2100	1940	1890

COMMENTS: 15-21 oxygen enrichment.

Fuel: Western Kentucky Coal   Date: 2/20   Injector: Divergent

INLET PARAMETERS							
Run No.	22	23	24	25	26	27	28
Fuel flow, #/hr	5.9	5.9	5.9	5.9	5.9	5.9	5.9
Air flow, SCFM	10.2	--	--	--	--	--	8.1
% swirl	44	44	44	44	44	44	44
Sec. air preheat, °F	525	414	430	442	434	419	331
Pri. air flow, SCFM	1.8	1.45	1.63	1.63	2.17	2.17	0.73
Inlet O_2, %	28.5	30.5	23.1	22.95	16.8	16.2	28.8
Inlet CO_2, %	--	--	--	--	--	--	--
Balance	N_2	Ar	Ar	Ar	Ar	Ar	N_2
% FGR	--	--	--	--	--	--	--
FLUE MEASUREMENTS							
% O_2, polar	4.8	2.95	2.15	4.65	2.4	3.8	3.25
% O_2, para.	--	--	--	--	--	--	--
S.R. by O_2	1.187	1.099	1.100	1.237	1.157	1.288	1.118
% CO	0.06	0.14	0.09	0.06	0.04	0.02	0.06
% CO_2	>20.0	>20.0	16.46	13.15	10.9	9.48	>20.0
NO, as meas., ppm	1015	820	830	830	770	740	375
NO, 0% EA, ppm	900	625	830	950	1125	1255	310
SO_2, as meas., ppm	1800	2030	1900	1750	1700	1400	1860

COMMENTS: 22 oxygen enrichment.
          23-27 Ar/O_2.

Fuel: Western Kentucky Coal   Date: 2/20   Injector: Axial

INLET PARAMETERS							
Run No.	29	30	31	32	33		
Fuel flow, #/hr	5.9	5.9	5.9	5.9	5.9		
Air flow, SCFM	11.0	12.2	13.8	10.9	12.3		
% swirl	44	44	45	44	44		
Sec. air preheat, °F	334	410	496	516	528		
Pri. air flow, SCFM	0.77	0.77	0.77	0.77	0.77		
Inlet O_2, %	27.3	26.9	26.3	27.2	26.7		
Inlet CO_2, %	--	--	--	--	--		
Balance	N_2	N_2	N_2	N_2	N_2		
% FGR	--	--	--	--	--		
FLUE MEASUREMENTS							
% O_2, polar	1.15	2.3	3.75	0.95	1.85		
% O_2, para.	--	--	--	--	--		
S.R. by O_2	1.041	1.087	1.154	1.034	1.069		
% CO	0.12	0.08	0.05	0.12	0.09		
% CO_2	>20.0	>20.0	>20.0	>20.0	>20.0		
NO, as meas., ppm	420	520	625	460	545		
NO, 0% EA, ppm	335	445	580	370	460		
SO_2, as meas., ppm	2050	1810	1620	2080	1880		

COMMENTS: 33 NO_x = 500 ppm, 0% EA.

Fuel: Western Kentucky Coal   Date: 2/26   Injector: Divergent

INLET PARAMETERS							
Run No.	1	2	3	4	5	6	7
Fuel flow, #/hr	5.9	5.9	5.9	5.9	5.9	5.9	5.9
Air flow, SCFM	14.1	15.2	15.9	16.1	15.1	16.0	15.6
% swirl	45	44	44	44	43	44	44
Sec. air preheat, °F	619	624	639	654	644	654	652
Pri. air flow, SCFM	1.8	1.8	1.8	1.8	1.2	1.2	2.1
Inlet O_2, %	21	21	21	21	21	21	21
Inlet CO_2, %	--	--	--	--	--	--	--
Balance	N_2	N_2	N_2	N_2	N_2	N_2	N_2
% FGR	--	--	--	--	--	--	--
FLUE MEASUREMENTS							
% O_2, polar	1.6	2.55	3.75	3.95	2.2	3.25	3.6
% O_2, para.	--	--	--	--	2.3	3.5	3.9
S.R. by O_2	1.077	1.129	1.203	1.216	1.114	1.186	1.213
% CO	0.06	0.06	0.06	0.02	0.05	0.04	0.03
% CO_2	17.9	16.1	14.6	14.6	15.78	15.46	15.78
NO, as meas., ppm	720	770	800	790	750	800	950
NO, 0% EA, ppm	780	875	975	975	840	960	1165
SO_2, as meas., ppm	1700	1610	1550	1520	1700	1610	1500

COMMENTS: 1-4 baseline conditions.
5-7 effect of primary air flow.

Fuel: Western Kentucky Coal   Date: 2/26   Injector: Divergent

INLET PARAMETERS							
Run No.	8	9	10	11	12	13	14
Fuel flow, #/hr	5.9	5.9	5.9	5.9	5.9	5.9	5.9
Air flow, SCFM	14.5	15.0	15.3	15.6	14.9	14.0	12.7
% swirl	45	45	45	45	44	46	44
Sec. air preheat, °F	646	646	646	651	646	625	621
Pri. air flow, SCFM	2.1	1.5	1.5	1.3	1.3	2.3	2.3
Inlet O_2, %	21	21	21	21	21	21	21
Inlet CO_2, %	--	--	--	--	--	--	--
Balance	N_2	N_2	N_2	N_2	N_2	N_2	N_2
% FGR	--	--	--	--	--	--	--
FLUE MEASUREMENTS							
% O_2, polar	2.5	2.5	3.3	3.45	2.35	3.0	2.1
% O_2, para.	2.7	2.7	3.5	3.25	2.65	3.3	2.3
S.R. by O_2	1.137	1.137	1.186	1.171	1.134	1.174	1.114
% CO	0.02	0.03	0.03	0.03	0.04	0.03	0.03
% CO_2	16.82	16.1	14.82	15.46	16.1	15.46	16.82
NO, as meas., ppm	915	670	690	710	700	930	940
NO, 0% EA, ppm	1050	770	830	840	800	1105	1055
SO_2, as meas., ppm	1650	1660	1600	1680	1750	1600	1700

COMMENTS: 8-14 effect of primary air flow.

Fuel: Western Kentucky Coal   Date: 2/26   Injector: Divergent

INLET PARAMETERS							
Run No.	15	16					
Fuel flow, #/hr	5.9	5.9					
Air flow, SCFM	13.2	13.4					
% swirl	44	44					
Sec. air preheat, °F	613	613					
Pri. air flow, SCFM	1.8	1.8					
Inlet O_2, %	21	21					
Inlet CO_2, %	--	--					
Balance	N_2	N_2					
% FGR	--	--					

FLUE MEASUREMENTS							
% O_2, polar	3.05	3.4					
% O_2, para.	--	--					
S.R. by O_2	1.163	1.192					
% CO	0.02	0.04					
% CO_2	>20.0	20.0					
NO, as meas., ppm	700	650					
NO, 0% EA, ppm	840	825					
SO_2, as meas., ppm	1520	1500					
% O_2 in primary air	16.0	11.8					

COMMENTS: 15-16 CO_2 addition.

Fuel: Western Kentucky Coal   Date: 2/27   Injector: Divergent

INLET PARAMETERS							
Run No.	1	2	3	4	5	6	7
Fuel flow, #/hr	6	6	6	6	6	6	6
Air flow, SCFM	14.4	15.1	14.8	14.4	14.5	15.7	15.9
% swirl	45	45	43	44	45	45	44
Sec. air preheat, °F	591	601	621	616	616	628	646
Pri. air flow, SCFM	1.8	1.8	1.8	1.81	1.81	1.78	1.79
Inlet O_2, %	21	21	21	21	21	21	21
Inlet CO_2, %	--	--	--	--	--	--	--
Balance	N_2	N_2	N_2	N_2	N_2	N_2	N_2
% FGR	--	--	--	--	--	--	--
Pri. O_2, %	21	21	17.3	17.7	14.3	12.8	0.0
FLUE MEASUREMENTS							
% O_2, polar	2.75	3.75	3.4	2.55	2.2	4.05	3.9
% O_2, para.	2.6	3.65	--	--	--	--	--
S.R. by O_2	1.131	1.196	1.184	1.132	1.113	1.234	1.243
% CO	0.02	0.02	0.02	0.03	0.03	0.02	0.02
% CO_2	16.46	15.46	17.9	18.32	>20.0	19.8	>20.0
NO, as meas., ppm	720	740	735	720	680	720	660
NO, 0% EA, ppm	820	895	895	840	790	935	925
SO_2, as meas., ppm	1600	1400	1380	1500	1450	1400	1100

COMMENTS: 1-7 effect of primary O_2.

Fuel: Western Kentucky Coal   Date: 2/27   Injector: Divergent

INLET PARAMETERS							
Run No.	8	9	10	11	12	13	
Fuel flow, #/hr	6	6	6	6	6	6	
Air flow, SCFM	14.8	15.6	14.7	13.2	11.5	11.7	
% swirl	44	44	45	45	42	42	
Sec. air preheat, °F	641	638	586	606	601	601	
Pri. air flow, SCFM	1.79	1.79	1.8	1.8	1.8	1.8	
Inlet O_2, %	21	21	21	21	21	21	
Inlet CO_2, %	--	--	--	--	--	--	
Balance	N_2	N_2	N_2	N_2	N_2	N_2	
% FGR	--	--	--	--	--	--	
Pri. O_2, %	0.0	0.0	21	25.8	26.0	30.5	
FLUE MEASUREMENTS							
% O_2, polar	1.0	2.1	3.2	4.05	2.35	3.1	
% O_2, para.	--	--	--	--	--	--	
S.R. by O_2	1.052	1.117	1.167	1.215	1.113	1.150	
% CO	0.06	0.05	0.02	0.04	0.04	0.02	
% CO_2	>20.0	>20.0	16.1	15.78	17.9	17.7	
NO, as meas., ppm	520	590	775	865	910	975	
NO, 0% EA, ppm	615	740	915	1035	990	1065	
SO_2, as meas., ppm	1350	1250	1500	1550	1550	1560	

COMMENTS: 8-13 effect of primary O_2.

Fuel: Western Kentucky Coal   Date: 3/24   Injector: Divergent

INLET PARAMETERS							
Run No.	1	2					
Fuel flow, #/hr	5.9	5.9					
Air flow, SCFM	13.3	12.5					
% swirl	44	43					
Sec. air preheat, °F	630	620					
Pri. air flow, SCFM	1.8	1.8					
Inlet O_2, %	21	21					
Inlet CO_2, %	--	--					
Balance	N_2	N_2					
% FGR	--	--					
FLUE MEASUREMENTS							
% O_2, polar	3.25	2.45					
% O_2, para.	3.35	2.55					
S.R. by O_2	1.177	1.129					
% CO	0.03	--					
% CO_2	15.78	--					
NO, as meas., ppm	790	765					
NO, 0% EA, ppm	940	870					
SO_2, as meas., ppm	2400	2410					

COMMENTS: 1-2 baseline.

Fuel: Western Kentucky Coal   Date: 3/25   Injector: Divergent

INLET PARAMETERS							
Run No.	1	2	3	4	5	6	7
Fuel flow, #/hr	5.9	5.9	5.9	5.9	5.9	5.9	5.9
Air flow, SCFM	13.0	12.4	11.6	10.9	14.2	16.0	14.0
% swirl	44	44	44	45	44	45	44
Sec. air preheat, °F	615	605	600	590	610	630	640
Pri. air flow, SCFM	1.8	1.8	1.8	1.8	1.8	1.8	1.5
Inlet O_2, %	21	21	21	21	21	21	21
Inlet CO_2, %	--	--	--	--	--	--	--
Balance	N_2	N_2	N_2	N_2	N_2	N_2	N_2
% FGR	--	--	--	--	--	--	--
FLUE MEASUREMENTS							
% O_2, polar	3.60	2.75	1.65	1.0	4.2	--	3.95
% O_2, para.	3.65	2.80	1.70	1.0	4.4	5.4	4.2
S.R. by O_2	1.197	1.144	1.082	1.047	1.248	1.340	1.234
% CO	0.03	--	0.03	--	0.02	0.02	0.03
% CO_2	15.78	--	17.9	--	15.14	13.9	15.14
NO, as meas., ppm	845	815	735	660	850	855	820
NO, 0% EA, ppm	1020	940	800	695	1075	1150	1025
SO_2, as meas., ppm	1370	1500	1720	1700	1400	1280	1400
NO_x (SR = 1.0)	--	945	815	--	1080	1165	--

COMMENTS: 1-6 baseline.
          7 effect of primary air flow rate.

Fuel: Western Kentucky Coal   Date: 3/25   Injector: Divergent

INLET PARAMETERS							
Run No.	8	9	10	11	12	13	14
Fuel flow, #/hr	5.9	5.9	5.9	5.9	4.4	4.4	4.4
Air flow, SCFM	12.5	14.2	13.0	13.3	11.4	9.6	8.7
% swirl	44	44	44	44	44	44	44
Sec. air preheat, °F	640	640	645	645	625	610	580
Pri. air flow, SCFM	1.5	1.25	1.25	1.0	1.3	1.3	1.3
Inlet O_2, %	21	21	21	21	21	21	21
Inlet CO_2, %	--	--	--	--	--	--	--
Balance	N_2	N_2	N_2	N_2	N_2	N_2	N_2
% FGR	--	--	--	--	--	--	--
FLUE MEASUREMENTS							
% O_2, polar	2.30	3.55	2.7	2.9	6.2	4.20	2.55
% O_2, para.	2.45	4.0	2.9	2.85	6.25	4.25	2.5
S.R. by O_2	1.123	1.220	1.150	1.147	1.396	1.237	1.126
% CO	0.05	0.04	0.04	0.03	0.03	0.03	0.03
% CO_2	17.18	15.46	16.25	16.1	13.0	14.82	16.46
NO, as meas., ppm	730	810	770	825	740	700	615
NO, 0% EA, ppm	825	1000	895	955	1055	875	700
SO_2, as meas., ppm	1600	1430	1500	1500	1200	--	1550

COMMENTS: 8-11 effect of primary air flow rate.
          12-14 reduced load.

Fuel: Western Kentucky Coal   Date: 3/25   Injector: Divergent

INLET PARAMETERS							
Run No.	15	16	17	18	19	20	21
Fuel flow, #/hr	4.4	4.4	4.4	4.4	5.9	5.9	5.9
Air flow, SCFM	9.1	9.1	8.0	7.4	12.1	11.0	10.4
% swirl	44	44	44	44	44	44	44
Sec. air preheat, °F	565	565	555	555	610	620	620
Pri. air flow, SCFM	1.3	1.8	1.8	1.8	1.8	1.8	1.8
Inlet O_2, %	21	21	21	21	21.25	21.25	20.9
Inlet CO_2, %	--	--	--	--	18.6	18.1	17.5
Balance	N_2	N_2	N_2	N_2	N_2	N_2	N_2
% FGR	--	--	--	--	--	--	--

FLUE MEASUREMENTS							
% O_2, polar	3.45	4.05	2.45	1.55	3.35	2.30	1.00
% O_2, para.	3.50	4.20	2.50	1.60	--	--	--
S.R. by O_2	1.187	1.234	1.126	1.077	1.177	1.115	1.047
% CO	0.03	0.03	0.03	0.04	0.02	0.02	0.02
% CO_2	15.14	15.0	16.82	17.9	--	--	--
NO, as meas., ppm	670	735	675	600	775	725	620
NO, 0% EA, ppm	804	920	765	650	910	805	655
SO_2, as meas., ppm	1500	1400	1500	1600	1200	1300	1400

COMMENTS: 15-18 reduced load.
19-21 CO_2 addition.

Fuel: Western Kentucky Coal   Date: 3/25   Injector: Axial

INLET PARAMETERS							
Run No.	22	23	24	25	26	27	28
Fuel flow, #/hr	5.9	5.9	5.9	5.9	5.9	5.9	5.9
Air flow, SCFM	12.7	13.7	14.4	15.8	13.5	14.9	14.0
% swirl	44	44	44	44	44	44	44
Sec. air preheat, °F	585	615	635	655	660	660	660
Pri. air flow, SCFM	1.0	1.0	1.0	1.0	0.6	0.6	0.8
Inlet O_2, %	21	21	21	21	21	21	21
Inlet CO_2, %	--	--	--	--	--	--	--
Balance	N_2	N_2	N_2	N_2	N_2	N_2	N_2
% FGR	--	--	--	--	--	--	--

FLUE MEASUREMENTS							
% O_2, polar	2.0	2.9	3.65	4.65	2.7	3.8	2.9
% O_2, para.	1.85	2.75	3.50	4.6	2.65	3.65	2.85
S.R. by O_2	1.090	1.141	1.187	1.262	1.135	1.197	1.147
% CO	0.06	0.06	0.07	0.03	0.07	0.04	0.05
% CO_2	17.54	16.1	15.14	13.6	16.1	15.14	16.46
NO, as meas., ppm	450	470	520	535	515	600	510
NO, 0% EA, ppm	495	540	625	685	590	725	590
SO_2, as meas., ppm	1900	1800	1750	1600	--	1650	1800

COMMENTS: 22-25 baseline.
          26-28 effect of primary air flow rate.

Fuel: Western Kentucky Coal   Date: 3/25   Injector: Axial

INLET PARAMETERS							
Run No.	29	30	31	32			
Fuel flow, #/hr	5.9	5.9	5.9	5.9			
Air flow, SCFM	14.4	13.0	13.3	13.2			
% swirl	44	44	44	44			
Sec. air preheat, °F	660	655	655	650			
Pri. air flow, SCFM	1.2	1.2	1.5	1.8			
Inlet O_2, %	21	21	21	21			
Inlet CO_2, %	--	--	--	--			
Balance	N_2	N_2	N_2	N_2			
% FGR	--	--	--	--			

FLUE MEASUREMENTS							
% O_2, polar	3.6	2.0	2.95	3.05			
% O_2, para.	3.5	1.9	2.8	3.05			
S.R. by O_2	1.187	1.093	1.144	1.159			
% CO	0.06	0.05	0.07	0.03			
% CO_2	15.14	17.54	16.82	15.78			
NO, as meas., ppm	540	500	540	590			
NO, 0% EA, ppm	650	550	625	690			
SO_2, as meas., ppm	1750	1850	1800	1740			

COMMENTS: 29-32 effect of primary air flow rate.

Fuel: Western Kentucky Coal   Date: 3/26   Injector: Divergent

INLET PARAMETERS							
Run No.	1	2	3	4	5	6	7
Fuel flow, #/hr	5.9	5.9	5.9	5.9	5.9	5.9	5.9
Air flow, SCFM	13.1	14.2	11.3	12.6	11.3	12.2	13.1
% swirl	44	43	43	44	44	44	44
Sec. air preheat, °F	140	130	130	120	120	115	115
Pri. air flow, SCFM	1.8	1.8	1.8	1.8	1.8	1.8	1.8
Inlet O_2, %	21	21	21	21	23.1	23.1	23.1
Inlet CO_2, %	--	--	--	--	--	--	--
Balance	N_2	N_2	N_2	N_2	N_2	N_2	N_2
% FGR	--	--	--	--	--	--	--
FLUE MEASUREMENTS							
% O_2, polar	2.65	3.7	0.65	0.93	2.05	3.46	4.5
% O_2, para.	2.65	3.7	0.65	0.93	--	--	--
S.R. by O_2	1.135	1.201	1.030	1.043	1.101	1.185	1.256
% CO	0.02	0.02	0.08	0.03	0.04	0.04	0.04
% CO_2	16.6	15.4	18.7	18.3	18.7	17.1	15.8
NO, as meas., ppm	730	770	555	600	640	725	755
NO, 0% EA, ppm	835	935	570	630	640	775	850
SO_2, as meas., ppm	1500	1420	1730	1660	1700	1560	1460

COMMENTS: 1-4 preheat turndown.
           5-7 oxygen enrichment.

Fuel: Western Kentucky Coal   Date: 3/26   Injector: Divergent

INLET PARAMETERS							
Run No.	8	9	10	11	12	13	14
Fuel flow, #/hr	5.9	5.9	5.9	5.9	5.9	5.9	5.9
Air flow, SCFM	--	--	--	--	--	--	--
% swirl	44	44	44	44	44	44	44
Sec. air preheat, °F	115	115	110	110	110	110	110
Pri. air flow, SCFM	1.57	1.57	1.81	3.09	3.04	1.22	1.0
Inlet O_2, %	21.15	20.8	21.3	20.7	20.6	20.6	20.4
Inlet CO_2, %	19.1	20.2	18.7	16.8	16.4	19.2	20.0
Balance	Ar	Ar	Ar	Ar	Ar	Ar	Ar
% FGR	--	--	--	--	--	--	--
FLUE MEASUREMENTS							
% O_2, polar	3.35	1.55	3.1	5.0	3.65	2.95	2.8
% O_2, para.	--	--	--	--	--	--	--
S.R. by O_2	1.178	1.075	1.162	1.293	1.197	1.153	1.144
% CO	--	--	--	--	--	--	--
% CO_2	--	--	--	--	--	--	--
NO, as meas., ppm	660	585	635	750	775	635	625
NO, 0% EA, ppm	780	660	735	1000	960	755	745
SO_2, as meas., ppm	--	--	--	--	--	--	--

COMMENTS: 8-14 Ar/O_2/CO_2, effect of primary velocity.

Fuel: Western Kentucky Coal   Date: 3/26   Injector: Divergent

INLET PARAMETERS							
Run No.	15	16	17	18			
Fuel flow, #/hr	4.4	4.4	4.4	4.4			
Air flow, SCFM	--	--	--	--			
% swirl	44	43	43	46			
Sec. air preheat, °F	110	110	110	110			
Pri. air flow, SCFM	1.13	1.13	1.13	1.57			
Inlet O_2, %	21.5	20.7	20.7	20.3			
Inlet CO_2, %	19.1	18.7	19.1	17.9			
Balance	Ar	Ar	Ar	Ar			
% FGR	--	--	--	--			
FLUE MEASUREMENTS							
% O_2, polar	4.45	2.65	1.80	3.1			
% O_2, para.	--	--	--	--			
S.R. by O_2	1.252	1.135	1.088	1.162			
% CO	--	--	--	--			
% CO_2	--	--	--	--			
NO, as meas., ppm	615	550	500	600			
NO, 0% EA, ppm	755	640	555	730			
SO_2, as meas., ppm	--	--	--	--			

COMMENTS: 15-18 reduced load with $Ar/O_2/CO_2$.

Fuel: Western Kentucky Coal   Date: 3/30   Injector: Axial

INLET PARAMETERS							
Run No.	1	2	3	4	5	6	7
Fuel flow, #/hr	5.9	5.9	5.9	5.9	5.9	5.9	5.9
Air flow, SCFM	--	--	--	--	--	--	--
% swirl	43	44	42	43	44	44	44
Sec. air preheat, °F	110	110	110	115	120	115	115
Pri. air flow, SCFM	1.0	1.0	1.0	1.0	.70	.70	1.3
Inlet O_2, %	20.7	20.85	21.0	20.85	21.0	20.85	21.15
Inlet CO_2, %	18.7	19.2	18.7	17.4	18.3	18.3	17.4
Balance	Ar	Ar	Ar	Ar	Ar	Ar	Ar
% FGR	--	--	--	--	--	--	--
FLUE MEASUREMENTS							
% O_2, polar	2.55	1.6	3.6	3.75	3.55	2.7	3.25
% O_2, para.	--	--	--	--	--	--	--
S.R. by O_2	1.131	1.077	1.193	1.204	1.189	1.138	1.169
% CO	--	--	--	--	--	--	--
% CO_2	--	--	--	--	--	--	--
NO, as meas., ppm	350	335	395	410	450	430	385
NO, 0% EA, ppm	405	365	475	505	540	500	450
SO_2, as meas., ppm	--	--	--	--	--	--	--

COMMENTS: 1-4 baseline fuel NO.
           5-7 effect of primary air flow.

Fuel: Western Kentucky Coal   Date: 3/30   Injector: Axial

INLET PARAMETERS							
Run No.	8	9	10	11	12		
Fuel flow, #/hr	5.9	5.9	5.9	5.9	5.9		
Air flow, SCFM	--	--	--	--	--		
% swirl	44	44	44	44	44		
Sec. air preheat, °F	115	115	110	110	110		
Pri. air flow, SCFM	1.8	1.3	1.0	1.0	1.0		
Inlet O_2, %	20.7	20.85	21.3	21.0	21.6		
Inlet CO_2, %	16.1	--	--	--	--		
Balance	Ar	Ar	Ar	Ar	Ar		
% FGR	--	--	--	--	--		
FLUE MEASUREMENTS							
% O_2, polar	3.45	3.35	3.25	3.85	4.5		
% O_2, para.	--	--	--	--	--		
S.R. by O_2	1.186	1.178	1.168	1.209	1.245		
% CO	--	--	--	--	--		
% CO_2	--	--	--	--	--		
NO, as meas., ppm	515	405	400	425	440		
NO, 0% EA, ppm	625	485	465	520	540		
SO_2, as meas., ppm	--	--	--	--	--		

COMMENTS: 8 effect of primary air flow, $Ar/O_2/CO_2$.
            9 effect of primary air flow, Ar/O_2.
            10-12 baseline Ar/O_2.

Fuel: Western Kentucky Coal   Date: 3/31   Injector: Divergent

INLET PARAMETERS							
Run No.	1	2	3	4	5	6	
Fuel flow, #/hr	5.9	5.9	5.9	5.9	5.9	5.9	
Air flow, SCFM	12.4	10.9	9.5	9.9	8.9	8.1	
% swirl	43	44	44	44	44	44	
Sec. air preheat, °F	545	535	545	540	535	520	
Pri. air flow, SCFM	1.8	1.8	1.8	1.8	1.8	1.8	
Inlet O_2, %	22.5	23.1	25.5	25.8	28.8	28.8	
Inlet CO_2, %	--	--	--	--	--	--	
Balance	N_2	N_2	N_2	N_2	N_2	N_2	
% FGR	--	--	--	--	--	--	

FLUE MEASUREMENTS							
% O_2, polar	3.2	2.45	2.5	3.65	3.8	2.45	
% O_2, para.	--	--	--	--	--	--	
S.R. by O_2	1.155	1.110	1.100	1.152	1.140	1.085	
% CO	0.03	0.03	0.03	0.03	0.03	0.06	
% CO_2	17.54	19.16	>20.0	>20.0	>20.0	>20.0	
NO, as meas., ppm	850	830	900	980	1090	1040	
NO, 0% EA, ppm	925	845	820	930	915	830	
SO_2, as meas., ppm	--	--	--	--	--	--	

COMMENTS: 1-6 oxygen enrichment.

Fuel: Western Kentucky Coal   Date: 3/31   Injector: Divergent

INLET PARAMETERS							
Run No.	7	8	9	10	11	12	13
Fuel flow, #/hr	5.9	5.9	5.9	5.9	5.9	5.9	5.9
Air flow, SCFM	--	--	--	--	--	--	--
% swirl	44	44	44	44	44	44	44
Sec. air preheat, °F	475	475	470	485	460	455	440
Pri. air flow, SCFM	1.8	1.8	1.8	1.8	1.8	1.8	1.8
Inlet O_2, %	21.6	24.2	24.0	26.7	26.7	29.7	30.1
Inlet CO_2, %	--	--	--	--	--	--	--
Balance	Ar	Ar	Ar	Ar	Ar	Ar	Ar
% FGR	--	--	--	--	--	--	--
FLUE MEASUREMENTS							
% O_2, polar	2.7	3.85	2.80	3.65	2.75	4.88	3.65
% O_2, para.	--	--	--	--	--	--	--
S.R. by O_2	1.133	1.175	1.122	1.146	1.106	1.181	1.127
% CO	0.03	0.04	0.03	0.03	0.04	0.04	0.03
% CO_2	15.60	17.3	17.54	20.0	>20.0	>20.0	>20.0
NO, as meas., ppm	775	865	840	935	915	1030	1025
NO, 0% EA, ppm	860	895	830	850	800	870	815
SO_2, as meas., ppm	--	--	--	--	--	--	--

COMMENTS: 7-13 oxygen enrichment, Ar/O_2.

Fuel: Western Kentucky Coal   Date: 3/31   Injector: Divergent

INLET PARAMETERS							
Run No.	14	15	16	17			
Fuel flow, #/hr	5.9	5.9	5.9	5.9			
Air flow, SCFM	--	--	--	--			
% swirl	44	44	44	44			
Sec. air preheat, °F	460	480	490	495			
Pri. air flow, SCFM	1.39	1.09	2.09	2.44			
Inlet O_2, %	21.1	21.3	20.6	20.3			
Inlet CO_2, %	--	--	--	--			
Balance	Ar	Ar	Ar	Ar			
% FGR	--	--	--	--			
FLUE MEASUREMENTS							
% O_2, polar	3.15	3.0	3.9	4.1			
% O_2, para.	--	--	--	--			
S.R. by O_2	1.163	1.153	1.218	1.236			
% CO	0.03	0.04	0.04	0.03			
% CO_2	14.5	14.82	13.6	13.0			
NO, as meas., ppm	720	680	880	925			
NO, 0% EA, ppm	840	780	1105	1200			
SO_2, as meas., ppm	--	--	--	--			

COMMENTS: 14-17 effect of primary air flow.

Fuel: Western Kentucky Coal   Date: 4/20   Injector: Divergent

INLET PARAMETERS							
Run No.	1	2	3	4	5	6	7
Fuel flow, #/hr	5.9	5.9	5.9	5.9	5.9	5.9	5.9
Air flow, SCFM	13.2	13.4	13.4	13.4	13.0	13.0	13.0
% swirl	60	60	60	60	44	44	44
Sec. air preheat, °F	100	100	100	100	110	110	110
Pri. air flow, SCFM	1.8	1.8	1.8	1.8	1.25	1.25	1.25
Inlet O_2, %	21	21	21	21	21	21	21
Inlet CO_2, %	--	--	--	--	--	--	--
Balance	N_2	N_2	N_2	N_2	N_2	N_2	N_2
% FGR	--	--	--	--	--	--	--
FLUE MEASUREMENTS							
% O_2, polar	2.45	2.25	2.25	--	2.35	2.05	2.05
% O_2, para.	2.65	2.50	2.50	--	2.2	2.0	2.0
S.R. by O_2	1.135	1.127	1.127	--	1.110	1.099	1.099
% CO	0.06	0.03	0.03	0.02	--	0.04	0.04
% CO_2	16.8	16.8	16.2	16.8	--	17.6	17.1
NO, as meas., ppm	635	630	800	--	590	640	675
NO, 0% EA, ppm	725	715	910	--	660	710	745
SO_2, as meas., ppm	--	--	--	--	--	--	--

COMMENTS: 1-4 shakedown.
          5-7 char/volatile tests, primary air.

Fuel: Western Kentucky Coal   Date: 4/20   Injector: Divergent

INLET PARAMETERS							
Run No.	8	9	10	11	12	13	14
Fuel flow, #/hr	5.9	5.9	5.9	5.9	5.9	5.9	5.9
Air flow, SCFM	13.0	14.6	13.5	14.4	13.9	12.8	12.8
% swirl	44	44	44	44	44	44	44
Sec. air preheat, °F	110	110	110	110	110	110	110
Pri. air flow, SCFM	1.25	1.25	1.50	1.50	1.8	1.8	1.8
Inlet O_2, %	21	21	21	21	21	21	21
Inlet CO_2, %	--	--	--	--	--	--	--
Balance	N_2	N_2	N_2	N_2	N_2	N_2	N_2
% FGR	--	--	--	--	--	--	--
FLUE MEASUREMENTS							
% O_2, polar	2.15	3.55	2.7	4.1	4.35	3.35	3.25
% O_2, para.	2.1	3.50	2.55	3.95	4.25	3.3	3.2
S.R. by O_2	1.104	1.188	1.130	1.217	1.238	1.175	1.169
% CO	--	0.04	0.03	0.03	0.02	0.03	0.03
% CO_2	--	15.4	16.4	14.9	14.8	16.8	16.8
NO, as meas., ppm	630	665	690	690	830	830	890
NO, 0% EA, ppm	700	800	785	850	1040	985	1050
SO_2, as meas., ppm	--	--	--	--	--	--	--

COMMENTS: 8-14 char/volatile tests, primary air.

Fuel: Western Kentucky Coal   Date: 4/20   Injector: Divergent

INLET PARAMETERS							
Run No.	15	16	17				
Fuel flow, #/hr	5.9	5.9	5.9				
Air flow, SCFM	12.8	12.8	12.8				
% swirl	44	44	44				
Sec. air preheat, °F	110	110	110				
Pri. air flow, SCFM	1.8	1.8	1.8				
Inlet O_2, %	21	21	21				
Inlet CO_2, %	--	--	--				
Balance	N_2	N_2	N_2				
% FGR	--	--	--				

FLUE MEASUREMENTS							
% O_2, polar	3.65	3.75	3.8				
% O_2, para.	3.65	3.75	3.85				
S.R. by O_2	1.197	1.204	1.211				
% CO	0.02	0.02	0.02				
% CO_2	15.4	15.4	15.4				
NO, as meas., ppm	940	1075	825				
NO, 0% EA, ppm	1140	1310	1010				
SO_2, as meas., ppm							

COMMENTS: 15-17 char/volatile testing, primary air.

Fuel: Western Kentucky Coal   Date: 4/20   Injector: Divergent

INLET PARAMETERS							
Run No.	3	4	6	7	14	15	16
Additive	NO	NO	NH_3	NO	NH_3	NO	NO
Rotameter setting	11	11	8.5	11	8.5	11	11
Add. flow (cc/min)	118	118	135	118	135	118	118
Injector location	p	pa	pa	pa	pa	pa	p
Sample location	s	s	p	p	p	p	s

FLUE MEASUREMENTS							
NO total conversion*	--	--	395	345	395	345	345
NO measured*	--	--	710	745	1050	1140	1310
NO without additive*	--	--	695	695	980	1005	1010
NO due to additive*	--	--	15	50	70	135	300
% conversion of add.	--	--	4	14	18	39	87
SR	--	--	1.099	1.099	1.169	1.197	1.204

COMMENTS: *ppm (STOICHI).

Fuel: Western Kentucky Coal   Date: 4/22   Injector: Divergent

INLET PARAMETERS							
Run No.	1	2	3	4	5	6	7
Fuel flow, #/hr	5.9	5.9	5.9	5.9	5.9	5.9	5.9
Air flow, SCFM	13.8	13.8	13.8	15.4	15.4	15.4	12.2
% swirl	44	44	44	44	44	44	44
Sec. air preheat, °F	585	585	585	590	595	595	575
Pri. air flow, SCFM	1.8	1.8	1.8	1.8	1.8	1.8	1.8
Inlet O_2, %	21	21	21	21	21	21	21
Inlet CO_2, %	--	--	--	--	--	--	--
Balance	N_2	N_2	N_2	N_2	N_2	N_2	N_2
% FGR	--	--	--	--	--	--	--

FLUE MEASUREMENTS							
% O_2, polar	3.35	3.6	3.55	4.6	4.65	4.5	2.15
% O_2, para.	3.3	3.6	3.65	4.8	4.85	4.7	2.2
S.R. by O_2	1.175	1.194	1.197	1.278	1.282	1.270	1.110
% CO	0.03	0.04	0.02	0.02	0.04	0.04	0.04
% CO_2	15.4	15.4	15.8	14.2	14.0	13.6	16.8
NO, as meas., ppm	750	830	825	780	830	835	750
NO, 0% EA, ppm	890	1000	1000	1010	1080	1075	835
SO_2, as meas., ppm	--	--	--	--	--	--	--

COMMENTS: 1-7 char/volatile tests, baseline.

Fuel: Western Kentucky Coal   Date: 4/22   Injector: Divergent

INLET PARAMETERS							
Run No.	8	9	10	11	12	13	14
Fuel flow, #/hr	5.9	5.9	5.9	5.9	5.9	5.9	5.9
Air flow, SCFM	12.2	12.2	13.7	14.5	13.6	13.6	13.6
% swirl	44	44	44	44	44	44	44
Sec. air preheat, °F	575	575	555	565	580	580	580
Pri. air flow, SCFM	1.8	1.8	1.0	1.0	1.4	1.8	2.0
Inlet O_2, %	21	21	21	21	21	21	21
Inlet CO_2, %	--	--	--	--	--	--	--
Balance	N_2	N_2	N_2	N_2	N_2	N_2	N_2
% FGR	--	--	--	--	--	--	--

FLUE MEASUREMENTS							
% O_2, polar	1.85	1.80	2.05	3.1	2.75	2.9	3.1
% O_2, para.	1.90	1.85	2.25	3.35	3.0	3.2	3.5
S.R. by O_2	1.093	1.091	1.112	1.177	1.156	1.168	1.187
% CO	0.03	0.04	0.04	0.04	0.03	0.03	0.03
% CO_2	17.6	17.2	16.8	16.0	15.8	15.5	15.2
NO, as meas., ppm	795	765	650	700	705	770	795
NO, 0% EA, ppm	875	840	730	835	825	910	955
SO_2, as meas., ppm	--	--	--	--	--	--	--

COMMENTS: 8-9 char/volatile tests, baseline.
10-14 effect of primary air flow.

Fuel: Western Kentucky Coal   Date: 4/22   Injector: Divergent

INLET PARAMETERS							
Run No.	2	3	5	6	8	9	
Additive	NO	NH_3	NH_3	NO	NO	NH_3	
Rotameter setting	11	7.6	7.6	11	11	7.6	
Add. flow (cc/min)	118	118	118	118	118	118	
Injector location	pa	pa	pa	pa	pa	pa	
Sample location	p	p	p	p	p	p	
FLUE MEASUREMENTS							
NO total conversion*	345	345	345	345	345	345	
NO measured*	1000	1000	1080	1075	875	840	
NO witnout additive*	935	940	1020	1010	810	810	
NO due to additive*	65	60	60	65	65	30	
% conversion of add.	19	17	17	19	19	9	
SR	1.194	1.197	1.282	1.270	1.093	1.091	

COMMENTS: *ppm (STOICHI).

Fuel: Western Kentucky Coal   Date: 4/22   Injector: Divergent

INLET PARAMETERS							
Run No.	15	16	17	18	19	20	21
Fuel flow, #/hr	5.9	5.9	5.9	5.9	5.9	5.9	5.9
Air flow, SCFM	13.3	12.5	12.0	11.6	11.2	9.9	9.9
% swirl	44	44	44	44	44	44	44
Sec. air preheat, °F	575	570	565	560	550	535	540
Pri. air flow, SCFM	2.3	2.6	2.6	3.0	3.0	3.0	3.0
Inlet O_2, %	21	21	21	21	21	21	21
Inlet CO_2, %	--	--	--	--	--	--	--
Balance	N_2	N_2	N_2	N_2	N_2	N_2	N_2
% FGR	--	--	--	--	--	--	--

FLUE MEASUREMENTS							
% O_2, polar	3.05	--	3.10	3.35	3.3	2.0	2.1
% O_2, para.	3.45	3.5	3.0	3.25	3.25	1.9	2.05
S.R. by O_2	1.184	1.187	1.156	1.171	1.171	1.093	1.101
% CO	0.03	0.03	0.03	0.03	0.03	0.03	0.03
% CO_2	15.8	15.4	15.9	15.8	15.8	17.1	17.0
NO, as meas., ppm	910	935	945	970	1115	1100	1015
NO, 0% EA, ppm	1090	1120	1105	1150	1320	1210	1125
SO_2, as meas., ppm	--	--	--	--	--	--	--

COMMENTS: 15-18 effect of primary air flow.
           19-21 char/volatile tests, lifted flames.

Fuel: Western Kentucky Coal   Date: 4/22   Injector: Divergent

INLET PARAMETERS							
Run No.	22	23	24	25	26	27	
Fuel flow, #/hr	5.9	5.9	5.9	5.9	5.9	5.9	
Air flow, SCFM	13.3	13.3	13.3	10.9	10.9	9.4	
% swirl	44	44	44	44	44	44	
Sec. air preheat, °F	450	450	450	450	450	535	
Pri. air flow, SCFM	3.0	3.0	3.0	3.0	3.0	3.0	
Inlet O_2, %	21	21	21	21	21	21	
Inlet CO_2, %	--	--	--	--	--	--	
Balance	N_2	N_2	N_2	N_2	N_2	N_2	
% FGR	--	--	--	--	--	--	
FLUE MEASUREMENTS							
% O_2, polar	4.9	5.0	5.15	3.25	3.65	2.4	
% O_2, para.	5.1	5.25	5.3	3.4	3.5	2.0	
S.R. by O_2	1.300	1.312	1.316	1.181	1.187	1.098	
% CO	0.02	0.02	0.02	0.03	0.02	0.02	
% CO_2	13.6	13.7	13.6	15.4	15.6	17.1	
NO, as meas., ppm	1005	1105	1040	1075	1025	1080	
NO, 0% EA, ppm	1325	1475	1390	1280	1230	1195	
SO_2, as meas., ppm	--	--	--	--	--	--	
NO_x (SR = 1.0)	--	--	--	1320	--	--	

COMMENTS: 22-27 char/volatile tests, lifted flames.

Fuel: Western Kentucky Coal   Date: 4/22   Injector: Divergent

INLET PARAMETERS							
Run No.	19	20	23	24	25	27	
Additive	NO	NO	NO	NH_3	NH_3	NH_3	
Rotameter setting	11	11	11	7.6	7.6	7.7	
Add. flow (cc/min)	118	118	118	118	118	118	
Injector location	pa	pa	pa	pa	pa	pa	
Sample location	p	p	p	p	p	p	

FLUE MEASUREMENTS							
NO total conversion*	345	345	345	345	345	345	
NO measured*	1320	1210	1475	1390	1280	1120	
NO without additive*	1215	1110	1330	1335	1220	1120	
NO due to additive*	105	100	145	55	60	75	
% conversion of add.	30	29	42	16	17	22	
SR	1.171	1.093	1.312	1.316	1.181	1.098	

COMMENTS: *ppm (STOICHI).

Fuel: Western Kentucky Coal   Date: 4/23   Injector: Divergent

INLET PARAMETERS							
Run No.	1	2	3	4	5	6	7
Fuel flow, #/hr	5.9	5.9	5.9	5.9	5.9	5.9	5.9
Air flow, SCFM	13.8	14.4	14.0	13.8	13.0	13.6	13.4
% swirl	44	44	44	44	44	44	45
Sec. air preheat, °F	540	555	570	575	575	575	575
Pri. air flow, SCFM	1.8	1.8	1.8	1.8	1.8	1.8	1.8
Inlet O_2, %	21	21	21	21	21	21	21
Inlet CO_2, %	--	--	--	--	--	--	--
Balance	N_2	N_2	N_2	N_2	N_2	N_2	N_2
% FGR	--	--	--	--	--	--	--
Primary O_2, %	21	21	24.4	24.4	27.2	27.2	30.0
FLUE MEASUREMENTS							
% O_2, polar	2.55	3.35	3.15	3.0	2.6	3.13	3.2
% O_2, para.	--	--	--	--	--	--	--
S.R. by O_2	--	--	--	--	--	--	--
% CO	0.03	0.03	0.06	0.06	0.02	0.02	0.03
% CO_2	16.6	15.8	16.6	16.6	17.6	16.6	16.8
NO, as meas., ppm	640	685	700	700	630	750	785
NO, 0% EA, ppm	730	815	805	800	690	845	875
SO_2, as meas., ppm	--	--	--	--	--	--	--

COMMENTS: 1-7 shakedown.

Fuel: Western Kentucky Coal   Date: 4/23   Injector: Divergent

INLET PARAMETERS							
Run No.	8	9					
Fuel flow, #/hr	5.9	5.9					
Air flow, SCFM	12.9	13.4					
% swirl	44	44					
Sec. air preheat, °F	575	575					
Pri. air flow, SCFM	1.8	1.8					
Inlet O_2, %	21	21					
Inlet CO_2, %	--	--					
Balance	N_2	N_2					
% FGR	--	--					
Primary O_2, %	30.0 .	30.0					
FLUE MEASUREMENTS							
% O_2, polar	2.65	3.15					
% O_2, para.	--	--					
S.R. by O_2	--	--					
% CO	0.03	0.03					
% CO_2	17.9	16.6					
NO, as meas., ppm	800	850					
NO, 0% EA, ppm	865	940					
SO_2, as meas., ppm	--	--					

COMMENTS: 8-9 shakedown.

Fuel: Western Kentucky Coal   Date: 4/23   Injector: Axial

INLET PARAMETERS							
Run No.	10	11	12	13	14		
Fuel flow, #/hr	5.9	5.9	5.9	5.9	5.9		
Air flow, SCFM	13.9	14.6	14.0	13.9	14.9		
% swirl	44	44	44	44	44		
Sec. air preheat, °F	555	575	605	600	595		
Pri. air flow, SCFM	1.0	1.0	1.0	1.0	1.0		
Inlet O_2, %	21	21	21	21	21		
Inlet CO_2, %	--	--	--	--	--		
Balance	N_2	N_2	N_2	N_2	N_2		
% FGR	--	--	--	--	--		
Primary O_2, %	21	21	26.4	30.5	30.6		
FLUE MEASUREMENTS							
% O_2, polar	2.65	3.0	2.8	2.6	3.4		
% O_2, para.	--	--	--	--	--		
S.R. by O_2	1.134	1.155	1.139	1.126	1.172		
% CO	--	--	--	--	--		
% CO_2	--	--	--	--	--		
NO, as meas., ppm	510	540	525	530	565		
NO, 0% EA, ppm	585	630	590	580	645		
SO_2, as meas., ppm	--	--	--	--	--		

COMMENTS: 10-14 enrichment of primary air.

Fuel: Western Kentucky Coal   Date: 4/23   Injector: Axial

INLET PARAMETERS							
Run No.	15	16	17	18	19	20	21
Fuel flow, #/hr	5.9	5.9	5.9	5.9	5.9	5.9	5.9
Air flow, SCFM	14.2	14.2	14.1	14.8	15.3	14.6	14.7
% swirl	44	44	44	44	44	44	44
Sec. air preheat, °F	595	595	595	595	595	600	600
Pri. air flow, SCFM	1.0	1.0	0.6	0.8	0.8	1.2	1.5
Inlet O_2, %	21	21	21	21	21	21	21
Inlet CO_2, %	--	--	--	--	--	--	--
Balance	N_2	N_2	N_2	N_2	N_2	N_2	N_2
% FGR	--	--	--	--	--	--	--
Primary O_2, %	33.6	38.2	21	21	21	21	21
FLUE MEASUREMENTS							
% O_2, polar	2.9	3.0	2.9	2.65	3.25	3.15	3.6
% O_2, para.	--	--	--	--	--	--	--
S.R. by O_2	1.141	1.144	1.149	1.134	1.171	1.164	1.193
% CO	--	--	--	--	--	--	--
% CO_2	--	--	--	--	--	--	--
NO, as meas., ppm	565	550	600	570	580	545	570
NO, 0% EA, ppm	620	600	695	650	685	640	690
SO_2, as meas., ppm	--	--	--	--	--	--	--

COMMENTS: 15-16 effect of primary O_2.
17-21 effect of primary air flow rate.

Fuel: Western Kentucky Coal   Date: 4/23   Injector: Axial

INLET PARAMETERS							
Run No.	22	23	24	25	26	27	28
Fuel flow, #/hr	5.9	5.9	5.9	5.9	5.9	5.9	5.9
Air flow, SCFM	13.9	13.8	14.6	14.1	13.3	13.5	13.5
% swirl	44	44	44	44	44	44	44
Sec. air preheat, °F	600	610	600	600	580	585	585
Pri. air flow, SCFM	1.5	1.8	1.8	2.1	2.1	2.4	2.7
Inlet O_2, %	21	21	21	21	21	21	21
Inlet CO_2, %	--	--	--	--	--	--	--
Balance	N_2	N_2	N_2	N_2	N_2	N_2	N_2
% FGR	--	--	--	--	--	--	--
FLUE MEASUREMENTS							
% O_2, polar	2.75	2.55	3.55	3.6	2.6	2.8	3.35
% O_2, para.	--	--	--	--	--	--	--
S.R. by O_2	1.140	1.129	1.189	1.193	1.131	1.143	1.177
% CO	--	--	--	--	--	--	--
% CO_2	--	--	--	--	--	--	--
NO, as meas., ppm	540	620	630	730	720	820	990
NO, 0% EA, ppm	620	705	760	880	820	945	1180
SO_2, as meas., ppm	--	--	--	--	--	--	--

COMMENTS: 22-28 effect of primary air flow rate.

Fuel: Western Kentucky Coal   Date: 4/23   Injector: Axial

INLET PARAMETERS							
Run No.	29	30	31	32	33	34	
Fuel flow, #/hr	5.9	5.9	5.9	5.9	5.9	5.9	
Air flow, SCFM	13.2	12.8	12.4	12.3	15.1	15.1	
% swirl	44	44	44	44	44	44	
Sec. air preheat, °F	570	570	565	560	585	585	
Pri. air flow, SCFM	1.8	1.8	1.8	1.8	1.0	1.0	
Inlet O_2, %	21	21	21	21	21	21	
Inlet CO_2, %	--	--	--	--	--	--	
Balance	N_2	N_2	N_2	N_2	N_2	N_2	
% FGR	--	--	--	--	--	--	
Primary O_2, %	28.0	32.5	36.5	40.0	21	21	
FLUE MEASUREMENTS							
% O_2, polar	3.0	3.1	3.1	3.1	3.3	3.25	
% O_2, para.	--	--	--	--	3.1	3.1	
S.R. by O_2	1.147	1.148	1.145	1.141	1.161	1.161	
% CO	--	--	--	--	--	--	
% CO_2	--	--	--	--	--	--	
NO, as meas., ppm	650	680	720	750	535	550	
NO, 0% EA, ppm	720	730	760	770	630	645	
SO_2, as meas., ppm	--	--	--	--	--	--	

COMMENTS: 29-32 enrichment of primary air, lifted flames.

Fuel: Western Kentucky Coal   Date: 4/28   Injector: Divergent

INLET PARAMETERS							
Run No.	1	2	3	4	5	6	7
Fuel flow, #/hr	5.9	5.9	5.9	5.9	5.9	5.9	5.9
Air flow, SCFM	11.5	11.6	12.5	12.5	13.8	13.9	13.9
% swirl	44	44	44	44	44	44	44
Sec. air preheat, °F	565	565	570	570	585	590	590
Pri. air flow, SCFM	1.8	1.8	1.8	1.8	1.8	1.8	1.8
Inlet O_2, %	21	21	21	21	21	21	21
Inlet CO_2, %	--	--	--	--	--	--	--
Balance	N_2	N_2	N_2	N_2	N_2	N_2	N_2
% FGR	--	--	--	--	--	--	--

FLUE MEASUREMENTS							
% O_2, polar	1.75	1.6	2.15	2.10	3.4	3.35	3.25
% O_2, para.	1.55	1.4	2.05	2.05	3.55	3.55	3.55
S.R. by O_2	1.074	1.066	1.101	1.101	1.190	1.190	1.190
% CO	--	--	--	--	--	--	--
% CO_2	--	--	--	--	--	--	--
NO, as meas., ppm	650	700	775	728	833	880	1100
NO, 0% EA, ppm	700	750	860	805	1000	1060	1325
SO_2, as meas., ppm	--	--	--	--	--	--	--

COMMENTS: 1-7 char/volatile tests, baseline.

Fuel: Western Kentucky Coal   Date: 4/28   Injector: Divergent

INLET PARAMETERS							
Run No.	2	3	6	7			
Additive	NO	NO	NO	NO			
Rotameter setting	11	11	11	11			
Add. flow (cc/min)	118	118	118	118			
Injector location	pa	pa	pa	p			
Sample location	p	p	p	s			
FLUE MEASUREMENTS							
NO total conversion*	345	345	345	345			
NO measured*	750	860	1060	1325			
NO without additive*	700	805	1000	1025			
NO due to additive*	50	55	60	300			
% conversion of add.	15	16	17	87			
SR	1.066	1.101	1.190	1.190			

COMMENTS: *ppm (STOICHI).

Fuel: Western Kentucky Coal   Date: 4/28   Injector: Divergent

INLET PARAMETERS							
Run No.	8	9					
Fuel flow, #/hr	5.9	5.9					
Air flow, SCFM	15.4	15.3					
% swirl	44	44					
Sec. air preheat, °F	595	595					
Pri. air flow, SCFM	1.8	1.8					
Inlet O_2, %	21	21					
Inlet CO_2, %	--	--					
Balance	N_2	N_2					
% FGR	--	--					

FLUE MEASUREMENTS							
% O_2, polar	--	4.55					
% O_2, para.	4.65	4.6					
S.R. by O_2	1.266	1.263					
% CO	--	--					
% CO_2	--	--					
NO, as meas., ppm	867	925					
NO, 0% EA, ppm	1115	1185					
SO_2, as meas., ppm	--	--					

COMMENTS: 8-9 char/volatile tests, baseline.

Fuel: Western Kentucky Coal   Date: 4/28   Injector: Axial

INLET PARAMETERS							
Run No.	10	11	12	13			
Fuel flow, #/hr	5.9	5.9	5.9	5.9			
Air flow, SCFM	13.9	13.9	13.0	13.0			
% swirl	44	44	44	44			
Sec. air preheat, °F	555	555	595	595			
Pri. air flow, SCFM	1.0	1.0	2.0	2.0			
Inlet O_2, %	21	21	21	21			
Inlet CO_2, %	--	--	--	--			
Balance	N_2	N_2	N_2	N_2			
% FGR	--	--	--	--			

FLUE MEASUREMENTS							
% O_2, polar	3.3	3.1	2.85	2.95			
% O_2, para.	3.2	3.05	2.85	2.9			
S.R. by O_2	1.168	1.159	1.147	1.150			
% CO	--	--	--	--			
% CO_2	--	--	--	--			
NO, as meas., ppm	500	510	980	890			
NO, 0% EA, ppm	590	595	1135	1030			
SO_2, as meas., ppm	--	--	--	--			

COMMENTS: 10-13 char/volatile tests.

Fuel: Western Kentucky Coal   Date: 4/28   Injector: Axial

INLET PARAMETERS							
Run No.	14	15	16	17	18		
Fuel flow, #/hr	5.9	5.9	5.9	5.9	5.9		
Air flow, SCFM	12.2	12.2	13.9	13.6	12.7		
% swirl	44	44	44	44	44		
Sec. air preheat, °F	595	595	555	565	570		
Pri. air flow, SCFM	2.7	2.7	1.0	1.4	1.8		
Inlet O_2, %	21	21	21	21	21		
Inlet CO_2, %	--	--	--	--	--		
Balance	N_2	N_2	N_2	N_2	N_2		
% FGR	--	--	--	--	--		

FLUE MEASUREMENTS							
% O_2, polar	3.2	3.2	3.2	3.3	2.85		
% O_2, para.	3.23	3.3	3.25	3.2	2.75		
S.R. by O_2	1.170	1.174	1.171	1.168	1.141		
% CO	--	--	--	--	--		
% CO_2	--	--	--	--	--		
NO, as meas., ppm	1240	1370	480	530	825		
NO, 0% EA, ppm	1465	1625	570	625	950		
SO_2, as meas., ppm	--	--	--	--	--		

COMMENTS: 14-18 char/volatile tests.

Fuel: Western Kentucky Coal   Date: 4/28   Injector: Axial

INLET PARAMETERS							
Run No.	11	12	15				
Additive	NO	NO	NO				
Rotameter setting	11	11	11				
Add. flow (cc/min)	118	118	118				
Injector location	pa	pa	pa				
Sample location	s	s	s				

FLUE MEASUREMENTS							
NO total conversion*	345	345	345				
NO measured*	595	1135	1625				
NO without additive*	578	1025	1470				
NO due to additive*	18	110	155				
% conversion of add.	5	32	45				
SR	1.159	1.147	1.174				

COMMENTS: *ppm (STOICHI).

Fuel: Western Kentucky Coal   Date: 6/16   Injector: Divergent

INLET PARAMETERS							
Run No.	1	2	3	4	5	6	7
Fuel flow, #/hr	5.9	5.9	5.9	5.9	5.9	5.9	5.9
Air flow, SCFM	14.3	12.3	11.0	14.6	13.2	13.8	15.3
% swirl	44.1	44	44	44	44	45	44
Sec. air preheat, °F	573	555	545	542	555	573	596
Pri. air flow, SCFM	1.8	1.8	1.8	1.8	1.8	1.8	1.8
Inlet O_2, %	21	21	21	21	21	21	21
Inlet CO_2, %	--	--	--	--	--	--	--
Balance	N_2	N_2	N_2	N_2	N_2	N_2	N_2
% FGR	--	--	--	--	--	--	--

FLUE MEASUREMENTS							
% O_2, polar	3.95	2.10	0.70	3.10	1.30	2.05	4.40
% O_2, para.	4.10	2.20	0.65	2.80	1.15	1.80	4.10
S.R. by O_2	1.227	1.109	1.029	1.143	1.054	1.087	1.226
% CO	--	--	--	--	--	--	--
% CO_2	--	--	--	--	--	--	--
NO, as meas., ppm	700	600	480	815	685	715	750
NO, 0% EA, ppm	870	670	495	940	725	782	932
SO_2, as meas., ppm	1740	1787	1857	1788	1777	1750	--

COMMENTS: 1-3 fuel injector plugging.
            4-7 char/volatile tests.

Fuel: Western Kentucky Coal   Date: 6/16   Injector: Divergent

INLET PARAMETERS							
Run No.	8	9	10	11	12	13	
Fuel flow, #/hr	5.9	5.9	5.9	5.9	5.9	5.9	
Air flow, SCFM	14.5	14.5	13.9	15.0	15.4	15.9	
% swirl	44	44	44	44	44	44	
Sec. air preheat, °F	596	596	586	596	593	598	
Pri. air flow, SCFM	1.8	1.8	1.8	1.8	1.8	1.8	
Inlet O_2, %	21	21	21	21	21	21	
Inlet CO_2, %	--	--	--	--	--	--	
Balance	N_2	N_2	N_2	N_2	N_2	N_2	
% FGR	--	--	--	--	--	--	
FLUE MEASUREMENTS							
% O_2, polar	2.70	2.25	1.00	1.95	2.55	3.00	
% O_2, para.	2.45	2.05	0.90	1.85	2.50	3.05	
S.R. by O_2	1.123	1.101	1.041	1.090	1.126	1.158	
% CO	--	--	--	--	--	--	
% CO_2	--	--	--	--	--	--	
NO, as meas., ppm	790	805	735	785	795	795	
NO, 0% EA, ppm	894	892	768	861	902	930	
SO_2, as meas., ppm	--	--	1713	1755	1703	1872	

COMMENTS: 8-13 char/volatile tests.

Fuel: Western Kentucky Coal   Date: 6/16   Injector: Divergent

INLET PARAMETERS							
Run No.	8	9	10	11	12	13	
Additive	NO	NO	NO	NO	NO	NO	
Rotameter setting	11	11	11	11	11	11	
Add. flow (cc/min)	118	118	118	118	118	118	
Injector location	pa	pa	pa	pa	pa	pa	
Sample location	p	p	p	p	p	p	
FLUE MEASUREMENTS							
NO total conversion*	345	345	345	345	345	345	
NO measured*	894	892	768	861	902	930	
NO without additive*	827	800	698	785	830	840	
NO due to additive*	67	92	70	76	72	90	
% conversion of add.	19	27	20	22	21	26	
SR	1.123	1.101	1.041	1.090	1.126	1.158	

COMMENTS: *ppm (SR = 1).

Fuel: Western Kentucky Coal   Date: 6/17   Injector: Divergent

INLET PARAMETERS							
Run No.	1	2	3	4	5	6	7
Fuel flow, #/hr	5.9	5.9	5.9	5.9	5.9	5.9	5.9
Air flow, SCFM	15.0	15.0	13.1	13.0	13.0	12.9	12.7
% swirl	44	44	44	44	44	44	44
Sec. air preheat, °F	631	631	611	598	598	--	525
Pri. air flow, SCFM	1.8	1.8	1.8	1.8	1.8	1.8	1.8
Inlet O_2, %	21	21	21	21	21	21	24
Inlet CO_2, %	--	--	--	--	--	--	--
Balance	N_2	N_2	N_2	N_2	N_2	N_2	N_2
% FGR	--	--	--	--	--	--	--
FLUE MEASUREMENTS							
% O_2, polar	4.05	4.00	--	2.95	3.60	3.45	3.90
% O_2, para.	4.15	4.10	--	3.15	3.90	3.80	--
S.R. by O_2	1.230	1.226	--	1.164	1.213	1.206	1.180
% CO	--	--	--	--	--	--	--
% CO_2	--	--	--	--	--	--	--
NO, as meas., ppm	810	880	--	760	770	730	925
NO, 0% EA, ppm	1009	1093	--	894	946	891	966
SO_2, as meas., ppm	1745	1740	--	1765	--	--	1619

COMMENTS: 1-3 fuel injector plugging.
           4-7 char/volatile tests.

Fuel: Western Kentucky Coal   Date: 6/7   Injector: Divergent

INLET PARAMETERS							
Run No.	8	9	10	11	12	13	14
Fuel flow, #/hr	5.9	5.9	5.9	5.9	5.9	5.9	5.9
Air flow, SCFM	11.6	11.6	11.6	11.6	11.6	11.6	9.2
% swirl	44	44	44	44	44	44	44
Sec. air preheat, °F	533	556	588	588	588	575	575
Pri. air flow, SCFM	1.8	1.8	1.57	1.57	1.57	1.57	1.8
Inlet O_2, %	24.3	24.3	24.3	24.3	24.3	24.3	27.9
Inlet CO_2, %	--	--	--	--	--	--	--
Balance	N_2	N_2	N_2	N_2	N_2	N_2	N_2
% FGR	--	--	--	--	--	--	--
FLUE MEASUREMENTS							
% O_2, polar	2.85	2.95	2.95	2.9	3.1	2.8	2.85
% O_2, para.	--	--	--	--	--	--	--
S.R. by O_2	1.123	1.128	1.128	1.125	1.135	1.121	1.105
% CO	--	--	--	--	--	--	--
% CO_2	--	--	--	--	--	--	--
NO, as meas., ppm	885	990	900	900	900	925	990
NO, 0% EA, ppm	866	974	885	883	892	903	830
SO_2, as meas., ppm	1664	--	--	--	1833	1612	738

COMMENTS: 8-14 char/volatile tests, oxygen enrichment.

Fuel: Western Kentucky Coal   Date: 6/17   Injector: Divergent

INLET PARAMETERS							
Run No.	15	16	17	18	19	20	21
Fuel flow, #/hr	5.9	5.9	5.9	5.9	5.9	5.9	5.9
Air flow, SCFM	9.2	9.6	9.6	--	--	--	--
% swirl	44	44	44	44	44	44	44
Sec. air preheat, °F	558	548	548	535	526	526	526
Pri. air flow, SCFM	1.80	1.35	1.35	1.81	1.81	1.81	1.81
Inlet O_2, %	27.9	28	28	21.1	21.1	21.2	21.3
Inlet CO_2, %	--	--	--	--	--	--	--
Balance	N_2	N_2	N_2	Ar	Ar	Ar	Ar
% FGR	--	--	--	--	--	--	--
FLUE MEASUREMENTS							
% O_2, polar	2.75	2.8	3.25	1.55	1.10	2.45	2.20
% O_2, para.	--	--	--	--	--	--	--
S.R. by O_2	1.101	1.102	1.121	1.074	1.051	1.121	1.107
% CO	--	--	--	--	--	--	--
% CO_2	--	--	--	--	--	--	--
NO, as meas., ppm	1110	950	875	538	555	612	652
NO, 0% EA, ppm	927	792	742	578	583	685	717
SO_2, as meas., ppm	--	958	1018	1235	1470	1568	1539

COMMENTS: 15-21 char/volatile tests.

Fuel: Western Kentucky Coal   Date: 6/17   Injector: Divergent

INLET PARAMETERS							
Run No.	5	9	13	15	16		
Additive	NO	NO	NO	NO	NO		
Rotameter setting	11	11	11	11	11		
Add. flow (cc/min)	118	118	118	118	118		
Injector location	pa	pa	pa	pa	pa		
Sample location	p	p	p	p	p		
FLUE MEASUREMENTS							
NO total conversion*	345	345	345	345	345		
NO measured*	946	974	883	927	792		
NO without additive*	891	875	868	825	720		
NO due to additive*	55	99	15	102	72		
% conversion of add.	16	29	4	30	21		
SR	1.21	1.128	1.121	1.101	1.102		

COMMENTS: *(0% EA).

Fuel: Western Kentucky Coal   Date: 6/17   Injector: Divergent

INLET PARAMETERS							
Run No.	22	23	24	25	26	27	28
Fuel flow, #/hr	5.9	5.9	5.9	5.9	5.9	5.9	5.9
Air flow, SCFM	--	--	--	--	--	--	--
% swirl	44	44	44	44	--	44	44
Sec. air preheat, °F	526	526	505	585	--	483	482
Pri. air flow, SCFM	1.57	1.57	1.81	1.81	1.81	1.81	1.81
Inlet O_2, %	21.8	21.8	21.6	21.5	19.0	18.9	18.7
Inlet CO_2, %	--	--	--	--	--	--	--
Balance	Ar	Ar	Ar	Ar	Ar	Ar	Ar
% FGR	--	--	--	--	--	--	--

FLUE MEASUREMENTS							
% O_2, polar	2.85	2.60	3.80	3.80	1.75	3.05	2.9
% O_2, para.	--	--	--	--	--	--	--
S.R. by O_2	1.140	1.126	1.199	1.200	1.095	1.180	1.171
% CO	--	--	--	--	--	--	--
% CO_2	--	--	--	--	--	--	--
NO, as meas., ppm	642	605	710	740	620	600	645
NO, 0% EA, ppm	711	662	838	878	755	795	875
SO_2, as meas., ppm	1529	1531	1416	1542	--	1590	1861

COMMENTS: 22-28 char/volatile tests.

Fuel: Western Kentucky Coal   Date: 6/17   Injector: Divergent

INLET PARAMETERS							
Run No.	29	30	31	32			
Fuel flow, #/hr	5.9	5.9	5.9	5.9			
Air flow, SCFM	--	--	--	--			
% swirl	44	44	23	23			
Sec. air preheat, °F	544	549	522	525			
Pri. air flow, SCFM	1.81	1.81	2.5	2.5			
Inlet O_2, %	24.0	24.0	19.1	19.1			
Inlet CO_2, %	--	--	--	--			
Balance	Ar	Ar	Ar	Ar			
% FGR	--	--	--	--			
FLUE MEASUREMENTS							
% O_2, polar	3.8	3.75	3.00	3.15			
% O_2, para.	--	--	--	--			
S.R. by O_2	1.174	1.172	1.174	1.184			
% CO	--	--	--	--			
% CO_2	--	--	--	--			
NO, as meas., ppm	825	750	960	1085			
NO, 0% EA, ppm	858	778	1252	1429			
SO_2, as meas., ppm	1403	1348	1696	1580			

COMMENTS: 29-32 char/volatile tests.

Fuel: Western Kentucky Coal   Date: 6/17   Injector: Divergent

INLET PARAMETERS							
Run No.	19	21	25	28	29		
Additive	NO	NO	NO	NO	NO		
Rotameter setting	11	11	11	11	11		
Add. flow (cc/min)	118	118	118	118	118		
Injector location	pa	pa	pa	pa	pa		
Sample location	p	p	p	p	p		
FLUE MEASUREMENTS							
NO total conversion*	345	345	345	345	345		
NO measured*	583	717	878	857	858		
NO without additive*	500	655	839	779	784		
NO due to additive*	83	62	39	78	74		
% conversion of add.	24	18	11	23	21		
SR	1.051	1.107	1.200	1.171	1.174		

COMMENTS: *(0% EA).

D.4 Montana Coal

The experimental data which were obtained during the Montana coal combustion studies are tabulated on the following pages. The terminology is identical to that described in Section D.1 except for the air flow rate entry which now refers to only the secondary air.

Fuel: Montana Coal   Date: 3/4   Injector: Divergent

INLET PARAMETERS							
Run No.	1	2	3	4	5	6	7
Fuel flow, #/hr	6.2	6.2	6.2	6.2	6.2	6.2	6.2
Air flow, SCFM	9.3	8.5	10.0	11.5	9.3	9.3	7.4
% swirl	44	43	44	44	44	--	43
Sec. air preheat, °F	556	531	538	553	538	--	482
Pri. air flow, SCFM	1.35	1.35	1.35	1.35	1.35	--	1.25
Inlet O_2, %	21	21	21	21	21	21	24.4
Inlet CO_2, %	--	--	--	--	--	--	--
Balance	N_2	N_2	N_2	N_2	N_2	N_2	N_2
% FGR	--	--	--	--	--	--	--

FLUE MEASUREMENTS							
% O_2, polar	2.25	1.15	3.45	--	2.65	--	2.1
% O_2, para.	2.15	1.10	3.4	5.2	2.65	--	--
S.R. by O_2	1.104	1.051	1.177	1.301	1.132	--	1.086
% CO	0.07	0.06	0.02	0.02	0.02	--	0.06
% CO_2	17.9	18.74	16.46	14.82	17.0	--	>20.0
NO, as meas., ppm	670	630	690	700	680	--	600
NO, 0% EA, ppm	745	665	825	930	780	--	565
SO_2, as meas., ppm	120	173	162	150	152	--	160

COMMENTS: 1-6 baseline conditions.
          7 oxygen enrichment.

Fuel: Montana Coal   Date: 3/4   Injector: Divergent

INLET PARAMETERS							
Run No.	8	9	10	11	12	13	14
Fuel flow, #/hr	6.2	6.2	6.2	6.2	6.2	6.2	6.2
Air flow, SCFM	8.2	8.4	8.5	--	--	--	--
% swirl	43	44	45	44	44	45	44
Sec. air preheat, °F	482	485	480	344	380	394	399
Pri. air flow, SCFM	1.25	1.25	1.25	1.35	1.35	1.35	1.35
Inlet O_2, %	24.2	24.2	23.4	20.6	20.4	22.8	22.4
Inlet CO_2, %	--	--	--	--	--	--	--
Balance	N_2	N_2	N_2	Ar	Ar	Ar	Ar
% FGR	--	--	--	--	--	--	--

FLUE MEASUREMENTS							
% O_2, polar	3.8	4.7	4.35	3.0	4.15	4.50	2.20
% O_2, para.	--	--	--	--	--	--	--
S.R. by O_2	1.170	1.220	1.208	1.156	1.234	1.224	1.099
% CO	0.05	0.02	0.02	0.06	0.03	0.03	0.03
% CO_2	19.16	18.32	16.82	15.46	13.75	15.14	17.31
NO, as meas., ppm	650	700	710	590	650	700	610
NO, 0% EA, ppm	670	755	785	705	840	805	635
SO_2, as meas., ppm	130	130	139	155	125	110	170

COMMENTS: 8-9 O_2 enrichment.
            10 23% O_2.
            11-12 21% O_2 in Ar.
            13-14 23% O_2 in Ar.

Fuel: Montana Coal   Date: 3/4   Injector: see Comments

INLET PARAMETERS							
Run No.	15	16	17				
Fuel flow, #/hr	6.2	6.2	6.2				
Air flow, SCFM	--	--	--				
% swirl	44	45	43				
Sec. air preheat, °F	408	412	420				
Pri. air flow, SCFM	1.35	.72	.72				
Inlet O_2, %	20.6	21	21				
Inlet CO_2, %	--	--	--				
Balance	Ar	Ar	Ar				
% FGR	--	--	--				

FLUE MEASUREMENTS							
% O_2, polar	1.6	3.45	2.3				
% O_2, para.	--	--	--				
S.R. by O_2	1.077	1.180	1.112				
% CO	0.06	0.06	0.20				
% CO_2	16.1	14.82	15.78				
NO, as meas., ppm	540	320	290				
NO, 0% EA, ppm	595	385	325				
SO_2, as meas., ppm							

COMMENTS: 15 axial injector, Ar/O_2.
            16-17 divergent injector, Ar/O_2.

Fuel: Montana Coal   Date: 3/10   .   Injector: Axial

INLET PARAMETERS							
Run No.	1	2	3	4	5	6	7
Fuel flow, #/hr	6.2	6.2	6.2	6.2	6.2	6.2	6.2
Air flow, SCFM	10.0	11.5	12.4	11.3	10.4	10.4	11.6
% swirl	44	44	44	44	44	44	44
Sec. air preheat, °F	550	553	558	558	553	553	550
Pri. air flow, SCFM	.73	.73	.73	.50	.50	1.0	1.0
Inlet O_2, %	21	21	21	21	21	21	21
Inlet CO_2, %	--	--	--	--	--	--	--
Balance	N_2	N_2	N_2	N_2	N_2	N_2	N_2
% FGR	--	--	--	--	--	--	--
FLUE MEASUREMENTS							
% O_2, polar	2.15	3.70	-5.1	3.6	2.35	2.75	4.5
% O_2, para.	1.95	3.45	-5.2	3.6	2.30	2.6	4.7
S.R. by O_2	1.094	1.180	1.301	1.189	1.112	1.129	1.264
% CO	0.14	0.03	0.03	0.03	0.11	0.04	0.04
% CO_2	18.11	16.28	14.5	16.1	17.54	--	14.82
NO, as meas., ppm	415	490	520	410	340	455	515
NO, 0% EA, ppm	455	585	690	495	380	520	665
SO_2, as meas., ppm	210	188	170	208	232	210	172
NO_x, 0% EA, ppm	455	--	--	--	--	--	675

COMMENTS: 1-3 baseline conditions.
           4-7 reduced primary air flow.

Fuel: Montana Coal   Date: 3/10   Injector: Axial

INLET PARAMETERS						
Run No.	8	9	10	11		
Fuel flow, #/hr	6.2	6.2	6.2	6.2		
Air flow, SCFM	11.1	9.9	9.7	8.7		
% swirl	44	44	43	43		
Sec. air preheat, °F	550	545	525	515		
Pri. air flow, SCFM	1.5	1.5	.73	.73		
Inlet O_2, %	21	21	23.1	23.25		
Inlet CO_2, %	--	--	17.6	19.6		
Balance	N_2	N_2	N_2	N_2		
% FGR	--	--	--	--		
FLUE MEASUREMENTS						
% O_2, polar	4.8	3.3	4.25	2.85		
% O_2, para.	4.9	3.45	--	--		
S.R. by O_2	1.278	1.180	1.206	1.127		
% CO	0.03	0.03	--	--		
% CO_2	14.82	16.46	--	--		
NO, as meas., ppm	680	660	465	430		
NO, 0% EA, ppm	885	790	520	445		
SO_2, as meas., ppm	165	200	200	230		
NO_x, 0% EA, ppm	900	--	--	445		

COMMENTS: 8-9 increased primary air flow.
          10-11 oxygen enrichment.

Fuel: Montana Coal   Date: 3/11   Injector: Divergent

INLET PARAMETERS							
Run No.	7	8	9				
Fuel flow, #/hr	6.2	6.2	6.2				
Air flow, SCFM	--	--	--				
% swirl	44	43	43				
Sec. air preheat, °F	200	193	186				
Pri. air flow, SCFM	.77	.60	1.7				
Inlet O_2, %	20.55	20.85	19.8				
Inlet CO_2, %	16.0	17.2	15.0				
Balance	Ar	Ar	Ar				
% FGR	--	--	--				
		·					

FLUE MEASUREMENTS							
% O_2, polar	3.1	3.3	3.2				
% O_2, para.	--	--	--				
S.R. by O_2	1.162	1.172	1.176				
% CO	--	--	--				
% CO_2	--	--	--				
NO, as meas., ppm	400	360	700				
NO, 0% EA, ppm	480	430	885				
SO_2, as meas., ppm	255	200	--				

COMMENTS: 7-9 $Ar/O_2/CO_2$.
            9 lifted flame.

Fuel: Montana Coal   Date: 3/11   Injector: Axial

INLET PARAMETERS							
Run No.	1	2	3	4	5	6	
Fuel flow, #/hr	6.2	6.2	6.2	6.2	6.2	6.2	
Air flow, SCFM	9.8	11.0	8.9	11.1	8.8	10.6	
% swirl	42	44	42	44	44	44	
Sec. air preheat, °F	545	543	530	348	280	243	
Pri. air flow, SCFM	.60	.60	.60	.60	.60	.60	
Inlet O_2, %	21	21	21	21	21	21	
Inlet CO_2, %	--	--	--	--	--	--	
Balance	N_2	N_2	N_2	N_2	N_2	N_2	
% FGR	--	--	--	--	--	--	

FLUE MEASUREMENTS							
% O_2, polar	2.65	4.60	2.0	4.5	3.2	--	
% O_2, para.	2.65	4.65	1.8	4.5	3.25	--	
S.R. by O_2	1.132	1.260	1.086	1.249	1.167	--	
% CO	0.04	0.02	0.05	0.02	0.03	--	
% CO_2	11.36	14.48	18.32	15.30	16.28	--	
NO, as meas., ppm	410	490	370	460	385	--	
NO, 0% EA, ppm	470	630	405	585	455	-	
SO_2, as meas., ppm	140	150	240	250	230	--	

COMMENTS: 1-3 reduced primary air flow.
           4-6 reduced air preheat.

D.5 FMC Coal Char

The following pages contain a complete tabulation of the experimental data obtained during the FMC coal char combustion studies. In general, the terminology is the same as that described in Section D.1 with the following exceptions:

1. In some tests a small amount of methane was added to the primary air/char stream just prior to the fuel injector. This gas flow is reported in standard cubic feet per minute (70°F, 1 atm).

2. NO emission data taken during tests where methane was added are shown corrected for dilution by methane combustion products and associated inerts.

3. The air flow rate entry refers to secondary air only.

Fuel: FMC Coal Char & Methane   Date: 3/15   Injector: Axial, flame mode

INLET PARAMETERS							
Run No.	1	2	3	4	5	6	7
Fuel flow, #/hr	6.7	6.7	6.7	6.7	6.7	6.7	6.7
Air flow, SCFM	14.2	15.7	17.6	17.6	16.0	13.7	13.7
% swirl	45	45	45	44	44	44	44
Sec. air preheat, °F	555	565	600	600	620	620	620
Pri. air flow, SCFM	1.0	1.0	1.0	1.0	1.0	1.0	.73
Inlet O_2, %	21	21	21	21	21	21	21
Inlet CO_2, %	--	--	--	--	--	--	--
Balance	N_2	N_2	N_2	N_2	N_2	N_2	N_2
% FGR	--	--	--	--	--	--	--
Methane, SCFM	0.50	0.50	0.50	0.35	0.35	0.35	0.35
FLUE MEASUREMENTS							
% O_2, polar	1.8	2.2	--	--	4.3	2.5	2.35
% O_2, para.	1.8	2.25	4.65	5.7	4.2	2.37	2.25
S.R. by O_2	1.092	1.118	1.281	1.369	1.247	1.126	1.118
% CO	0.10	0.11	0.11	0.10	0.11	0.11	0.12
% CO_2	16.1	15.62	13.6	13.45	14.82	16.46	16.64
NO, as meas., ppm	165	180	185	208	218	210	207
NO, 0% EA, ppm	180	200	240	285	270	235	230
SO_2, as meas., ppm	1300	1300	1200	1200	1250	1400	1400
NO, CH_4 free	230	255	300	350	335	290	285

COMMENTS:

Fuel: FMC Coal Char & Methane   Date: 3/15   Injector: Axial, flame mode

INLET PARAMETERS							
Run No.	8	9	10	11	12	13	
Fuel flow, #/hr	6.7	6.7	6.7	6.7	6.7	6.7	
Air flow, SCFM	15.8	15.7	13.9	15.6	--	--	
% swirl	44	44	44	37	37	35	
Sec. air preheat, °F	635	635	635	220	220	160	
Pri. air flow, SCFM	.72	1.4	1.4	1.0	1.0	1.0	
Inlet O_2, %	21	21	21	21	20.4	21.0	
Inlet CO_2, %	--	--	--	--	13.6	11.0	
Balance	N_2	N_2	N_2	N_2	Ar	Ar	
% FGR	--	--	--	--	--	--	
Methane, SCFM	0.35	0.35	0.35	0.35	0.35	0.35	
FLUE MEASUREMENTS							
% O_2, polar	3.6	3.3	2.42	1.25	0.7	2.15	
% O_2, para.	3.45	3.20	2.3	--	--	--	
S.R. by O_2	1.194	1.178	1.121	1.062	1.034	1.113	
% CO	0.06	0.07	--	--	0.04	--	
% CO_2	15.46	16.1	16.82	--	13.6	10.92	
NO, as meas., ppm	195	235	228	180	155	227	
NO, 0% EA, ppm	235	275	255	190	165	255	
SO_2, as meas., ppm	1200	1380	1400	--	1550	1600	
NO, CH_4 free	285	340	315	235	205	311	

COMMENTS:

Fuel: FMC Coal Char & Methane   Date: 3/16   Injector: 3/4" s. s. tube reactor mode

INLET PARAMETERS							
Run No.	1	2	3	12	13	14	15
Fuel flow, #/hr	6.7	6.7	6.7	6.7	6.7	6.7	6.7
Air flow, SCFM	16.3	19.2	14.9	15.2	17.8	14.6	13.6
% swirl	44	45	44	44	44	44	44
Sec. air preheat, °F	415	450	490	435	520	580	595
Pri. air flow, SCFM	1.8	1.75	3.9	1.8	1.9	1.8	1.8
Inlet O_2, %	21	21	21	21	21	21	21
Inlet CO_2, %	--	--	--	--	--	--	--
Balance	N_2	N_2	N_2	N_2	N_2	N_2	N_2
% FGR	--	--	--	--	--	--	--
Methane, SCFM	0.40	0.40	0.40	0.35	0.35	0.35	0.35
FLUE MEASUREMENTS							
% O_2, polar	--	4.35	3.65	3.15	4.55	1.85	1.3
% O_2, para.	2.85	4.25	3.4	3.35	4.40	1.8	1.3
S.R. by O_2	1.555	1.251	1.191	1.188	1.262	1.092	1.065
% CO	0.11	0.09	0.09	0.06	0.06	0.09	0.21
% CO_2	16.1	13.3	15.8	15.9	13.3	17.5	19.2
NO, as meas., ppm	260	280	295	310	330	300	300
NO, 0% EA, ppm	300	350	350	370	415	330	320
SO_2, as meas., ppm	1310	1290	1380	1400	1350	1600	1730
NO, CH_4 free	375	435	435	455	515	405	395

COMMENTS:

Fuel: FMC Coal Char & Methane   Date: 3/16   Injector: Divergent, flame mode

INLET PARAMETERS							
Run No.	4	6	7	8	9	10	11
Fuel flow, #/hr	6.7	6.7	6.7	6.7	6.7	6.7	6.7
Air flow, SCFM	16.0	15.9	20.2	17.4	15.6	20.6	15.1
% swirl	44	44	45	44	45	45	45
Sec. air preheat, °F	570	545	--	510	465	440	435
Pri. air flow, SCFM	1.8	1.8	1.8	1.8	1.8	1.8	2.35
Inlet O_2, %	21	21	21	21	21	21	21
Inlet CO_2, %	--	--	--	--	--	--	--
Balance	N_2	N_2	N_2	N_2	N_2	N_2	N_2
% FGR	--	--	--	--	--	--	--
Methane, SCFM	0.70	0.70	0.70	0.55	0.40	0.75	0.0
FLUE MEASUREMENTS							
% O_2, polar	1.75	--	0.85	--	2.0	3.0	--
% O_2, para.	1.65	6.5	0.80	--	1.8	3.0	2.85
S.R. by O_2	1.084	1.444	1.039	--	1.092	1.165	1.155
% CO	0.76	--	0.11	0.46	0.07	0.09	--
% CO_2	16.1	17.2	18.3	19.2	16.5	14.8	--
NO, as meas., ppm	100	--	180	--	215	190	350
NO, 0% EA, ppm	110	--	185	--	235	220	405
SO_2, as meas., ppm	--	1320	1400	1400	1550	1200	--
NO, CH_4 free	160	--	275	--	290	330	--

COMMENTS:

Fuel: FMC Coal Char   Date: 3/17   Injector: 3/4" s. s. tube reactor mode

INLET PARAMETERS							
Run No.	1	2	3	4	5	6	7
Fuel flow, #/hr	6.7	6.7	6.7	6.7	6.7	6.7	6.7
Air flow, SCFM	12.2	12.6	16.3	11.6	10.3	13.2	12.1
% swirl	44	44	44	44	44	44	44
Sec. air preheat, °F	560	540	585	580	570	555	545
Pri. air flow, SCFM	1.8	1.8	1.8	1.8	1.8	1.8	1.8
Inlet O_2, %	21	21	21	21	21	21	21
Inlet CO_2, %	--	--	--	--	--	--	--
Balance	N_2	N_2	N_2	N_2	N_2	N_2	N_2
% FGR	--	--	--	--	--	--	--
FLUE MEASUREMENTS							
% O_2, polar	3.05	3.25	3.00	2.05	0.50	3.65	2.95
% O_2, para.	3.30	3.55	3.25	2.25	0.55	4.25	3.45
S.R. by O_2	1.185	1.201	1.181	1.118	1.026	1.251	1.194
% CO	0.03	0.07	0.06	0.07	0.14	0.05	0.06
% CO_2	16.46	18.61	16.1	17.54	>20.0	16.28	17.18
NO, as meas., ppm	340	420	300	415	340	460	465
NO, 0% EA, ppm	405	505	355	465	350	575	555
SO_2, as meas., ppm	1650	1810	1450	1970	2110	1710	--

COMMENTS: 1 divergent injector.
            3 methane added at 0.35 SCFM.

Fuel: FMC Coal Char   Date: 3.17   Injector: 3/4" s. s. tube reactor mode

INLET PARAMETERS							
Run No.	8	9	10				
Fuel flow, #/hr	6.7	6.7	6.7				
Air flow, SCFM	11.9	13.3	10.7				
% swirl	44	44	44				
Sec. air preheat, °F	595	605	595				
Pri. air flow, SCFM	1.8	1.8	1.8				
Inlet O_2, %	21	21	21				
Inlet CO_2, %	--	--	--				
Balance	N_2	N_2	N_2				
% FGR	--	--	--				
FLUE MEASUREMENTS							
% O_2, polar	2.85	3.85	1.75				
% O_2, para.	2.80	3.80	1.75				
S.R. by O_2	1.152	1.218	1.090				
% CO	0.06	0.06	0.12				
% CO_2	18.32	17.0	19.58				
NO, as meas., ppm	340	350	340				
NO, 0% EA, ppm	390	425	370				
SO_2, as meas., ppm	1750	1700	1880				

COMMENTS:

Fuel: FMC Coal Char & Methane   Date: 3/18   Injector: Axial, flame mode

INLET PARAMETERS							
Run No.	1	2	3	4	5	6	7
Fuel flow, #/hr	6.7	6.7	6.7	6.7	6.7	6.7	6.7
Air flow, SCFM	15.8	17.2	19.5	11.4	--	--	--
% swirl	44	44	44	44	44	44	44
Sec. air preheat, °F	575	620	640	620	485	495	510
Pri. air flow, SCFM	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Inlet O_2, %	21	21	21	21	26.7	26.9	26.4
Inlet CO_2, %	--	--	--	--	--	--	--
Balance	N_2	N_2	N_2	N_2	Ar	Ar	Ar
% FGR	--	--	--	--	--	--	--
Methane, SCFM	0.35	0.35	0.35	0.0	0.35	0.35	0.35
FLUE MEASUREMENTS							
% O_2, polar	1.7	3.1	3.95	2.8	1.7	2.88	3.43
% O_2, para.	1.5	3.05	3.9	2.8	--	--	--
S.R. by O_2	1.076	1.168	1.225	1.152	1.066	1.118	1.144
% CO	0.16	0.11	0.11	0.15	0.04	0.06	0.06
% CO_2	17.72	16.28	15.78	17.9	17.18	16.82	15.94
NO, as meas., ppm	250	250	250	350	280	280	288
NO, 0% EA, ppm	270	290	305	405	235	245	265
SO_2, as meas., ppm	1340	1400	1390	1600	2200	2170	2130
NO, CH_4 free	330	360	380	405	290	300	325

COMMENTS:

Fuel: FMC Coal Char & Methane   Date: 3/18   Injector: Axial, flame mode

INLET PARAMETERS							
Run No.	8	9	10	11	12	13	14
Fuel flow, #/hr	6.7	6.7	6.7	6.7	6.7	6.7	6.7
Air flow, SCFM	--	--	--	12.9	16.5	15.4	15.3
% swirl	--	49	44	44	43	44	44
Sec. air preheat, °F	515	535	565	610	640	650	615
Pri. air flow, SCFM	.87	1.0	1.0	1.0	1.0	1.0	1.0
Inlet O_2, %	21.0	21.0	21.3	23.9	24.5	24.0	24.1
Inlet CO_2, %	--	--	--	--	--	--	--
Balance	Ar	Ar	Ar	N_2	N_2	N_2	N_2
% FGR	--	--	--	--	--	--	--
Methane, SCFM	0.35	0.35	0.35	0.35	0.35	0.35	0.35
FLUE MEASUREMENTS							
% O_2, polar	1.87	2.35	4.1	0.6	4.35	1.75	3.4
% O_2, para.	--	--	--	--	--	--	--
S.R. by O_2	1.096	1.124	1.240	1.025	1.219	1.078	1.163
% CO	0.04	0.04	0.04	0.13	0.07	0.05	0.06
% CO_2	13.0	12.74	11.44	>20.0	17.18	>20.0	19.16
NO, as meas., ppm	185	185	195	275	325	310	325
NO, 0% EA, ppm	205	210	240	250	340	295	330
SO_2, as meas., ppm	2200	2180	2180	1800	1800	1890	1680
NO, CH_4 free	250	255	295	305	415	360	405

COMMENTS:

Fuel: FMC Coal Char & Methane   Date: 3/18   Injector: Axial, flame mode

INLET PARAMETERS							
Run No.	15						
Fuel flow, #/hr	6.7						
Air flow, SCFM	13.8						
% swirl	44						
Sec. air preheat, °F	620						
Pri. air flow, SCFM	1.0						
Inlet O_2, %	24.1						
Inlet CO_2, %	--						
Balance	N_2						
% FGR	--						
Methane, SCFM	0.35						
FLUE MEASUREMENTS							
% O_2, polar	2.1						
% O_2, para.	--						
S.R. by O_2	1.095						
% CO	0.06						
% CO_2	>20.0						
NO, as meas., ppm	310						
NO, 0% EA, ppm	295						
SO_2, as meas., ppm	1850						
NO, CH_4 free	365						

COMMENTS:

Fuel: FMC Coal Char   Date: 3/18   Injector: 3/4" s. s. tube reactor mode

INLET PARAMETERS							
Run No.	16	17	18	19	20	21	22
Fuel flow, #/hr	6.7	6.7	6.7	6.7	6.7	6.7	6.7
Air flow, SCFM	--	--	--	--	--	--	--
% swirl	44	44	44	44	44	44	33
Sec. air preheat, °F	490	490	485	450	450	440	170
Pri. air flow, SCFM	1.9	1.8	1.8	1.8	1.8	1.8	1.8
Inlet O_2, %	21.6	21.1	21.0	21.8	27.0	27.0	20.7
Inlet CO_2, %	--	--	--	--	--	--	14.8
Balance	Ar	Ar	Ar	Ar	Ar	Ar	Ar
% FGR	--	--	--	--	--	--	--
FLUE MEASUREMENTS							
% O_2, polar	3.2	1.95	0.5	4.25	4.45	3.15	3.6
% O_2, para.	--	--	--	--	--	--	--
S.R. by O_2	1.178	1.101	1.024	1.251	1.195	1.130	1.205
% CO	0.06	0.10	0.21	0.04	0.06	--	--
% CO_2	15.78	16.64	17.9	14.82	20.0	--	--
NO, as meas., ppm	355	320	270	370	420	395	410
NO, 0% EA, ppm	405	350	275	445	390	350	505
SO_2, as meas., ppm	2280	2500	2750	2120	2600	--	1370
NO_x, 0% EA, ppm	--	360	--	--	--	--	--

COMMENTS:

Fuel: FMC Coal Char & Methane   **Date:** 3/18   **Injector:** Axial, flame mode

INLET PARAMETERS							
Run No.	23	24	25				
Fuel flow, #/hr	6.7	6.7	6.7				
Air flow, SCFM	--	--	--				
% swirl	44	44	44				
Sec. air preheat, °F	150	150	150				
Pri. air flow, SCFM	1.0	1.0	1.0				
Inlet O_2, %	20.3	20.3	--				
Inlet CO_2, %	14	13.2	12.8				
Balance	Ar	Ar	Ar				
% FGR	--	--	--				
Methane, SCFM	0.35	0.35	0.35				
FLUE MEASUREMENTS							
% O_2, polar	2.15	3.0	--				
% O_2, para.	--	--	--				
S.R. by O_2	1.113	1.165	--				
% CO	--	--	--				
% CO_2	--	--	--				
NO, as meas., ppm	200	200	--				
NO, 0% EA, ppm	231	245	--				
SO_2, as meas., ppm	1380	1400	1450				
NO, CH_4 free	285	300	--				

COMMENTS:

D.6   Natural Gas

The experimental data which were obtained during the natural gas combustion studies are listed on the following three pages. Natural gas was fired through the divergent coal injector to investigate the formation of thermal NO under conditions similar to those of a coal flame. In general, the parameters were the same as those described in Section D.1 except that the fuel flow was measured in standard cubic feet per minute (70°F) and there was no primary air flow.

Fuel: Natural Gas   Date: 1/13   Injector: Divergent

INLET PARAMETERS							
Run No.	1	2	3	4			
Fuel flow, #/hr	--	1.2	1.2	1.1			
Air flow, SCFM	13.4	13.2	13.7	14.9			
% swirl	45	46	45	44			
Sec. air preheat, °F	100	100	100	100			
Pri. air flow, SCFM	--	--	--	--			
Inlet O_2, %	21	21	21	21			
Inlet CO_2, %	--	--	--	--			
Balance	N_2	N_2	N_2	N_2			
% FGR	--	--	--	--			
FLUE MEASUREMENTS							
% O_2, polar	2.55	1.8	3.25	4.35			
% O_2, para.	2.5	1.75	3.15	4.35			
S.R. by O_2	1.121	1.082	1.158	1.234			
% CO	0.07	0.04	0.07	0.07			
% CO_2	10.4	11.1	10.2	9.5			
NO, as meas., ppm	50	49	51	51			
NO, 0% EA, ppm	57	53	60	64			
SO_2, as meas., ppm	--	--	--	--			

COMMENTS: Fuel flow is in CMF at 70°F.

Fuel: Natural Gas   Date: 1/14   Injector: Divergent

INLET PARAMETERS							
Run No.	1	2	3	4			
Fuel flow, #/hr	1.0	1.2	1.2	1.2			
Air flow, SCFM	13.0	12.7	12.5	12.4			
% swirl	45	45	45	45			
Sec. air preheat, °F	610	600	620	625			
Pri. air flow, SCFM	--	--	--	--			
Inlet O_2, %	21	21	21	21			
Inlet CO_2, %	--	--	--	--			
Balance	N_2	N_2	N_2	N_2			
% FGR	--	--	--	--			
FLUE MEASUREMENTS							
% O_2, polar	3.75	2.6	1.9	0.55			
% O_2, para.	3.65	2.45	1.8	0.5 5			
S.R. by O_2	1.189	1.119	1.072	1.022			
% CO	0.04	0.04	0	0			
% CO_2	9.7	10.7	10.8	11.7			
NO, as meas., ppm	94	92	90	85			
NO, 0% EA, ppm	114	104	98	87			
SO_2, as meas., ppm	--	--	--	--			

COMMENTS: Fuel flow is in CFM at 70°F.

Fuel: Natural Gas   Date: 2/20   Injector: Divergent

INLET PARAMETERS							
Run No.	1	2	3 ·	4			
Fuel flow, #/hr	1.1	1.0	1.1	1.2			
Air flow, SCFM	10.3	10.7	10.1	9.5			
% swirl	44	45	44	44			
Sec. air preheat, °F	520	525	525	520			
Pri. air flow, SCFM	--	--	--	--			
Inlet O_2, %	24.9	24.8	29.1	29.4			
Inlet CO_2, %	--	--	--	--			
Balance	N_2	N_2	N_2	N_2			
% FGR	--	--	--	--			
FLUE MEASUREMENTS							
% O_2, polar	1.8	4.4	4.5	1.25			
% O_2, para.	--	--	--	--			
S.R. by O_2	1.068	1.190	1.157	1.038			
% CO	0.07	0.07	0.07	0.35			
% CO_2	13.6	12.05	18.3	17.7			
NO, as meas., ppm	159	175	460	480			
NO, 0% EA, ppm	145	180	395	360			
SO_2, as meas., ppm	--	--	--	--			

COMMENTS: Fuel flow is in CFM at 70°F.

APPENDIX E

ADIABATIC FLAME TEMPERATURE CALCULATION

E.1 Introduction

This appendix describes the Fortran computer program CHERYL.FOR, which was developed to calculate the theoretical flame temperature (adiabatic) of hydrocarbon systems. As described in Chapter 8, the adiabatic flame temperature was found to be a useful correlating parameter for thermal NO formation.

The program contains the required composition and enthalpy data for natural gas, methane, methanol, and distillate oil in addition to the four coals and coal char used in this study. Any other fuel can be used by simply providing the appropriate physical property data. The oxidant is specified in terms of the stoichiometric ratio (relative to the fuel) and the chemical composition, i.e., relative percentages of N_2, O_2, Ar, H_2O, CO_2, CO, SO_2, and SO_3. At present, only fuel-lean cases can be run. The program does, however, allow variations in oxidizer and fuel preheat and in the amount and temperature of flue gas being recirculated (fgr).

In essence, the calculation is simply a multicomponent enthalpy balance with the allowance for equilibrium dissociation of CO_2 and H_2O vapor due to the high temperature. It is, however, not a true adiabatic equilibrium because free radicals are not included.

Section E.2 of this appendix describes the overall formulation of the enthalpy balance equations and Section E.3 discusses the solution algorithm. Section E.4 describes the detailed program structure and discusses each of the subroutines and functions in depth. Section E.5 defines the notation used in the actual Fortran coding. A complete listing of the program is contained in Section E.6 and Section E.7 discusses the runs which were made to validate the calculation procedure.

E.2   Formulation of Equations

The theoretical flame temperature calculation assumes that the fuel at temperature T_f reacts adiabatically with the oxidant at temperature T_a in the presence of a specified amount of recirculated flue gas at temperature T_r. From an overall enthalpy balance on the system it can be shown that:

$$\sum_a n_i \int_{T_o}^{T_a} Cp_i dT + \sum_f n_i \int_{T_o}^{T_f} Cp_f dT + \sum_r n_i \int_{T_o}^{T_r} Cp_i dT$$

$$- \Delta H_c = \sum_{f\ell} n_i \int_{T_o}^{T_{adb}} Cp_i dT \qquad (E-1)$$

where

a = reference to oxidant specie,

r = reference to recirculated flue gas specie,

f = reference to fuel specie,

$f\ell$ = reference to flue specie,

n_i = moles of specie i,

Cp_i = molar heat capacity of specie i,

T_o = reference temperature for ΔH_c,

T_{adb} = adiabatic flame temperature, and

ΔH_c = heat of combustion at T_o.

The molar heat capacity of each specie was related to the gas temperature by an empirical power-law equation (Smith and Van Ness, 1975):
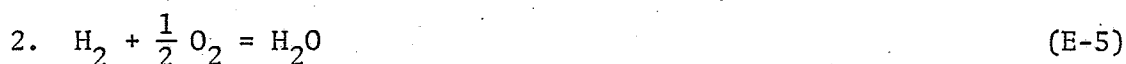
$$Cp_i = \alpha_i + \beta_i T + \gamma_i T^2 \tag{E-2}$$

The CO_2 and H_2O equilibrium constants were also based on empirical temperature relations from Spiers (1962):

1. $CO + \frac{1}{2} O_2 = CO_2$ \hfill (E-3)

$$\log K_1 = \frac{\alpha_1}{T} + \beta_1 \log T + \gamma_1 T + \delta_1 T^2 + \varepsilon_1 \tag{E-4}$$

where

$$K_1 = \frac{[CO_2]}{[CO][O_2]^{1/2}}$$

2. $H_2 + \frac{1}{2} O_2 = H_2O$ \hfill (E-5)

$$\log K_2 = \frac{\alpha_2}{T} + \beta_2 \log T + \gamma_2 T + \delta_2 T^2 + \varepsilon_2 \tag{E-6}$$

where

$$K_2 = \frac{[H_2O]}{[H_2][O_2]^{1/2}}$$

E.3 Solution Procedure

Figures E-1 and E-2 show the conceptual layout of the solution algorithm used to calculate the adiabatic flame temperature for a given
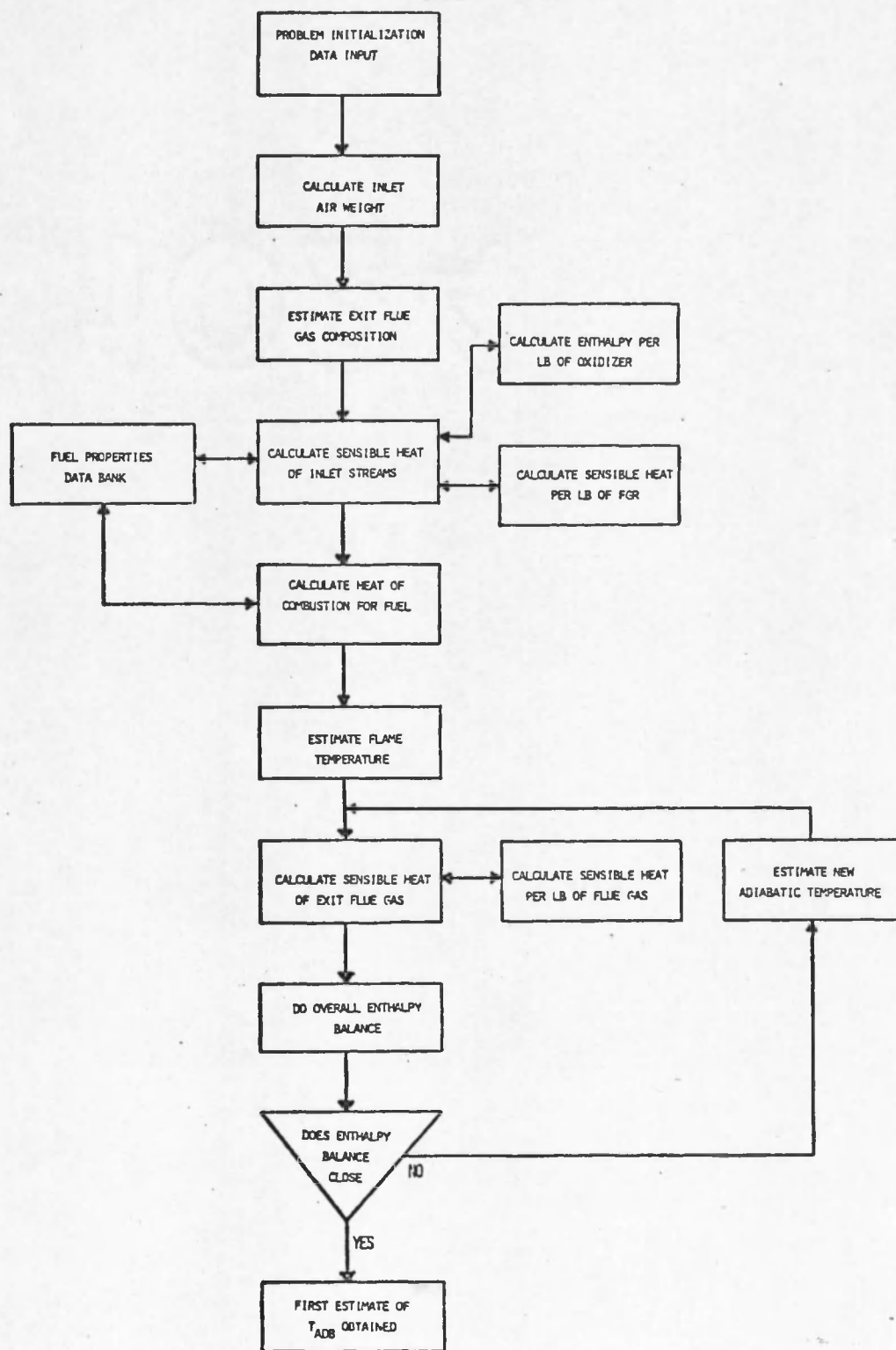
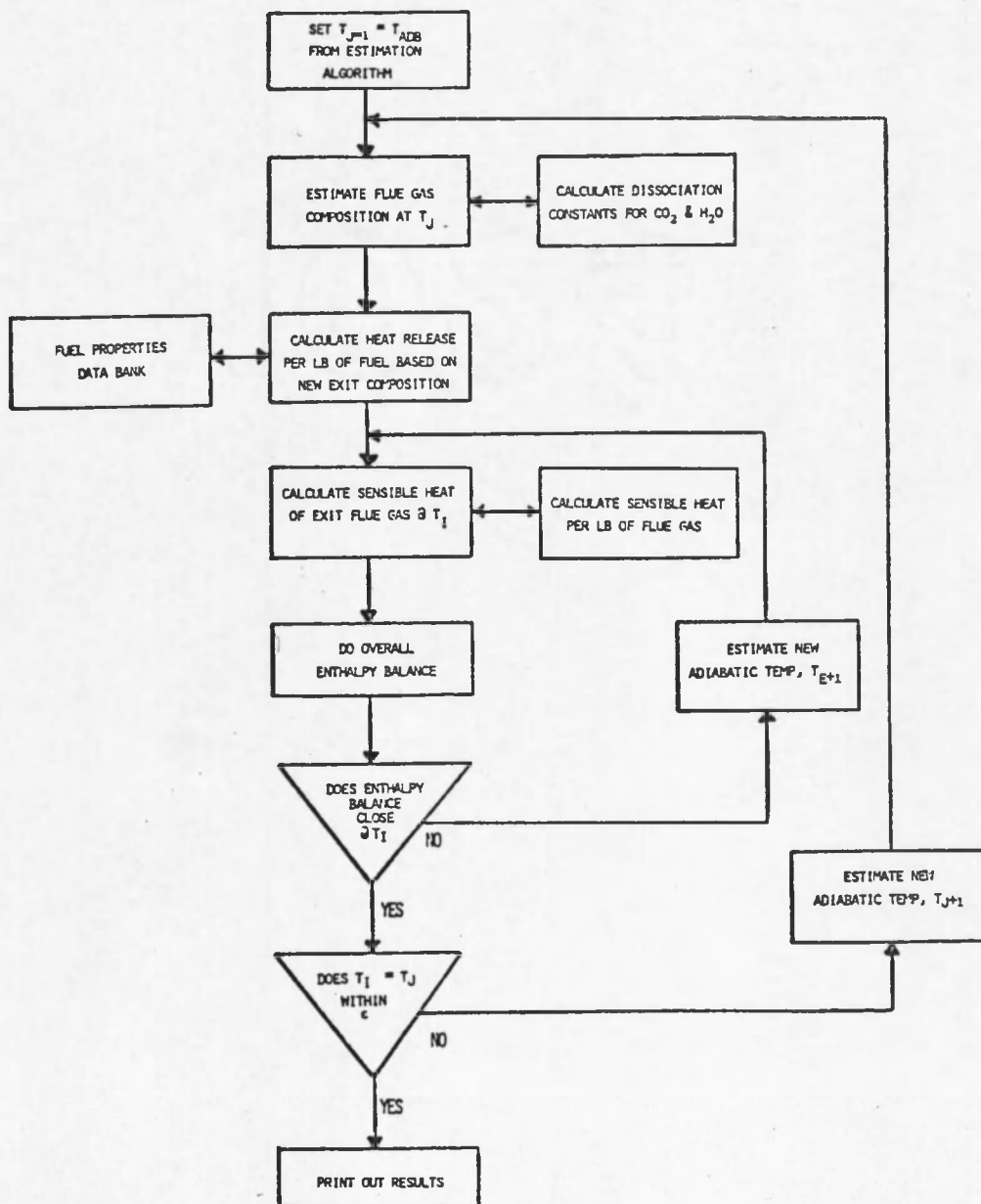Figure E-1. Algorithm for initial T_{adb} estimate.

Figure E-2. Algorithm for calculation of adiabatic flame temperature (equilibrium considerations included).

set of inlet compositions and conditions. The first portion of the
procedure (shown in Figure E-1) assumes that the fuel burns completely to
CO_2 and H_2O vapor and uses the reducing interval method to iteratively
determine the theoretical flame temperature at which the overall enthalpy
balance is satisfied. This temperature is then used as the initial esti-
mate for the main calculation (Figure E-2) in which the enthalpy balance
is coupled with consideration of the CO_2 and H_2O equilibrium.

The main algorithm has both inner and outer iterative loops as
shown in Figure E-2. First, the equilibrium exit composition is
calculated for the jth overall adiabatic temperature estimate. Then, the
enthalpy balance is iteratively solved (using the reducing interval
method) for this particular exit composition. If the iterative solution
of the enthalpy balance results in a temperature within $\pm$ 2°F of the
temperature T_j, on which the equilibrium composition was based, the
system is considered converged. If not, a new temperature estimate,
T_{j+1}, is calculated and the cycle repeated.

E.4 Detailed Program Description

E.4.1 Main Program

The main program of the CHERYL.FOR computer code functions pri-
marily as the executive system for the calculations. Except for the
final heat balance and new parameter estimates, all detailed calculations
are done in specific subroutines. Initially, the main program calls a
user-supplied subroutine to direct the data input. In this way, the user

is required to input only those parameters he wishes to vary, all others are set by the subroutine itself.

All of the major subroutines and functions which were used in this investigation are described in the following sections. The program does, however, contain features which were developed by the author for use in other studies. These are included in the program listing, but not discussed in detail.

E.4.2 Subroutines

DREAD. This subroutine handles the problem initialization. It directs the user specification of calculation type and fuel. Fuel composition and the default oxidizer composition arrays are also defined.

ERDA. This subroutine directs the data input for the calculations used in this investigation. The user must supply the secondary air preheat ($°F$), the stoichiometric ratio, the O_2 and CO_2 mole fractions, the type of inert (N_2 or Ar), and the fraction of flue gas recirculated. The primary percentage, primary air temperature, and flue gas recirculation temperature are automatically set by the subroutine.

ESTMS. This subroutine controls the specie mass balances. Based on the inlet fuel and oxidizer compositions, it calculates the exit flue gas composition assuming complete combustion to CO_2 and H_2O vapor. All calculations and concentrations are on a mass basis.

INHET. This subroutine controls the calculation of the sensible heat of the inlet fuel, oxidizer, and fgr, i.e.:

$$\sum_a n_i \int_{T_o}^{T_a} Cp_i dT + \sum_f n_i \int_{T_o}^{T_f} Cp_i dT + \sum_r n_i \int_{T_o}^{T_r} Cp_i dT$$

where the symbols are defined with equation E-1 in Section E.2.

GHCON. This subroutine is called by INHET to calculate the enthalpy change, in Btu/hr, associated with increasing the temperature of a specified gas stream from the reference temperature (25°C) to the specified temperature. Note that this same subroutine is thus called separately for the inlet oxidizer, the recirculated flue gas, and the exit flue gas, each with a different temperature and perhaps composition.

OFTS. This data subroutine contains the physical property data on the fuels.

HTGEN. This subroutine calculates the heat release due to the combustion process.

CONV. This subroutine converts a weight fraction array into a mole fraction array.

RECON. This subroutine converts a mole fraction array into a weight fraction array.

KVAL. This subroutine calculates the equilibrium constants for the CO_2 and H_2O reactions.

REC. This subroutine controls the flue gas recirculation mass balance and interrelates the various definitions of percent flue gas recirculation.

DPRT. This subroutine controls the print-out of the results.

E.4.3 Functions

AIRWT. This function subprogram calculates the weight (in lbs) of air required to burn one lb of the specified fuel at the stoichiometry specified.

OUTHT. This function calculates the sensible heat content of the exit flue gas stream at the jth estimate of the adiabatic flame temperature, i.e.:

$$\sum_{f\ell} n_i \int_{T_o}^{T_{adb}} Cp_i \, dT$$

E.5 Nomenclature

Table E-1 defines the major Fortran parameters used in the CHERYL.FOR program. In general, gaseous streams are specified by a total weight (lbs) and a weight fraction array with a consistent set of indices. The fuel stream is specified by a mass fraction array and is taken to be unit mass (1 lb).

E.6 CHERYL.FOR Computer Code

The following pages contain a complete listing of the Fortran computer program CHERYL.FOR, which was used for the adiabatic flame temperature calculation. The code is currently in an interactive configuration and was run on a DEC-10 timesharing system during the investigation; however, it has also been run in the batch mode on an IBM 360-65 system.

Table E-1. Notation for adiabatic flame temperature calculations.

Computer Code	Description
ACOMP(I)	weight fraction of specie I in inlet oxidizer:

            1 = nitrogen

            2 = oxygen

            3 = argon

            4 = water vapor

            5 = CO_2

            6 = CO

            7 = SO_2

            8 = SO_3

API   if the fuel is an oil this is the API gravity, if a non-oil this is a fuel index:

            1 = Colorado coal

            2 = natural gas

            3 = propane

            4 = methane

            5 = methanol

            6 = Pittsburgh coal

            7 = Western Kentucky coal

            8 = Montana coal

            9 = FMC coal char

ATEMP   mean temperature of oxidizer (°F)

Table E-1--Continued.

Computer Code	Description
AWT	weight (in lbs) of oxidizer required for one lb of fuel at specified stoichiometry
ECOMP(I)	weight fraction of specie I in flue gas stream: 1 to 8 = same as ACOMP(I) 9 = NO 10 = H_2
EXAIR	stoichiometric ratio (SR)
FC	fuel code -- input by user; FC uses same numerical code as API
HCONT	HCONT is the sensible heat (in Btu/lb) required to heat a gas stream from 77°F to a specified temperature
KA	equilibrium constant: $CO + \frac{1}{2} O_2 = CO_2$
KB	equilibrium constant: $H_2 + \frac{1}{2} O_2 = H_2O$
OCOMP(I)	weight fraction of specie I in fuel: 1 = carbon 2 = hydrogen 3 = nitrogen 4 = sulfur 5 = oxygen

Table E-1--Continued.

Computer Code	Description
	6 = ash
	7 = water
OTEMP	inlet temperature of fuel (°F)
PC	problem code -- specifies which user subroutine will be called to direct data input
PREC	recirculation fraction:

$$PREC = \frac{lbs\ fgr}{lbs\ fgr\ +\ lbs\ air\ +\ lbs\ fuel}$$

Computer Code	Description
PRIP	primary stoichiometry fraction
PRIT	primary air temperature (°F)
RTEMP	temperature of fgr (°F)
SAT	temperature of secondary air (°F)
T	current estimate of adiabatic flame temperature (°F)
TEWT	total exit flue gas weight in lbs
THG	heat generated due to combustion
THI	sensible heat of reactants
THO	sensible heat of flue gas stream
VAL	minus heat of combustion (Btu/lb)
XINC	temperature increment in interaction loop (°F)

```
      DIMENSION EMF(15)
      REAL KA, KB, NUREC
      COMMON/ INPUT / NRU, NWU
      COMMON/ TITL / TITLE(20)
      COMMON/ AIR / ACOMP(15), ATEMP, EXAIR, ADEN
      COMMON/ WT / AWT, AMMASS, FGWT, ADWT, OWT
      COMMON/ RES / VOF, TAU, FR, XLBG, TLOSS
      COMMON/ QUEGAS / INDQ,QCOMP(15)
      COMMON/ FUEL / OCOMP(15), OTEMP, API, OVISC, CVAL, ADCOMP(15)
      COMMON/ FLUREC / ECOMP(15), AMCOMP(15), RTEMP, PREC, F
      COMMON/ HEAT / AHC, RHC, AMHC, OHC
      COMMON/ MOL / SUMN, SUMA, SUMM, SUMO
      COMMON/ FARMIX/ FMCOMP(15), FMMASS,CHFUEL
      COMMON/ XNU / NUREC
        NAMELIST/XMAIN/ACOMP, ECOMP, AWT, TEWT, THO, THI,THG
        DATA YES/1HY/
C
C
C*******************************************************************************
C*******************************************************************************
C**                                                                         **
C**                                                                         **
C**                  DWP  SUPER ADIABATIC FLAME PROGRAM                      **
C**                                                                         **
C**                                                                         **
C*******************************************************************************
C
```

```
          NRU = 5
          NWU = 5
          NDU = 31
1         CONTINUE
          CALL DREAD(NP)
          IF ( NP .EQ. 0) GO TO 999
3         CONTINUE
          IF ( NP .EQ. 1) CALL BLAIR( RTEMP,EXAIR,PREC)
          IF (NP.EQ.2) CALL SHOFF(NB,ATEMP,RTEMP,EXAIR,PREC)
          IF(NP .EQ. 3.0) CALL JOST( ATEMP,EXAIR,PREC,OTEMP)
          IF( NP .EQ. 4.0) EXAIR = 1.15
          IF (NP.EQ.5.) CALL ERDA(ATEMP,EXAIR,DGLR,RTEMP,ACOMP)
          IF (NP .EQ. 5.0) CALL REC(DGLR,1,PREC)
          NN = 0
C
C
C

          IF ( RTEMP .EQ. -1.0) GO TO 1
          DXA = 0.0
5         CONTINUE
C
      D=1.0
      AWT= AIRWT(D)
      CALL ESTMS(TEWT)
C       TEWT IS LBS OF AIR + FUEL + FGR
      IF (TEWT.GT.10.E5 ) GO TO 900
      CALL INHET (TEWT, THI)
      CALL HTGEN ( TEWT, THG )
      T = 1000.0
      XINC = 500.0
10    CONTINUE
      DO 50 I=1,10
      THO = OUTHT(T,TEWT,ECOMP)
```

```
         Z = THO - THI - THG
         IF (Z) 48,48,55
  48     CONTINUE
         T = T + XINC
  50     CONTINUE
  55     CONTINUE
         T = T - XINC
         XINC = XINC / 10.0
         T = T + XINC
         IF ( XINC .LE. 1.0 ) GO TO 60
         GO TO 10
  60     CONTINUE
           OLDT = T
C
C        THIS IS THE END OF THE FIRST CALCULATION PASS.   NOW WE MUST
C        ACCOUNT FOR THE HIGH TEMPERATURE DISSOCIATION OF H2O AND CO2.
C
         IF ( T .GT. 3600.0 ) T = 3580.0
           IF (OLDT .GT. 5000.0) T = 4100.0
C        THIS IS TO INSURE THE FIRST ESTIMATE OF THE CO LEVEL IS NOT TOO
C        HIGH FOR THE LOOP TO CONVERGE
         NIT = 0
           GO TO 400
C
```

```
200      CONTINUE
         CALL HTGEN(TEWT,THG)
         T = T - 1000.0
         XINC = 500.0
210      CONTINUE
         DO 250   I=1,10
         THO = OUTHT(T,TEWT,ECOMP)
         Z = THO - THI - THG
         IF ( Z .GT. 0.0 ) GO TO 255
         T = T + XINC
250      CONTINUE
255      CONTINUE
         T = T - XINC
         XINC = XINC / 10.0
         T = T + XINC
         IF ( XINC .LE. 0.1 ) GO TO 260
         GO TO 210
260      CONTINUE
         DELT = ABS( T - RT)
         IF ( DELT .LT. 2.0) GO TO 300
           IF ( NIT .GE. 30) GO TO 280
         GO TO 100
280        CONTINUE
           WRITE(5,282) T, RT, OLDT
282        FORMAT ( 3F10.0)
           READ (5,284) T
284        FORMAT(1F)
           GO TO 100
300        CONTINUE
         CALL DPRT (T,OLDT)
900      CONTINUE
         GO TO 3
400        CONTINUE
100        CONTINUE
           NIT = NIT + 1
```

```
         IF(NIT .GE.5 .AND. NIT .LT.30) T=(T+RT)/2.0
         RT = T
         DO 410  I=1,15
         EMF(I) = ECOMP(I)
410      CONTINUE
         CALL CONV(EMF)
         CALL KVAL(T, KA, KB)
C        NOW WE CALCULATE NEW CO AND H2 CONC
         XCO2 = EMF(5)
         XO2 = EMF(2)
         IF( XO2 .LT. 0.0001) XO2 = 0.0001
         EMF(2) = XO2
         XCO = XCO2/KA/XO2**0.5
         XH2O = EMF(4)
         XH2 = XH2O/KB/XO2**0.5
C        NOW WE NORMALIZE THE NEW MOLE FRACTION
C        ARRAY AND CONVERT ITBACK TO WEIGHT FRACTIONS
         EMF(6) = XCO
         EMF(10) = XH2
         SUM = 0.0
         DO 430  I=1,11
         SUM = SUM + EMF(I)
430      CONTINUE
         DO 440  I = 1,11
         EMF(I) = EMF(I)/SUM
440      CONTINUE
         CALL RECON(EMF)
         DO 450  I=1,11
         ECOMP(I) = EMF(I)
450      CONTINUE
         GO TO 200
920      FORMAT(4E14.4)
999      CONTINUE
         STOP
         END
```

```
          SUBROUTINE DREAD (NP)
          COMMON/ INPUT / NRU, NWU
          COMMON/ TITL / TITLE(20)
          COMMON/ AIR / ACOMP(15), ATEMP, EXAIR, ADEN
          COMMON/ RES / VOF, TAU, FR, XLBG, TLOSS
          COMMON/ QUEGAS / INDQ,QCOMP(15)
          COMMON/ WT / AWT, AMMASS, FGWT, ADWT, OWT
          COMMON/ FUEL / OCOMP(15), OTEMP, API, OVISC, CVAL, ADCOMP(15)
          COMMON/ FLUREC / ECOMP(15), AMCOMP(15), RTEMP, PREC, F
          NAMELIST/XREAD/OCOMP, OTEMP, API, OVISC, ACOMP, ATEMP, EXAIR,
         $ADEN, RTEMP, PREC,ADCOMP, QCOMP, CVAL
C
C         THIS SUBROUTINE HANDLES THE PROBLEM INIALIZATION
C
          WRITE(5,10)
10        FORMAT(/,'ENTER PROB CODE, FUEL CODE')
          READ (5,12) PC,FC
12        FORMAT(2F)
          NP = IFIX(PC)
          IF ( NP .EQ. 0) RETURN
          API = FC
          DO 20 I=1,15
          OCOMP(I) = 0.0
          ACOMP(I) = 0.0
          QCOMP(I) = 0.0
20        CONTINUE
          IF ( FC .EQ. 1.0) GO TO 100
          IF ( FC .EQ. 2.0) GO TO 200
          IF( FC .EQ. 4.0) GO TO 400
          IF ( FC .EQ. 5.0) GO TO 500
          IFC = IFIX(FC-5.0)
          GO TO (600,700,800,900),IFC
          IF( FC .EQ. 36.0) GO TO 3600
          RETURN
100       CONTINUE
```

```
C          COAL NO 1 - COLORADO
C          B&W ANALYSIS
           OCOMP(1) =0.731
           OCOMP(2) = 0.051
           OCOMP(3) = 0.012
           OCOMP(4) = 0.011
           OCOMP(5) = 0.097
           OCOMP(6) = 0.098
           OTEMP = 70.0
           GO TO 1200
C
C
C
200        CONTINUE
C          NATURAL GAS IS ASSUMED TO BE CH4
C          W.R.T. CHEMICAL COMPOSITION ONLY
C          W.R.T. CHEMICAL COMPOSITION ONLY!
C
C
C

           OCOMP(1) = 0.75
           OCOMP(2) = 0.25
           OTEMP = 70.0
           GO TO 1200
400        CONTINUE
C          METHANE
```

```
              OCOMP(1) = 0.75
              OCOMP(2) = 0.25
              OTEMP = 70.0
              GO TO 1200
   500        CONTINUE
C             METHANOL
              OCOMP(1) = 0.375
              OCOMP(2) = 0.125
              OCOMP(5) = 0.500
              OTEMP = 70.0
              GO TO 1200
   3600       CONTINUE
C             DISTILLATE OIL
              OCOMP(1) = 0.868
              OCOMP(2) = 0.131
              OCOMP(4) = 0.001
              OTEMP = 70.0
              GO TO 1200
   600        CONTINUE
C             COAL NO 2 - PITTSBURGH
              OCOMP(1) = .7723
              OCOMP(2) = .0515
              OCOMP(3) = .0123
              OCOMP(4) = .0259
              OCOMP(5) = .0587
              OCOMP(6) = .0793
              OTEMP = 70.
              GO TO 1200
```

```
700       CONTINUE
C         COAL NO 3 - WESTERN KENTUCKY
          OCOMP(1) = .6948
          OCOMP(2) = .0479
          OCOMP(3) = .0129
          OCOMP(4) = .0297
          OCOMP(5) = .0882
          OCOMP(6) = .0783
          OCOMP(7) = .0482
          OTEMP = 70.0
          GO TO 1200
800       CONTINUE
C         COAL NO 4 - MONTANA
          OCOMP(1) = .5285
          OCOMP(2) = .0347
          OCOMP(3) = .0138
          OCOMP(4) = .0072
          OCOMP(5) = .1104
          OCOMP(6) = .0920
          OCOMP(7) = .2132
          OTEMP = 70.0
          GO TO 1200
C
900       CONTINUE
C         COAL NO 5 - FMC CHAR
          OCOMP(1) = .728
          OCOMP(2) = .0088
          OCOMP(3) = .0099
          OCOMP(4) = .0347
          OCOMP(5) = .0066
```

```
                OCOMP(6)  =  .212
                OTEMP = 70.0
                GO  TO  1200
1200            CONTINUE
                ACOMP(1)  =  0.768
                ACOMP(2)  =  0.232
                ATEMP = 77.0
                RETURN
                END
```

```
       SUBROUTINE ERDA( ATEMP, EXAIR, DGLR, RTEMP, ACOMP)
       REAL LBS
       DIMENSION ACOMP(15)
C
C      THIS SUBROUTINE CONTROLS THE DATA INPUT
C
       ORT = RTEMP
       OAT = ATEMP
       OEA = EXAIR
       WRITE (5,10)
10     FORMAT(' ENTER SEC PREHEAT, EXAIR')
       READ (5,12) SAT, EXAIR
12     FORMAT (2F)
       PRIP = 0.14
       PRIT = 75.0
       IF( EXAIR .EQ. 0.0) EXAIR = OEA
       ATEMP =   ((EXAIR-PRIP)*(SAT+460.) + PRIP*(PRIT+460.))/EXAIR -460.
       IF( SAT .EQ. 0.0) ATEMP = OAT
       RTEMP = SAT
```

```
         IF( SAT .EQ. 0.0) RTEMP = ORT
         DO 15 I = 1,15
         ACOMP(I) = 0.0
15       CONTINUE
         XO2 = O2MF
         WRITE (5,20)
20       FORMAT( ' ENTER MOLE FRAC O2, MOLE FRAC CO2' )
         READ (5,12) O2MF,CO2F
         IF( O2MF .EQ. 0.0) O2MF = XO2
         WRITE (5,30)
30       FORMAT ( ' IF ARGON RUN ENTER 1.0')
         READ (5,12) ARG
         IF ( ARG .EQ. 1.0) GO TO 40
C        THIS IS THE NITROGEN LOOP
         A = O2MF*32.0
         B = (1.0 - O2MF-CO2F)*28.16
         C = CO2F*44.011
         LBS = A + B + C
         ACOMP(1) = B / LBS
         ACOMP(2) = A / LBS
         ACOMP(5) = C/LBS
         GO TO 50
40       CONTINUE
```

```
          A = O2MF * 32.0
          B = (1.0 - O2MF - CO2F)*39.95
          C = CO2F*44.011
          LBS = A + B + C
          ACOMP(1) = 0.0
          ACOMP(2) = A / LBS
          ACOMP(3) = B / LBS
          ACOMP(5) = C/LBS
50        CONTINUE
          WRITE (5,52)
52        FORMAT(' ENTER DGLR FRAC, NO REREAD OPT. ')
          READ (5,12) DGLR
          RETURN
          END
```

```
      SUBROUTINE ESTMS( TEWT)
      DIMENSION EWT(15)
      COMMON/ WT / AWT, AMMASS, FGWT, ADWT, OWT
      COMMON/ FLUREC / ECOMP(15), AMCOMP(15), RTEMP, PREC, F
      COMMON/ AIR / ACOMP(15), ATEMP, EXAIR, ADEN
      COMMON/ FUEL / OCOMP(15), OTEMP, API, OVISC, CVAL, ADCOMP(15)
      NAMELIST/ XEX/ AWT, BXT, EWT, ECOMP, EXAIR, OCOMP
C
C     THIS IS THE MASS BALANCE SUBROUTINE
C
      D = 1.0
      AWT = AIRWT(D)
      IF (EXAIR .LT. 1.0) WRITE (5,XEX)
100   CONTINUE
      EWT(1) = ACOMP(1)*AWT
      EWT(2) = OCOMP(5) + ACOMP(2)*AWT - OCOMP(2)*32.0*0.25/1.008 -
     2 OCOMP(1)*32.0/12.011 - OCOMP(4)*32.0/32.066 - OCOMP(3)*32.0*0.5/1
     34.008
      EWT(3) = ACOMP(3)*AWT
      EWT(4) = OCOMP(2)*18.016*0.5/1.008 + ACOMP(4)*AWT + OCOMP(7)
      EWT(5) = OCOMP(1)*44.011/12.011 + ACOMP(5)*AWT
      EWT(6) = ACOMP(6)*AWT
      EWT(7) = OCOMP(4)*64.066/32.066 + ACOMP(7)*AWT
      EWT(9) = OCOMP(3)*30.008/14.008
      IF(EWT(9) .LT. .05) GO TO 4
      EWT(9) = 0.0
      EWT(1) = ACOMP(1) * AWT + OCOMP(3) * 1.0
      EWT(2) = OCOMP(5) + ACOMP(2)*AWT - OCOMP(2)*32.0*0.25/1.008 -
     2 OCOMP(1)*32.0/12.011 - OCOMP(4)*32.0/32.066
4     CONTINUE
```

```
        DO 5 I= 10, 15
        EWT(I) = 0.0
5       CONTINUE
9       CONTINUE
        TEWT = 0.0
        DO 10   I=1,15
        TEWT = TEWT + EWT(I)
10      CONTINUE
        DO 15  I = 1,15
        ECOMP(I)  = EWT(I) / TEWT
15      CONTINUE
        BXT = TEWT
        TEWT= BXT/(1.0- PREC)
        FGWT = TEWT
        RETURN
        END
```

```
      SUBROUTINE INHET(TEWT, TTHI)
      DIMENSION XCOMP(15)
      DIMENSION DEC(15)
      DIMENSION DAC(15)
      COMMON/ FLUREC / ECOMP(15), AMCOMP(15), RTEMP, PREC, F
      COMMON/ AIR / ACOMP(15), ATEMP, EXAIR, ADEN
      COMMON/ QUEGAS / INDQ, QCOMP(15)
      COMMON/ HEAT / AHC, RHC, AMHC, OHC
      COMMON/ FUEL / OCOMP(15), OTEMP, API, OVISC, CVAL, ADCOMP(15)
      NAMELIST/ XINHT/ AHC, OHC, RHC, THI, XCOMP
C
C
C
C        THIS SUBROUTINE CALCULATES THE SENSIBLE HEAT
C        CONTENT OF THE INLET STREAMS
C
C
      T = ATEMP
      DO 10   I=1,8
      DAC(I) = ACOMP(I)
10    CONTINUE
      DO 15   I=9,15
      DAC(I) = 0.0
15    CONTINUE
      CALL GHCON( T, DAC, HCON)
      D = 1.0
      TA = AIRWT(D)
      AHC = TA*HCON
C        AHC IS THE HEAT CONTENT OF THE INLET AIR STREAM IN
C        BTU BASED ON 77 DEG. F
17    CONTINUE
      IF ( API .LT. 10.0 ) GO TO 20
      XAI = API
      CALL OFTS( 1, XAI, SPG)
      T = OTEMP
```

```
      OHC = ( 0.388*(T-77.) + .000225*(T**2-77.**2))/SPG**0.5
C        OHC IS THE HEAT CONTENT OF THE OIL IN BTU/LB BASED
C        ON A 77 DEG. F BASELINE TEMP.
      GO TO 30
20    CONTINUE
      T = OTEMP
C     API = 1.0 FOR COLORADO COAL
C     API = 2.0 FOR NATURAL GAS
C     API = 3.0 FOR PROPANE
C
C
C
C     API = 4.0 FOR METHANE
C     API = 5.0 FOR METHANOL
C        API = 6.0 FOR PITTSBURGH COAL
C        API = 7.0 FOR WESTERN KENTUCKY COAL
C        API = 8.0 FOR MONTANA COAL
C        API = 9.0 FOR FMC COAL CHAR
         IF( API .GE. 6.0 .AND. API .LE. 9.0) GO TO 21
      IF ( API .NE. 1.0) GO TO 23
21       CONTINUE
      ACT = ((T-77.0)/1.8 + 0.0)
      OCP = 0.20 + 0.00088*ACT + 0.0015*38
C        THE 38 IS WT. PERCENT VOLATILE MATTER
C     THIS FORMULA IS FROM 3-217 PERRY
      OHC =OCP*(T-77.0)
      GO TO 30
```

```
23      CONTINUE
        IF(API.NE.2.0) GO TO 24
        OHC = 0.5335*(T-77.0)
        GO TO 30
24      CONTINUE
        IF(API.NE.3.0) GO TO 25
        OHC = 0.390* ( T-77.0)
        GO TO 30
25      CONTINUE
        IF(API.NE.4.0 ) GO TO 26
        OHC = .526 * (T - 77.0)
        GO TO 30
26      CONTINUE
        OHC = ( 0.388*(T-77.) + .000225*(T**2-77.**2))
30      CONTINUE
C          THIS NEXT PART CALCULATES THE ENTHALPY OF THE
C          RECIRCULATION AIR AND SUMS THE HEAT INPUT
  100 CONTINUE
        RWT = PREC * TEWT
        DO 110 I = 1, 15
        DEC (I) = ECOMP(I)
  110 CONTINUE
        CALL GHCON (RTEMP, DEC, HCON)
        RHC = HCON * RWT
C
C
C
C          RHC IS THE HEAT CONTENT OF THE RECIRCULATED FLUE GAS
C          IN BTU
        THI     = AHC + OHC + RHC
        TTHI = THI
        RETURN
        END
```

```
      SUBROUTINE GHCON (FTEMP, COMP,HCON)
      DIMENSION A(11), B(11), C(11), MW(11), COMP(15), AD(11), BD(11),
     2 CD(11), MWD(11), HCT(11)
      REAL MW, MWD
      DATA A/ 6.524, 6.418,4.954,7.256, 6.214, 6.420, 7.116, 6.077, 7.02
     20, 6.947, 3.381/
      DATA B/ 1.250, 3.102, 0.0, 2.298, 10.396, 1.665, 9.512, 23.537,
     2 -0.370, -0.200,18.044/
      DATA C/ -0.001, -0.923, 0.0, 0.283, -3.545, -0.196, 3.511, -0.687,
     2 2.546, 0.481, -4.3/
      DATA MW/ 28.016, 32.0, 39.944, 18.016, 44.011, 28.011, 64.066,
     2 80.066, 30.008, 2.016 , 16.034/
      NAMELIST/ XXGC/ AD, BD, CD, MWD, MW
```

```
C
C          THIS SUBROUTINE CALCULATES THE ENTHALPY CHANGE WHEN
C          A SPECIFIED GAS IS HEATED FROM 77 TO FTEMP DEG F.
C
           DO 20  I=1,11
           AD(I) = A(I)
              BD(I)=B(I)/1800.
              CD(I)=C(I)/3.24E+06
           MWD(I) = MW(I)
20         CONTINUE
              BL=536.7
           T = 459.7 + FTEMP
           DO 30  I=1,11
           HCO = AD(I)*(T-BL) + BD(I)/2.0*(T**2-BL**2) + CD(I)/3.0*( T**3-BL*
          2*3)
C          HCO IS THE HEAT CONTENT OF THE SPECIE IN BTU/ LB MOLE
           HCT(I) = HCO*COMP(I)/MWD(I)
30         CONTINUE
           HCON = 0.0
           DO 40  I=1,11
           HCON = HCON + HCT(I)
40         CONTINUE
           HCONT = HCON
C          NOTE THAT 77 DEG IS THE BASELINE TEMPERATURE
C          HCONT IS IN BTU/LB
           RETURN
           END
```

```
      SUBROUTINE OFTS (IX, API, VAL )
      DIMENSION SPG(50), HCONT(50)
      DATA SPG/ 29*0.9, 0.8762, 0.8708, 0.8654, 0.8602, 0.8550, 0.8498,
     2 0.8448, 0.8398, 0.8348, 0.8299, 0.8251, 10*0.7/
      DATA HCONT/ 29*18000., 18250., 18280., 18310., 18330., 18360.,
     1 18390., 18410., 18430., 18460., 18480., 18510., 10*18600./
C
C         THIS SUBROUTINE CONTAINS THE FUEL DATA
C
      SPG(12) = 0.9861
      HCONT(12) = 17620.
      SPG(19) = .9402
      HCONT(19) = 17900.
      SPG(23) = .9156
      HCONT(23) = 18030.0
      Z = IX - 1
      IF (Z) 10, 10, 200
10    CONTINUE
      N = IFIX(API)
      VAL = SPG(N)
      RETURN
200   CONTINUE
C     IF CVAL IS GIVEN, THIS PORTION OF THE SUBROUTINE WILL NOT BE CALLED.
      ZA = IX-2
      IF(ZA) 210, 210, 300
210   CONTINUE
      N = IFIX(API)
```

```fortran
        VAL   = HCONT(N)
C       API = 1.0 IS COAL
C       API = 2.0 IS NATURAL GAS
C       API = 3.0 FOR PROPANE
C       API = 4.0 FOR METHANE
        IF ( API .EQ. 1.0) VAL = 12540.0
        IF ( API .EQ. 2.0) VAL = 20500.0
        IF(API.EQ.3.0) VAL = 19930.
        IF ( API .EQ. 4.0) VAL = 21502.0
        IF( API.EQ.5 ) VAL = 8575.
          IF( API .EQ. 6.0) VAL = 13397.
          IF( API .EQ. 7.0) VAL = 11985.
          IF (API .EQ. 8.0) VAL = 8400.
C       THESE ARE NET HEATING VALUES
C       HCONT IS THE HEATING VALUE OF THE FUEL IN BTU/LB
        RETURN
300     CONTINUE
        RETURN
        END
```

```
      SUBROUTINE HTGEN ( TEWT, TTHG)
      REAL NOW, NOH
      COMMON/ FUEL / OCOMP(15), OTEMP, API, OVISC, CVAL, ADCOMP(15)
      COMMON/ FLUREC / ECOMP(15), AMCOMP(15), RTEMP, PREC, F
      NAMELIST/ XHTG/ ECOMP, SO2H, NOH, THG, EXAIR, HCONT, H2H, COH, CH
C
C
C     THIS SUBROUTINE CALCULATES THE ENERGY RELEASED
C     DUE TO THE COMBUSTION
C
C
      XAI = API
      HCONT = CVAL
      IF(CVAL.GT.1.0) GO TO 10
      CALL OFTS ( 2, XAI, HCONT)
10    CONTINUE
      XTEWT= (1.0-PREC) * TEWT
      COW = XTEWT * ECOMP(6)
      SO2W = XTEWT*ECOMP(7)
      NOW = XTEWT * ECOMP(9)
      H2W = XTEWT * ECOMP(10)
      CW = XTEWT * ECOMP(11)
      COH = -4343.6*COW
      SO2H =((70.94*453.6)/(64.066*3.97))*SO2W
        NOH =((-21.60*453.6)/(30.008*3.97))*NOW
      H2H = -51571.4*H2W
      CH = -14086.8*CW
      THG = HCONT + H2H + COH + CH + SO2H + NOH
      TTHG = THG
      RETURN
      END
```

```fortran
      SUBROUTINE CONV (A)
      REAL MW
      DIMENSION A(15), MW(12), B(12)
      DATA MW / 28.016, 32.0, 39.944, 18.016, 44.011, 28.011, 64.066, 80
     2.066, 30.008, 2.016, 12.011, 32.064/
C
C
C     THIS SUBROUTINE CALCULATES THE MOLE FRACTIONS FROM
C     THE  WEIGHT FRACTION DISTRIBUTION
C
C
      SB = 0.0
      DO 10  I=1,12
      B(I) = A(I) / MW(I)
      SB = B(I) + SB
10    CONTINUE
      DO 20  I=1,12
      A(I) = B(I) / SB
20    CONTINUE
      RETURN
      END
```

```
      SUBROUTINE RECON (A)
      REAL MW
      DIMENSION A(15), B(11), MW(11)
      DATA MW/ 28.016, 32.0, 39.944, 18.016, 44.011, 28.011, 64.066,
     2 80.066, 30.008, 2.016, 12.011 /
C
C
C
C        THIS SUBROUTINE CONVERTS A MOLE FRACTION ARRAY
C        INTO A WEIGHT FRACTION ARRAY
C
C
      SB = 0.0
      DO 10  I=1,11
      B(I) = A(I) * MW(I)
      SB = SB + B(I)
10    CONTINUE
      DO 20  I=1,11
      A(I) = B(I) / SB
20    CONTINUE
      RETURN
      END
```

```
·SUBROUTINE KVAL( TF, KA, KB )
   REAL KA,KB
C
C
C     THIS SUBROUTINE CALCULATES THE DISSOCIATION CONSTANTS
C     FOR  THE CO2 AND H2O REACTIONS
C
C
   TK = (TF - 32.0)/1.8 + 273.15
   XA = 69894.4/TK + 4.1470*ALOG10(TK)
1  + 0.378*TK/1000.0 -0.0972*(TK/1000.)**2 -
2  36.04838
   KA = EXP(2.303*XA/4.571)
   TK1 = TK/1000.0
   XB = 57111.1/TK - 2.6135*ALOG10(TK) -.84834*TK1
1  + 0.19602*TK1**2 - 2.96716
   KB = EXP(2.303*XB/4.571)
   RETURN
   END
```

```
      SUBROUTINE REC( DGLR, NE, XPR)
      REAL MWF,MF,MA
   REAL OMW, MW
   DIMENSION OMW(15), MW(15)
      DIMENSION X(11), Y(11), Z(11)
   COMMON/ MOL / SUMN, SUMA, SUMM, SUMO
   COMMON/ FUEL / OCOMP(15), OTEMP, API, OVISC, CVAL, ADCOMP(15)
   COMMON/ FLUREC / ECOMP(15), AMCOMP(15), RTEMP, PREC, F
   COMMON/ AIR / ACOMP(15), ATEMP, EXAIR, ADEN
   COMMON/ WT / AWT, AMMASS, FGWT, ADWT, OWT
   NAMELIST/ XMOLES/X, Y, SUMA, SUMN, SUMO,SUMM
   DATA MW /28.016,32.0,39.944,18.016,44.011,28.011,64.066,
  1  80.066,30.008,2.016,12.011,4*1./
   DATA OMW/12.011, 1.008, 28.016, 32.064, 32.0, 100.0, 18.016, 8*1./
C
C     THIS SUBROUTINE DOES THE RECIRCULATION MASS BALANCES
C
      IF( NE .EQ. 1) GO TO 100
   SUMO = 0.0
   SUMA = 0.0
    SUMR = 0.0
    FGRW = PREC*(AWT + 1.0)/(1.0 - PREC)
      FGRW IS THE LBS OF FLUE GAS RECIRCULATED
```

```fortran
      DO 40 I = 1,11
      X(I) = OCOMP(I) / OMW(I)
      Y(I) = ACOMP(I) * AWT/ MW(I)
        Z(I) = ECOMP(I) *FGRW/MW(I)
40    CONTINUE
      DO 43 I = 1,11
      SUMO = SUMO + X(I)
      SUMA = SUMA + Y(I)
        SUMR = SUMR + Z(I)
43    CONTINUE
        DGLR = SUMR/(SUMR + SUMA)
      RETURN
100     CONTINUE
        CALL ESTMS(XX)
        AWT = AIRWT(1.0)
        SUMA = 0.0
        SUMB = 0.0
C
C
C
        DO 140 I=1,11
        X(I) = ECOMP(I)/MW(I)
        Y(I) = AWT*ACOMP(I)/MW(I)
        SUMA = SUMA + Y(I)
        SUMB = SUMB + X(I)
140     CONTINUE
        MWF = 1.0/SUMB
        MA = SUMA
        MF = MA *(DGLR/(1.0-DGLR))
        F = MF*MWF
        PREC = F/ ( AWT + 1.0 + F)
        XPR = PREC
        RETURN
        END
```

```
      SUBROUTINE DPRT(T,OLDT)
      REAL NUREC
      DIMENSION BCOMP(15)
      DIMENSION CCOMP(15)
      DIMENSION WACOM(15), WECOM(15), WAMCOM(15)
      DIMENSION OXY(15), SN(15), RATIO(15)
      COMMON/ INPUT / NRU, NWU
      COMMON/ TITL / TITLE(20)
      COMMON/ AIR / ACOMP(15), ATEMP, EXAIR, ADEN
      COMMON/ WT / AWT, AMMASS, FGWT, ADWT, OWT
      COMMON/ RES / VOF, TAU, FR, XLBG, TLOSS
      COMMON/ QUEGAS / INDQ, QCOMP(15)
      COMMON/ FUEL / OCOMP(15), OTEMP, API, OVISC, CVAL, ADCOMP(15)
      COMMON/ FLUREC / ECOMP(15), AMCOMP(15), RTEMP, PREC, F
      COMMON/ HEAT / AHC, RHC, AMHC, OHC
      COMMON/ MOL / SUMN, SUMA, SUMM, SUMO
      COMMON/ FARMIX/ FMCOMP(15), FMMASS, CHFUEL
      COMMON/ XNU / NUREC
      XAWT = AWT
C
C
C         THIS SUBROUTINE DIRECTS THE OUTPUT OF RESULTS
```

```
             GO TO 900
900          CONTINUE
             WRITE(5,910) ATEMP, RTEMP, EXAIR, PREC
910          FORMAT (/,2F10.0,2F10.3)
             ATC = (ATEMP-32.0)/1.8
             RTC = (RTEMP-32.0)/1.8
             CALL REC( DGLR, 2, XXX)
             WRITE(5,915) DGLR
915          FORMAT (2F10.4)
             TK = (T-32.0)/1.8 + 273.15
             CALL CONV (ECOMP)
             OTK = (OLDT -32.0)/1.8 + 273.15
             WRITE (5,920) T, TK,OTK,ECOMP(6)
920          FORMAT (3F10.0,E14.4)
             RETURN
             END
```

```
      SUBROUTINE WETDRY( COMP)
      DIMENSION COMP(15)
      VOL= 1.0- COMP(4)
      DO 5 I= 1,11
      COMP(I)= COMP(I)/VOL
5     CONTINUE
      COMP(4)= 0.0
      RETURN
      END
```

```fortran
        SUBROUTINE BLAIR  (RTEMP,EXAIR,PREC)
        EXAIR = 1.15
        RTEMP = 350.0
        WRITE (5,10)
10      FORMAT ( ' ENTER PREC FRAC')
        READ (5,12) PREC
12      FORMAT (1F)
        RETURN
        END
C
C
        SUBROUTINE JOST( ATEMP,EXAIR,PREC,OTEMP)
        EXAIR = 1.045
        PREC = 0.0
        WRITE(5,10)
10      FORMAT(/, 'ENTER INLET TEMP')
        READ(5,12) ATEMP
12      FORMAT(1F)
        OTEMP = ATEMP
        RETURN
        END
```

```
      FUNCTION AIRWT(D)
      COMMON/ FUEL / OCOMP(15), OTEMP, API, OVISC, CVAL, ADCOMP(15)
      COMMON/ AIR / ACOMP(15), ATEMP, EXAIR, ADEN
      NAMELIST/ XAIR / OCOMP, ACOMP, TO, TA
C
C
C
C     THIS FUNCTION CALCULATES THE WEIGHT OF AIR
C     REQUIRED TO BURN ONE LB OF FUEL
C
C
C
      F = D
      CO = OCOMP(1)*32.0/12.011
      HO = OCOMP(2)*32.0*.5/2.016
      SO = OCOMP(4)*32.0/32.064
      TO = CO + HO + SO -OCOMP(5)
        TA=TO*EXAIR/ACOMP(2)
      AIRWT =-TA
      RETURN
C     TA IS THE TOTAL AIR NEEDED IN LBS
      END
```

```
      FUNCTION OUTHT (XT, TTEWT, COMP)
      DIMENSION COMP(15)
      DIMENSION DEC(15)
      NAMELIST/ XOUT/ DEC, T, HCON, TEWT
C
C
C        THIS FUNCTION CALCULATES THE SENSIBLE HEAT OF THE
C        EXIT STREAMS AT TEMPERATURE XT
C
C
      TEWT=TTEWT
      DO 10  I=1,15
      DEC(I) = COMP(I)
10    CONTINUE
      DEC(11) = 0.0
      T = XT
      CALL GHCON( T, DEC, HCON)
      PHC = 0.0
      WT = 0.0
      ZD = COMP( 11)
      IF ( ZD .LT. .0001) GO TO 30
20    CONTINUE
C        THE FOLLOWING LOOP CALCULATES THE HEAT CAPAACITY OF
C        THE CARBON PARTICULATE IN THE FLUE GAS.
      DELH = 0.1844*(T-77.0) + .000244*(T**2 - 77.0**2)
      WT = TEWT*DEC(11)
      PHC = DELH*WT
30    CONTINUE
      OUTHT = HCON*(TEWT - WT) + PHC
      RETURN
      END
```

E.7 Program Verification

To insure that the program was functioning properly, test cases were run and the results compared with literature values from Martin (1975). These results are shown below. They indicate that the CHERYL.FOR code does indeed calculate adiabatic flame temperature properly.

Conditions	Adiabatic Temperature (from Martin, 1975) (°F)	T_{adb} Calculated by CHERYL code (°F)
1. Distillate oil	3423	3424
HHV = 19,700 Btu/lb		
SR = 1.15		
air temp = 77°F		
oil temp = 70°F		
2. Methanol	3201	3208
HHV = 9,760 Btu/lb		
SR = 1.15		
air temp = 77°F		
fuel temp = 70°F		
3. Methanol	2962	2966
same as 2; 10% fgr		
4. Methanol	2706	2709
same as 2; 20% fgr		
5. Methanol	2442	2443
same as 2; 30% fgr		

APPENDIX F

COMPUTATIONAL DETAILS OF THE CHAR/VOLATILE MODELING

F.1 Introduction

This appendix describes the numerical details of the combined theoretical/experimental analysis of the fate of fuel nitrogen in self-sustaining, pulverized coal flames. The basis for the analysis, the derivation of the equations and the ultimate results were all discussed in Chapter 11; hence, Appendix F focusses on the final system of equations and the analytical solution thereof.

Conceptually, the coal combustion process was divided into two parts: volatile combustion and char burnout. Each was initially assumed to contribute a significant amount of fuel NO; however, to obtain quantitative predictions, it was necessary to apply a set of material balance equations and empirical relations twice, in a coupled manner, to the results from a series of special experiments.

F.2 Nomenclature

Table F-1 describes the principal nomenclature used both in developing the equations (Chapter 11) and in the actual computer code, LYNN.F4. Unless otherwise noted, all variables are based on a unit mass of original coal, dry and mineral matter free (DMMF). Primed variables refer specifically to the cases where a small amount of volatile nitrogen was added to the fuel stream.

Table F-1. Notation for char/volatile analysis.

Algebraic Representation	Computer Code	Definition
β_c	BC	empirical char nitrogen conversion coefficient
β_v	BV	empirical volatile nitrogen conversion coefficient
w_{add}	WADD	weight of volatile N additive used
w_c	WC	weight of char (DMMF)
w_t	WT	initial weight of fuel (DMMF)
w_t'	WTA	weight of fuel in additive case (coal + add)
w_v	WV	weight of volatiles evolved (DMMF)
x_c	XC	fractional conversion of char N to NO
x_t	XT	overall mean conversion of fuel N to fuel NO
x_t'	XTA	overall mean conversion of all fuel N to NO in additive case
x_v	XV	fractional conversion of volatile N to NO
x_v'	XV2	fractional conversion of volatile N to NO in additive case
y_{add}	YADD	weight fraction nitrogen in volatile additive
y_c	YC	weight fraction nitrogen in char
y_t	YT	weight fraction nitrogen in original fuel

Table F-1--Continued.

Algebraic Representation	Computer Code	Definition
$y_t{'}$	YTA	total weight fraction nitrogen in fuel-additive case
y_v	YV	weight fraction nitrogen in volatiles
$y_v{'}$	YV2	weight fraction nitrogen in volatile-additive case

F.3 System of Equations

F.3.1 Knowns

The following parameters were known at the beginning of a case study:

$\beta_c = 540$ from an empirical fit of char data discussed in Chapter 10.

$w_{add} = 3.75E - 3\,(NO)$ from the metered additive flow per unit

$\quad\quad = 2.12E - 3\,(NH_3)$ mass of coal (DMMF).

$w_t = 1.0$ unit weight of initial coal.

$x_t = \dfrac{FNO}{2941}$ where FNO is the measured fuel NO in ppm (STOICHI).

$x_t{'} = \dfrac{FNO + ANO}{3276}$ where ANO is the measured ppm due to addition of additive.

$y_{add} = .4667\ (NO)$ based on additive composition.

$\quad\quad = .8235\ (NH_3)$

$y_t = 0.0148$ based on fuel analysis (DMMF).

$y_t{'} = 0.0165$ based on additive flow rate and composition.

F.3.2 Unknowns

Ten other parameters were completely unknown at the start of the calculation: β_v, w_c, $w_t{'}$, w_v, x_c, x_v, $x_v{'}$, y_c, y_v, and $y_v{'}$. These were determined by solving the ten simultaneous equations described in the next section.

F.3.3 Equations

Six independent mass balance equations were written for each pair of test conditions:

1. Total mass balance:

base: $$w_t = w_v + w_c \tag{F-1}$$

base + add: $$w_t' = w_t + w_{add} \tag{F-2}$$

2. Nitrogen balance:

base: $$y_t w_t = y_v w_v + y_c w_c \tag{F-3}$$

base + add: $$y_t' w_t' = y_v'(w_v + w_{add}) + y_c w_c \tag{F-4}$$

3. NO mass balance:

base: $$x_t y_t w_t = x_v y_v w_v + x_c y_c w_c \tag{F-5}$$

base + add: $$x_t' y_t' w_t' = x_v' y_v'(w_v + w_{add}) + x_c y_c w_c \tag{F-6}$$

These equations were supplemented with four empirical relations:

1. Char conversion:

$$x_c = \frac{2SR - 1.32}{1 + \beta_c y_c} \tag{F-7}$$

2. Volatile conversion:

base: $$x_v = \frac{1}{1 + \beta_v y_v} \tag{F-8}$$

base + add: $$x_v' = \frac{1}{1 + \beta_v y_v'} \tag{F-9}$$

3. Volatile evolution (from Blair, 1976):

$$\frac{y_v}{y_t} = 1.92 - \frac{0.559}{w_v} \tag{F-10}$$

F.4   Solution Procedure

The ten equations just described were rearranged and combined into a set of nine equations which could be solved progressively, based on an initial estimate of the weight of volatiles, w_v. First equation F-10 was rearranged:

$$y_v = y_t * (1.92 - \frac{0.559}{w_v})$$ (F-11)

and equations F-1 and F-3 combined:

$$y_c = \frac{y_t w_t - y_v w_v}{w_t - w_v}$$ (F-12)

$$x_c = \frac{2SR - 1.32}{1 + \beta_c y_c}$$ (F-7)

Equations F-1 and F-5 were also combined:

$$x_v = \frac{x_t y_t w_t - x_c y_c * w_t - w_v)}{y_v w_v}$$ (F-13)

and equation F-4 was rearranged using F-3 and the definition of y_t' to give:

$$y_v' = \frac{y_v w_v + y_{add} w_{add}}{w_v + w_{add}}$$ (F-14)

Equation F-8 was solved for β_v:

$$\beta_v = \frac{1 - x_v}{x_v y_v}$$ (F-15)

while equation F-9 remained unchanged:

$$x_v' = \frac{1}{1 + \beta_v y_v}$$ (F-9)

Finally, equation F-6 was rearranged using the definition of y_v' and solved for the volatile weight, w_v:

$$w_v = \frac{x_t'y_t'w_t' - x_v'y_{add}w_{add} - x_cy_cw_t}{x_v'y_v - x_cy_c} \qquad \text{(F-16)}$$

where w_t' is known from equation F-2:

$$w_t' = w_t + w_{add} \qquad \text{(F-2)}$$

This system was solved using the half-interval numerical procedure. The initial guess for the weight of the volatiles was 0.5 based on the physics of the system which demand $0 \le w_v \le 1.0$. In general, convergence was rapid and the method stable.

F.5   LYNN.F4 Computer Code

The following pages contain a complete listing of the Fortran computer code LYNN.F4 which was used to solve the system of char/volatile equations. It was written in an interactive formate and was run on a DEC-10 timesharing system. The user specifies:

1. The fuel NO emissions in ppm (STOICHI), the additive used and the increase in emissions associated with it in ppm (STOICHI), and the stoichiometric ratio of the test condition.

2. β_c and the volatile evolution model parameters (1.92 and 0.559 for the Western Kentucky coal).

3. An initial guess for w_v (usually 0.5).

The program then solves the system of equations and prints out:

1. The weights: w_v, w_c, and w_t.

2. The weight fractions: y_v, y_c, and y_t.

3. The fractional conversions: x_v, x_c, x_t.

4. The char and volatile NO in ppm (STOICHI).

The program is equipped with a "reread" option so that successive runs can be made in which the user changes only input lines of interest, i.e., it is not necessary to re-enter all the inputs to only change one parameter.

```
C
C
C          THIS PROGRAM SOLVES  THE CHAR/VOLATILE SYSTEM
C          OF EQUATIONS USING THE HALF-INTERVAL METHOD
C
C

           DIMENSION NCOMP(2),YADD(2),WADD(2)
           INTEGER OID
           DATA YT/0.0148/
           DATA WADD(1),WADD(2),YADD(1),YADD(2)/3.75E-3,2.12E-3,
      1          0.4667,0.8235/
           DATA NCOMP(1),NCOMP(2)/2HNO,3HNH3/
           DATA IYES/1HY/
C
C
C          DATA INPUT SECTION
C
C
```

```
1          WRITE(5,51)
51         FORMAT(///,1X,70(1H*),///,1X,27HENTER FUEL NO IN PPM STOIC.,
    1             /1X,25HADDITIVE NO IN PPM STOIC.,
    2             /1X,26HADDITIVE CODE; NO-1, NH3-2
    3             /1X,11HSTOIC RATIO)
           OFNO = FNO
           OEX = EXAIR
           OANO = ANO
           OID = ID
           READ(5,61) FNO,ANO,ID,EXAIR
 61        FORMAT(2F,I,F)
           IF(FNO .EQ. 0.0) FNO = OFNO
           IF( ANO .EQ. 0.0) ANO = OANO
           IF( FNO .EQ. 0.0) ID = OID
           IF( EXAIR .EQ. 0.0) EXAIR = OEX
           WRITE(5,52) FNO,ANO,NCOMP(ID),EXAIR
 52        FORMAT(1X,2G10.3,A5,G10.3)
           WRITE(5,53)
 53        FORMAT(1X,42HENTER CHAR SLOPE, MODEL PARAMETERS XM1 XM2)
           OBC = BC
           OM1 = XM1
           OM2 = XM2
           READ(5,62) BC,XM1,XM2
 62        FORMAT(10F)
           IF ( BC .NE. 0.0 ) GO TO 71
           BC = OBC
           XM1 = OM1
           XM2 = OM2
 71        CONTINUE
           WRITE(5,54) BC,XM1,XM2
 54        FORMAT(1X,10(G10.3,3X))
           WRITE(5,55)
 55        FORMAT(1X,4HOK ?)
           READ(5,63) IOK
 63        FORMAT(A1)
           IF(IOK.NE.IYES) GO TO 1
```

```
C
C        INITIALIZATION AND ORGINAL VOLATILE WEIGHT
C        ESTIMATE
C
C


         XT=FNO/2941.
         WT=1.
         XTA=(FNO+ANO)/3276.
         WTA=WT+WADD(ID)
         YTA=0.0165
   2     WRITE(5,56)
  56     FORMAT(1X,31HENTER GUESS WEIGHT OF VOLATILES)
         OWV = WV
         READ(5,62)WV
         IF ( WV .EQ. 0.0) WV = OWV
         WRITE(5,54)WV
         WRITE(5,55)
         READ(5,63)IOK
         IF(IOK.NE.IYES)GO TO 2
```

```
C
C       SOLUTION OF EQUATIONS
C
C

        N=1
        WVOLD=0.
3       IF(N.GT.50) GO TO 4
        IF(WV.LE.0.7) YV=YT*(XM1-XM2/WV)
        IF(WV.GT.0.7) YV=0.98*YT*WT/WV
        YC=(YT*WT-YV*WV)/(WT-WV)
        PHI = 0.02*(EXAIR-1.0)*100. +0.68
        XC = (1.0/(1.0 + BC*YC))*PHI
        XV=(XT*YT*WT-XC*YC*(WT-WV))/(YV*WV)
        YV2=(YV*WV+YADD(ID)*WADD(ID))/(WV+WADD(ID))
        BV=(1-XV)/(XV*YV)
        XV2=1/(1+BV*YV2)
        WVNEW=(XTA*YTA*WTA-YADD(ID)*WADD(ID)*XV2-XC*YC*WT)/
1              (XV2*YV-XC*YC)
C
C
C
C
C       CALCULATION OF THE NEXT ESTIMATE OF THE
C       VOLATILE WEIGHT BY HALF-INTERVAL METHOD.
C
C

        DEV=ABS(WVNEW-WV)
        IF(DEV.LT.0.000001) GO TO4
        IF(WVNEW.GT.WV) WVNEXT=WV-ABS(WV-WVOLD)*0.5
        IF(WVNEW.LT.WV) WVNEXT=WV+ABS(WV-WVOLD)*0.5
        WVOLD=WV
        WV=WVNEXT
        N=N+1
        GO TO 3
```

```
C        CALCULATION OF CHAR AND VOLATILE NO
C
C
4        WC=WT-WV
         CNO=XC*YC*WC*FNO/(XT*YT*WT)
         VNO=XV*YV*WV*FNO/(XT*YT*WT)
C
C
C        PRINT OUT OF RESULTS
C
C
C


         WRITE(5,59) WV,WVNEW,WC,WT,YV,YC,YT,XC,XV,XT,CNO,VNO,FNO
59       FORMAT(///,1X,13HFINAL RESULTS,
1        //,1X,48HQUESSED VOLATILE WEIGHT                         = ,G14.7,
2        /,1X,48HCALCULATED VOLATILE WEIGHT                       = ,G14.7,
3        /,1X,48HCHAR WEIGHT                                      = ,G14.7,
4        /,1X,48HTOTAL FUEL WEIGHT                                = ,G14.7,
5        /,1X,48HNITROGEN WEIGHT FRACTION IN VOLATILE             = ,G14.7,
7        /,1X,48HNITROGEN WEIGHT FRACTION IN CHAR                 = ,G14.7,
8        /,1X,48HNITROGEN WEIGHT FRACTION IN FUEL                 = ,G14.7,
9        /,1X,48HFRACTIONAL CONVERSION OF N TO NO IN CHAR         = ,G14.7,
2        /,1X,48HFRACTIONAL CONVERSION OF N TO NO IN VOLATILES    = ,G14.7,
3        /,1X,48HOVERALL MEAN CONVERSION                          = ,G14.7,
4        /,1X,48HNO FROM CHAR                                     = ,G14.7,
5        /,1X,48HNO FROM VOLATILES                                = ,G14.7,
6        /,1X,48HNO FROM TOTAL FUEL                               = ,G14.7)
         GO TO 1
         STOP
         END
```

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