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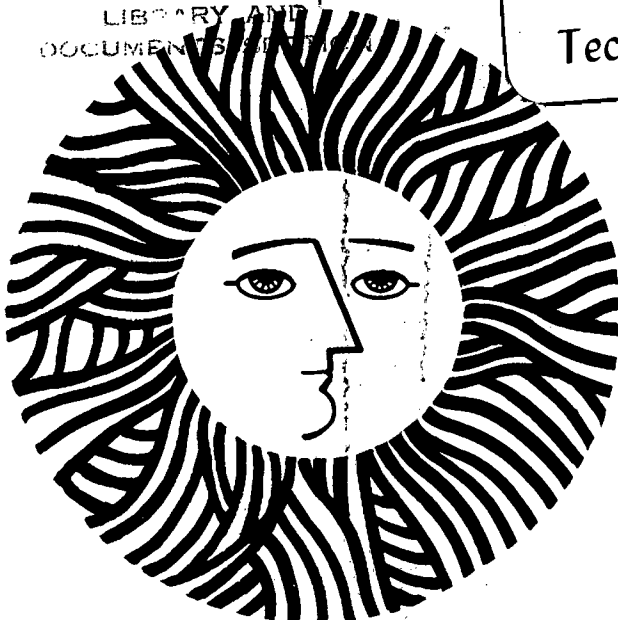
J.F. La Fond, J.R. Hart, and R.F. Sawyer

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A STAGED FLUIDIZED BED COMBUSTOR FOR THE STUDY
OF POLLUTANT FORMATION AND DESTRUCTION

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ABSTRACT

A laboratory two-stage fluidized bed combustor has been constructed for the study of the formation and destruction of pollutant species. Characterization of the facility for several configurations and a range of fuel flow rates (fuel/air mixture ratios) has been accomplished in terms of stable operating conditions, temperatures, pressures, and gas composition through the device. A variety of operating parameters are available, including number of stages, bed depths, bed materials, fuel, oxidizer, and dopant flow rates, and residence times. Not all of these parameters are independent for stable operation.

Initial studies used propane as the fuel, air as the oxidizer, and NO as a dopant to simulate fuel nitrogen. Species monitoring included CO, CO₂, NO and total hydrocarbons. Stable two stage operation was obtained with a fuel rich mixture in the first stage followed by air injection and completion of combustion in the second stage. A maximum reduction of 66% of the input NO dopant was obtained under two stage operation.

The facility has the additional capabilities of operating either or both beds in a two-dimensional spouted mode, optical access for flow visualization, and addition of a third stage. In addition to the study of pollutant formation and destruction, the apparatus is suited to the investigation of the combustion of low-quality fuels and the incineration of toxic wastes.

INTRODUCTION

The primary objective of this work was to characterize the newly constructed two-stage fluidized bed combustion facility. Performance of the combustor was observed in three different configurations, each under various operating conditions. These configurations were: single bed, single bed with overfire air, and double bed (i.e., two fluidized beds stacked one over the other). Also, preliminary studies to determine the effectiveness of staged combustion on the reduction of nitrogen oxides were carried out. Propane was the fuel used in all cases.

Interest in fluidized bed combustion has risen with the increased desire to burn low-quality fuels. Among the many attractive features of fluidized bed combustion is the system's pollution control capabilities. Reduction of sulfur oxides is expected by the addition of sorbent material (e.g., limestone) into the bed. Low combustion temperatures reduce the production of nitric oxide (NO) caused by thermal fixation of atmospheric nitrogen and oxygen, although Furusawa et al. (1978) have suggested that local hot spots within the bed can cause higher thermal NO production than predicted. However, many low-quality fuels are high in nitrogen content, causing the formation of nitrogen oxides from fuel-bound nitrogen. Fuel NO dominates NO emissions from the fluidized bed combustion of fuels high in nitrogen, up to 90% according to Beer and Martin (1978). Normal fluidized bed operation is incapable of preventing the formation of NO from fuel-bound nitrogen.

Efforts to understand the formation and reduction of nitrogen oxides in combustion processes are becoming increasingly more frequent (at least 22 papers

at the Eighteenth Symposium on Combustion dealt in some way with the nitrogen oxide problem). Several researchers have successfully obtained substantial reduction of NO emissions by altering combustion conditions in fluidized beds (Parks, 1973; Gibbs et al., 1976; Furusawa et al., 1978; Beer and Martin, 1978; HIRAMA et al., 1980). These studies have shown that by burning fuel-rich (i.e., under substoichiometric conditions) NO emissions can be drastically reduced. Gibbs et al. (1976) report three NO destruction reactions that take place in the rich combustion of coal: 1) coal volatiles - NO, 2) CO - NO, and 3) the heterogeneous char - NO reactions. Rich combustion, of course, is undesirable from the standpoint of combustion efficiency and carbon monoxide emissions. To avoid these problems, staged combustion has been proposed and studied as a possible solution. With staging, rich combustion takes place in a first stage causing a reduction of nitric oxide and producing various combustibles. These combustibles can then be burned in a second stage improving overall combustion efficiency. The second stage may consist of secondary air injection into either the freeboard space or a second suspended bed. In practical fluidized bed systems burning solid fuels, a second bed provides the advantages of causing a baffling effect to enhance char burnout in the first stage and increases the heat transfer capabilities of the second stage.

A second application of staged fluidized bed combustors is for the incineration of toxic wastes. Such facilities offer the potential advantages of control of residence time, temperature, and provision of a reducing atmosphere for the optimal conversions of toxic substances to less noxious compounds. Little work on this application is evident in the literature.

EXPERIMENTAL FACILITY AND CHARACTERIZATION

This section describes the facility and its operating parameters.

Apparatus

Schematic diagrams are shown in Figures 1 and 2. Table 1 lists the probe locations referred to in Figure 2. The bench-scale two-stage fluidized bed combustor is fabricated primarily with type 304 stainless steel. It contains GE 124 quartz windows for viewing both combustion zones. Additionally, the gas stream temperatures, pressures, flow rates, and species concentrations are monitored. While no external heating is provided, some temperature control can be provided through application of insulation.

The combustor is fired with propane and air, and has a maximum thermal input of about 15 KW and a turndown ratio of about 6 to 1. Maximum flow rates attainable are 0.4 gm/sec of propane, 5.2 gm/sec of primary and secondary air. Residence times vary from 400 to 2000 msec for cold flow and from 100 to 500 msec for hot flow in the first stage. A complete listing of operating parameters is shown in Table 2.

The flow channel of the combustor has a rectangular cross section of 50 mm by 100 mm. A rectangular geometry was chosen for easier optical access and for future two-dimensional spouted bed studies. The total combustor height is 700 mm. The two stages are 200 mm high each, while each of the three inter-stage sections are 100 mm high. Quartz windows (121 mm x 127 mm x 6.4 mm) may be placed on either side of each stage to allow observation of bed activity and the combustion zone. In this study only one window is used in each stage, with stainless steel plates in place of the rear windows. Gasketing between stages and around windows was accomplished with Fiberfrax ceramic fiber paper.

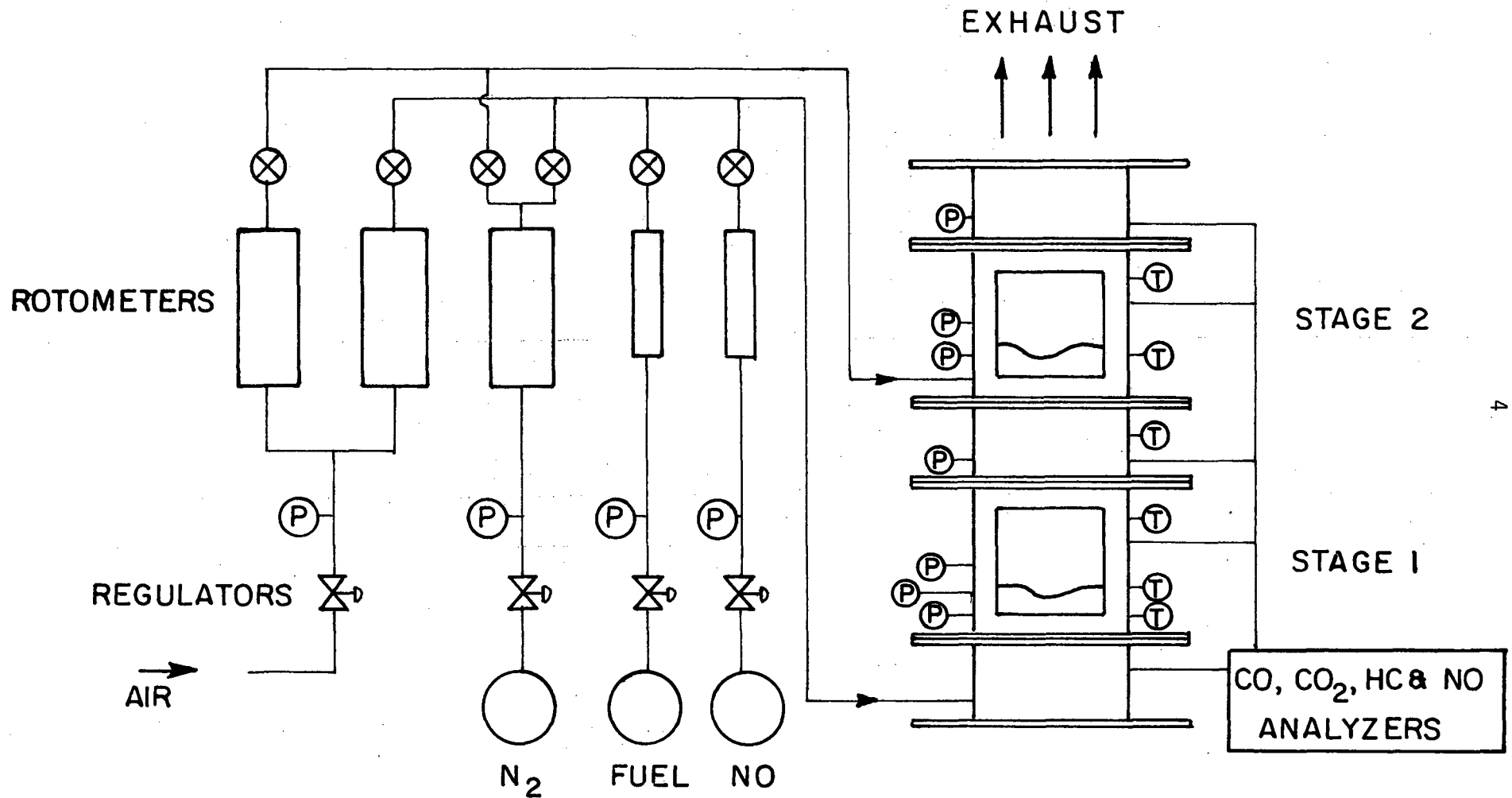


Figure 1. Two-stage fluidized bed combustion facility.

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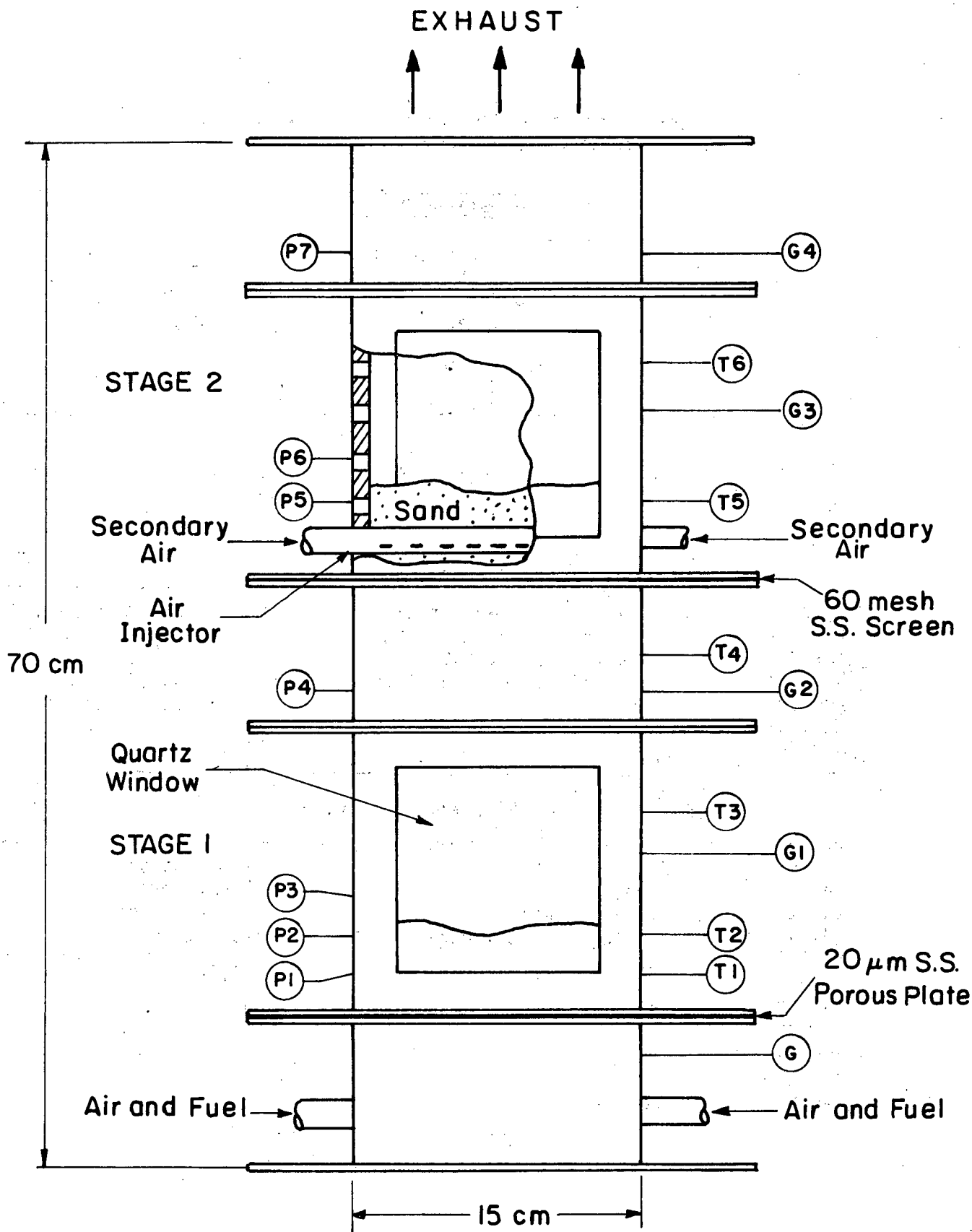


Figure 2. Two-stage fluidized bed combustor. Pressure, temperature and gas sampling probe locations are listed in Table 1.

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Table 1. Position of pressure, temperature, and gas sampling probes.
Height in mm above the first stage distributor plate.

Pressure		Temperature		Gas	
P1	28(mm)	T1	28(mm)	G1	112(mm)
P2	56	T2	56	G2	222
P3	84	T3	140	G3	410
P4	222	T4	246	G4	517
P5	353	T5	353		
P6	381	T6	438		
P7	517				

Table 2. Staged fluidized bed combustor characteristics.

General Characteristics	
Combustor Internal Dimensions (each stage)	50 mm x 100 mm x 300 mm
Air (primary and secondary) Flow Rate Range	0.9 - 5.2 gm/sec
Inlet Flow Velocity Range (1st stage)	0.14 - 0.80 m/sec
Residence Time Range (1st stage, cold flow)	400 - 2000 msec
Fuel Flow Rate Range	0.06 - 0.41 gm/sec
Maximum Power Level	15 kW
Bed Temperature Range	800 - 1100°C

Characteristics of These Experiments

Primary Air Flow Rate	1.275 gm/sec
Secondary Air Flow Rate	0.95 gm/sec
Inlet Flow Velocity (1st stage)	~ 0.2 m/sec
Residence Time (1st stage, cold flow)	1500 msec
Fuel Flow Rate Range	0.068 - 0.138 gm/sec
Power Level	3.8 kW
Dopant/Inlet Concentration	NO/500 ppm
Bed Material	Silica
Bed Particle Size Range	0.8 - 1.2 mm
First Stage Bed Height	50 mm
Second Stage Bed Height	55 mm

Mixing of the air and propane takes place approximately 500 mm before entering the plenum below the first stage. A set of injection jets guarantees even flow into the plenum. The distributor at the base of the first stage is a stainless steel 20 μm porous plate (3.2 mm thickness). In this study the bed material is 99% pure silica sifted to a diameter between 0.8 and 1.2 mm. The silica has a density of 2.58 gm/cm^3 . The first stage bed height is 50 mm (i.e., static height from the distributor plate). The second stage distributor is a 60 mesh stainless steel screen. Directly above this screen, within the second bed is the secondary air injector, Figure 2. The second bed is composed of the same silica material at a static height of 55 mm. Silica was chosen over alumina to minimize the possibility of catalytic effects on NO reduction reactions.

Forty-two ports (twenty-one on each side) along the length of the combustor facilitate access for temperature, pressure, and gas composition measurements. Ports utilized in this study are labeled in Figure 2, with Table 1 providing heights above the first distributor for each port.

Operating Conditions

The facility was successfully operated under a variety of conditions in three different configurations. These configurations include: single bed, single bed with secondary air addition above the bed, and double bed with secondary air injected into the second bed. The codes provided in Table 3 are used throughout this paper to identify the various operating conditions and configurations in the presentation of data. ϕ_1 , is used to indicate the first stage equivalence ratio,

$$\phi = \frac{\text{fuel flow/air flow}}{(\text{fuel flow/air flow})_{\text{Stoichiometric}}}$$

Table 3. Operating Condition Codes.

		Single Bed		Double Bed	
		No Secondary Air	Secondary Air	No Secondary Air	Secondary Air
COLD	$\phi = 0$	C/SB	-	C/DB	-
HOT	$\phi = 1.27$	H/SB/1	H/SB/SA/1 $\phi_2 = 0.73$	H/DB/1	-
	$\phi = 1.48$	H/SB/2	H/SB/SA/2 $\phi_2 = 0.85$	H/DB/2	H/DB/SA/2A,B $\phi_2 = 0.85$

A - combustion outside second bed

B - combustion inside second bed

while ϕ_2 corresponds to the overall equivalence ratio in cases where secondary air is added. Note the two different conditions for the hot double bed configuration with secondary air (denoted A and B). Here, a distinction must be made between: A, where combustion is attached to the top of the second bed, and B, where combustion occurs within the second bed.

Dilution Correction

In cases in which secondary air is added, compositions measured in the second stage are corrected to account for the effect of dilution, allowing comparisons with single stage measurements.

The dilution correction consists of simply multiplying second stage measurements by the ratio of the total flow (primary plus secondary air flow rates) to the primary flow. Under the operating conditions used in these experiments this correction factor is 1.745. This method of dilution correction was double-checked by comparing hydrocarbon readings with and without secondary air (but with no secondary combustion) operating at a first stage equivalence ratio of 1.27. A factor of 1.72 (550 ppm to 320 ppm) was obtained by this method.

Temperature Profiles

Temperatures are measured by means of six bare Pt/Pt-13% Rh (R-type) 0.2 mm diameter thermocouples. A multi-channel internally-compensating digital thermometer provides fast and clear temperature readings.

Figure 3 shows horizontal temperature profiles at three different thermocouple heights. Heat transfer losses to the combustor walls cause a sharp decrease in gas temperature near the walls. The temperature within the fluidized beds is fairly uniform. All measurements were within 10% of the average bed temperatures.

At a probe height of 246 mm, all profiles seem to be of the same shape. The cases with overfire air have the highest temperatures. In the single bed, secondary air case, secondary combustion occurs near the thermocouple location causing the temperature rise. The double bed, secondary air case temperature is higher due to a richer combustion mixture. Rich combustion causes an upward shift in the vertical temperature profile, resulting in a higher temperature reading at this probe site than with less rich combustion mixtures.

At a thermocouple height of 438 mm above the first stage distributor (approximately 140 mm above the second stage distributor) for the single bed case, the profile becomes even less uniform than it is at 246 mm, as is

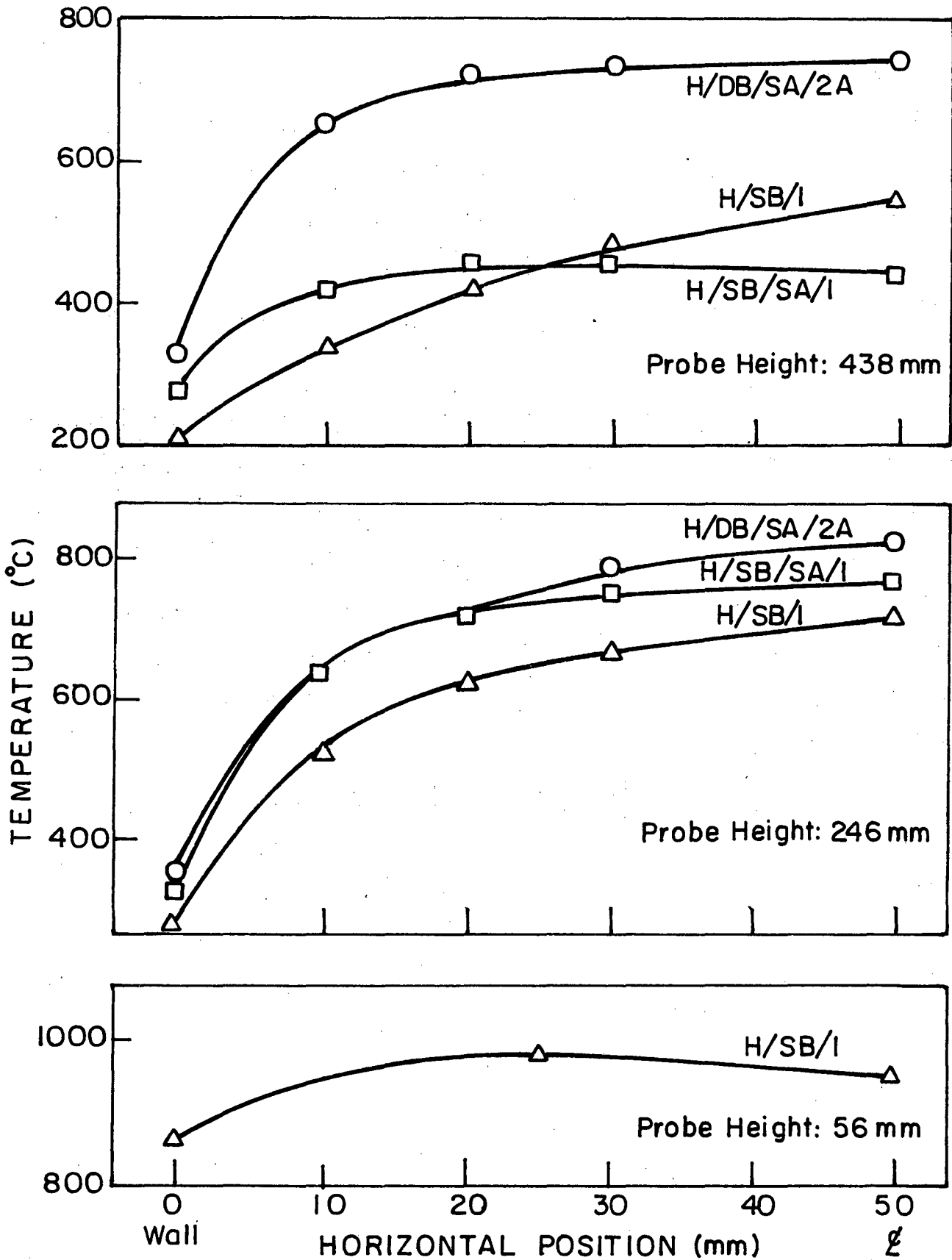


Figure 3. Horizontal temperature profiles at three different probe heights.

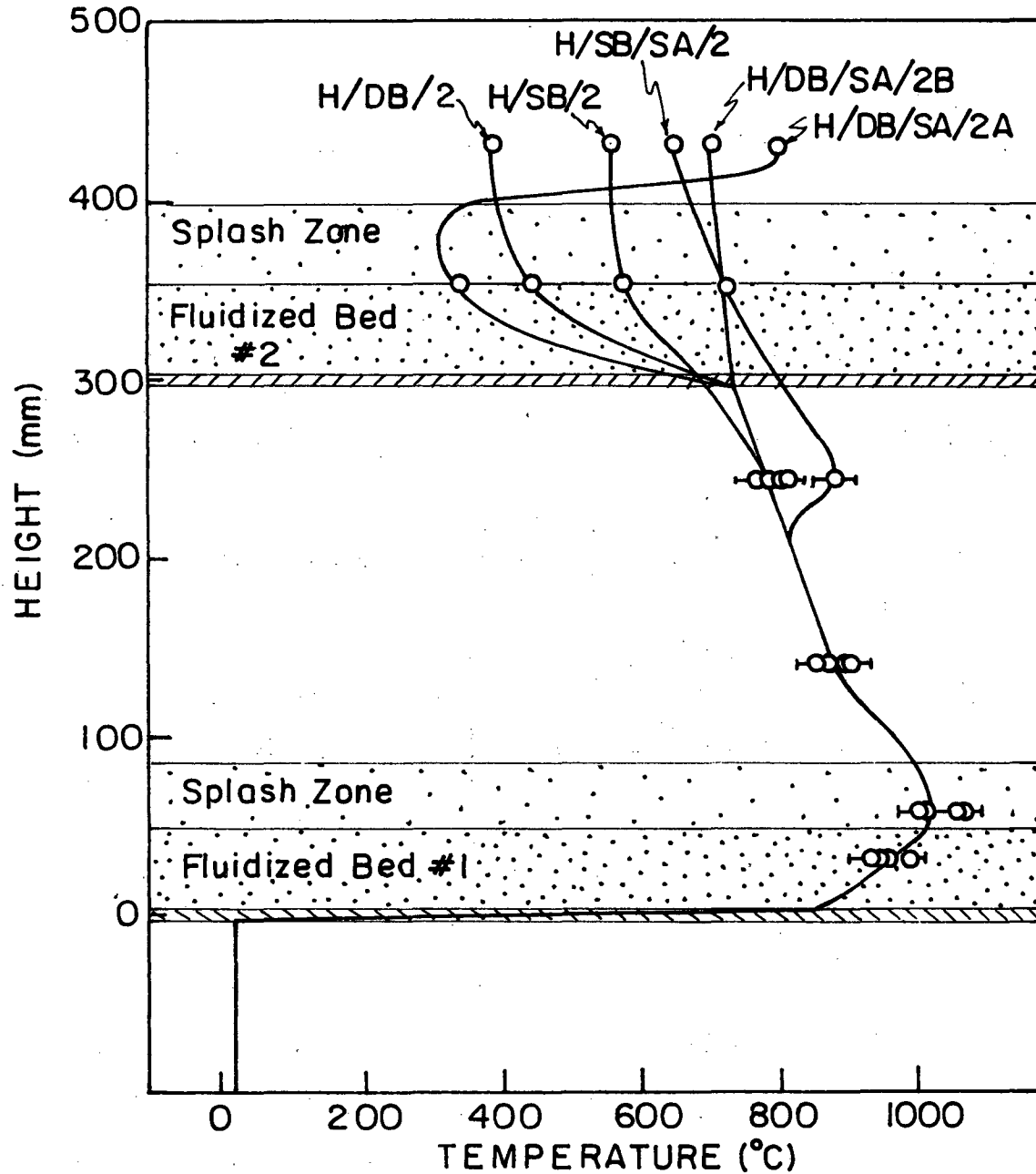
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expected. The addition of secondary air causes a flattening of temperature profiles above the point of injection due to enhanced mixing.

Vertical temperature profiles with measurements made at the combustor centerline are presented in Figure 4. In all these cases, the first stage equivalence ratio was $\phi_1 = 1.48$. For the single bed configuration, there is a steady decline in temperature along the length of the combustor when no secondary air is added. With secondary air, a temperature rise occurs at a height slightly over 200 mm corresponding to the location of secondary combustion. In the double bed configuration, three cases are recorded. First, with no secondary air addition, there is a large temperature drop across the second bed due to increased heat transfer losses. Second, for secondary air addition but combustion taking place above the second bed, a large temperature drop through the bed is followed by a sharp rise above the bed. Finally, with combustion within the second bed, heat release within the bed nearly equals the heat losses.

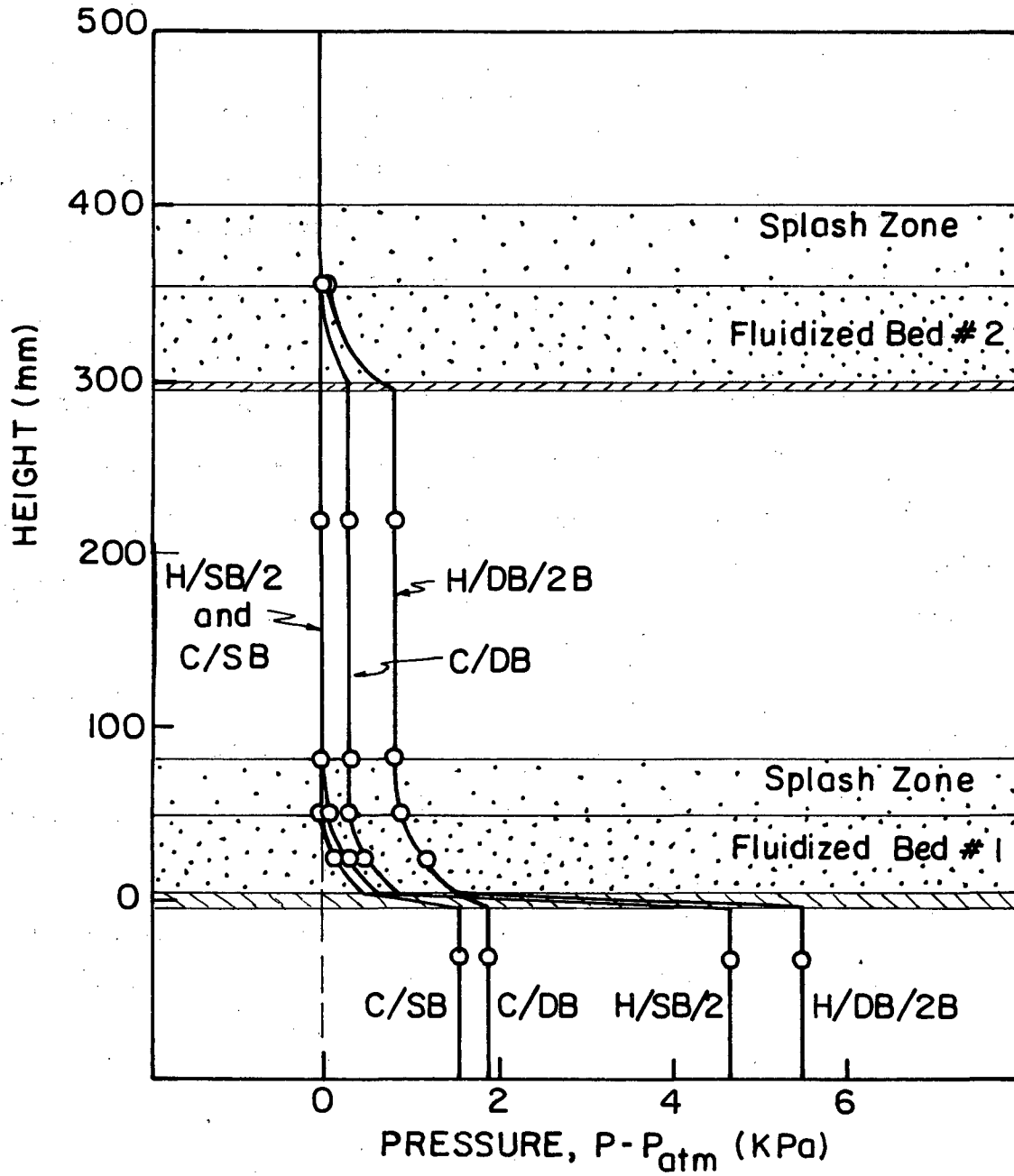
Pressure

Seven pressure taps along the combustor's length are connected to a water manometer to provide vertical pressure profiles. Pressure along the length of the combustor are shown in Figure 5. In all cases, the total pressure drop never exceeds 6 KPa. Notice that the pressures for the hot cases are substantially higher than those without combustion, particularly through the porous distributor plate. The increased pressure drop across the distributor plate can be explained by the expansion of inlet gases as they heat up through the hot plate. It was observed that with increased operation, the silica particles experienced attrition and cracking from thermal stress. As some of the bed particles decrease in size, the pressure drop was found to increase slightly.



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Figure 4. Vertical temperature profiles for a variety of combustor configurations and operating conditions.



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Figure 5. Vertical pressure profiles.

Although Beer and Martin (1978) have reported increased reductions in NO emission when operating under elevated pressures, the small pressure changes of these experiments should have no significant effect on NO emission.

Composition Measurement

The reactant composition is monitored at four locations along the combustor. See Figure 2 and Table 1 for the exact location of the sample probes. Quartz tubes (3 mm OD) are used as probes and are connected to the gas analyzers by Teflon tubing. Probe selection is made using a five-way valve.

The gas stream may be analyzed either with or without water vapor. The species monitored include CO, CO₂, NO, NO_x, and HC (as propane). The CO and CO₂ measurements were made with Beckman (IR 315) NDIR analyzers using dry gas samples. The NO and NO_x determinations were made by a Thermo Electron Corp. (12A) chemiluminescent analyzer. The unburned hydrocarbons were analyzed by a Beckman (402) FID analyzer.

Input NO concentrations were obtained by metering in small amounts of pure NO upstream of the combustor. The concentrations were checked by sampling the input gas from the mixing plenum. By using NO as a dopant, fuel-nitrogen NO formation is simulated. This simulation seems reasonable in light of experimental findings by Gibbs et al. (1976). They found, in coal combustion, that NO formation occurs almost immediately upon the injection of the fuel into the bottom of the bed.

NO Horizontal Profiles

At the outset of these experiments, there was some concern about the accuracy of using centerline gas samples as being representative of species concentrations for the entire channel cross section. A series of tests were carried out to determine horizontal profiles of NO concentration. As seen in

Figure 6, NO was nearly uniform in both the first and second beds under a variety of conditions. In the worst case, the NO concentration dropped approximately 15% from the centerline to the wall in the second stage of the double bed configuration. It can be concluded from Figure 6 that centerline measurements represent average cross-sectional species concentrations. Similar results were found by Parks (1973). This information assures that NO reductions seen at the centerline are not caused by mixing phenomena but by actual destruction of NO.

RESULTS AND DISCUSSION

Parameters Varied

A large number of parameters can be varied in operation of the staged fluidized bed facility, including bed height, bed temperature, bed particle size, fluidization velocity, equivalence ratio, and NO input concentration. In these tests, the alteration of only two parameters was sufficient to exhibit the capabilities of the facility and to characterize the combustor. These two parameters were: 1) configuration (see previous section for description of the three configurations), and 2) equivalence ratio or fuel flow rate. Primary and secondary air flow rates were maintained constant throughout at 1.275 gm/sec (0.2 m/sec cold inlet velocity) and 0.95 gm/sec, respectively. The bed heights were approximately 50 mm of 0.8 to 1.2 mm silica particles in the first stage and 55 mm of the same particles in the second stage. The NO input concentration was held at 500 ppm. No effort was made to control bed temperatures.

NO Concentration

Nitrogen containing species quantification was not thoroughly accomplished in these studies, primarily due to the usual difficulties in measuring these compounds in combustion gases, particularly in rich mixtures. The "disappearance" of NO is likely to be due to a number of different causes, including

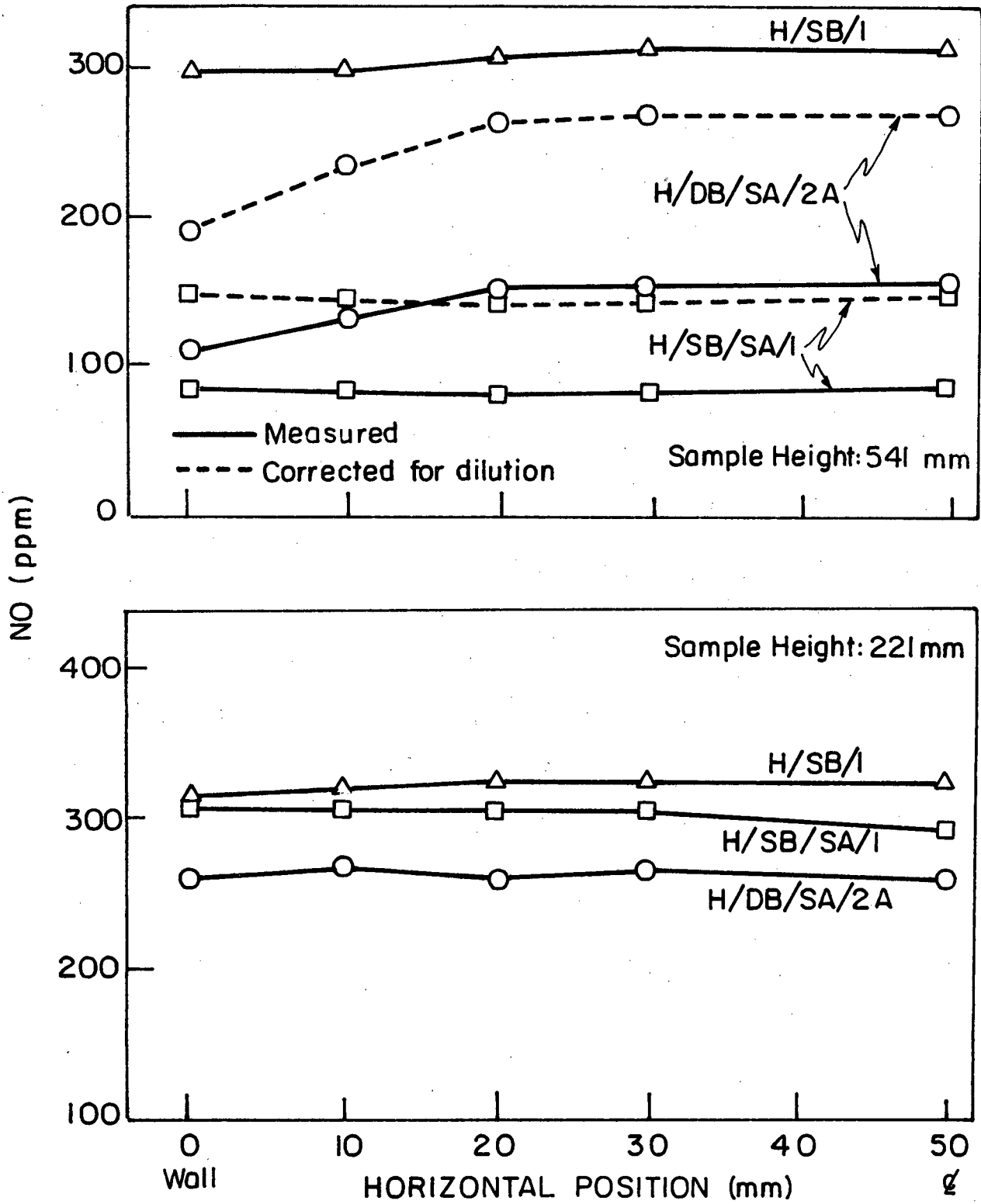


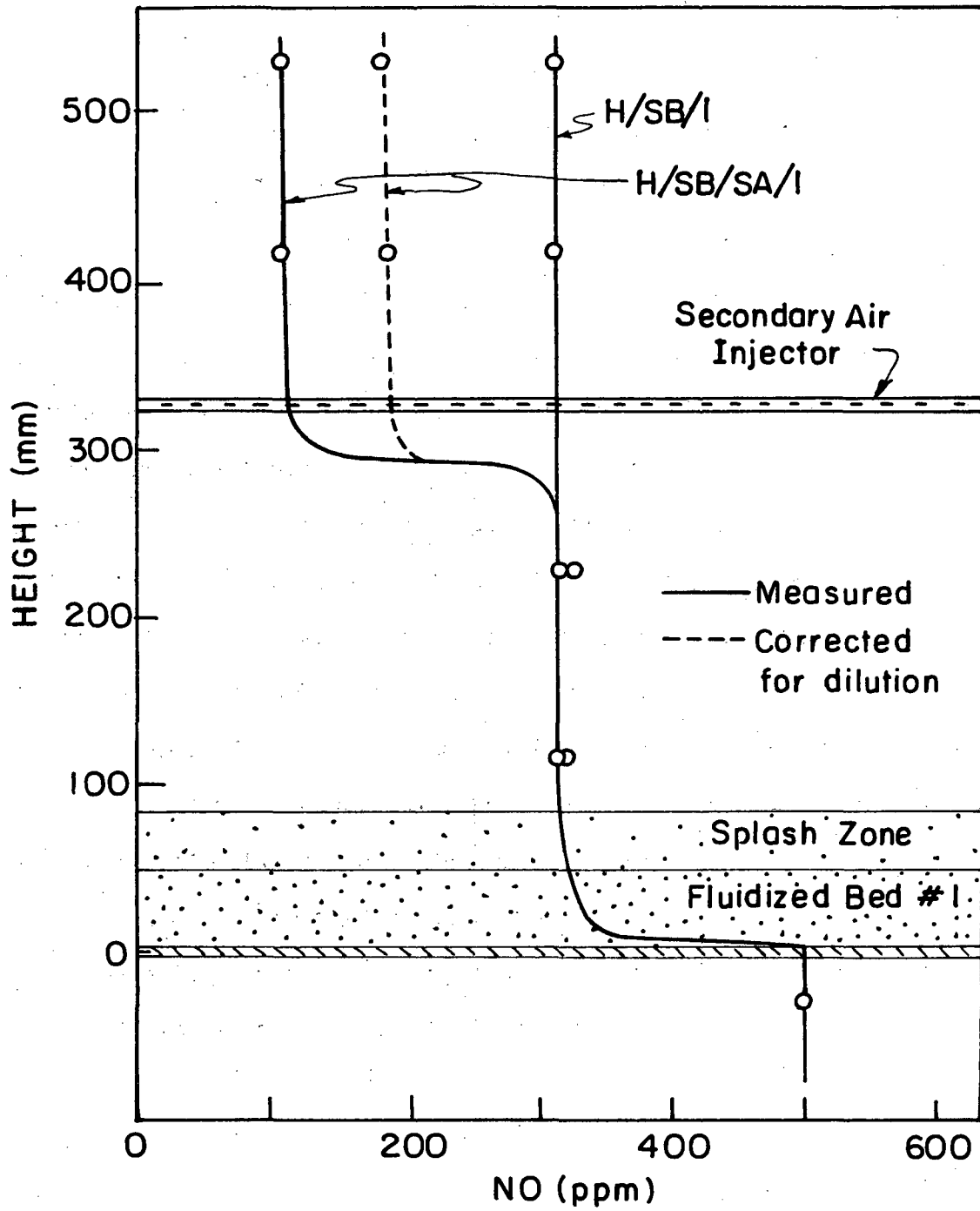
Figure 6. Horizontal NO concentration profiles at two different sample heights.

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conversion to N_2 , conversion to NO_2 , especially under lean conditions, and conversion to other nitrogen containing species, particularly under fuel rich conditions. It was felt that a measurement of NO rather than NO_x provided adequate preliminary characterization of the facility and avoided the complications of NO reduction in the chemiluminescent converter, especially under fuel rich conditions, Parks (1973). The present experiments, it must be emphasized, are for the purpose of characterizing the facility, and cannot be used to provide any great insight into the complex nitrogen chemistry which is occurring.

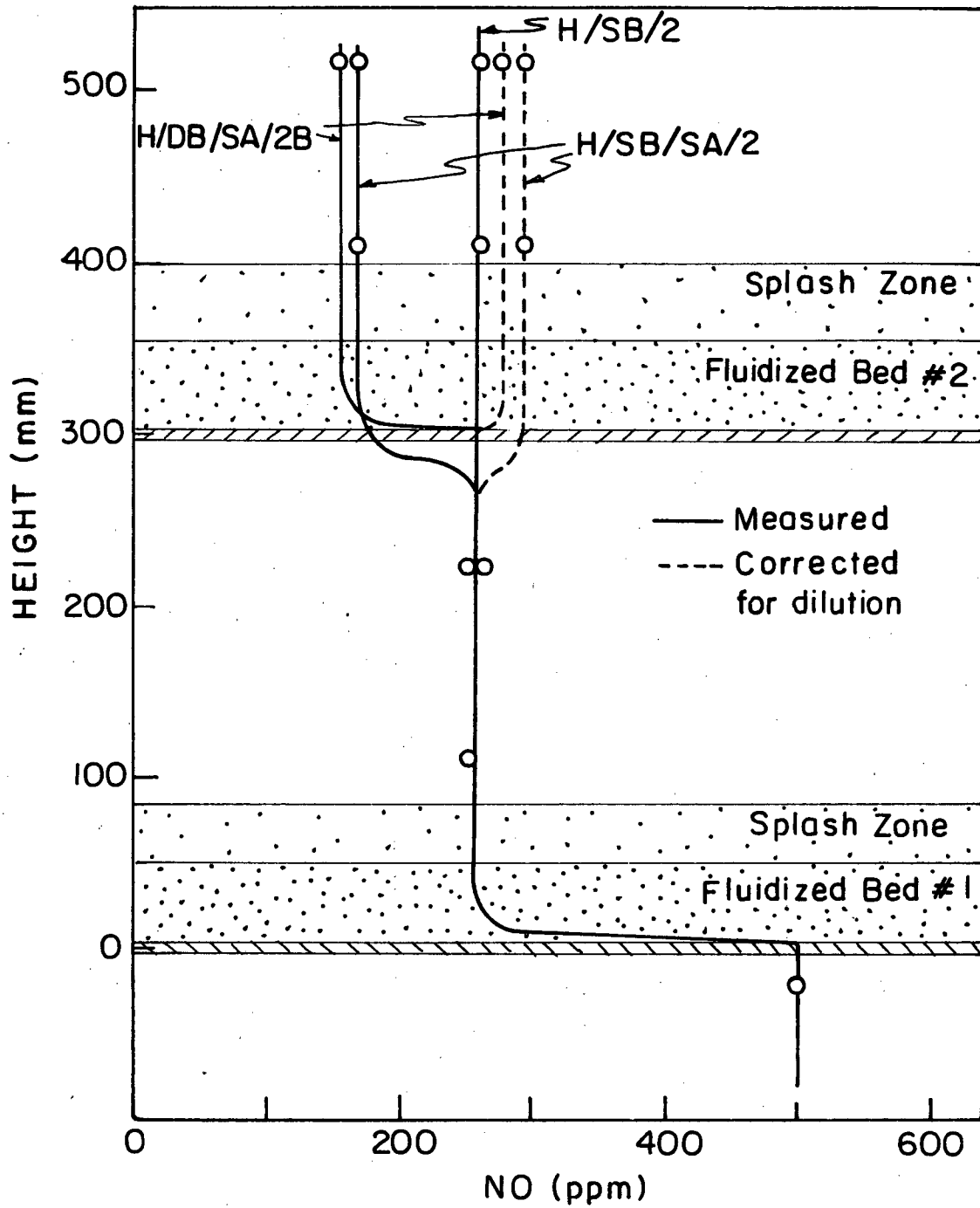
NO concentrations were measured along the length of the combustor. These measurements provide information on residence time restrictions and the effect of staged combustion in both the overfire air and double bed configurations. Figure 7 shows that for a first stage equivalence ratio of $\phi_1 = 1.27$, the NO reduction (to about 315 ppm) is complete by the time the gas leaves the first bed. This would indicate that the residence time is adequate under these operating conditions. Parks (1973) also found in his studies that gas phase NO reduction occurs almost immediately - within 20 mm of the distributor plate. With the addition of secondary air, the NO concentration was further reduced to approximately 100 ppm (175 ppm when corrected for dilution). Note that the reduction is shown to occur below the secondary air injector in Figure 7. This is due to the downward projection of the secondary air stream causing a flame to form below the injector. A more detailed study is required to explain the mechanism of this increased reduction.

As seen in Figure 8, when operating at the richer first stage equivalence ratio of 1.48, the addition of secondary air actually increases the NO concentration from approximately 250 to 280 ppm (when corrected for dilution). This characteristic of NO production rather than reduction was evident in both the



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Figure 7. Vertical NO profiles. Single bed with and without overfire air configurations, $\phi_1 = 1.27$.



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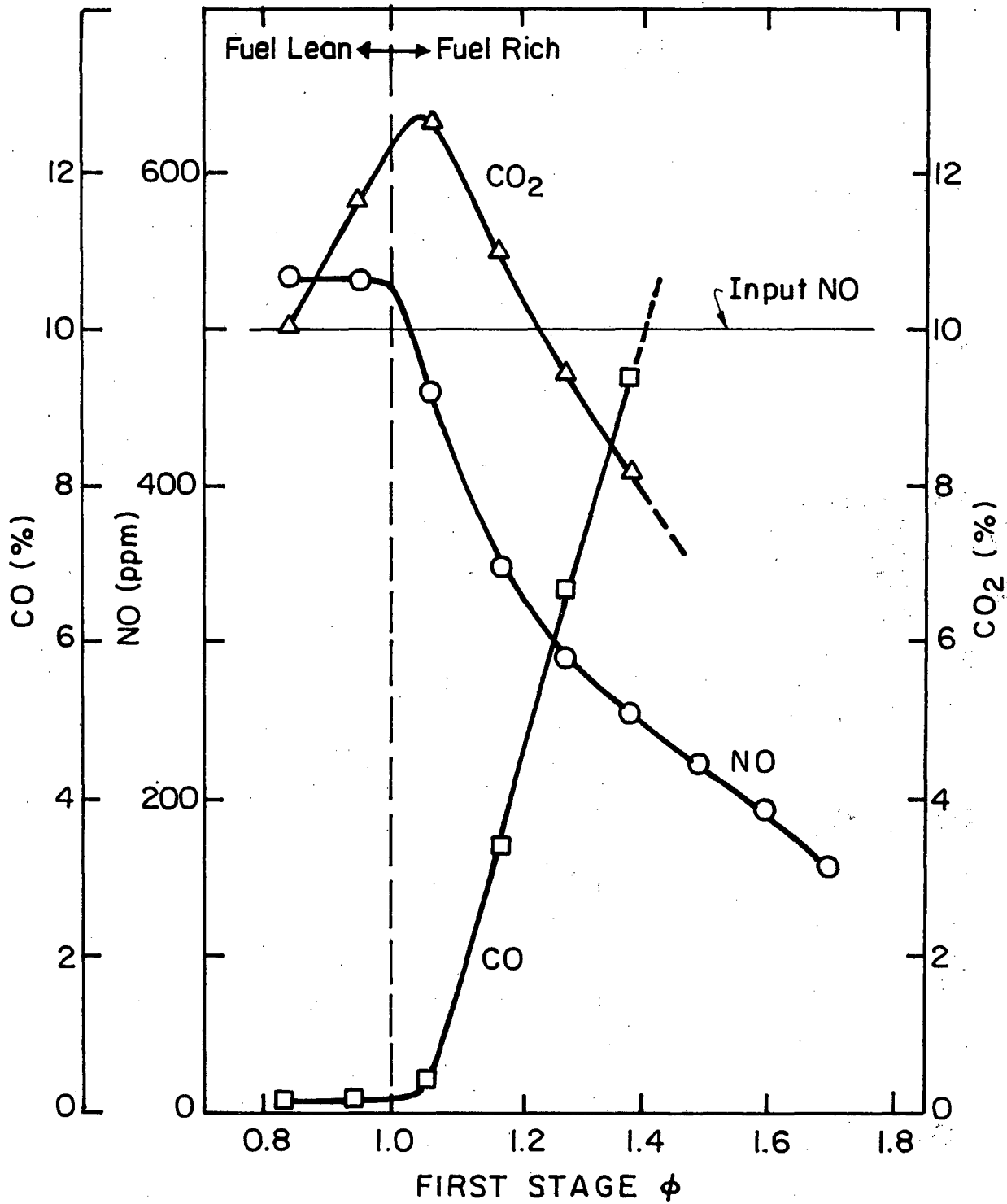
Figure 8. Vertical NO profiles. Single bed with and without overfire air, and double bed configurations, $\phi_1 = 1.48$.

overfire air and double bed configurations and probably is the result of the oxidation of a nitrogenous compound (e.g., NH_3 or HCN). To better understand the relationship between equivalence ratio and gas composition, a series of experiments were carried out measuring CO , CO_2 , NO and in some cases hydrocarbons at the outlet of the combustor.

Gas Composition with Change of ϕ

First, CO , CO_2 and NO concentrations were measured for the single bed configuration as the equivalence ratio was varied from 0.83 to 1.69. The results of this experiment are provided in Figure 9. Notice the sharp rise in CO , the drop off in CO_2 and the decline in NO as the combustion becomes more fuel rich. A comparison was made between results of this study and those reported by Parks (1973) under very similar conditions. At an equivalence ratio of 1.2 and bed temperature near 1200 K, Parks has reported a reduction of 32% while this study found a reduction of 34% of input NO .

Next, the same procedure was followed for the case with overfire air addition, Figure 10. The CO , CO_2 and NO curves, when corrected for dilution, follow the single bed results very closely until a first stage equivalence ratio of about 1.12. This corresponds to the condition in which a flame was observed to form at the secondary air injector. The NO concentration drops to a minimum value of approximately 170 ppm (corrected for dilution) at a first stage ϕ of 1.27 and an overall ϕ of 0.73. This maximum NO reduction of 66% is compared to other staged combustion studies in Table 4. As the mixture becomes richer, the outlet NO concentration rises. Figure 11 compares the NO concentration of single bed experiments both with and without overfire air. Note that the outlet concentrations cross at a first stage ϕ of approximately 1.42. Beyond this point, burning in stages does not further reduce NO compared to single stage operation.



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Figure 9. CO, CO₂ and NO concentrations with variation of ϕ , for single bed configuration.

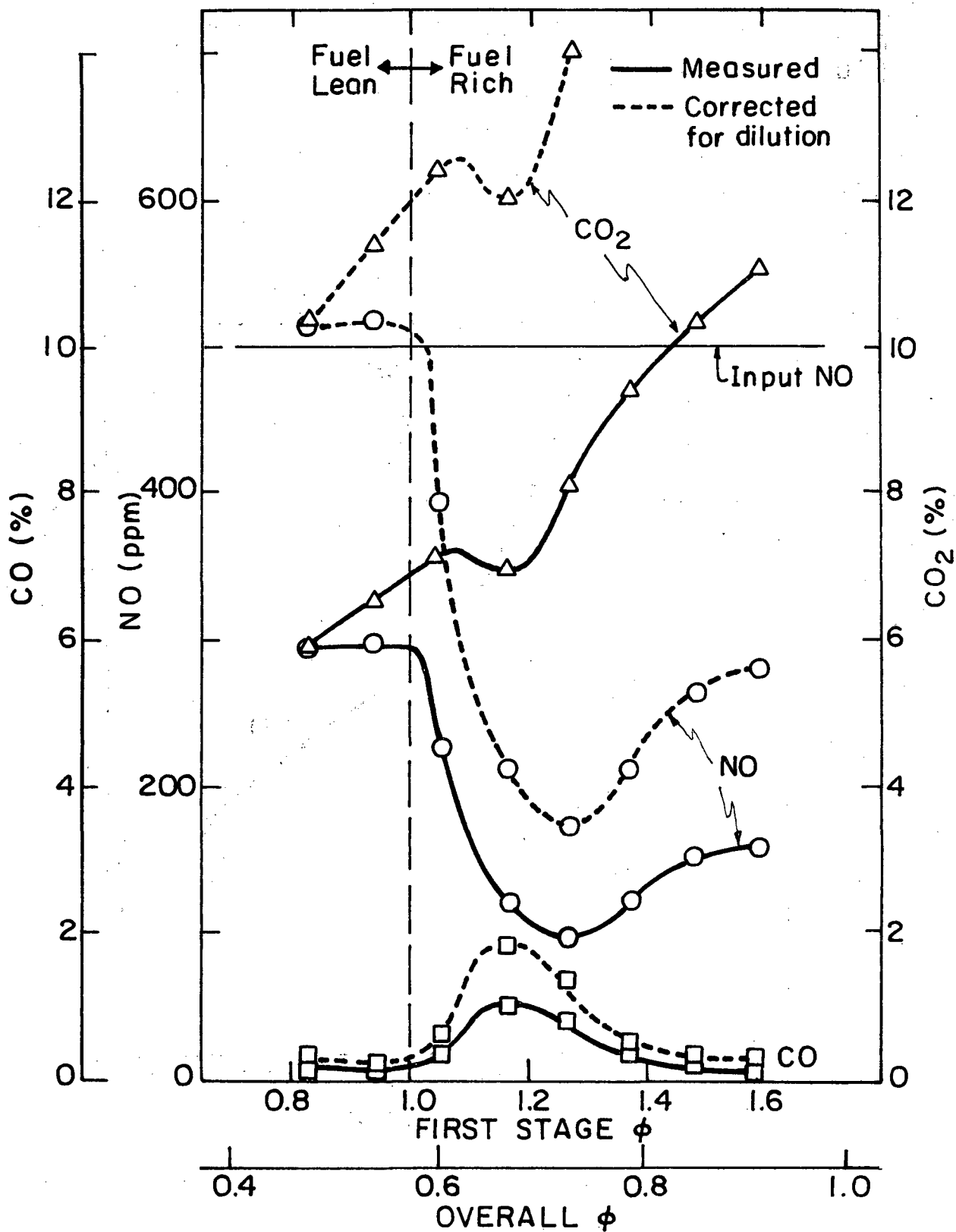


Figure 10. CO, CO₂ and NO concentrations with change in ϕ , for single bed, overfire air configuration. XBL 819-6561

Table 4 Comparison of staged combustion studies.

Study	Fuel	N Input	Max. NO Reduction	ϕ_1^*	ϕ_2^{**}	Comments
Gibbs et al. (1976)	Coal	1.5 wt. %	33%	1.25	1.00	Fluidized bed with overfire air
Martin and Dederick (1978)	H ₂	NH ₃ (1410 ppm)	52%	1.2	0.80	Premixed jet flame combustor
Gerhold et al. (1978)	No. 2 oil	Pyridine	80%	1.25	0.80	Staged adiabatic combustor
Beer et al. (1980)	No. 6 oil	0.7 wt. %	70%	1.6	0.95	Staged combustion in furnace
Hirama et al. (1980)	Coal	0.8 wt. %	50%	1.0	0.87	Staged fluidized beds
This study (1981)	Propane	NO (500 ppm)	66%	1.27	0.73	Staged fluidized beds

* First stage equivalence ratio

** Overall equivalence ratio

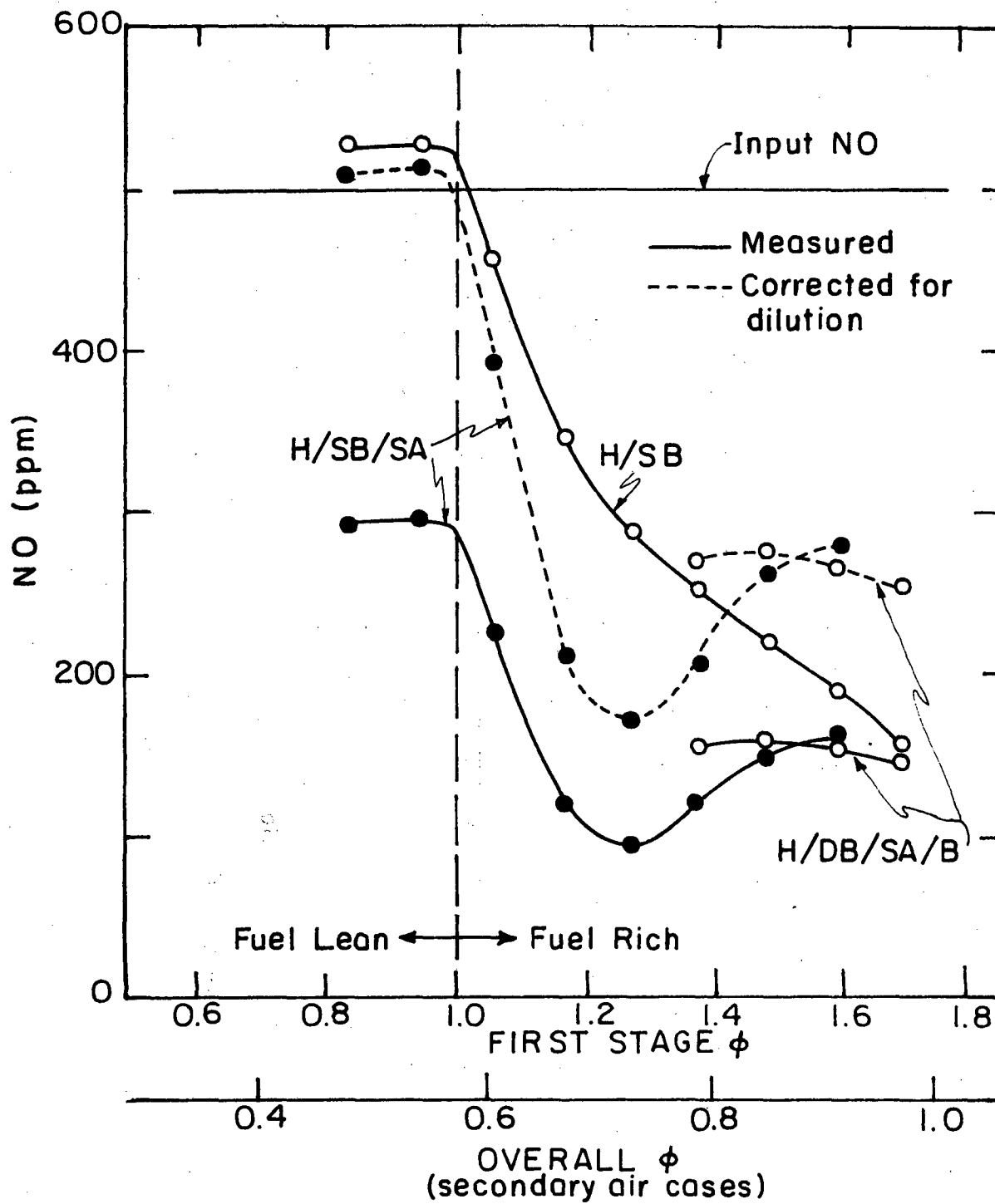


Figure 11. NO concentrations with change in ϕ , for single bed with and without overfire air, and double bed configurations. XBL 819-6565

Included in Figure 11 are results from double bed experiments. These results again show a higher NO level than obtained in the single bed, although the overall reduction is still nearly 50% of the input NO in all cases. Data could only be obtained over the limited range of first stage ϕ 's of 1.37 to 1.69 when operating in the double bed configuration. An even smaller range was obtainable until the second stage was insulated with ceramic fiber paper and fiber glass. Leaner mixtures resulted in a loss of combustion in the second bed. It is felt that the high heat losses (always a problem in small scale combustors) within the second bed is the cause. By further reduction of heat losses along the entire combustor, a much wider range of operating conditions should be obtainable.

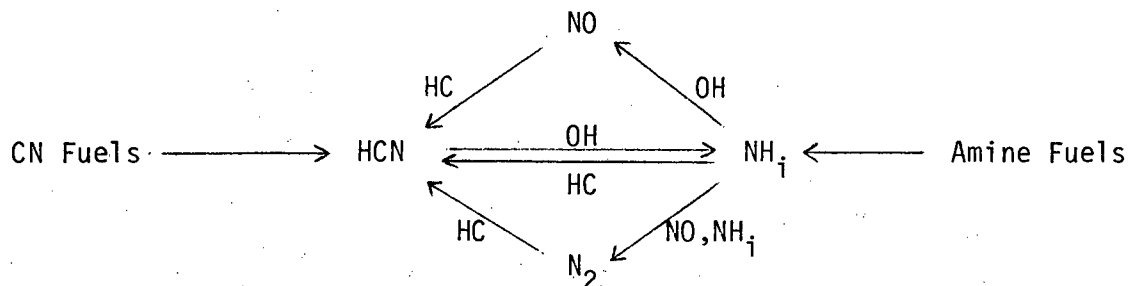
It appears that optimum NO reduction occurs by burning with overfire air at a first stage equivalence ratio between 1.17 and 1.37. The data shown in Figures 9,10 and 11 may be in error up to $\pm 10\%$ because full thermal equilibrium was not obtained at each operating condition which requires waiting up to 45 minutes between each change of conditions. However, double-checking some data points at full thermal equilibrium confirmed the characteristics exhibited in Figures 9,10 and 11. NO production from the combustor both with and without NO doping was consistently between 30 and 50 ppm.

Reaction Mechanism

The understanding of gas phase NO reduction kinetics remains poor and even less is known of these reactions in fluidized beds. It has been assumed that heterogeneous char - NO reactions dominate the NO reduction activity in fluidized beds burning solid fuels. A number of researchers have studied the fate of fuel-bound nitrogen in coal combustion (Kunii et al., 1980; Wendt and Schulze, 1976; Wendt et al., 1978). The gas phase reduction of NO is thought to result from

the interaction between nitric oxide and incomplete combustion products, carbon monoxide, or unburned hydrocarbons, during the combustion process, Parks (1973). In a study carried out in a combustion tunnel, Muzio et al. (1976) showed that the injection of CO or H₂ does not cause a selective reduction of nitric oxide. NO reduction therefore occurs during the process of combustion and not after the formation of CO and hydrogen. This seems to agree with the flat NO profiles of Figures 7 and 8.

Peterson (1981) recently proposed the following scheme for fuel nitrogen reactions for rich stoichiometries:



He warns, "A key factor in using two stage combustion is to recognize that any nitrogenous species other than N₂ or N₂O which exit the first stage are likely to be converted to NO in the lean second stage." This may very well explain the rise in NO concentrations in the second stage exhibited in Figures 8, 10 and 11 at very rich mixtures.

Carbon Balance

A carbon balance is presented in Table 5 for a variety of operating conditions. The table shows the fraction of input carbon that leaves the combustor in the form of CO, CO₂ and hydrocarbons. Measurements of hydrocarbons were made only in the double bed configuration. In all cases, hydrocarbon measurements were below 200 ppm which is negligible compared to measured

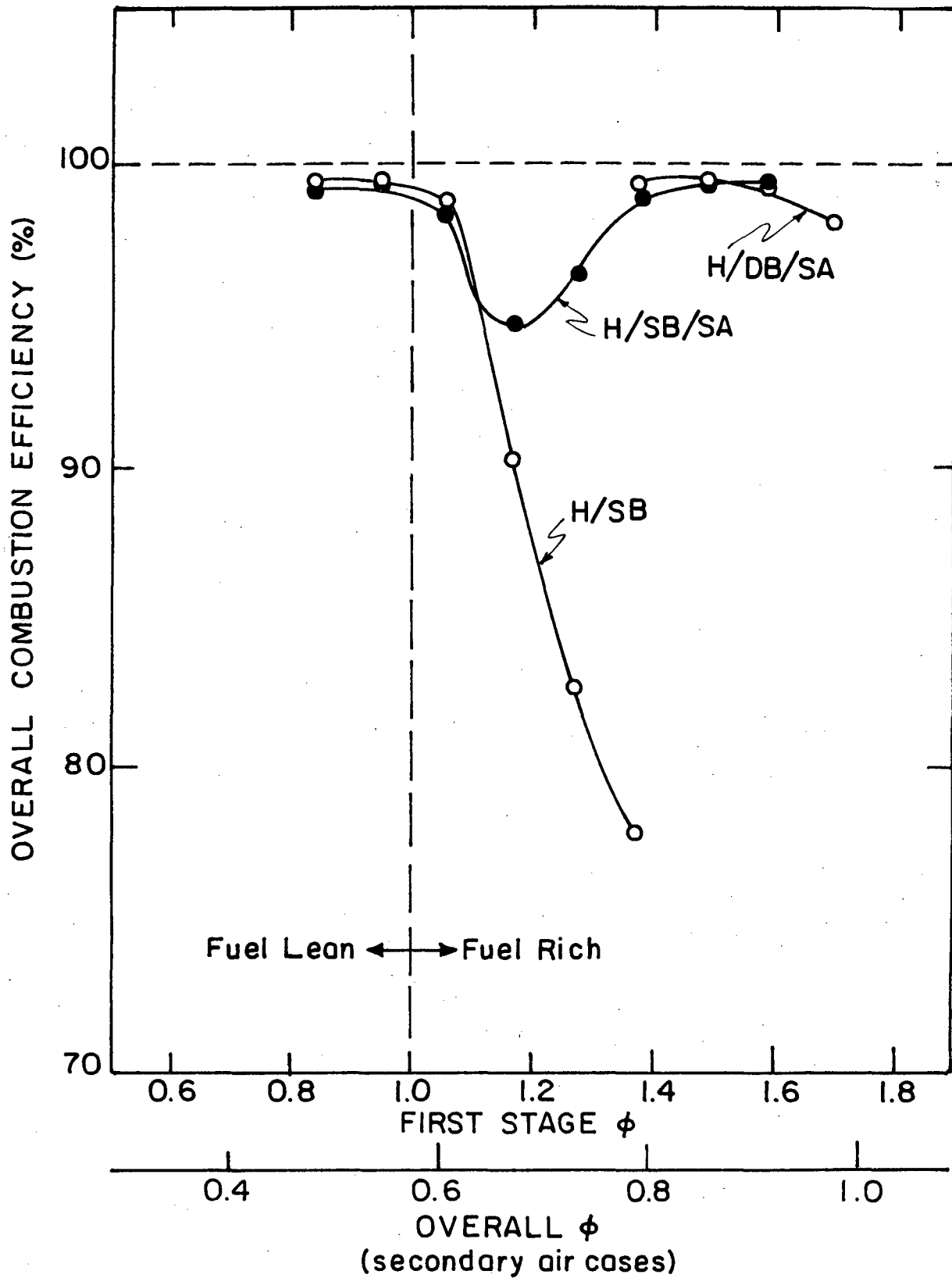
Table 5. Carbon balance.

Configuration	ϕ_1	CO (ppm)	CO ₂ (ppm)	HC (ppm, propane)	Carbon Out
					$\frac{\text{CO, CO}_2}{\text{Carbon In C}_3\text{H}_8}$
Single bed	0.83	1,600	90,000	*	0.906
	1.27	61,000	86,600	*	0.998
	1.37	87,500	76,100	*	0.997
Single bed with secondary air	0.83	2,300	92,500	*	0.934
	1.27	11,200	120,700	*	0.880
	1.37	3,800	137,200	*	0.872
Double bed with secondary air	1.37	2,200	146,000	140	0.913
	1.48	2,300	162,000	160	0.939

* Not measured.

CO and CO₂. The low input-to-output carbon ratios at some conditions are thought to be due to uncertainties in the carbon input rate (fuel flow rate), the air flow rate, readings from the CO and CO₂ analyzers, and from mixing non-uniformities. Drift was particularly troublesome with the CO₂ analyzer.

Combustion efficiencies were calculated for several operating conditions based on CO and CO₂ measurements, Figure 12. An efficiency of 100% corresponds to complete conversion of input carbon to CO₂. It was assumed here that output hydrocarbons were negligible. The efficiencies were plotted versus the first stage equivalence ratio for each of the three configurations. Note the increase in overall efficiency when burning in stages. The efficiency of the overfire air case dips slightly past $\phi_1 = 1$ due to a lack of secondary combustion. Once combustion forms in the second stage, the efficiency once again rises.



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Figure 12. Overall combustion efficiency with change in ϕ for single bed with and without overfire air, and double bed configurations.

SUMMARY AND CONCLUSIONS

Staged fluidized bed combustion is an effective method of pollution control. Selective combustion modification can cause substantial reduction of nitrogen oxides formed from fuel-bound nitrogen.

In this study, a two-stage fluidized bed facility has been demonstrated and characterized. The combustor burns propane doped with NO and air. Gas phase NO reduction was measured under three different configurations. Maximum NO reduction while operating in the two-staged mode was found to be approximately 66%.

NO profiles have shown that there are no residence time restrictions for this apparatus. Substantial NO reduction can be obtained without significant loss of overall combustion efficiency. Optimum operating conditions for NO reduction were found to be a single bed configuration with overfire air operating between a first stage equivalence ratio of 1.17 and 1.37.

For very rich mixtures, two stage combustion causes an increase in NO concentration between the first and second stages. It is thought that nitrogenous compounds such as NH_3 and HCN are oxidized in the second stage when operating at very rich mixtures. Further investigation including a more complete nitrogen balance must be made to support this hypothesis.

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