

REDUCTION OF NITRIC OXIDE BY CARBONACEOUS SOLIDS  
IN AN ATMOSPHERIC PRESSURE FLUIDIZED-BED REACTOR

By

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Abstract

The fluidized-bed combustion process, due to its ability to control pollutant emissions and its inherent capability to accommodate a wide variety of fuels, has been the subject of accelerating development for industrial and utility applications. However, fluidized-bed combustion boilers based on the current design and operation may not be able to meet the future stringent standards on nitrogen oxides emissions without additional provisions. In this paper, a preliminary study on the reduction reactions of nitric oxide with three different carbonaceous solids using a 9.6-centimeter diameter, electrically heated, batch fluidized-bed reactor operated at various design and operating conditions is discussed. Results of this investigation indicates that the NO reduction reaction appears to be dependent upon not only the operating variables such as bed temperature, carbonaceous solid loading in the bed, but also on the physical properties of the carbonaceous solids as well. Prediction of NO reduction by one of the carbonaceous solids using a two-phase bubble model shows good agreement with experimental data within the range of experimental conditions.

Introduction

Among the various techniques for direct conversion of the chemical energy in coal to thermal energy, the fluidized-bed combustion (FBC) process appears to be one of the most attractive means due to its inherent features. The higher heat capacity of the solid bed material leads to good combustion stability which, consequently, permits use of essentially all fossil fuels including low-grade fuels high in ash and/or moisture content and low in heating value, such as coal refuses, peat, oil shales, etc. The use of a sulfur-accepting sorbent affords in situ capture of the sulfur dioxide evolving from the burning of sulfur-bearing fuels. Bed temperature is maintained sufficiently low and, thus, results in relatively low emissions of nitrogen oxides and less slagging and fouling problems than in conventional coal-fired boilers. Lastly, the presence of vigorous particle mixing in the fluidized bed provides higher bed-to-surface heat transfer rates which results in less heat exchange surface relative to conventional coal-fired boilers. As a consequence, fluidized-bed combustion boilers fueled by coals and low-grade fuels have been the subject of accelerating developments for industrial and utility applications both in the U.S. and abroad. In recent years a number of fluidized-bed boilers have been

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constructed and operated to demonstrate a variety of industrial and utility applications and process reliability; for example<sup>1,2,3</sup> the commercial prototype fluidized-bed boiler at Georgetown University, the industrial application of a fluidized-bed boiler at Great Lakes Naval Training Station, and the prototype anthracite culm fluidized-bed combustion boiler at the industrial park in Shamokin, PA. In addition, a 20 MWe fluidized-bed boiler pilot plant is currently under construction by TVA for the utility application<sup>3</sup>.

At present, the EPA nitrogen oxides emission standard is 0.6 lb NO<sub>x</sub>/million Btu input; most of the fluidized-bed combustion boilers, which are based on the current design and operation principles, can meet the standard without additional efforts. However, it is anticipated that nitrogen oxides emission standard may become more stringent in the future. The fluidized-bed boilers using the current design and operation principles may not be able to meet the stringent standards for NO<sub>x</sub> emissions without additional provisions. It is, therefore, the objective of this project to investigate and determine the pertinent design and operational variables which affect NO<sub>x</sub> emissions from fluidized-bed combustion boilers. Results of this investigation may enable further insight to be gained into the mechanism of NO<sub>x</sub> destruction in the bed and provide design and operational information for the future development of low-NO<sub>x</sub> fluidized-bed combustion boilers to meet the anticipated stringent EPA nitrogen oxides emission standards.

### Experimental Facility

Experiments on nitrogen oxides reduction were conducted using an electrically heated, laboratory-scale, fluidized-bed reactor, which is shown schematically in Figure 1. This laboratory-scale batch fluidized-bed reactor consists of a 9.6-cm diameter, 47 cm tall, stainless steel cylindrical vessel. The lower section of the vessel is surrounded by a 20-cm tall, 1.36 KW electric heater, such that the bed can be heated to about 1000°C. The stainless steel cylindrical vessel is also heavily insulated with Fiberfrax. The bed is supported on a 6.35 mm thick stainless steel perforated gas distributor with fifty-six (56), 0.8-mm diameter orifices.

Bed temperature was regulated and controlled by a transformer. Reaction temperature was measured by a chromel-alumel thermocouple with a Hastalloy sheath of 3.175 mm diameter. Readings were displayed in degrees on a digital thermometer. The thermocouple was suspended at a point which was 5 cm from the distributor; the axial temperature distribution in the bed and freeboard was measured by moving the thermocouple.

Temperature recordings in the bed above 2.5 cm from the distributor indicated that the bed temperatures were essentially uniform. However, a temperature gradient of approximately 18°C/cm was observed in the freeboard section of the reactor. The bed was fluidized by pure nitrogen gas; carbon monoxide, methane, and nitric oxide could also be introduced into the fluidizing gas stream in controlled amounts. All gas flow rates were measured by rotameters. Exit gas composition was continuously monitored by preset gas analyzers as shown below:

Compound	Principle of Operation	Instrument <sup>1</sup>
NO	Chemiluminescence	Thermo-Electron, Series 10
CO	IR	MSA-LIRA, Model 303
CO <sub>2</sub>	IR	MSA-LIRA, Model 303
O <sub>2</sub>	Paramagnetic	Leeds and Northrup
Total HC	Flame Ionization	Beckman, Model 400

<sup>1</sup>The use of brand names is for the identification purposes only and does not constitute endorsement by the Department of Energy.

The analyzed flue gas concentrations were registered on a six-channel strip chart recorder.

#### Materials Used for the Experiments, Chars and Coke

Nitric oxide reduction experiments were conducted using two different chars and a coke. Char 1 was produced from Wyoming sub-bituminous coal by Occidental Research Corporation's (OCR) Flash Pyrolysis process, with BET (Brunauer-Emmett-Teller) surface area of 290 m<sup>2</sup>/g, a size range of 30 x 70 mesh, and a density of 2.010 g/cm<sup>3</sup>. Its chemical composition is listed in Table 1. Char 2 was made in situ from Pitts- wick bituminous coal (8 x 12 mesh in size). The Pitts- wick coal was fed a little at a time into the bed where sand was fluidized and heated to a temperature of 850°C by the preheated nitrogen gas to prevent the coal from clinking. The coal was then pyrolyzed in a nitrogen atmosphere for half an hour to produce Char 2. The chemical composition of Char 2 and its parent coal are also listed in Table 1. Char 2 had a BET surface area of 2.4683 m<sup>2</sup>/g and a density of 2.288 g/cm<sup>3</sup>. It is important to note that the analytical data for Char 2 on a weight basis, such as its chemical composition and surface area, are not as precise as desired because the char samples contained a certain amount of sand which could not be completely separated from the char before analysis.

Metallurgic coke, obtained from Mercury Coal and Coke, Inc., near Morgantown, was also used in these tests. It was ground and screened to obtain coke particles of 12 to 20 mesh size. The coke particles were then fluidized with nitrogen in the hot fluidized bed at 900°C for one hour. After the material was cooled, the test feedstock coke was obtained. The BET surface area of this coke was 0.8668 m<sup>2</sup>/g and its density was 2.067 g/cm<sup>3</sup>. Its chemical composition is listed in Table 1.

#### Bed Material

Glass sand with a mean particle diameter of 0.286 mm was used as the bed material. The size distribution of the sand is listed in Table 2. The BET surface area was 0.846 m<sup>2</sup>/g and its density was 2.664 g/cm<sup>3</sup>.

The minimum fluidization velocity of the sand was determined experimentally at elevated temperature. A pressure drop versus gas velocity is plotted in Figure 2. As can be seen, the minimum fluidization velocity is approximately 5.5 cm/sec at a bed temperature of 822°C.

#### Experimental Procedure

The experimental procedures for NO reduction by Char 1 and by metallurgic coke were precisely the same. First, the reactor containing 1164 g of sand was heated while the sand was simultaneously fluidized with preheated nitrogen. When the desired reaction temperature was reached, the fluidizing gas was turned off and a feed hopper with a long dipleg was inserted rapidly into the reactor through a stop-cock in the feedline on top of the reactor. A weighed amount of char (or coke) was then poured into the hopper from which it dropped onto the hot sand. The hopper was then removed, the cock closed, and the nitrogen switch was turned on immediately such that the char was distributed evenly throughout the bed. When the bed temperature had restabilized at the desired level, a measured flow of nitric oxide was admitted. The concentrations of each component in the exit gas were continuously monitored and recorded on a six-channel strip chart recorder.

In order to reach the required steady-state conditions in a short duration of time, the experiments to determine NO reduction capability of Char 1 and coke were conducted in sequence from low temperature (600°C) to high temperature (850°C) at the same carbon loading.

The experimental procedure for the reduction of nitric oxide by Char 2 was similar to the procedure for Char 1 and metallurgic coke as described above, except that the tests were carried out in a temperature sequence from 850°C (highest) to lower temperatures, since Char 2 was produced "in situ" under a nitrogen atmosphere at 850°C which was the highest chosen reaction temperature for an experiment.

### Experimental Results and Discussion

Experiments on the reduction of NO by carbonaceous solids were carried out at various operating conditions. Results of these experiments and their corresponding operating conditions are presented in Tables 3, 4, and 5 for Char 1, Char 2, and metallurgic coke respectively. A discussion of these data is presented below.

#### Effect of Char Surface Area and Porosity on Nitric Oxide Reduction

Experimental results of NO reduction by a batch of carbonaceous solids in the absence of oxygen were plotted in Figure 3 at identical operating conditions. Results shown in Figure 3 indicate that heterogeneous reduction of NO by Char 1 and Char 2 are significantly higher than that achieved with metallurgic coke. The reactivities of the three carbonaceous solids are compared in Table 6. Differences in the reduction of NO by these carbonaceous solids may be attributed to the differences in physical properties, such as specific surface area and porosity. Char 1, which gives the highest NO reduction, poses the highest specific surface area, although its carbon content is less than the metallurgic coke. Scanning Electron Microscope (SEM) porosity measurement also indicates that Char 1 exhibits the highest porosity. As can be seen in Figure 4, micropores with size ranging from 100  $\mu\text{m}$  to 0.3  $\mu\text{m}$  cover nearly 100 percent of its surface. Although the metallurgic coke has the highest carbon content among the three tested carbonaceous solids, its specific surface area is the smallest. The coke also has comparatively smaller pores which range in size from 10  $\mu\text{m}$  to 1.5  $\mu\text{m}$  and cover only about 1 percent of its surface as can be seen in Figure 5. Figure 6 shows the porosity measurement of Char 2, which has pore sizes ranging from 40  $\mu\text{m}$  to 1  $\mu\text{m}$  and covering 45 percent of its surface. A comparison of the data presented in Table 6 and the porosity measurements given by SEM indicates that the low NO conversion rate achieved by metallurgic coke may be attributed to its small BET surface area as well as its low porosity. Interpretation of these data suggests that internal diffusion may also play an important role in determining the overall reaction rate of a large porous solid particle, which has relatively low porosity and small BET surface area, with a reactant gas.

#### Effect of Bed Temperature in Nitric Oxide Reduction by Chars

The reduction reaction between NO and char was found to be strongly influenced by operating bed temperature. Figures 7 and 8 show the effect of bed temperature on NO reduction by Char 1 and Char 2. As can be seen, nitric oxide concentration in the exit gas decrease with increasing bed temperature of both Char 1 and Char 2. Within the range of operating conditions, NO reductions of 90 percent or better were attainable provided that the bed temperature was maintained at or above 800°C. As the bed temperature was raised, further, NO outlet concentration decreased continuously, but at a decreasing rate. However, thermodynamic calculations indicated that at a temperature of 900°C, equilibrium concentrations of thermal NO may reach 500 ppm for a mixture of 2 percent oxygen and 75 percent nitrogen<sup>4</sup>. In view of the current practice in design and operation of fluidized-bed combustion boilers, the use of excess oxygen at higher bed temperatures may promote the formation of thermal NO. The higher bed temperature is also unfavorable to the sulfation reaction of natural sorbents in the atmospheric pressure fluidized bed. Therefore, an optimum temperature range for NO<sub>x</sub> and SO<sub>2</sub> emission control appears to be 800° to 850°C.

## Effect of Char Loading on Nitric Oxide Reduction

The effect of char loading in the fluidized bed on NO reduction by char is illustrated in Figure 9. As can be seen, the reduction of NO increases with increase in char loading. At bed temperature of 750°C, the effect of char loading is most important around 1 percent where it results in a NO reduction of 87 percent. At higher char loading, the reduction of NO is generally higher; however, the effect of the char loading becomes less significant. The same trend can also be observed at the temperature range below 750°C, even though the reduction of NO falls below 60 percent due to the strong temperature dependence of the reduction reaction. Higher char loading in the bed may increase the chances of clinker formation which is caused by local temperature excursion as a consequence of the poor solid mixing and the inability to dissipate the heat of combustion. In addition, the loss of unburnt carbon in the drained spent-bed material may become unacceptable if the char loading in the bed becomes too high. However, recent developments in fluidized-bed combustion technology have indicated that two-stage combustion systems with the increased char loading in the first stage enhances the overall reduction of nitric oxide emission significantly<sup>5</sup>.

### Prediction of NO Reduction by Char 1

Recent experimental studies<sup>6</sup> on the reduction reaction of nitric oxide with char have concluded that the reaction is first order with respect to the NO concentration. This practice is, hence, adopted in the present study. The reaction rate constants of the reaction of NO with Char 1 at the corresponding temperatures and char loadings were calculated based on the experimental data presented at Table 3. The activation energy and the frequency factor within the range of operating conditions are 31.7 kcal/mol and  $9.66 \times 10^8 \text{ sec}^{-1}$  respectively. The rate constants of NO-char plotted as a function of inverse temperatures for several experimental studies<sup>7</sup> are compared with the present results in Figure 10. As can be seen, the reaction rate constants obtained from the present experiment show good agreement with previous investigations. The NO-char reaction kinetics can be represented by the following correlation and this was employed in the NO emission modeling. In view of the low

$$k = 9.66 \times 10^8 \exp \left( - \frac{31,700}{RT} \right) \text{ sec}^{-1},$$

superficial velocity, the shallow bed, and relatively small bed diameter, a two-phase bubble model<sup>8</sup> with both the bubble and emulsion phases treated as plug flow was employed for the prediction of NO conversion. The NO reduction by Char 1 was calculated using this approach over the range of experimental conditions. The comparison of calculated versus test data values may be observed in Table 3, as well as Figure 7. As can be seen in Figure 7, the calculated values for NO reduction show excellent agreement with experimental data.

### Conclusions

Tests to determine the NO reduction capability of two different chars and a metallurgic coke were conducted in an electrically heated, batch, fluidized-bed reactor in the absence of oxygen. Based on the experimental results, the following conclusions can be drawn.

- o Reduction of nitric oxide depends strongly on the physical properties of the carbonaceous solids such as specific surface area and pore size distribution; and, to a lesser extent, on the carbon content.
- o Reduction reaction between NO and carbonaceous solids was found to be strongly influenced by bed temperature. Within the range of operating conditions, the degree of NO reduction increases with bed temperature. However, the formation of thermal NO and the unfavorable sulfation reaction for natural sorbents in an

atmospheric pressure fluidized bed at higher temperature posts an upper limit on temperature range for NO<sub>x</sub> and SO<sub>x</sub> emission control. A preferred operating temperature range from this standpoint appears to be 800°-850°C.

- o NO reduction by char increases with char loading in the bed. With 1 percent of char loading in the bed, 90 percent or better NO reduction is attainable for both Char 1 and Char 2 provided that bed temperature is maintained at or above 800°C.
- o Reaction rate constants based on the present experimental data show good agreement with the previous investigations. The rate constant can be represented by the following correlation:

$$k = 9.66 \times 10^8 \exp \left( - \frac{31,700}{RT} \right) \text{ sec}^{-1}$$

- o Prediction of nitric oxide reduction by Char 1 using a two-phase bubble model gives good agreement with the experimental data within the range of experimental conditions.

#### References

1. Proceedings of the Fifth International Conference on Fluidized-Bed Combustion, Washington, DC, December 1977.
2. Proceedings of DOE/WVU Conference on Fluidized-Bed Combustion System Design and Operation, Morgantown, WV, October 1980.
3. The proceedings of the Sixth International Conference on Fluidized-Bed Combustion, Atlanta, Georgia, August 1980.
4. Pereira, F. J. M. A., "Nitric Oxide Emission from Fluidized Coal Combustion," Ph.D. Thesis, University of Sheffield, 1975.
5. Gibbs, B. M., F. J. Pereira, and J. M. Béer, "The Influence of Air Staging on the NO Emission from a Fluidized-Bed Coal Combustor," Paper Presented at 16th Symposium (International) on Combustion, The Combustion Institute, Pittsburgh, PA, 461, 1977.
6. Béer, J. M., A. F. Sarofim, S. S. Sandhu, M. Andrei, D. Bachovchin, L. K. Chan, T. Z. Chang, and A. M. Sprouse, "NO<sub>x</sub> Emissions from Fluidized Coal Combustion," EPA Grand No. R804978020 Report, 1979.
7. Furusawa, T., D. Kunii, A. Oguma, and N. Yamada, "Kinetic Study of Nitric Oxide Reduction by Carbonaceous Materials," Kagaku Kogaku Ronbunshu, 4 (6), 562 (1978).
8. Davidson, J. F. and D. Harrison, "Fluidized Particles," Cambridge University Press., 1963.

TABLE 1  
Chemical Analysis of Carbonaceous Solids

	Char 1	Char 2	Pittswick Bituminous Coal	Metallurgic Coke
<u>Ultimate Analysis, Wt %</u>				
Moisture	2.09	0.63	1.35	0.09
Ash	16.79	60.05	14.15	10.07
Sulfur	0.83	1.64	3.85	0.83
Hydrogen	1.35	0.40	5.04	0.53
Nitrogen	0.96	0.66	0.98	0.84
Total Carbon	75.24	37.90	69.10	87.40
Oxygen (by difference)	2.74	1.28	5.53	0.23
<u>Elemental Analysis, Wt %</u>				
Silicon, SiO <sub>2</sub>	35.06	84.51	49.16	44.19
Aluminum, Al <sub>2</sub> O <sub>3</sub>	16.91	7.62	23.66	19.34
Iron, Fe <sub>2</sub> O <sub>3</sub>	14.84	5.38	17.72	17.76
Calcium, CaO	11.32	0.49	1.55	5.75
Magnesium, MgO	4.48	0.01	0.85	0.98
Sodium, Na <sub>2</sub> O	--	--	1.23	2.20
Potassium, K <sub>2</sub> O	0.70	0.62	2.59	1.53
Phosphorus, P <sub>2</sub> O <sub>5</sub>	0.73	0.05	0.05	0.32
Titanium, TiO <sub>2</sub>	0.85	0.34	1.21	1.21
Sulfur, SO <sub>3</sub>	6.50	1.63	1.72	4.06

TABLE 2  
Screen Analysis of Sand

Size Range, mm	Wt %
-0.589 + 0.419	2.2
-0.419 + 0.249	72.7
-0.249 + 0.179	18.9
-0.179 + 0.150	4.2
-0.150	1.0

Mean Diameter,  $d_p = 0.286$  mm

TABLE 3  
Experimental Results of NO Reduction by Char 1

Run No.	Char g	Char Wt %	Sand g	T °C	NO <sub>in</sub> ppm	NO <sub>out</sub> ppm	N <sub>2</sub> M <sup>3</sup> /hr	U <sub>mf</sub> cm/S	U cm/S	L <sub>mf</sub> cm	L <sub>f</sub> cm	$\epsilon_{mf}$	$\left(\frac{NO_{out}}{NO_{in}}\right)_{exp.}$	$\left(\frac{NO_{out}}{NO_{in}}\right)_{cal.}$	k l/sec
5-28-1	12	0.01031	1164	600	965	745	0.85	5.5	10.6	10	12.065	0.42	0.772	0.837	15.477
5-28-2	12	0.01031	1164	650	965	615	0.85	5.5	11.2	10	12.065	0.42	0.637	0.637	28.622
5-28-3	12	0.01031	1164	700	965	360	0.85	5.5	11.8	10	12.065	0.42	0.373	0.360	67.269
5-28-4	12	0.01031	1164	750	965	125	0.85	5.5	12.4	10	12.065	0.42	0.130	0.128	155.295
5-28-5	12	0.01031	1164	800	965	25	0.85	5.5	13.0	10	12.065	0.42	0.026	0.030	341.263
6-5-1	24	0.02062	1164	600	980	660	0.85	5.5	10.6	10	12.065	0.42	0.673	0.701	11.842
6-5-2	24	0.02062	1164	650	980	390	0.85	5.5	11.2	10	12.065	0.42	0.397	0.409	29.532
6-5-3	24	0.02062	1164	700	980	150	0.85	5.5	11.8	10	12.065	0.42	0.153	0.137	65.746
6-5-4	24	0.02062	1164	750	980	10	0.85	5.5	12.4	10	12.065	0.42	0.010	0.023	199.890
6-8-1	36	0.03093	1164	600	975	580	0.85	5.5	10.6	10	12.065	0.42	0.595	0.588	10.389
6-8-2	36	0.03093	1164	650	975	300	0.85	5.5	11.2	10	12.065	0.42	0.308	0.264	25.311
6-8-3	36	0.03093	1164	700	975	60	0.85	5.5	11.8	10	12.065	0.42	0.062	0.055	67.035
6-9-1	48	0.04124	1164	600	985	475	0.85	5.5	10.6	10	12.065	0.42	0.482	0.494	10.969
6-9-2	48	0.04124	1164	643	985	215	0.85	5.5	--	--	--	--	0.218	--	--

TABLE 4  
Experimental Results of NO Reduction by Char 2

Run No.	Char* g	Sand g	T °C	NO <sub>in</sub> ppm	NO <sub>out</sub> ppm	N <sub>2</sub> M <sup>3</sup> /hr	U cm/S	U <sub>mf</sub> cm/S	NO <sub>out</sub> /NO <sub>in</sub>
6-1-7	12.85	1164	850	955	0	0.85	13.6	5.5	0
6-1-8	12.85	1164	800	955	75	0.85	13.0	5.5	0.079
6-1-9	12.85	1164	750	955	250	0.85	12.4	5.5	0.262
6-1-10	12.85	1164	700	955	525	0.85	11.8	5.5	0.550
6-1-11	12.85	1164	650	955	700	0.85	11.2	5.5	0.733
6-1-12	12.85	1164	600	955	790	0.85	10.6	5.5	0.827
6-3-1	25.7	1164	850	940	30	0.85	13.6	5.5	0.032
6-3-2	25.7	1164	800	940	62	0.85	13.0	5.5	0.066
6-3-3	25.7	1164	750	940	165	0.85	12.4	5.5	0.176
6-3-4	25.7	1164	700	940	490	0.85	11.8	5.5	0.521
6-3-5	25.7	1164	650	940	665	0.85	11.2	5.5	0.707
6-3-6	25.7	1164	600	940	760	0.85	10.6	5.5	0.809

\*Calculated values based on the assumption that volatiles in the coal escaped during char formation.

TABLE 5  
Experimental Results of NO Reduction by Metallurgic Coke

Run No.	Coke g	Sand g	T °C	NO <sub>in</sub> ppm	NO <sub>out</sub> ppm	N <sub>2</sub> M <sup>3</sup> /hr	U cm/S	U <sub>mf</sub> cm/S	NO <sub>out</sub> /NO <sub>in</sub>
6-3-7	24	1164	700	940	900	0.85	11.8	5.5	0.957
6-3-8	24	1164	750	940	855	0.85	12.4	5.5	0.910
6-3-9	24	1164	800	940	770	0.85	13.0	5.5	0.819
6-3-10	24	1164	850	940	620	0.85	13.6	5.5	0.660

TABLE 6  
Comparison of Reactivity for Different Carbonaceous Solids

	Size Mesh	BET Surface Area m <sup>2</sup> /g	Char g	Bed Material (Sand) g	N <sub>2</sub> M <sup>3</sup> /hr	T °C	NO <sub>in</sub> ppm	NO <sub>out</sub> ppm	Reactivity Mole-of-NO-Reduced/g-of-char · hr
Char 1	30 x 70	290	24	1164	0.85	700	980	150	1.31 x 10 <sup>-3</sup>
Char 2	8 x 12	2.4683	25.7	1164	0.85	700	940	490	6.64 x 10 <sup>-4</sup>
Coke	12 x 20	0.9	24	1164	0.85	700	940	900	6.32 x 10 <sup>-3</sup>

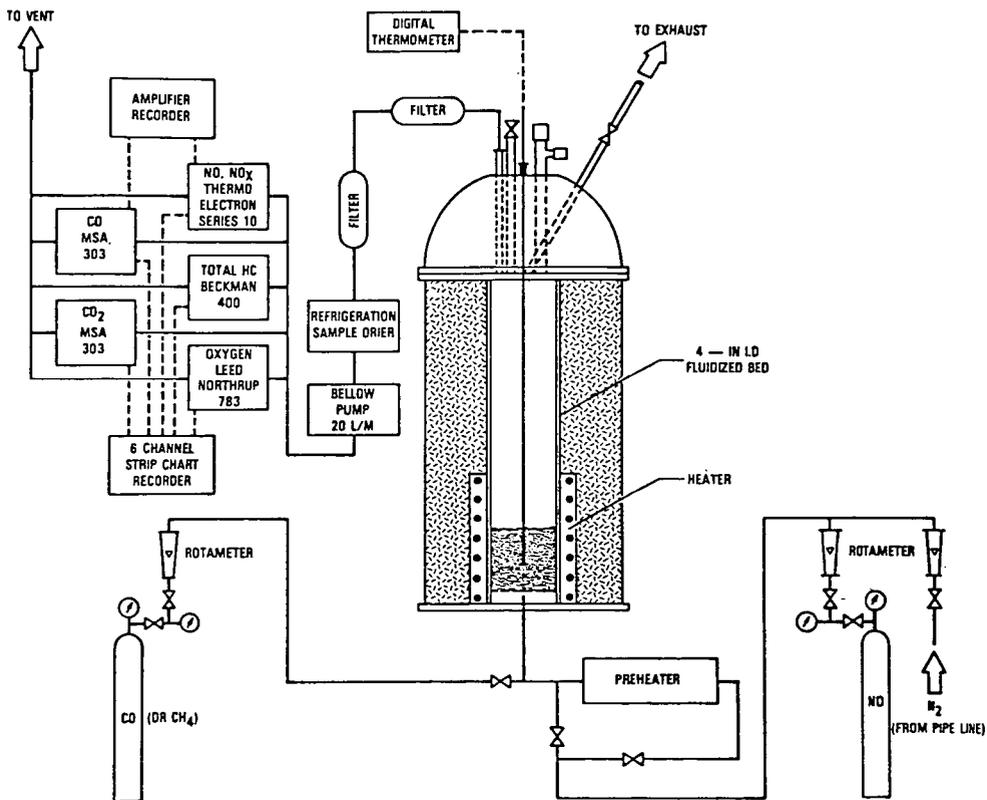


FIGURE 1 — SCHEMATIC DIAGRAM OF EXPERIMENTAL APPARATUS

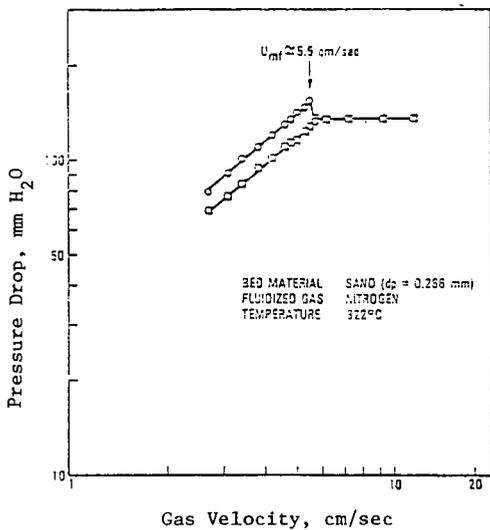


FIGURE 2. Pressure Drop Versus Gas Velocity

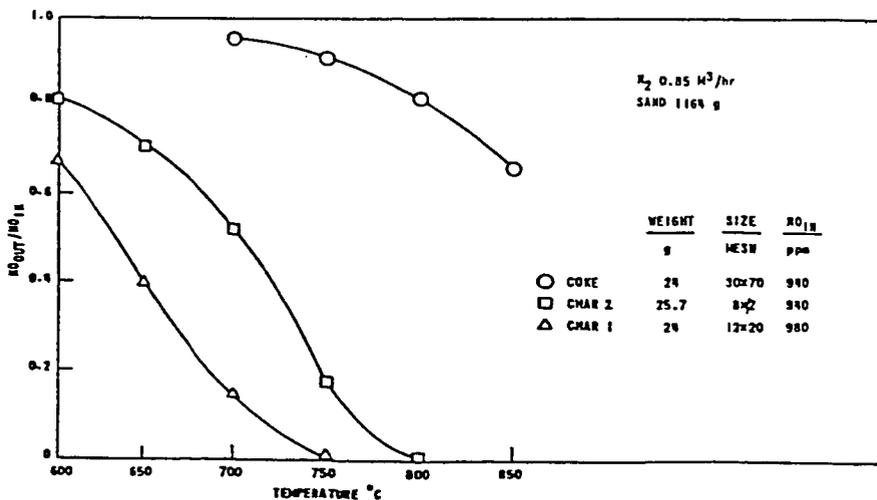


FIGURE 3. Comparison of NO Reduction by Different Carbonaceous Solids

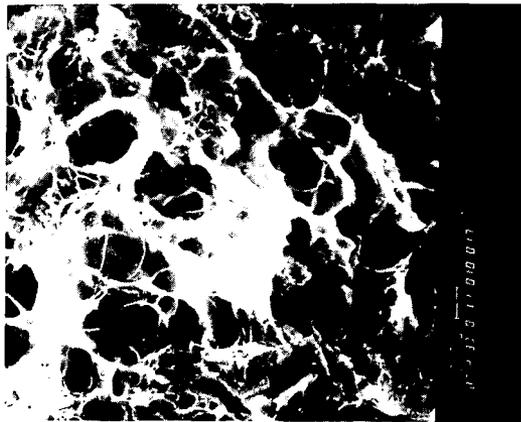


FIGURE 4  
IMAGE OF SEM POROSITY MEASUREMENT OF CHAR 1



FIGURE 5  
IMAGE OF SEM POROSITY MEASUREMENT OF  
METALLURGIC COKE

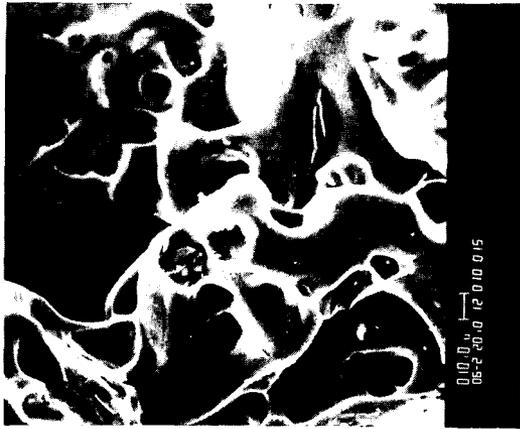


FIGURE 6  
IMAGE OF SEM POROSITY MEASUREMENT OF CHAR 2

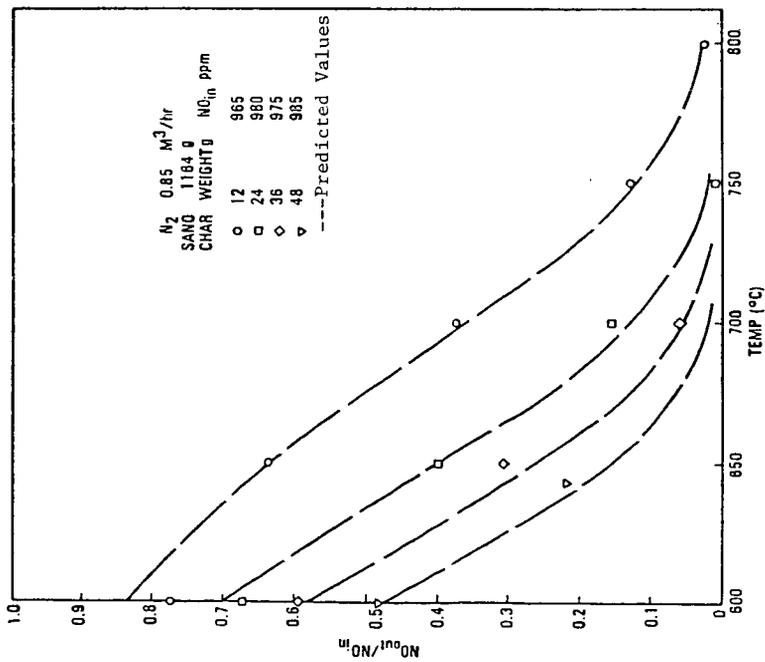


FIGURE 7. Temperature Effect on Reduction of NO by Char I

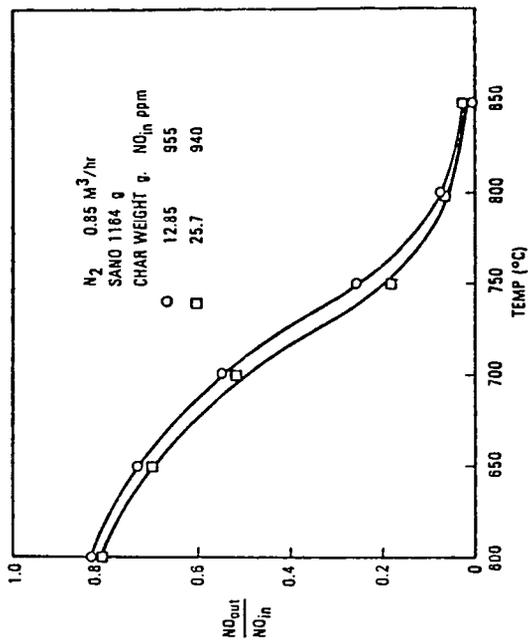


FIGURE 8. Temperature Effect on Reduction of NO by Char 2

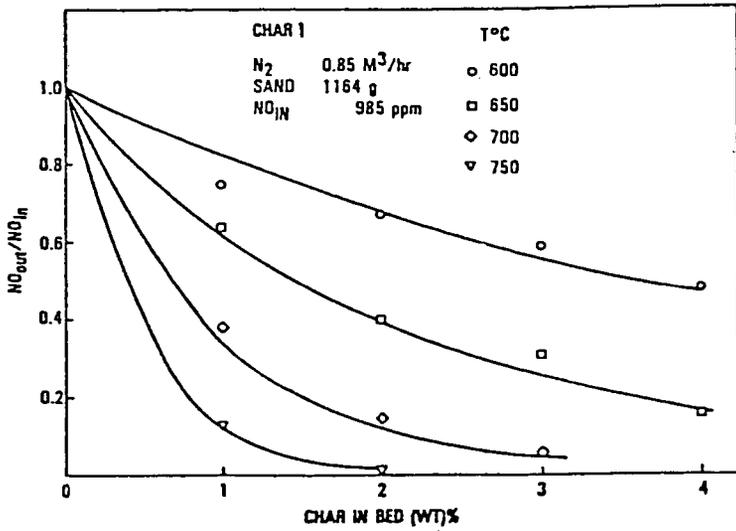


FIGURE 9. Effect of Char Loading on NO Reduction

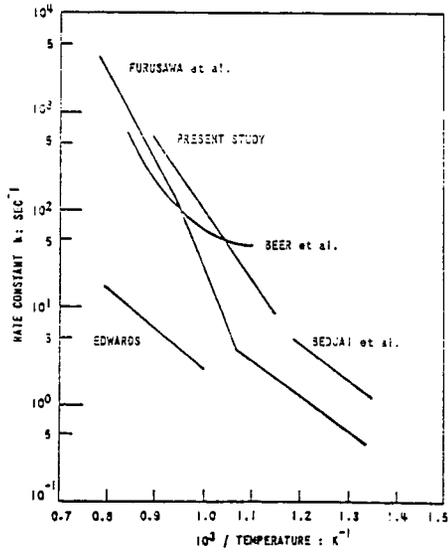


FIGURE 10. Comparison of Rate Constants for NO Reduction by Char