Nitrogen Oxide Abatement by Distributed Fuel Addition

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ABSTRACT

Experiments were conducted to investigate the processes that influence the destruction of NO in the fuel rich stage of the reburning process. The objective is to gain a better understanding of the mechanisms that control the fate of coal nitrogen in the fuel rich zone of a combustion process.

Time resolved profiles of temperature, major (CO_2, CO, H_2O, O_2, H_2 and N_2), nitrogenous (NO, HCN and NH_3) and hydrocarbon (CH_4 and C_2H_2) species were obtained for various reburning tests. A slow continuous source of HCN was observed in the reburn zone for most tests. HCN formation from NO + CH_i reactions would partially explain this trend. It has been proposed in the past that these reactions would be fast (less than 0.1 s) and the produced HCN would be short lived. However, evidence was provided in this study indicating that NO + CH_i reactions might contribute to HCN formation at longer residence times in the reburn zone. Reactions of molecular nitrogen with hydrocarbon radicals were determined to be a significant source of HCN formation, especially as NO levels decreased in the reburn zone. The results of several tests would justify the exclusion of continued coal devolatilization in the reburn zone as a major source of HCN.

INTRODUCTION

Some of the objectives of this research project are to gain a better understanding of the interconversion reactions that control the destruction of NO in the fuel rich zone of the reburning process and to develop a predictive model. Such a model would be beneficial in the design of a reburning process and in identifying its limitations in reducing NO emissions.

The interconversion reactions that govern the destruction and formation of nitrogenous species in post flame flue gases have been investigated by a large number of researchers. A comprehensive literature review was provided by Bose (1989). The following is a review of the major findings of his study.

Bose (1989) studied the mechanisms that govern the fate of coal nitrogen in fuel rich coal post flames and presented evidence that NO + CH_i reactions would not influence NO destruction except in regions close to hydrocarbon injection points. NO reduction was found to occur primarily by NO + NH_i reactions and the reduction was approximately first order with respect to NO and NH_3. Homogeneous gas phase mechanisms were found to dominate the destruction of nitrogenous species with the exception of an indirect heterogeneous effect on HCN formation. HCN did not decay in coal post flames as would be expected if this species were the only source of NH_3. The author hypothesized that heterogeneous release of nitrogen from the coal residue would provide a continuous source of HCN. Reactions of CH_i with molecular nitrogen were excluded as a possible source of HCN formation.

A coal independent kinetic model was developed by Bose based on

homogeneous gas phase mechanisms taken from literature data. Partial equilibria for NH_i and CH_i radicals were assumed. The OH radical concentration was assumed to be in super equilibrium due to rapid temperature quench rates in the combustor. The reaction H + OH + M ----> H_2O + M was identified as rate controlling for OH recombination and a correlation for the OH equilibrium overshoot was derived from fundamental kinetic considerations. The model successfully predicted NO decay in fuel rich coal flame flue gases, but failed to account for all nitrogen species. The deficiency in the nitrogen balance was explained in terms of an unknown nitrogen species that might exist in post flame flue gases and would decay to form NH_3. There is no direct evidence in the literature to support this hypothesis. Thus, there still exists a need for a simplified model that can predict the fate of all nitrogenous species in coal post flames.

In this report, the results of various reburning tests are presented and the findings of this study are compared to those of other researchers. The development of a predictive model will be the focus of future work.

DISCUSSION

Three sets of reburning experiments were performed: coal burning tests, special reburning tests and gas burning tests. The coal burning tests utilized Utah Bituminous coal as primary fuel and natural gas as reburn fuel. In the special reburning tests, the effectiveness of non hydrocarbon reburn fuels was tested and the effectiveness of fuel lean reburning was examined. Utah Bituminous coal was used as a primary fuel in these tests. The gas burning tests utilized natural gas (doped or undoped with NH_3) as primary fuel and natural gas as reburn fuel. The results of all these tests are presented in Table 1 as time resolved profiles of all the relevant species.

Coal Burning Tests

These reburning tests were conducted to investigate the destruction and formation of the nitrogenous species under various conditions in the reburn zone. Reburn zone stoichiometric ratios varied from 0.68 to 0.86 and primary NO levels ranged from 780 ppm to 1140 ppm.

Figures 1-5 show the results of five reburning tests under different conditions with reburn zone entrance temperatures close to 1500 K. The results are presented as the percentage of coal nitrogen converted to nitrogenous species. All five tests show similar trends for NO, HCN and NH_3. NO decayed over long time scales while HCN became the dominant volatile nitrogenous species at longer residence times (longer than 0.6 s) and was present in amounts greater than either NO or NH_3. Final nitrogenous species levels were in the range of 72-123 ppm for NO, 87-202 ppm for HCN and 47-81 ppm for NH_3.

Figures 5 and 6 compare the results of two reburning tests at different reburn zone entrance temperatures, 1485 K and 1657 K, respectively. The NO decay rate was lower in the low temperature test (Figure 5), but HCN and NH_3 levels were higher with an increase in HCN concentration with time which indicates a source of HCN formation. Similar observations were reported by Bose (1989) for fuel rich coal burning tests. On the other hand, decay in both NO and HCN was observed in the high temperature test (Figure 6), with HCN concentration decaying to negligible levels within 0.5 s. This is not in agreement with the results of Bose at comparable temperatures. Examining the trends for CH_4 concentrations in both studies would help to explain the observed difference between the results of this study and those of Bose. The profiles for CH_4 in Figure 7a shows that the decay in HCN corresponded to the decay of CH_4 which also decayed to negligible levels within 0.5 s. The results of Bose show a similar correspondence between the trends of HCN and those of CH_4. This would suggest that hydrocarbon decay in the fuel rich zone of a combustion process would play a key role in HCN formation and destruction mechanisms. Thus, the effect of temperature on the fate of nitrogenous species should be examined in view of its effect on hydrocarbon decay rates. The effect of hydrocarbon decomposition on HCN profiles will be discussed further.

To summarize, HCN profiles for all coal burning tests, except those at high temperature (Figure 6), show slow and continuous increase in HCN concentrations with time. Thus, there must exist a source of HCN in the reburn zone, otherwise, HCN concentrations would decay to correspond to increasing NH_3 concentrations. Furthermore, the results suggest a correspondence between the trends of HCN and those of hydrocarbons that is not limited only to short residence times. There are

three possible sources of HCN formation: NO + CH_i reactions, CH_i + N_2 reactions and the continued evolution of coal nitrogen in the reburn zone. Identifying the source of HCN formation will be addressed in the following sections.

Special Reburning Tests

In this set of experiments, the effectiveness of two non hydrocarbon reburn fuels, namely CO and H_2, was tested. Also, a test was conducted to examine the effectiveness of reburning in a fuel lean reburn zone. These experiments would also verify the significance of hydrocarbon reduction of NO in reburning. The profiles are presented as the percentage of coal nitrogen converted to nitrogenous species.

Figure 8 shows the results of a fuel lean reburning test in which the reburn zone stoichiometry was at 1.03. A 45% reduction in NO, relative to uncontrolled emissions, was obtained and less than 3 ppm of either HCN or NH_3 were measured. This verifies the effectiveness of fuel lean reburning in reducing NO emissions as was shown in previous work (report no. 6). The reduction in NO was mostly due to NO + CH_i reactions in the reburn zone. The hydrocarbon concentration profile (Figure 9) might suggest that reducing hydrocarbon radicals might have existed long enough for these reactions to take place. Since adequate mixing was achieved in the reburn zone (report no. 8), NO reduction under fuel lean conditions could not be attributed to mixing inhomogeneities. Instead, it is hypothesized that NO reduction due to NO + CH_i reactions would be faster than CH_i decomposition rates in a fuel lean environment. An example of CH_i decomposition under fuel lean conditions is the destruction of CH_2 radicals through CH_2 + O_2 reactions (Glarborg, 1986). As temperature increases,

hydrocarbon decomposition rates would also increase which might explain the drop in fuel lean reburning effectiveness which corresponded to increasing reburn zone temperatures (report no. 6). The results of Myerson (1975) suggest a similar effect of temperature on NO reduction by hydrocarbons under fuel lean conditions.

Two non hydrocarbon fuels, CO and H_2, were tested as reburn fuels and the results are shown in Figures 10 and 11, respectively. NO was reduced by 30% in CO reburning and by less than 10% in H_2 reburning. Low levels of HCN (less than 6 ppm) and NH_3 (less than 16 ppm) were measured in both cases. These results are in agreement with the results of Greene et al. (1985). The researchers showed that the reburning effectiveness of CO and H_2 as reburn fuels was far below that of hydrocarbon reburn fuels, except for very fuel rich reburn zone stoichiometries (less than 0.8) and low levels of primary NO (190 ppm). In short, it is clear that NO reduction by hydrocarbons is the driving force in the reburning process.

The results shown in Figures 6, 10 and 11 provide evidence that continued coal devolatilization in the reburn zone is not a significant source of HCN formation, since HCN levels were low (less than 8 ppm) in all three tests. Thus, two other possibilities remain as possible sources of HCN formation: NO + CH_i reactions and CH_i + N_2 reactions.

Gas Burning Tests

The gas burning tests were conducted to investigate the relative significance of the two possible sources of HCN. These reburning experiments allowed the manipulation of primary NO levels and thus, the contribution of NO + CH_i reactions to HCN formation could be varied. Primary NO levels were varied by

doping the primary fuel (natural gas) with varying amounts of NH_3. The results are presented in two fashions: as time resolved concentration profiles of nitrogenous species and as time resolved profiles of the percentages of nitrogenous species relative to uncontrolled NO emissions (no reburn fuel introduction).

Figures 12-15 show the results of four tests at different reburn zone entrance temperatures ranging from 1353 K to 1466 K. These tests can be viewed as blank runs since the purpose of these tests was to minimize primary NO levels and thus to minimize the contribution of NO + CH_i reactions to HCN formation. In these tests, NO was formed due to the thermal fixation of molecular nitrogen (thermal NO) and the initial levels were in the range of 24-33 ppm. All four tests show similar trends for all nitrogenous species with final NO levels in the range of 11-15 ppm, HCN levels in the range of 20-50 ppm and NH_3 levels less than 5 ppm. NO profiles show slow decay with time while HCN profiles show increase in HCN concentration with time, indicating a source of HCN formation. The profiles show that conversions to HCN exceed 100% in all four cases. Thus, nitrogenous species interconversion reactions would not account for all the formation of the HCN. Similar observations were reported by Lanier et al. (1986), who proposed that as primary NO levels decrease, HCN formation from CH + N_2 reaction would become increasingly important. Therefore, it is clear that CH_i + N_2 reactions are a significant source of HCN formation, most likely due to CH + N_2 reaction. To show the effect of temperature on HCN formation from this reaction, the results of three tests at different reburn zone temperatures were plotted as seen in Figure 16. Higher temperatures increased HCN formation which was expected since the reaction CH + N_2 ----> HCN + N has an activation energy of about 13600 cal/g mol (Glarborg, 1986).

Figures 17 and 18 show the results of reburning tests in which the primary fuel was natural gas doped with NH_3. That resulted in uncontrolled NO emission levels of 715 ppm and 153 ppm, respectively. The trends are similar to those of coal burning tests with HCN becoming less dominant as the primary NO increased. To show the effect of primary NO levels on HCN formation, the results of tests at different primary NO levels were plotted as seen in Figure 19.

HCN formation in the reburn zone was in part due to NO + CH_i reactions and in part due to CH + N_2 reaction. Figure 19c shows that the variation in HCN concentration with primary NO levels is close to being linear which may suggest that the contribution of CH + N_2 reaction to HCN formation is not strongly dependent on the primary NO level. However, the two routes for HCN formation are interdependent since they both compete for CH_i radicals. If the assumption of little dependence of HCN formation from CH + N_2 reaction on primary NO levels is extrapolated to coal burning and a level of 200 ppm of HCN is assumed, the contribution of this route to HCN formation may be as high as 20%.

Figures 19b and 19c show that HCN formation from CH_i + N_2 reactions dominate at low primary NO levels and HCN formation from NO + CH_i reactions become increasingly important as the primary NO level increases. Both routes are limited by the availability of CH_i reducing radicals. Thus, HCN formation reactions are terminated when hydrocarbon decomposition into reducing radicals is terminated. Figure 19a shows that reducing hydrocarbon radicals may survive for as long as 0.4 s in the reburn zone. In all three tests, rapid increase in HCN levels continued until about 0.4 s in the reburn zone and then leveled off. Thus, it may be deduced that both routes for HCN formation occur over time scales

that are characteristic of hydrocarbon decomposition. In other words, hydrocarbon decomposition in the reburn zone is limiting and the time scale for HCN formation is that of hydrocarbon decomposition into reducing radicals, regardless of the origin of HCN. This leads to an interesting conclusion, since it has been proposed in the past that NO decay by hydrocarbon radicals is dominant for a short time (less than 0.1 s) in the reburn zone after which NO decay by NH_i radicals would dominate and the reduction would be first order with respect to NO and NH_3. This hypothesis was tested using the results of this study and the results of gas burning experiments conducted by Bose (1989), as seen in Figure 20. It is obvious that in the case of reburning, NO decay is not dominated by NO + NH_i reactions, as indicated by the scatter of the points in Figure 20. Therefore, i.e. in the reburn zone, NO decay proceeds through two competing routes: through NO + CH_i reactions and NO + NH_i reactions. Both routes are significant in destroying NO in the reburn zone, except for very short times or very long times where one route may dominate.

To summarize, there are two possible sources of HCN formation in the reburn zone: NO + CH_i reactions and CH_i + N_2 reactions. Although the first route for HCN formation dominates at higher primary NO levels (coal burning), the second route is significant and may contribute as much as 20% to HCN formation. Similarly, there are two routes of NO decay in the reburn zone: NO + CH_i reactions and NO + NH_i reactions and both routes are significant in the reburning process.

CONCLUSIONS

Several reburning experiments were conducted to examine the processes that influence the formation and destruction of nitrogenous species in the reburn zone. Several conclusions can be drawn from this study:

1. Continued coal devolatilization can be excluded as a significant contributor to HCN formation in the reburn zone.

2. This study verifies the significance of CH_i radicals as the driving force in the reburning process.

3. The time scale of HCN formation in the reburn zone is determined by the time scale of hydrocarbon decomposition.

4. There are two contributors to HCN formation in the reburn zone: NO + CH_i reactions and CH_i + N_2 reactions. The relative significance of these two routes depends on the primary NO level, with the first route becoming more important as the primary NO level increases.

5. There are two routes to NO decay in the reburn zone: NO + CH_i reactions and NO + NH_i reactions. This study shows that both effects may be significant at any time in the reburn zone, depending on the availability of CH_i radicals.

FUTURE WORK

This study contributes to the understanding of the processes that occur in the fuel rich stage of the reburning process. The next step is the development and testing of a theoretical model that can predict the formation and destruction of all nitrogenous species in the reburn zone. The model that was developed by Bose (1989) will be utilized as a building block and modified as necessary in view of the findings of this study.

Additional experiments are needed to examine reburning using Lignite coal as a primary fuel. Also, the use of coal as a reburn fuel and the effect of reburn fuel nitrogen content will also be studied.

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TABLE 1

COAL BURNING TESTS:

COAL #2: SR1=1.062, SR2=0.676(P3) NG reburn, COAL 0.918 kg/h, NOp=841

RT,s	T, K	% CO2	% CO	% H2	% H2O	% O2	% CH4	% N2	ppm NO	ppm HCN	ppm NH3	%NO	%HCN	%NH3
0.00	1478	15.1	0.1	0.0	7.4	1.2	0.0	76.2	841	0	0.0	32.5	0.0	0.0
0.18	1438	12.1	2.3	1.4	12.2	0.0	0.9	70.9	316	69	48.0	14.3	3.1	2.2
0.57	1361	10.4	3.7	2.3	11.4	0.0	0.9	71.2	106	154	69.5	4.8	6.9	3.1
0.98	1296	10.6	3.6	2.7	10.6	0.0	1.1	71.2	81	170	73.6	3.6	7.6	3.3
1.40	1240	10.4	4.0	2.8	10.4	0.0	1.2	71.1	72	181	81.2	3.2	8.2	3.7

COAL #3: SR1=1.256, SR2=0.803(P3) NG reburn, COAL 0.930 kg/h, NOp=782

RT,s	T, K	CO2	CO	H2	H2O	O2	CH4	N2	NO	HCN	NH3	%NO	%HCN	%NH3
0.00	1464	12.8	0.1	0.0	6.3	4.1	0.0	76.8	782	0	0.0	35.5	0.0	0.0
0.16	1439	10.6	2.7	1.9	7.0	0.0	2.3	75.2	256	101	26.5	12.7	5.0	1.3
0.49	1411	9.9	3.6	1.9	10.3	0.0	0.4	73.2	120	105	47.2	6.1	5.3	2.4
0.84	1331	10.3	3.2	1.7	11.3	0.0	0.3	73.2	89	87	57.7	4.5	4.5	2.9
1.20	1269	10.1	3.2	1.7	11.2	0.0	0.4	73.3	76	87	74.1	3.8	4.4	3.8

COAL #6:SR1=1.178 O2 add,SR2=0.795(P3)NG reburn,COAL 1.092kg/h,NOp=1142

RT,s	T, K	CO2	CO	H2	H2O	O2	CH4	N2	NO	HCN	NH3	%NO	%HCN	%NH3
0.00	1514	17.5	0.1	0.0	7.9	3.0	0.0	71.5	1142	0	0.0	41.3	0.0	0.0
0.17	1446	13.2	3.9	2.5	8.2	0.0	2.4	69.5	230	136	36.1	9.2	5.5	1.5
0.52	1352	12.7	4.4	2.8	10.8	0.0	0.9	68.3	156	176	59.1	6.4	7.2	2.4
0.90	1293	12.4	4.6	3.0	10.8	0.0	0.8	68.3	112	187	54.3	4.6	7.7	2.2
1.30	1238	12.4	4.6	3.1	10.6	0.0	0.8	68.4	72	202	70.8	2.9	8.3	2.9

COAL #9: SR1=1.108, SR2=0.715(P3) NG reburn, COAL 0.973 kg/h, NOp=854

RT,s	T, K	CO2	CO	H2	H2O	O2	CH4	N2	NO	HCN	NH3	%NO	%HCN	%NH3
0.00	1482	14.4	0.1	0.0	7.1	1.9	0.0	76.4	854	0	0.0	34.3	0.0	0.0
0.17	1447	10.9	2.8	2.2	7.3	0.0	2.7	73.8	232	113	33.1	10.4	5.1	1.5
0.53	1361	10.6	3.3	2.4	9.7	0.0	1.3	72.4	131	143	43.9	6.0	6.5	2.0
0.91	1298	10.6	3.4	2.7	9.5	0.0	1.3	72.4	104	147	46.6	4.8	6.7	2.1
1.30	1228	10.7	3.3	2.6	9.6	0.0	1.3	72.3	72	159	57.1	3.3	7.3	2.6

LOW TEMPERATURE TEST:
COAL #10: SR1=1.104, SR2=0.862(P3)NG reburn, COAL 0.973 kg/h, NOp=831

RT,s	T, K	CO2	CO	H2	H2O	O2	CH4	N2	NO	HCN	NH3	%NO	%HCN	%NH3
0.00	1485	14.6	0.1	0.0	7.1	1.9	0.0	76.3	831	0	0.0	33.4	0.0	0.0
0.17	1448	11.4	1.5	0.5	9.6	0.2	0.4	76.4	330	58	19.1	14.7	2.6	0.9
0.54	1380	10.9	2.1	0.9	9.3	0.1	0.4	76.3	150	112	40.0	6.7	5.0	1.8
0.92	1312	11.0	2.1	1.0	9.3	0.0	0.4	76.2	136	86	38.6	6.1	3.8	1.7
1.32	1239	11.0	2.1	1.0	9.2	0.0	0.4	76.2	123	106	47.1	5.5	4.7	2.1

HIGH TEMPERATURE TEST:
COAL #7:SR1=1.120 high T,SR2=0.863(P3)NG reburn,COAL 1.660kg/h,NOp=1009

RT,s	T, K	CO2	CO	H2	H2O	O2	CH4	N2	NO	HCN	NH3	%NO	%HCN	%NH3
0.00	1657	14.5	0.0	0.0	7.0	2.1	0.0	76.3	1	0	0.0	41.1	0.0	0.0
0.09	1612	11.8	3.2	1.4	9.0	0.1	0.5	73.8	396	80	28.6	17.3	3.5	1.3
0.29	1568	11.7	3.4	1.0	10.4	0.0	0.0	73.5	327	24	31.9	14.3	1.1	1.4
0.49	1513	11.7	3.5	1.1	10.4	0.0	0.0	73.3	269	11	27.2	11.8	0.5	1.2
0.69	1456	11.5	3.7	1.3	10.2	0.0	0.0	73.3	216	7.6	26.4	9.5	0.3	1.2

SPECIAL REBURNING TESTS:

Fuel Lean Reburning:
COAL #4: SR1=1.240, SR2=1.031(P3) NG reburn, COAL 0.930 kg/h, NOp=814

RT,s	T, K	CO2	CO	H2	H2O	O2	CH4	N2	NO	HCN	NH3	%NO	%HCN	%NH3
0.00	1424	13.0	0.1	0.0	6.4	3.9	0.0	76.6	814	0.0	0.0	36.5	0.0	0.0
0.17	1383	11.3	0.4	0.2	8.5	0.8	0.1	78.6	412	2.1	2.2	20.0	0.1	0.1
0.54	1347	11.4	0.2	0.1	8.8	0.6	0.0	78.8	360	1.6	2.4	17.5	0.1	0.1
0.91	1287	11.5	0.2	0.2	8.8	0.6	0.0	78.8	383	1.9	1.6	18.6	0.1	0.1
1.31	1208	11.6	0.1	0.1	8.8	0.6	0.0	78.7	410	2.1	2.0	19.9	0.1	0.1

CO Reburning:
COAL #5: SR1=1.241, SR2=0.908(P3) CO reburn, COAL 0.840 kg/h, NOp=833

RT,s	T, K	CO2	CO	H2	H2O	O2	CH4	N2	NO	HCN	NH3	%NO	%HCN	%NH3
0.00	1536	13.1	0.1	0.0	6.4	3.9	0.0	76.6	833	0.0	0.0	37.4	0.0	0.0
0.17	1567	18.5	5.3	0.6	5.0	0.0	0.0	70.6	660	9.3	3.7	33.8	0.5	0.2
0.52	1442	19.3	3.4	0.4	5.3	0.0	0.0	71.6	635	5.9	4.9	32.1	0.3	0.3
0.90	1354	19.4	2.9	0.4	5.3	0.0	0.0	72.0	592	4.5	6.5	29.8	0.2	0.3
1.30	1274	19.2	2.8	0.4	5.3	0.0	0.0	72.3	511	2.9	12.3	25.6	0.2	0.6

H_2 Reburning:
COAL #8: SR1=1.225, SR2=0.899(P3) H2 reburn, COAL 0.960 kg/h, NOp=814

RT,s	T, K	CO2	CO	H2	H2O	O2	CH4	N2	NO	HCN	NH3	%NO	%HCN	%NH3
0.00	1512	13.1	0.1	0.0	6.5	3.7	0.0	76.7	814	0.0	0.0	36.0	0.0	0.0
0.16	1481	7.0	4.0	5.2	11.4	0.0	0.0	72.4	673	6.3	8.2	33.2	0.3	0.4
0.48	1448	8.3	3.0	2.1	14.5	0.0	0.0	72.1	688	4.5	6.6	34.0	0.2	0.3
0.81	1371	8.4	2.9	2.1	14.5	0.0	0.0	72.2	676	3.8	8.0	33.4	0.2	0.4
1.16	1286	8.8	2.7	2.3	14.3	0.0	0.0	72.0	647	4.0	15.9	32.1	0.2	0.8

GAS BURNING TESTS:

A. NO NH_3 DOPING:

GAS RUN 1: SR1=1.100, SR2=0.854(P3) NG reburn, 0.6 SCFM, NOp=31.4

RT,s	T, K	CO2	CO	H2	H2O	O2	CH4	N2	NO	HCN	NH3	%NO	%HCN	%NH3
0.00	1450	8.0	0.0	0.0	17.3	1.7	0.0	73.0	31	0	0.0	0.0	0	0.0
0.13	1402	7.3	1.0	0.8	17.5	0.1	1.2	72.1	22	57	4.0	73.3	194	13.5
0.41	1348	7.3	1.2	1.3	17.6	0.0	0.8	71.7	17	45	5.5	58.0	155	19.0
0.70	1302	7.0	1.6	1.5	17.8	0.0	0.6	71.4	23	53	10.0	80.7	182	34.3
1.00	1250	7.0	1.6	1.5	17.9	0.1	0.5	71.3	21	41	10.0	73.7	142	34.6

GAS RUN 4: SR1=1.08, SR2=0.864(P3) NG reburn, 0.6 SCFM, NOp=33

RT,s	T, K	CO2	CO	H2	H2O	O2	CH4	N2	NO	HCN	NH3	%NO	%HCN	%NH3
0.00	1466	8.0	0.1	0.0	17.2	1.9	0.0	72.9	32.7	0.0	0.0	0.0	0	0.0
0.13	1423	7.8	0.8	0.6	19.0	0.2	0.4	71.3	21.5	22.2	1.8	71.0	73	5.9
0.40	1370	7.5	1.2	1.2	17.8	0.1	0.6	71.5	16.0	48.4	3.3	52.9	160	10.9
0.69	1324	7.4	1.3	1.3	17.9	0.1	0.6	71.4	15.2	53.5	3.9	50.2	177	12.8
0.98	1271	7.4	1.3	1.3	17.9	0.1	0.6	71.3	14.8	49.5	4.3	48.9	164	14.1

GAS RUN 5: SR1=1.132, SR2=0.872(P4) NG reburn, 0.5 SCFM, NOp=24

RT,s	T, K	CO2	CO	H2	H2O	O2	CH4	N2	NO	HCN	NH3	%NO	%HCN	%NH3
0.00	1354	7.9	0.0	0.0	16.8	2.2	0.0	73.1	24.0	1.0	1.1	0.0	0	0.0
0.33	1274	7.5	0.7	0.7	18.0	0.2	0.7	72.3	12.3	24.6	2.1	51.4	103	8.9
0.69	1219	7.4	0.7	0.7	17.8	0.2	0.8	72.4	11.9	24.2	3.0	49.6	101	12.3
1.07	1158	7.4	0.7	0.7	17.8	0.1	0.8	72.5	11.5	20.5	2.2	47.9	85	9.2

GAS RUN 6: SR1=1.132, SR2=0.872(P3) NG reburn, 0.5 SCFM, NOp=24

RT,s	T, K	CO2	CO	H2	H2O	O2	CH4	N2	NO	HCN	NH3	%NO	%HCN	%NH3
0.00	1382	7.9	0.0	0.0	16.8	2.2	0.0	73.1	24.0	1.0	1.1	0.0	0	0.0
0.16	1349	7.4	0.7	0.6	18.0	0.1	0.8	72.4	11.5	14.5	2.7	47.8	60	11.3
0.50	1297	7.4	0.8	0.8	18.3	0.1	0.5	72.2	9.4	27.0	5.2	39.3	113	21.9
0.85	1246	7.3	0.8	0.7	18.2	0.1	0.6	72.2	12.7	37.3	2.7	52.9	156	11.3
1.21	1191	7.3	0.8	0.7	18.3	0.1	0.6	72.2	11.9	34.3	2.5	49.5	143	10.2

GAS RUN 7: SR1=1.132, SR2=0.872(P2) NG reburn, 0.5 SCFM, NOp=24

RT,s	T, K	CO2	CO	H2	H2O	O2	CH4	N2	NO	HCN	NH3	%NO	%HCN	%NH3
0.00	1392	7.9	0.0	0.0	16.8	2.2	0.0	73.1	24.0	1.0	1.1	0.0	0	0.0
0.16	1366	7.7	0.8	0.6	18.5	0.1	0.4	71.9	18.7	24.2	2.0	78.7	102	8.2
0.32	1338	7.4	0.9	0.7	18.2	0.1	0.6	72.1	16.0	31.9	4.6	66.7	133	19.2
0.66	1281	7.4	0.9	0.8	18.1	0.1	0.6	72.1	13.1	40.9	2.4	54.8	171	9.9
1.39	1179	7.4	1.0	0.9	17.7	0.1	0.7	72.2	13.2	37.3	2.6	55.0	156	11.0

B. NH_3 DOPING:

GAS RUN 2: SR1=1.104, SR2=0.857(P3) NG reburn, 0.6 SCFM, NOp=715

RT,s	T, K	CO2	CO	H2	H2O	O2	CH4	N2	NO	HCN	NH3	%NO	%HCN	%NH3
0.00	1440	7.9	0.0	0.0	17.2	1.8	0.0	73.0	715	6	1.2	0.0	0	0.0
0.13	1401	7.4	0.9	0.7	18.1	0.1	0.9	71.9	344	68	9.7	51.3	10	1.4
0.41	1352	7.3	1.1	1.1	18.4	0.1	0.5	71.4	249	138	22.3	37.4	21	3.4
0.70	1304	7.3	1.2	1.1	18.3	0.1	0.5	71.4	217	146	23.3	32.5	22	3.5
1.00	1249	7.3	1.2	1.2	18.2	0.1	0.6	71.4	205	143	25.6	30.7	21	3.9

GAS RUN 3: SR1=1.099, SR2=0.860(P3) NG reburn, 0.6 SCFM, NOp=153

RT,s	T, K	CO2	CO	H2	H2O	O2	CH4	N2	NO	HCN	NH3	%NO	%HCN	%NH3
0.00	1455	8.1	0.0	0.0	17.3	1.7	0.0	72.9	153	0.0	0.0	0.0	0	0.0
0.13	1407	7.5	1.0	0.8	17.7	0.1	1.0	71.9	85.6	50.3	4.1	60.1	35	2.9
0.41	1353	7.4	1.2	1.2	18.1	0.1	0.6	71.4	63.1	75.1	7.9	44.6	53	5.6
0.70	1305	7.3	1.3	1.3	18.0	0.1	0.6	71.4	58.2	76.0	10.1	41.1	54	7.1
1.00	1254	7.3	1.3	1.3	18.1	0.1	0.5	71.3	56.5	76.4	11.2	40.0	54	7.9

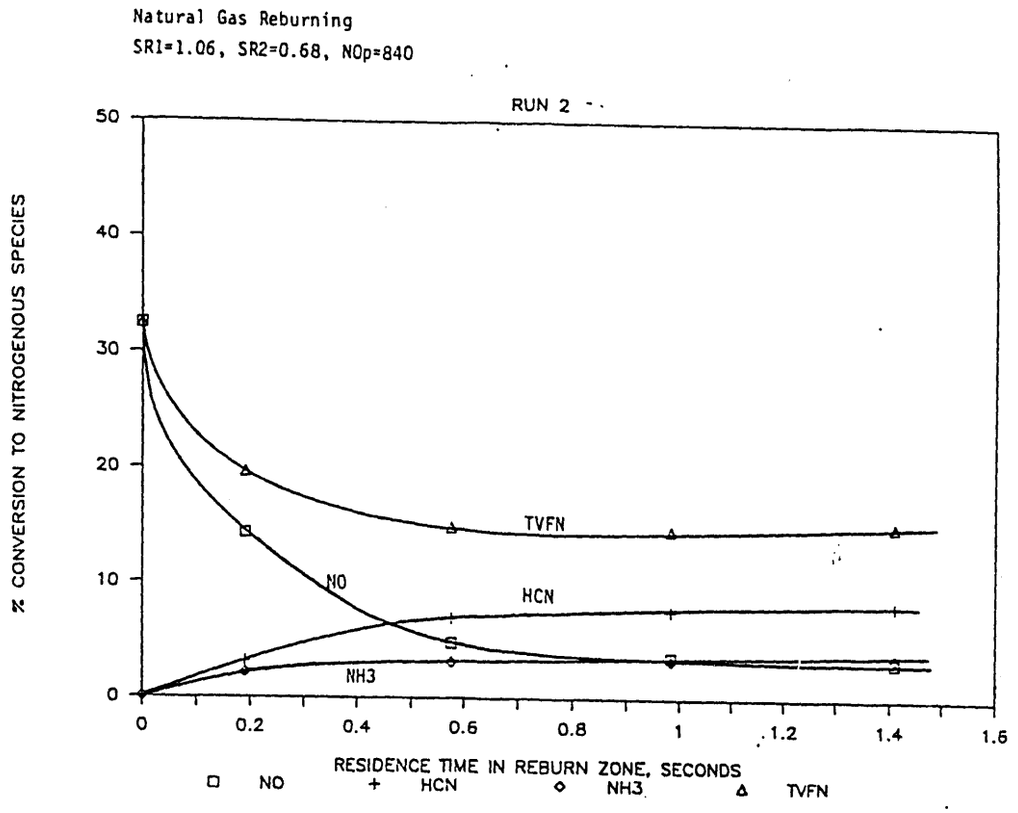

FIGURE 1. Coal Burning Test #2, SR2=0.68

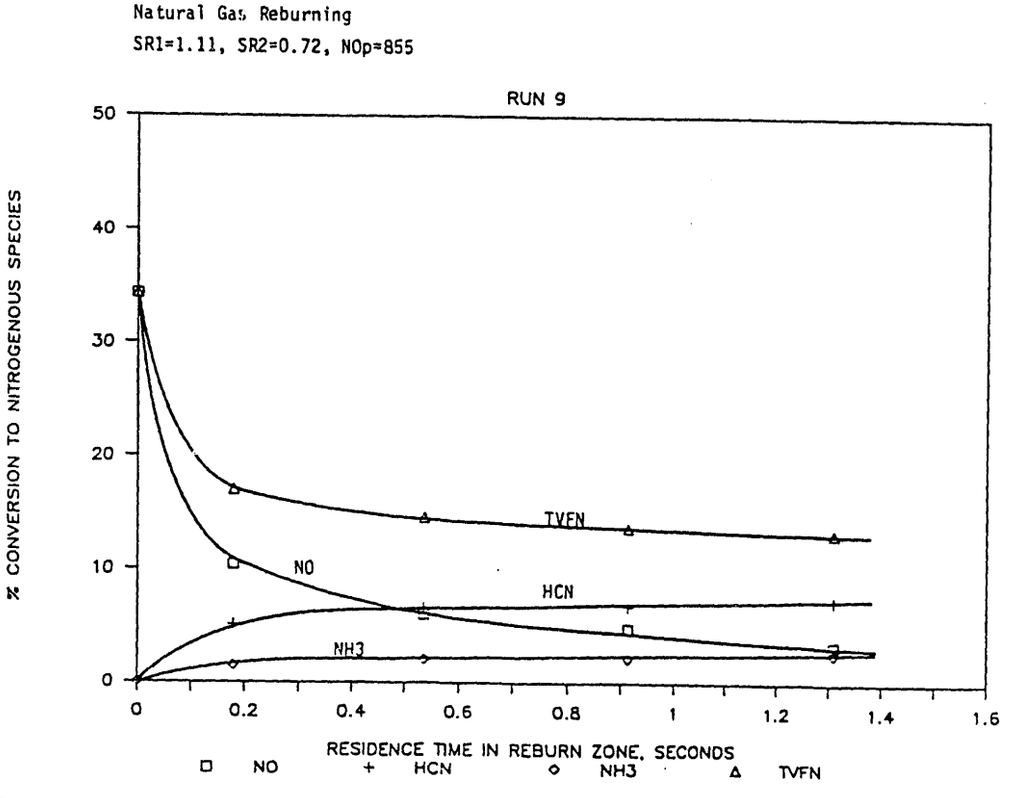

FIGURE 2. Coal Burning Test #9, SR2=0.72

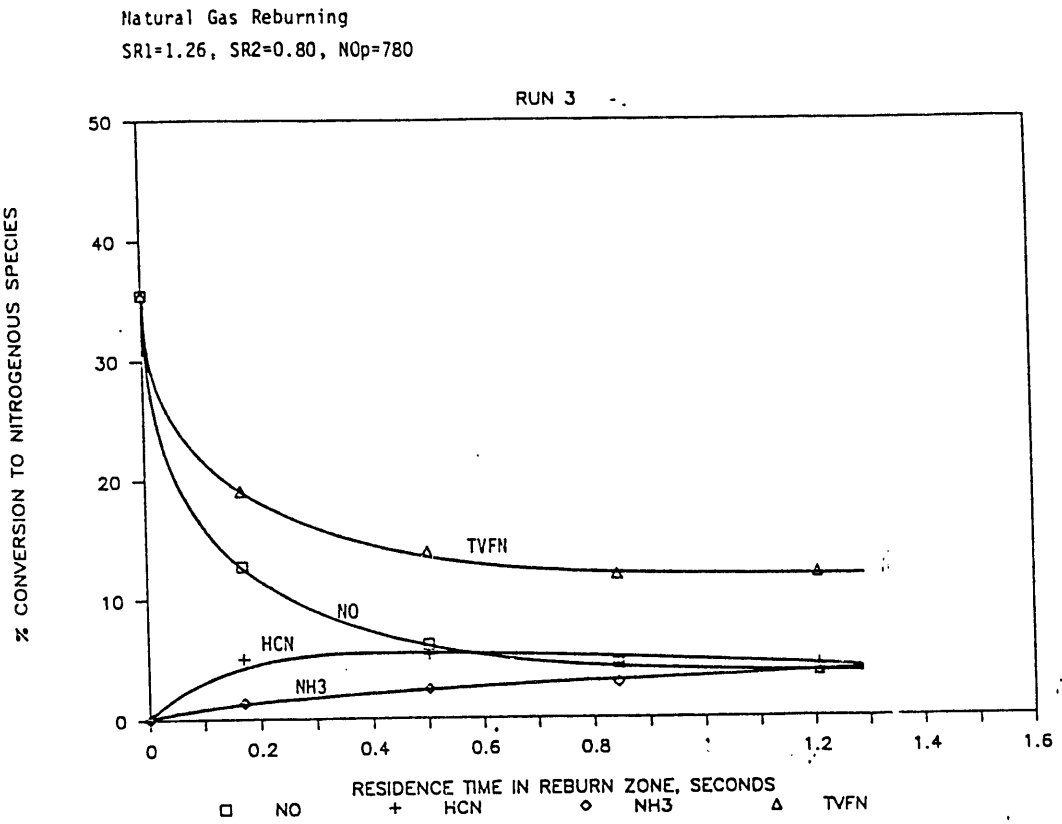

FIGURE 3. Coal Burning Test #3, SR2=0.80

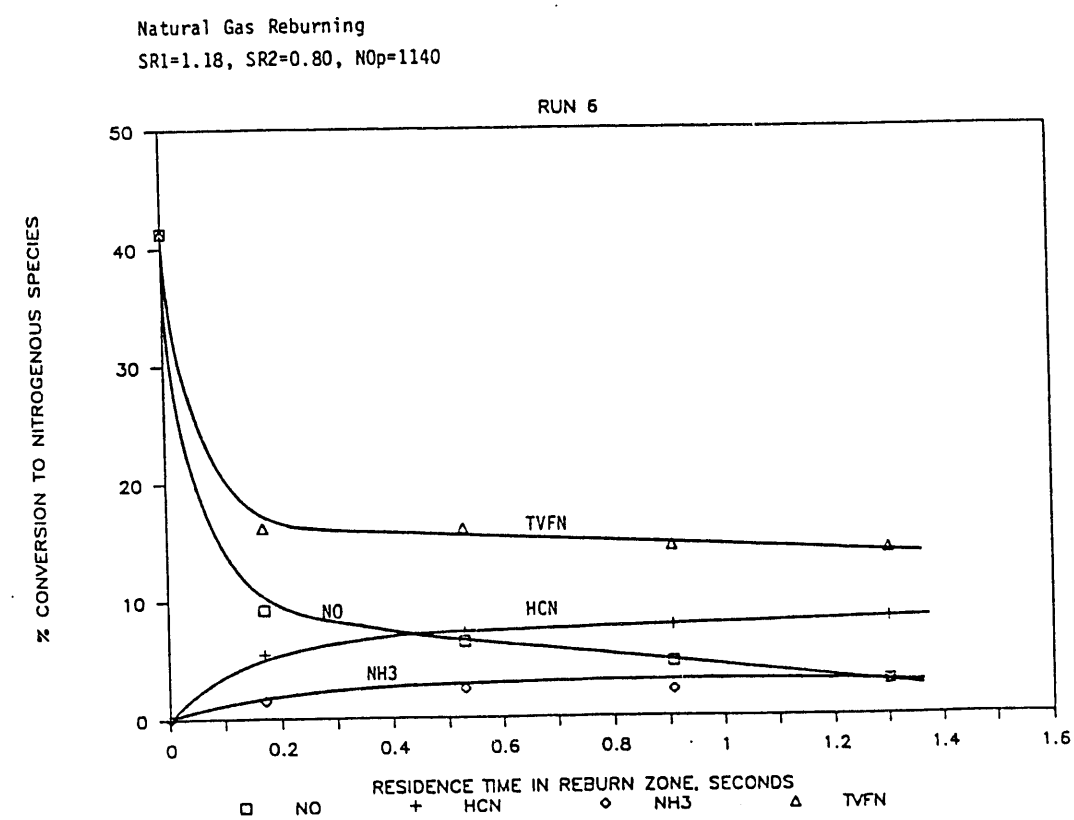

FIGURE 4. Coal Burning Test #6, SR2=0.8, 02 Enrichment in Primary Zone

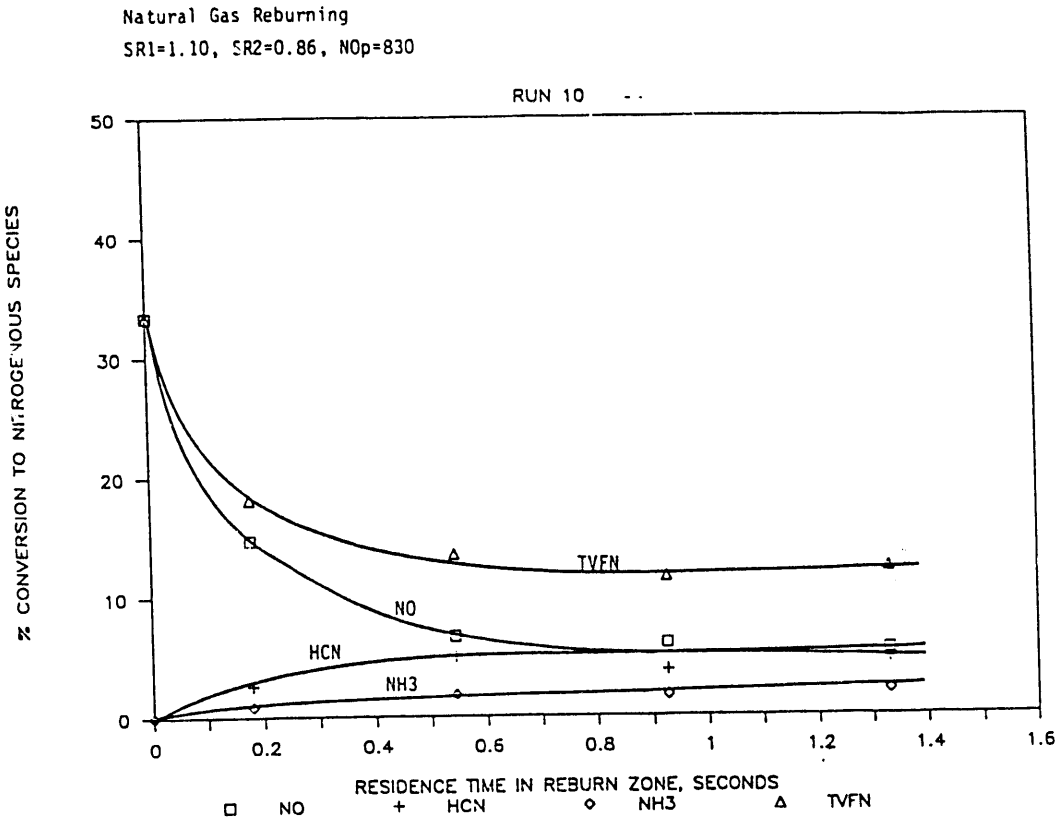

FIGURE 5. Coal Burning Test #10, SR2=0.86
Reburn Zone Entrance Temperature at 1485 K

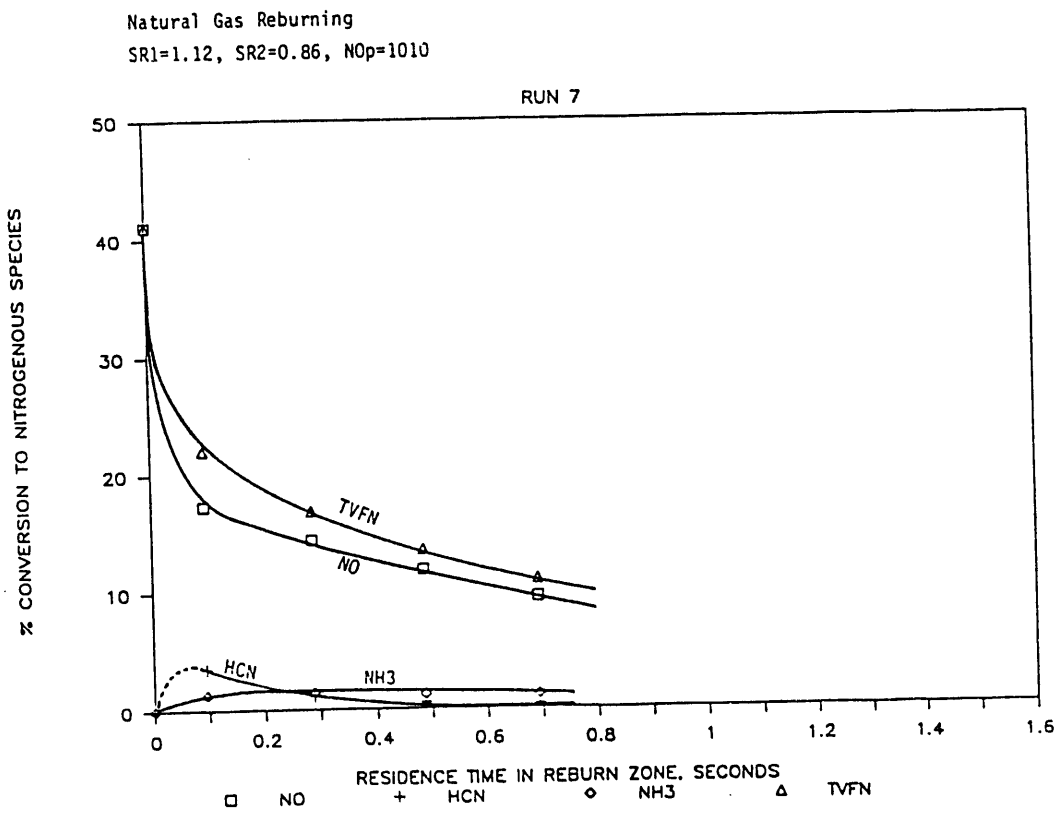

FIGURE 6. Coal Burning Test #7, SR2=0.86
Reburn Zone Entrance Temperature at 1657 K

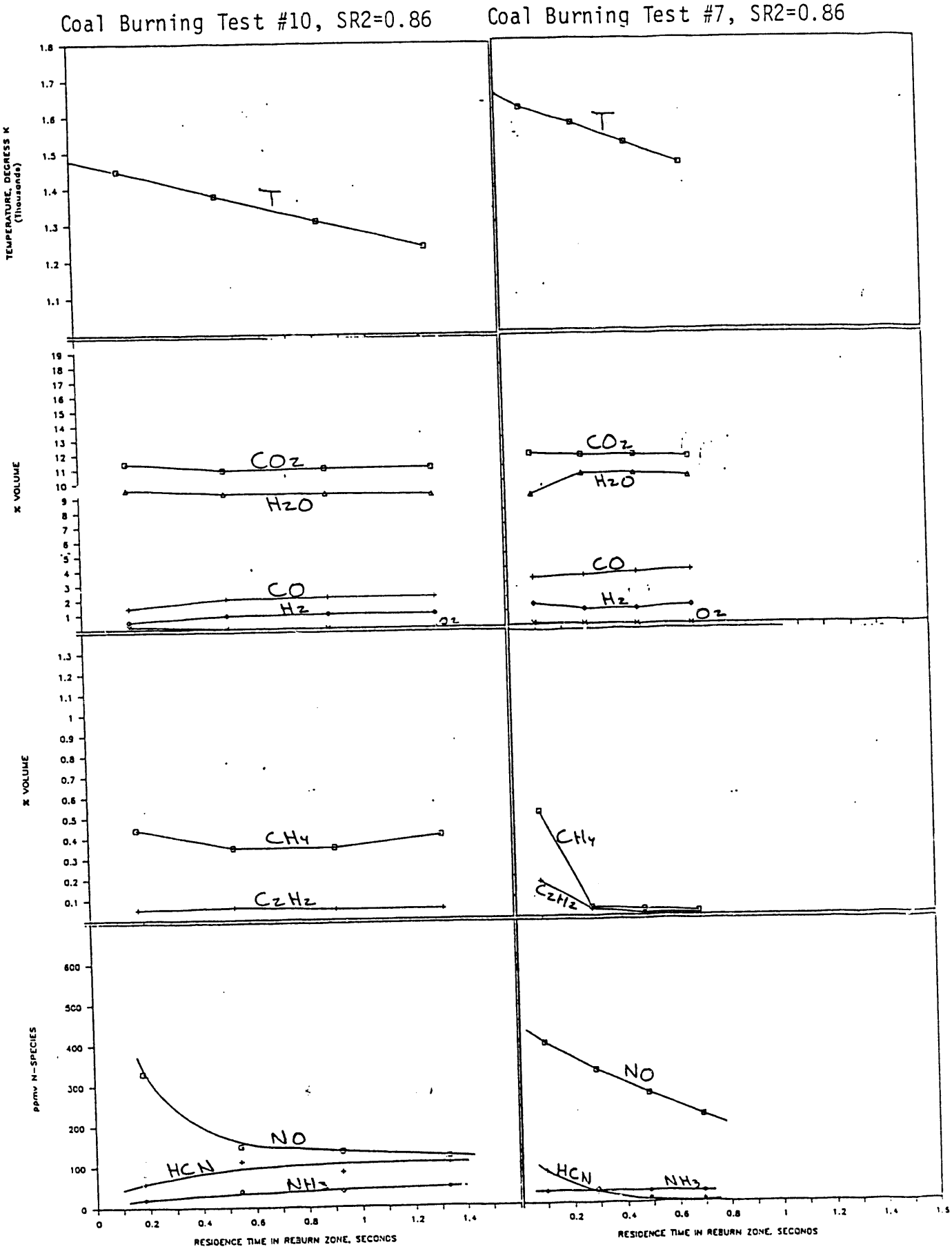

FIGURE 7. Detailed Species Profiles

(a) T2=1485 K

Detailed Species Profiles

(b) T2=1657 K

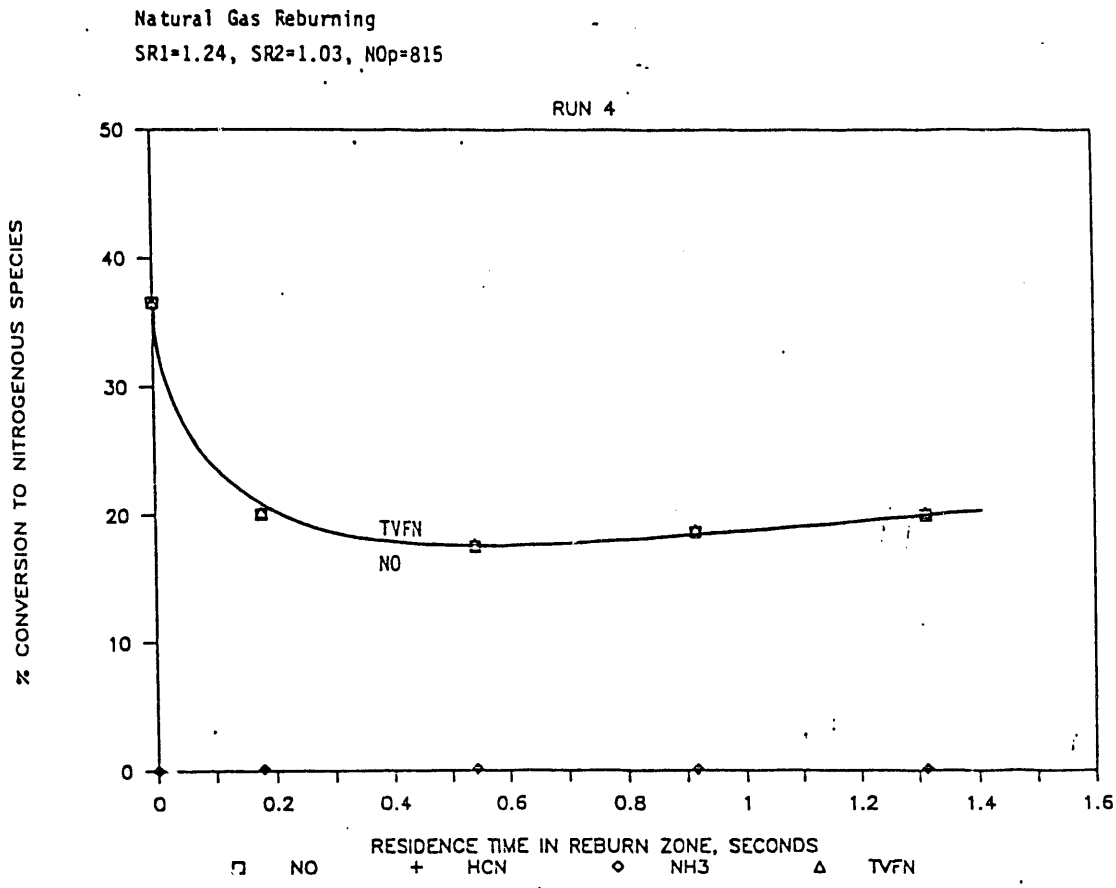

FIGURE 8. Fuel Lean Reburning: SR1=1.24, SR2=1.03

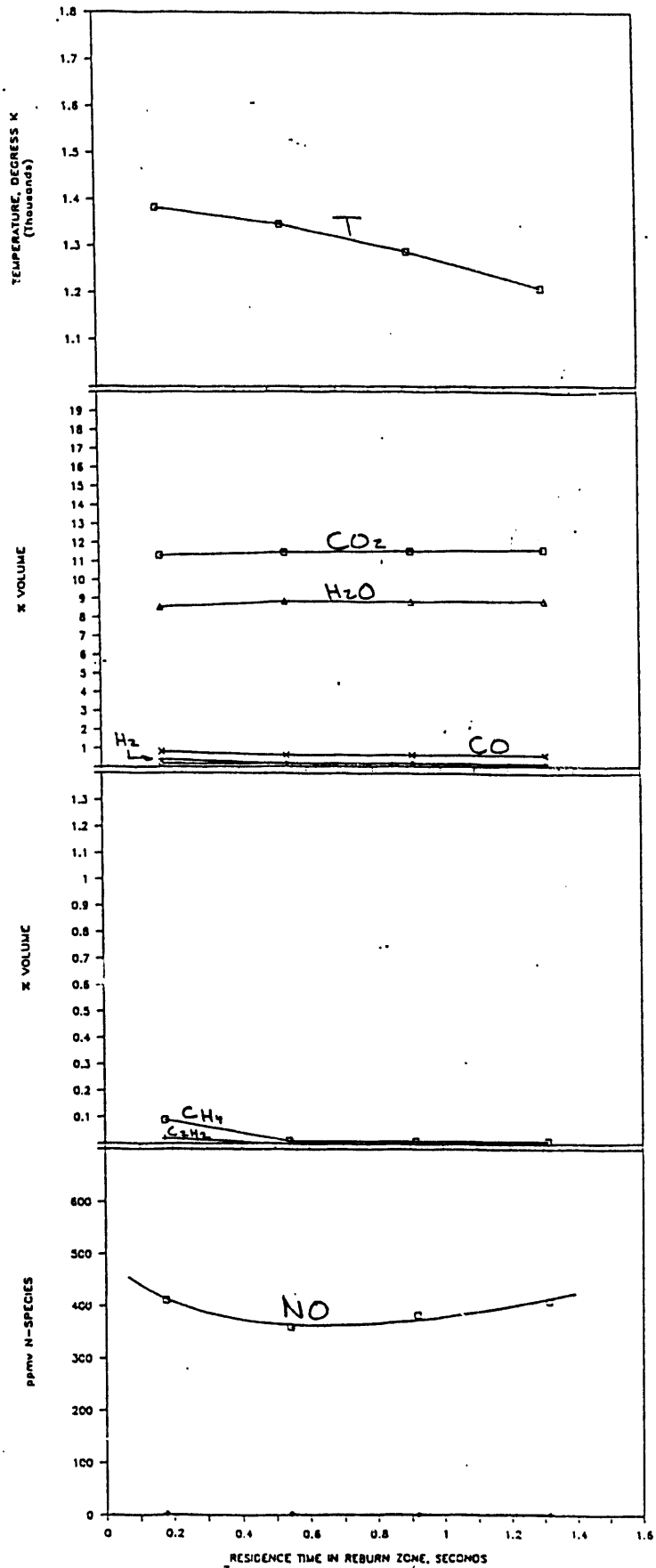

FIGURE 9. Detailed Species Profiles
Fuel Lean Reburning
SR1=1.24, SR2=1.03

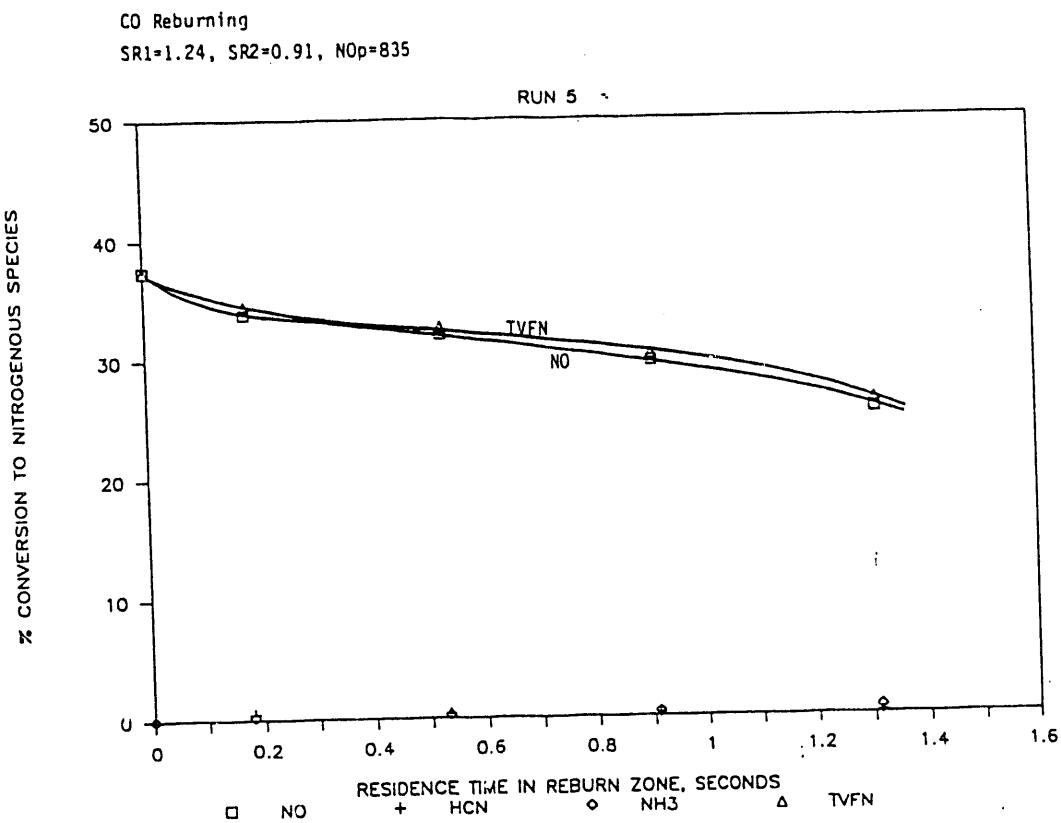

FIGURE 10. Reburning with CO, Utah Bituminous Coal Primary Fuel

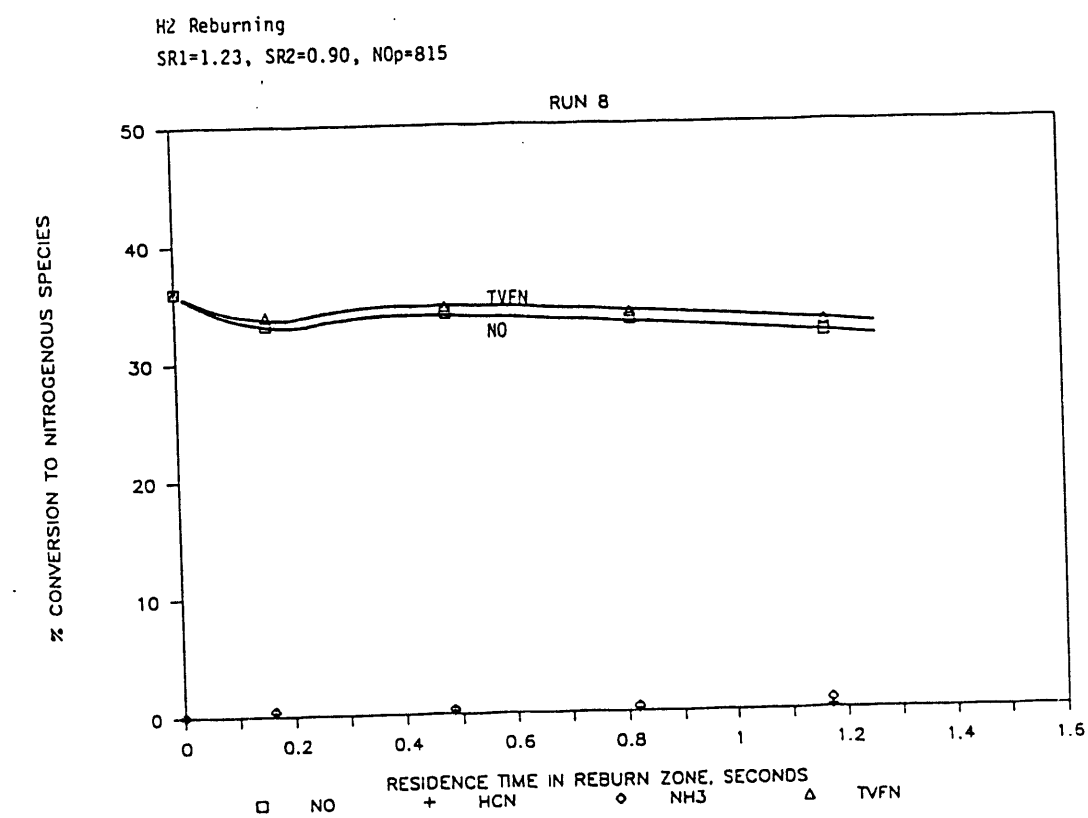

FIGURE 11. Reburning with H2, Utah Bituminous Coal Primary Fuel

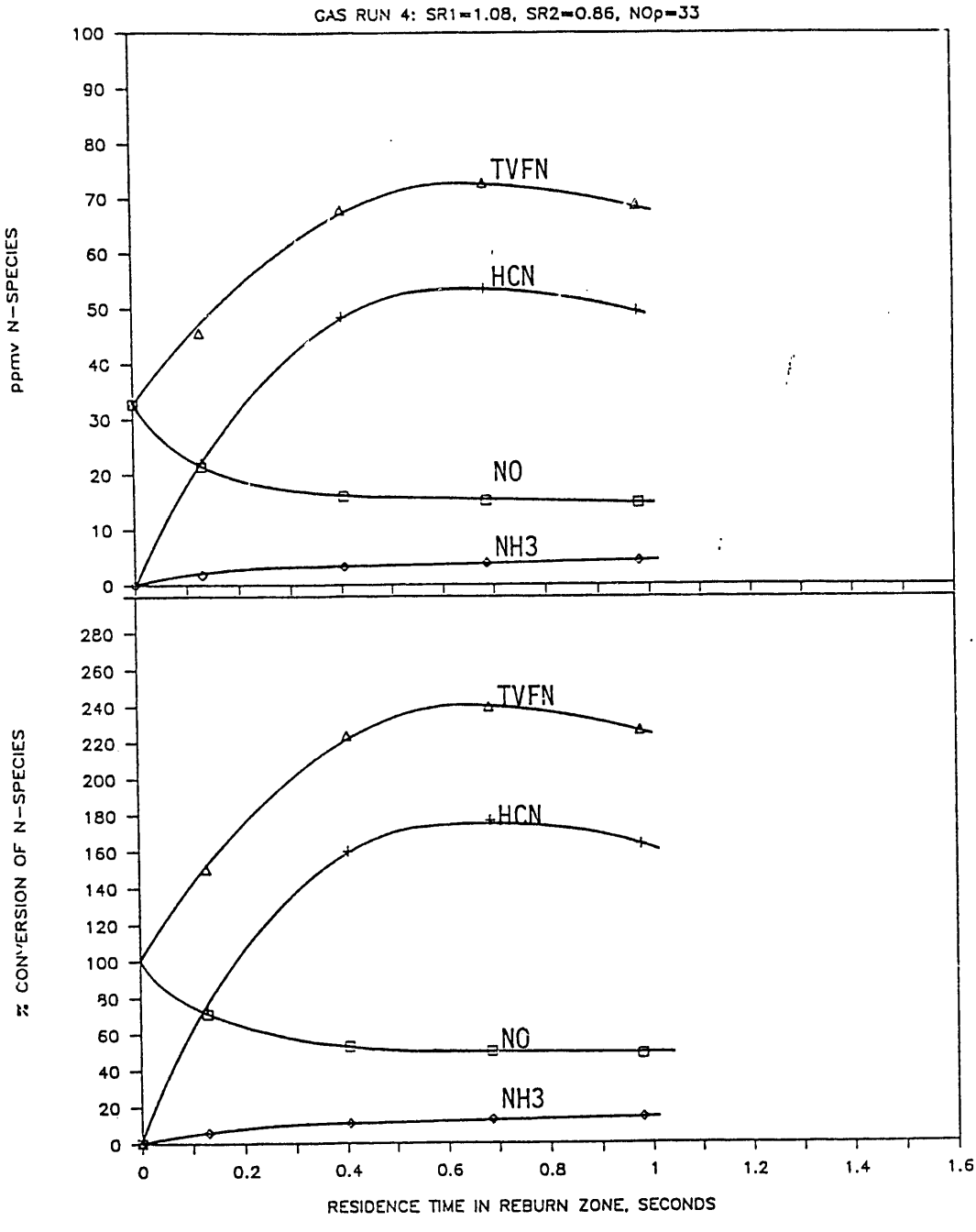

FIGURE 12. Gas Burning Test #4

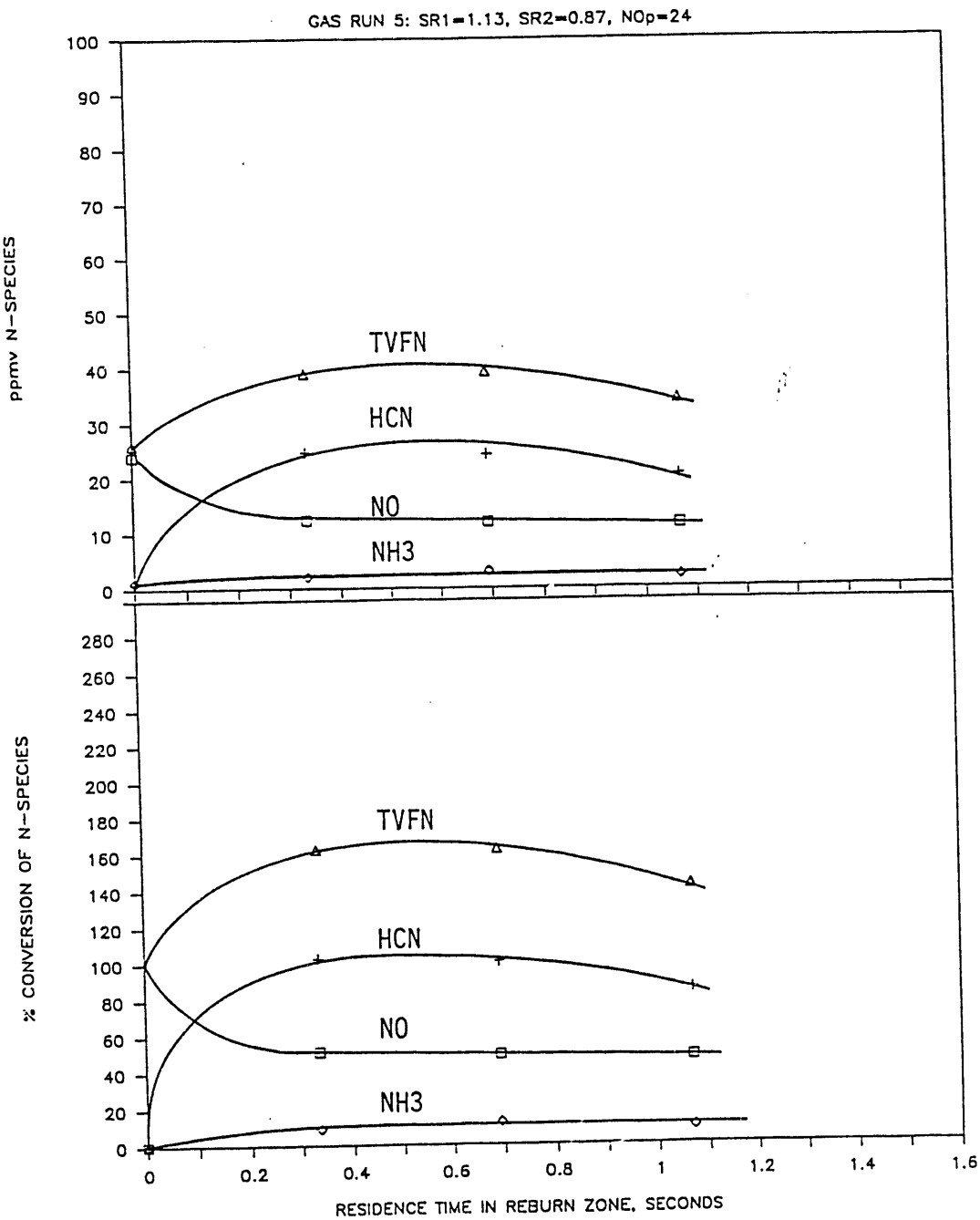

FIGURE 13. Gas Burning Test #5

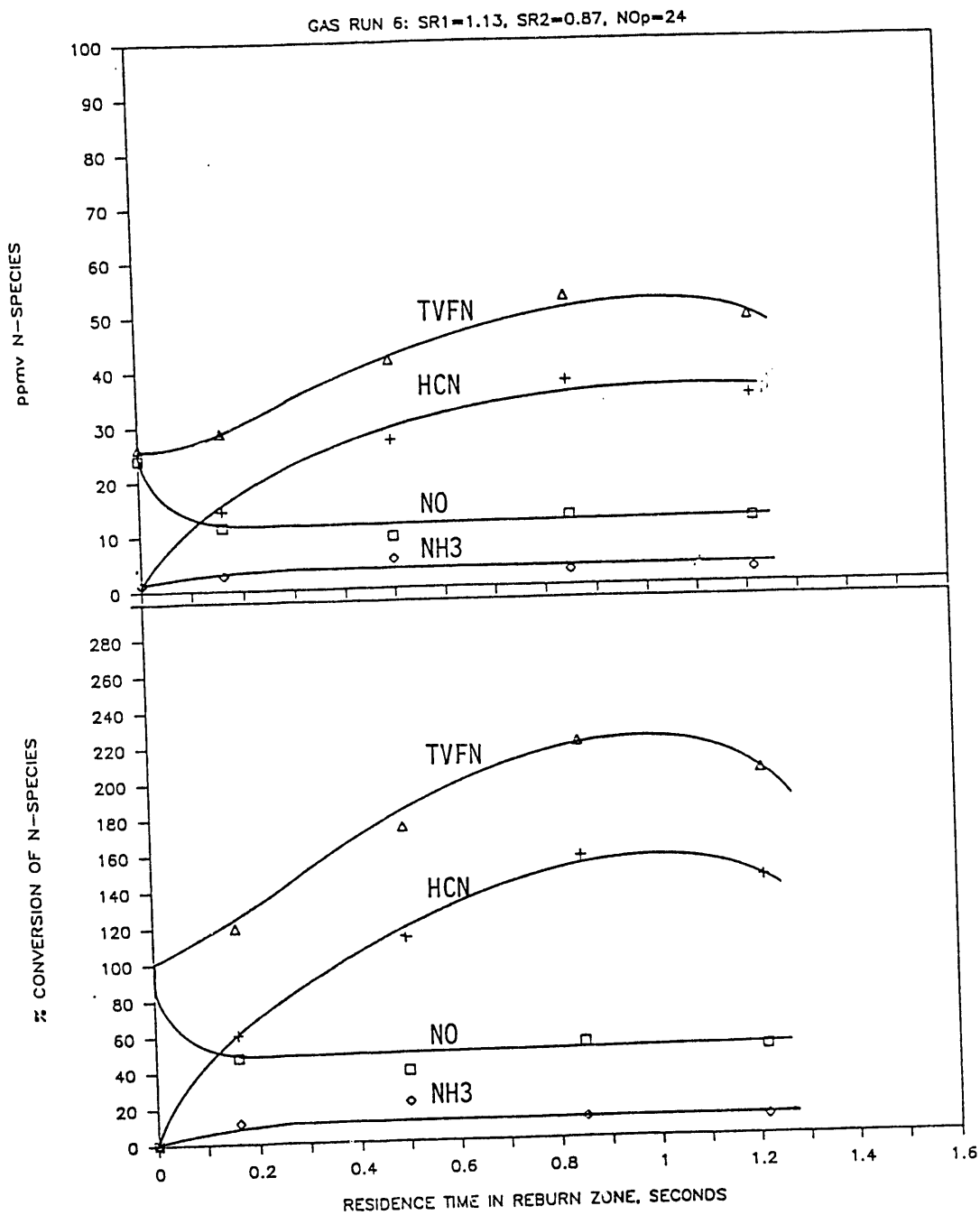

FIGURE 14. Gas Burning Test #6

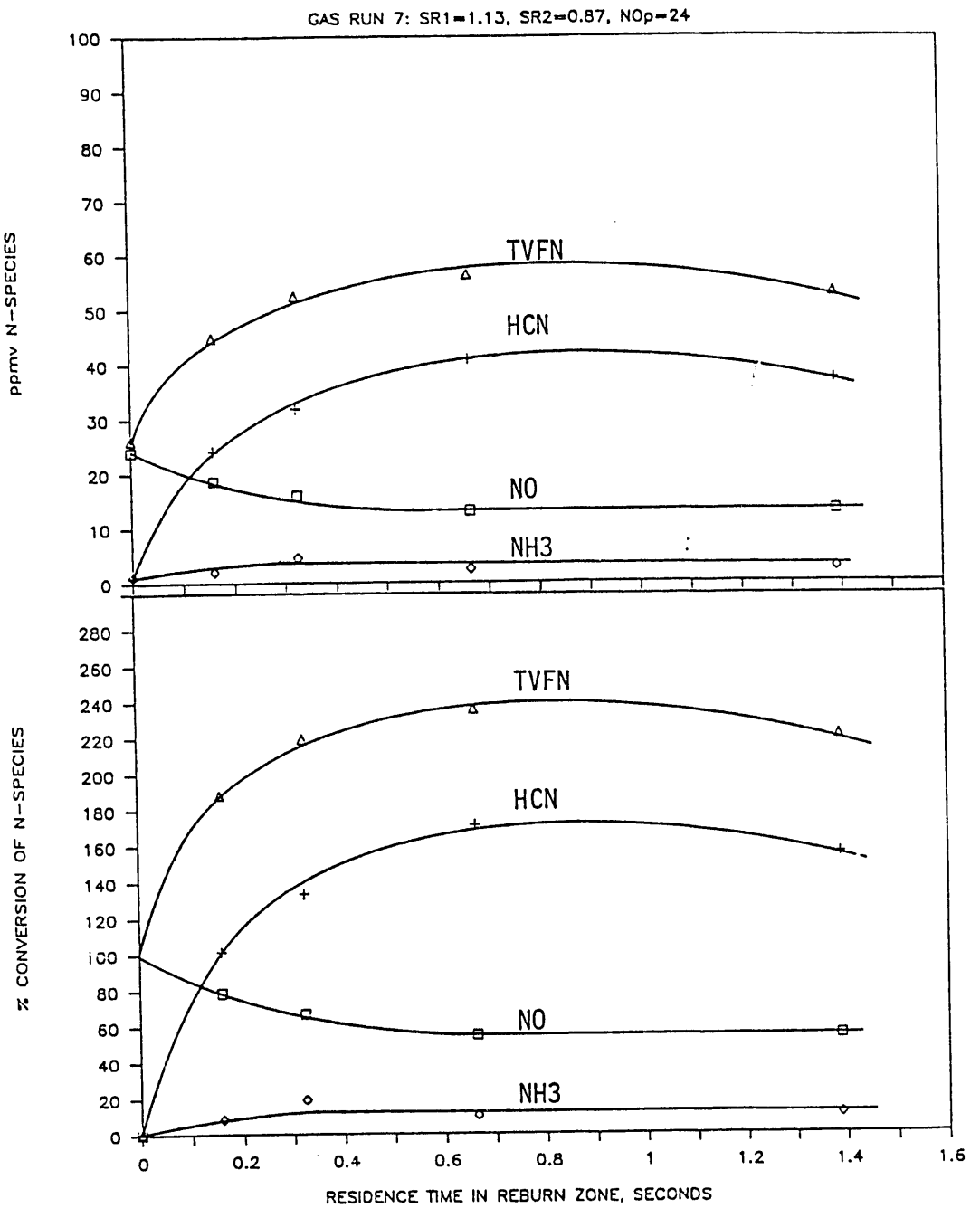

FIGURE 15. Gas Burning Test #7

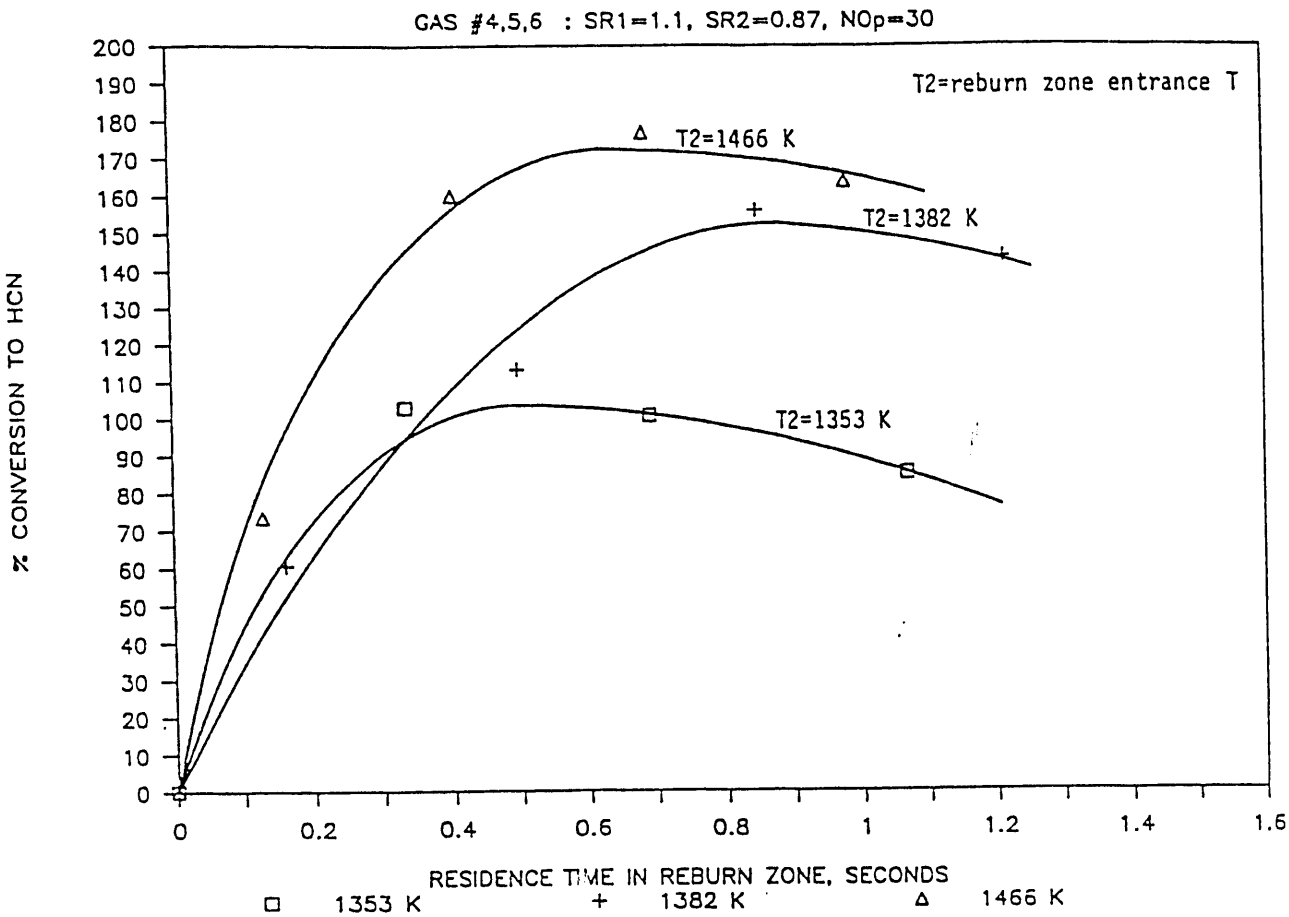

FIGURE 16 . Effect of Reburn Zone Entrance Temperature on HCN Formation

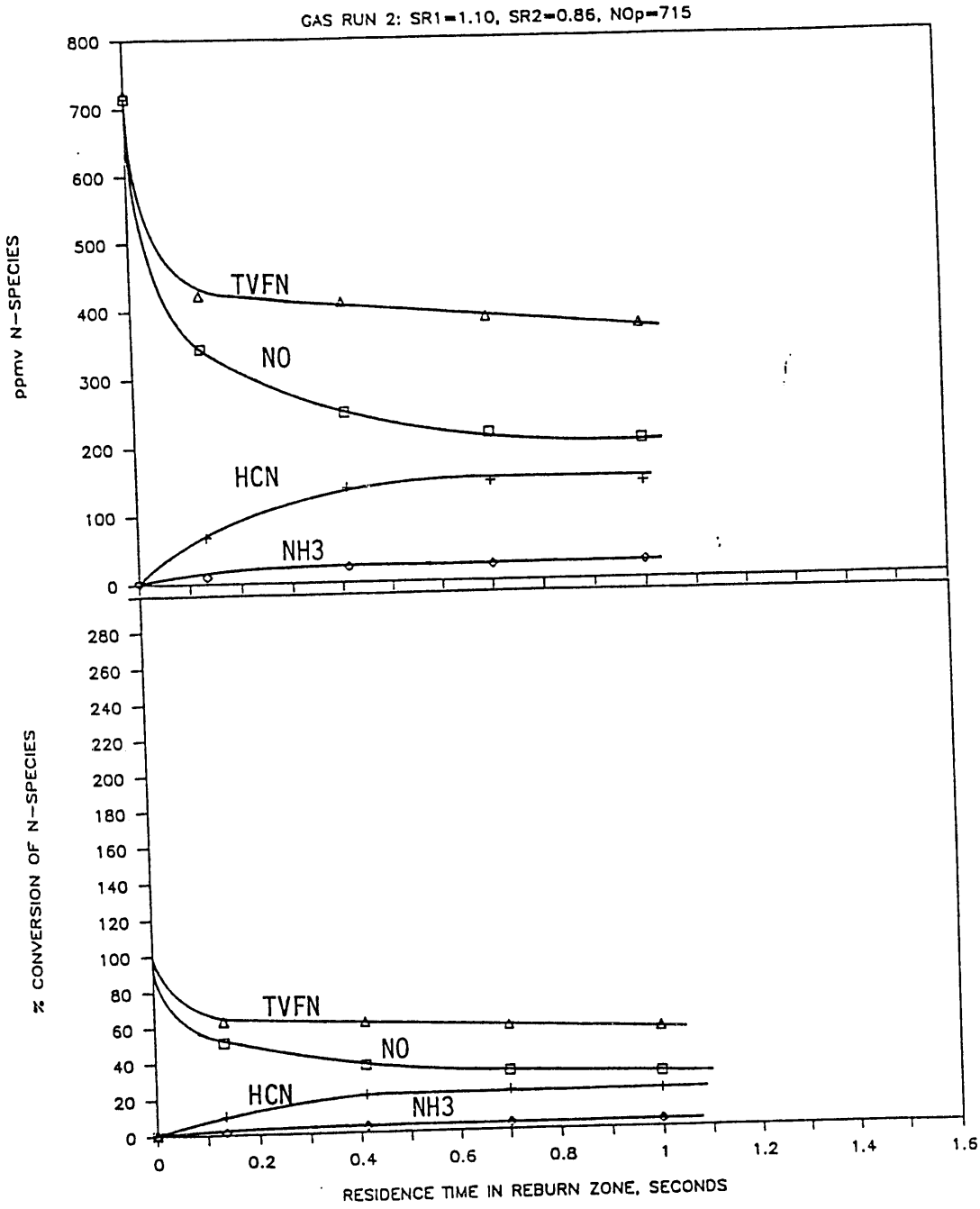

FIGURE 17. Gas Burning Test #2, Natural Gas/NH3 Primary Fuel

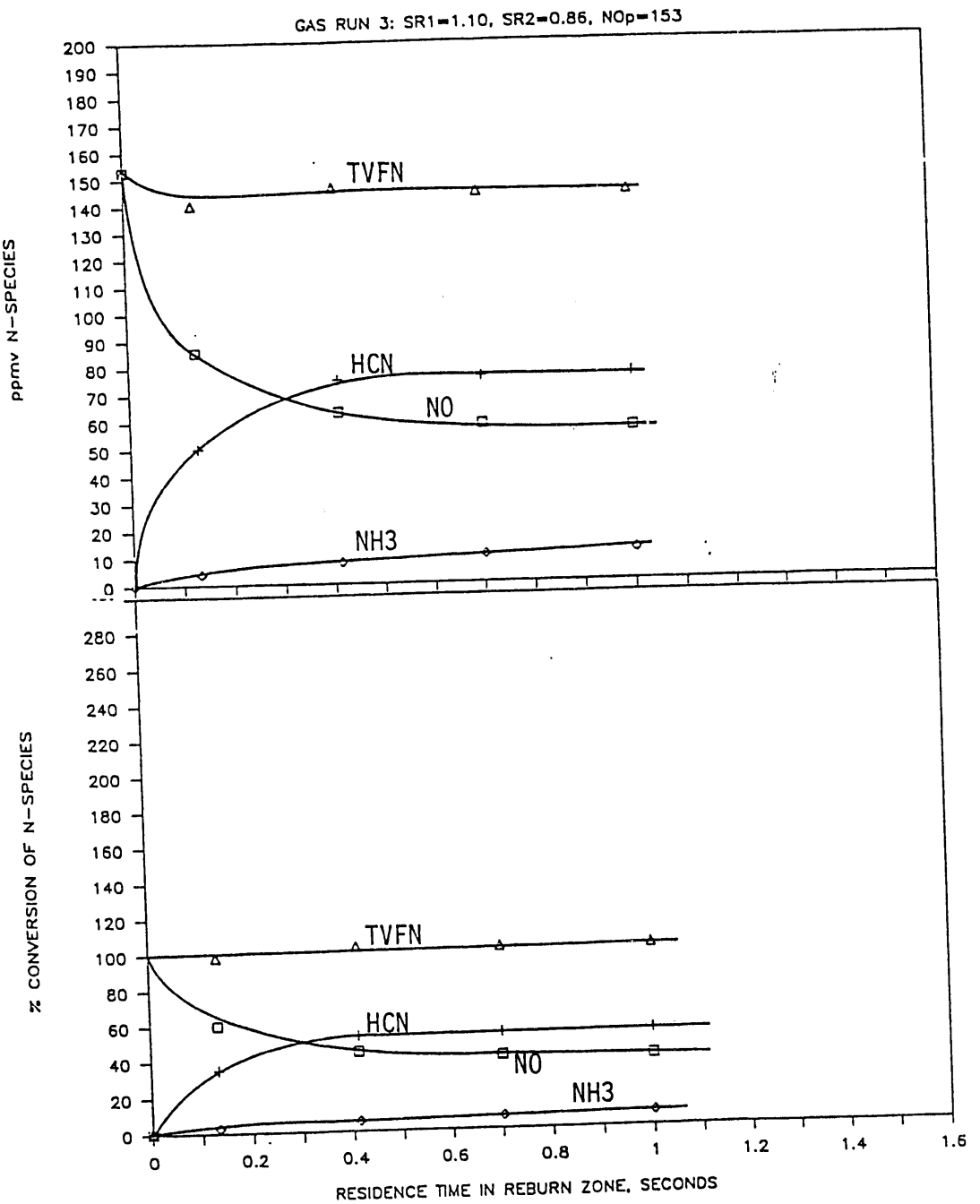

FIGURE 18. Gas Burning Test #3, Natural Gas/NH3 Primary Fuel

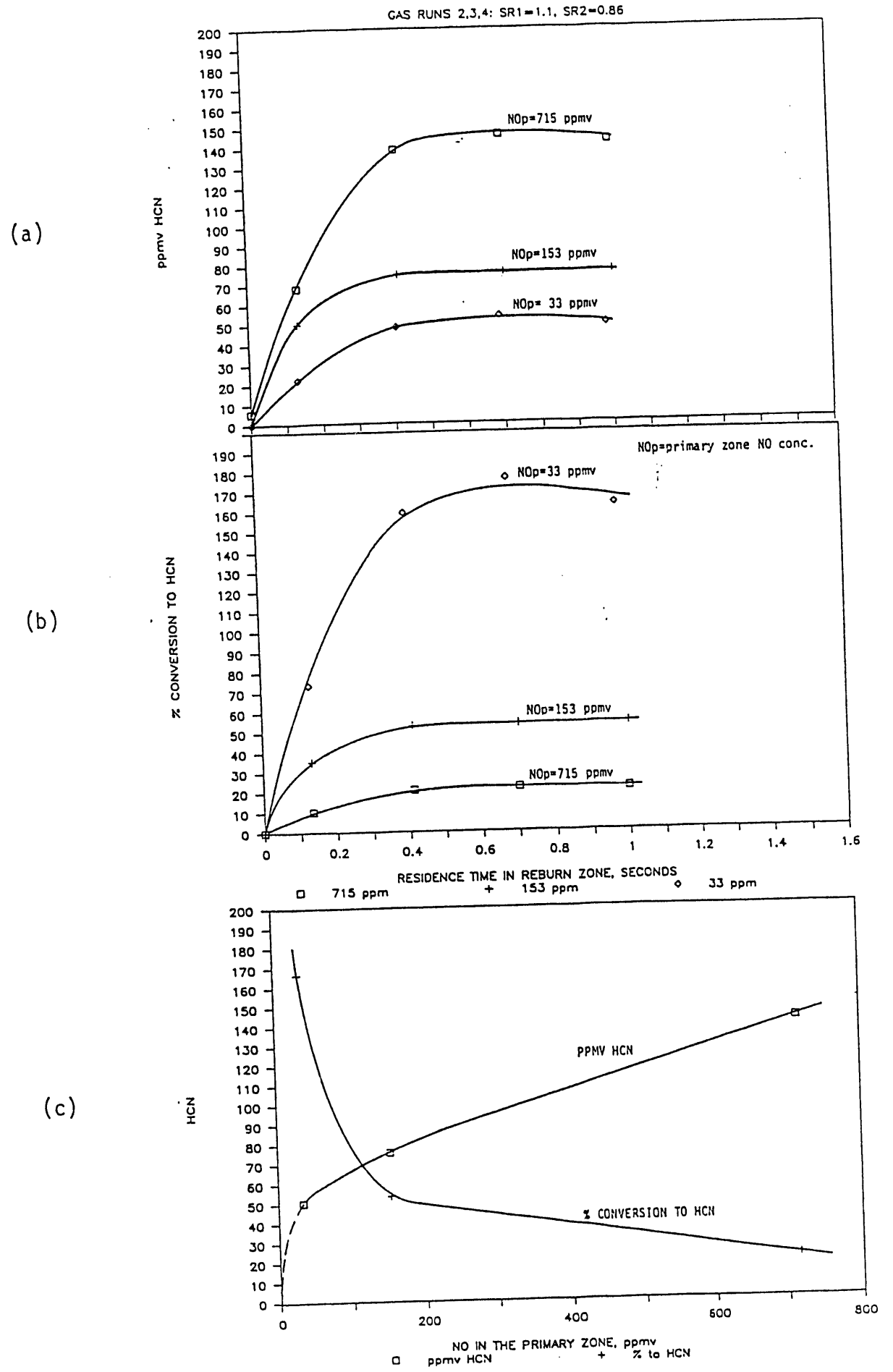

FIGURE 19. Effect of Primary NO Concentration on HCN Formation

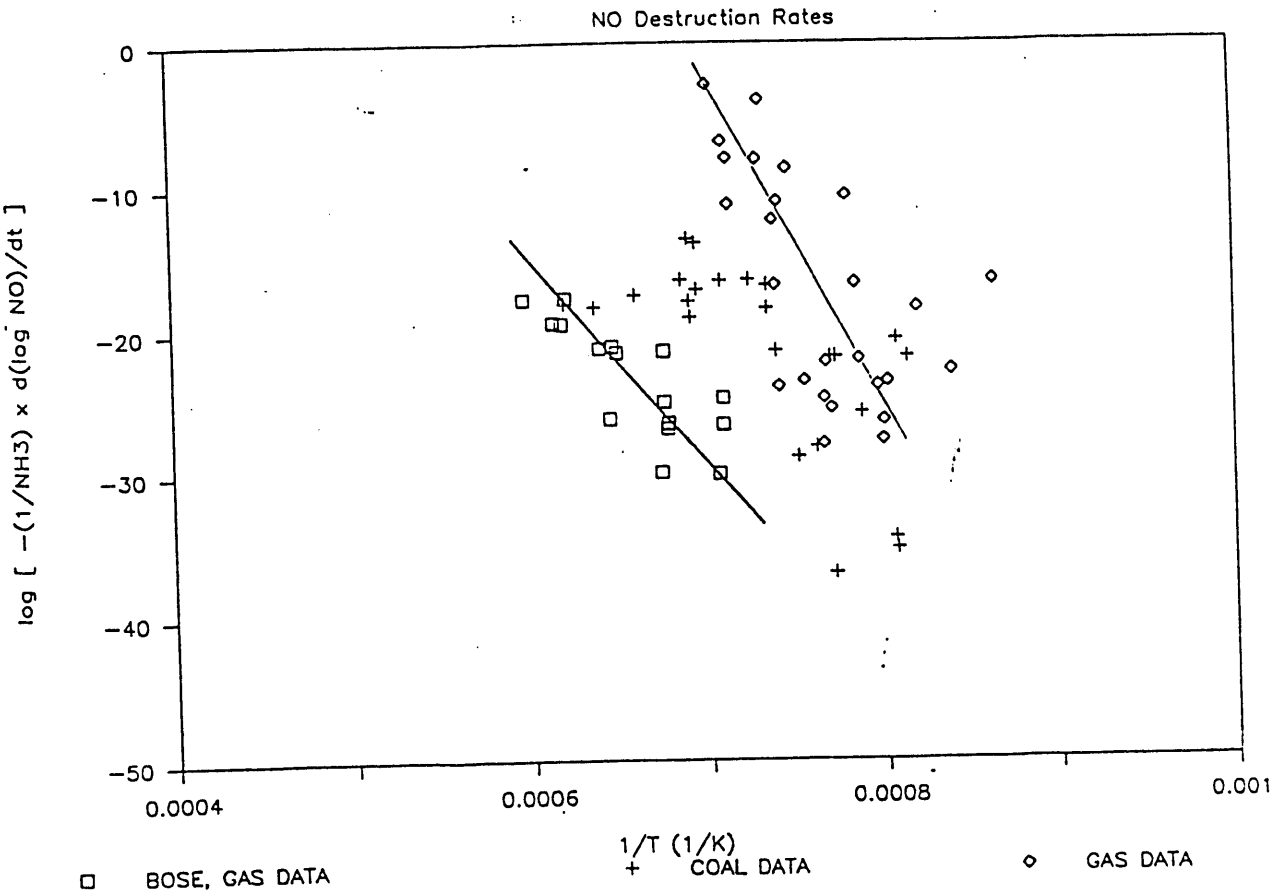

FIGURE 20. NO Decay Rates Based on NO + NHi Reactions

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