INFLUENCE OF DESIGN VARIABLES ON THE PRODUCTION OF THERMAL AND FUEL NO FROM RESIDUAL OIL AND COAL COMBUSTION

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ABSTRACT

A versatile laboratory furnace was used to investigate the nitrogen oxide (NO) emissions resulting from the combustion of both low sulfur residual oil and pulverized coal. The relative contributions of thermal fixation and fuel nitrogen oxidation to the total NO emissions were determined by comparing the results from combustion with air with those from combustion with the appropriate argon/oxygen mixture. Subsequent testing on both oil and coal was then conducted to determine how the total NO and these relative contributions from fuel NO and thermal NO depended on burner throat velocity, excess air, air preheat, secondary air swirl, and flue gas recirculation. In each case care was exercised to allow only one of the above variables to be changed at a time.

For coal firing under all conditions tested, it was shown that the bulk of the NO results from fuel nitrogen oxidation. For residual oil, it appeared that although fuel NO was always significant, the thermal NO contribution was negligible at low preheat conditions, but was significant at high preheat conditions. Increased burner throat velocities and flue gas recirculation gave small NO reductions which were probably associated with elimination of much of the thermal NO. Increased air preheat increased NO with both coal and oil. Thermal and fuel NO increased markedly with increasing excess air for both oil and coal.

This paper summarizes results obtained under ROAP 21ADG-Task 42. The experimental work was sponsored by the U.S. Environmental Protection Agency and the analysis by the National Science Foundation. Work was completed October 1, 1973.

INTRODUCTION

It is now well established that NO emissions from natural gas, propane, and distillate oil flames can be significantly reduced using a variety of combustion modification techniques. Reduction of NO emissions from pulverized coal and residual oil combustion has proved a more difficult task, however, because in the latter cases NO is the result of both thermal oxidation of atmospheric nitrogen and the oxidation of bound nitrogen compounds in the fuel. Previous work by a variety of investigators[1-12] has shown that the conversion of bound nitrogen can be significant under many conditions. In general the results support the conclusions of Martin[13] and Turner[5] for oil combustion:

1. A significant portion of the nitrogen content of a liquid fuel is converted to NO during combustion of the fuel.
2. The fraction of fuel nitrogen converted to NO in oil combustion increases with excess air and decreases with increased nitrogen concentration.
3. Conversion does not appear to be a strong function of compound type.

With pulverized coal combustion the situation is not as clear: opinions of workers in the field are conflicting. Heap[14] and Sternling and Wendt[6] postulated that the most significant fraction of the total NO emission from pulverized coal combustion is fuel NO; on the other hand, Fine[7] indicated that this was unlikely in diffusion flames such as occur in the combustion process.

PURPOSE

The work reported in this paper is part of a larger program utilizing a versatile laboratory combustor to examine methods of control of NO and other emissions through both burner and combustion modifications. Specific goals of this portion of the program were:

1. To measure the relative contributions of thermal and fuel NO to the total NO emissions from residual oil and pulverized coal flames.
2. To determine the effect of burner and combustion parameters on total NO emissions and to interpret the data in terms of effects on fuel NO and thermal NO.

UNITS OF MEASURE--CONVERSIONS

The Environmental Protection Agency's policy is to express all measurements in Agency documents in metric units. When implementing this practice will result in lack of clarity or undue cost, conversion factors are provided for the non-metric units used in the document.

The following conversions to the metric system may be used.

To convert from	To	Multiply by
°F	°C	5/9(°F-32)
ft/sec	cm/sec	30.48
gph	liters/hr	3.79
in.	cm	2.54
psi	kg/cm^2	0.07

EXPERIMENTAL FACILITY

FURNACE DESIGN

The experimental furnace is illustrated in Figure 1. The combustion chamber is vertical with the burner mount on top. The walls are made of a high temperature plastic refractory and normally run about 2600°F* with 530°F air preheat. A 1.5 inch water positive pressure is maintained within the chamber. The chamber is cylindrical: it has a diameter of approximately 16 inches and is approximately 55 inches long. The six observation ports provide good access in two planes and at varying heights for flame observation, photography, and insertion of either a water-cooled gaseous sampling or temperature probe. The water-cooled burner is designed to accept a variety of injectors for gas, oil, or pulverized coal as fuel.

To cool the combustion gases prior to the flue, a forced air heat exchanger is attached at the bottom of the furnace perpendicular to its center line. It consists of concentric steel cylinders, ≈ 75 inches long.

SUPPORT EQUIPMENT

The combustor supporting devices are shown in Figure 2 and are designed to provide a wide choice of operating conditions with optimum individual process parameter control. Under normal operating conditions combustion air is supplied by an ambient temperature main blower through a manifold to the

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*Although it is EPA's policy to use the metric system for quantitative descriptions, non-metric units are used in this paper to reflect actual instrumentation used. Readers more accustomed to metric units are asked to use the Table of Conversions on page 2 to facilitate translation.

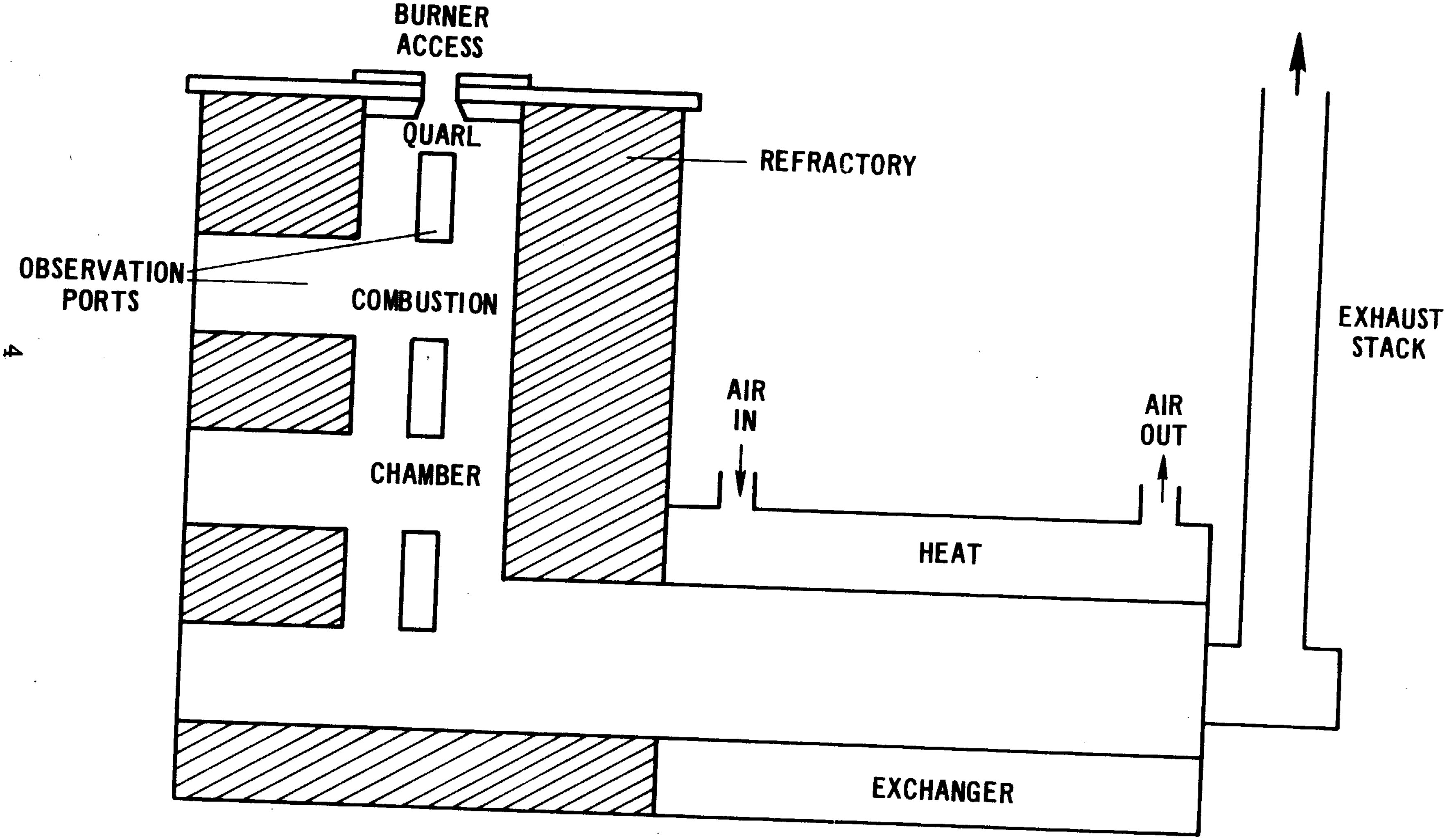

Figure 1. Furnace design.

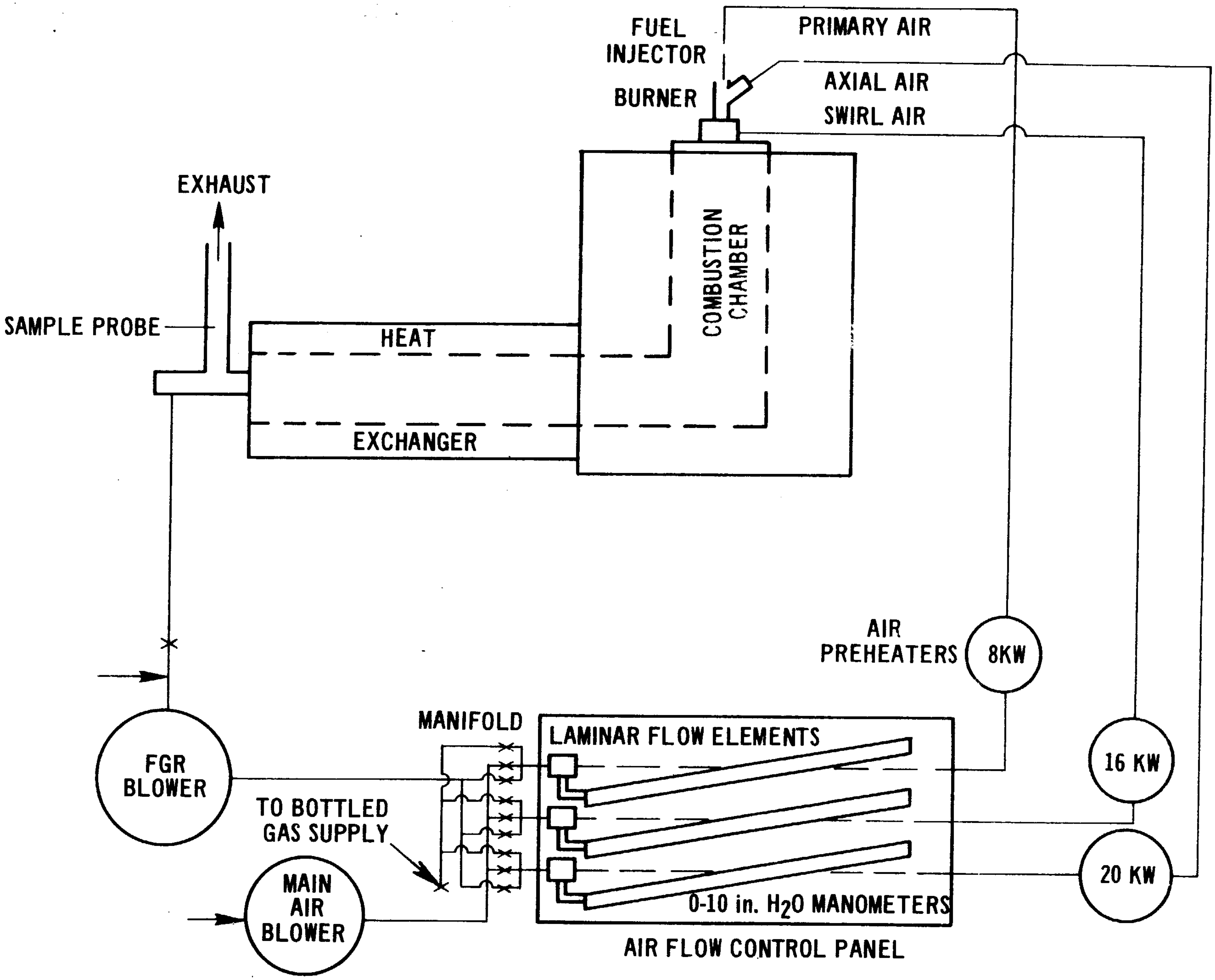

Figure 2. Support equipment.

swirl, axial, and primary (coal only) air lines. A high-temperature (600°F) blower forces flue gas from the exhaust stack (mixed with ambient air) through a second part of the distribution manifold to the proper air line(s). The third main section of the manifold is connected to a bottled gas supply and provides a 21 percent oxygen-in-argon atmosphere to the three air lines. The flow in each of the three air lines (swirl, axial, and primary) is controlled by the manifold valves and is filtered for dust and particulate removal before going through laminar flow elements which are connected to inclined water monometers for measuring the quantities delivered. Each line also has an electric air preheater with proportional controller to provide controlled air temperatures from ambient to 700°F.

FURNACE BURNER

A specially designed water-cooled burner as illustrated in Figure 3 is provided with separate axial air inlet and swirl chamber. The axial air enters through a port angled at ≈ 45 degrees into the center pipe and then passes through straightening vanes. Swirl air enters a vaned swirl chamber via two tangential ports 180 degrees opposed and passes through twelve 3/8 - inch swirl vanes as shown in Figure 4. The ID of the burner itself is 2.067 inches; however, nine burner inserts are provided so that axial air velocity can be maintained at 100 ± 10 ft/sec for a variety of mass flows, air preheats, etc. Thus when the inlet air temperature is doubled the burner throat area is also doubled to maintain constant velocity. By proper insert selection, other constant air velocities can be maintained for various mass flows, air preheats, etc. The burner is fitted with a 35-degree refractory quarl and has an adjustable collar at the top (inlet) to allow for varying the position of the fuel injector relative to the quarl exit.

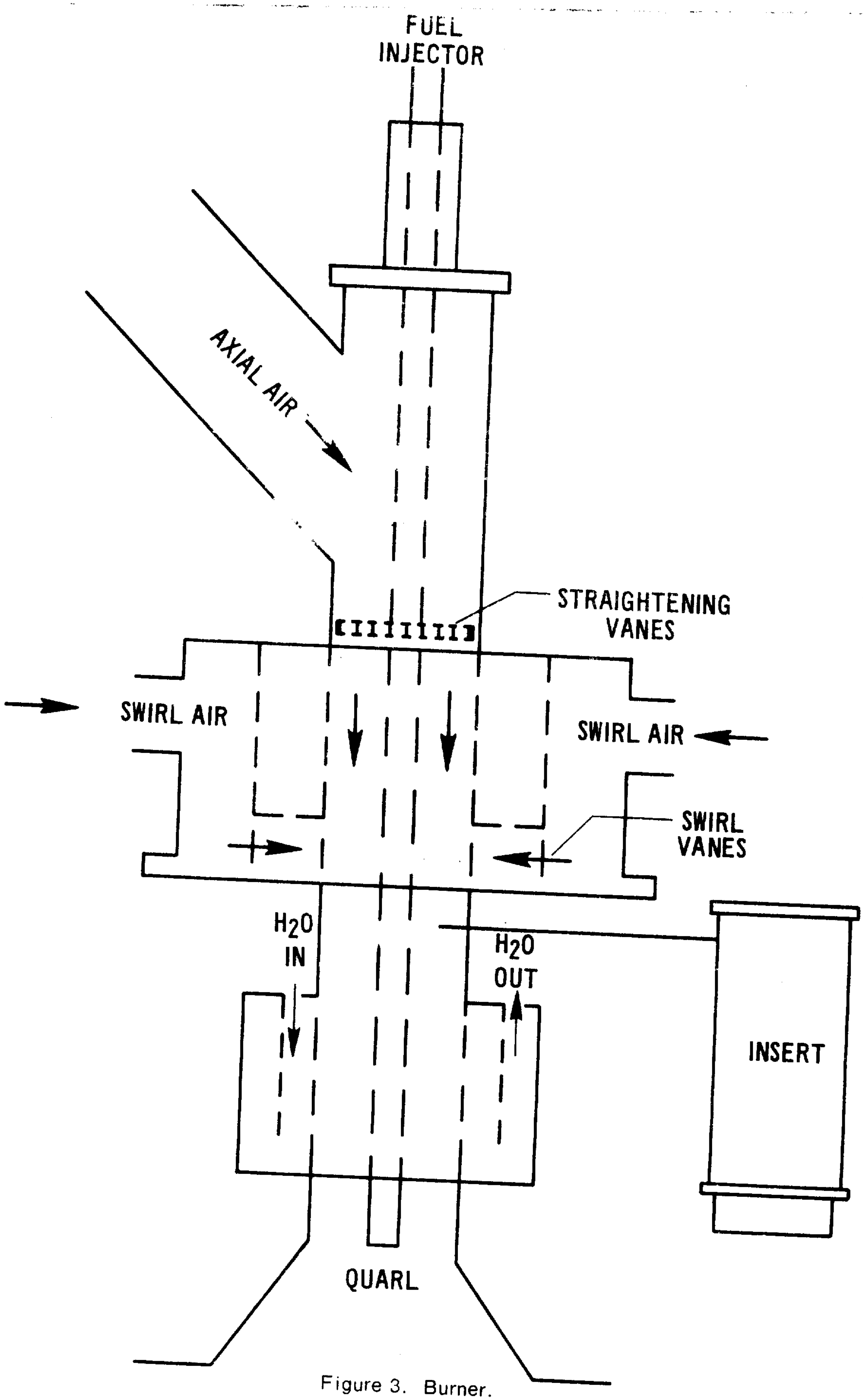

Figure 3. Burner.

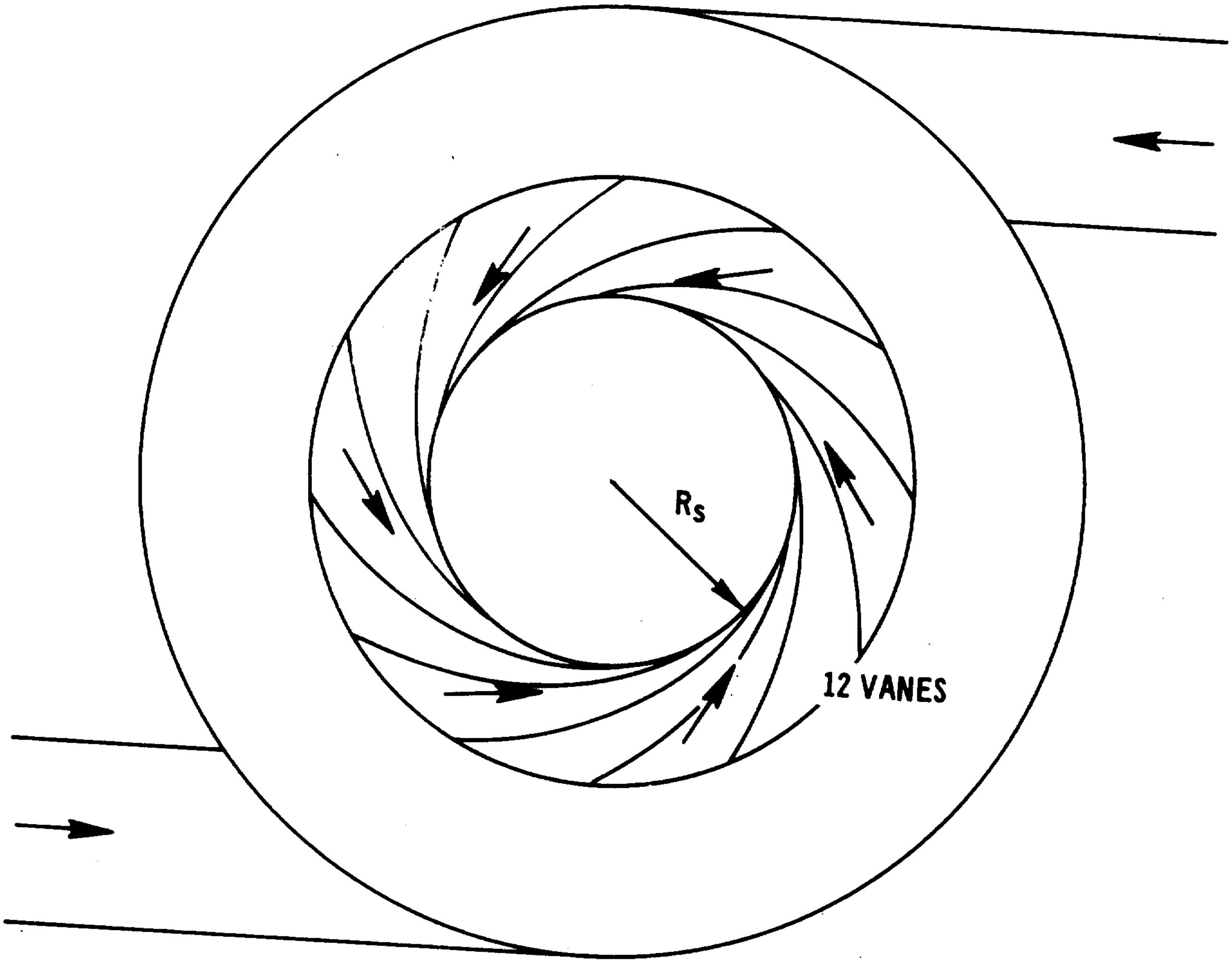

Figure 4. Swirl vanes.

FUEL INJECTORS

The fuel injectors used in this study, Figure 5, are characterized as rapid-mixing injectors because they produce short bulbous flames. The oil injector is a commercial 2.5 GPH high-pressure (100 psi) nozzle with an 80-degree solid spray angle. The divergent coal injector has six equally spaced 0.17-inch holes angled to distribute the coal away from the axis.

STANDARD FUELS

Compositions of the fuels used in this study are given in Table 1. Both the distillate oil (#2) and the residual oil (#6) are supplied by a constant-volume displacement metering pump which is electronically controlled to maintain constant speed. The residual oil also passes through an electric preheating system which maintains the temperature at 190°F. In some tests the nitrogen content of the residual oil is artifically increased by 0.3 wt percent by adding the appropriate amount of quinoline to the oil supply prior to the combustor. The quinoline is supplied at a constant rate from a special pressurized feed apparatus which is controlled by a micro-needle valve and measured by a calibrated rotameter. (At any given test condition the normal residual and increased N cases are run consecutively to minimize possible errors due to slightly different combustor conditions, preheat temperatures, etc.) Pulverized coal is delivered to the injector along with the primary air by a vibrating hopper screw feeder. Feed rate is controlled by a variable-speed gear motor drive.

ANALYTICAL PROCEDURES

The flue gas sampling system used in this work is shown in Figure 6. It consists of: paramagnetic oxygen analysis; nondispersive infrared analysis for carbon monoxide and carbon dioxide; flame ionization analysis for unburned

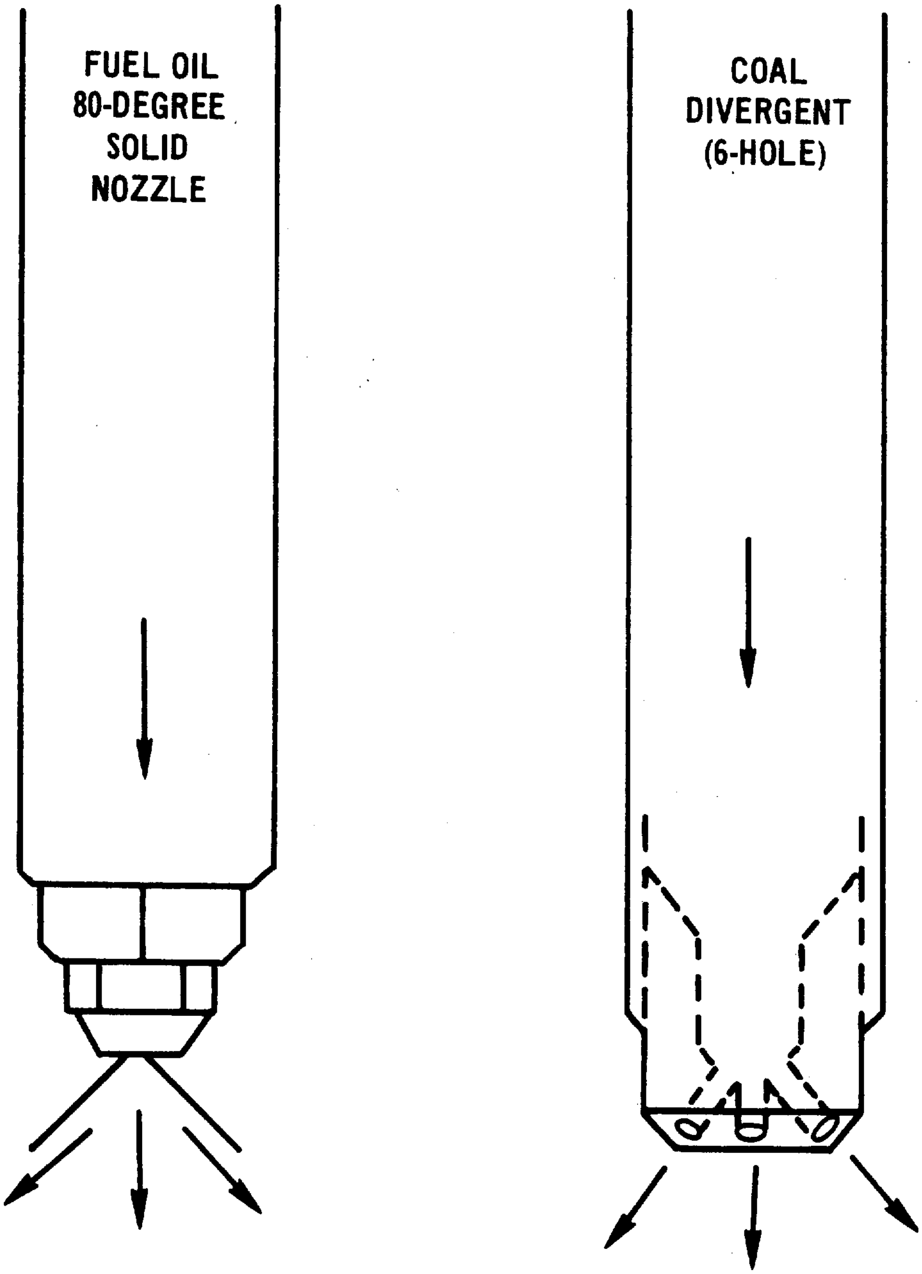

Figure 5. Rapid-mixing injectors.

Table 1. FUEL ANALYSIS

	Wt Percent		
Component	Distillate Oil	Low Sulfur Residual Oil	Coal
C	87.0	86.8	69.6
H	12.9	12.4	5.3
S	0.22	1.02	3.0
N	0.05	0.20	1.17
O	0.15	ND	9.6
Ash	0.004	ND	10.4

ND = Not Determined

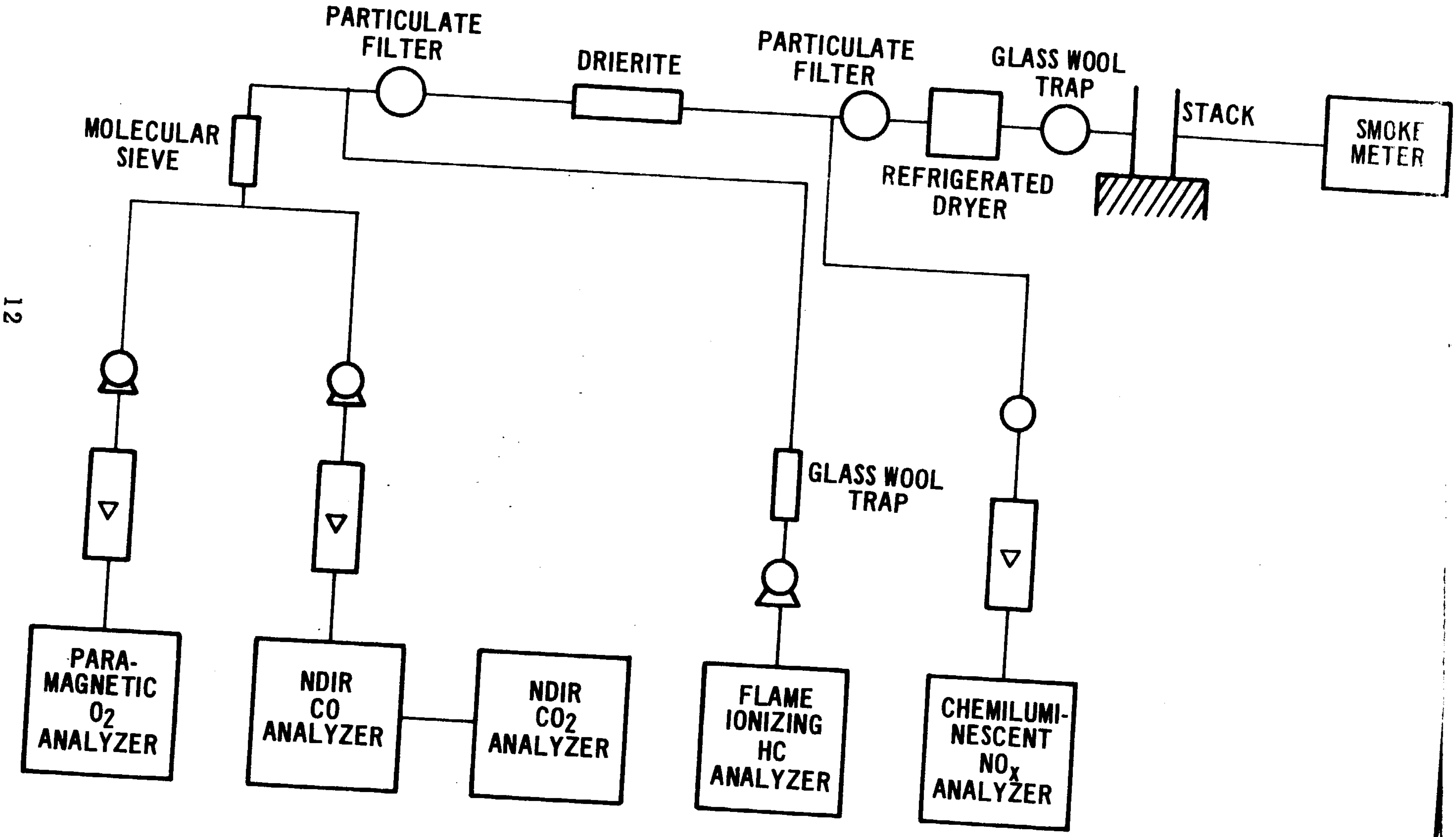

Figure 6. Analytical system.

hydrocarbons; chemiluminescent analysis for NO and NO_2; and sequential sampling for Bacharach smoke number. Sample conditioners consist of a refrigerated dryer (water condenser) and a particulate filter in the main sample line. When burning coal, a glass wool trap is placed upstream of the dryer. The chemiluminescent unit requires no additional moisture removal. A drierite ($CaSO_4$) dessicant cannister and a second particulate filter protect the remaining analyzers. The HC analyzer has an additional glass wool trap for moisture protection. The O_2, CO, and CO_2 analyzers are further moisture protected by molecular sieve traps (Grace SMR 4-635).

The Drierite cannisters are changed daily and the sieves are replaced as dictated by moisture indicators. The particulate filters are inspected daily and replaced as needed. The glass wool trap is replaced before each coal test. All instruments are calibrated with zero and span gas twice daily or before each test if required.

The sample probe is a 3/8 - inch diameter quartz tube placed inside the exhaust stack. All sample lines are either stainless steel or Teflon tubing.

SAFETY FACILITY

Flame-failure safe operation is assured by a Honeywell R4150 flame safeguard detection system. The flame signal for both gas ignition pilot and main flames is produced by an ultraviolet flame detector. An automatic power-off cutout is provided for both air flow loss and burner cooling water flow loss. In addition a thermal limit switch is provided for any unusual temperature rise at the burner.

DISCUSSION OF RESULTS

DEFINITION OF TERMS

Before considering the results it is important to explicitly define the terminology used. All emissions data are presented as ppm NO, dry, reduced to stoichiometric (zero percent excess air). The percent swirl is defined as the ratio of the mass of the air introduced through the swirl vanes to the total inlet air (swirl plus axial) times 100 percent.

Flue gas recirculation is defined as follows:

$$\text{Percent FGR} = \frac{\text{wt FGR}}{\text{wt air} + \text{wt fuel}} \times 100\%$$

where

wt FGR = weight of flue gas recirculated

wt air = weight of the combustion air used

wt fuel = weight of fuel burned

EVALUATION OF THE Ar/O_2 COMBUSTION ATMOSPHERE

The initial experimental series was designed to assess the usefulness and validity of replacing combustion air with a mixture of 21 percent oxygen in argon. This technique provides a means of separating the thermal and fuel NO contributions since with an Ar/O_2 atmosphere there can be no thermal NO. It does, however, suffer from at least two potential weaknesses: (1) since the Ar/O_2 is commercial grade it might contain as much as 0.5 percent impurities (e.g., N_2 or NO) which would invalidate the results; and (2) substitution of the Ar/O_2 for air results in a flame that is approximately 400°F hotter due to the difference in heat capacities of the Ar and N_2. The latter would considerably complicate the interpretation of the results if fuel nitrogen conversion is strongly temperature dependent.

To evaluate the possibility of contamination of the Ar/O_2 mixture by N_2 and to demonstrate that there were no air leaks in the combustion system, a test was run with distillate oil. Since distillate is almost completely free of fuel-bound nitrogen (<0.05 percent) and does not contain significant N_2 (as natural gas does), it results in essentially only thermal NO. Therefore, when it is burned in an atmosphere containing no nitrogen the NO emissions should be very nearly zero. Figure 7 shows the results of the first test with distillate oil in which the combustion air was completely replaced with a mixture of 21 percent oxygen and 79 percent argon. As the data indicate, NO emissions were reduced from 217 ppm with air to 11.8 ppm with Ar/O_2. Thus, it is possible to prevent the formation of thermal NO by burning the fuel in an Ar/O_2 atmosphere. The 12 ppm could be due to trace impurities but are more likely the result of the nearly complete oxidation of the small amount of fuel nitrogen in the distillate oil. Total conversion of 0.01 percent nitrogen would result in about 15 ppm.

Assessment of the effect of flame temperature change on fuel nitrogen conversion is more difficult. In one test series quinoline was added to the residual oil in sufficient quantity to increase the fuel nitrogen by 0.3 wt percent. By comparing the resulting emissions with those obtained under identical conditions without quinoline in the oil it was possible (in principle) to determine a ppm NO resulting from the quinoline and thereby a percent conversion. Figure 8 shows the results of this type testing with both an air atmosphere and an Ar/O_2 atmosphere. As the data indicate, the conversion of the quinoline was constant, within the experimental error, even though the

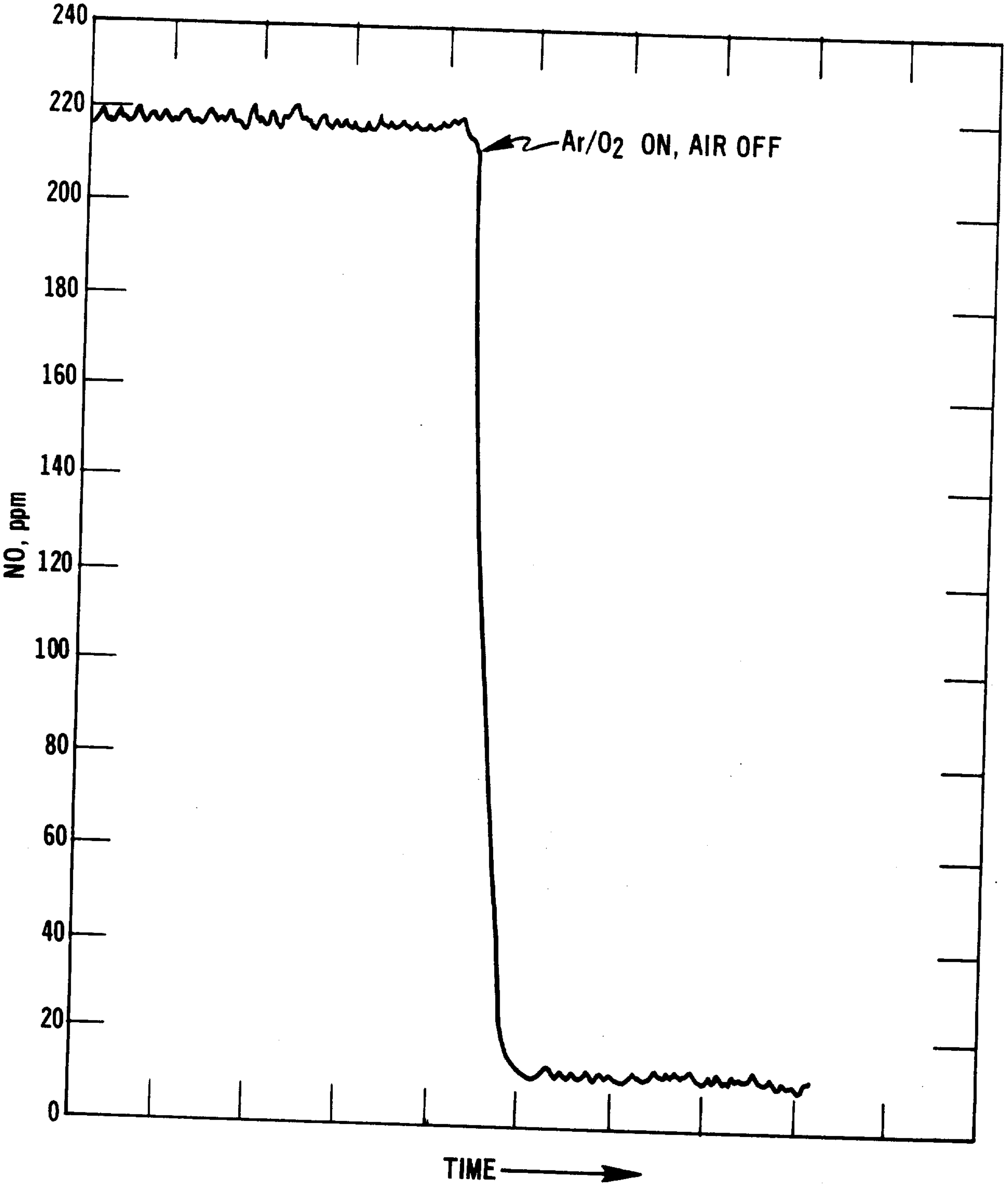

Figure 7. Replacing combustion air with Ar/O_2 eliminates thermal NO (distillate oil).

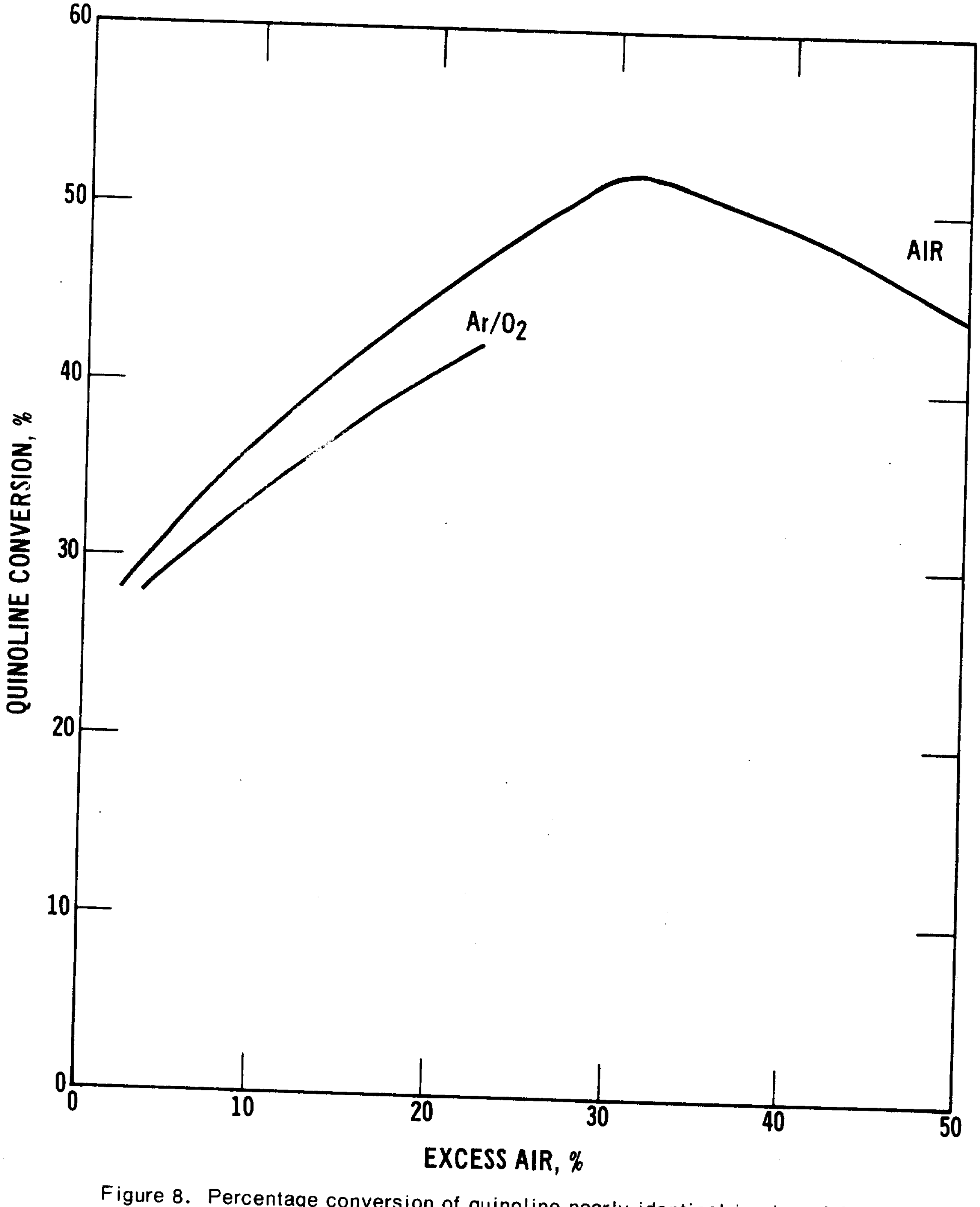

Figure 8. Percentage conversion of quinoline nearly identical in air and Ar /O_2 atmospheres (residual oil).

theoretical flame temperature increased by over 400°F in the Ar/O_2 case. Since quinoline is representative of many fuel-bound nitrogen compounds, these data suggest that: (1) fuel nitrogen conversion is not strongly temperature dependent and the Ar/O_2 substitution results are, therefore, directly applicable; and (2) it is possible to determine the percent conversion of the nitrogen in a compound such as quinoline by comparing the NO emissions with and without the quinoline.

The temperature dependence of fuel nitrogen conversion was further examined by dropping the preheat on the Ar/O_2 mixture from 530°F to 70°F in another residual oil series. Figure 9 shows these results. In each case the conditions (swirl, throat velocity, oil preheat, etc.) were identical except for the inlet Ar/O_2 temperature (and therefore the flame temperature). As the data indicate, little effect of flame temperature was observed.

Thus, available evidence strongly suggests that the conversion of fuel nitrogen to NO is not heavily temperature dependent. Specifically, (1) the conversion of a typical nitrogen compound, quinoline, was found to be relatively insensitive to flame zone temperature (Figure 8); (2) changing the flame zone temperature of residual oil burning in an Ar/O_2 atmosphere had little effect on NO emissions (Figure 9); and (3) both Martin[13] and Turner[15] found the conversion of fuel nitrogen to be relatively insensitive to temperature reduction schemes such as flue gas recirculation.

Finally, it was concluded that replacement of the combustion air with Ar/O_2 was a valid technique for evaluating the contribution of fuel NO to the total NO emissions because: it was shown that in the absence of fuel nitrogen, combustion in Ar/O_2 results in essentially zero NO; and the reactions of interest (conversion of fuel nitrogen to NO) are not strongly temperature dependent.

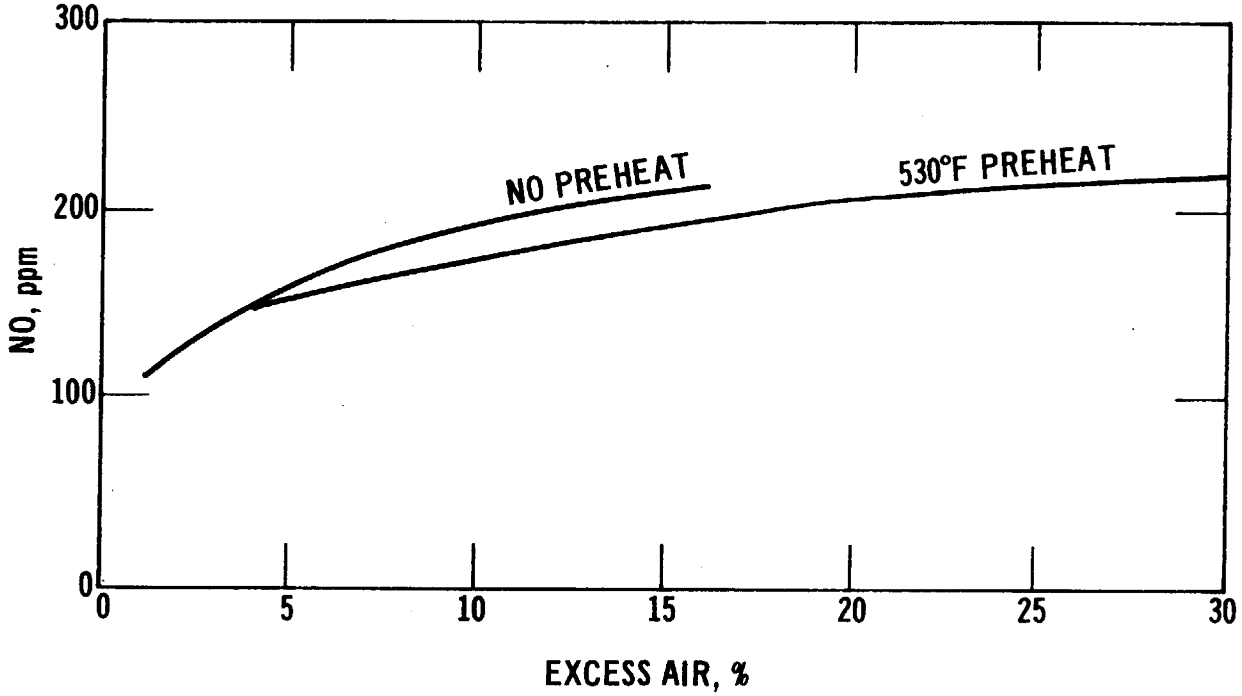

Figure 9. Flame zone temperature has little effect on fuel NO (residual oil).

NO. 6 OIL COMBUSTION

THERMAL NO VS FUEL NO

Figure 10 shows the effect of excess air on the NO emissions from residual oil combustion at 530°F oxidizer preheat, 100 ft/sec burner throat velocity, and 60 percent swirl with both air and Ar/O_2 as oxidizers. Several trends are worth noting:

1. Residual oil in air combustion shows a strong dependence upon excess air level at this high level of preheat. Ar/O_2 data, however, are considerably flatter. This suggests that at these high preheat temperatures thermal NO (difference between the air and Ar/O_2 lines) is a strong function of excess air. Fuel NO, however, increases only moderately with excess air.
2. At very low excess air levels (<5 percent) the bulk of NO emissions are the result of the oxidation of fuel nitrogen. As excess air is increased, thermal NO increases: by 25 percent excess air, total NO emission is due to nearly equal contributions from the fuel and thermal mechanisms.

Figure 11 shows the results of a similar test series with no air or Ar/O_2 preheat (burner throat temperature approximately 100°F). As with the high preheat data, both thermal and fuel NO increase with increasing excess air. The absolute level of fuel NO is nearly the same as in the high preheat cases; fuel nitrogen conversion is not extremely temperature sensitive. Thermal NO, however, is much lower than the preheat cases (Figure 10) due to its exponential dependence on temperature. These data suggest that, in systems which do not utilize air preheat, bulk gas temperature reduction will result in

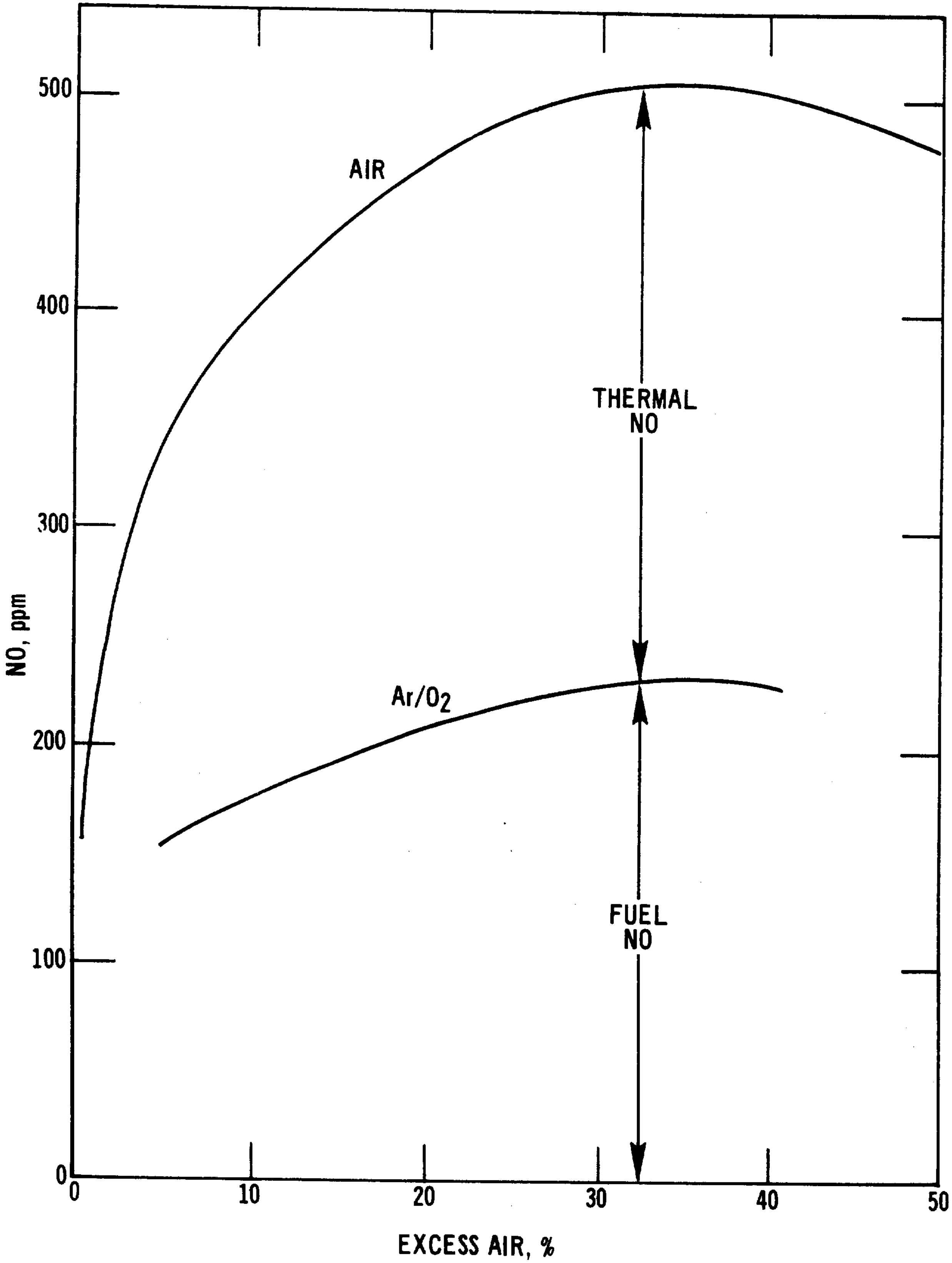

Figure 10. At high prepeat (530°F), atmospheric fixation and fuel nitrogen oxidation contribute significantly to total NO (residual oil).

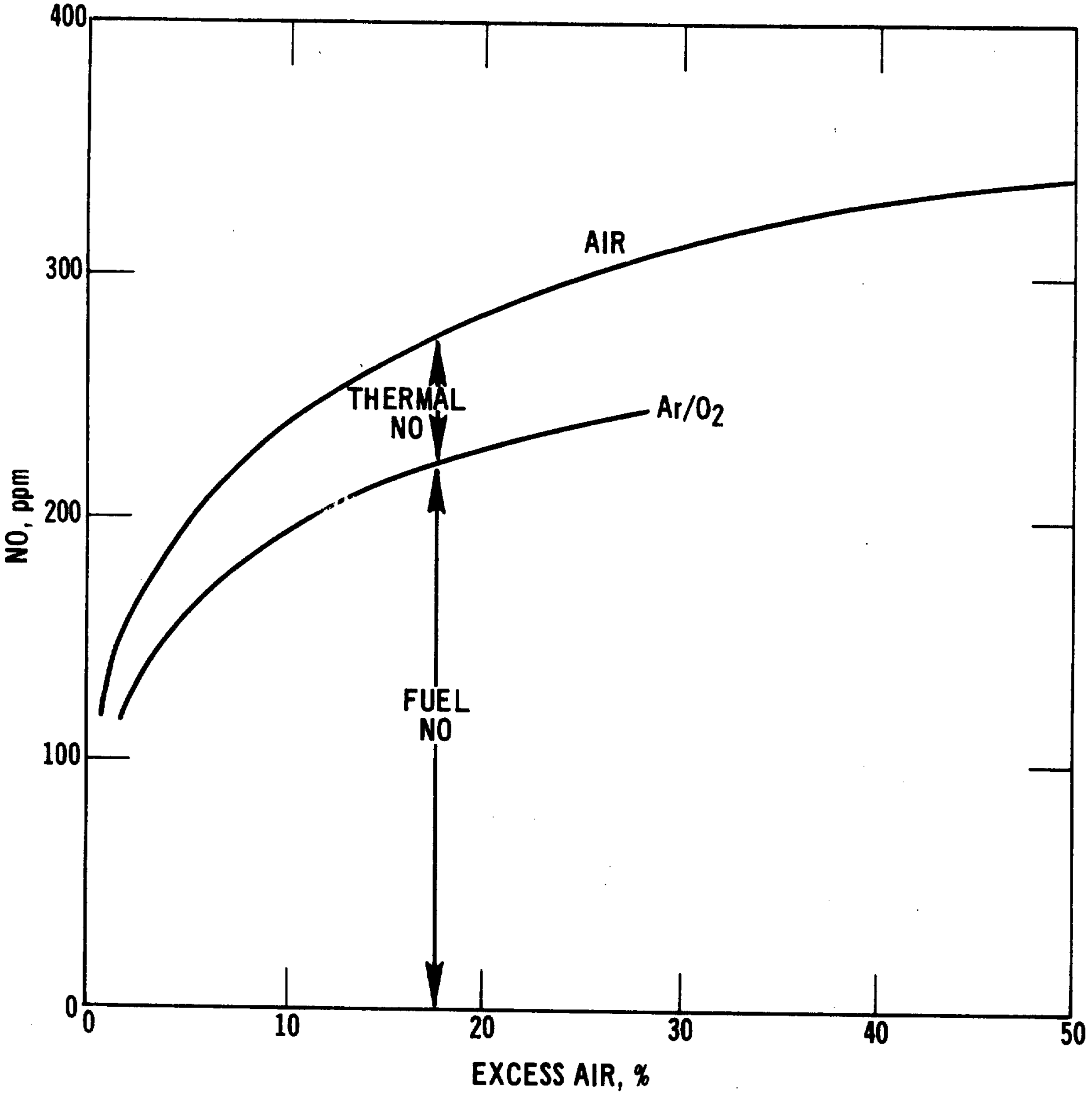

Figure 11. Without air preheat most total NO results from fuel nitrogen oxidation (residual oil).

smaller percentage reductions in NO because less of the total NO emissions are the result of thermal fixation.

In summary, results indicate that, under all conditions tested, fuel nitrogen conversion accounts for at least 50 percent of the total NO from residual oil combustion. Both thermal and fuel NO increase with increasing excess air and, at high air preheat levels, significant amounts of thermal NO can be produced with residual oil. It now remains to consider the various burner and combustion modification techniques in light of these data.

LOW EXCESS AIR

Figure 12 shows the effect of reducing the available excess air at various swirl levels (no air preheat). As expected, reduced excess air results in reduced NO at all swirl settings. It must be noted, however, that the 1 percent case cannot be considered industrially significant because smoke numbers of 9 and 10 were observed over the entire swirl range. The 5 percent excess air case gave zero smoke numbers above 60 percent swirl.

In Figure 13 these data are compared to those of Turner[15] who conducted a very thorough investigation of NO emissions from residual oil combustion in a package boiler. Considering the marked difference in physical size, boiler type, and fuel composition, the agreement is quite good.

REDUCED AIR PREHEAT

Figure 14 shows the results of changing the air preheat at various swirl levels. Reducing the preheat from 530°F to 300°F results in a significant drop in NO emissions. The reduction is almost certainly associated with a reduction in thermal NO. Turning the preheat off completely (100°F inlet air)

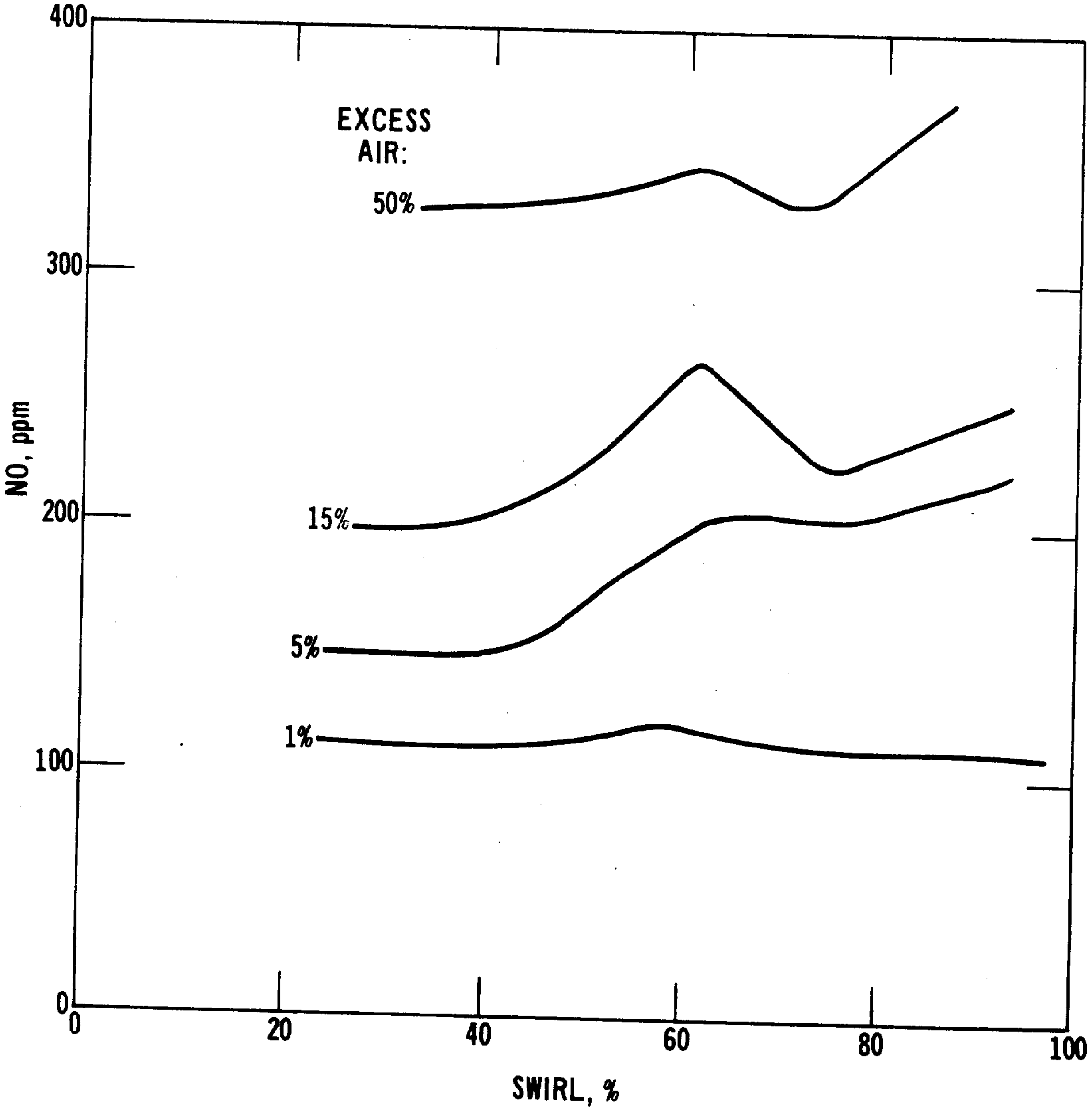

Figure 12. Decreasing excess air decreases NO emissions (no air preheat--residual oil).

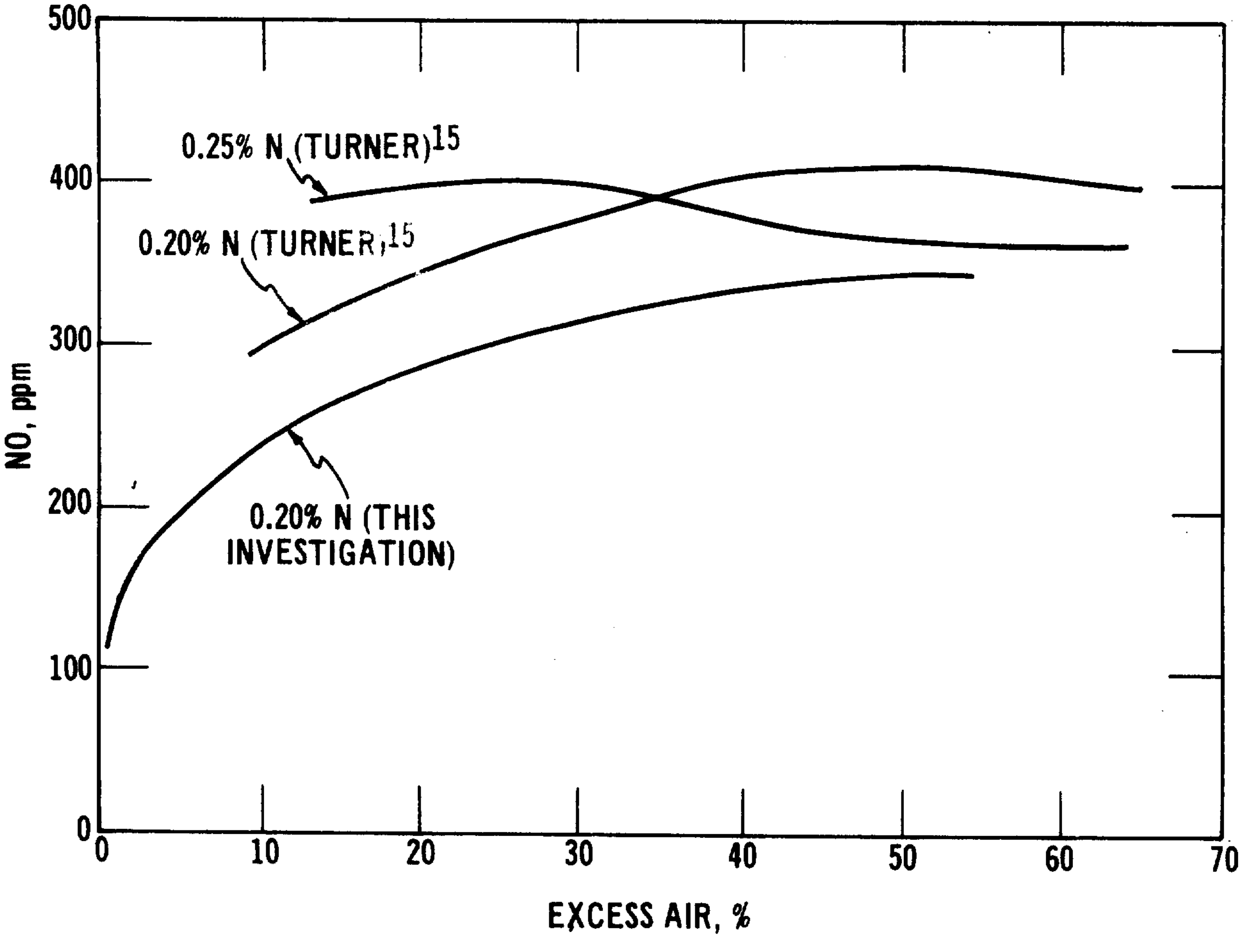

Figure 13. Effect of excess air compared to that measured by Turner[15] (residual oil).

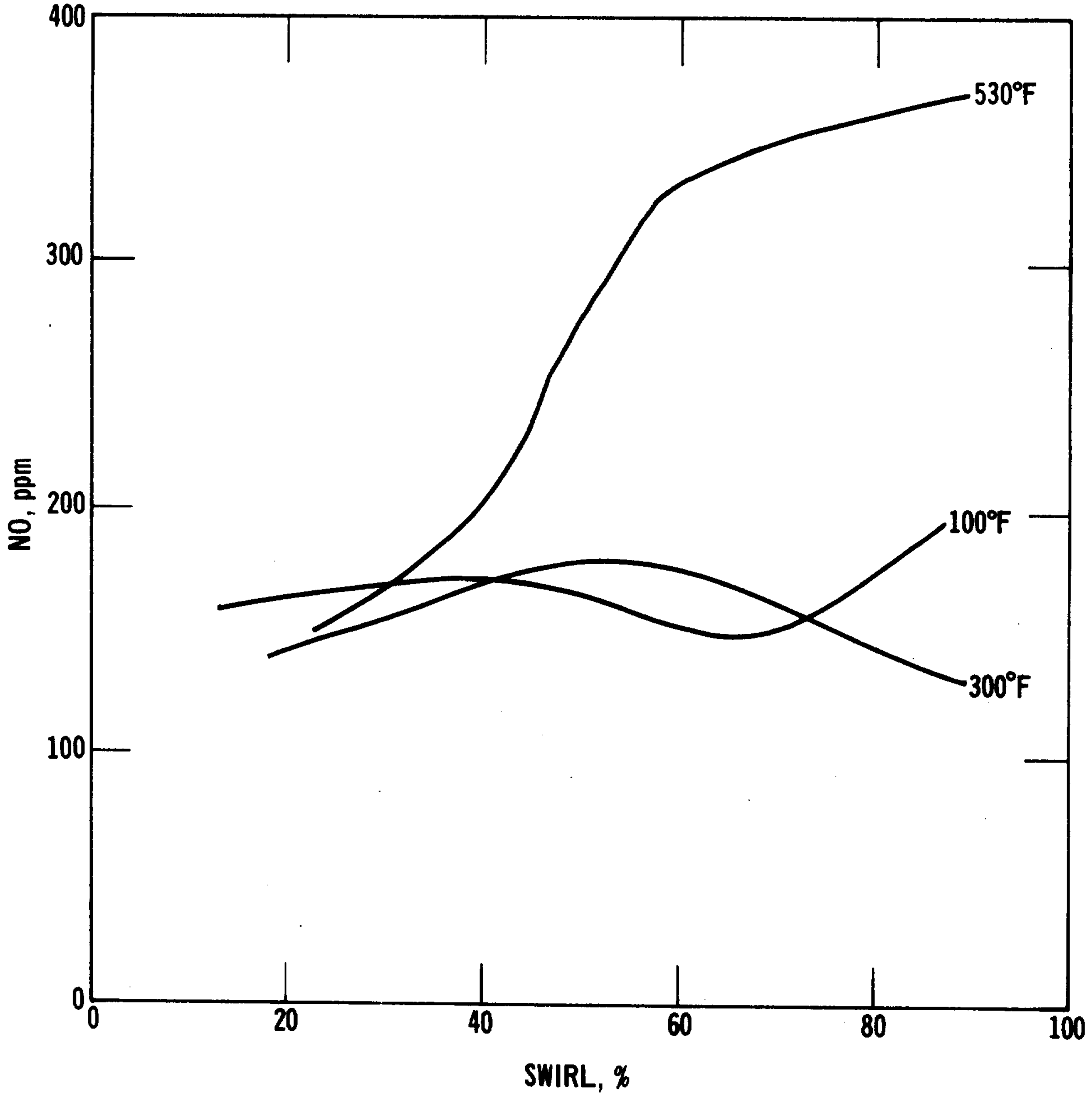

Figure 14. Increasing air preheat increases total NO emissions (residual oil).

gave no further reduction. This is not particularly surprising since the Ar/O_2 tests previously discussed indicate that at low preheat and low excess air the bulk of the NO from residual oil is the result of fuel nitrogen oxidation.

To further investigate the effect of preheat, sufficient quinoline was added to the residual oil to increase the fuel nitrogen by 0.3 wt percent. In Figure 15 the percent conversion of the added quinoline is plotted at various preheat levels. Note that, except at the extreme swirl limit, the percent conversion of the quinoline is constant (within the limits of the experiment).

FLUE GAS RECIRCULATION

The effect of 25 percent flue gas recirculation at 5 percent excess air is shown in Figure 16. The NO emissions were decreased to about 200 ppm over most of the swirl range. As in previous work[16] swirl had little effect on the NO emissions at this high FGR level. In Figure 17 data taken with 25 percent flue gas recirculation are compared to those obtained without FGR for a variety of excess air levels. (All data are at 100 ft/sec throat velocity, 530°F preheat, and 60 percent swirl.) The dotted line, indicating the results of testing with Ar/O_2 substituted for combustion air, is representative of fuel NO, as has been discussed. Thus the data support the conclusion of Martin[13] and Turner[15] that flue gas recirculation significantly decreases formation of NO via the thermal mechanism but does not markedly affect fuel nitrogen conversion. The data also indicate that at lower excess air levels the FGR does not completely eliminate the thermal NO.

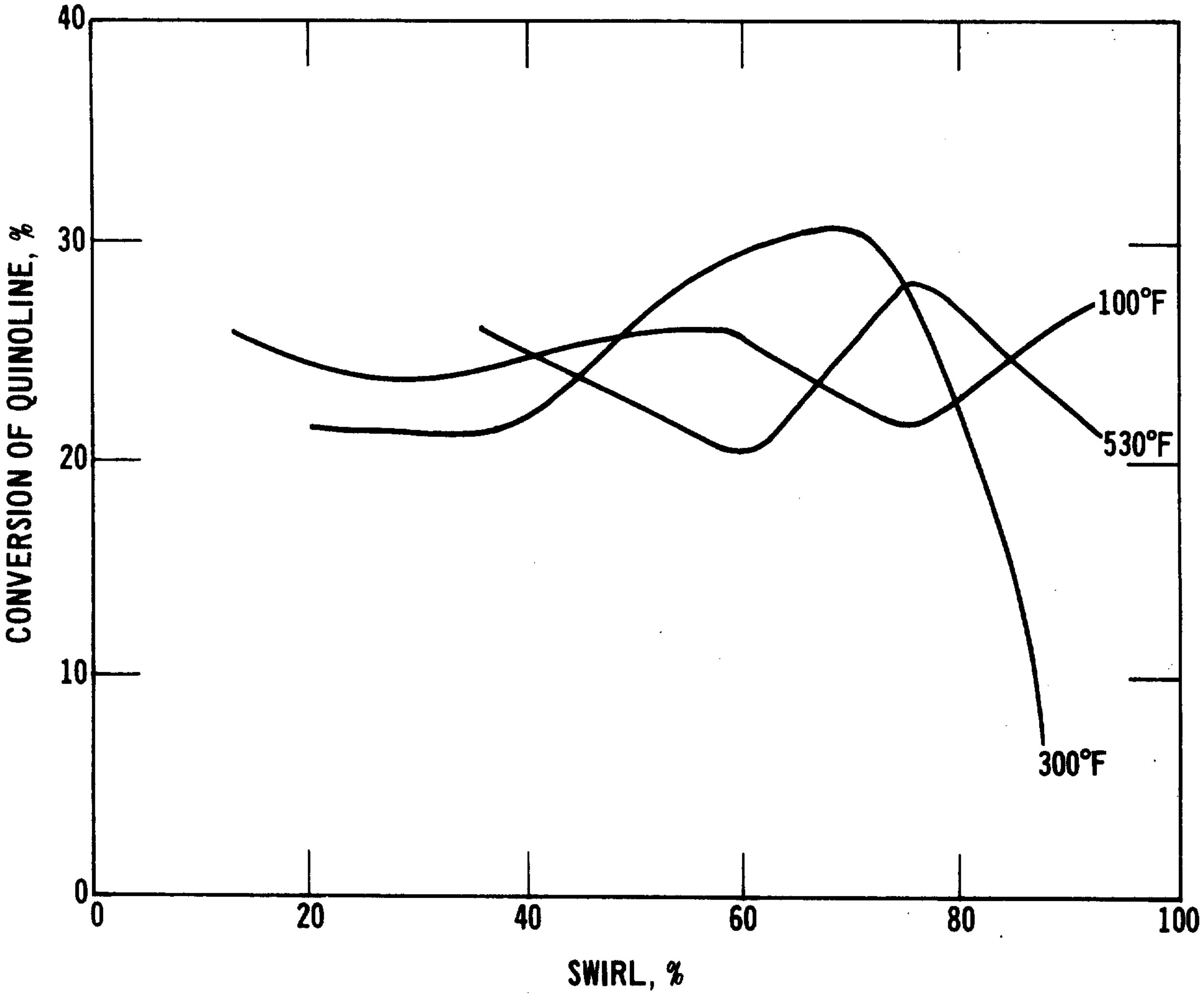

Figure 15. Air preheat has little effect on conversion of added quinoline (residual oil).

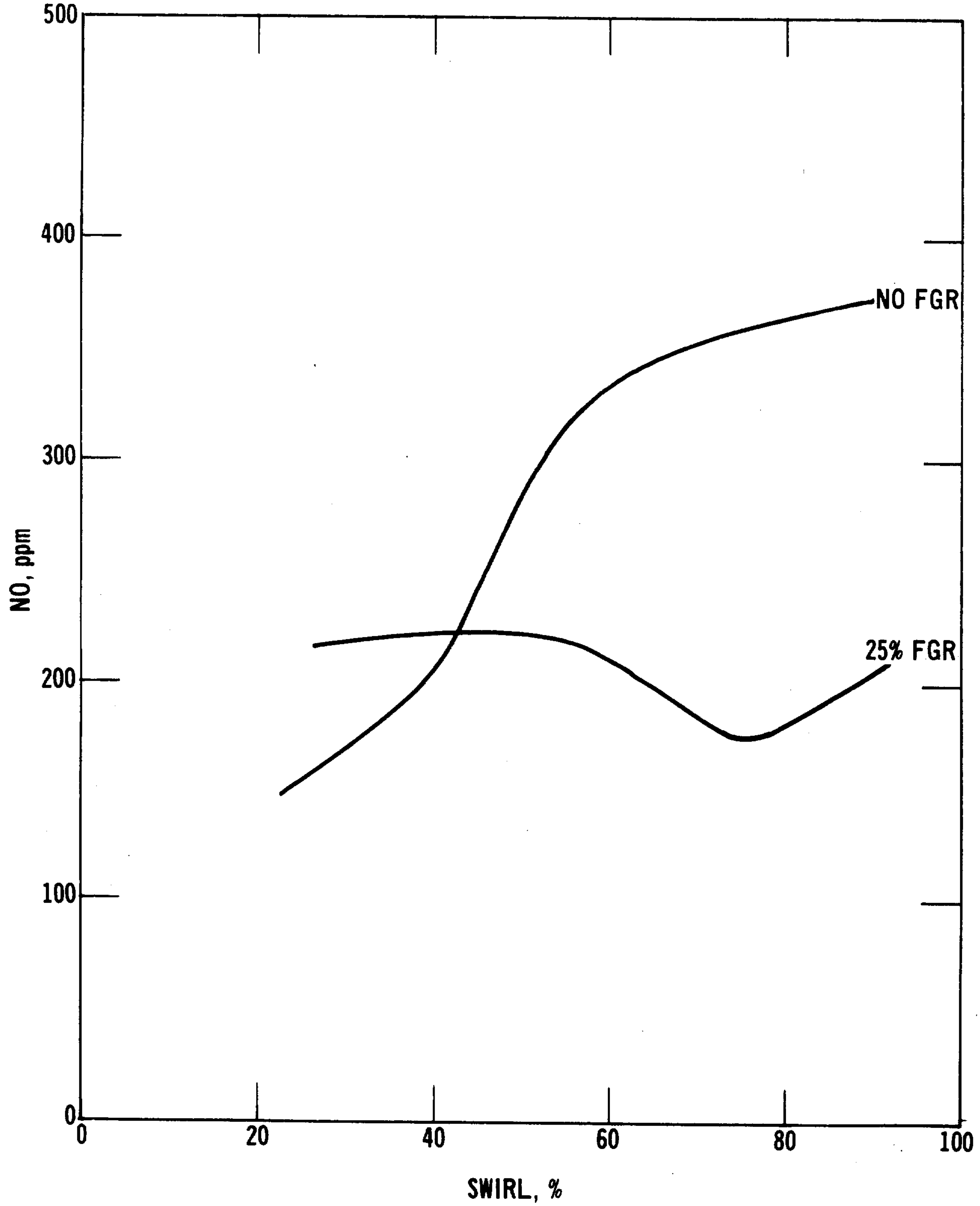

Figure 16. Flue gas recirculation reduces NO emissions (530°F preheat--residual oil).

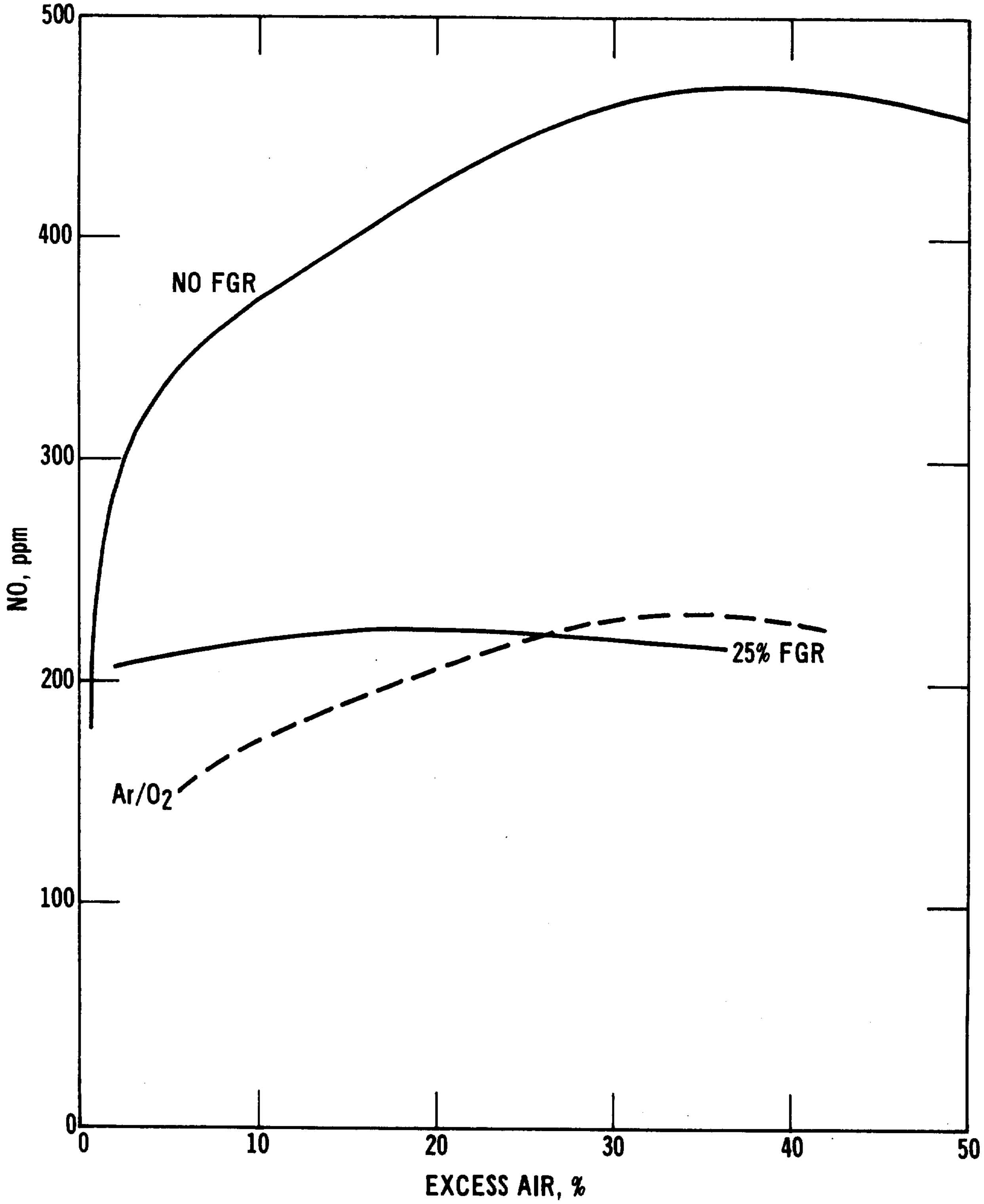

Figure 17. Flue gas recirculation essentially eliminates thermal NO (residual oil).

INCREASED BURNER THROAT VELOCITIES

Previous work by Pershing[16], Heap[17], and Hemsath[18] has shown that increasing the velocity of the combustion air stream is an acceptable means of reducing NO emissions from natural gas, propane, or distillate oil flames where the bulk of the NO is from thermal fixation. Increased velocity increases entrainment of "cooled" combustion gases and thereby reduces the bulk burning temperature through "internal" flue gas recirculation. Figure 18 shows the results of increasing the throat velocity from 100 ft/sec to 200 ft/sec (at 5 percent excess air and 530°F preheat). NO emissions decreased to about 200 ppm which is almost exactly the level observed with 25 percent FGR (Figure 16). Of particular interest is the fact that at 60 percent swirl both the 25 percent FGR case and the 200 ft/sec case gave about 210 ppm NO. This is only about 50 ppm above the level measured with the Ar/O_2 and, therefore, suggests that both increased throat velocity and FGR are essentially eliminating thermal NO.

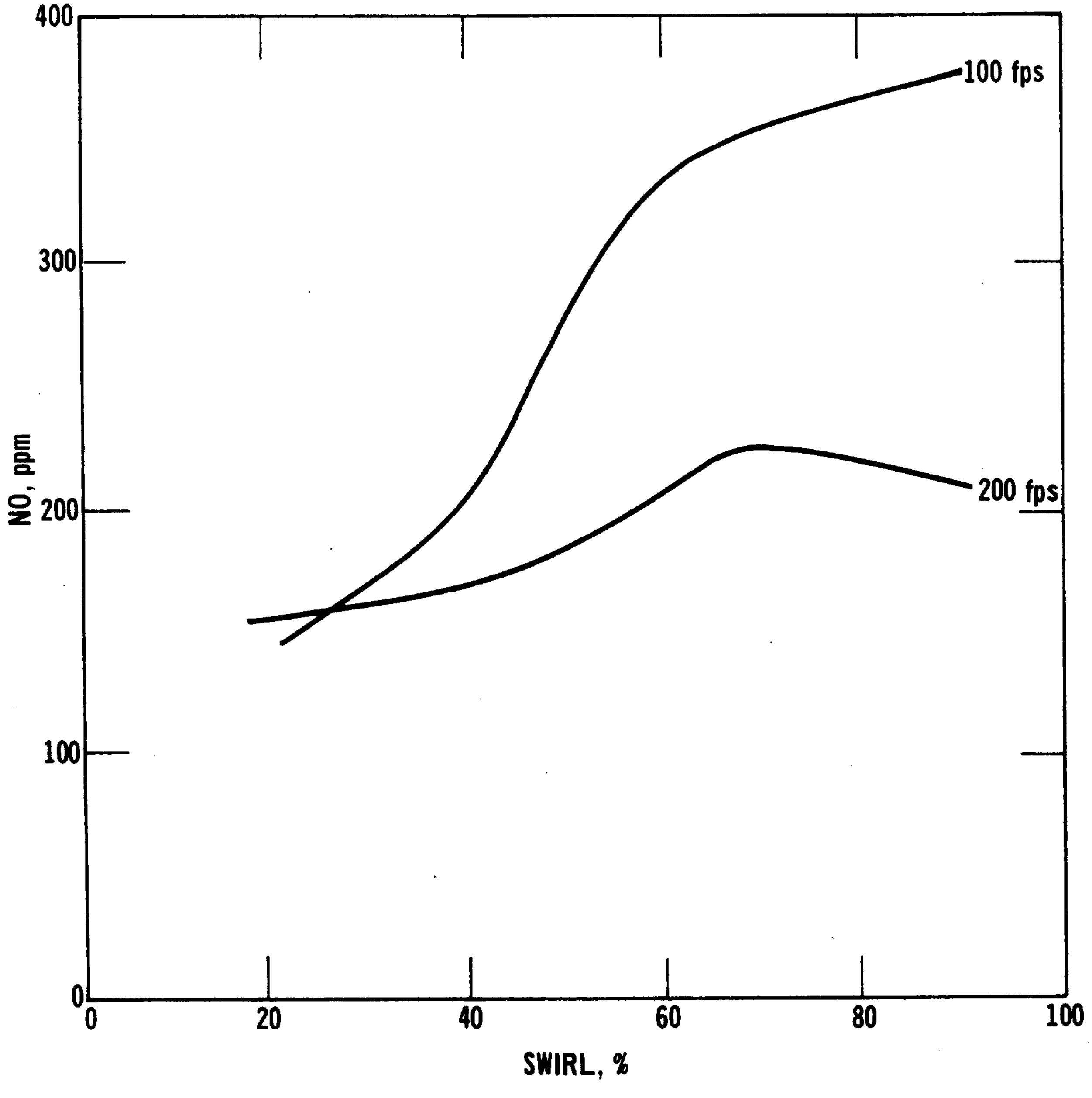

Figure 18. Increasing burner throat velocity reduces NO emissions (residual oil).

PULVERIZED COAL COMBUSTION

THERMAL NO VS FUEL NO

Figure 19 shows the effect of excess air on the NO emissions from pulverized coal combustion at 530°F secondary preheat, 100 ft/sec secondary velocity, and 82 percent swirl with both air and Ar/O_2 as oxidizers (in primary, axial, and swirl streams). (Here as in all of the coal tests the primary mass flow was always maintained at about 15 percent of the stoichiometric air requirement.) As the data indicate, the curves appear to converge as excess air approaches zero. Assuming that the difference between the lines is the thermal contribution, it amounts to 130 ppm at 20 percent excess air and 50 ppm at 5 percent excess air. Both thermal and the fuel NO appear to increase markedly with excess air; however, at all times the fuel contribution completely dominates the total NO emission.

Note that there is a basic difference in behavior here between the fuel nitrogen in the coal and that in the residual oil just discussed. It appears that the conversion of the bound nitrogen in the oil is much less sensitive to the overall excess air than the conversion of the nitrogen in the coal.

LOW EXCESS AIR

Figure 20 shows the effect of reducing available excess air at various swirl levels, with primary air flow held constant. Each curve exhibits essentially the same shape with respect to swirl and, as expected, increasing excess air markedly increases the NO. Based on the results just discussed this is almost certainly due to increased fuel nitrogen conversion. Figure 21 shows the results obtained here and by other investigations plotted on a common basis (as percent reduction in NO emissions with respect to 20 percent excess air). As the data indicate, results of this investigation agree with those

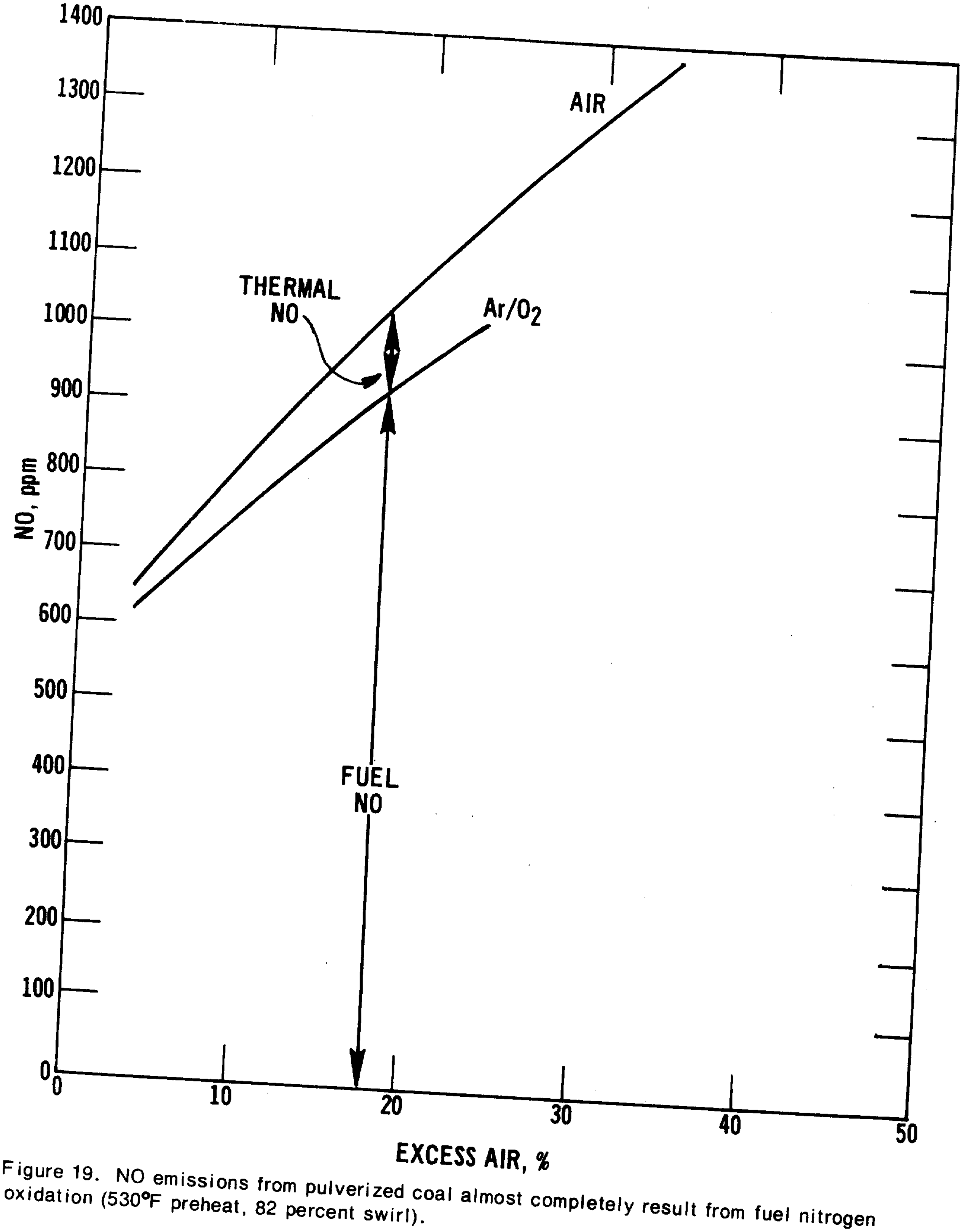

Figure 19. NO emissions from pulverized coal almost completely result from fuel nitrogen oxidation (530°F preheat, 82 percent swirl).

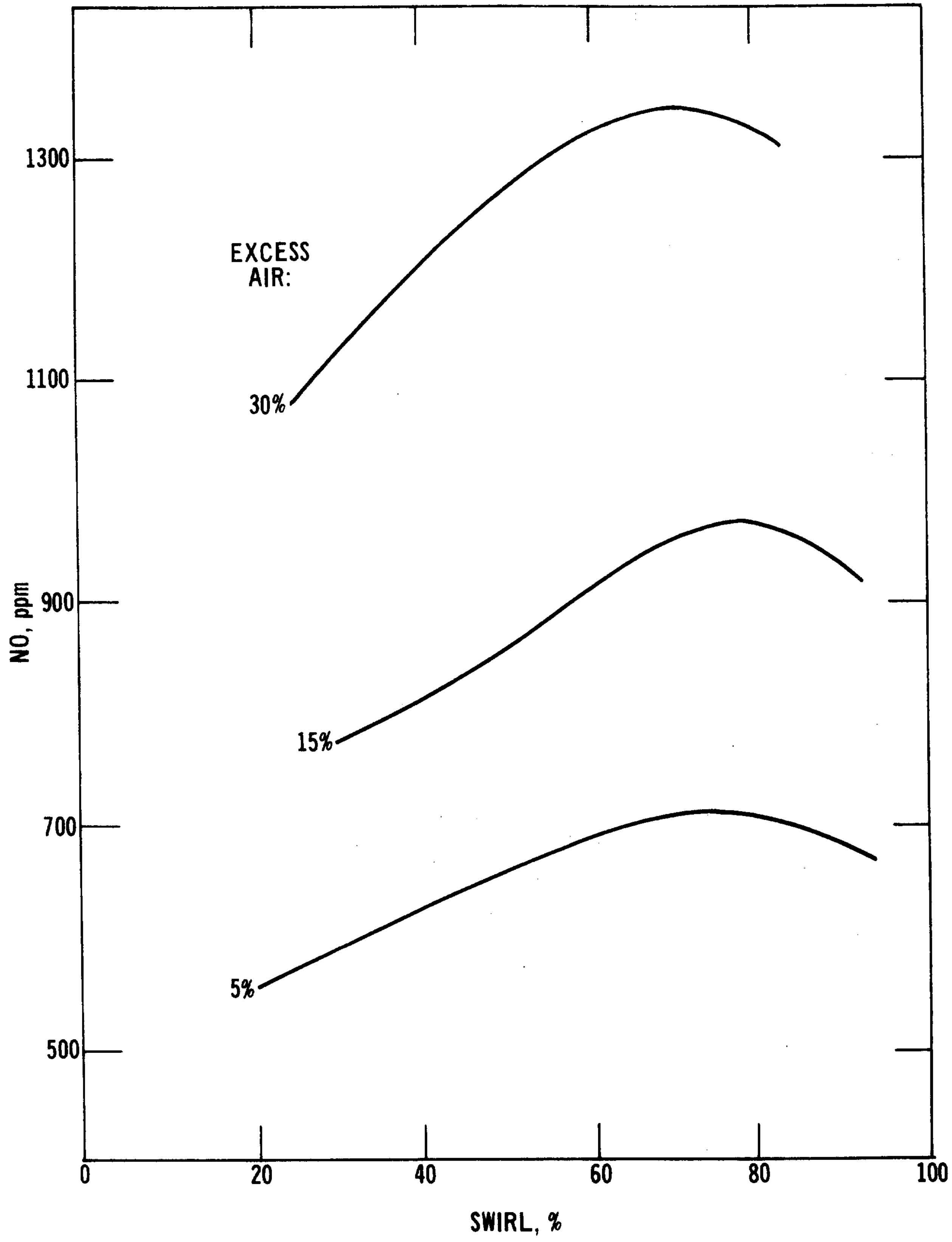

Figure 20. Decreasing excess air decreases NO emissions (pulverized coal).

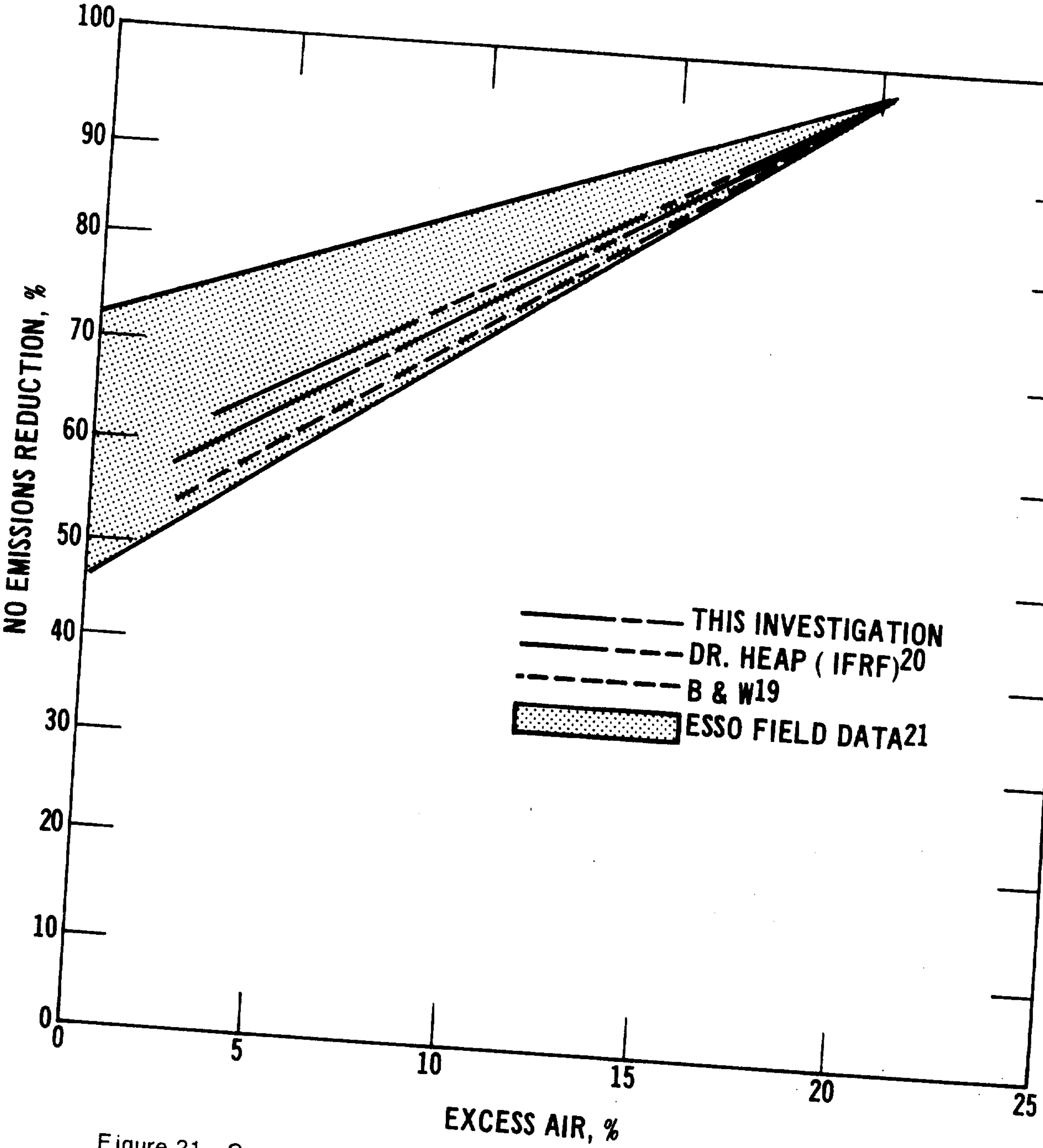

Figure 21. Comparison of various data on effect of excess air (pulverized coal).

obtained in previous pilot scale work by Babcock and Wilcox[19] and by the International Flame Research Foundation[20] and with full-scale field testing by Esso Research and Engineering[21].

REDUCED AIR PREHEAT

Figure 22 shows the results of reducing the secondary preheat temperature from 530°F to 300°F. As the data indicate, a significant drop was observed (30 percent on the average). This is a larger reduction than is normally observed in practice. It is also greater than would have been expected based on the other data obtained here.

FLUE GAS RECIRCULATION

Figure 23 shows the effect of 25 percent flue gas recirculation at 5 percent excess air. In general the NO emissions were reduced by about 9 percent. Of particular interest is the fact that, at 82 percent swirl, the emissions were reduced 41 ppm. (When combustion air was replaced by Ar/O_2 at these identical conditions, NO emissions dropped 50 ppm.) Thus it appears that flue gas recirculation is essentially eliminating thermal NO: FGR is largely ineffective with coal because most of the NO emissions are the result of bound nitrogen conversion.

INCREASED BURNER THROAT VELOCITY

Figure 24 shows the effect of increasing burner throat velocity (secondary) at various swirl levels. Again the NO emissions were reduced by an average of about 9 percent. In this case the emission reduction at 82 percent swirl was 43 ppm. These data, as all the rest, tend to confirm that probably 80 to 90 percent of the NO emissions from pulverized coal combustion are the result of fuel nitrogen oxidation.

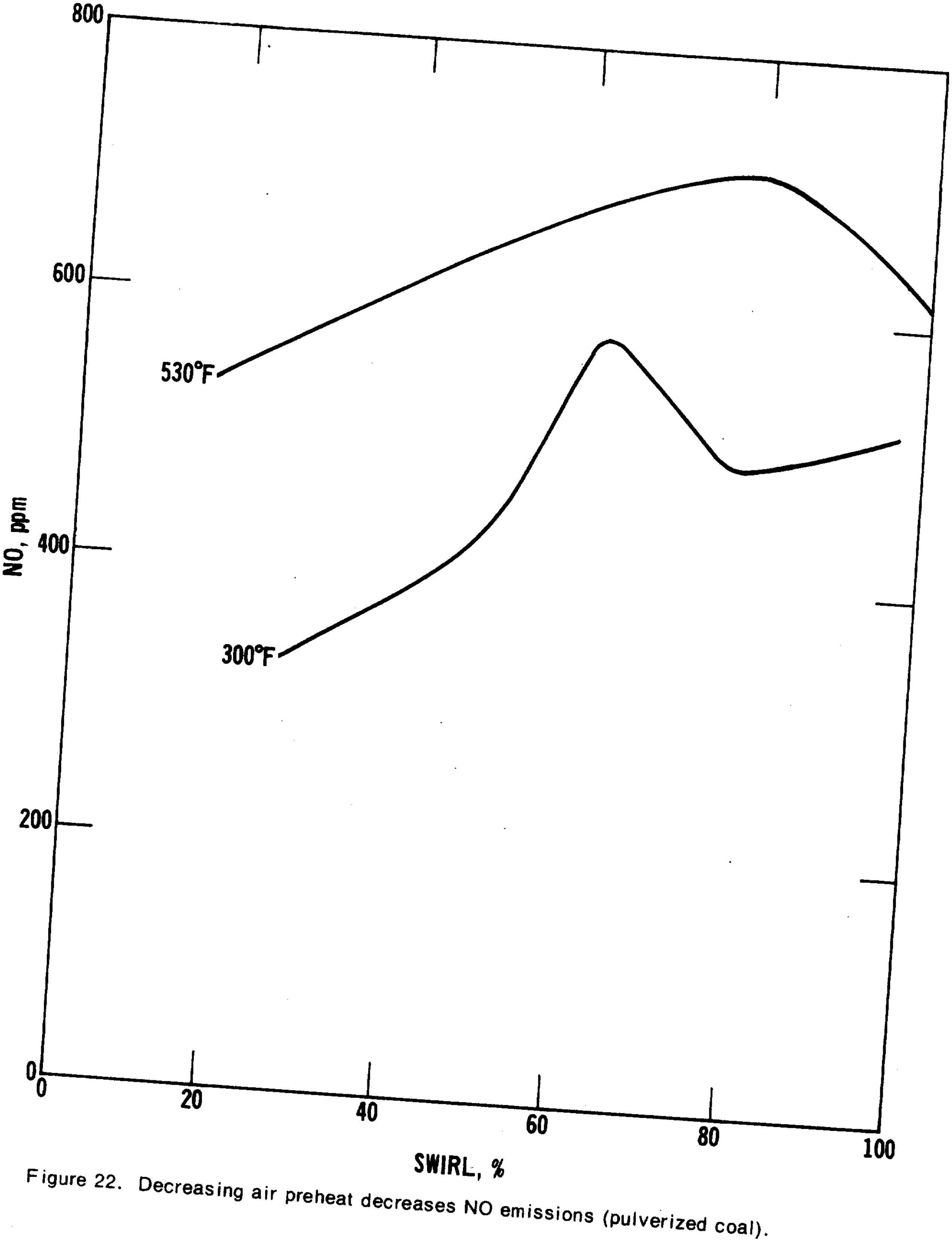

Figure 22. Decreasing air preheat decreases NO emissions (pulverized coal).

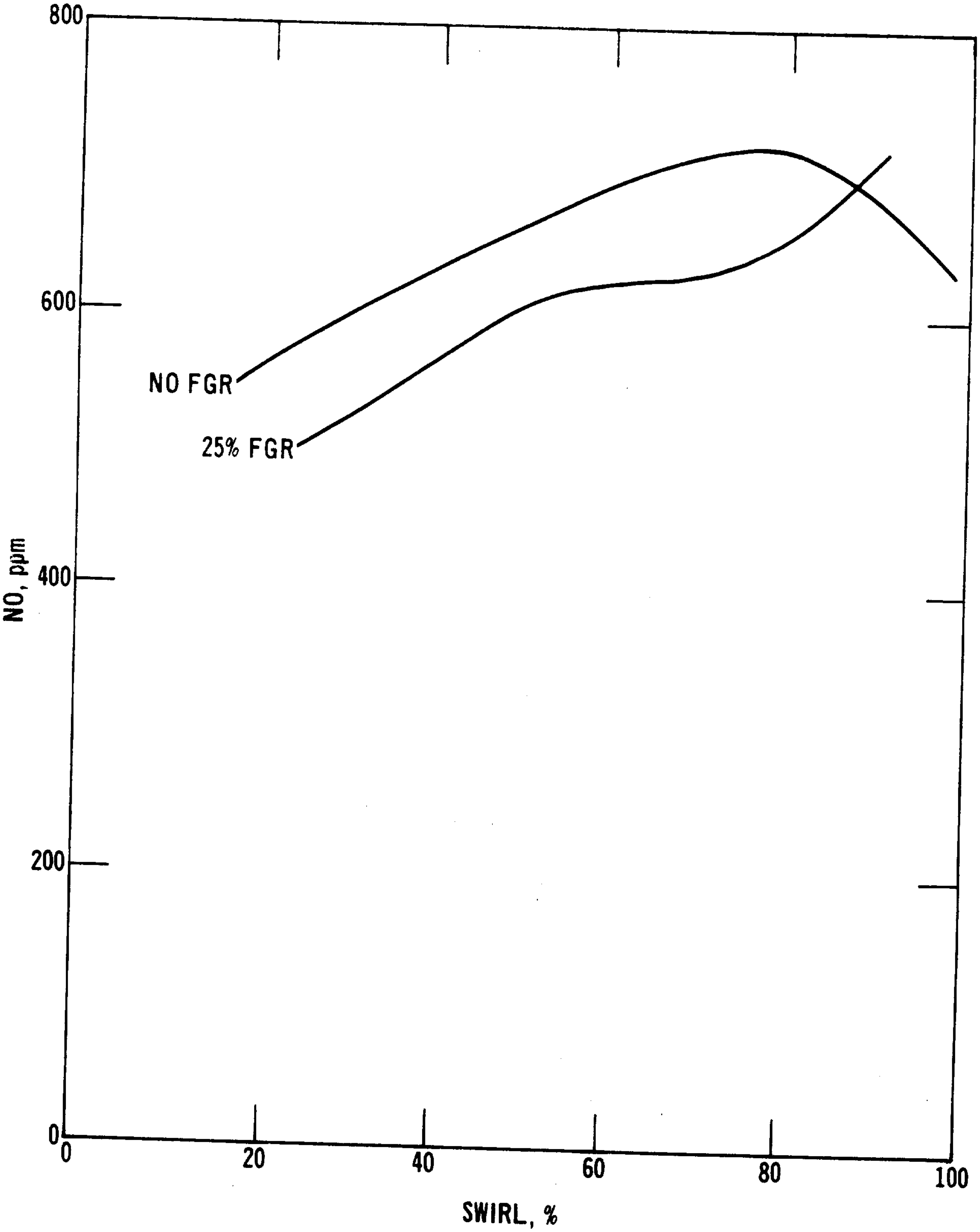

Figure 23. Flue gas recirculation has little effect on NO emissions (pulverized coal).

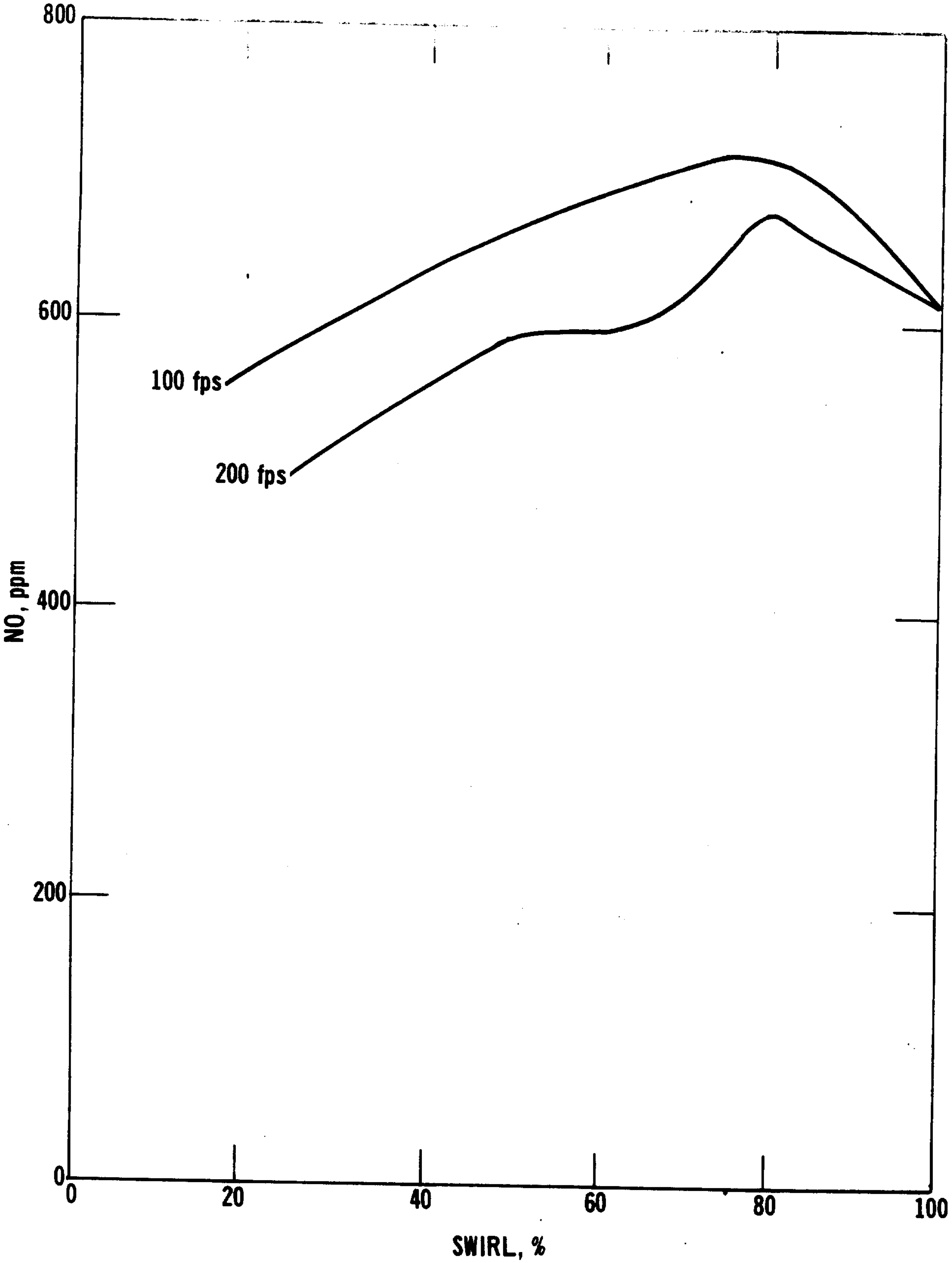

Figure 24. Increasing burner throat velocity has little effect on NO emissions (pulverized coal).

CONCLUSIONS

The following conclusions can be drawn with respect to the experimental system and fuels utilized here.

1. Replacement of the combustion air with a mixture of 21 percent oxygen in argon is a valid technique for determining the percentage of the total NO emissions which are formed by the oxidation of bound nitrogen in the fuel.
2. The conversion of fuel-bound nitrogen to NO during residual oil combustion is:
   a. Responsible for a significant portion (>50 percent) of total NO emissions under all conditions examined.
   b. The major source of NO emissions under conditions of no air preheat.
   c. Relatively insensitive to flame zone temperature in the 3200°F range.
   d. Increased by increasing the excess air.
   e. Relatively unaffected by the addition of flue gas recirculation or by increased burner throat velocity. This is because previous work has shown that these abatement measures reduce bulk flame temperatures.
3. The conversion of fuel-bound nitrogen to NO during pulverized coal combustion is:
   a. Responsible for 80-90 percent of the total NO emissions.
   b. Increased markedly by increasing excess air.
   c. Unaffected by flue gas recirculation or changes in burner throat velocity. This is because, as was shown for oil, the conversion of fuel nitrogen is relatively insensitive to flame temperature.

4. The formation of thermal NO during both oil and coal combustion is:
    a. Increased by increasing the excess air.
    b. Decreased by abatement methods or combustion modifications which tend to decrease the bulk flame temperature. These include adding flue gas recirculation, increasing burner throat velocity, and decreasing air preheat. Further, the effects are in agreement with previous work on thermal NO from natural gas, distillate oil, and propane.
5. There appear to be significant differences in the NO formation characteristics of oil and coal combustion. For example, fuel nitrogen conversion during coal combustion exhibits a much stronger dependence on excess air than that observed with residual oil. The reason for this is not clear; it may relate to differences in the environment where the bound nitrogen species are oxidized.

    Further, at a given set of test conditions (swirl, air preheat, excess air, throat velocity, and heat input) the absolute amount of thermal NO was significantly less for coal combustion than for residual oil combustion. One possible explanation of this is that with coal large amounts of XN are formed quickly (through bound nitrogen oxidation) and this XN reacts with the thermal NO to form the $N \equiv N$ bond.

IMPLICATIONS

The results obtained here suggest several practical implications.

1. Under conditions typical of small, single-burner, *residual-oil* boilers (no air preheat, water walls, and >10 percent excess air), the bulk of NO emissions are probably the result of fuel nitrogen oxidation. Addition of flue gas recirculation, water injection, or any other method that lowers flame temperatures is not likely to lower NO emissions significantly.
2. In multi-burner *residual-oil* systems utilizing high air preheat, flue gas recirculation can be expected to lower (but not eliminate) NO emissions.
3. NO emissions from *coal* combustion can be reduced by reducing excess air.
4. Flue gas recirculation, water injection, or any other method of control that depends on lowering flame temperatures is not likely to be really effective in controlling NO emissions from pulverized *coal* combustion.

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