EPA-600/2-77-025
January 1977

Environmental Protection Technology Series

REDUCTION OF NITROGEN OXIDE EMISSIONS FROM FIELD OPERATING PACKAGE BOILERS: Phase III of III

Industrial Environmental Research Laboratory
Office of Research and Development
U.S. Environmental Protection Agency
Research Triangle Park, North Carolina 27711

RESEARCH REPORTING SERIES

Research reports of the Office of Research and Development, U.S. Environmental Protection Agency, have been grouped into five series. These five broad categories were established to facilitate further development and application of environmental technology. Elimination of traditional grouping was consciously planned to foster technology transfer and a maximum interface in related fields. The five series are:

1. Environmental Health Effects Research
2. Environmental Protection Technology
3. Ecological Research
4. Environmental Monitoring
5. Socioeconomic Environmental Studies

This report has been assigned to the ENVIRONMENTAL PROTECTION TECHNOLOGY series. This series describes research performed to develop and demonstrate instrumentation, equipment, and methodology to repair or prevent environmental degradation from point and non-point sources of pollution. This work provides the new or improved technology required for the control and treatment of pollution sources to meet environmental quality standards.

EPA REVIEW NOTICE

This report has been reviewed by the U.S. Environmental Protection Agency, and approved for publication. Approval does not signify that the contents necessarily reflect the views and policy of the Agency, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.

EPA-600/2-77-025
January 1977

REDUCTION OF NITROGEN OXIDE EMISSIONS FROM FIELD OPERATING PACKAGE BOILERS PHASE III OF III

by

M.P. Heap, C. McComis, and T.J. Tyson (Ultrasystems)
and
R.E. McMillan, R.E. Sommerlad, and F.D. Zoldak
(Foster Wheeler Energy Corporation)

Ultrasystems, Inc.
2400 Michelson Drive
Irvine, California 92664

Contract No. 68-02-0222
ROAP No. 21ADG-043
Program Element No. 1AB014

EPA Project Officer: G. Blair Martin

Industrial Environmental Research Laboratory
Office of Energy, Minerals, and Industry
Research Triangle Park, NC 27711

Prepared for

American Petroleum Institute
1801 K Street, NW
Washington, DC 20006

U.S. Environmental Protection Agency
Office of Research and Development
Washington, DC 20460

ABSTRACT

This report describes the final phase of a program to determine the optimum methods of applying both flue gas recirculation and staged combustion to control NO_x emissions from residual oil-fired package boilers. Experimental investigations were carried out in a laboratory firetube boiler simulator and an application program was conducted on two boilers operating in the field. The ultimate goal of the program was to determine if package boilers could operate in the field after modification to control nitrogen oxide emissions without encountering practical problems.

A 12×10^6 Btu/hr firetube boiler and a 25×10^6 Btu/hr heat output watertube boiler were modified to extract cooled combustion products from the stack and add them to the combustion air in the windbox. The effectiveness of flue gas recirculation as a method of controlling NO_x emissions was found to be dependent upon boiler type. It was most effective in the firetube boiler; approximately 30 percent reduction in emissions was obtained with 40 percent recirculation. NO_x reductions achieved by staged combustion were greater in the field tests than in the laboratory investigation. Forty-five percent reductions were achieved without undue smoke emissions when 70 percent of the stoichiometric air requirements were applied to the burner.

Based upon the results of these investigations it is doubted whether flue gas recirculation is a cost-effective NO_x control technique for residual oil-fired package boilers; however, staged combustion techniques show significant promise for pollution control.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF FIGURES (CONT'D)

LIST OF FIGURES (CONT'D)

LIST OF TABLES

1.0 SUMMARY

1.1 Scope of the Program

There have been a considerable number of investigations detailing the application of flue gas recirculation or staged combustion techniques to control nitrogen oxide emissions from Utility Boilers. In comparison, very little is known concerning the practical aspects of applying these same techniques to package boilers.

A package boiler is described in the ABMA Lexicon as:

> "a boiler equipped and shipped complete with fuel burning equipment, mechanical draft equipment, automatic controls and accessories. Usually shipped in one or more major sections."

Although boilers with a capacity up to 250,000 lbs of steam per hour can be shipped as a single unit by rail or truck, larger units (250,000 to 350,000 lbs of steam per hour) must be modularized. Thus, the term packaged encompasses a wide range of equipment, size range, design type and fuel capability. The investigations described in this report are somewhat more limited in scope since they are mainly concerned with firetube boilers and practical experiments with equipment in the lower size range (up to 25,000 lbs of steam per hour).

This report describes the final phase of a program jointly supported by the API and EPA. These phases were:

- Phase I - Construction of a versatile combustor (EPA Report R2-73-292a)
- Phase II - Experimental investigations in that versatile combustor to determine the optimum method of applying both flue gas recirculation and staged combustion to control NO_x emissions (EPA Report R2-73-292b)
- Phase III - Demonstration of the applications of these techniques to operating boilers in the field and extension of the laboratory experiments.

The ultimate goal of the total program was to demonstrate that package boilers could be operated in the field without practical problems after modification to control nitrogen oxide emissions. The techniques used to control emissions were identified after an extensive series of laboratory investigations with flue gas recirculation and staged combustion as the prime control candidates.

1.2 Laboratory Investigations

Equipment

An axisymmetric calorimetric combustor constructed to simulate the combustion chamber of a firetube boiler was used in the laboratory investigations. All the results were obtained with a modified commercial burner in which the combustion air supplied to the primary and secondary streams could be controlled separately. The combustor was designed to allow the addition of flue gas recirculation or staged combustion air at various locations. The investigations were restricted to measurements of combustion product composition; the major emphasis being nitrogen oxides and smoke.

Results

All attempts to control nitrogen oxide emissions from fuel oil flames were generally limited by excessive smoke formation. The results of the laboratory investigations can be summarized by:

1. NO_x emissions were found to be lower when steam was used as the atomizing medium rather than air.
2. The modified burner, when operated with a primary/secondary ratio of 50:50, did not duplicate the results from an unmodified burner burning the same fuel.
3. As expected, NO_x emissions were found to be higher when burning oil of a higher nitrogen content. However, trends with excess air and load were found to be different for the two oils tested.
4. Emission characteristics were found to be dependent upon oil nozzle capacity.

5. The method of injection and the location of staged air addition was found to have an influence on smoke emission during staging. Radial staged air injection was found to be superior to tangential injection.

6. The effectiveness of staging as an NO_x control technique was improved by modifying conditions at the burner to improve mixing in the early stages of heat release. In this way, lower NO_x concentrations were obtained before smoke emissions became excessive.

The results of the laboratory investigations can be considered encouraging but not representative of the ultimate expectation in NO_x control for oil fired package boilers. However they gave a strong indication of the direction that future work in this area should take. With one exception all other attempts to control NO_x emissions from residual oil fired systems have yielded similar results - a maximum of 50% reduction in NO_x emissions with increased particulate emissions. The problem of NO_x control for nitrogen containing liquid fuels cannot be minimized. Although more is known now of the fate of fuel nitrogen during residual oil combustion than was known when this program began more attention must be paid in the future to minimizing the tradeoff between reduced fuel NO formation and increased soot production.

Limitations of the Laboratory Investigations

It is generally accepted that the formation of nitrogen oxides in the type of combustors studied in this investigation is mainly controlled by turbulent transport which dictates the rate at which fuel and air are mixed. In the present investigation, only a limited series of experiments were carried out in which changes were made to the burner to influence the fuel/air mixing process. It was found that staging performance could be improved significantly by varying the axial and tangential velocity distribution at the burner throat.

The commerical burner used in the laboratory investigation was modified and operated in an unnatural mode with a fixed air distribution between the primary and secondary streams. Apparently this distribution varies with load in the commercial burner which may never operate with an equal flow in the primary and secondary streams. Very little information is available on the influence of fuel type or the atomization method on the effectiveness of control techniques. The investigations were restricted to Input-Output (I/O) parametric studies; information has not been generated to allow an explanation to be given for the observed phenomena. Consequently, it is very difficult to generalize these results to the many different situations likely to be encountered in the field. As the commercial burner was not operated as it would be in the field, it is even difficult to claim that these investigations relate to one class of practical firetube boiler burners.

Perhaps the most serious limitation of the experimental investigation is the restriction to firetube boiler conditions. It may well be that emission control techniques optimized for firetube boilers will not be optimum for watertube boilers. The combustion chamber of a firetube boiler is characterized by a large length to diameter ratio which imposes different requirements for flame shape than those for watertube boilers. The general control principles for the two boiler types will be the same but their method of implementation could be very different.

1.3 Investigations Involving Practical Boilers

Equipment

The choice of boilers tested during the field investigation was dictated in part by convenience to the Foster Wheeler Corporation. The other major criterion was that the tests should be made with two boilers of different design burning the same oil. The two boilers tested were:

- a watertube boiler, 25,000 lbs/hr steam, and
- a firetube boiler, 12,000 lbs/hr steam.

Staged combustion investigations were conducted only in the firetube boiler on an experimental basis. However, both boilers were modified to accept flue gas recirculation to the windbox. These modifications included a fan, ductwork and an automatic control system.

Results

Although only tested in the firetube boiler, control of NO_x emissions by staged combustion techniques proved more successful in the field than in the laboratory investigations. Forty-five percent reductions in NO_x emissions were achieved without undue smoke emissions when approximately 70 percent of the stoichiometric air requirement was supplied through the burner. The improved performance in the field could be attributed to changes made to the secondary air injection system based upon laboratory experience and differences between the laboratory combustor and the field test boiler.

The effectiveness of flue gas recirculation as a method of controlling NO_x emissions was found to be dependent upon boiler type. Figure 1-1 allows a comparison to be made between the influence of FGR on NO_x emissions from the two boilers tested at three loads and 20 percent excess air. The results strongly suggest that FGR is not a cost effective control technique for residual oil fired watertube boilers in this size range. Comparison between the laboratory results and the results of other workers suggests that the results for the firetube boiler are typical and approximately 30 percent reductions in emissions can be expected with up to 40 percent recirculation. This is because reductions in flame temperature (achieved by FGR) have only a minimal effect upon the oxidation of fuel nitrogen to nitric oxide.

The difference in the design of the two boilers and burners probably results in differences in the amount of fuel NO contained in the total emission. As FGR will only be effective in reducing thermal NO formation, it can be concluded that the watertube with its low level of combustion intensity, produced very little thermal NO and boilers of this type would be poor candidates for NO_x control through FGR.

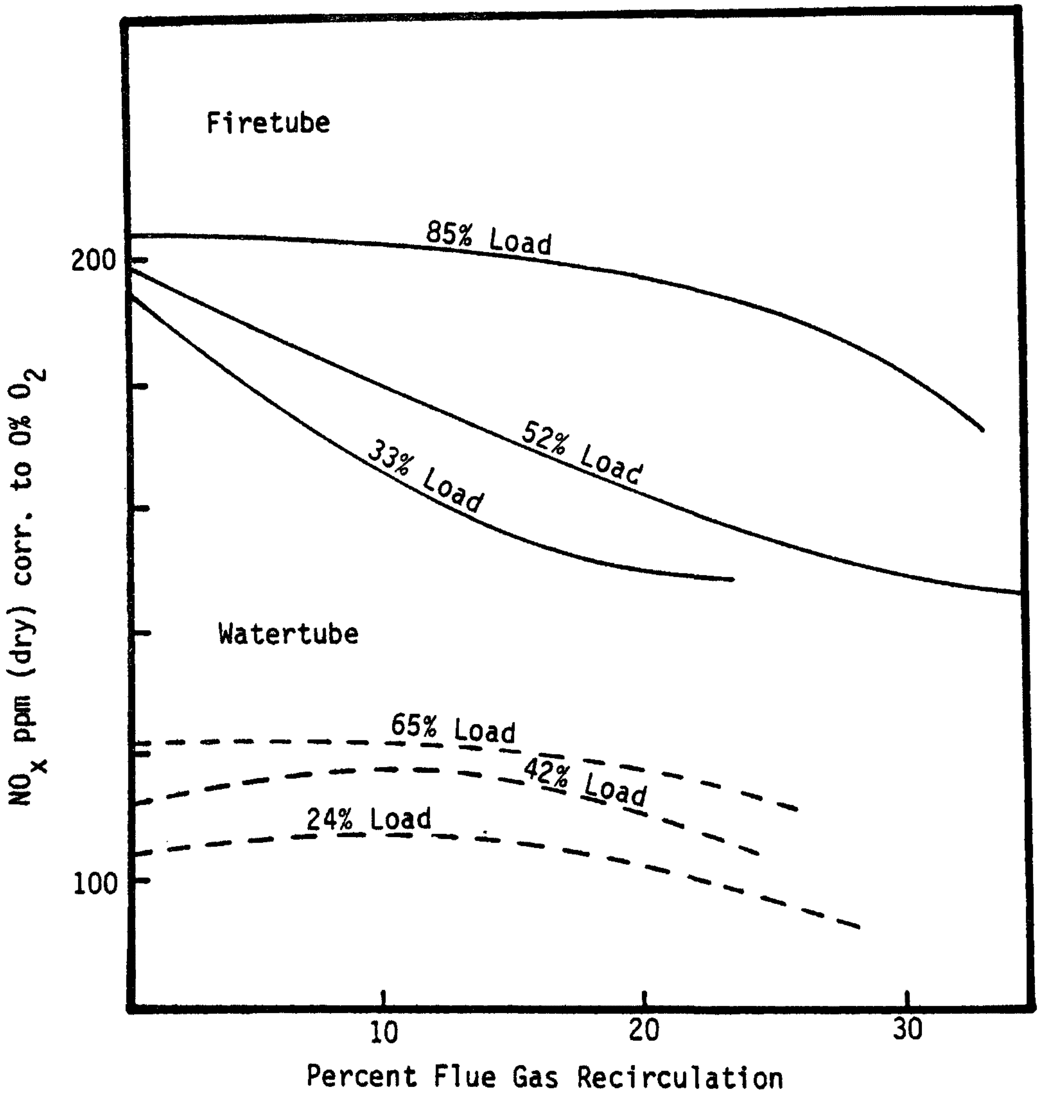

Figure 1-1. Comparison of FGR Effectiveness as a Control Technique for Watertube and Firetube Package Boilers (20 Percent Excess Air)

Problems

The field investigations had two objectives, not only were they planned to serve as a demonstration of NO_x control techniques, but they were also intended to uncover potential practical problems associated with the application of these techniques. The boilers chosen for testing were done so with a knowledge of the requirements of the control system to be installed and yet problems were uncovered that could not have been anticipated. Changes in the geometry of the firetube boiler windbox to accommodate the flue gas recirculation inlet resulted in the initiation of severe pulsations at several boiler loads. Successive modifications succeeded in alleviating the problem but not in eliminating it. Flame instability occurred in the watertube boiler with the addition of greater than 30 percent recirculation at all boiler loads. Without prior direct experience, neither of these practical problems could be predicted. There is no reason to believe that these two boilers represent special cases and it must be expected that similar problems could occur with other units. The age of equipment and the lack of available space in the vicinity of most package boilers will tend to extend the problems of retrofit, particularly with respect to flue gas recirculation even if it were to be shown to be an effective control technique.

On the basis of a field test of two package boilers it is difficult to draw definite conclusions concerning NO_x control techniques. Consequently, the most serious limitation of the field investigation is their restriction to two boilers. No influence of scale can be established (e.g., does a 6,000 lbs/hr of steam firetube behave differently when fitted with FGR or staged combustion equipment than an 18,000 lbs/hr of steam unit).

1.4 NO_x Control Techniques for Package Boilers

The scope of the present study was too limited to establish the absolute cost and the effectiveness of conventional NO_x control techniques as applied to package boilers. However, cost information when considered in relation to the results summarized earlier, does give a strong indication of the area in which future work should be directed.

Summary of Control Technique Costs

The application of NO_x control techniques to package boilers can be considered from three viewpoints:

1. Retrofit of existing equipment already installed.
2. Shop retrofit of a new boiler of existing design before installation.
3. Redesign of the boiler/burner combination.

The direction of this investigation was heavily biased towards the first two alternatives. The cost of equipping the two boilers for flue gas recirculation was approximately $20,000 (1.6 to 0.8 dollars per lb of steam). This cost included design, equipment purchase, fabrication and installation. The cost of installation of a new boiler would be approximately $3.1 per lb of steam. It could be expected that experience would allow economies to be made, thus reducing unit cost. However, based upon this cost comparison, retrofit of medium-sized boilers with FGR would appear to be expensive. This statement is enforced by a recognition that each retrofit in the field would be in some way unique. Consequently, for nitrogen containing fuels alternative, more cost effective control techniques should be sought.

Theoretically, staged heat release offers the possibility to control both thermal and fuel NO and appears to offer more promise. The major drawback appears to be the strong possibility of an emissions tradeoff between particulate and NO_x. The staged combustion investigations described in this study can only be considered as experimental; this is reflected in the cost incurred of $28,000. If a separate air injection were necessary some distance along the firetube, then this could be accomplished in a new boiler without this expense.

Although the cost of the boiler modifications to control NO_x could be reduced somewhat in the future they are still high. Particularly when compared to the initial capital cost. A complete new burner system including fuel nozzle, oil pump, blower controls, etc. could be purchased for the same as the cost of the flue gas recirculation system. Thus, any control technique which could be developed requiring some modification to the existing burner would appear to be the most promising from an econimic viewpoint. Two areas of burner redesign are suggested.

- Modification of the fuel injection system, i.e., atomizer characteristics; and
- Redistribution of the combustion air to prevent rapid mixing of all the air and fuel. This could be accomplished by injecting some of the air around the periphery of the firetube or around the exit of a watertube register burner.

Areas Requiring Further Study

Based upon experience gained during the present investigations, several areas requiring more detailed investigation can be defined.

- Optimization of control technique for fuel-type - if package boilers are to have dual or multi-fuel capability, then the pollution control technique must be optimized for all fuels. This study was too restricted in this manner.
- Optimization of the total combustion system for efficiency and pollutant control - if fuel/air mixing is controlling pollutant formation the total system (e.g., burner and staging equipment) should be optimized. It may not be sufficient to add staging equipment to a boiler without modifying the burner.
- Investigations of staged preheated air addition to reduce soot formation.

- In retrofit situations combustion pulsation and ignition instabilities may limit the application of various control techniques. A basic understanding of these phenomena could allow these problems either to be avoided or to be overcome more easily.
- Efforts must be made to allow the results of this type of investigation to be generalized to a wider class of equipment.

Conclusion

Flue gas recirculation does not appear to be a cost effective NO_x control technique for fuels containing bound nitrogen burning with low intensity in cold wall combustors. Staged combustion has shown greater promise for NO_x control; however, further work is necessary to establish the optimum method of applying staged combustion techniques to package boilers. This work should be directed toward using the burner as the staging device because this will probably be the most economic approach for liquid fuels.

2.0 INTRODUCTION

Steam and hot water boilers with heat inputs ranging from 3 to 400 x 10^6 Btu/hr presently account for approximately 50 percent of the oil fired in stationary boilers and emit 16 percent of the nitric oxides attributed to all stationary boilers. It remains to be proven whether these sources have a more serious impact upon urban pollution problems because they are usually situated at the centers of population. In view of the national energy problems, it is necessary that all attempts to reduce combustion-generated pollutants do not increase fuel usage.

The two previous phases of the present program were concerned with the construction of laboratory simulator and the definition of promising NO_x control techniques[1,2]. These techniques have been applied to two boilers operating in the field. This report deals mainly with the reduction of pollutant emissions associated with oil firing. Further work is in progress (EPA Contract 68-02-1498) to provide more information on the use of staged combustion and flue gas recirculation to control pollutant emissions from packaged boilers. The scope of the work with residual fuel oil will be extended and comparison will be made with natural gas and alcohol fuels.

3.0 SUMMARY OF PHASE II LABORATORY INVESTIGATIONS

During the second phase of this three-phase program investigations were carried out in a specially constructed laboratory combustor to establish NO_x control techniques suitable for oil-fired package boilers. Four control options were investigated:

- Burner Modifications. The commercial burner had been modified to independently vary the swirl level and the air distribution in the primary and secondary ducts. The other parameters investigated were associated with the atomization of the fuel oil, viz. oil temperature, atomization air pressure and the use of nitrogen as an atomizing fluid.
- Flue Gas Recirculation. The influence of the addition of cooled combustion products to the combustion air was investigated. The combustion products could be mixed with the primary, secondary or total air streams, injected separately through the gas ring or through ports in the refractory burner throat.
- Staged Combustion. Second stage air was added through sidewall injectors or from a rear boom to allow the influence of staged heat release to be investigated.
- Combined Flue Gas Recirculation and Staging. The influence of simultaneous addition of cooled combustion products and staged heat release. It was intended that these investigations would define the optimum NO_x control technique which could then be tested in the field.

The experimental system used in the laboratory investigations has been described in detail elsewhere(1). The axisymmetric calorimetric combustor was custom-built to enable recirculated products and second stage air to be injected at various locations. A schematic layout of the combustor and the associated air and flue gas supply system is presented in Figure 3-1. The total combustion air supply could be divided into two variable streams, referred to as first and second stage air. As indicated in Figure 3-1, the first stage air was supplied through the burner and the second stage air could be

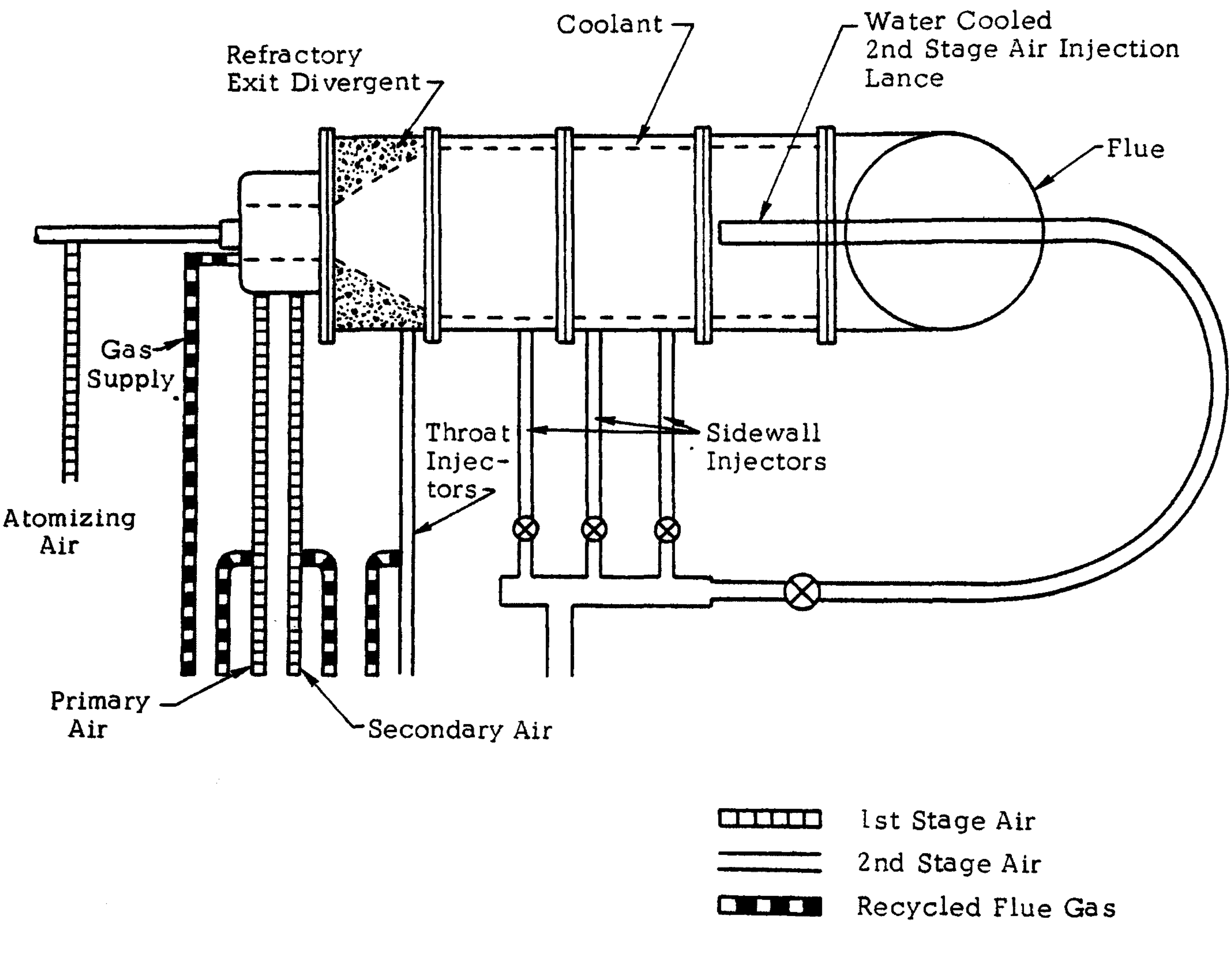

Figure 3-1. Laboratory Combustor - Schematic

injected either through throat injectors, sidewall injectors or through a lance inserted from the rear of the combustor. Axial movement of this lance allowed the influence of the position of second stage air injection to be investigated. The combustor was fired by a modified commercial burner, the details of which are presented in Figure 3-2. The major modification allowed the total air supplied to the burner (first stage air) to be divided into primary and secondary air streams. The primary air flow was essentially axial; some rotation could be imposed upon the secondary stream by closing the inlet air damper while maintaining the mass flow rate constant. Recycled combustion products could be added to the primary, secondary or the total air streams or injected separately through the gas ring or the throat injectors.

Muzio et al[3] have discussed the complete laboratory results in detail and only those results which have implications for the field demonstrations will be summarized in this report.

Burner Modifications

Smoke and NO_x emissions from No. 6 fuel oil were found to be very sensitive to the primary-secondary air ratio. NO_x emissions were reduced and smoke emissions were increased as the proportion of air in the primary stream was reduced. In retrospect, these results are not compatible with the field investigations since the burners used in the field tests did not have separate primary and secondary air streams. Emissions were insensitive to variations in secondary swirl at 50 percent primary air flow. Increasing atomizing air pressure from 14 to 36 psig caused a reduction in the NO emission on the order of 20 percent. However, changes in oil temperature were found to have minimal effects.

Flue Gas Recirculation

Investigations with three fuels, natural gas, No. 2 and No. 6 fuel oil, indicated that the effectiveness of flue gas recirculation as an NO_x control technique was limited by the nitrogen content of the fuel. Flue gas recirculation has only a minor influence on the conversion of fuel bound nitrogen to nitric oxide. Thus, its effectiveness as a control technique is minimal if the major portion of the NO_x emission is attributable to fuel nitrogen oxidation. During

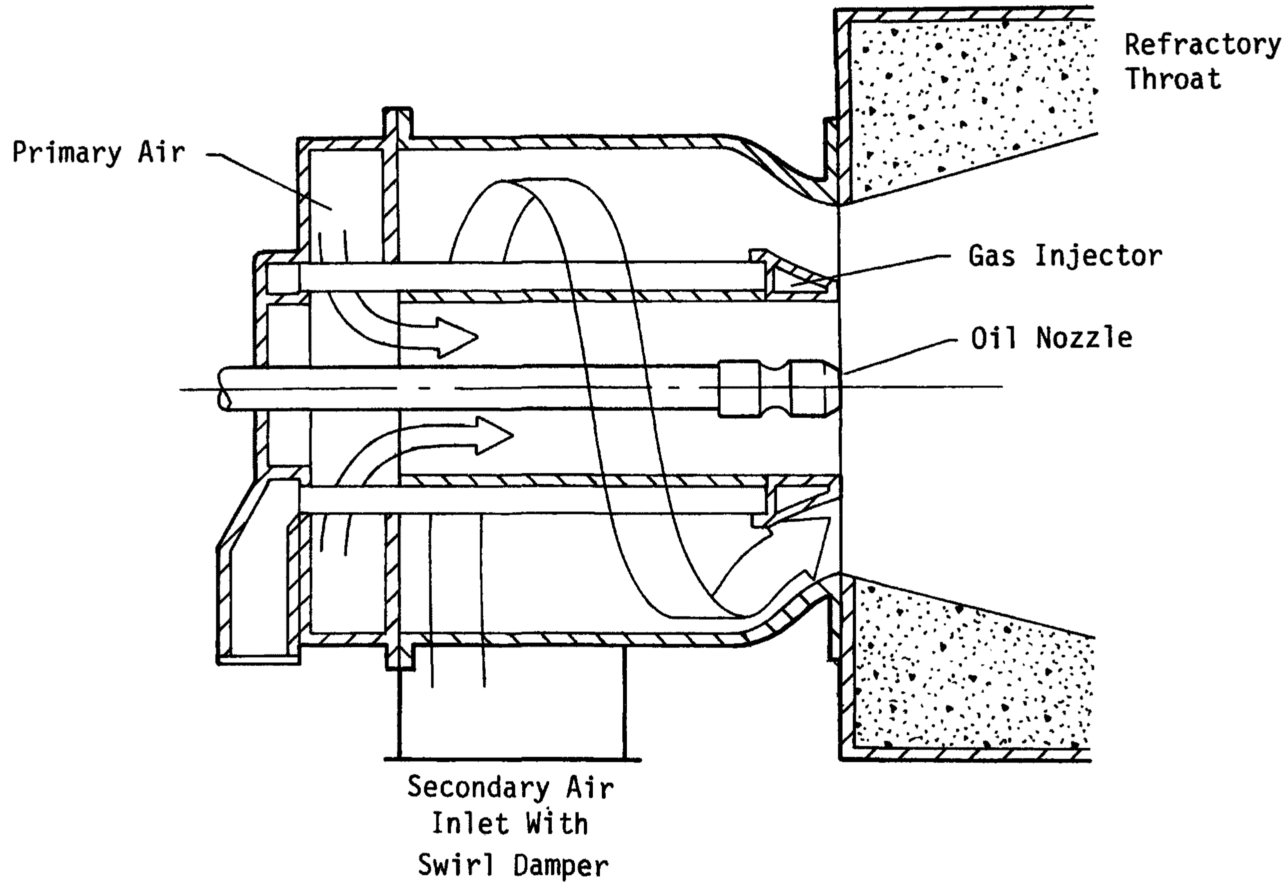

Figure 3-2. Sketch of Modified Commercial Burner Used in the Laboratory Investigations

the Phase II investigations flue gas recirculation was added at five separate locations and the results indicated that only three of these locations were effective and only two could be considered as having practical value. Figure 3-3 gives an example of the influence of percent recirculation on NO and smoke emissions for fixed load, excess air, and primary/secondary air distribution. The maximum reduction was observed when the combustion products were injected through the gas ring. This reduction was accompanied by a visual degeneration of combustion conditions and an increased smoke emission and cannot, therefore, be considered suitable for practical equipment. The results suggest that the addition of cooled combustion products to the total air supply will provide the most effective use of FGR as an NO_x control technique. Under certain circumstances an optimum recirculation rate was found; if high recirculation rates were added to the primary air stream, emissions tended to increase. This can be attributed to increases in the rate of air/fuel mixing in the early stages of heat release.

Staged Combustion

The effectiveness of staged heat release as a control technique was limited by the direct tradeoff between reduced NO and increased smoke emissions. Only modest reductions were obtained before smoke emissions became excessive. The optimum location for staged air injection was approximately two combustor diameters downstream from the fuel nozzle. These results were disappointing, particularly in the light of the results reported by Siegmund and Turner[4]; however, it should be noted that these workers had to significantly downrate the boiler to achieve these results and the staged air was available at 50 psig. Smoke emissions could be reduced somewhat by lining the inside of the combustor with refractory, but this did not improve the effectiveness of staging since baseline emissions were increased. It should be noted that during these investigations no changes were made to the burner during the staging process.

Combined Methods

Combining staged combustion with flue gas recirculation was found to be an effective method of reducing NO_x emissions without producing excessive smoke.

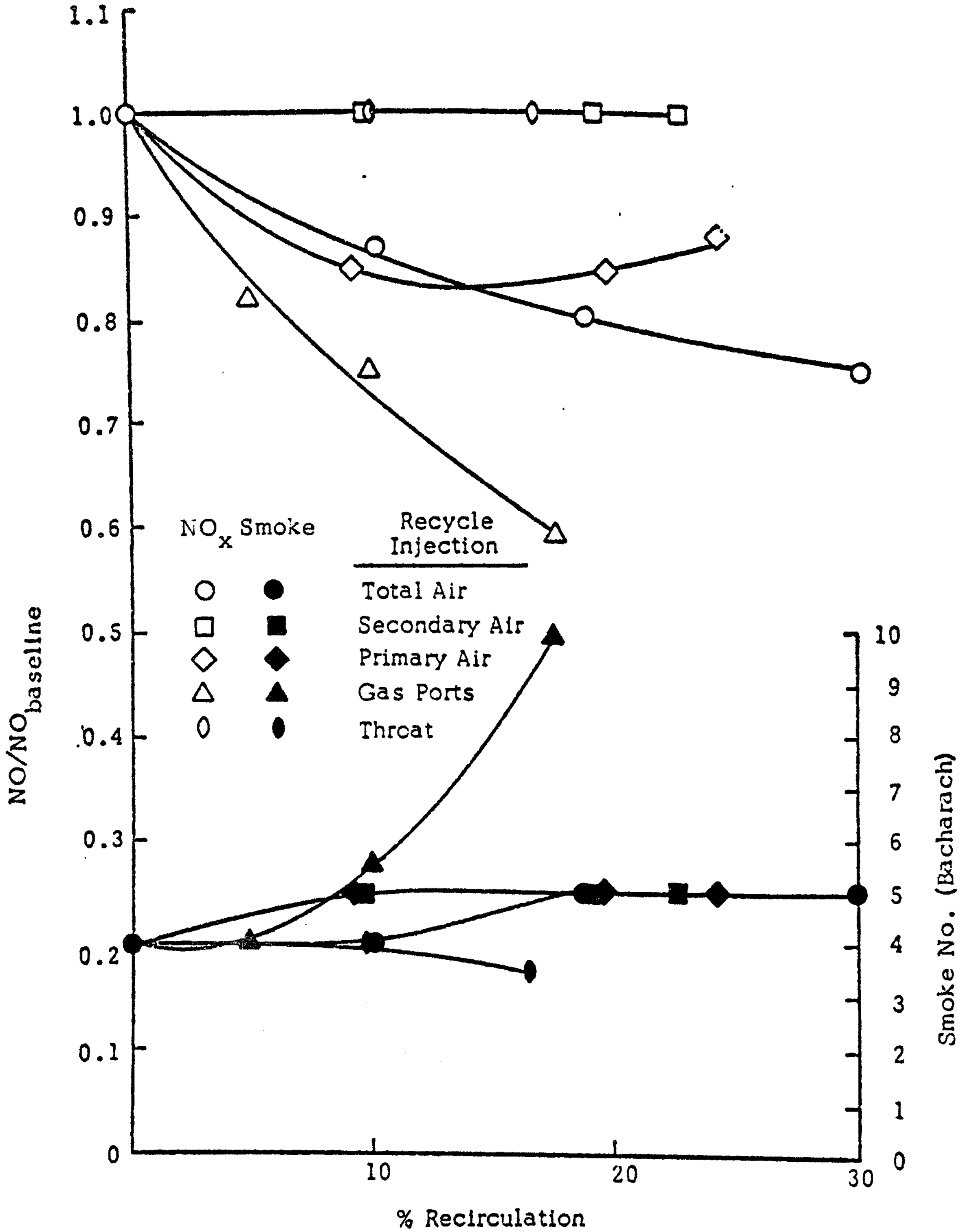

Figure 3-3. The Influence of Flue Gas Recycle Injection Location on NO_x and Smoke Emissions (No. 6 Fuel Oil, 17 Percent Excess Air, Load 3.4×10^6 Btu/hr and Baseline Emission 273 ppm)

$$\left(\% \text{ Recirculation} = \frac{\text{mass of recirculated products}}{\text{mass of air} + \text{mass of fuel}} \times 100 \right)$$

A major question concerning the results of these investigations and one which will be returned to later in this report is their applicability to practical systems. Although a commercial burner had been used in the laboratory investigations, questions arise as to its typicality and to what extent the minor modifications, carried out to provide experimental versatility, had influenced its performance. It is doubtful whether this particular burner would operate in the field with the combustion air divided equally between the primary and secondary streams and almost certainly the relative air flows will change with load. Also, the majority of firetube boilers are fired by burners which do not have separated primary and secondary air streams.

4.0 LABORATORY INVESTIGATIONS

The API-EPA Steering Committee expressed concern over the modest NO_x reductions achieved in the Phase II laboratory investigations. It could not be established whether these results were attributable to fuel oil properties or to peculiarities in the experimental combustor. Consequently, it was decided that the third phase of the project should proceed along two parallel paths.

- Additional laboratory experiments to provide further information in an attempt to explain the Phase II observations.
- Continue with the field demonstration as originally intended although it was recognized that the staged combustion investigations would necessarily be experimental and could not be considered as a demonstration of a practical system.

The laboratory investigations carried out during Phase III were planned to investigate the influence of fuel oil properties, the method of fuel oil atomization and to provide further information on the application of staged combustion control techniques to oil field package boilers.

4.1 The Influence of Fuel Oil Type

The EPA-Combustion Research Section operates an almost identical experimental combustion system to that described in Section 3[5]. The EPA combustor is fired by the same model commercial burner as used at Ultrasystems, but in an unmodified state, which represents the only significant difference between the two systems. However, the performance of the two combustors was found to be very different; in particular, smoke emissions were considerably lower from the EPA combustor. Tests were carried out at Ultrasystems with the oil used in the EPA combustor to provide a direct comparison of the influence of oil type on pollutant emission. Table 4-1 compares the properties of the two oils.

Table 4-1. Properties of the "EPA" and "Ultrasystems" No. 6 Fuel Oil

Characteristics	Ultrasystems	EPA
Gravity, ^{o}API	16.7	Not Available
Flash Point, PMCC ^{o}F	165	
Pour Point, ^{o}F	80	
Viscosity SSF at 122 ^{o}F, sec	97	
Heat of Combustion, gross Btu/lb	17,746	
Ash %	0.02	
Sulphur %	0.42	1.02
Nitrogen % (by Keldahl)	0.36	0.20
Carbon %	87.68	86.81
Hydrogen %	11.61	12.37

The influence of excess air on the emission of NO_x and smoke for the two oils as a function of load is presented in Figure 4-1. Contrary to expectations, smoke emissions from the two oils were generally similar and at high load the EPA oil gave a higher smoke emission than the Ultrasystems' oil. Similar trends were found for NO_x emissions, although the absolute levels reflected the difference in nitrogen content of the two oils. The influence of the primary/secondary air ratio on NO_x emissions was found to be markedly different for the two oils (see Figure 4-2). The emission characteristics for the EPA oil show a similar trend with load whereas NO_x emission from the Ultrasystems' oil appears to be much more sensitive to primary/secondary ratio at low loads. These results could be attributable to variations in the atomization properties of the oils. However, if this were so, it might be reasonable to expect that the smoke emissions would also be different.

The emission characteristics of the unmodified commercial burner can be seen in Figure 4-3; emissions decrease as the load increases. This is contrary to experience with the modified burner. Emissions increase as the load increases when the primary/secondary ratio is maintained constant. If the relevant results from Figure 4-2 are plotted on Figure 4-3 they suggest that the unmodified commercial burner does not operate with the combustion air split 50:50 between the primary and secondary stream. It appears that the unmodified burner operates at

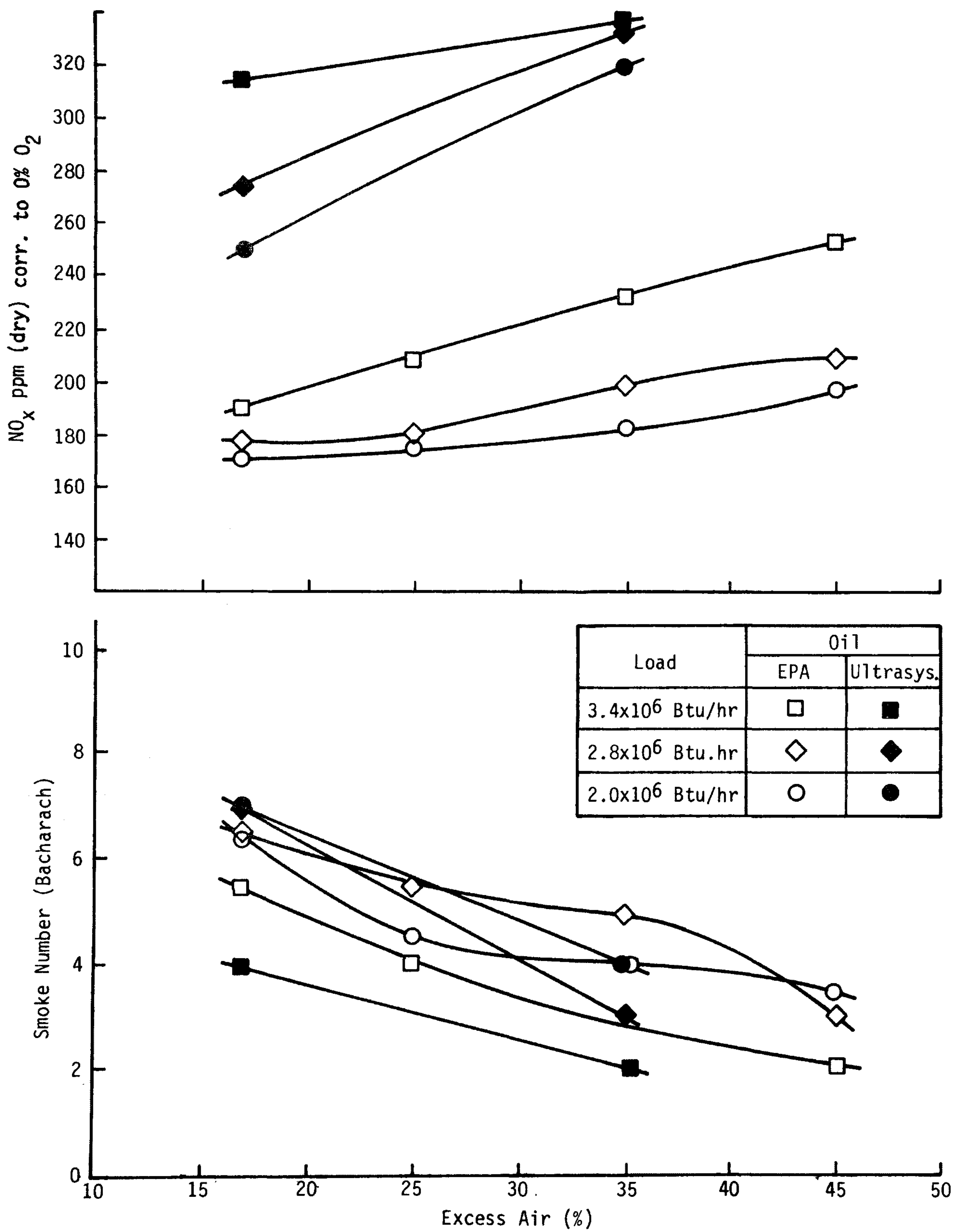

Figure 4-1. Comparison of Oil Types - the Effect of Excess Air on Emission

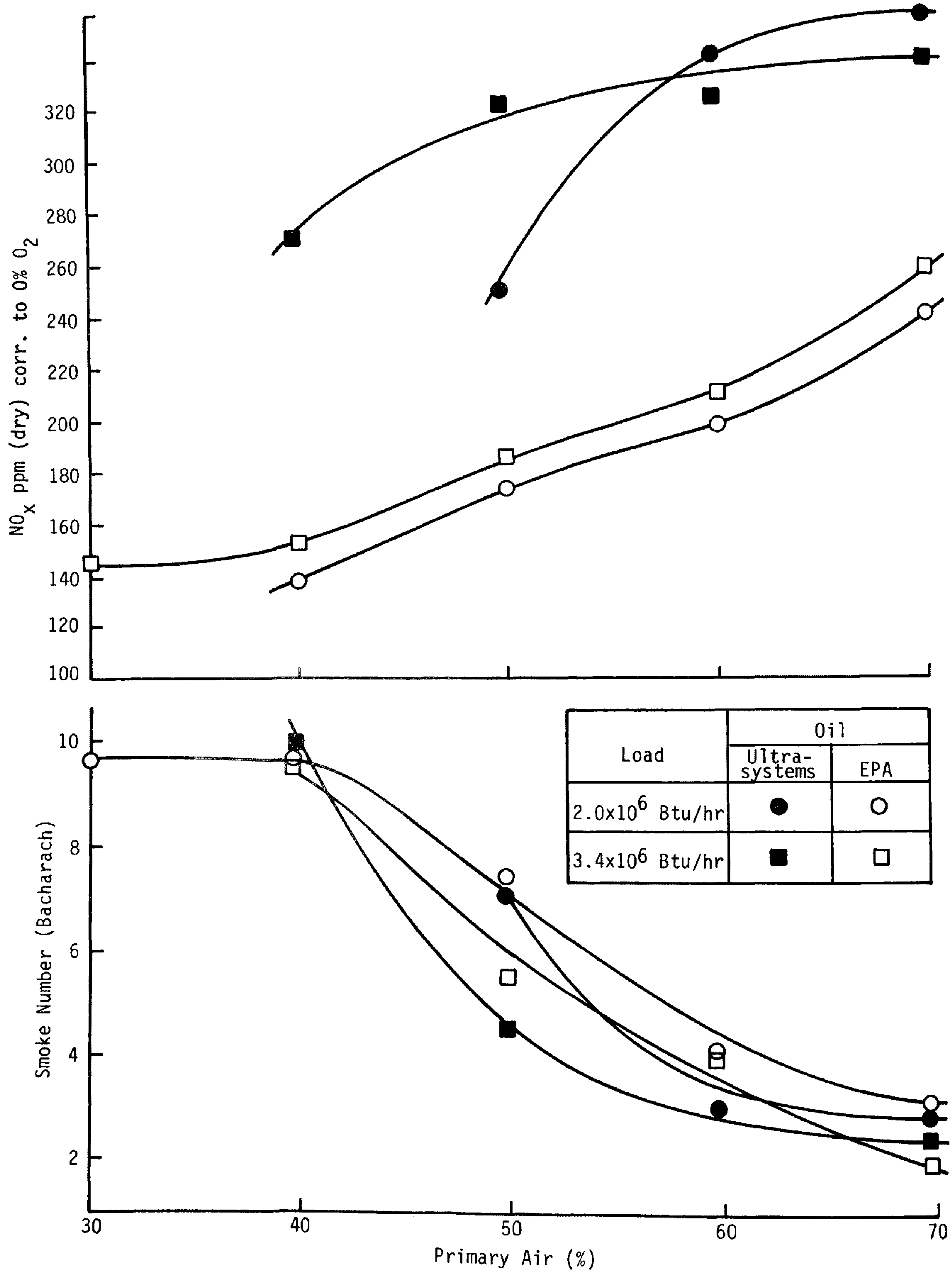

Figure 4-2. Comparison of Oil Types - the Effect of Primary/Secondary Air Ratio

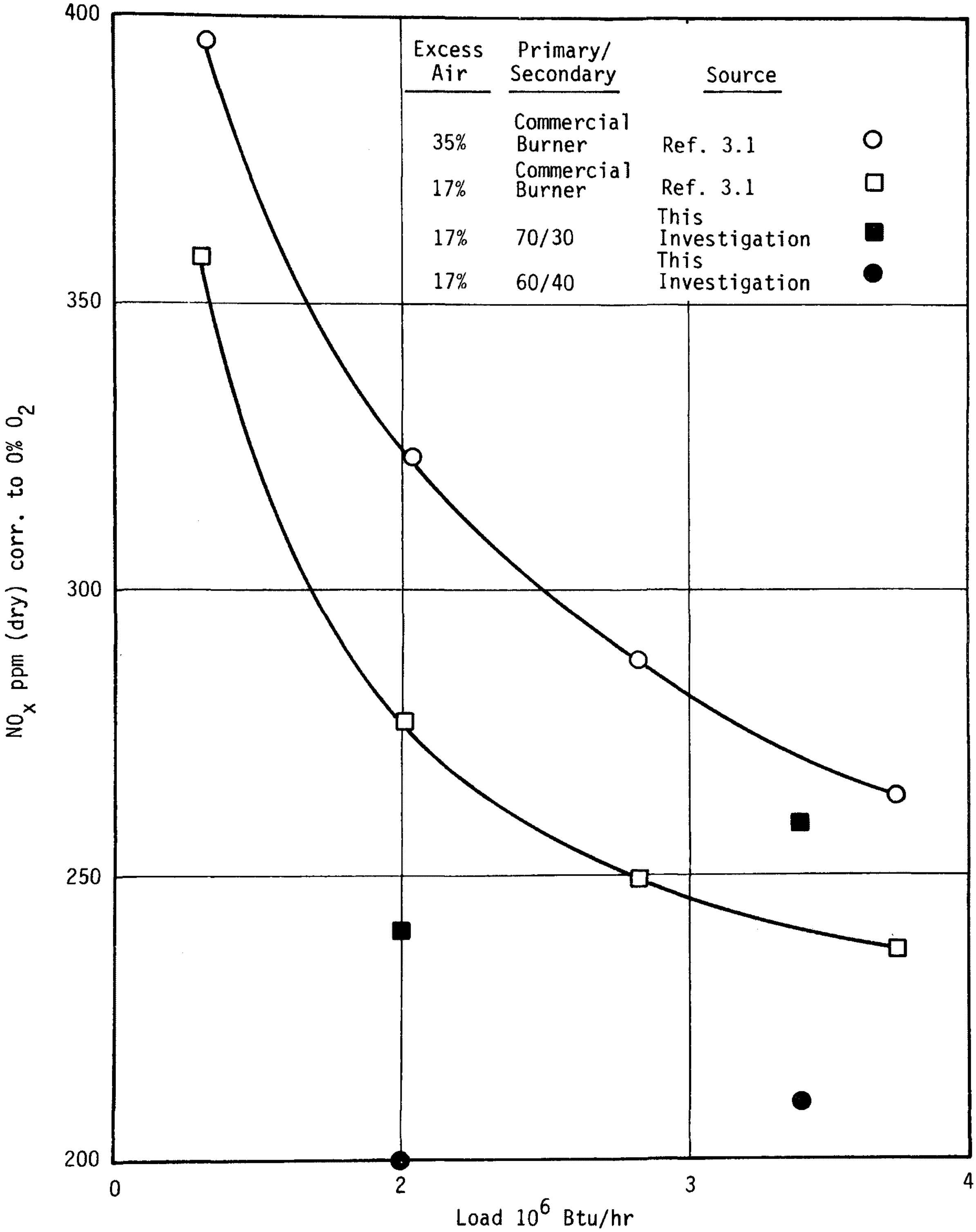

Figure 4-3. Operation of the Unmodified Burner

higher primary air flows at low loads (P/S of 80/20) and at a P/S of approximately 65/35 at maximum load. This trend is consistent with common practice as the increase in primary air flow would act to reduce smoke emissions at low load.

In general, the tests with the EPA oil were inconclusive. It was thought that the "Ultrasystems" oil had a higher smoking potential than the EPA oil; however, the results did not substantiate this hypothesis. Perhaps the most confusing set of results refer to the influence of primary/secondary ratio on NO_x emissions; no explanation can be given for the completely different NO_x emissions characteristics of the two oils.

4.2 Atomization Parameters and Pollutant Formation

The larger size ranges of package boilers frequently utilize steam as the atomization medium and the oil nozzle fitted to the commercial burner used in this investigation was equally suitable for either air or steam. Figures 4-4 and 4-5 compared the emissions characteristics of the laboratory combustor using air and steam as atomizing agents. NO_x emissions were generally lower with steam and the smoke emissions higher. Trends with variation of the primary/secondary ratio were similar for both air and steam. However, there appears to be an optimum steam pressure of approximately 35 psig for minimum NO_x emissions.

All of the Phase II data had been obtained with one 80 gallon per hour nozzle. A duplicate nozzle was obtained to determine whether or not the emission data could be duplicated for two nozzles of the same capacity. Similar trends were observed for both nozzles (see Figure 4-6).

The characteristics of a 100 gallon per hour nozzle are compared with those of the 80 gallon per hour nozzle at a fixed atomizing air pressure (20 psig) in Figure 4-7. NO_x emissions are similar for the two nozzles at high and low primary air ratio. However, the larger nozzle produces 80 ppm more NO than the smaller nozzle at a primary/secondary ratio of 60/40. Figures 4-8 and 4-9 compare the performance of the 100 gallon nozzle with either air or steam as the atomizing medium. In general, smoke emissions were lower with the larger nozzle than with the smaller nozzle which was the specified size for the nominal burner capacity.

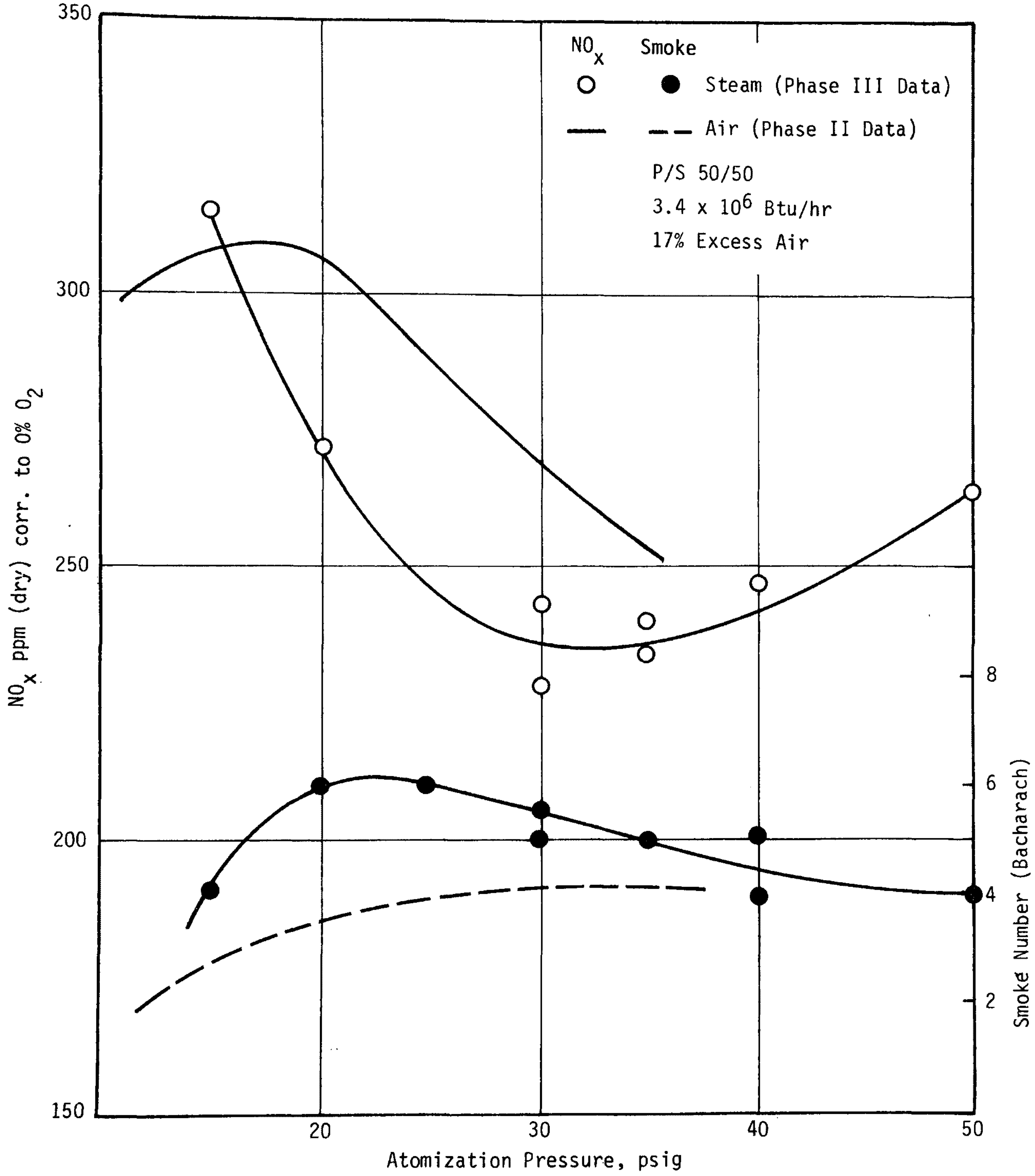

Figure 4-4. The Influence of Atomization Method

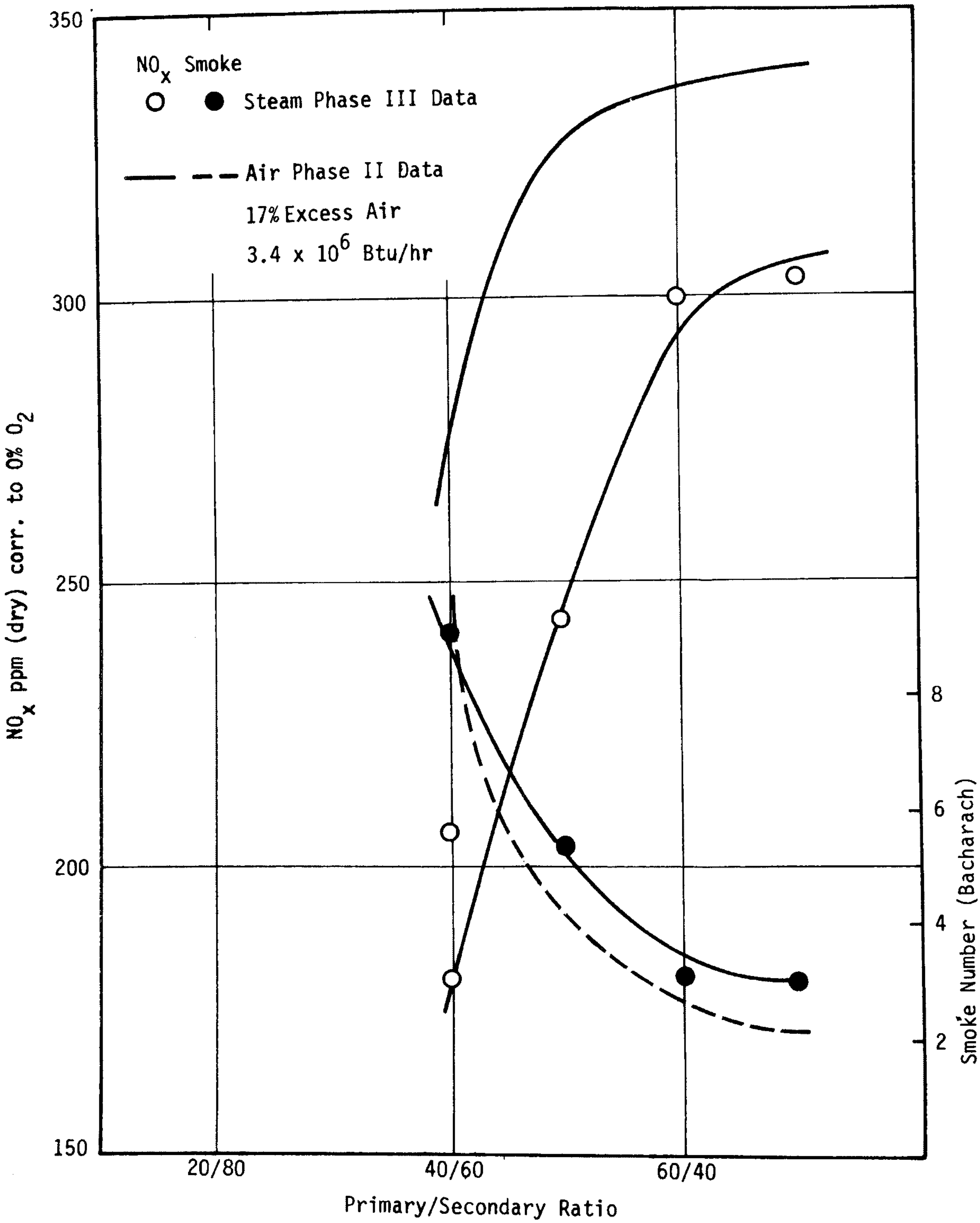

Figure 4-5. The Influence of Atomization Medium

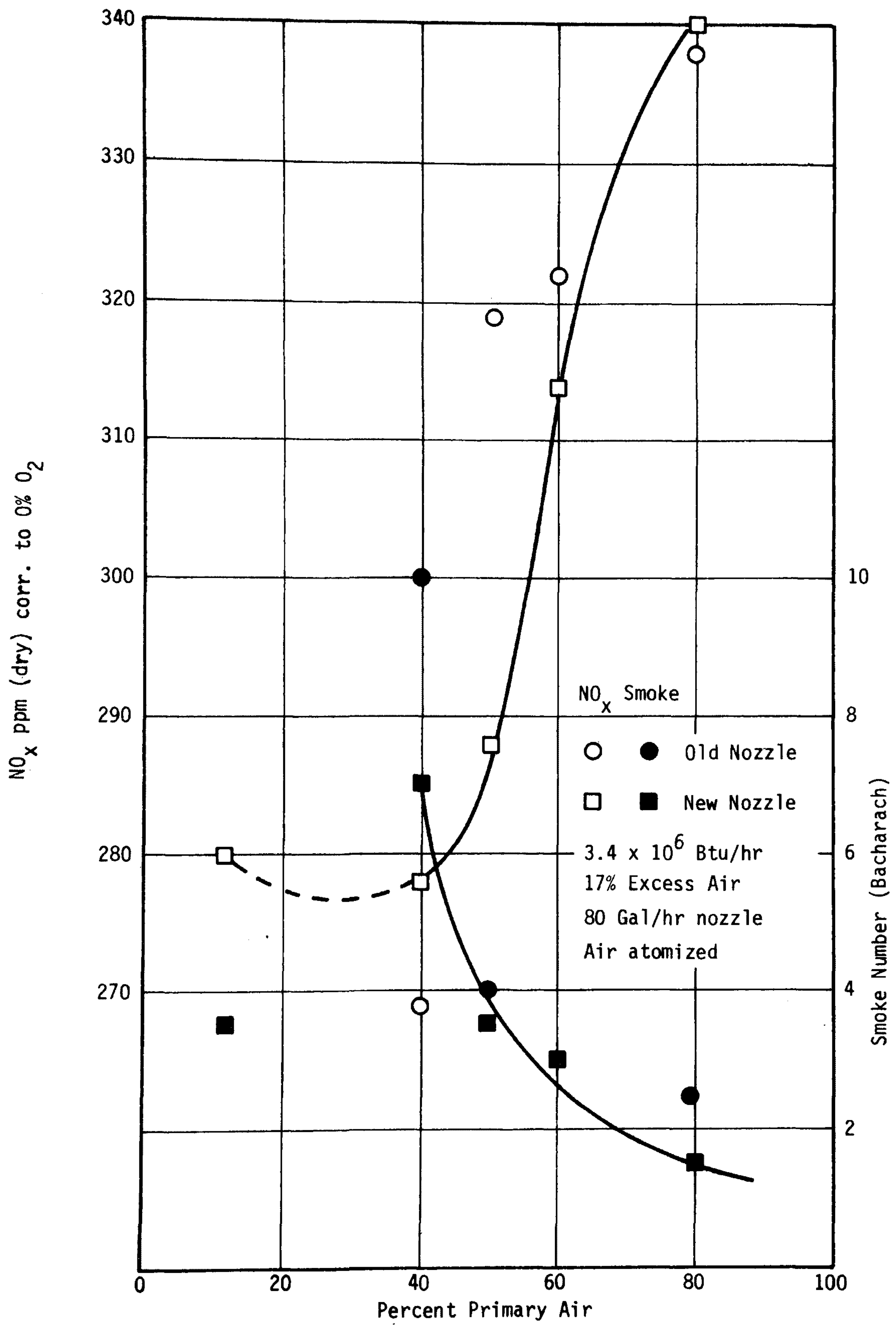

Figure 4-6. Reproducibility Tests - Duplicate Oil Nozzles

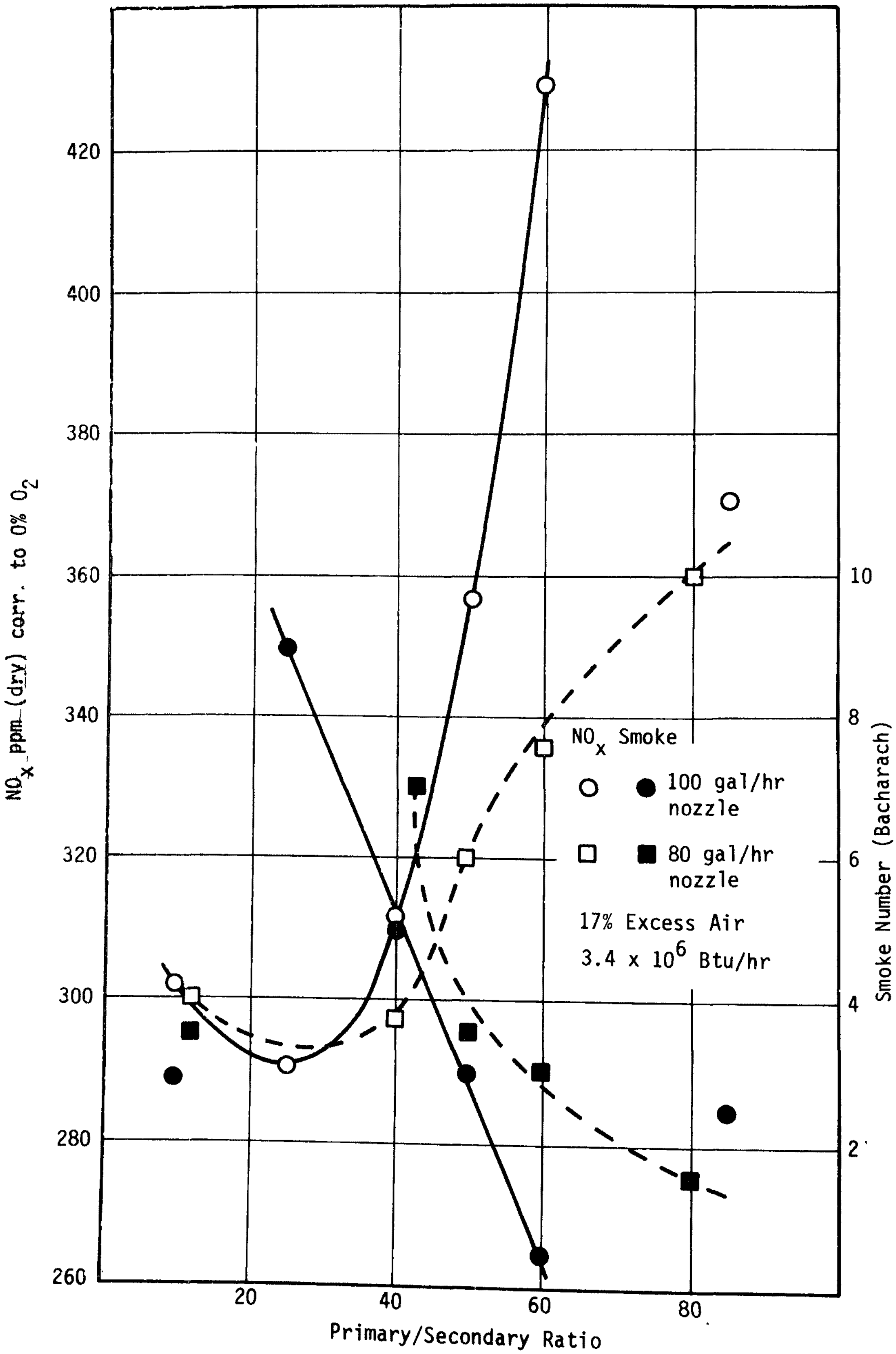

Figure 4-7. The Influence of Nozzle Capacity

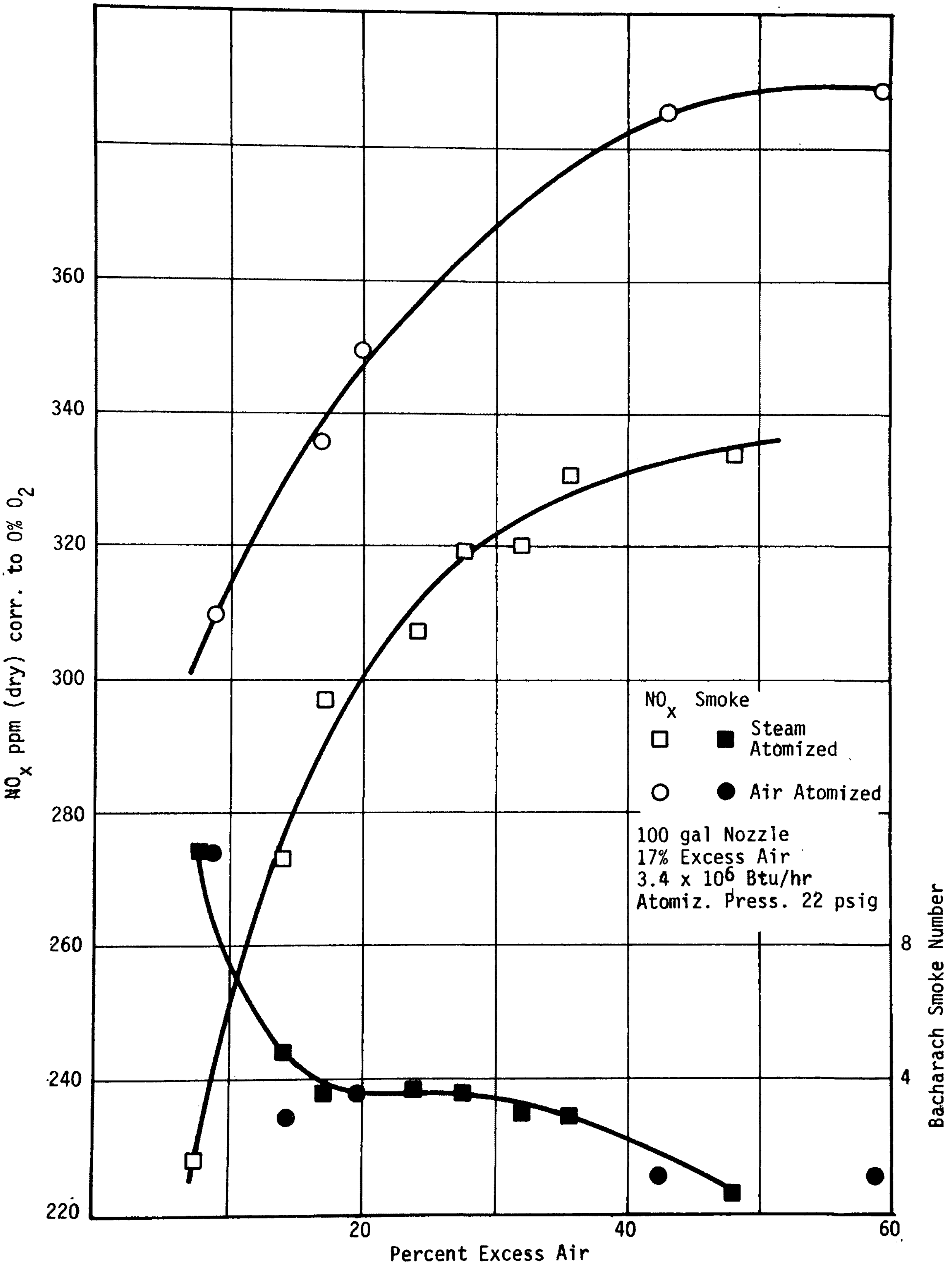

Figure 4-8. The Influence of Atomizing Medium

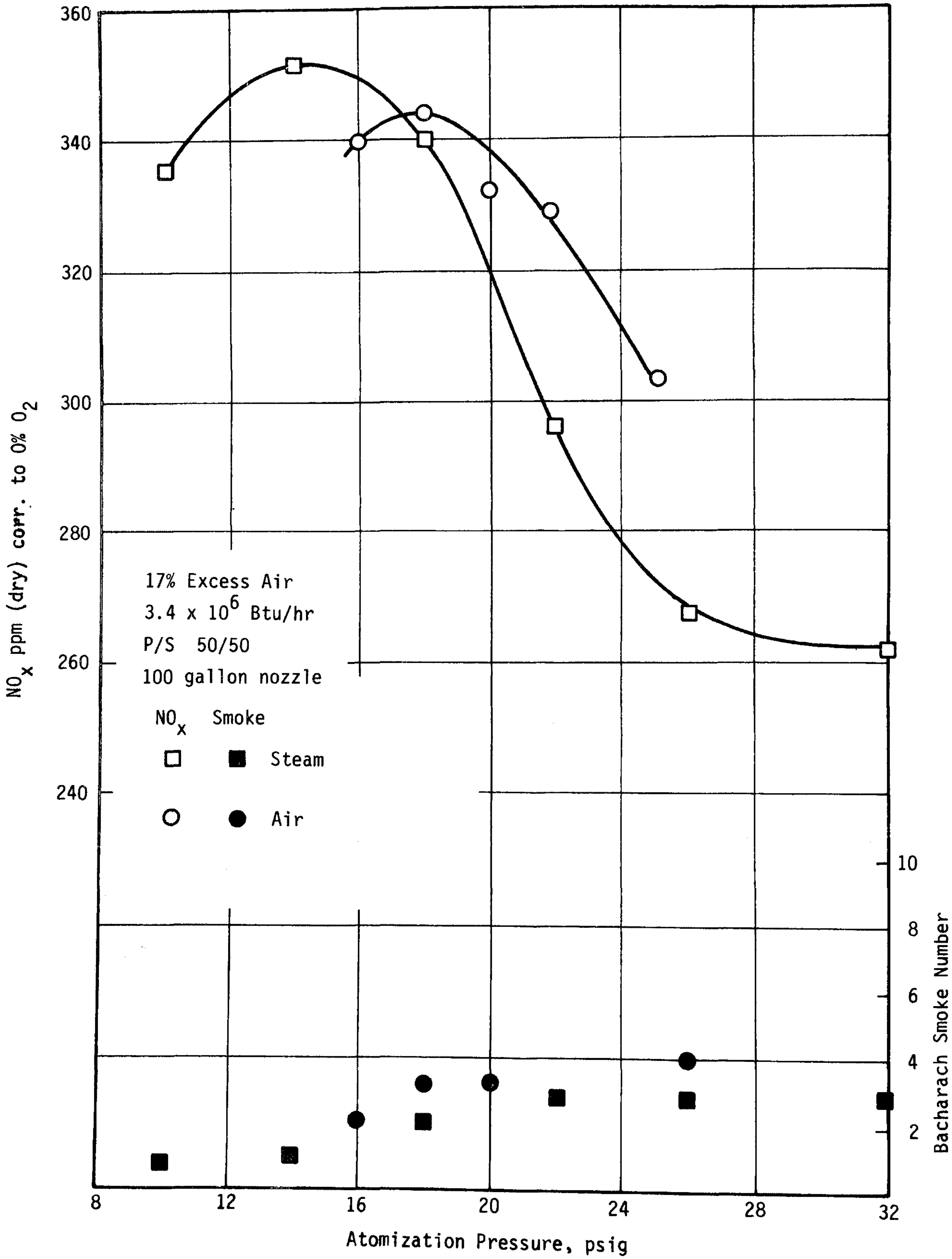

Figure 4-9. The Influence of Atomization Medium

The influence of swirl level and excess air on emissions for the large nozzle are compared in Figure 4-10. The "swirl" level had only a minor influence on emissions with the 100 gallon nozzle. This was similar to observations made during the Phase II investigations.

No attempt was made to vary the spray angle of the nozzle; all the results reported to date refer to an included cone angle of 70^{o}. Muzio et al[3] suggested that the decreased NO_x emission produced with increasing atomization air pressure resulted from the narrowing of the spray angle. This effect had been observed when the oil was sprayed in the open air. If the spray angle is reduced, then NO_x emissions would tend to be reduced. Heap et al[6] have demonstrated that for fixed air flow conditions NO_x emissions from heavy fuel oil flames are reduced as the spray angle is reduced when either mechanical or steam atomization was employed. Reduced emissions can be explained by postulating that the narrower spray angles produce more rich conditions in the early stages of combustion, and therefore, less fuel NO is formed.

4.3 Staged Combustion Investigations

The majority of the Phase II staged combustion investigations involved a fixed set of burner conditions (primary/secondary ratio, atomizer size, atomizing air pressures, swirl damper setting). In the Phase II investigations the sidewall staging injectors were positioned close to the burner. In an attempt to provide further information on staging prior to the field tests, the location of the first series of sidewall injectors was changed. The first and last coolant sections in the experimental combustor were exchanged, thus the sidewall staging injectors 1, 2 and 3 were situated 2.2, 2.6 and 3.5 combustor diameters from the fuel injector. No changes were made to the burner, and the conclusions with this new location of the staging injectors were essentially the same as those reported in Section 3.0 - modest reductions in NO_x emissions were achieved with attendant increases in smoke emissions.

It is generally accepted that reductions in NO_x emissions from No. 6 fuel oil flames by staging the heat release are primarily due to reducing the net rate of fuel nitrogen oxidation. This is accomplished because the percentage conversion

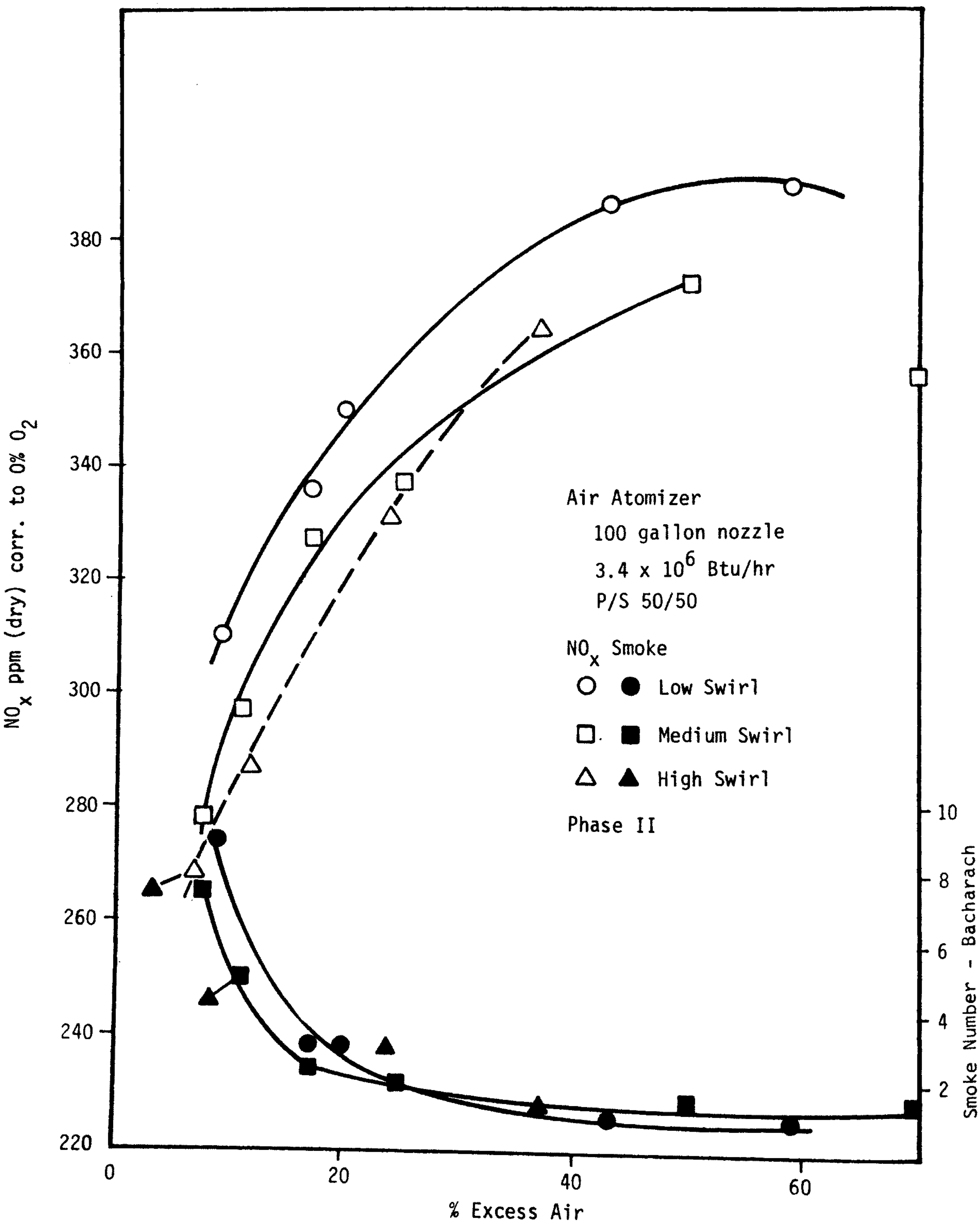

Figure 4-10. The Influence of Swirl and Excess Air

of fuel nitrogen compounds to NO is dependent upon the stoichiometry of the heat release zones. The general requirements of any staging system are:

- a primary region which allows complete reaction of all fuel nitrogen intermediates under fuel rich conditions;
- a secondary region in which the staged air is rapidly mixed with the products of the primary region, thus providing the maximum opportunity for carbon burnout since those conditions in the primary region which restrict NO formation also promote soot formation.

Since the burner was originally designed to satisfy criteria which did not include staged air addition, it could be expected that the results with staging would not be optimum unless attention was paid to the fuel/air mixing process in the primary region. A series of exploratory investigations were carried out in which burner conditions were varied in an attempt to improve staging performance.

Primary/Secondary Ratio. Muzio et al[3] report that changing the primary/secondary ratio during staging had a negligible effect upon NO emissions. Since it has been shown that unstaged NO_x and smoke emissions are lower than baseline emissions (50/50/ P/S ratio) with primary/secondary ratios less than 20/80, it is reasonable to expect that some effect of primary/secondary ratio would be evident during staging. Exploratory measurements confirmed that there was an effect of primary/secomdary air flow during staging. Lower absolute NO_x levels could be achieved at lower smoke numbers with low primary air flows (see Figures 4-13 and 4-14).

Atomization Pressure. The influence of both atomization pressure and primary/secondary ratio can be judged from the results presented in Figures 4-11 and 4-12. With a total of 40 percent of the combustion air divided equally between staging injectors 2 and 3, (i.e., 70 percent of the stoichiometric air requirement at the burner) lower NO_x emissions at lower smoke numbers was observed at a primary/secondary ratio of 15:85 than at a ratio of 85:15.

Nozzle Capacity. Table 4-2 compares NO_x and smoke emissions for various staging conditions with three oil nozzle sizes for steam and air atomization. Under these conditions, it appears that steam atomization allows

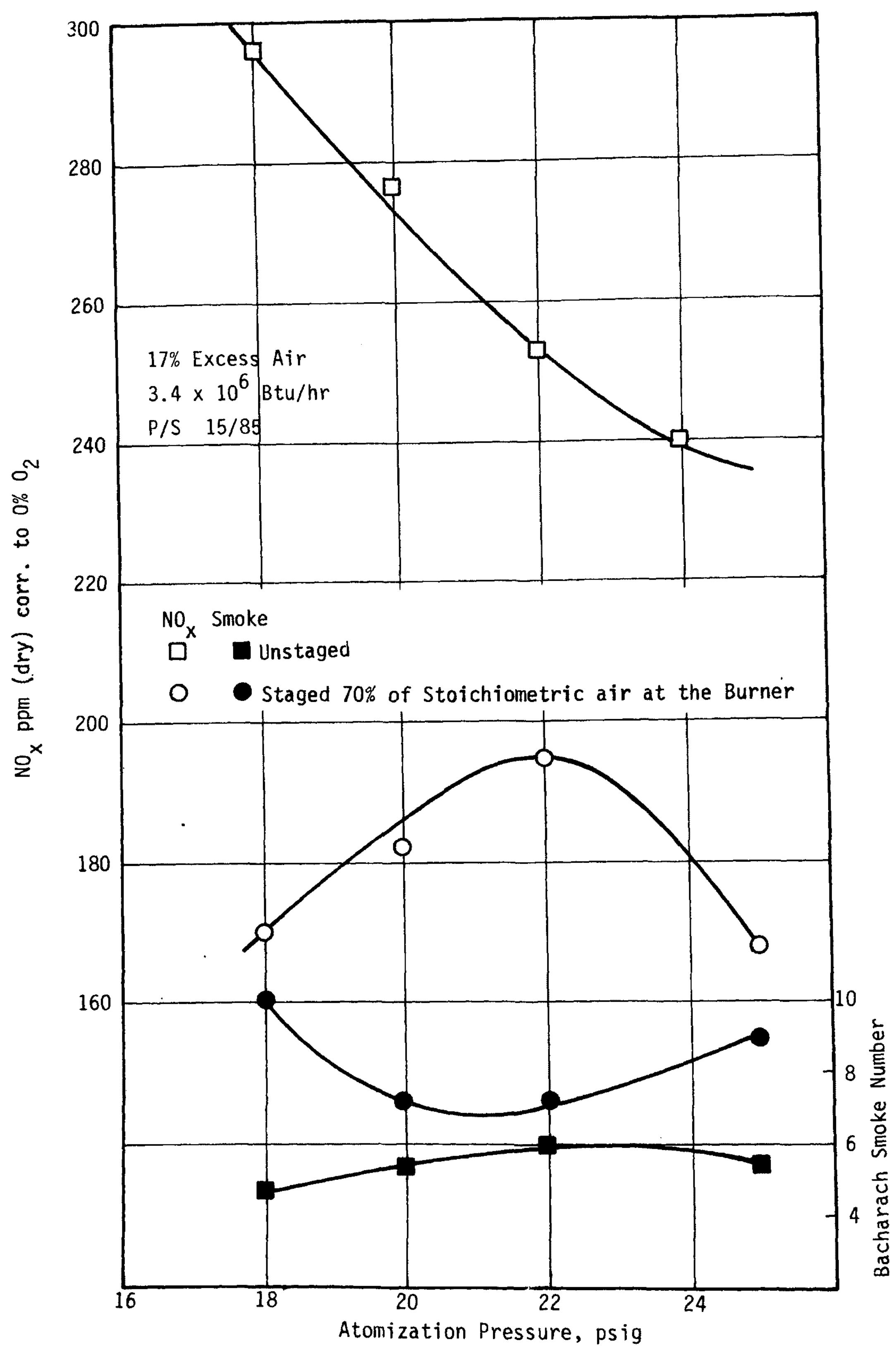

Figure 4-11. The Influence of Atomization Pressure on Staging Performance (P/S 15/85)

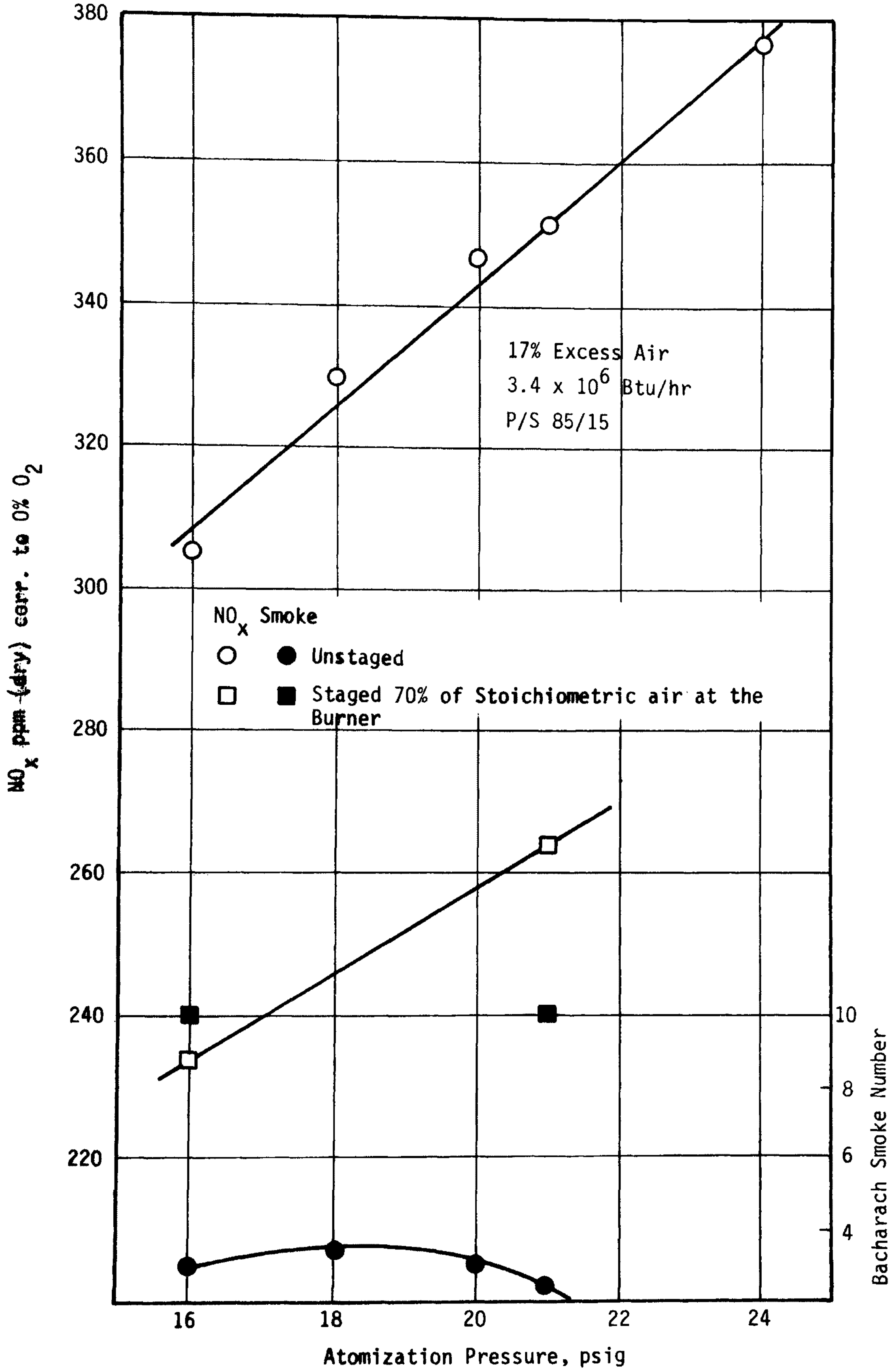

Figure 4-12. The Influence of Atomization Pressure on Staging Performance (P/S 85/15)

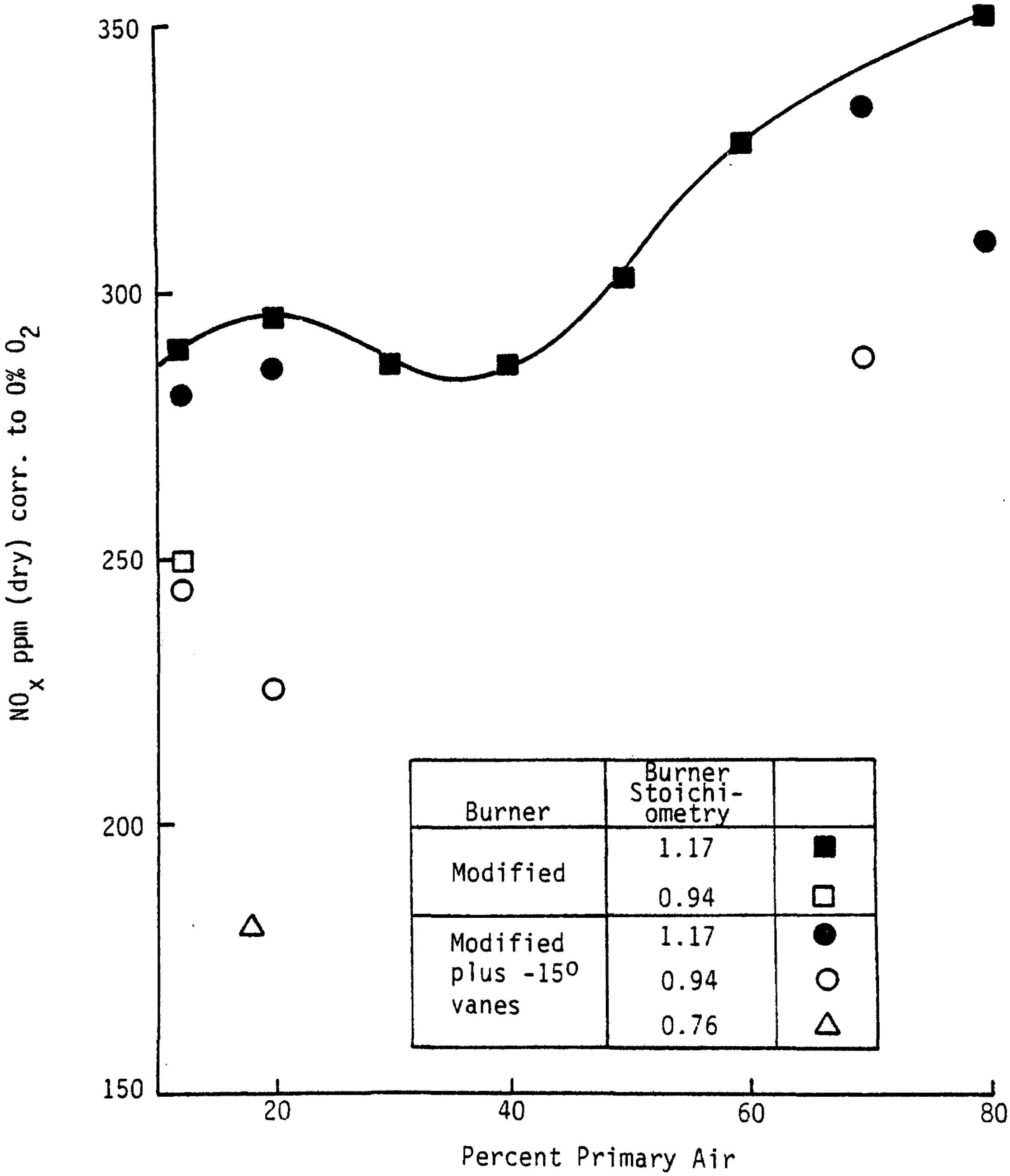

Figure 4-13. The Influence of Primary Air Percentage and Swirl Level on NO Emissions (17 Percent Excess Air 3.4×10^4 Btu/hr Heat Input)

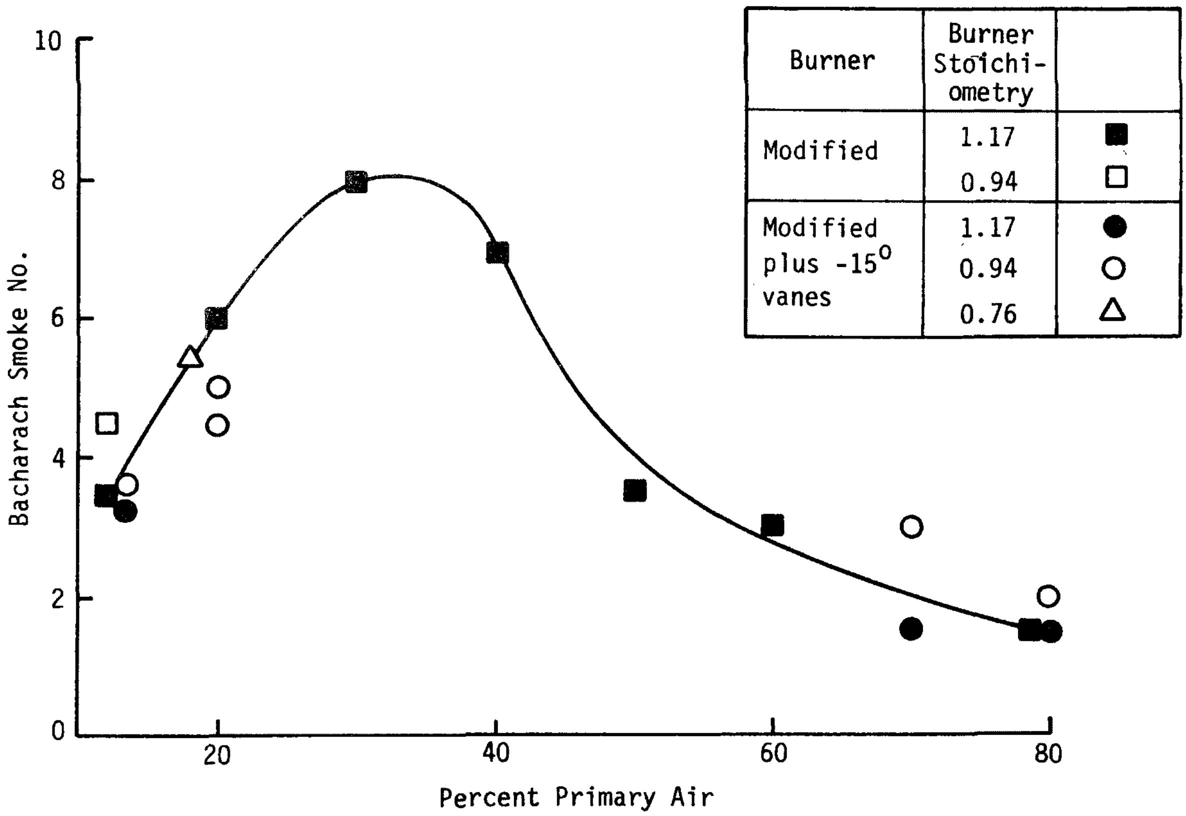

Figure 4-14. The Influence of Primary Air Percentage and Swirl Level on Smoke Emissions (17 Percent Excess Air 3.4×10^4 Btu/hr Heat Input)

Table 4-2. The Influence of Nozzle Capacity on Staging Performance

Percentage of Total Air Added Through Sidewall Injectors			NO_x ppm (dry) corr. to 0% O_2				Smoke Number			
1	2	3	Air 60 gal.	Air 80 gal.	Air 100 gal.	Steam 100 gal.	Air 60 gal.	Air 80 gal.	Air 100 gal.	Steam 100 gal.
-	-	-	278	285	292	269	4 1/2	3 1/2	4	3
20	-	-	230	242	258	245	5	4	4	4 1/2
-	20	-		226	236	216		5	5 1/2	
-	-	20	216	194	219	221	8	8	6 1/2	
20	20	-	198	194	225		8 1/2	7	7 1/2	6
-	20	20		188	193	196		8	7 1/2	6

higher staging levels, and therefore, low NO levels with lower smoke emissions to be obtained.

The objective of these tests was to demonstrate that staging could be an effective technique for NO_x control provided due attention was paid to burner conditions. The best results (i.e., low NO_x and low smoke) (see Figures 4-13 and 4-14) were achieved by fitting a 15 degree vane swirler to the oil nozzle to rotate the primary air in the opposite sense to the secondary air swirl. Forty-five percent reductions in NO emissions from "baseline" conditions were obtained with an increase in the smoke level of 3.5 to 5.5 on the Bacharach scale.

Species concentration measurements carried out under another EPA-sponsored study (EPA Contract 68-02-1500) indicated that rapid mixing of the second stage air with the partially oxidized products of the primary region was not being achieved. The sidewall injectors were designed to promote swirling second stage air injection[3]. This construction directed the air jet away from the axis of the combustor. Thus, the second stage air jets did not penetrate to the combustor axis and mixing with the bulk of the partial oxidation products was delayed.

New sidewall injectors were constructed to inject the staged air directly toward the combustor axis and Table 4-3 compares emissions with the old and new injector designs for various staging levels and injection locations. With a burner stoichiometry of 0.94, the design of the injector had no effect upon the NO emission. However, for the two cases where the injection took place close to the burner, smoke emissions were reduced. When 40 percent of the total air was staged (burner stoichiometry of 0.70) both the smoke and NO emissions were influenced by the injector design. With the new injector design, NO emissions were higher when 20 of the 40 percent staging air was added at x/D = 2.2.

After consideration of the results of these laboratory investigations, the staging system for the field tests was designed with radial staged air injection. The number of injection points was also increased from four to eight in order to promote mixing.

Table 4-3. The Influence of Method of Staged Air Injection Upon Pollutant Emissions

Percentage of Total Air Added Through Sidewall Injectors			NO ppm (Dry) Corr. to 0% O_2		Smoke No. Bacharach Scale	
$\frac{X}{D} = 2.2$	$\frac{X}{D} = 2.6$	$\frac{X}{D} = 3.52$	Old Design	New Design	Old Design	New Design
20	-	-	242	248	4	3
-	20	-	227	234	5	3 1/2
-	-	20	194	187	8	8
-	20	20	188	178	8	6 1/2
20	20	-	194	221	7	5

17 Percent Excess Air

Heat Input 3.4 x 10^6 Btu/hr

5.0 FIELD INVESTIGATIONS

The laboratory investigations carried out during Phase II did not provide sufficient information to allow the design of the optimum NO_x control system for package boilers. Nevertheless, the decision was taken to continue with Phase III of the project - a demonstration of pollutant control techniques in the field, although it was recognized that the field investigations would be on a more experimental basis than was originally intended. Two boilers, one firetube and the other of watertube construction were modified to allow vitiation of the combustion air with cool recirculated flue gases. Staged combustion control techniques were investigated only in the firetube boiler.

5.1 Selection of the Test Boilers

The boilers tested during the field demonstration were both located in the same boiler house and their choice represents an inevitable compromise between the ideal and the practically attainable. In selecting the field units the following criteria were considered to be of particular importance:

- information should be provided on both watertube and firetube designs;
- the units to be tested should be typical of modern practice. The value of the demonstration would be negated if the data were to be obtained on equipment of outmoded design;
- the units to be tested should reflect the bulk of the population of package boilers both with respect to type and size;
- the units tested should be capable of burning both natural gas and heavy fuel oil;
- the same oil supply should be burned in both units;
- it must be possible to investigate both flue gas recirculation and staged combustion techniques in the units;
- the owners of the units must be cooperative since the tests could not be carried out without some interruption of the normal routine;
- the cost of the demonstration could not exceed the budget, this criteria limited both the size and the location of the units which could be considered.

The aid of the American Boiler Manufacturers Association was solicited in order to determine the type, size and characteristics of the "typical package boiler". The ABMA were most helpful and provided survey data on sales of both watertube and firetube boilers. This data was reviewed and is presented in Tables 5-1 and 5-2 respectively. The firetube boiler data is based upon orders placed within the stated calendar year on high pressure (>15 psig steam) boilers, low pressure boilers and hot water heaters. Table 5-1 indicates that the major portion of the firetube population lies in the 100 to 200 hp range (3,450 to 6,900 lbs of steam per hour). In recent years the bulk of the watertube units ordered lies in the 21 - 40 x 10^3 lbs steam per hour range (see Table 5-2).

Several steps were taken to locate units which could be tested and which satisfied the criteria discussed earlier. The ABMA, state and local air pollution regulatory agencies were contacted in an attempt to locate candidate units. Possible test sites were visited at the Bell Laboratories in Whippany, New Jersey, and Passaic Pioneer Properties in Passaic, New Jersey. Following these inquires a series of possible plans were drawn up which had four different approaches:

- Test units owned and operated by the Foster Wheeler Energy Corporation;
- Rent a firetube boiler for installation near a Foster Wheeler-owned unit;
- Test units located in the vicinity of the Foster Wheeler Energy Corporation;
- Rent both a firetube and a watertube boiler.

The candidate plans which were prepared based upon a survey of the various test sites are presented in Table 5-3. Certain of these plans were rejected because the units normally burned natural gas and the cost of conversion to fire fuel oil was prohibitive. When the two boilers were not located in the same physical plant the same oil supply could not be guaranteed for both units. The typicality of the units were also considered, units with rotary cup atomizers and a watertube boiler with a water cooled front wall were rejected because these designs were not typical of the major portion of package boilers. The expense associated with renting units eliminated those possibilities from consideration.

Table 5-1. 10 Year Survey of Package Firetube Boiler Sales
(Including High and Low Pressure Steam and Hot Water Units)

(Supplied by ABMA)

Year Unit Capaicty HP (Less than or equal to)	1972	1971	1970	1969	1968	1967	1966	1965	1964	1963
15	27	31	55	365	42	41	85	82	100	83
20	63	54	67	112	102	135	150	215	198	190
25	26	32	54	81	51	53	57	71	113	80
30	150	142	191	291	235	290	352	409	300	345
40	164	153	175	257	255	226	363	383	365	364
50	176	208	222	316	249	274	426	392	341	373
60	269	301	288	416	348	346	480	474	459	450
70	83	110	106	177	136	193	169	214	179	197
80	221	235	264	337	329	366	427	440	426	391
100	410	458	488	670	645	692	823	785	749	676
125	350	299	441	518	445	557	587	560	469	475
150	517	494	490	671	520	483	571	559	489	476
200	462	479	501	689	514	600	664	629	500	534
225	13	43	15	40	8	16	40	30	5	9
150	280	286	301	306	323	340	283	321	249	277
300	261	290	279	419	337	307	335	328	258	219
350	150	175	189	224	163	135	173	169	151	132
400	150	169	171	202	173	132	188	127	110	90
500	167	190	181	178	190	149	157	163	91	86
600	195	198	198	293	227	180	197	141	116	125
>601	81	75	56	0	0	0	0	28	7	4
Total	4215	4422	4732	6562	5292	5517	6602	6520	5675	5576
No. of Companies	15	15	15	15	13	10	10	11	10	10

Table 5-2. 10 Year Survey of Packaged Watertube Boiler Sales
(Supplied by ABMA)

Year Unit Capacity 10^3 lb/hr	1972	1971	1970	1969	1968	1967	1966	1965	1964	1963	1962
10	2	3	3	16	7	10	6	6	19	25	23
11-20	72	64	81	140	121	118	161	180	159	178	177
21-30	142	116	149	145	145	155	199	161	166	132	138
31-40	120	101	117	129	98	98	113	101	97	89	89
41-50	78	65	65	90	72	63	114	83	101	50	47
51-60	83	64	91	80	72	62	69	59	76	38	52
61-70	21	19	24	32	33	15	38	29	20	24	5
71-80	25	42	51	51	54	34	58	32	21	21	17
81-90	10	13	14	18	8	15	9	5	7	7	2
91-100	43	29	31	38	43	36	44	51	64	16	17
101-150	48	73	110	114	66	39	66				
151-250	30	28	38	17				50	27	13	7
250+	3	2	3	4							
Total	677	619	777	873	754	675	921	759	757	593	574
Less than 250 psig, percent	79	82	75	75	76	77	76	76	75	85	80
Sat. Steam, percent	87	90	84	85	85	79	82	82	83	87	90

Table 5-3. Possible Candidate Plans

Plan	Firetube (FT)				Watertube (WT)			
	Capacity 10^3 lb/hr	Owner	Mfg.	Location	Capacity 10^3 lb/hr	Owner	Mfg.	Location
1. F.W.-Owned Units	5	FW*	S	Livingston, NJ	50	FW*	FW	Dansville, NY
2. Rent Firetube	6.9	CB or C*	CB	Dansville, NY	50	FW*	FW	Dansville, NY
2a. Rent Firetube	6.9	Wabash*	CB	Dansville, NY	50	FW*	FW	Dansville, NY
3. Test Watertube only						FW*	FW	Dansville, NY
4. Area Location	12	Essex County* Correction Center	S	Caldwell, NJ	25	ECCC*	S	Caldwell, NJ
5. Area Location	20	Passaic* Pioneer Prop.	CB	Passaic, NJ	25	PPP*	CB	Passaic, NJ
6. Area Location	6.9	Bell Labs	S	Whippany, NJ	25	BL	N	Whippany, NJ
7. Area Location	Range	Sandoz	CB	E. Hanover, NJ	25	ER&E	B&W	Florham Park, NJ
8. Rent FT and WR	6.0	Wabash	CB	Anywhere	75	Wabash	M or N	Anywhere

Code

B&W - Babcock & Wilcox
C - Cyclotherm
CB - Cleaver Brooks
ER&E - Esso Research and Engineering
FW - Foster Wheeler
M - Murray
N - Nebraska
S - Superior

*Natural Gas Available

The units ultimately selected for the field demonstration were located at the Essex County Correction Center (ECCC) which is plan No. 4 in Table 5-3. This site had several advantages over other locations. the same oil supply was assured for both units, the test site was close to the FWEC Research Center and the units were both of modern design. Although the watertube units fall into the most popular size range for boilers of this type, comparison with Table 5-1 indicates that the capacity of the firetube boiler is higher than the bulk of the population; however, it is believed that there will be a shift towards larger sizes in the future. Unfortunately, during the advanced stages of preparation it was learned that changes in the hosts operating procedure would result in a considerable decrease in the steam demand. Maximum foreseeable steam demand appeared to be less than 20,000 lbs of steam per hour and this would be strongly dependent upon climatic conditions. Recognizing that this would cause certain difficulties, the API-EPA Steering Committee recommended that the tests be carried out as planned.

5.2 Equipment Used in the Field Investigations

5.2.1 The Watertube Boiler

The watertube boiler tested at ECCC was built by Superior Combustion Industries and was designed to fire No. 5 fuel oil or natural gas. Natural gas is available on an interruptible basis. The boiler is fired by a register burner, a schematic of which is shown in Figure 5-1. The natural gas is injected from a gas ring and the oil gun utilizes steam atomization. The front wall of this "D" type forced draft unit is refractory lined and the gas passage is horizontal. The combustion gases exit the radiant section, turn through 180^{0} before passing through the convective section. The unit is rated at 25,000 lbs of steam per hour at 250 psig, and no provision if available for air preheat.

The flue gas recirculation system was designed to recirculate 30 percent of the full load combustion products through the wind box. The system installed in the watertube boiler is shown in Figure 5-2. The recirculation fan was located at grade level between the two watertube boilers adjacent to the stack breeching for both boilers. The flue gases were withdrawn before the boiler breeching dampers and the 12 in. ID ducts carried the gases over the boiler before entering the windbox normal to the downward flow of the combustion air. The ductwork

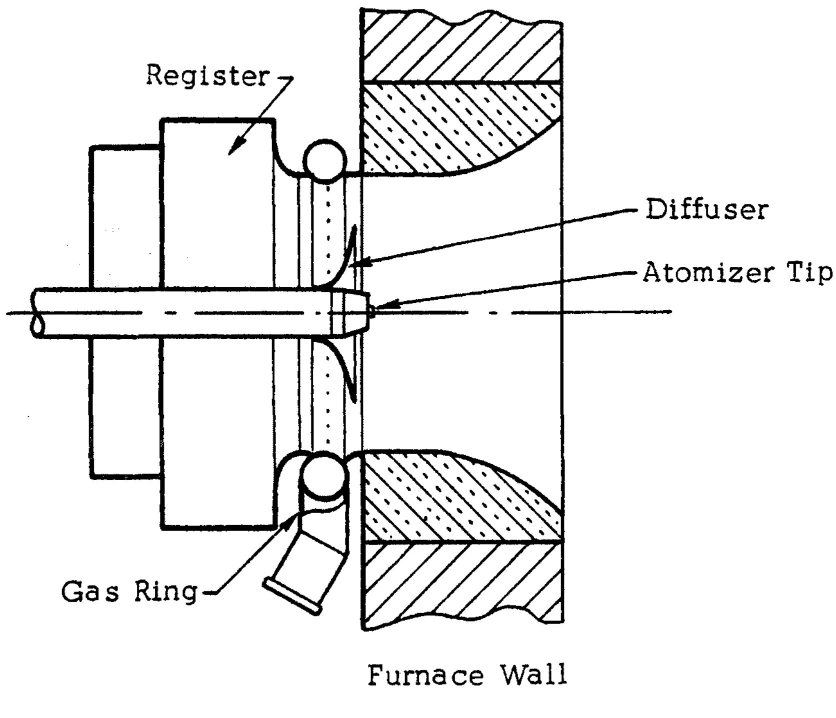

Figure 5-1. Register Burner Installed in the Watertube Boiler

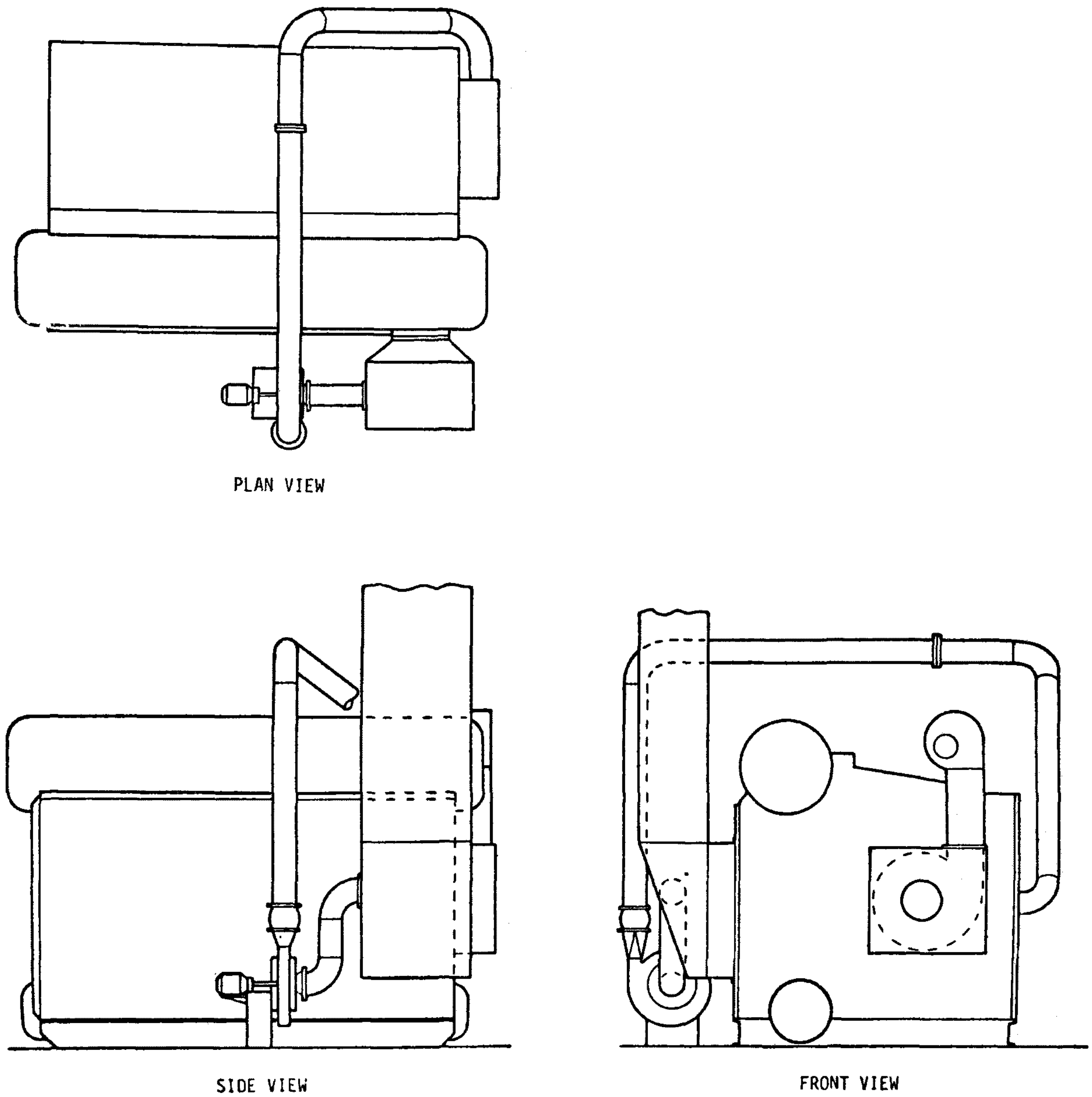

Figure 5-2. Layout of Flue Gas Recirculation System for the Watertube Boiler

was fabricated from rolled No. 10 gauge carbon steel plate with longitudinally welded seams. Fabricated ductwork was used because of the difficulty in obtaining light wall pipe or tubing within the available time. The mass of recirculating combustion products was controlled by a damper installed at the immediate discharge of the fan and metered by an ASME standard orifice installed in the horizontal duct passing over the boiler.

5.2.2 The Firetube Boiler

The application of both flue gas recirculation and staged combustion control techniques were investigated in the firetube boiler which was also manufactured by the Superior Combustion Industries and a sketch of the burner firetube arrangement is shown in Figure 5-3. The boiler was designed to burn No. 5 fuel oil with an air atomized tip. Natural gas can also be burned and it is injected from a ring embedded in the refractory throat and the boiler is refractory lined for the first 2.5 feet. The unit has four gas passes, one radiant and three convective passes. The firetube and second pass are surrounded by water and the third and fourth passes lie in the vapor space at the top of the boiler. The forced draft unit is rated at 12,000 lbs of steam per hour at 250 psig.

Details of the flue gas recirculation system installed in the firetube boiler are presented in Figure 5-4. All ductwork was 10 in. ID and the control and metering system was similar to that used on the watertube boiler. The recirculation fan was placed on the grating above and to the rear of the boiler. Combustion gases were withdrawn from the stack at this level and entered the windbox tengentially in the same flow direction as the combustion air from the F.D. fan. When the windbox was breeched to accept the recirculation ductwork a baffle plate, not detailed on any Superior drawings, was found in the windbox. This baffle plate reduced the volume of the windbox and also obstructed the recirculation gas entry. Since at that time no function could be attributed to this plate, it was removed, although subsequent experience appeared to indicate that this was an error.

The only practical entry for the second stage combustion air supply was through the rear of the firetube unit, although this was made difficult because the boiler backed up to a 3 ft thick wall leaving only limited space for access.

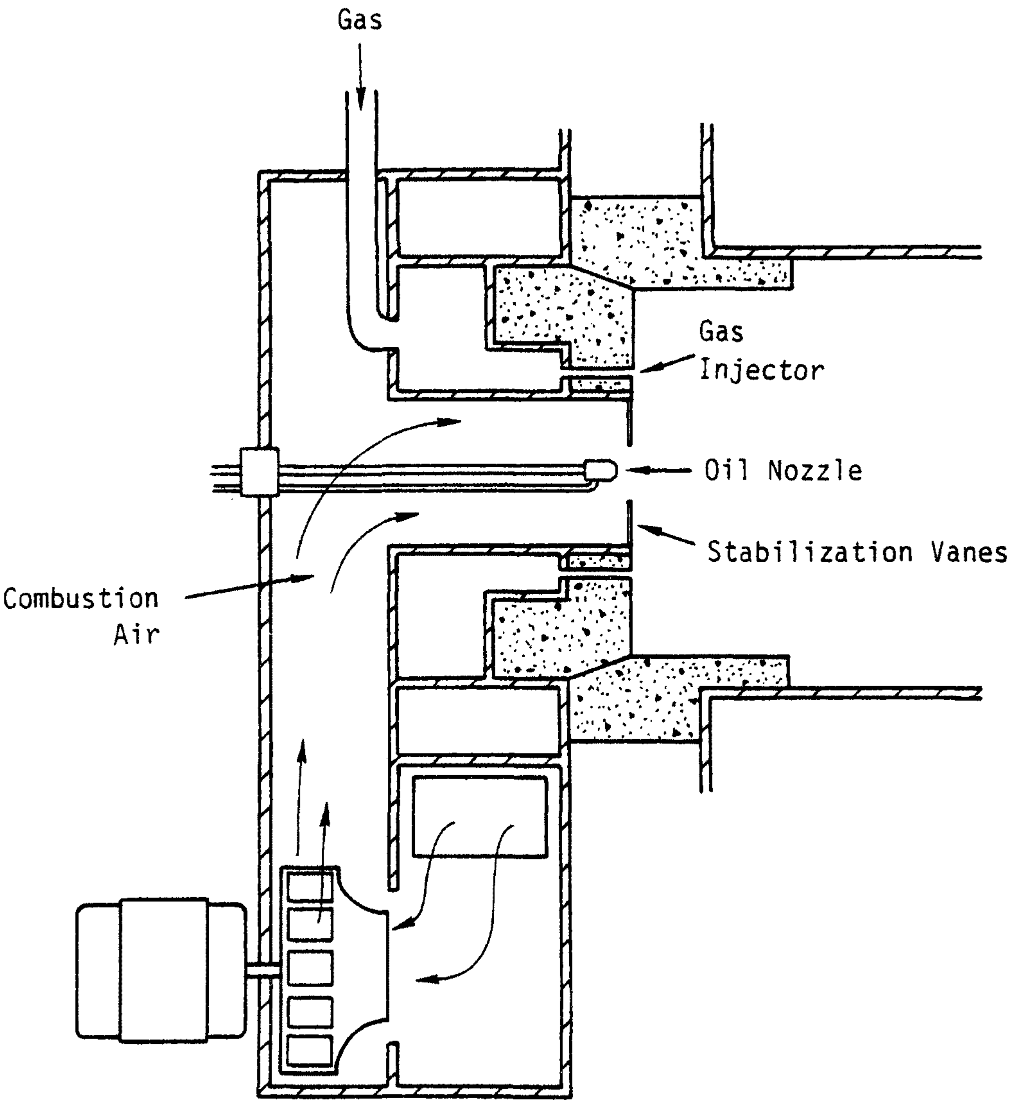

Figure 5-3. Sketch Showing the Windbox Burner Arrangement of the Firetube Burner

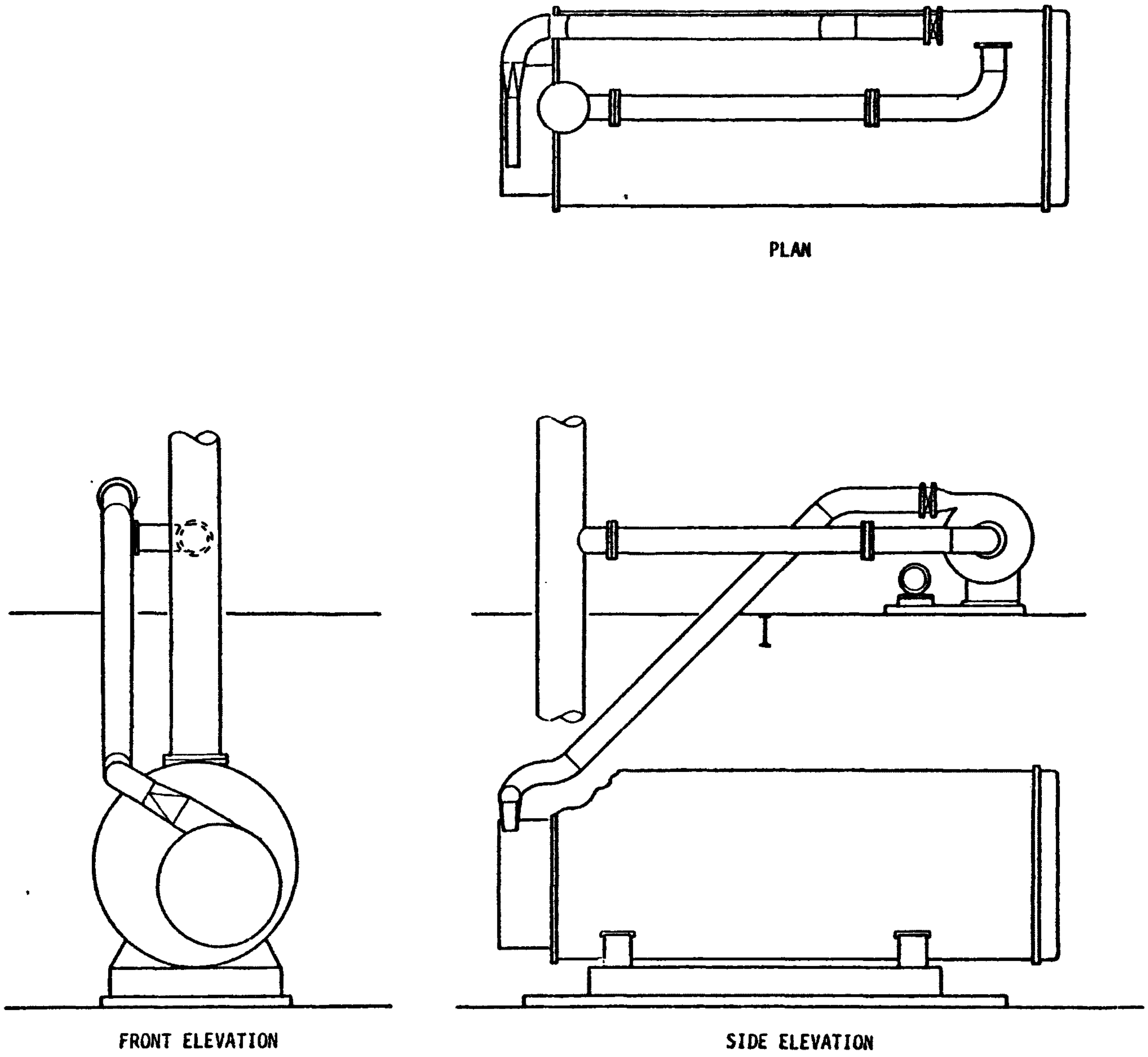

Figure 5-4. Layout of Flue Gas Recirculation System for the Firetube Boiler

Penetration of the front wall was rejected because it would necessitate cutting through 30 inches of refractory in the form of three cast refractory rings. The general arrangement of the staging system installed in the firetube boiler is shown in Figure 5-5. Ambient air was supplied by a separate fan to a distribution ring at the rear of the boiler. This ring supplied eight 2-inch stainless steel staging pipes which entered the firetube through the rear door. These pipes were laid along the wall of the firetube and provision was made to allow the axial location of the staging injectors to be varied in later experiments. The staged air was injected radially through fishtail orifices. The configuration of the staged air injectors and reasons for the design will be discussed later. Burner stoichiometry was varied by throttling the combustion air supply and maintaining a constant overall excess air by increasing the air flow through the staging injectors.

5.2.3 Automatic Controls for Flue Gas Recirculation

Firetube Boiler

The control logic for automatic operation of the firetube boiler is a motor driven mechanical linkage activated by a pressure signal. As both air and fuel quantities are regulated directly by the linkage, the controls for the flue gas recirculation system were also tied directly to the linkage. This was accomplished by incorporating a cam-follower mechanism on the modulating motor of the linkage. The resulting signal activates a ratio control which maintains a constant ratio between air/fuel and FGR. Another signal from a differential pressure call reading pressure drop across an orifice, in the FGR duct, is fed to the ratio controller and compared with the signal from the cam-follower. If these two signals do not balance, a signal is sent to another controller which resulates a butterfly valve in the FGR duct to increase or decrease flow. In this manner, a flue gas recirculation flow is established in proportion to the air and fuel flow as signaled by the cam-follower position. The ratio of recirculated flue gas to air and fuel may be regulated by the ratio controller. A schematic of this system is shown in Figure 5-6.

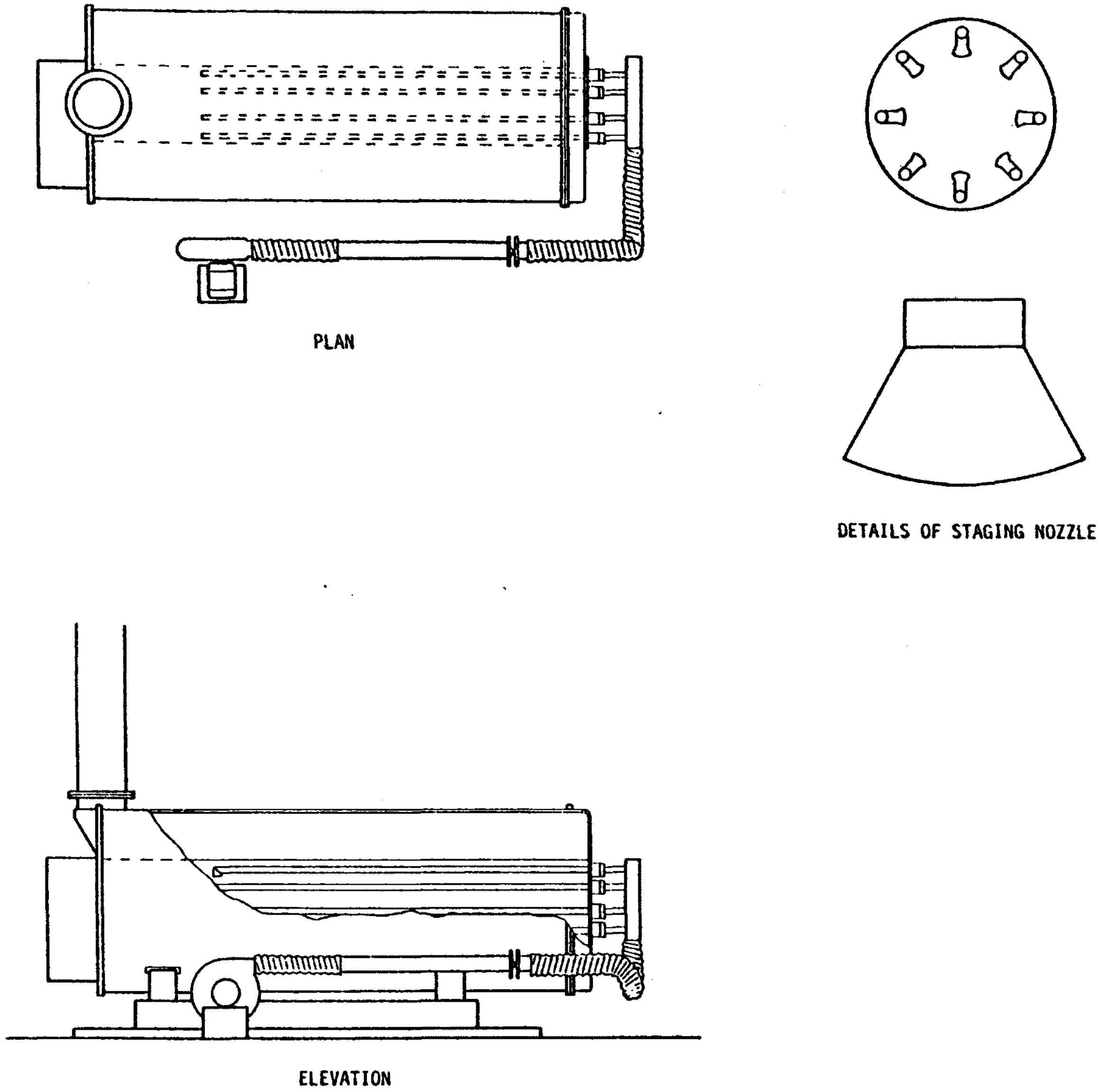

Figure 5-5. Details of Equipment Used in the Staging Investigation

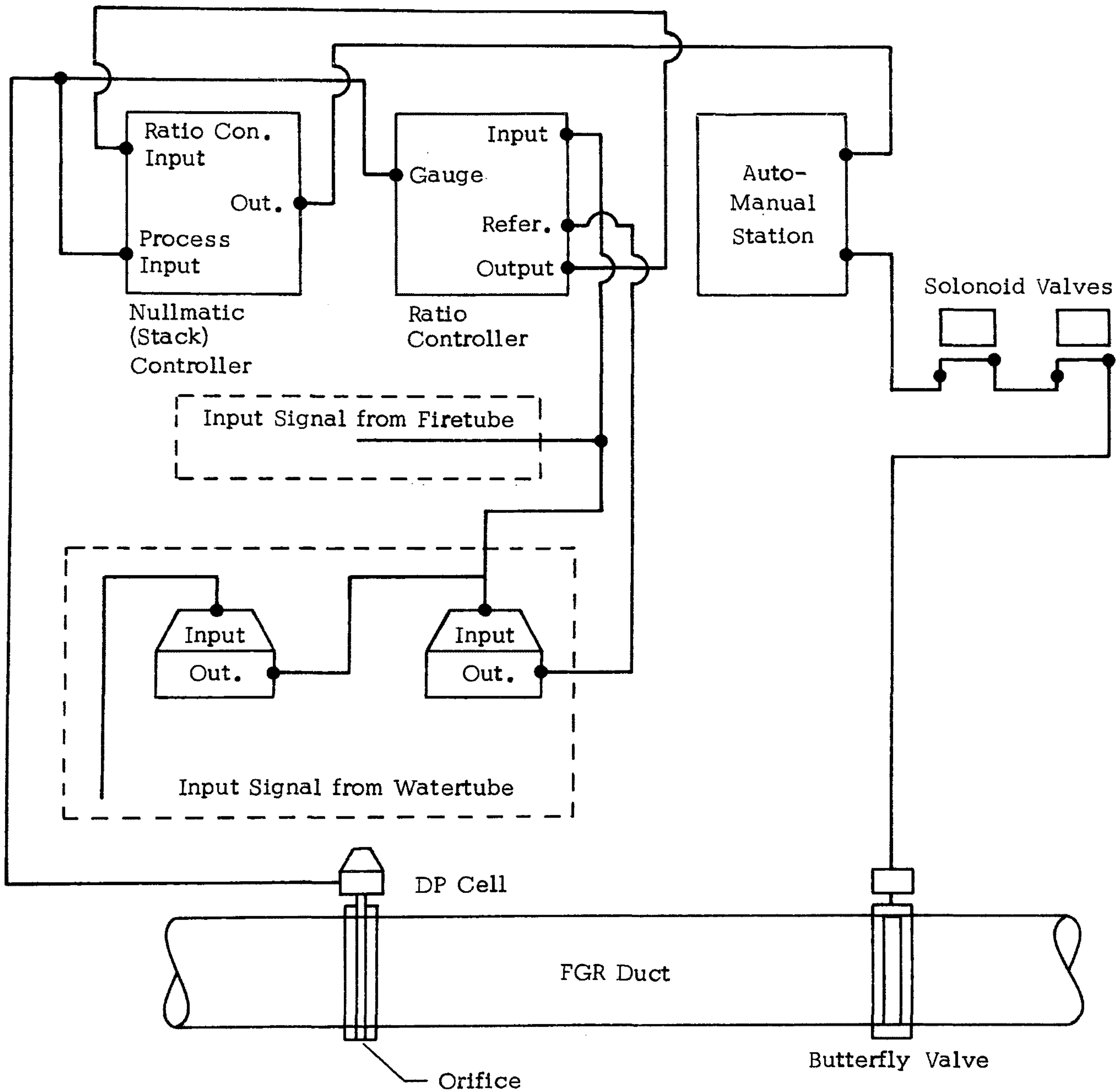

Figure 5-6. Schematic of Automatic Controls for Flue Gas Recirculation

Watertube Boiler

The control system for the watertube boiler is similar to that of the firetube with the exception that the initial control signal originates from a pneumatic source indicating total air flow to the boiler. In this case, if the boiler load were to change, the fuel flow would change correspondingly causing an air flow change and, thus, an FGR rate change. The schematic diagram for this system is the same as for the firetube.

5.2.4 Flue Gas Measurement Systems

The sample was withdrawn from a port in the flue of each boiler via a 0.5 in. O.D. x 0.049 in. wall stainless steel tube and passed to a condensate trap immersed in an ice bath. The cooled sample gas was supplied via a 1/4 in. O.D. teflon tube to the instrument manifold. The instruments used to continuously monitor the concentration of several combustion products are listed below; in some instances backup instruments were employed to ensure continuity if one instrument failed during any particular test.

NO/NO_x. The primary instrument used to determine both NO and NO_x was a Thermo-Electron Chemiluminescence Analyzer, backup measurements were made with a Theta Sensor US-6000 analyzer.

O_2. Oxygen concentrations were measured by both the Theta Sensor analyzer and a Teledyne Model 320 AX Portable Analyzer with a Class A-3 cell, the former instrument being used as the primary reference.

CO. An infrared absorption analyzer (MSA Model LIRA-303) was used to determine the carbon monoxide content of the flue gases.

SO_2. The Theta Sensor US-600 was used to determine the sulfur dioxide content of the flue gases.

Smoke. Smoke readings were taken with a Bacharach smoke tester.

Certified zero and calibration gases were used to calibrate these monitors throughout the investigation. Frequent calibration checks were used to ensure the reliability of the data.

The instrumentation available in the boiler house was used to establish the boiler load. Although this was adequate for normal operation, more precise information of fuel and steam flow would have been desirable for this investigation.

5.3 Result of the Field Investigations

The field investigations were carried out in three separate periods punctuated by the need for equipment modification. These three different test periods correspond to

- Boiler Performance Tests;
- Flue Gas Recirculation Tests; and
- Staged Combustion Tests in the Firetube Boiler.

Although a rigid test matrix had been agreed upon for the baseline tests, inability to control excess air level and boiler demand required some relaxation of the test matrix. The exploratory nature of the FGR and Staged Combustion tests necessitated that the test program depend largely upon the initiative and the experience of the test supervisor. All the results for the three sections of the field investigation are presented in Appendix 1.

5.3.1 Boiler Performance Tests

The boiler performance tests were carried out to determine the influence of operational parameters on pollutant emissions from the two test boilers. These tests not only established a baseline against which to judge the effectiveness of the various control techniques, but also allowed an assessment to be made of whether or not their performance was typical of the total set of package boilers. The operational parameters investigated were:

- Fuel type - natural gas and No. 5 fuel oil;
- Load - the range was dependent upon demand and boiler characteristics (limited to 70 percent full load for the watertube boiler by maximum possible demand);

- Excess air - a wide variation dependent upon fuel type and load; and
- Burner parameters - register setting, oil temperature, steam pressure.

Firetube Boiler

The emission characteristics of the firetube boiler fired with natural gas and fuel oil can be judged from Figure 5-7. All the test data is presented in Tables 1 and 2 in Appendix 1. With liquid fuel, NO_x emissions appear to be insensitive to load at low and medium loads but emissions increase as the load is increased to maximum. Smoke emissions appeared to be insensitive to load because of load demand, however, at low and medium loads NO_x emissions increase with increasing load. The difference in behavior of the firetube boiler with the two fuels is probably due to small fraction of the total emission attributable to thermal NO for oil firing at low load. Emissions from fuel oil flames showed a stronger dependence upon excess oxygen than did emissions from gas flames, although it should be noted that the oil was burned satisfactorily with a lower level of excess air which probably reflects the less effective fuel/air mixing obtained with natural gas firing. Only one test was carried out to investigate the influence of oil temperature variation (20^oF variation); virtually no effect upon either NO_x or smoke was observed.

Watertube Boiler

The results for the watertube boiler fired by oil tend to exhibit more scatter than those reported for the firetube boiler as shown in Figure 5-8. Contrary to the trends found in the firetube boiler, NO_x emissions increase with increasing load for low and medium loads and then show a slight decrease as the load is increased still further. Several examples can be seen in Figure 5-8 where data is plotted for the same nominal load and 50 ppm difference in emissions can be seen for almost the same oxygen concentration.

Figure 5-9 shows the influence of register setting on NO_x and smoke emission for a fixed load. Closing the register causes an increase in the rotational motion of the combustion air flow, but it also increases the burner pressure

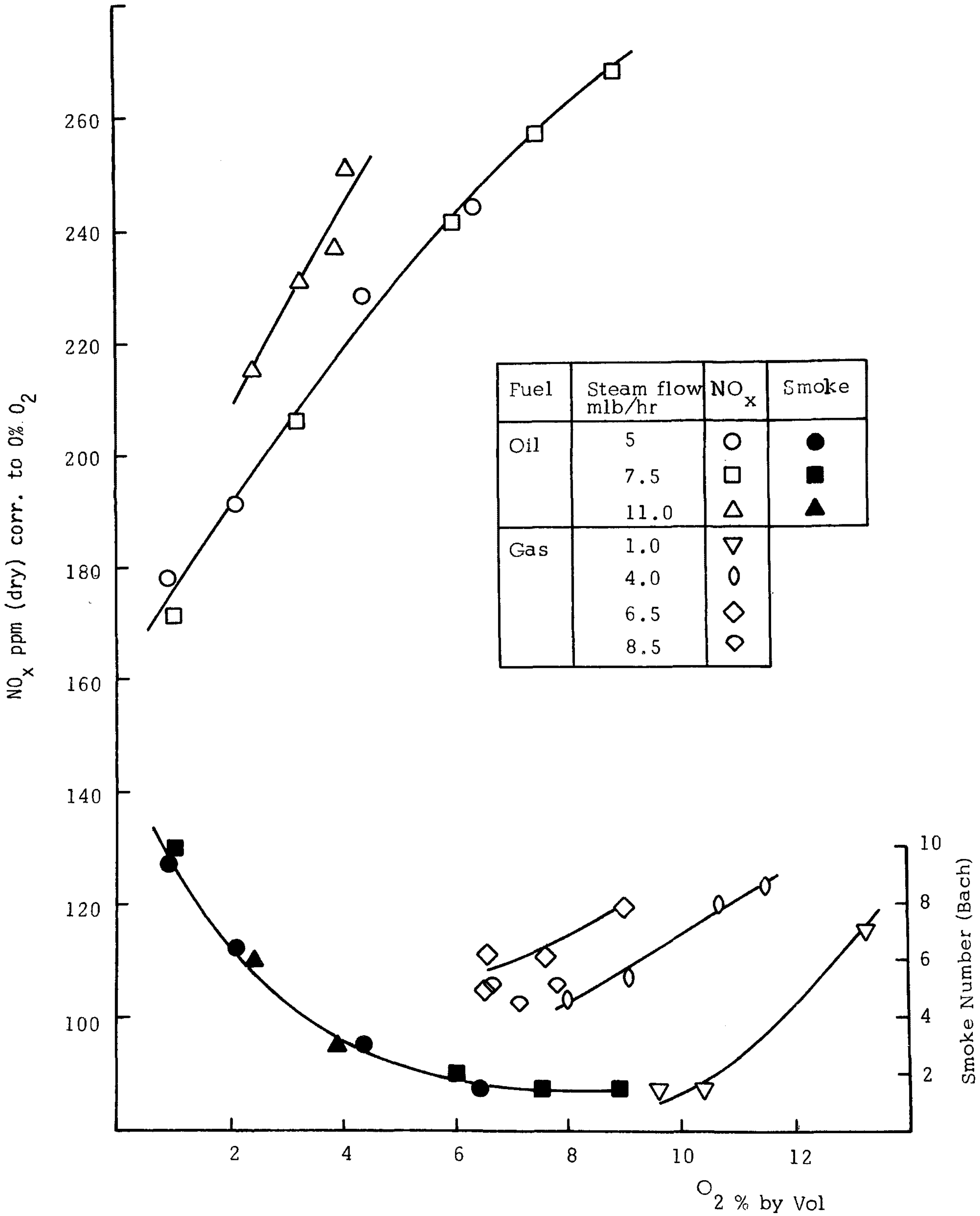

Figure 5-7. The Influence of Load and Excess Air on Pollutant Emissions from the Firetube Boiler (Boiler Performance Tests)

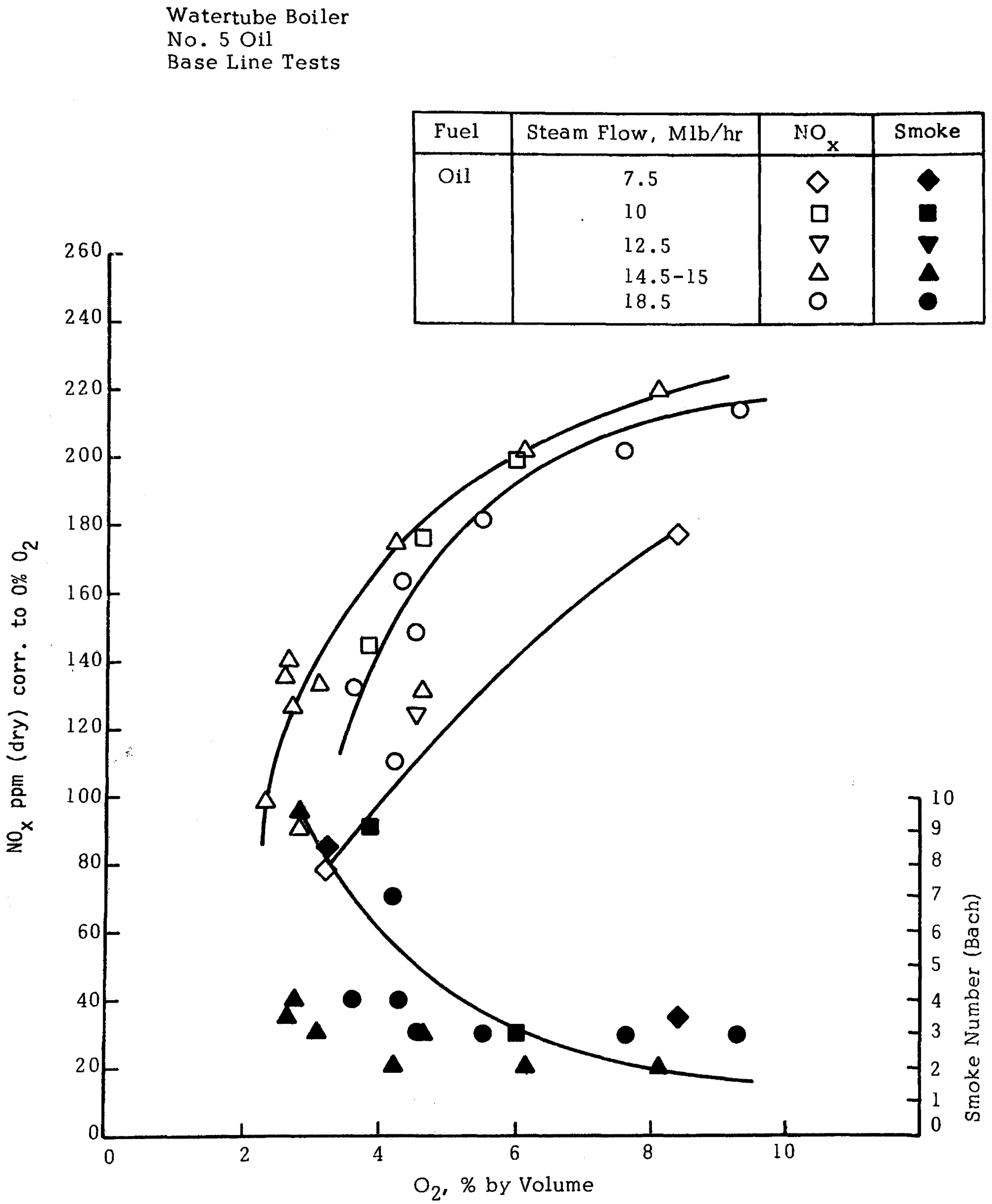

Figure 5-8. The Influence of Load and Excess Air on Pollutant Emissions from the Watertube Boiler (Boiler Performance Tests)

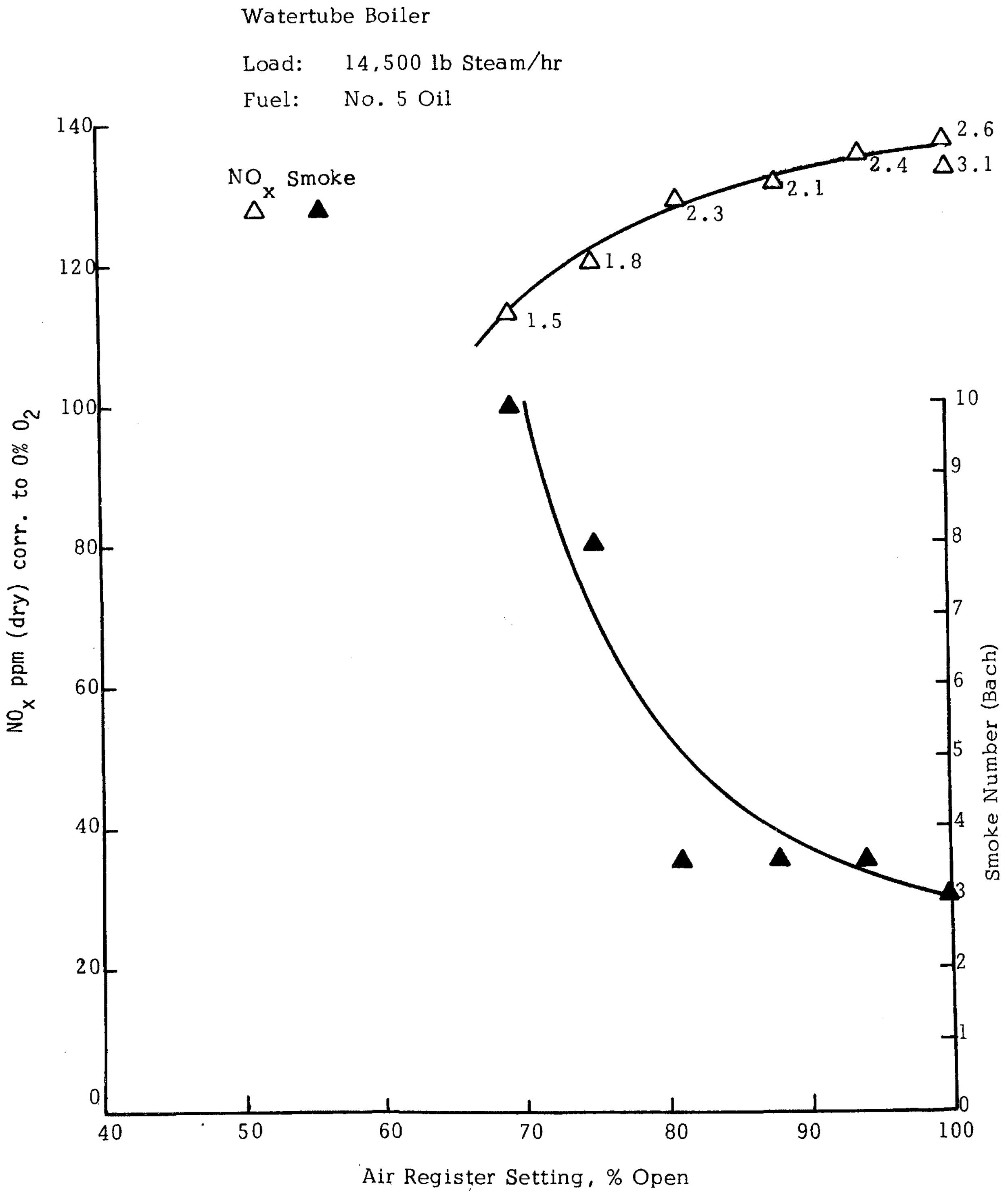

Figure 5-9. The Influence of Register Position on Pollutant Emissions - Watertube Boiler (Boiler Performance Test Figures Beside Symbols Denote O_2 Percentage)

drop which tends to reduce the total air flow. Thus, as can be seen in Figure 5-9, the flue gas oxygen content drops as the register closes and the resulting change in emissions cannot be attributed to one effect. Decreasing the excess oxygen content from 3 to 2 percent at fixed register setting reduces NO_x emissions by approximately 40 ppm at 14,500 lbs of steam per hour (see Figure 5-8). Thus, it appears that closing the register at a constant excess air level could cause a slight increase in NO_x emissions since the decrease in emissions caused by the reduction of excess air alone is greater than that produced by the combined effect of excess air and register setting.

Wide variations in oil temperature and steam pressure were not possible due to operational limitations. Also, variations in these two parameters were accompanied by unexplained changes in flue gas oxygen concentration. It appears that reductions in fuel oil temperature cause a reduction in NO_x emissions (Figure 5-10). Interpolating information from Figure 5-7 suggests that NO_x emissions are reduced by reduced atomizing steam pressure (Figure 5-11).

The influence of load on emissions from the watertube boiler when fired with natural gas is rather erratic (see Figure 5-12). At 4.5 percent oxygen, maximum emissions occur at medium loads. Emissions at low and maximum load are almost the same. Certainly the peak emission occurs at different excess air levels for different loads. Closing the register and increasing the swirl causes an increased emission with natural gas even though the excess air was reduced (see Figure 5-13). This result can be attributed to an improvement in fuel/air mixing which causes an increase in the NO_x emission. Visual observations tend to support this argument since under normal operating conditions the flame could be described as "soft", indicative of slow air/fuel mixing.

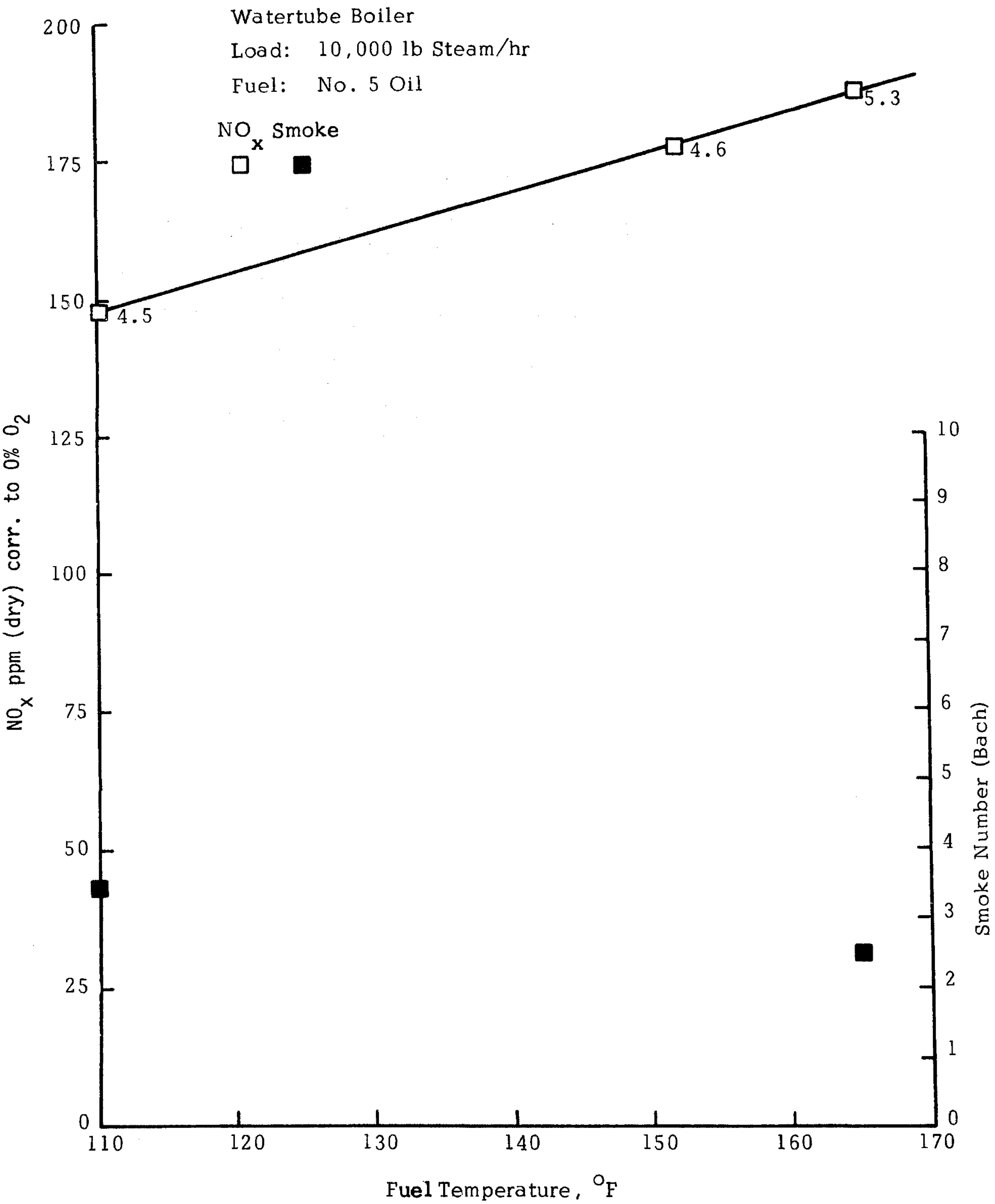

Figure 5-10. The Influence of Fuel Oil Temperature on Pollutant Emissions from the Watertube Boiler (Boiler Performance Tests)

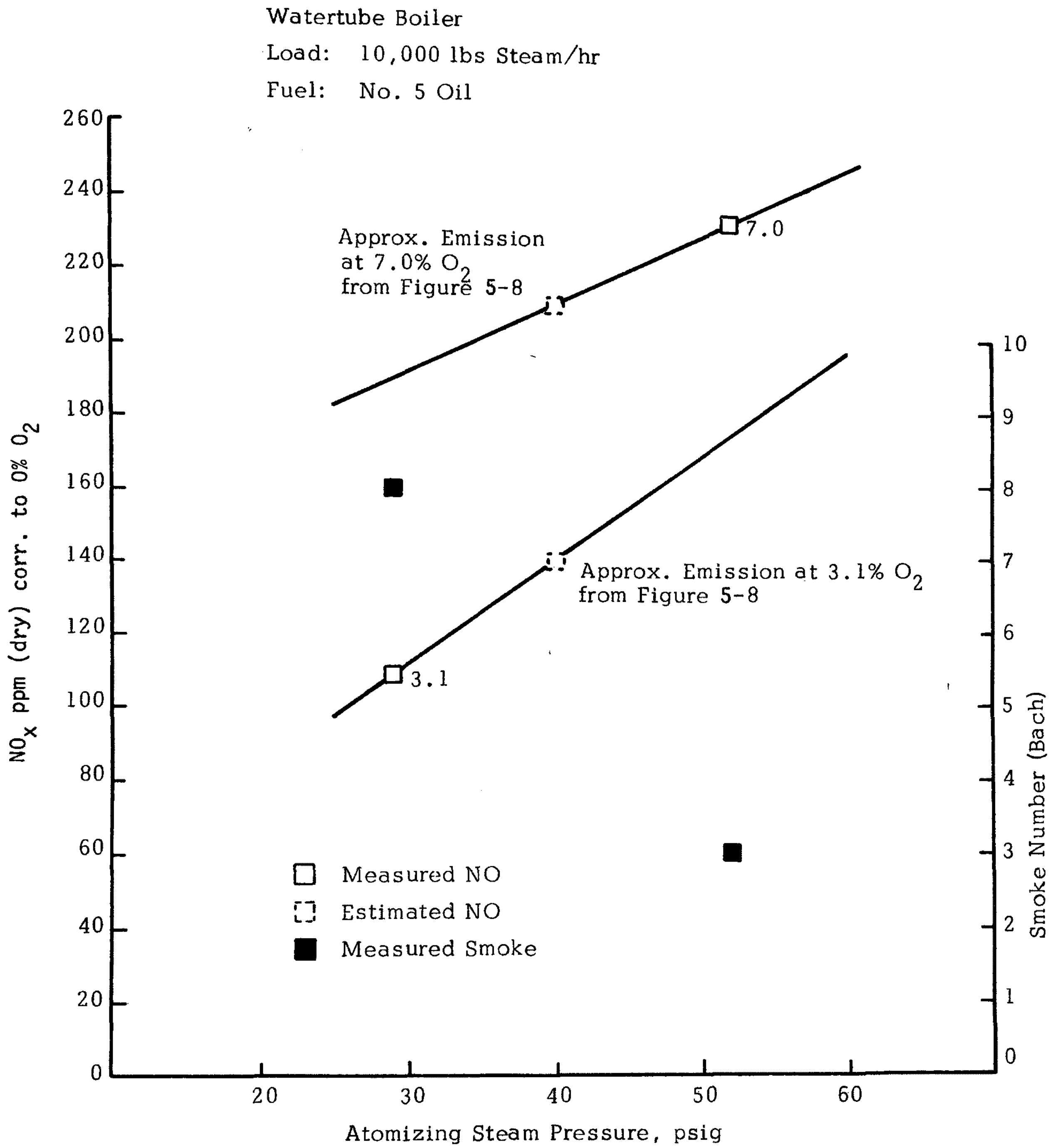

Figure 5-11. The Influence of Atomizing Steam Pressure on Pollutant Emissions from the Watertube Boiler (Boiler Performance Tests)

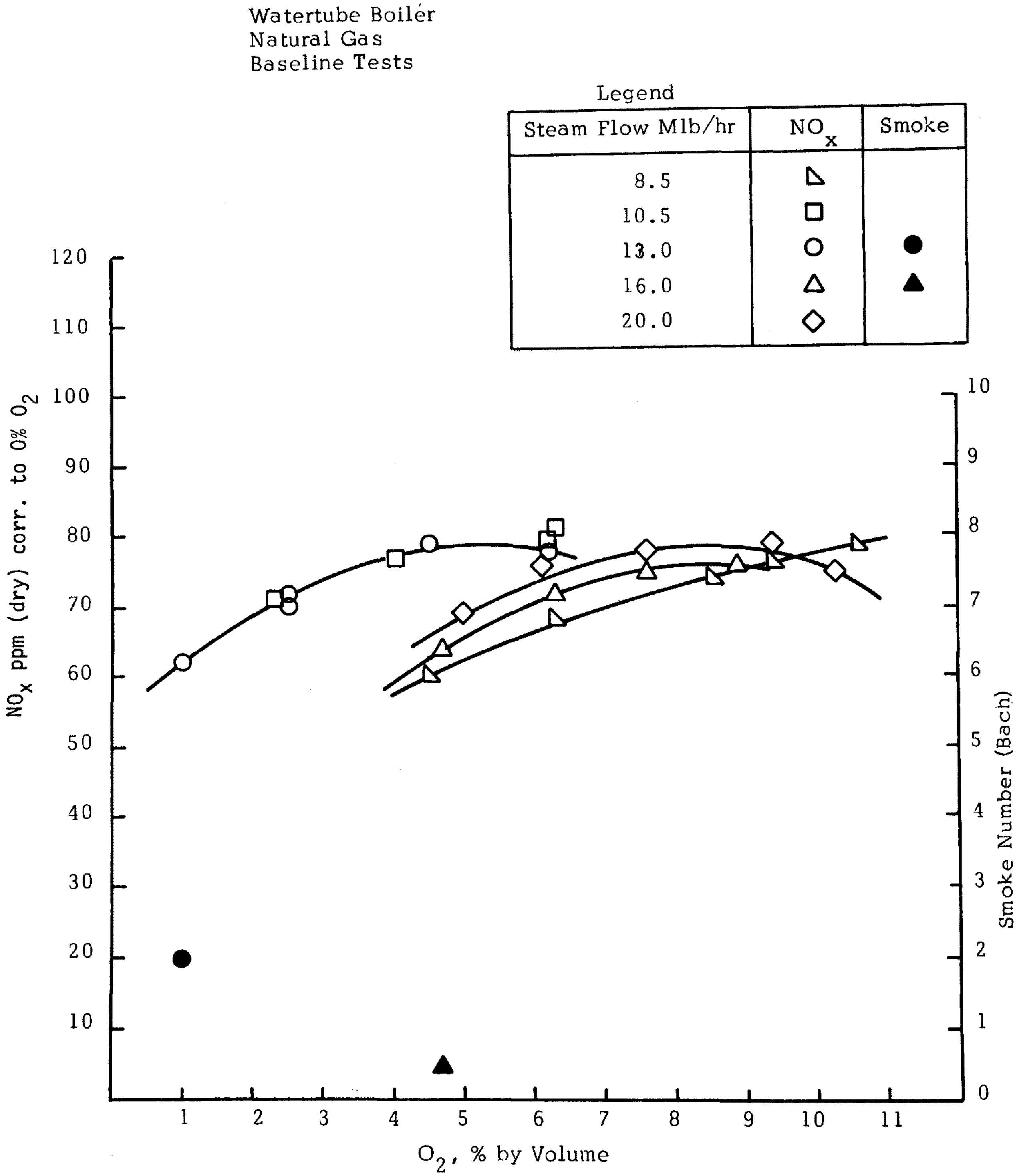

Figure 5-12. The Influence of Load and Excess Air on NO_x Emissions from the Watertube Boiler (Boiler Performance Tests)

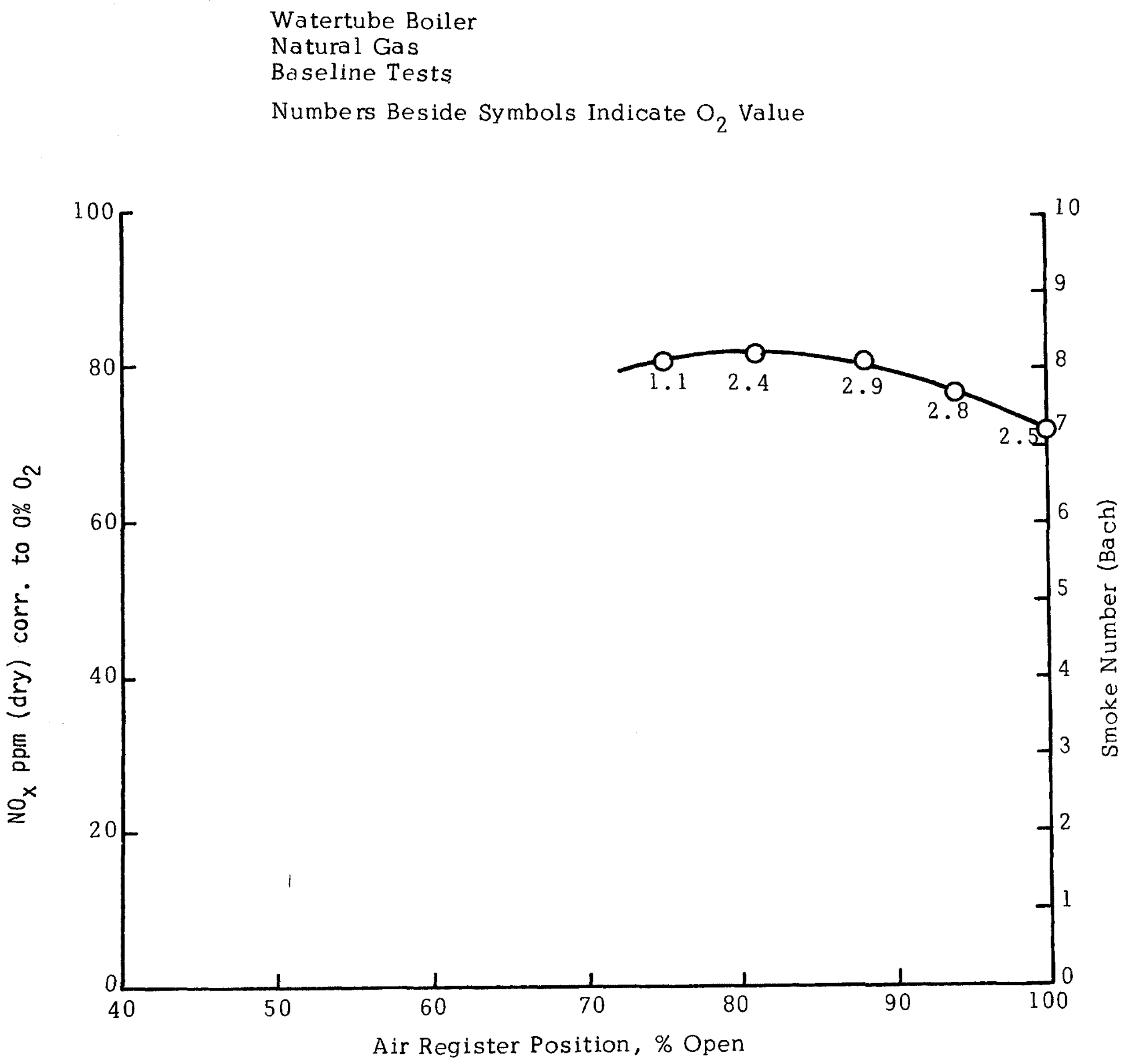

Figure 5-13. The Influence of Register Setting on NO_x Emissions from the Watertube Boiler Fired by Natural Gas (Boiler Performance Tests)

5.3.2 Flue Gas Recirculation Tests

The extent of the test matrix for the flue gas recirculation tests was dictated by the range of load and excess air levels that were practically attainable. Flue gas recirculation tests were performed on both boilers firing oil and the extent of the tests can be judged from the matrix presented in Table 5-4. As part of the flue gas recirculation tests, emission data was obtained without recirculation, thus allowing a comparison to be made of the boiler performance before and after modifications. A change in the emission characteristics of both boilers was observed. Emission levels were, in general, found to be lower after modification. A more detailed discussion of these baseline changes is presented in Appendix 2, which are confused because of contradictory fuel analyses for nitrogen content. In most instances measured NO_x and smoke emissions were lower after modifications had been made to the boilers. No explanation is available for the observed shift in baseline emissions, although several possibilities are listed in Appendix 2:

- changes in fuel properties;
- errors in analyses; and
- real changes due to modifications carried out to the boilers.

Firetube Boiler

The influence of flue gas recirculation on both NO_x and smoke emissions from the firetube boiler at nominal loads of 4,000, 6,200 and 10,000 lbs steam per hour can be seen in Figures 5-14, -15 and -16. It can be seen that the addition of flue gas to the combustion air had a significant influence on NO_x emissions at all loads. Smoke emissions were low (<2 Bacharach) for most conditions. Excessive smoking conditions were only observed at high load and low excess air levels. Flue gas recirculation did not reduce smoke emissions; in general, smoke emissions tended to increase slightly. This effect was also observed in the laboratory investigations.

Table 5-4. Flue Gas Recirculation Tests

Boiler	Nominal Load MLB/Hr	Nominal O_2 % Vol.	Nominal Flue Gas Recirculation Percentages
Firetube	4.0 (Low)	2	0, 20, 30, 40, 50
		4	0, 20, 30, 40
		6	0, 20, 20, 40
	6.2 (Medium)	4	0, 20, 20, 35
		7	0, 10, 30, 40
	10.0 ± 1.0 (High)	2.5 ± 0.5	0, 10, 15, 20
		3.5	0, 10, 20, 25
		6	0, 10, 20
Watertube	6.5 (Low)	3.0	0, 10, 20, 25, 30
		4.6	0, 10, 20, 25
	10.0 (Medium)	2.0	0, 10, 20, 25, 30
		3.3	0, 10, 20
	15.5 ± 0.5 (Medium)	2	0, 10, 20, 30
		3	0, 10, 15, 20
		4.1	0, 10, 15, 20, 25
		5.2	0, 10

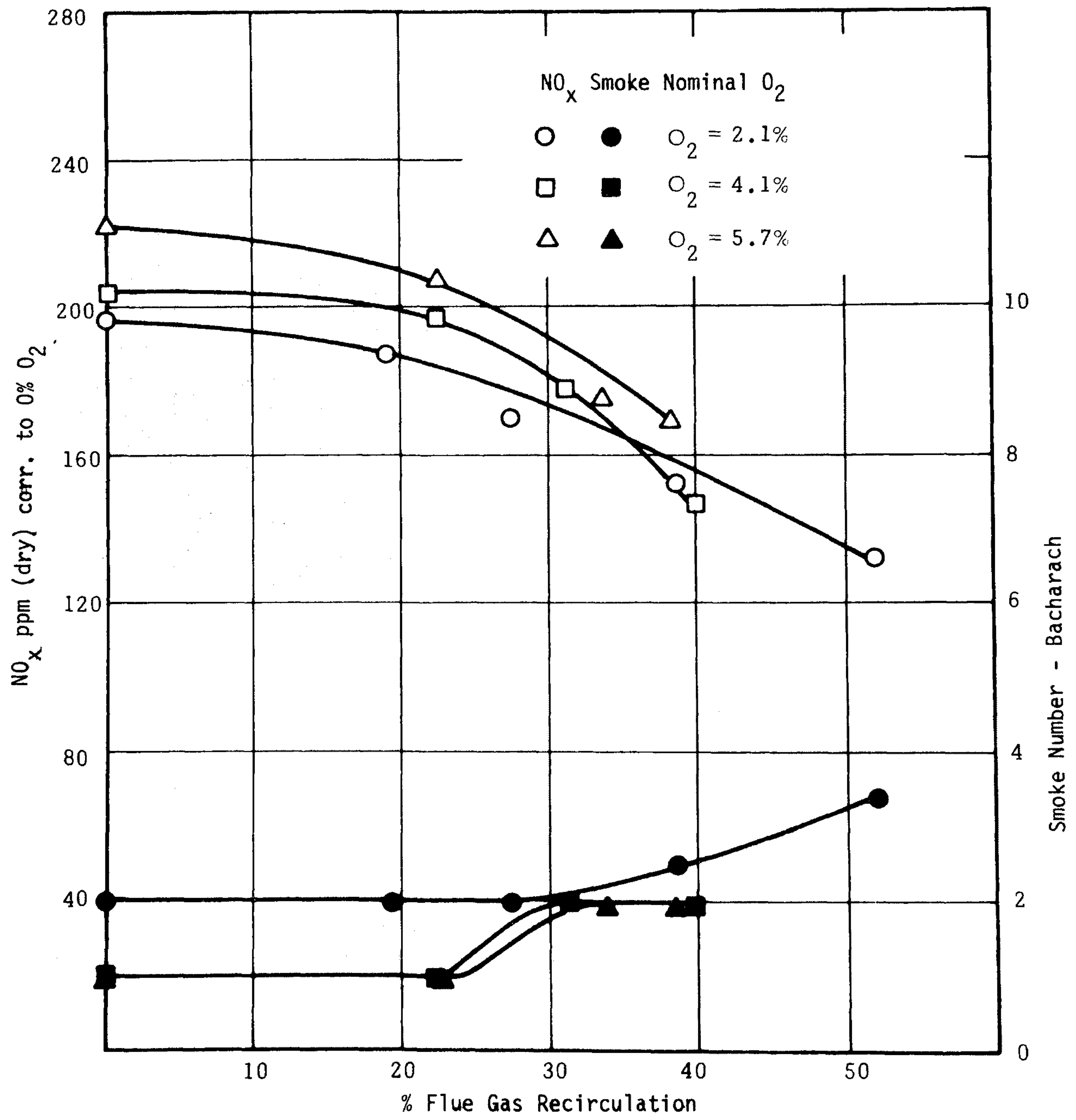

Figure 5-14. The Influence of FGR on NO_x and Smoke Emissions, Firetube Boiler, 4,000 lbs Steam per Hour

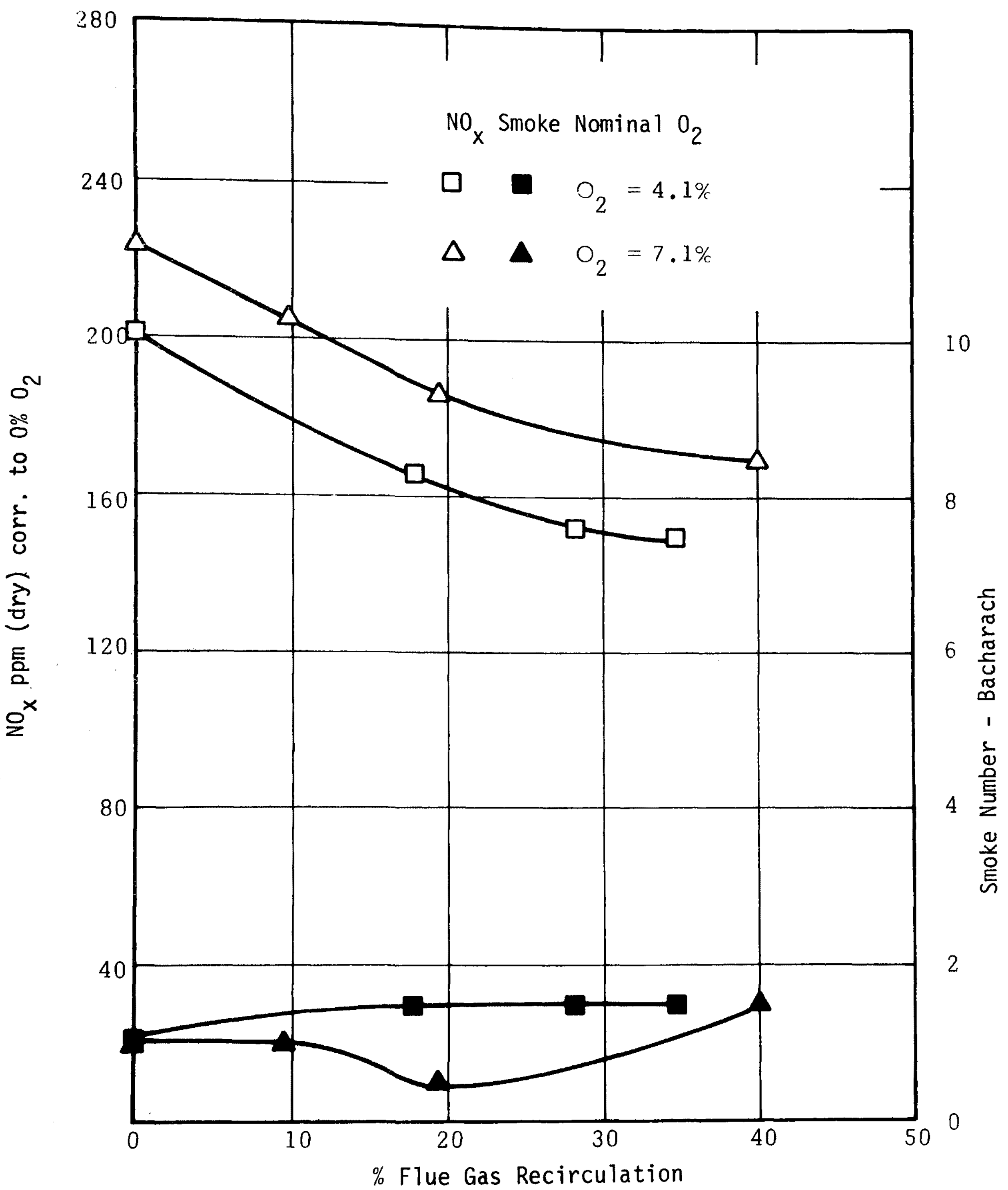

Figure 5-15. The Influence of FGR on NO_x and Smoke Emissions, Firetube Boiler, 6,200 lbs Steam per Hour

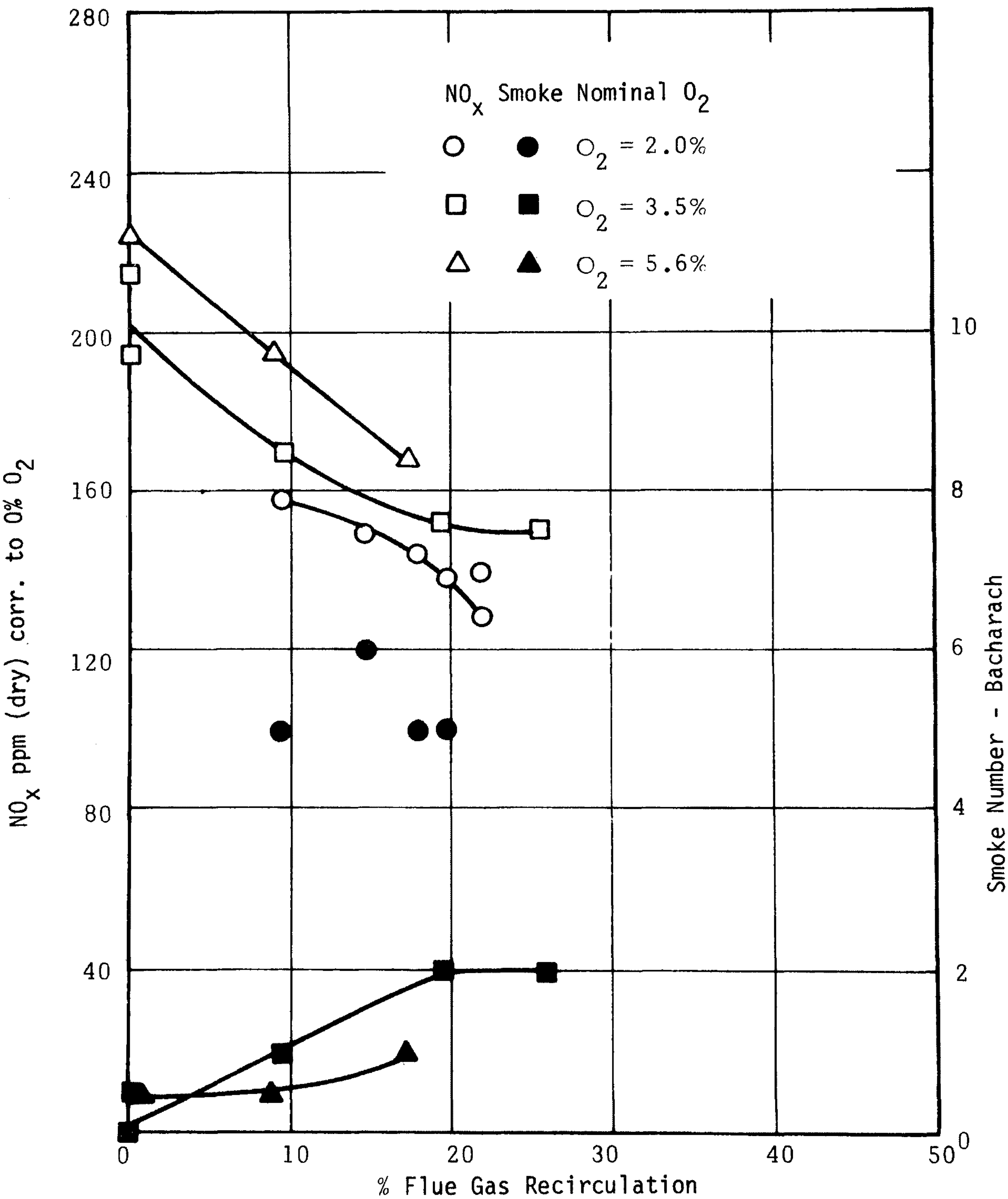

Figure 5-16. The Influence of FGR on NO_x and Smoke Emissions, Firetube Boiler, 10,3000 lbs Steam per Hour

One interesting feature of these results is that under certain boiler loads and excess air levels the influence of flue gas recirculation does not appear to be tailing off at high recirculation rates. This effect is contrary to the observations in experimental combustors and of most other workers. This effect could be attributed to reduced ignition stability. The ignition zone could be moving downstream as the amount of recycled flue gases is increased.

Watertube Boiler

As stated previously, reductions in the total steam demand due to procedural changes limited the extent of the testing with the watertube boiler. Recirculation rates in the watertube tests were limited by ignition instability which occurred around 25 percent recirculation. Significant NO_x reductions were not obtained by adding cooled combustion products to the combustion air in the windbox of the watertube boiler. Low recirculation rates often produced an increased emission. The results for three boiler loads are presented in Figures 5-17, -18 and -19. Smoke emissions were not increased by flue gas recirculation. In some instances smoke emissions were reduced by the addition of small quantities of recirculation which also caused a reduction in carbon monoxide emissions. NO_x emissions from the watertube boiler are somewhat lower than might be expected. This can be attributed to the relatively low combustion intensity. Visual observations suggest that fuel/air mixing rates are low, producing a "loose soft" flame. The increased burner pressure drop due to the addition of recirculation improved the oxygen/fuel mixing as indicated by the reduced smoke and carbon monoxide emissions.

5.3.3 Staged Combustion

The original concept for the staged combustion investigations was that they would represent a test of a commercial system. The laboratory results did not provide sufficient data for such a system to be designed with any reasonable probability of success. Consequently, the staging air delivery system was constructed to include considerable flexibility by allowing the axial location of the injectors to be varied. Time and funds restricted the tests in this program to a single location; however, the investigation will be extended in the future under EPA Contract 68-02-1498.

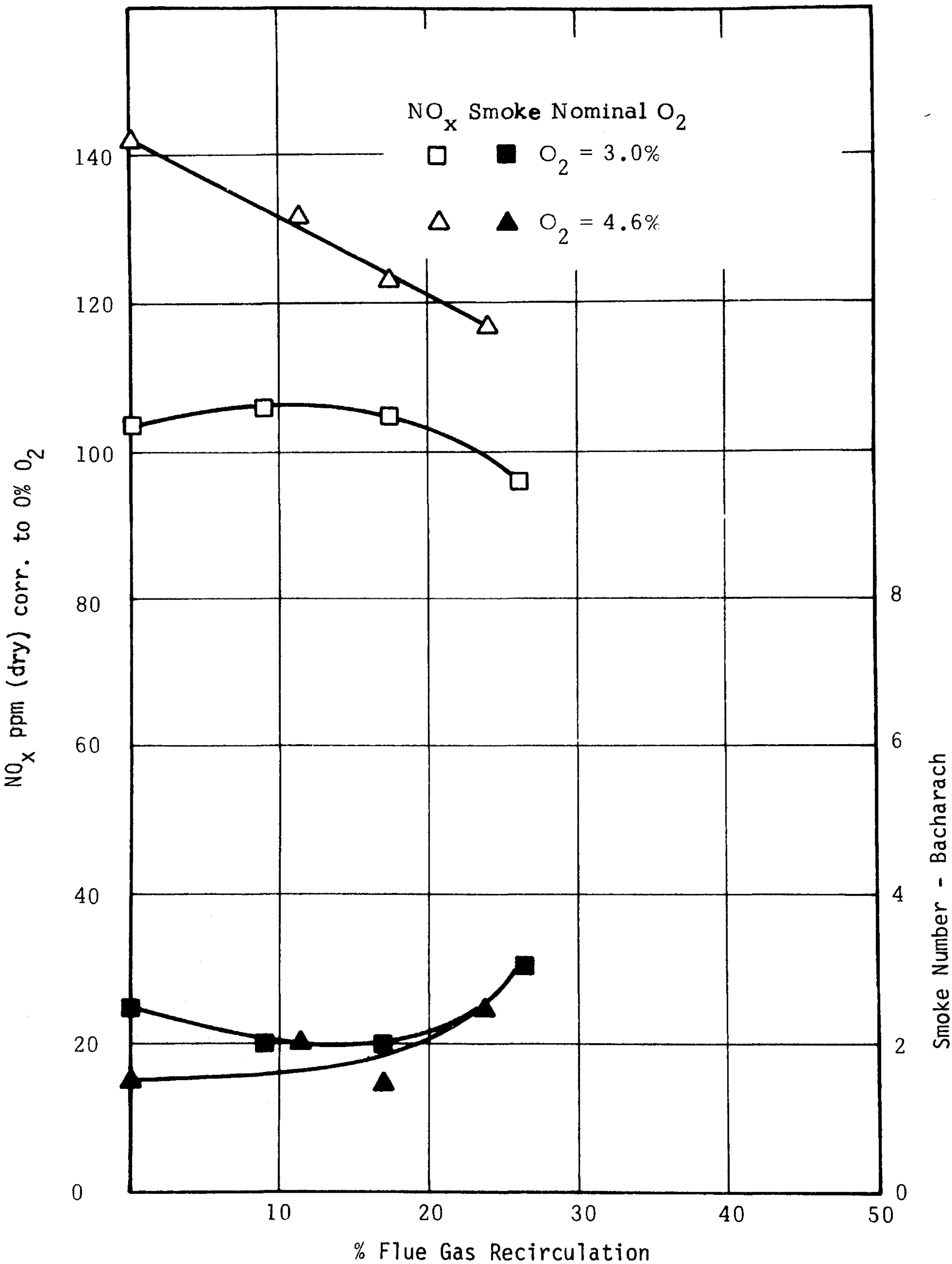

Figure 5-17. The Influence of FGR on NO_x and Smoke Emissions, Watertube Boiler, 6,500 lbs Steam per Hour

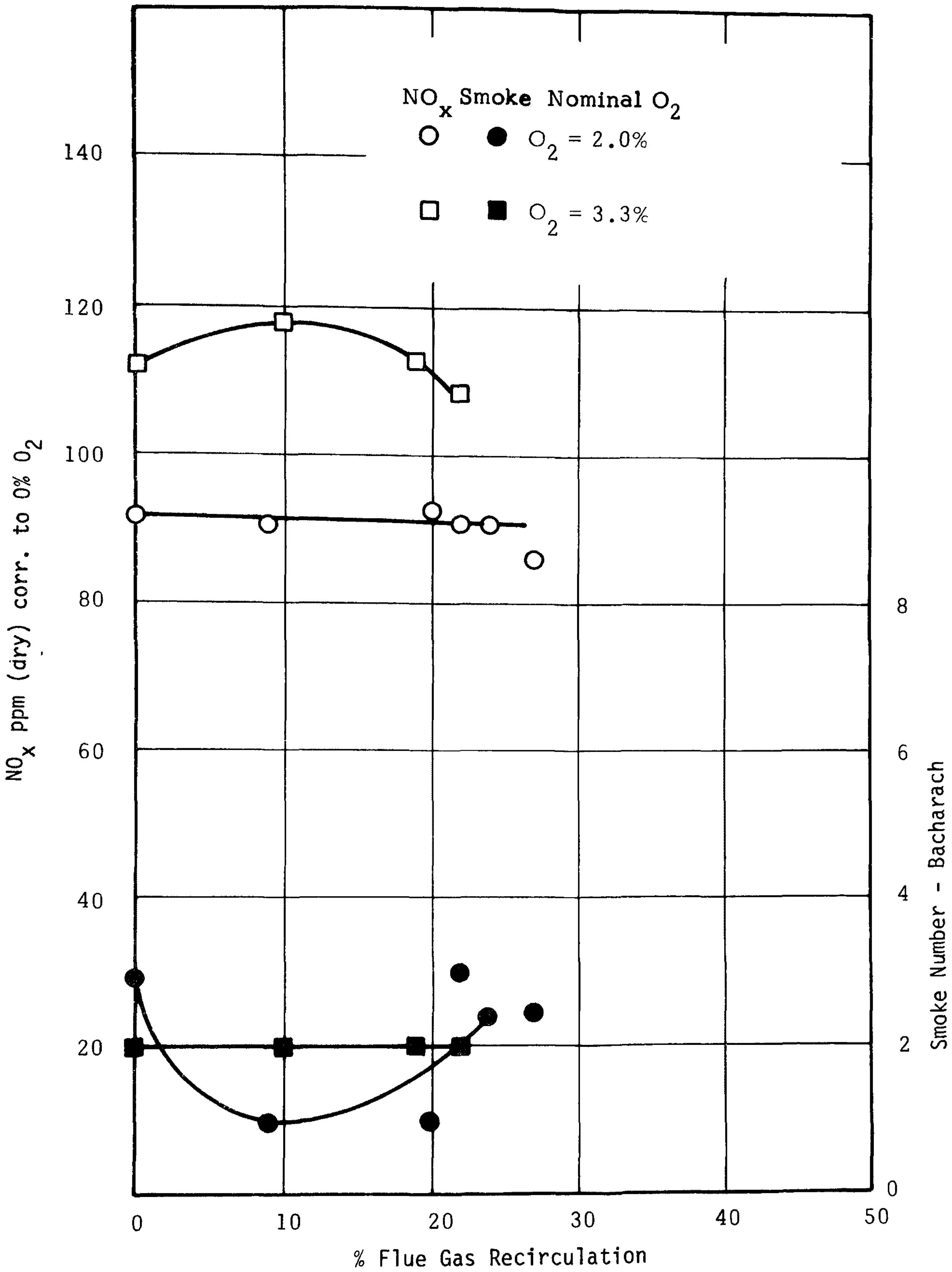

Figure 5-18. The Influence of FGR on NO_x and Smoke Emissions, Watertube Boiler, 10,000 lbs Steam per Hour

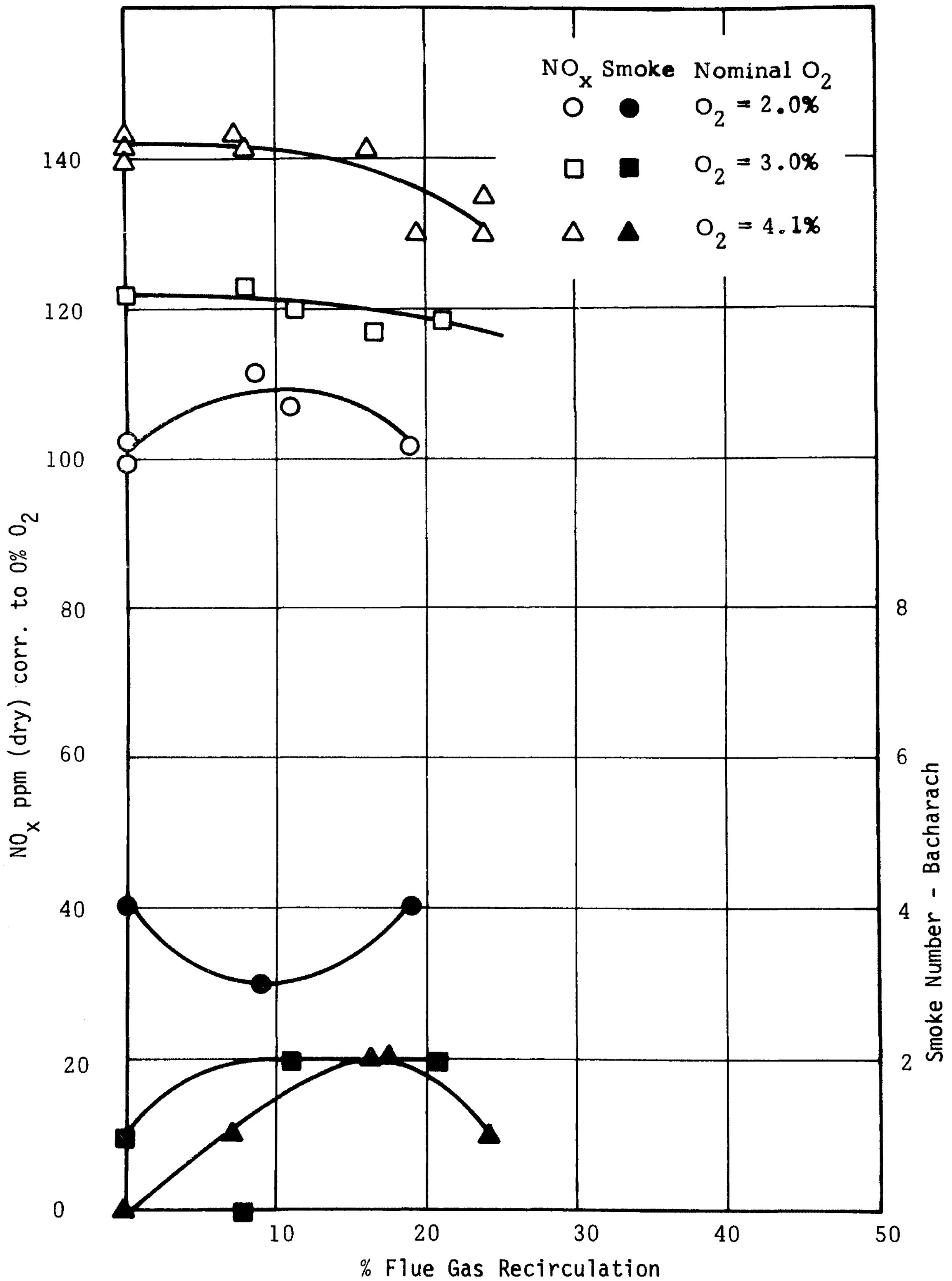

Figure 5-19. The Influence of FGR on NO_x and Smoke Emissions, Watertube Boiler, 16,000 lbs Steam per Hour

The experimental data obtained during the staging investigations is tabulated in Appendix 1. The staged air was added 1.5 firetube diameters downstream from the burner tip. This location was chosen to prevent excessive smoke formation based upon the results of the laboratory investigations. NO_x data for one boiler load (6,000 lbs steam per hour) and several excess air levels are presented in Figure 5-20 where it can be seen that the overall excess air has only a slight effect upon total emissions (c.f., 2 percent O_2 and 5 percent O_2). Almost 50 percent reduction in emissions were obtained without any attempt to optimize the system. Laboratory investigations had shown that optimum burner conditions for unstaged operation (e.g., air distribution, atomization conditions) might not be optimum for staged operation. Although smoke emissions increased with reduced burner stoichiometries, they were only excessive (i.e. > 4) in two of the tests (see Figure 5-21).

The staged combustion investigations were limited to one load because combustion instabilities were encountered at high loads as the air flow through the windbox was reduced.

5.4 Operational Experience

One of the objectives of this field demonstration was to try to identify some of the problems which must be solved before retrofit of package boilers for NO_x control can be considered. Since the boilers tested were "handpicked", it is reasonable to assume that the problems associated with modification would not be exaggerated even though the suitability for control was not a major criteria in this selection. Problems which might be encountered during retrofit for NO_x control can be divided into two groups: those which can be solved by adequate planning, and those which will only be uncovered during operation of the system. Naturally, this is an oversimplification since it will also depend upon the definition and the extent of the planning task. Those problems which can be included in the former group are:

- Limitations of Available Space. The equipment associated with the control technique must be designed to operate in an existing and often confined space. Thus, the siting of fans and ductwork are crucial, also the installation of the control system should not hinder the normal operation of the boiler.

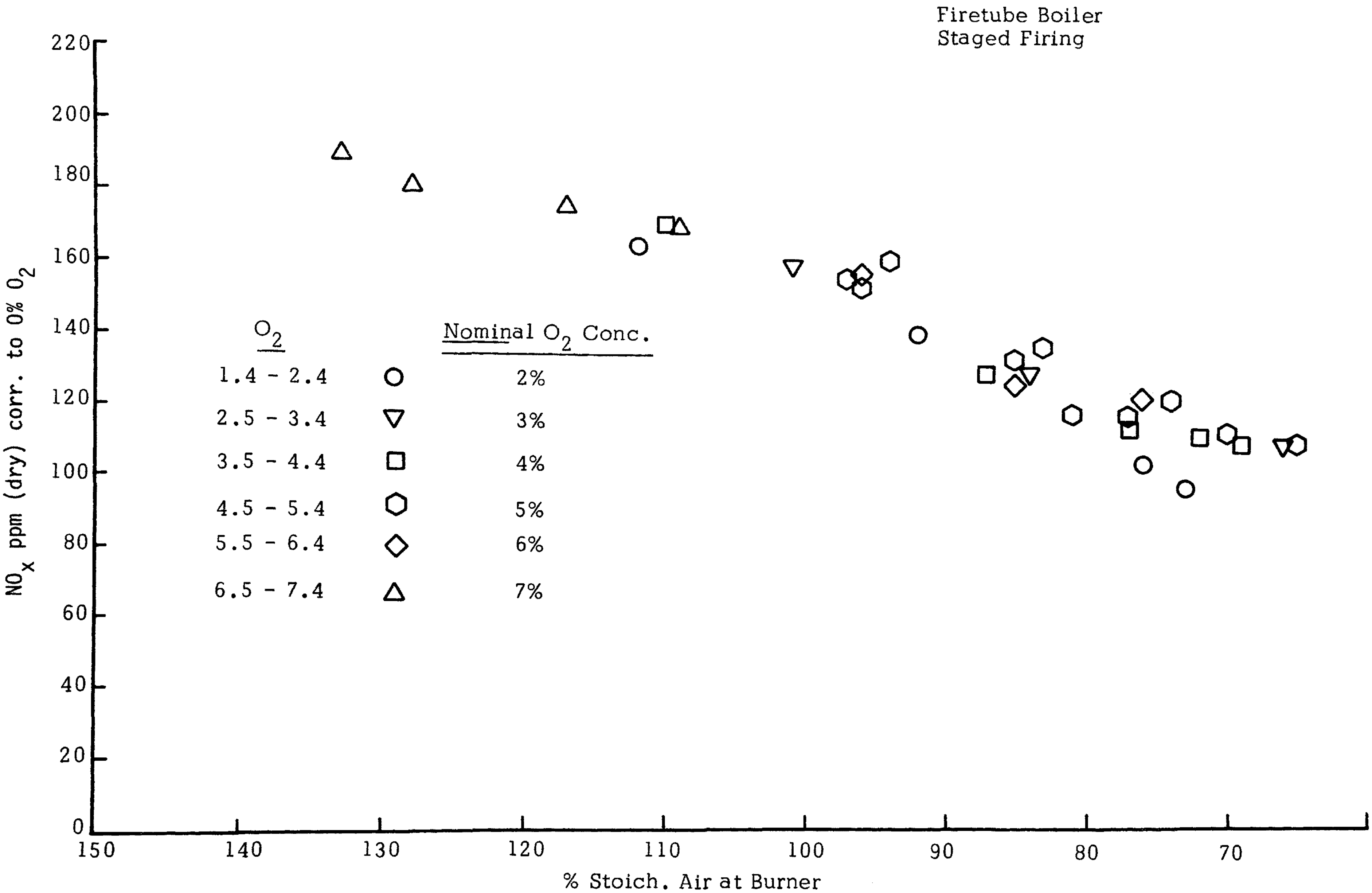

Figure 5-20. The Influence of Staging on NO_x Emissions from the Firetube Boiler (6,000 lbs of Steam per Hour)

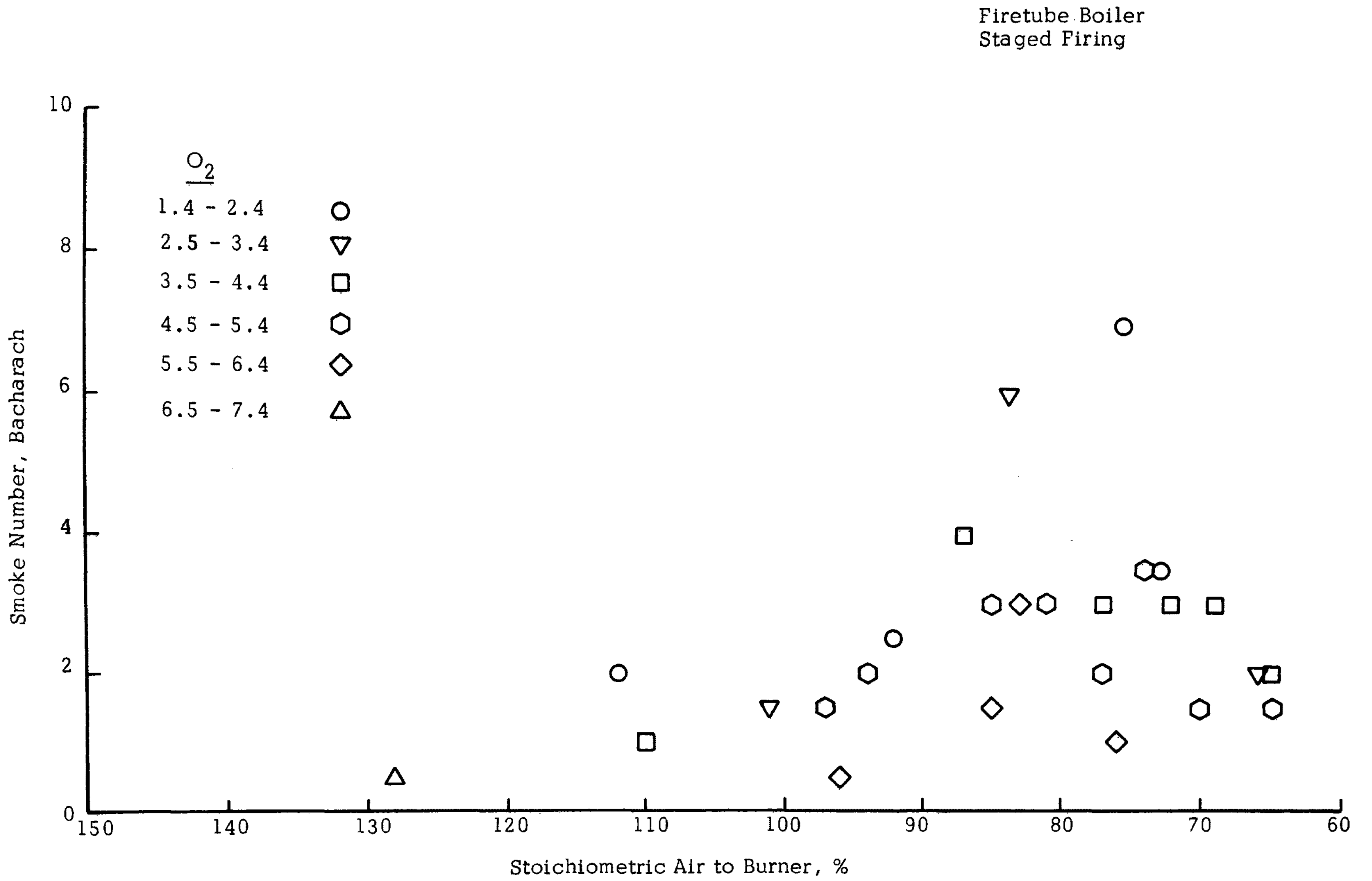

Figure 5-21. The Influence of Staging on Smoke Emission from the Firetube Boiler (6,000 lbs of Steam per Hour)

- Minimum Downtime. Boiler downtime can be minimized by adequate planning, but for some period of time the boiler must be taken out of service.

Since the boilers at ECCC were chosen because of their suitability for the project, it is safe to assume that the problems which could be overcome by planning would be minimized. It was stipulated initially that there would be no cutting and welding of pressure parts at ECCC, and therefore, problems associated with this subject could not be uncovered.

Several problems which fall into the latter group, operational problems, were found during the investigations at ECCC. A major problem with the operation of the firetube boiler was believed to be associated with the removal of the baffle plate which was found when the windbox was opened to install flue gas recirculation ducting. After removal of this baffle, serious instability problems occurred during normal boiler operation with FGR. The instability problem was only alleviated when almost the whole of the baffle plate was replaced. Flow straightening vanes placed in the FGR entry had no beneficial effect. Finally, the boiler vibrations were reduced to an acceptable level at most loads when an opening, equal to the area of the FGR duct, was left in the baffle. However, there were still certain conditions under which vibrations became excessive. It should be noted that it cannot be stated with absolute certainty that instability problems were unknown before the boiler was modified to accept flue gas recirculation.

High speed movie films taken during staging indicated that an intermittent "flashback condition" occurred at certain loads and excess airs. It could not be ascertained as to whether this was due to fluctuations in the oil supply pressure or to the reduced air flow through the burner throat. Ignition stability problems were encountered with the watertube boiler at flue gas recirculation rates in excess of 25 percent at most loads.

Potential long-term problems due to equipment deterioration were not found; however, it should be noted that none of the equipment was used continuously for a sustained test.

6.0 DISCUSSION AND CONCLUSIONS

6.1 Typicality of Field Test Units

Cato et al[7] have provided a considerable body of data on the pollutant emission characteristics of industrial boilers. Considerable effort was expended during the present investigation to ensure that the units tested in the field were typical of the whole class of package boilers. Figure 6-1 presents the baseline data obtained by Cato et al for boilers similar in size to those tested at the Essex County Correction Center. Baseline results from the laboratory combustor are also included. The boilers tested in this study appear to have similar characteristics to a wide range of boilers. Emissions from the ECCC firetube appear to be in the higher range for both No. 5 fuel oil and natural gas; whereas those from the watertube boiler appear to be in the lower range.

One of the difficulties associated with comparing the data from liquid fuel fired equipment is the nitrogen content of the fuel. Studies by Barrett et al[8] and Cato et al[7] give regression equations relating NO emissions and fuel nitrogen content. These relationships can be compared with the baseline emissions measured at ECCC in Figure 6-2. As noted previously, emissions from the watertube boiler appear to be low. Also, flue gas recirculation had only a minor influence on NO_x emissions, indicating that thermal NO_x formation was probably low.

The general conclusions of Cato et al which relate to this present study are:

- NO emission from natural gas fired boilers are weakly dependent upon excess air and normally range from 50 to 120 ppm dry corrected to 3 percent O_2;
- There does not appear to be any significant difference between NO_x emissions from firetube and watertube boilers in their common size range;
- Decreased oil temperatures tend to increase NO_x emissions.

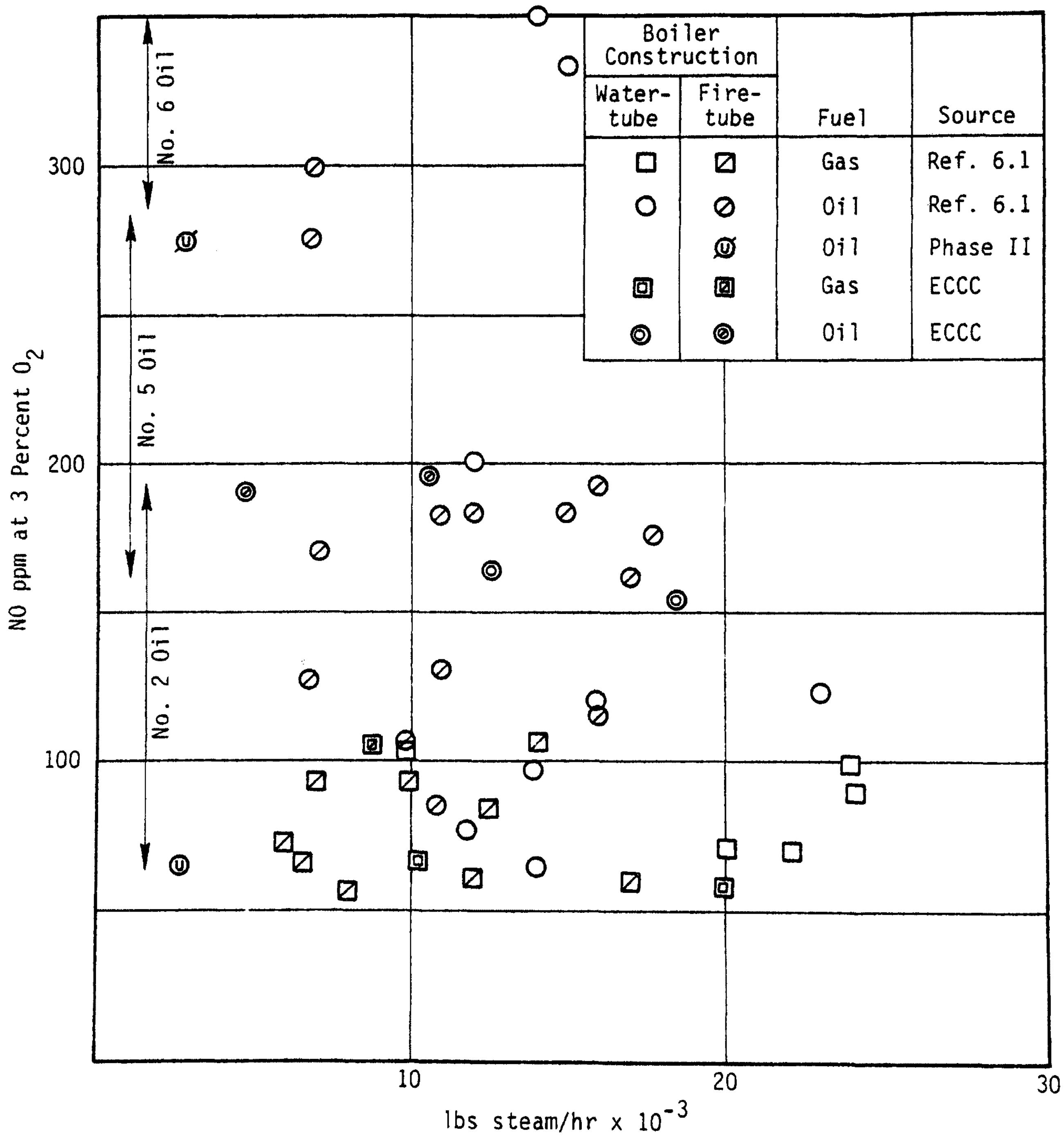

Figure 6-1. Comparison of Boiler Performance Data with that of Cato et al[7]

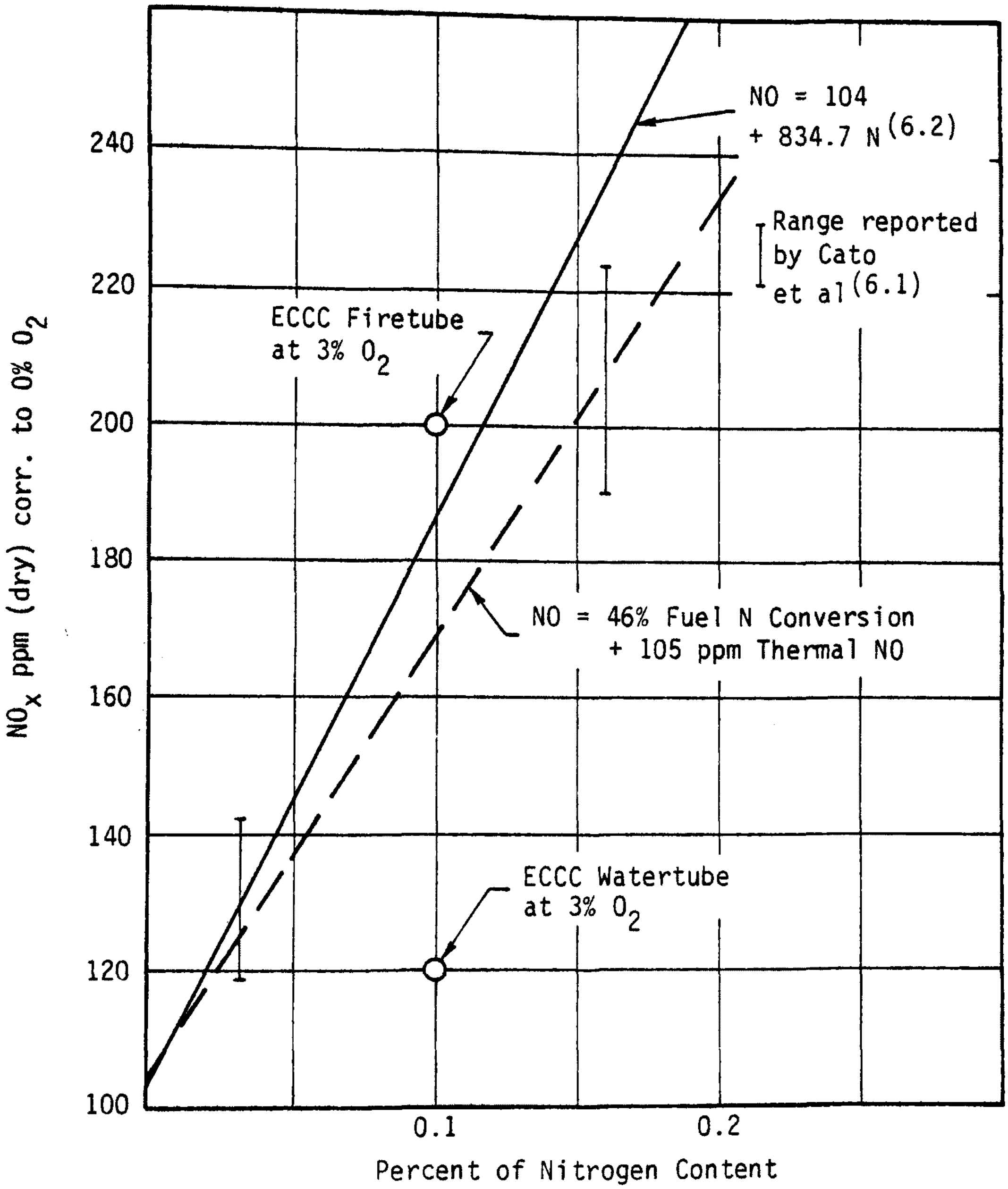

Figure 6-2. Relationship of Fuel Nitrogen Content and NO Emissions from Industrial Boilers

Experience in both the field tests and the laboratory investigations appears to be in direct conflict with the last conclusion.

As discussed in Appendix 2, the nitrogen content of the fuel oil used in the field tests is open to question. However, comparison with the available data suggests that the emission characteristics of the firetube boiler are typical of that class of equipment. Even recognizing that the watertube boiler was not tested at full capacity, it appears to be a naturally low NO_x emitter. It is, of course, not possible to ascertain as to whether the conversion problems encountered at ECCC are likely to be representative. The boilers chosen for testing were done so with a knowledge of the requirements of the control system to be installed and yet problems were uncovered which could not have been anticipated. There is no reason to believe that the two boilers tested in the field represent special cases, and it must be expected that similar problems would occur with other units.

6.2 Comparison of Laboratory and Field Test Results

A detailed discussion of the mechanisms of nitric oxide formation in turbulent diffusion flames is outside the scope of this report. Nitrogen oxides are formed from two sources of nitrogen during the combustion of fossil fuels, molecular nitrogen, and nitrogen compounds which occur naturally in both liquid and solid fuels. The reactions controlling the rate of oxidation of molecular nitrogen, producing thermal NO are strongly temperature dependent and only proceed at significant rates above 1600^{o}C. It was originally thought that the reaction between nitrogen molecules and oxygen atoms was mainly responsible for NO production in flames. However, it is now known that hydrocarbon radicals formed in flame zones also provide a path for thermal NO formation. The conversion of fuel-bound nitrogen producing fuel NO depends upon the nitrogen content of the fuel and upon oxygen availability. The amount of both fuel and thermal NO is strongly dependent upon the rate of fuel/air mixing and bulk gas temperatures which are functions of the combustion system. The rate at which the fuel and air are mixed is controlled by burner design parameters and the bulk gas temperature in the region of interest is dependent upon the volumetric heat release rate and the temperature of the enclosure. Consequently, it is readily apparent that NO formation in turbulent diffusion flames is system-dependent and detailed comparisons between the laboratory and the field is difficult.

The laboratory combustor was designed as a firetube simulator. Consequently, it would be expected that similarities could be found between the results obtained with the firetube boiler in the field and the laboratory combustor. However, the watertube boiler has several important characteristics which differentiate it from the laboratory combustor:

- it is three dimensional and not axisymmetric;
- the burner has a register and is very different from either of the firetube boiler burners;
- the flame is less confined by the boiler walls; and
- visually, the flame in the watertube is of low intensity.

Thus, it would be expected that the emission characteristics of the watertube boiler would not be simulated by the laboratory combustor.

Figure 6-3 compares the fractional reduction in NO_x emission achieved by flue gas recirculation. The data presented includes that taken in the field test, the laboratory investigation as well as comparative data from other works:

- Curve 1 presents Phase II laboratory data for a No. 2 fuel oil (nitrogen content 0.05 percent).
- Curve 2 presents Phase II laboratory data for a No. 6 fuel oil (nitrogen content 0.36 percent).
- Curve 3 is taken from the work of Armento and Sage[(9)] and relates to experiments conducted in a circular tunnel furnace with a register burner and No. 6 fuel oil (nitrogen content 0.23 percent) but with preheated air.
- Curves 4a and 4b are taken from the work of Turner et al[(10)] and were obtained in a 50 HP Cleaver Brooks Boiler for high nitrogen and low nitrogen oils (curve 4a 0.77 percent nitrogen, curve 4b 0.03 percent nitrogen).

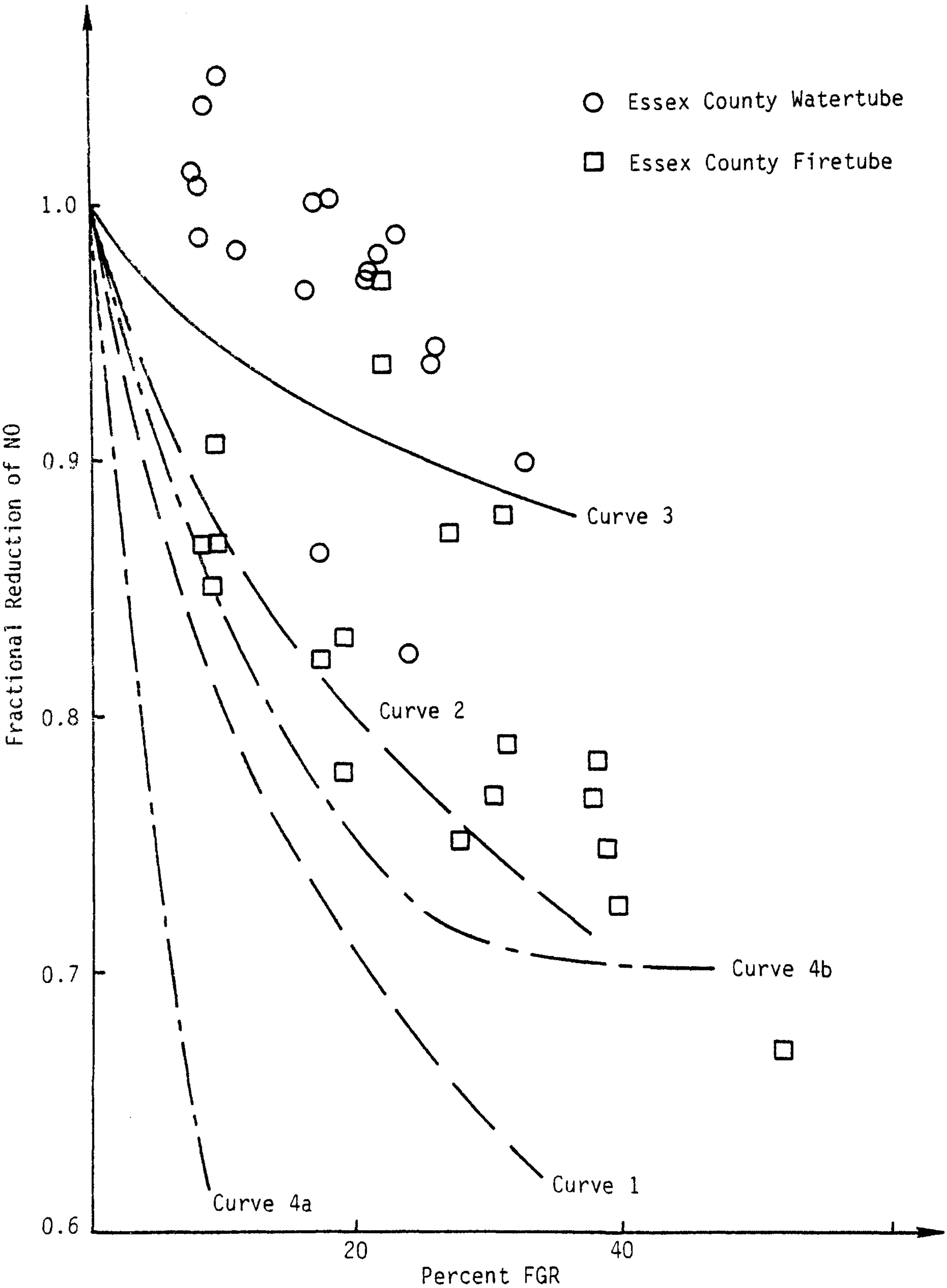

Figure 6-3. Fractional Reduction of NO Achieved by FGR Comparison of Field and Laboratory Data

Although Martin and Berkau[11] found that FGR slightly reduced fuel NO emissions, its primary effect is the reduction of thermal NO. It is difficult to draw general conclusions based upon the results of one field test. However, the comparisons presented in Figure 6-3 strongly suggest that for firetube boilers burning No. 5 or No. 6 fuel oil, a 30 percent reduction in emissions could be expected with approximately 40 percent FGR. The absolute reduction would depend upon the amount of refractory in the firetube. Larger reductions could be expected for No. 2 fuel oil.

It is a gross oversimplification to state the FGR will only eliminate thermal NO since the increased burner throat velocity will influence the rate of fuel/air mixing which could also influence fuel NO formation. The addition of FGR to the windbox of the watertube boiler had very little effect upon NO emissions. Indeed, it actually increased NO emissions under certain circumstances. It is contended that this particular burner/boiler combination has low NO characteristics by virtue of the slow rate of fuel/air mixing (confirmed by visual observations) and generous furnace volume. Virtually the total emission can be attributed to fuel NO and the increased emission with the addition of FGR is due to improved mixing caused by the increased burner pressure drop. When comparing the ECCC data with that of Armento and Sage it should be remembered that the experimental tunnel was partially refractory covered and the air was preheated. Both of these factors would tend to increase the amount of thermal NO formation. Therefore, in watertube boilers without preheat, it is reasonable to expect that a 15 percent reduction in NO could be obtained by recycling 40 percent of the flue gases when firing fuel oil.

As discussed earlier, the performance of the laboratory system during staging could be improved by optimizing the burner conditions. It is encouraging that the field tests were successful even without making changes to the burner. The improved performance can be due to:

- a burner system which was initially more suitable for staged combustion;
- improved design of the staged air injectors;
- the second stage was heated before injection which would tend to prevent chilling and help carbon burnout.

6.3 Cost of Emission Control

It is most difficult to accurately assess the cost of NO_x emission control for residual oil-fired packaged boilers based solely upon the experience gained during this program. Four different situations can be envisaged in which the cost of additional pollution control equipment will be different; these are:

1. The modification of field operating boilers in a similar way to the exercise carried out at ECCC.
2. Shop retrofit of a new or used boiler prior to use in the field.
3. Manufacturer incorporation of the additional equipment in a new boiler.
4. A new boiler design which is dictated by the requirements of the pollution control equipment.

It is not possible to assess the costs associated with the fourth situation and there is a considerable degree of uncertainty associated with the estimates for the other three possibilities. Presented below are the actual costs for the modifications carried out during this program. These costs are naturally high because they reflect a necessary learning experience. Having gained this experience, future work of a similar nature would be less costly. An attempt has been made to estimate the costs associated with the third alternative listed above and the most uncertain figure in these estimates is that associated with design costs since this will depend upon the frequency of the exercise and the sales volume of boilers with additional pollution control equipment.

Flue Gas Recirculation

Retrofit of an existing unit to accept flue gas recirculation involves both the addition of new equipment as well as alteration of the existing plant. Depending upon the boiler house layout, a considerable design effort may also be required. Table 6-1 presents an approximate breakdown of design, installation and equipment costs associated with the retrofit of FGR systems to the two boilers at ECCC.

Table 6-1. Cost Breakdown for Fitting FGR to the Two Boilers at ECCC (1975 Dollars)

	Firetube	Watertube
Design (including drafting)	$ 5,000	$ 5,000
Fabrication of Duct	2,900	2,900
Installation of Duct	1,800	1,800
Blower	1,500	1,900
Butterfly Valve	490	540
Flanges	600	900
Electrical Hardware	450	550
Installation (other than duct)	5,000	5,000
Controls System	2,600	2,600
Total	$20,340	$21,190

If a flue gas recirculation system were to be applied to a new boiler, costs should be considerably less than for a retrofit. The cost of design would be small, as the system would be an integral part of the boiler. Perhaps the blower could be eliminated entirely by upgrading the forced draft fan and utilizing this as both the FD and FGR fan, although this would impose more severe restraints on the control system. The amount of duct work could also be reduced, thus lowering the cost. Table 6-2 is an estimate of the cost of including an FGR system in a new package boiler by the manufacturer.

Table 6-2. Approximate Cost Breakdown for Application of Flue Gas Recirculation to New Boilers

Design (In excess of normal)		$ 500
Fabrication and Installation of Duct work		2,000
Blower (use FD fan)		--
Fittings		800
Electrical Hardware (No additional)		--
Installation (In excess or normal)		1,000
Automatic Controls		2,600
	Total	$6,900

Staged Combustion

Although the staged combustion equipment was not considered as a practical proposition, it is instructive to examine an approximate cost breakdown (Table 6-3).

Table 6-3. Breakdown of Costs for Staged Combustion Investigation

	As Carried Out At Essex County	Estimated for New Boiler
Design	$ 7,000	$2,000
Control and Measurement	700	3,400
Materials	2,680	500
Installation	18,000	3,700
Total	$28,280	$9,600

In addition to these costs, approximately $1,000 would be required for a blower. However, in this case, the blower was supplied by Foster Wheeler.

If a staging system were to be included in the original design of a firetube boiler, cost savings over a retrofit could be realized in design, materials and possibly installation. Instead of penetrating the rear of the boiler, side penetration would be utilized. This would increase boiler costs due to additional pressure welds and the possibility of rearranging tubing locations. However, the forced draft fan could be used as the air supply, and there would be less need for high temperature alloys. Automatic controls would be an additional cost.

The costs given in Table 6-3 refer to a new package boiler of existing design which would be modified before delivery to the customer. If a new class of boiler were to be offered for sale whose design had been altered to more readily include these additional facilities, the cost of this new class would not contain all those items listed in Tables 6-2 and 6-3. Design costs, for instance, would be minimal and additional fabrication costs could be reduced considerably.

6.4 Implication of Results on New Design

The results of the FGR tests on the two boilers indicate that, with the fuel fired, FGR has a definite effect on lowering NO_x in the firetube boiler and an insignificant effect in reducing it in the watertube boiler. Therefore, FGR is not recommended as a method for controlling NO_x emissions on a watertube boiler of the size tested and firing the fuel tested. However, it is very difficult to draw completely general conclusions on the basis of one series of laboratory investigations and tests on two field boilers. Combustion systems giving rise to considerably thermal NO formation (e.g., firetube with refractory front section, refractory firebox watertube boiler) will probably be responsive to FGR as a control technique, but emissions are not expected to be lowered by greater than 30 percent for No. 5 or No. 6 fuel oil.

The FGR system on the firetube boiler appeared satisfactory except for the experience with pulsations described earlier. However, the FGR fan was oversized, as higher FGR rates at high boiler loads did not cause further reductions in NO_x. In a new design, the system could be made more compact incorporating air and FGR fans in one combined function. This would facilitate air/flue gas mixing and lower the temperature of the gas entering the windbox. It may be advantageous to rearrange the location of boiler components which presently pass through the windbox. This would avoid any difficulty with respect to obstructions inside the windbox and problems associated with pressure fluctuations, and perhaps temperature sensitive components. Additional consideration must be given to the rearrangement of external equipment associated with boiler operation to enable ease in the fitting of FGR components. Finally, testing should be performed to determine the causes of combustion instability so that the severe vibrations previously experienced would not occur.

REFERENCES

1. Muzio, L.J., and Wilson, R.P., Jr., "Experimental Combustor for Development of Package Boiler Emission Control Techniques," Phase I of III, EPA Report R2-73-292-a, 1973.

2. Muzio, L.J., Wilson, R.P., Jr., and McComis, C., "Package Boiler Flame Modifications for Reducing Nitric Oxide Emissions," Phase III of III, EPA Report R2-73-292-b, 1974.

3. Muzio, L.J., Wilson, R.P.. Jr., and McComis, C., "Package Boiler Flame Modifications for Reducing Nitric Oxide Emissions," Phase II of III, EPA Report R2-73-292-b, 1974.

4. Siegmund, W.C., and Turner, D.W., "NO_x Emissions from Industrial Boilers: Potential Control Methods," ASME Paper 73 IPWRIO, 1973.

5. Lachapelle, D., Private communcation.

6. Heap, M.P., Lowes, T.M. and Martin, G.B., "The Optimization of Aerodynamic Design Variables to Control the Formation of Nitric Oxide in Fossil Fuel Flames", Fluid Mechanics of Combustion, p. 75, The American Society of Mechanical Engineers (1974).

7. Cato, G.A., Buening, H.J., DeVivo, C.C., Morton, B.G., and Robinson, J.M., "Field Testing: Application of Combustion Modifications to Control Pollutant Emissions from Industrial Boilers - Phase I". EPA Report 650/2-74-078-a.

8. Barrett, R.E. and Miller, S.E., "Field Investigation of Emissions from Combustion Equipment for Space Heating, Final Report". Battelle-Columbus Laboratories, Columbus, Ohio. Prepared for the U.S. Environmental Protection Agnecy and the American Petroleum Institute. EPA Report No. R2-73-084a. NTIS No. PB 223-148, or API Publ. 4180, June 1973.

9. Armento, W.J., "Effects of Design and Operating Variables on NO_x from Coal-fired Furnaces, Phase I". Babcock and Wilcox, EPA 650/2-74-002a, NTIS PB 229-986/AS, January 1974.

10. Turner, D.W., Andrews, R.L., and Siegmund, C.W., "Influence of Combustion Modification and Fuel Nitrogen Content on Nitrogen Oxides Emissions from Fuel Oil Combustion". Presented at 64th Annual AIChE Meeting, San Francisco, November 1971.

11. Martin, G.B. and Berkau, E.E., "Evaluation of Various Combustion Modification Techniques for Control of Thermal and Fuel-Related Nitrogen Oxide Emissions". 14th Symposium (International) on Combustion, Pennsylvania State University, August 1972.

APPENDIX 1

TABULATED FIELD TEST DATA

Table A1-1. Boiler Performance Data ECCC Firetube Boiler No. 5 Fuel Oil

Test	Steam Flow lb/hr x 10^{-3}	NO_x ppm dry	NO_x ppm dry corr. to 0% O_2	CO ppm dry by vol.	Smoke Bacharach Scale	Fuel Oil Temp. °F	SO_2 ppm dry by vol.	O_2 % by vol. dry
A	4	170	230			155	450	5.5
E	5	180	199		6.5	150	568	2.1
F	5.5	170	178	120	9.5	155	665	0.9
G	5.5	180	228		3	155	500	4.4
H	5	170	244		1.5	150	438	6.4
I	7.5	165	257		1.5	155	383	7.5
J	7.25	155	268		1.5	155	343	8.9
K	7.5	173	241		2	155	433	6.0
L	7.5	175	206		5	155	527	3.2
M	7.5	163	171	>1000	(10)		615	1.0
N	11	193	237		3	160	512	3.9
O	11.5	190	215		6	160	550	2.4
P	11	202	250			160		4.1
N(R)	11	195	231			160		3.3
Q	11	197	239	3		140		3.7
R	8	175	260			150		6.9

Table A1-2. Boiler Performance Data ECCC Firetube Boiler Natural Gas

Test	Steam Flow lb/hr x 10^{-3}	NO_x ppm dry	NO_x ppm dry corr. to 0% O_2	CO ppm dry	O_2 % dry by vol.
A-1	1	42	115	20	13.3
B-1	1	44	87	20	10.4
C-1	1	47	87	20	9.6
D-1	0.75	38	130	20	14.9
E-1	3.75	61	107	15	9.1
F-1	4	64	103	15	8.0
G-1	4	59	120	17	10.7
H-1	4	56	123	5	11.5
I-1	7	73	105	5	6.5
J-1	6.5	71	111	15	7.6
K-1	6.5	68	119	5	9.0
L-1	8.5	68	102	15	7.1
M-1	8	72	105	40	6.6
N-1	8.75	66	105	40	7.8

Table A1-3. Boiler Performance Data ECCC Watertube No. 5 Fuel Oil

Test	Steam Flow (lb/hr x 10^{-3})	NO_x ppm dry	NO_x ppm dry corr. to 0% O_2	CO ppm dry	O_2 % dry by vol.	SO_2 ppm dry	Smoke No. Bacharach	Atom. Steam Press. psig	Fuel Oil Temp.	Air Regis. % Open
1	10	139	177	-	4.6	531	-	39	152	100
2	10.5	118	144	-	3.8	565	9	39	152	100
3	10	142	199	-	6.0	488	3	40	152	100
4	10	155	232	-	7.0	422	3	52	152	100
5	10	93	109	-	3.1	572	8	20	152	100
6	10	117	148	-	4.5	530	3.5	36	110	100
7	10.25	140	187	0	5.3	502	2.5	39	165	100
8	15	123	140	25	2.6	607	3.5	50	148	100
9	15	135	220	-	8.1	408	2	52	147	100
10	15.5	143	202	-	6.1	466	2	52	147	100
11	15	140	175	-	4.2	528	2	51	150	100
12	15	110	126	100	2.7	584	4	50	150	-
13	15.25	87	98	>3000	2.3	788	-	52	150	-
14	15	78	90	3000	2.8	653	9.5	51	150	-
15	15	120	170	-	6.2	478	15	63	150	-
16	15	102	131	-	4.6	529	3	50	150	-
17	19	130	163	-	4.3	535	4	61	151	-
18	18.5	120	215	-	9.3	365	3	60	150	-
19	18.5	130	203	-	7.6	416	3	61	149	-
20	18.5	135	182	-	5.5	486	3	60	149	-
21	18.5	110	132	100	3.6	575	4	60	150	-
22	18.5	88	110	1150	4.2	579	7	59	150	-
23	18.5	117	148	-	4.5	520	3	60	150	-
24	12.5	98	124	-	4.5	517	3	43	149	-
25	7.5	107	178	-	8.4	371	3.5	32	147	-
26	7.5-10	66	78	2500	3.2	585	8.5	37	149	-
27	14.5	113	133	-	3.1	518	3	48	152	-
28	14.75	105	113	>3000	1.5	675	10+	49	152	-
29	14.5	110	120	2200	1.8	630	8	49	152	-
30	14.5	115	129	500	2.3	600	3.5	48	152	81
31	14.5	118	131	-	2.1	590	3.5	47	152	88
32	14.5	120	135	25	2.4	603	3.5	47	150	94
33	14.5	120	137	-	2.6	600	-	48	152	-

Table A1-4. Boiler Performance Data ECCC Watertube Natural Gas

Test	Steam Flow (lb/hr x 10^{-3})	NO_x ppm dry	NO_x ppm dry corr. to 0% O_2	CO ppm dry	Smoke No. Bacharach	Air Register % Open
1-A	13.5	62	70	30	0	100
2-A	13.0	55	78	15	0	100
3-A	13.0	62	79	0	0	100
4-A	13.0	59	62	690	2	100
5-A	10.0	62	77	15	0	100
6-A	10.25	57	81	30	0	100
7-A	10.5	62	80	30	0	100
8-A	10.5	63	71	50	0	100
9-A	13.0	64	72	30	0	100
10-A	13.5	67	77	15	0	94
11-A	13.5	70	81	15	0	88
12-A	13.0	73	82	15	0	81
13-A	12.75	77	81	400	0	75
14-A	12.5	64	72	30	0	100
15-A	20.0	50	78	20	0	100
16-A	20.0	38	75	15	0	100
17-A	19.75	44	79	20	0	100
18-A	19.5	54	76	30	0	100
19-A	19.25	53	69	785	0	100
20-A	15.75	51	72	5	0	100
21-A	16.0	44	76	5	0	100
22-A	16.25	49	77	20	0	100
23-A	15.5	50	64	925	0.5	100
24-A	8.25	44	74	0	0	100
25-A	8.0	39	79	0	0	100
26-A	8.5	42	76	0	0	100
27-A	8.5	48	68	0	0	100
28-A	8.5	47	60	470	0	100

Table A1-5. Flue Gas Recirculation Watertube No. 5 Oil

Test	%FGR	Steam Flow ($lb/hr \times 10^{-3}$)	NO_x ppm dry	NO_x ppm dry corr. to 0% O_2	CO ppm dry	O_2 % dry by vol.	SO_2 ppm dry	Smoke No. Bacharach
1	0	9.75	94	112	10	3.3	215	2
2	10.1	10.0	99	118	38	3.4	209	2
3	18.8	10.0	95	113	52	3.4	210	2
4	21.9	10.5	93	109	53	3.0	215	2
5	22.2	10.0	82	91	110	2.1	225	3
6	27.2	10.2	78	86	112	1.9	225	2.5
7	23.5	10.2	82	91	110	2.1	225	2.5
8	19.9	9.8	84	93	110	2.1	223	1
9	8.9	10.2	82	91	111	2.0	225	1
10	0	10.3	83	92	210	2.1	235	3
11	0	6.5	110	142	30	4.7	182	1.5
12	11.4	6.7	102	132	27	4.7	175	2
13	17.3	6.5	96	123	30	4.6	180	1.5
14	24.1	7.0	91	117	30	4.6	175	2.5
15	0	6.5	89	104	37	3.0	170	2.5
16	9.0	6.5	92	106	30	2.8	176	2
17	17.4	6.0	89	105	30	3.1	179	2
18	26.5	6.4	84	96	30	2.7	180	3
19	33.0	6.5	80	92	30	2.8	177	-
20	0	4.8	91	157	30	8.8	141	-
21	0	14.6	112	139	20	4.0	178	-
22	8.0	16.2	113	141	20	4.2	175	-
23	19.4	15.0	106	130	20	3.9	176	-
24	24.1	14.9	108	135	20	4.2	173	-
25	7.5	15.0	113	135	20	3.4	181	-
26	9.2	15.5	110	148	20	5.4	170	-
27	10.7	15.8	97	107	47	2.0	183	-
28	0	15.6	91	100	365	1.9	183	-
29	0	15.5	105	122	22	2.9	198	1
30	0	16.0	114	141	20	4.0	192	0
31	8.1	15.8	106	123	27	2.9	192	0
32	11.1	15.8	103	120	20	3.0	198	2
33	21.2	16.0	101	119	20	3.1	196	2

Table A1-5. Flue Gas Recirculation Watertube No. 5 Oil (Cont.)

Test	% FGR	Steam Flow ($lb/hr \times 10^{-3}$)	NO_x ppm dry	NO_x ppm dry corr. to 0% O_2	CO ppm dry	O_2 % dry by vol.	SO_2 ppm dry	Smoke No. Bacharach
34	28.4	15.6	90	102	20	2.4	200	3
35	24.0	16.3	103	130	15	4.3	191	1
36	16.8	16.0	100	117	20	3.0	192	2
37	16.4	16.2	113	141	20	4.2	187	2
38	19.0	16.8	92	102	45	2.0	200	4
39	7.6	16.8	112	143	20	4.5	196	1
40	8.8	16.5	102	112	32	1.9	204	3
41	0	16.7	115	146	20	4.4	197	1
42	0	16.0	89	98	213	1.9	200	4
43	0	16.0	110	131	-	3.4	197	-
44	0	15.2	113	149	-	5.0	131	-
45	0	15.5	93	103	-	2.1	215	-

Table A1-6. Flue Gas Recirculation Firetube No. 5 Oil

Test	% FGR	Steam Flow (lb.hr x 10^{-3})	NO_x ppm dry	NO_x ppm dry corr. to 0% O_2	CO_2 ppm dry	O_2 % dry by vol.	SO_2 ppm dry	Smoke No. Bacharach
1	0	4.0	167	180	-	1.5	248	4
2	0	4.1	162	204	-	4.3	203	1
3	22.7	4.0	160	198	-	4.0	197	1
4	31.5	4.0	145	179	-	4.0	204	2
5	40.2	4.0	118	148	-	4.2	205	2
6	0	3.9	160	223	-	5.9	181	1
7	22.5	4.0	152	209	-	5.7	180	1
8	32.0	3.9	129	176	-	5.6	178	2
9	38.6	4.1	123	171	-	5.9	174	2
10	0	4.2	175	197	-	2.3	225	2
11	19.3	4.2	168	188	-	2.2	224	2
12	27.8	4.3	153	171	-	2.2	225	2
13	38.8	4.0	139	154	-	2.0	230	2.5
14	52.7	3.8	118	132	-	2.2	230	3.5
15	0	6.0	145	224	-	7.4	162	1
16	9.8	6.0	134	203	40	7.1	160	1
17	19.8	6.0	123	186	40	7.1	160	0.5
18	39.8	6.4	113	170	45	7.0	160	1.5
18a	28.9	6.5	120	171	40	6.2	170	1.5
19	34.8	6.2	120	150	40	4.1	198	1.5
20	28.2	6.3	123	152	40	4.0	200	1.5
21	17.8	6.3	133	166	40	4.2	200	1.5
22	0	6.3	162	202	40	4.1	191	1
23	0	11.25	174	215	35	4.1	210	0.5
24	0	11.0	175	200	38	3.0	223	1
25	9.4	11.0	145	170	50	3.1	210	2.5
26	18.0	11.0	127	144	58	2.5	220	5
27	22.2	11.0	119	128	225	1.5	228	7
28	19.9	10.5	125	138	78	2.0	223	5
29	14.7	10.75	135	149	85	1.5	228	6

Table A1-6. Flue Gas Recirculation Firetube No. 5 Oil (Cont.)

Test	% FGR	Steam Flow (lb.hr x 10^{-3})	NO_x ppm dry	NO_x ppm dry corr. to 0% O_2	CO_2 ppm dry	O_2 % dry by vol.	SO_2 ppm dry	Smoke No. Bacharach
30	9.5	11.25	141	158	55	2.3	223	5
31	0	9.25	161	224	56	5.9	200	0.5
32	8.9	9.0	140	194	45	5.8	198	0.5
33	17.3	9.0	130	168]	60	4.7	210	1
34	25.6	9.8	125	150	70	3.5	224	2
35	19.4	10.0	127	152	70	3.4	228	2
36	9.5	9.9	141	169	70	3.5	228	1
37	0	9.9	162	195	70	3.5	231	0

Table A1-7. Staged Combustion Firetube No. 5 Fuel Oil

Test	Load	Fuel Flow	Burner Stoich.	O_2 % dry by vol.	NO_x ppm dry	NO_x ppm dry corr. to 0% O_2	SO_2 ppm dry	CO ppm dry	Smoke No. Bacharach
1	4,000	380	133	6.8	129	191	120	20	-
2	6,000	380	117	7.3	115	176	118	20	-
3	6,000	380	109	6.8	115	170	122	20	-
4	7,000	380	96	5.4	113	152	138	30	-
5	6,000	380	128	6.6	125	182	122	30	0.5
6	6,000	380	97	5.3	116	155	132	30	1.5
7	6,000	380	96	6.3	110	157	125	30	0.5
8	6,000	380	85	5.1	100	132	140	40	3.0
9	6,000	380	83	5.1	97	135	130	30	3.0
10	6,000	380	74	5.2	90	120	138	40	3.5
11	10,000	380	119	3.6	172	208	163	50	3.0
12	13,000	380	121	4.8	157	204	148	50	-
13	11,000	380	121	4.0	170	210	152	50	1.5
14	11,500	380	113	5.1	155	205	142	50	1.0
15	11,000	380	117	5.7	150	206	137	60	0
16	7,000	380	127	8.0	130	210	110	60	-
17	8,000	380	145	8.9	116	201	100	50	0
18	7,000	380	98	5.0	126	165	135	50	0
19	8,000	380	103	6.5	119	172	121	52	0
20	7,100	380	95	7.5	112	145	111	50	0
21	7,000	380	91	8.0	106	171	110	50	0
22	7,000	380	91	8.4	104	173	102	50	0
23	7,000	380	87	8.3	103	170	103	50	0
24	5,500	380	112	2.4	146	165	158	60	2.0
25	5,000	380	110	4.4	135	171	140	58	1.0
26	5,000	380	92	1.5	129	139	179	185	2.5
27	5,500	380	94	4.9	123	160	135	65	2.0
28	6,000	380	87	3.8	105	128	150	70	4.0
29	6,000	380	76	2.0	92	102	170	145	7.0
30	6,000	380	77	3.6	94	113	152	60	3.0

Table A1-7. Staged Combustion Firetube No. 5 Fuel Oil (Cont.)

Test	Load	Fuel Flow	Burner Stoich.	O_2 % dry by vol.	NO_x ppm dry	NO_x ppm dry corr. to 0% O_2	SO_2 ppm dry	CO ppm dry	Smoke No. Bacharach
31	6,000	380	85	5.9	90	125	140	65	1.5
32	5,500	380	76	5.9	87	121	130	50	1.0
33	6,000	380	65	4.5	85	108	145	55	1.5
34	5,800	380	65	4.2	86	108	150	58	2.0
35	5,500	380	70	4.8	86	111	140	55	1.5
36	6,000	380	66	3.2	91	107	160	60	2.0
37	5,500	380	77	4.8	89	115	140	55	2.0
38	5,500	380o	72	4.2	88	110	149	56	3.0
39	5,750	380	69	3.7	88	107	150	60	3.0
40	6,000	380	81	5.3	87	116	134	55	3.0
41	5,750	380	73	1.4	87	95	161	250	3.5
42	6,000	380	84	3.3	108	128	155	75	6.0
43	6,000	380	101	3.0	135	158	160	60	1.5

APPENDIX 2
BOILER PERFORMANCE BEFORE AND AFTER MODIFICATION

Operational problems could be attributed to the modifications made to either of the two boilers which were tested in the field have been discussed earlier. Any influence of these modifications on the emission characteristics of the boilers ought to be able to be assessed by comparing boiler performance data obtained before and after the modification. The relevant data is presented in Figures A2-1 and -2 for the firetube and watertube boilers, respectively. It can be seen that in most instances the reported smoke and NO_x baseline emissions are lower after modification. There are three possible explanations which could account for this variation in baseline performance:

- Errors in flue gas concentration measurement.
- The influence of boiler modifications on combustion conditions.
- Changes in fuel oil properties.

Of these possibilities, the first two can almost certainly be discounted, no maintenance was carried out between tests which would influence the results.

The experimental procedure included frequent calibration checks of all flue gas analytical equipment. Provided the calibration gases were certified correctly, systematic measurement errors are unlikely. As both smoke and NO_x emissions were lower after modification, an error in flue gas oxygen concentration determination could not explain the results. All physical alterations to the boiler to allow recirculation of flue gases were associated with either the stack or the windbox. When no flue gases are being recirculated (even though the duct work is in place), it is unlikely that the slight modification to the windbox would drastically change combustion conditions. Variations in fuel properties offers the most plausible explanation for the difference in emission characteristics observed before and after modification.

A fuel oil sample was taken during each set of tests (performance, flue gas recirculation and staging) for both boilers. These samples were analyzed by the FWEC Analytical Laboratory according to ASTM (or equivalent) standards. Samples were resubmitted for analysis when it became apparent that certain

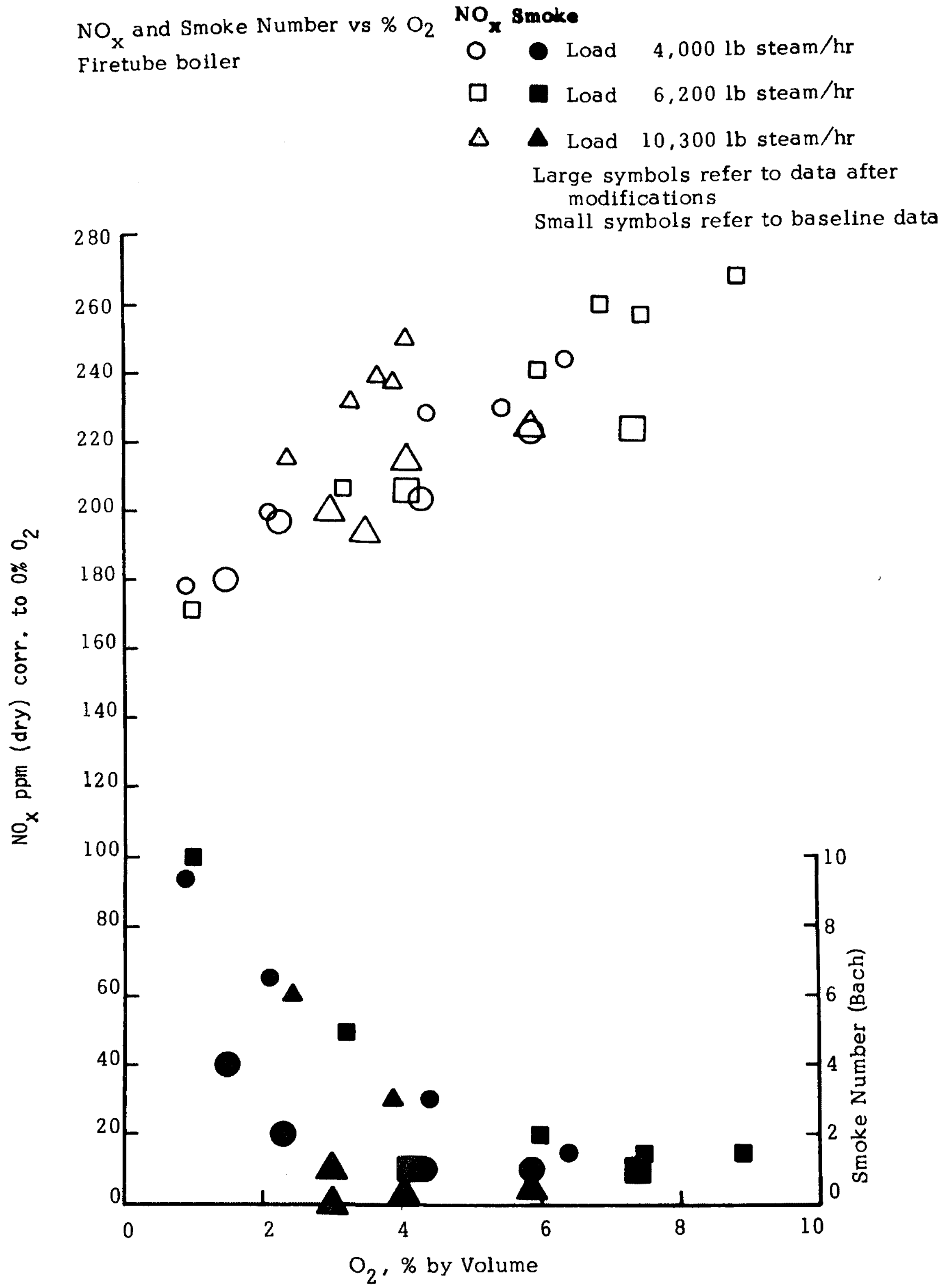

Figure A2-1. Comparison of Boiler Performance Data Before and After Modification (Firetube Boiler)

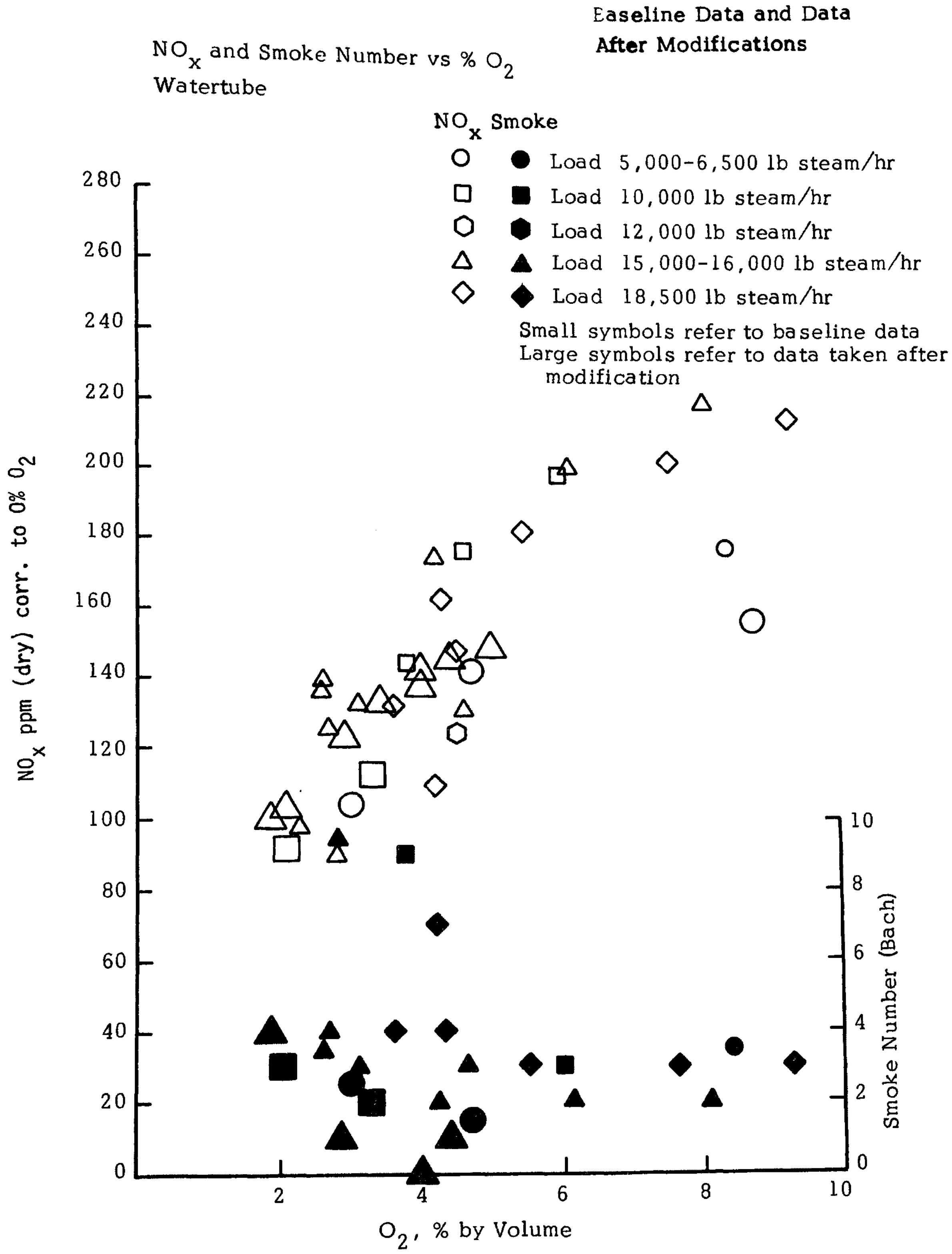

Figure A2-2. Comparison of Boiler Performance Data Before and After Modification (Watertube Boiler) discrepancies existed. Results of the oil analyses for the various samples are presented in Table A2-1. The oil analysis data contains serious anomalies which makes interpretation of the data difficult. The following anomalies are readily apparent:

- The carbon concentration in the original firetube boiler performance oil is low and the reproducibility is poor compared to other samples.
- Nitrogen concentrations show a wide spread both in original analyses and reanalysis. However, the anomalies are inconsistent. The reproducibility of samples taken from the watertube boiler is excellent. However, variations in the other analyses cast doubt on the authenticity of all the results.
- Values of 2 to 4 percent O_2 are most improbable and suggest errors in the values of the other elements.

Carbon, hydrogen and nitrogen concentrations were determined with a Perkin-Elmer Model 240 Elemental Analyzer which has been shown to give results equivalent to those obtained using ASTM methods for carbon, hydrogen and nitrogen in coal. Evidence exists showing that oil analyses change with time and certain trace metal compounds can be lost (see T.F. Yen*).

Measured flue gas sulfur dioxide concentrations confirmed that the oil burned during the performance tests had a higher sulfur content than that used in the subsequent tests. Thus, it could be inferred that the nitrogen content of oil used in the performance tests would be higher which could account for the change in NO_x emissions before and after boiler modifications. A 1 percent sulfur fuel would normally contain more nitrogen than a 0.3 percent sulfur fuel.

The original fuel analysis did not provide evidence in support of the above hypothesis (see Table A2-1) and a further analysis was carried out by an independent laboratory. In this instance the nitrogen content was determined by the Kjeldahl method. The results of the third analysis are presented in

---

*The Fate of Trace Metals in Petroleum, T. F. Yèn, Ann Arbor Science, 1975.

Table A2-1.

FUEL OIL ANALYSES

	Sample Description	Performance Firetube Orig.	Performance Firetube Re-anal.	Performance Watertube Orig.	Performance Watertube Re-anal.	FGR Firetube Orig.	FGR Firetube Re-anal.	FGR Watertube Orig.	FGR Watertube Re-anal.	Staging Firetube Orig.
	Analysis Date	5/3/74	4/1/75	5/3/74	4/1/75	1/23/75	4/1/75	1/23/75	4/1/75	5/1/75
Ultimate Anal. Percent by Wt. as Received	C	82.95	84.63	85.20	85.23	85.81	85.94	85.88	86.45	86.81
	H_2	12.04	12.16	12.30	12.25	12.51	12.37	12.61	12.70	12.68
	O_2	3.83	2.41	1.15	1.52	0.89	1.10	1.00	0.35	0.00
	N_2	0.11	0.04	0.13	0.15	0.11	0.02	0.08	0.09	0.01
	S	1.00	0.67	1.06	0.75	0.38	0.38	0.34	0.30	0.45
	Ash	0.02	0.04	0.06	0.02	0.02	0.09	0.01	0.01	0.01
	Moisture	0.05	0.05	0.10	0.08	0.28	0.10	0.08	0.10	0.04
	Higher Heating Value Btu/lb Fuel	18,747	19,075	18,694	19,099	18,814	19,091	18,861	19,188	19,219
	Specific Gravity at 60/60	0.9065		0.9106		0.9054		0.9047		0.9007

ASTM STANDARDS

Constituent		Same Laboratory and Time (Repeatability)	Different Laboratory (Reproducibility)
Sulfur	0.1 to 0.5	0.04	0.05
	0.5 to 1.0	0.06	0.09
	1.0 to 1.5	0.08	0.15
Ash		0.2-0.3	0.3-0.5
Carbon*		0.3	-
Hydrogen*		0.07	-
Nitrogen*		0.05	-
Moisture		± 1%	± 5%

Standards for coal as ASTM standards not available for petroleum products

Table A2-2. Inspection of the sets of analyses reveals several notable differences. In the independent analysis:

- oxygen contents obtained by difference are more consistent and lower than the original analysis;
- carbon contents are higher and hydrogen contents are lower than the original analysis;
- nitrogen contents are considerably higher than the original analysis.

In view of the earlier discussions, the differences in the nitrogen content are most disturbing. If values of 0.2 percent nitrogen are correct, then emissions from both boilers appear to be low compared to measurements reported by other workers (see Figure 6-2).

Variations in fuel properties are the most probable reason for the difference in emission levels before and after modifications. The lower sulfur content probably suggests a lower nitrogen content, although the various fuel analyses do not show this trend consistently.

Table A2-2. Independent Analysis

Component	Sample		
	Firetube FGR	Watertube FGR	Firetube Staging
Sulfur, %	0.44	0.40	0.32
Carbon, %	86.79	86.75	86.84
Hydrogen, %	12.17	12.29	12.31
Nitrogen, %	0.22	0.19	0.26
Oxygen, % (by difference)	0.38	0.37	0.27

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA-600/2-77-025	2.	3. RECIPIENT'S ACCESSION NO.
4. TITLE AND SUBTITLE Reduction of Nitrogen Oxide Emissions from Field Operating Package Boilers--Phase III of III		5. REPORT DATE January 1977
		6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) M. P. Heap, C. McComis, and T. J. Tyson; R. E. McMillan, R. E. Sommerlad, and F. D. Zoldak (Foster Wheeler Energy Corp.)		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Ultrasystems, Inc. 2400 Michelson Drive Irvine, California 92664		10. PROGRAM ELEMENT NO. 1AB014; ROAP 21ADG-043
		11. CONTRACT/GRANT NO. 68-02-0222
12. SPONSORING AGENCY NAME AND ADDRESS * EPA, Office of Research and Development Industrial Environmental Research Laboratory Research Triangle Park, NC 27711		13. TYPE OF REPORT AND PERIOD COVERED Final; 6/71-10/76
		14. SPONSORING AGENCY CODE EPA-ORD

15. SUPPLEMENTARY NOTES IERL-RTP project officer for this report is G. B. Martin, Mail Drop 65, 919/549-8411 Ext 2235. First two in this series were EPA-R2-73-292a and -292b. (*) The American Petroleum Institute cosponsored this study.

16. ABSTRACT The report describes the final of three phases of a program to determine the optimum methods of applying both flue gas recirculation (FGR) and staged combustion (SC) to control nitrogen oxides (NOx) emissions from residual oil-fired package boilers. Experimental investigations were carried out in a laboratory firetube boiler simulator, and an application program was conducted on two boilers operating in the field. The ultimate goal of the program was to determine if package boilers can operate in the field after modification to control NOx emissions without encountering practical problems. A 12 million Btu/hr firetube boiler and a 25 million Btu/hr heat output watertube boiler were modified to extract cooled combustion products from the stack and add them to the combustion air in the windbox. The effectiveness of FGR as a method of controlling NOx emissions was found to be dependent upon boiler type. It was most effective in the firetube boiler: approximately 30% reduction in emissions was obtained with 40% recirculation. NOx reductions achieved by SC were greater in the field tests than in the laboratory investigation. Reductions of 45% were achieved without undue smoke emissions when 70% of the stoichiometric air requirements were applied to the burner.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group	
Air Pollution	Fuel Oil	Air Pollution Control	13B	21D
Boilers	Oxygen	Stationary Sources	13A	
Combustion	Smoke	Package Boilers	21B	
Emission	Test Equipment	Flame Modification		14B
Nitrogen Oxides		Flue Gas Recirculation	07B	
		Staged Combustion		

18. DISTRIBUTION STATEMENT Unlimited	19. SECURITY CLASS *(This Report)* Unclassified	21. NO. OF PAGES 116
	20. SECURITY CLASS *(This page)* Unclassified	22. PRICE

EPA Form 2220-1 (9-73)