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Four Corners 4
Table IV
NO_x = 1.27 lb/MMBtu
(Ref 3)

DEVELOPMENT OF AN ULTRA-LOW NO_x PULVERIZER COAL BURNER

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DEVELOPMENT OF AN ULTRA-LOW NO_x PULVERIZED COAL BURNER

INTRODUCTION

An advanced low NO_x burner has been developed which achieves NO_x emission levels as low as 0.25 $lb/10^6 Btu$; equivalent to reductions of up to 75% from turbulent burner levels. The Internal Fuel Staged™ design is based upon concepts developed and patented by Foster Wheeler in the late 1970's. Development of the IFS design was not undertaken at that time in favor of proceeding with the Controlled Flow/Split-flame low NO_x design. The latter is Foster Wheeler's standard low NO_x burner which as been in utility and industrial service, in both new unit and retrofit applications, since 1979.

The CF/SF burner was developed to achieve at least 50% NO_x reduction in retrofit applications and meet the 1979 New Source Performance Standard, of 0.5 $lb/10^6$ Btu for sub-bituminous and 0.6 $lb/10^6$ Btu for bituminous coals, without the simultaneous use of supplementary NO_x controls such as overfire air.

The IFS design, having a NO_x control capability significantly greater than that of the CF/SF, was delayed in development simply because there was no commercial market for a system with such low NO_x capabilities. By 1989 it became apparent that new source requirements were tending toward 0.3 $lb/10^6$ Btu and retrofit requirements toward 0.5 or lower.

Although the CF/SF design operates below the 0.5 level, in both new units and retrofits without overfire air, and below 0.3 with overfire air, Foster Wheeler decided to advance the technological capability by developing the IFS. Commenced in May 1990, the IFS development was completed in September 1990 and has been offered commercially, with considerable success, since that time.

Development testing was done on Foster Wheeler's 80 million Btu/hr Combustion and Environment Test Facility. Since substantial testing of the CF/SF burner had been performed on the CETF and correlated with utility boiler data, and there are over 5,000 MW of retrofitted and over 7,000 MW of new units with this design, all development testing of the IFS was comparative with CF/SF data.

Typical NO_x emissions from the CF/SF burner, on theCETF, are about 0.4 $lb/10^6$ Btu. Typical IFS emissions are 0.25-028 $lb/10^6$ Btu, at least one-third lower; both without overfire air.

It should be noted that the IFS design differs from the CF/SF in only a single component: the fuel injector's nozzle. Consequently, it represents only a minor change in overall design since all other burner components, and the operating method, are identical to the CF/SF design. The IFS coal nozzle is, therefore, easily retrofittable to CF/SF burners currently in operation, thereby converting it to the IFS.

CONTROLLED FLOW/SPLIT-FLAME LOW NO_x BURNER

The CF/SF design shown in Fig. 1 is based upon the principle of Internal Staging™ of the flame. This principle was developed and defined by Foster Wheeler in the 1970's.

INTERNAL STAGING™ is defined as:

A low NO_x burner design which two-stages the secondary air flow and stages the primary air/fuel flows within the burner's throat while maintaining classical turbulent burner flame patterns and low pressure drop: < 4.0" H_2O.

The Controlled Flow/Split-flame name is derived from the operating functions of the burner:

- Controlled Flow for the dual register design which provides for the control of inner and outer swirl zones along with a sleeve damper which allows independent control of the quantity of secondary air flow to each burner.

- Split-Flame for the coal injection nozzle which develops a split-flame pattern for obtaining low NO_x emissions.

Key criteria within the overall design philosophy are summarized as follows:

- Mechanical reliability to be such that after long term operation movable components would still operate.

- Combustion air flow and swirl to each burner to be independently controllable.

- Adjustable primary air/coal velocity to ensure optimum relation between primary and secondary air streams.

- No increase in primary or secondary air pressure drop so that existing PA and FD fans can be used.

- Burner capacity to cover the complete range of industrial and utility use: approximately 30 to 300 million Btu/hr.

- Plug-in retrofitability, i.e., no pressure part changes, no burner piping rearrangement and no major windbox modifications when installed on most existing wall-fired boilers.

The CF/SF low NO_x burner's components and their functions are described below:

- <u>Perforated Plate with Sleeve Damper</u>: used to control secondary air flow on a per burner basis. By measuring the pressure drop across the perforated plate an index of air flow is obtained. The air distribution, vertically and horizontally, within the windbox is thus optimized by adjusting the sleeve dampers to obtain equal burner stoichiometries. This is a one time optimization after which the "open" position is fixed. The sleeve damper has "closed", "ignite" and "open" positions and is used, instead of the main radial vane register, to shut off the air flow when the burner is out of service. It is controlled by an electrically operated linear drive, but is not modulated with load.

- <u>Dual Series Registers</u>: provide improved flame shape control by two-staging the secondary air. A key mechanical reliability feature of this configuration is that the blades and drive mechanisms, set back from the furnace wall, are well "shaded" from direct flame radiation. Consequently, the registers operate at windbox temperature and do not overheat, warp or bind. Additionally, once the flame is optimized for proper shape, the registers are fixed. They remain in their optimum position and are not modulated with load or closed when the burner is taken out of service since the sleeve damper performs the latter function. The burner essentially becomes a fixed register type with the option for adjusting the register if a major fuel change occurs; the drive mechanisms being manual.

- Split-Flame Nozzle: segregates coal into four concentrated steams. The result is that the volatiles in the coal are driven out and are burned under more reducing conditions than otherwise would occur without the split flame nozzles. Combustion under these conditions converts the nitrogen species contained in the volatiles to N_2, substantially reducing NO_x formation.

- Adjustable Coal Nozzle: allows primary air/coal velocity to be optimized without changing primary air flow. The proper relationship between primary and secondary air is important for both good combustion and flame shaping. Once optimized no further adjustment is required.

Succinctly, only the sleeve damper, used to shut off the secondary air flow, is moved when the burners are taken in or out of service. Thus, after optimization, the burners become fixed register types.

Mechanical reliability of the design concepts, materials and operational methodology has been fully confirmed by commercial experience.

ADVANCED OVERFIRE AIR SYSTEM

NO_x emissions from the burning of pulverized coal have three (2) sources: Thermal NO_x generated from thermal fixation of atmospheric nitrogen (N_2) at high flame temperatures, conversion of bound nitrogen in the coal's volatile fraction and conversion of bound nitrogen in the coal's char fraction. The latter being the most difficult part of the emission to control.

Foster Wheeler's NO_x control philosophy has been based upon using the CF/SF low NO_x burner which achieves a high degree of thermal and volatile-fraction fuel NO_x reduction; with char-fraction fuel NO_x reduction to a lesser degree. This low NO_x burner's effectiveness is uniformly consistent in reducing NO_x emissions by 50-60% from uncontrolled levels. When lower levels are required an advanced overfire air system (AOFA) can be incorporated to increase NO_x control to the 70-80% range. These results are valid for both new steam generators and retrofittable existing units.

Figure 2 schematically illustrates a typical AOFA system. It is characterized by a set of overfire air ports placed well above the top burner level to provide relatively long residence time between the top burner level and the overfire air port level. One port is located above each burner column with an additional port near each sidewall. This is illustrated in Figure 2 where a four-burner wide arrangement uses six overfire air ports on each firing wall.

Older overfire air arrangements, which used fewer ports and shorter residence time, can achieve only about 20-30% NO_x reduction from the low NO_x burner's level. This AOFA system increases the NO_x reduction capability to the 40-50% range. Foster Wheeler demonstrated this system's capability in the early 1980's when two (2) new utility boilers, a 275 MW front-wall fired unit and a 550 MW opposed-fired unit, were tested. The combination of the CF/SF low NO_x burner and the above noted AOFA principles enabled both units to operate at NO_x levels of about 0.2 lb/10^6 Btu. During subsequent commercial operation the overfire air ports were closed since the NO_x regulations to be attained were only those of the 1977 NSPS. Without overfire air both units operated at about 0.4lb/10^6 Btu.

The AOFA System was not commercialized by Foster Wheeler until the late 1980's since there was no regulatory need to achieve emission levels below 0.3 lb/10^6 Btu. This system is now being incorporated on several new steam generators, ranging in size from 65MW to 550 MW. In early 1990 it was retrofitted to a 500 MW unit, having the arrangement shown in Figure 2, where NO_x emissions were reduced 78% to about 0.26 lb/10^6 Btu.

FIELD EXPERIENCE: CF/SF AND AOFA

Since its introduction in 1979, when retrofitted to the 360 MW San Juan No. 1 unit of Public Service New Mexico, the CF/SF low NO_x burner has been successfully retrofitted to a total of ten (10) utility boilers. Table I summarizes this experience, which totals 5,135 MW. The average NO_x reduction attained on these units is nearly 60% without overfire air; and nearly 80% with AOFA.

Table II is a listing of the projects underway for 1991: eight (8) units totalling 3,635 MW. Options in these projects add another 2,380 MW for a total of over 11,000 MW and over 600 burners.

The NO_x control capability and results are summarized on Figure 3, which contains data from four of the ten utility units, two industrial units and Foster Wheeler's Combustion and Environmental Test Facility. Table III lists the range of fuel properties in these retrofit applications. The NO_x control capability is consistent.

Figure 3 graphically illustrates the NO_x control effectiveness of the low NO_x Controlled Flow/Split-Flame burner. The plot is of total NO_x emission against Burner zone Liberation Rate (a measure of heat input to the burner zone; the higher this number the hotter the lower furnace), for turbulent burners, CF/SF low NO_x burner and CF/SF in combination with AOFA. The data show both industrial and utility units with burner capacities ranging from 30 to 300 million Btu/hr. The curves are not load curves but, rather, represent the full load NO_x emission for each value of Burner Zone Liberation Rate.

Conclusions drawn from the summary information contained in this figure are:

1. NO_x control is independent of burner capacity: large burners and small burners achieve the same degree of NO_x reduction.

2. The low NO_x burner (lower two curves) is much less sensitive in the thermal environment than is the turbulent burner. There is a much smaller slope of the NO_x vs BZLR low NO_x curves than for the turbulent burner curves indicating a very small amount of thermal NO_x is emitted by the low NO_x burner (due to its lower flame temperature).

3. NO_x reduction in the higher temperature units is somewhat greater than in the lower temperature (lower BZLR) units due to the substantial decrease in thermal NO_x in the former.

4. Uncontrolled NO_x emissions from single wall-fired units is higher than from opposed-fired units, yet this difference is eliminated by the CF/SF burner.

5. Foster Wheeler's Advanced Overfire Air System provides an additional NO_x reduction of 40-50% (to total reduction of 70-80%) below levels emitted by the low NO_x burner only.

Foster Wheeler has retrofitted wall-fired steam generators from all major domestic boiler manufacturers, including an 800 MW opposed-fired unit originally equipped with three-nozzle "cell" burners. The effectiveness of the CF/SF low NO_x burner is the same regardless of the boiler in which it is installed.

Of utmost importance to steam generator operation are its performance and efficiency. In none of the low NO_x burner retrofits performed by Foster Wheeler have either boiler performance of efficiency been deteriorated from pre-retrofit conditions. Typically efficiency is improved due to:

- Reduced excess air operation yielding lower stack losses and reduced forced draft and induced draft fan power.
- Lower burner pressure drop yielding further F.D. fan power savings.
- Cleaner furnace walls (reduced slagging).
- Unburned carbon levels equal to, or lower than, original equipment burners.

Succinctly, unit operations are equal to, or better than, pre-retrofit while NO_x is reduced at least 50% without overfire air.

Also shown on Figure 3 is the effectiveness of AOFA on three utility units and the CETF. All results, without and with AOFA, are uniformly consistent in terms of NO_x control.

Two projects are of particular interest: Units 1 and 7 on Figure 3. Unit 1 is an 800 MW boiler originally equipped with 18-3 nozzle cell burners and was retrofitted with 48 CF/SF burners in early 1989. Unit 7 is a 500 MW boiler retrofitted with CF/SF burners and AOFA in early 1990. Since the results of these two retrofits are typical of all others they will be briefly discussed below.

1. <u>Four Corners Unit No. 4:</u> Cell Burner Boiler - Arizona Public Service

   This boiler is a Babcock & Wilcox opposed-fired, supercritical steam generator with a maximum continuous rating (MCR) of 5,446,000 lb/hr main steam flow at 1000/1000F and 3590 psig. The unit was fired by 18, 3 nozzle cell burners (54 throats). Turbine rating is 820 MWG (780 MW net). Unit 4, along with its sister Unit 5, was built in the late 1960's; and went into commercial operation in 1969 and 1970, respectively. In 1971 the State of New Mexico instituted a retroactive NO_x emission limit of 0.7 $lb/10^6 Btu$ for coal-fired units constructed prior to 1971. Over the years Arizona Public Service conducted several test and evaluation programs to arrive at an acceptable means of achieving the NO_x limit without degrading boiler operability, performance or efficiency. In 1988 Foster Wheeler was contracted with to provide a low NO_x conversion with a guarantee lower than the State limit (0.65 vs 0.7). The unit was experiencing severe slagging, wide spacial variation of Furnace Exit Gas Temperature and resultant high superheater outlet metal temperatures.

   Consequently, Arizona Public Service chose to proceed with a complete revision of the lower furnace. This consisted of replacing both front and rear firing walls with a new burner arrangement, six (6) burners wide and four (4) burners high.

Foster Wheeler's scope of supply consisted of 48 CF/SF low NO_x burners, twelve burner wall panels (each containing four throats), new ignitors and scanners and miscellaneous equipment. Arizona Public Service had already contracted with B&W to supply nine new MPS-89N pulverizers for each unit (Unit 5 mills were previously installed and Unit 4 mills were installed during the low NO_x conversion). Due to the new firing configuration the total number of mills purchased for both units was reduced from 18 to 16.

It should be emphasized that this conversion represents the most extensive modification that can be performed on a cell-burner boiler's firing system. However, the method chosen was designed not only to reduce NO_x emissions but also to improve boiler operability. In particular to produce a more uniform Furnace Exit Gas Temperature (convert to one mill supplying a burner level) and reduce slagging (vertically spreading the burners). Slag reduction also occurs because of the lower flame temperature inherent in the CF/SF burner.

Other cell burner equipped boilers may not require modification as extensive as Four Corners 4 & 5. In many units only a direct low NO_x burner replacement may be acceptable.

Also, of the total of 23 units either completed, underway or as contractual options, the two Four Corners units are the only ones requiring panel replacement. The vast majority of boilers, regardless of original equipment manufacturer, can be retrofitted with Foster Wheeler low NO_x burners without pressure part modification.

The results of this retrofit are summarized on Table IV which compares pre and post-conversion conditions.

Significantly, burner pressure drop has been reduced 2-2.5" H_2O which will yield substantial forced draft fan power savings.

During the past nearly two years since start-up the unit has operated according to system load requirements, almost continually at full load. The following results have been observed:

- - There is no flame impingement on any heat transfer surface and no extension of flames.

- - Slagging and clinkering have been nearly eliminated on Unit 4. The furnace walls are now the cleanest they have been since initial unit start-up 20 years ago. In contrast the unconverted Unit 5 continues to have the same level of slag accumulation that Unit 4 had prior to conversion.

- - There has been no increase in FEGT, instead it appears to have decreased as a result of increased furnace absorption caused by the clean walls.

- - Combustion efficiency has not been decreased, as indicated by CO and unburned carbon levels.

In summary, NO_x emissions, have been reduced about 60% with no degradation in boiler performance or efficiency. Unit operability has been significantly improved due to the near elimination of the slagging/clinkering problems and elimination of excessive superheat tube metal temperatures.

Unit 5 is currently undergoing retrofit.

2. Hsin-Ta #1: Taiwan Power Corp: This is a 500 MW Foster Wheeler natural circulation unit in commercial operation since 1978. Originally equipped with an early non-split flame low NO_x burner (FW Controlled Flow design) and a basic 1970's vintage overfire air system, it was designed to meet a NO_x regulation of 0.7 lb/10^6 Btu. More recently, the NO_x regulations in Taiwan have been reduced. As a result TPC purchased 24 CF/SF low NO_x burners and the AOFA system for both Foster Wheeler units on that site.

Unit 1 was converted in early 1990, and has been operating for approximately ten (10) months. Because of the simultaneous use of CF/SF burners and AOFA this unit's operating data will be presented in more detail than Four Corners #4. The firing system and geometrical arrangement are as shown schematically in Figure 2.

After start-up and low NO_x optimization a series of performance tests were done over a period of several weeks. Since Taiwan imports most of its coal, fuels from the US, Australia and South Africa were fired as part of normal plant operations. Table V lists the typical range of coals fired at this station. Fuels varied on a day-to-day basis. As shown on the table volatile matter varied from 22.5% to 36.1% with fuel nitrogen contents covering the relatively high range of 1.85% to 2.28%.

However, the low NO_x systems effectiveness is such that there is no significant affect of these fuel properties on NO_x emissions. Boiler performance and efficiency variations were only those normally expected due to fuel properties affecting gas weights and moisture content.

Figure 4 compares NO_x emissions as a function of load for the CF/SF burner with AOFA closed and open. Load was reduced in the manner normal for that station with pulverizers taken out of service at the same loads they were prior to the low NO_x retrofit. The unit achieved full load with all mills in service or any single mill out of service. Consequently full load testing was performed with all mills in or one top or bottom mill out of service.

NO_x emissions decrease monotonically from full load values average 0.464 and 0.266 lb/10^6 Btu with AOFA ports closed and open, respectively. For simplicity of graphical illustration only seven (7) data points are shown, out of a much larger set. The temporal and fuel-property related variations in emissions cover a narrow range: at not time did NO_x emissions exceed 0.5 or 0.3 with AOFA closed or open, respectively.

Figure 5 is a similar plot of windbox-to-furnace pressure drop as a function of load. These results are also typical of the Foster Wheeler low NO_x system. At full load with AOFA closed and all mills in service ΔP does not exceed 3.0" H_2O. When AOFA ports are opened ΔP decreases to less than 1.5" H_2O at full load. In both cases ΔP decreases monotonically as load decreases.

Figure 6 illustrates the change in variability of the NO_x emission as more sophisticated NO_x controls are used at full load. From a mean ($\bar{X}$) emission of 1.23 lb/10^6 Btu and standard deviation (S) of 0.06 in the uncontrolled case, $\bar{X}$ and S are decreased to 0.464 and 0.032 with CF/SF burner and no overfire air. When AOFA ports are opened $\bar{X}$ = 0.266 and S = 0.012. The data includes all mill combinations and the range of fuels listed in Table V.

The following summarizes the results of Figures 4, 5 and 6.

- - NO_x does not increase as load is decreased.

- - Full load pressure drop is no greater than for typical turbulent burner values, less than 3.5" H_2O at full load.

- - High burner pressure drop is not needed to attain high NO_x reduction and low absolute emission level.

- - NO_x emission variability due to operating condition and fuel properties decreases with the use of more sophisticated NO_x controls.

Although the above results and conclusions are presented for two specific retrofitted units, they are typical of data obtained on all other retrofits as well as from thousands of additional MW's of new steam generators utilizing the same equipment.

INTERNAL FUEL STAGED™ LOW NO_x BURNER DEVELOPMENT

The development of the IFS low NO_x burner has been performed on the Combustion and Environmental Test Facility (CETF) located at Foster Wheeler's manufacturing facility in Dansville, NY.

Among the types of test work being performed at the CETF are burner development, low NO_x furnace design evaluations, sulfur dioxide control by dry sorbent injection, fuels evaluations, integrated combustion/emissions control testing and customer support and problem analysis.

The CETF's furnace (Fig. 7) is arranged to produce conditions which closely match those of commercial equipment, for example:

- Furnace residence time is limited to about 2 sec. max. between the burner centerline and furnace exit.

- Furnace Exit Gas Temperature (FEGT) is about 2200°F and can be varied, by adjusting total furnace absorption.

- Burner/furnace aerodynamics are similar to those of commercial equipment as are furnace mixing patterns, due to both overall geometry and the two-burner-high arrangement.

The arch configuration, which is required to provide proper conditions for low volatile fuel combustion, is also important to produce the desired velocities/residence times and FEGT with horizontal firing. The reduced upper furnace cross-section is responsible for the increased velocity and resultant decreased residence time. Decreased upper furnace heat transfer surface reduces absorption above the burner zone, thereby increasing FEGT to levels normally achieved in commercial equipment.

Although not currently equipped with a superheater, the unit has screen tubes at the furnace exit followed by a water-cooled economizer which yield realistic gas quenching rates. In this way all flue gas constituents, gaseous and particulate, are comparable to field equipment. Commercial practices, used throughout the CETF system design, have been mated with research-oriented considerations wherever practicable to maximize the usefulness and flexibility of the system.

The CETF utilizes a direct-fired system (i.e., hot-primary-air-swept ball mill) feeding either a single 75 million Btu per hour arch-fired twin-cycle burner assembly or two 40 million Btu per hour horizontally-fired burners (shown) which fire into a refractory-lined water-jacketed furnace. The water jacket operates under water-head pressure and utilizes natural circulation, producing steam which is vented to the air through a steam drum above the furnace. Combustion gases leaving the furnace flow over horizontal, convection tube surfaces (economizer) cooled by forced-water circulation. The gases then pass through a two-stage air heater (a tubular air heater followed by a heat pipe air heater), a baghouse dust collector, an induced-draft fan, and then the stack. The level of sulfur dioxide is controlled by injecting a sodium-based sorbent into the gas stream prior to the baghouse. In addition to back-end sulfur dioxide cleanup, the CETF has the capability of furnace injection of calcium-based sorbents for evaluation of in-situ sulfur dioxide control.

IFS DESCRIPTION

The IFS concept, as noted in the introduction, was conceived in the 1970's but not developed at that time. Internal Fuel Staging is defined as:

> A low NO_x burner which two-staged the secondary air flow and internally stages the fuel flow and primary air flow such that co-axial flames are developed within the burner's throat while maintaining classical turbulent burner flame patterns and low pressure drop: < 4.0" H_2O.

Figure 8 schematically illustrates the IFS design. The philosophy of this development was to utilize as much of the commercially-proven hardware of the Controlled Flow/Split-Flame low NO_x burner as possible. As can be seen in Fig. 8, the IFS differs from the CF/SF in only one respect: the coal injector's nozzle.

All other mechanisms and functions are identical to those of the CF/SF, including operating method. Externally, the two burners appear to be identical. However, internally the fuel injection's nozzle has been redesigned to produce split-flames surrounding a co-axial internal flame. The result is NO_x emissions approximately one-third lower than those attained with the CF/SF design.

Table VI is a comparison of the key features of the CF/SF and the IFS. The similarity is so great that an operator would note no difference between the two designs, other than the lower emission from the IFS.

The IFS burner is intended for use in both new and retrofit applications. Also, if units which are already equipped with the CF/SF design require lower emissions all that is necessary is to replace the fuel injector.

IFS PERFORMANCE RESULTS

Due to extensive performance and emission data available for the CF/SF low burner, from the CETF and new and retrofit field applications, IFS testing on the CETF is compared to CF/SF data.

Boiler performance results demonstrate no adverse difference in either furnace absorption or Furnace Exit Gas Temperature on the CETF between the two low NO_x burner designs. Since extensive field data already exits which shows no change in boiler performance when the CF/SF is retrofitted to boilers initially equipped with turbulent burners, it can be inferred the IFS design will, similarly, not adversely affect boiler performance.

A wide range of fuels, sub-bituminous and bituminous have been tested on the CETF using the CF/SF burner. For the IFS development testing two baseline bituminous coals have been used: a low volatile and several high volatile coals.

Table VII compares NO_x and CO data at full load for the two burner designs with the high and low volatile coals. NO_x is reduced 33-35% below CF/SF levels using the IFS. For all data, overfire air ports are closed and excess O_2 is 3.4-3.6%. Note that for both fuels the variability in NO_x emission decreases significantly, to about the same standard deviation. Typical coal analyses are listed in Table VIII.

Figure 9 compares NO_x and air-to-coal ratio (A/C) to load. Over a turndown ratio of nearly 3:1 NO_x decreases monotonically with load from about 0.27 to about 0.21 $lb/10^6$ Btu. A/C increases as load decreases from about 2.1:1 to about 2.6:1, covering the range of typical vertical roller pulverizers. This is a significant result in that reduced load operation does not deteriorate the IFS burner's performance: NO_x does not increase as load decreases.

It is also instructive to compare the CF/SF NO_x data from the 500 MW boiler, without and with overfire, to the CF/SF and IFS data from the CETF without overfire air. Figure 10 presents such a comparison. The mean uncontrolled emissions for the 500 MW and the CETF are 1.23 and 1.04 $lb/10^6$ Btu for the fuel ranges listed in Tables V and VIII respectively. The 500 MW unit's emission in higher than that of the CETF because it is a hotter unit and was firing higher nitrogen fuels than the CETF.

On each unit, NO_x is reduced by over 60% with the CF/SF low NO_x burner without overfire air. Note that both the uncontrolled data and CF/SF data have nearly identical standard deviations approximately 0.06 and 0.03, respectively. When overfire air ports are open on the 500 MW unit NO_x is further decreased to a mean value of 0.266 $lb/10^6$ Btu: a total reduction of over 78%.

On the CETF the IFS low NO_x burner yields a mean NO_x emission of 0.269 $lb/10^6$ Btu <u>without</u> overfire air: a total reduction of nearly 75%. Note that the standard deviations on the 500 MW unit with overfire air ports <u>open</u> is about the same as that of the CETF when the IFS is used with overfire air ports <u>closed</u>. Again illustrating that more sophisticated NO_x controls become less sensitive to operating conditions and fuel parameters.

A further comparison from this data is the NO_x reduction from CF/SF levels due to AOFA or IFS. On the 500 MW unit NO_x reduced 42.7% when the OFA ports are open. On the CETF, the IFS burner reduces NO_x 33.6% below CF/SF levels. The IFS low NO_x burner is achieving a NO_x reduction capability that is 80% of the additional reduction AOFA attains beyond CF/SF levels.

The relationship of the IFS results to field data are graphically illustrated on Figure 11, which is a simplified version of Figure 3. Clearly, many commercial boilers will be able to operate at levels below 0.4 $lb/10^6$ Btu without AOFA. Where lower levels are required the IFS low burner can be supplemented with the AOFA System.

SUMMARY

Foster Wheeler's standard Controlled Flow/Split-flame NO_x burner has been successfully retrofitted to ten (10) utility steam generators ranging in size from 225 MW to 800 MW, with an additional 6000 MW either underway or as options to existing contracts. In 1991 3635 MW will be retrofitted. Of these three units, two B&W and one Foster Wheeler, will be receiving the new Internal Fuel Staged™ low NO_x burner design.

The IFS burner development has been successfully completed and it has been offered commercially for new steam generator and retrofit use. The full range of emissions and boiler performance guarantees are offered. In addition to the above noted retrofits, the IFS will be installed on the following new steam generators:

2 x 65 MW; NO_x guarantee:	0.32
2 x 150 MW*; NO_x guarantee:	0.27
1 x 550 MW; NO_x guarantee:	0.32

* These Units will also be equipped with Foster Wheeler's SCR system to achieve 0.1 $lb/10^6$ Btu at the Stack

The IFS design achieves NO_x levels one-third lower than those attained by the standard CF/SF low NO_x burner, when tested on the Combustion and Environmental Test Facility. NO_x levels below 0.27 $lb/10^6$ Btu without simultaneous use of overfire air, are routinely attained with a wide variety of bituminous coals with NO_x emissions showing little sensitivity to operating mode or fuel characteristics. These performance results are obtained at low burner pressure drop and with short flames which do not cause adverse changes to furnace absorption rates or Furnace Exit Gas Temperature.

It is fully expected that these results will be duplicated in the new unit and retrofit applications currently underway.

Table I
Low NO_x Burner
Retrofit Experience

Year	MW	NO_x ($lb/10^6$ Btu) Before	After	Reduction (%)	OEM
1979	360	0.95	0.42	56	FW
1980	525	*	0.40	—	FW
1981	275	*	0.40	—	FW
1986	650	1.0	0.41	59	FW
1987	500	1.15	0.55	52	FW- UK
1989	800 (Cell)	1.25	0.50	60	B&W
1990	800	1.10	0.45	59	FW
1990	500	1.23	0.27^+	78	FW
1990	500	1.15	0.50	56	FW - UK
1990	225	1.15	0.50	56	FW
Total	5135 MW				

* New Boiler Converted during erection

$^+$ With Advanced Overfire Air System

NOTE: Boiler ages range from 10 to 25 years

Table II
Low NO_x Burner
Retrofits Underway of 1991

Unit Size (MW)	No. of Burners	Boiler OEM
800 MW (Cell-Burner)	48	B&W
150 MW	16	B&W
200 MW (3 x 200)*	18 (54)	B&W
650 MW	24	FW
500 MW	24	FW
525 MW	24	FW
650 MW (2 x 650)	24 (48)	FW
160 MW (3 x 160)	16 (48)	FW
Total 3635 MW	194	

*( ) = Contractual Options

Table III
Range of Fuel Properties

HHV	8000	-	13.500 Btu/lb
N_2	1.0	-	2.3 %
Si	0.5	-	3.5 %
Ash	5.0	-	2.5 %
Average NO_x Level	0.45 lb/10^6 Btu		
NO_x Reduction	55 - 60 % (No OFA))		

Table IV
Four Corners # 4 Data
800 MW Cell-Burner Unit

Parameter	Pre-Conversion	Post-Conversion
No. Mill in Service	All (9)	All (8)
Excess Air (%)	18	13 - 15
NO_x (lb/10^6 Btu)	1.27	0.48 - 0.52
CO (ppm)	< 40	20 - 40
Burner Δ P ("H_2O)	5-6	3-3.5
Carbon Loss (% Eff.)	< 0.1	< 0.1

Results:
Performance and efficiency not degraded
Eliminated slagging and clinkering
Significant power savings

Table V
500 MW Advanced Low NO_x Retrofit
Range of Fuels Fired
(As Received)

VM (%)	22.51	28.07	36.15
FC (%)	54.05	52.63	41.47
Ash (%)	15.55	12.45	12.01
H_2O (%)	7.49	6.85	10.37
C	64.49	67.39	61.99
H	3.79	4.11	4.79
O	5.48	6.27	8.70
N	2.07	2.28	1.85
S	0.73	0.65	0.59
HHV (Btu/lb)	10,909	11,605	11,018

Table VI
Low NO_x Burner Comparison

Desgn Parameter	**CF/SF**	**IFS**
Registers	Dual	Dual
Adjustments	Manual	Manual
Sec. Air Flow Control	Elec. Sleeve Damper	Elec. Sleeve Damper
Fuel Injector	Split-Flame	Split-Flame Plus Coaxial Internal Flame
Primary Air Velocity Control	Yes	Yes
NO_x Reduction	55 - 60%	70 - 75%
NO_x Level	0.4 lb /10^6 Btu	0.27 lb / 10^6 Btu

Table VII
CETF Comparative Data
CF/SF vs IFS

Fuel V.M. (%)		23		33	
N_2 (%)		1.87		1.59	
Xs O_2 (%)		3.5 - 3.6		3.5 - 3.6	
Burner Type		CF/SF	IFS	CF/SF	IFS
NO_x (lb/10^6 Btu):	Avg.	0.41	0.273	0.40	0.260
	Std. Dev.	0.033	0.014	0.035	0.011
CO	Avg.	54	59	70	75
	Std. Dev.	13	11	15	17
NO_x Reduction (%)		—	33.4	—	35.0

Table VIII
CETF Fuels: IFS Testing

VM	32.70	23.49
FC	48.16	59.41
ASH	9.11	4.34
H_2O	10.03	7.86
C	67.34	77.37
H	4.50	4.68
O	5.60	3.19
N	1.59	1.87
S	1.85	0.79
HHV	11,935	13,877
NO_x Reduction	79.5%	73%
NO_x Level	0.266	0.273

No significant difference in NO_x emissions due to coal characteristics

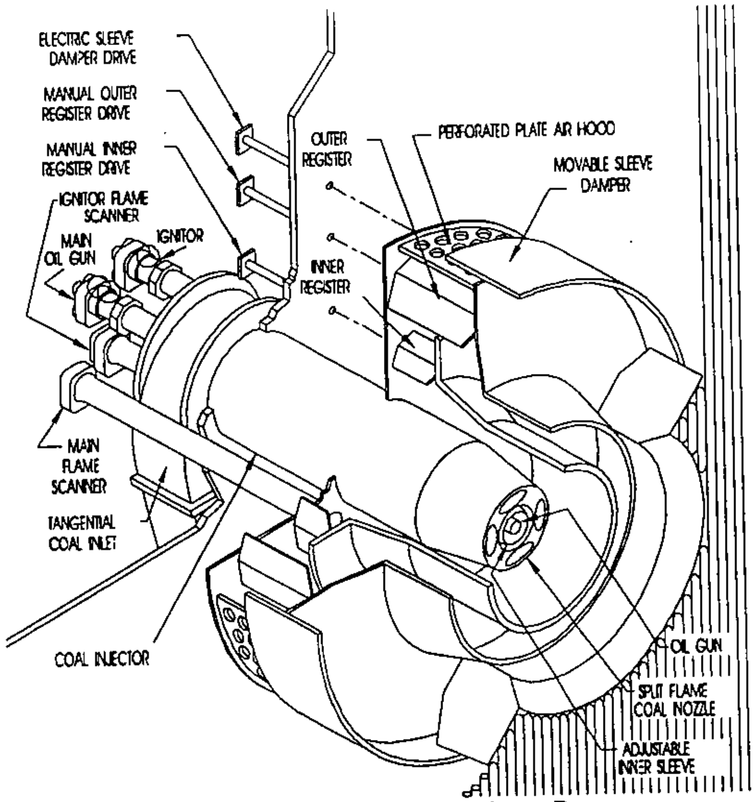

Fig 1. Controllled Flow Split Flame Burner

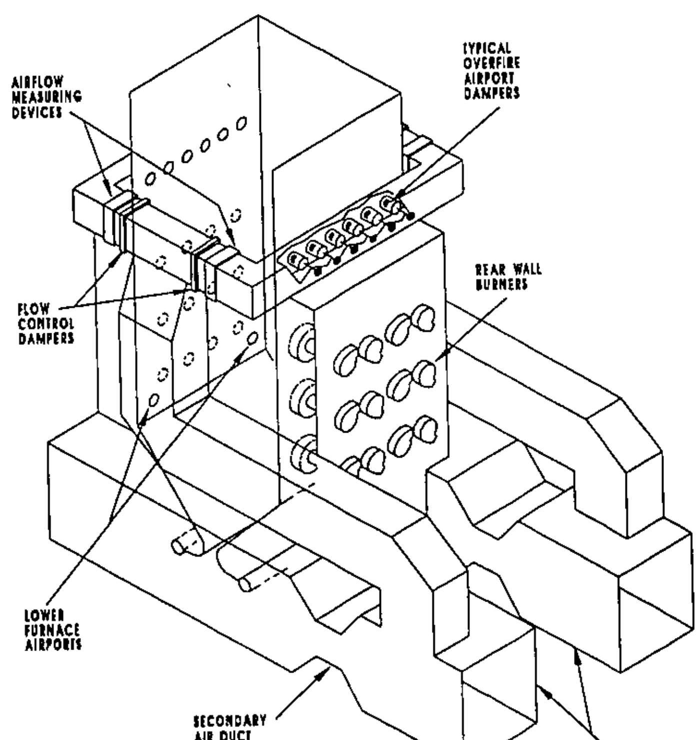

Fig 2. Typical Advanced Overfire Airport System

NOx REDUCTION SUMMARY

(1) 800 MW Four Corners #4
(2) 626 MW Pleasants #2
○ 275 MW Front Wall Fired
(3) 360 MW Front Wall Fired
• 525 MW Opposed Fired

(4) 110,000 Lb/Hr. 4 Burner
(5) 125,000 Lb/Hr. 4 Burner
(6) CETF
(7) 500 MW Opposed Fired

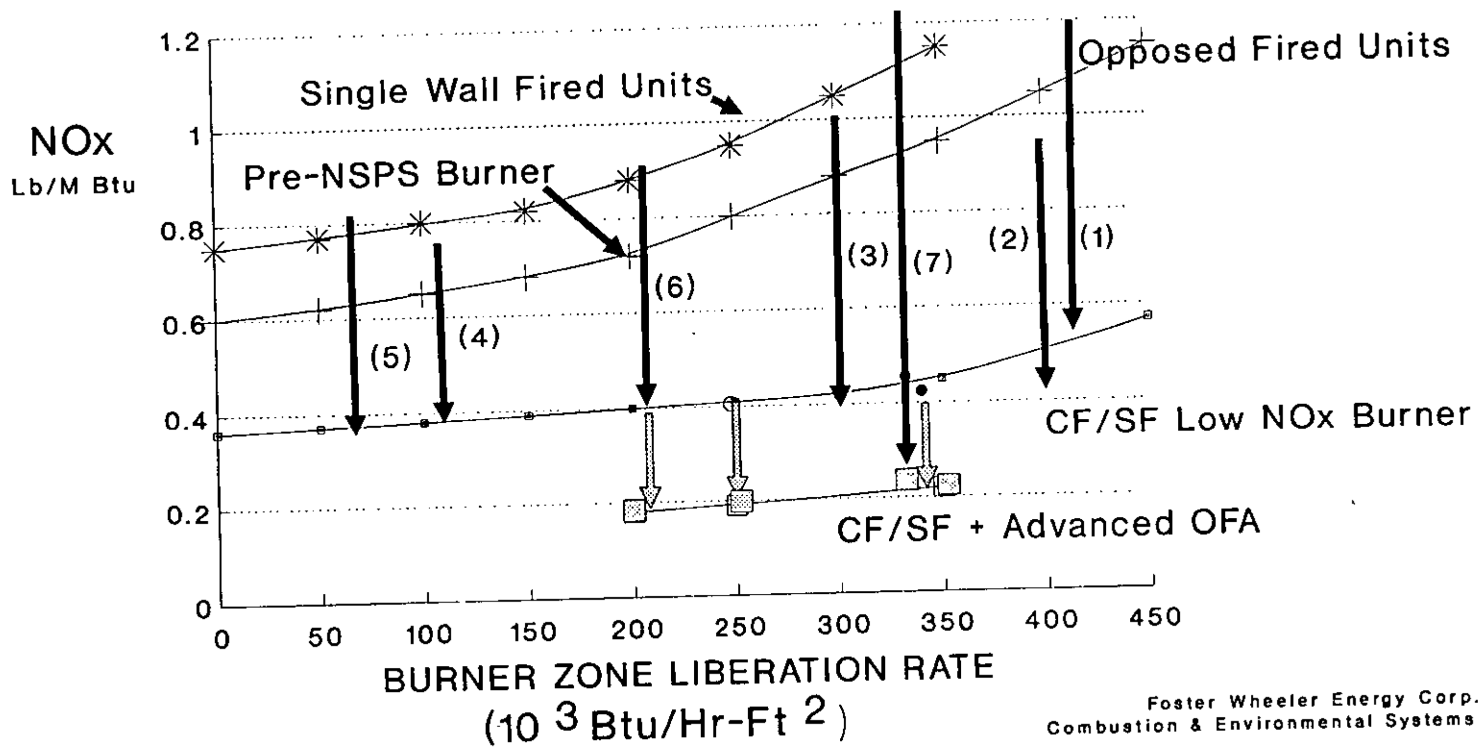

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Figure 3

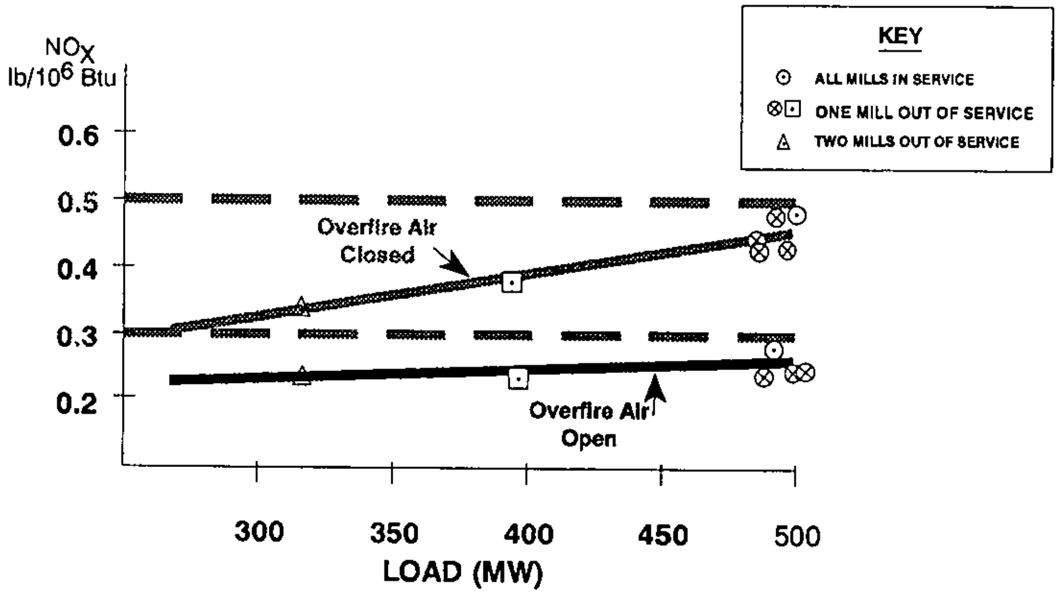


Figure 4. Advanced Low NO_x Retrofit 500 MW Boiler NO_x vs Load

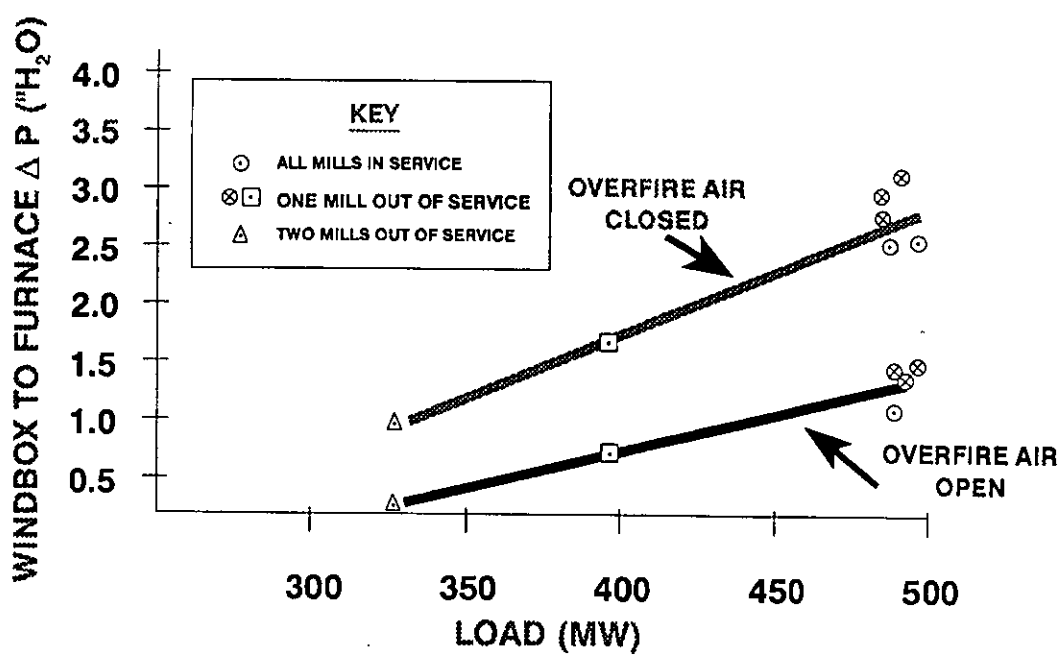
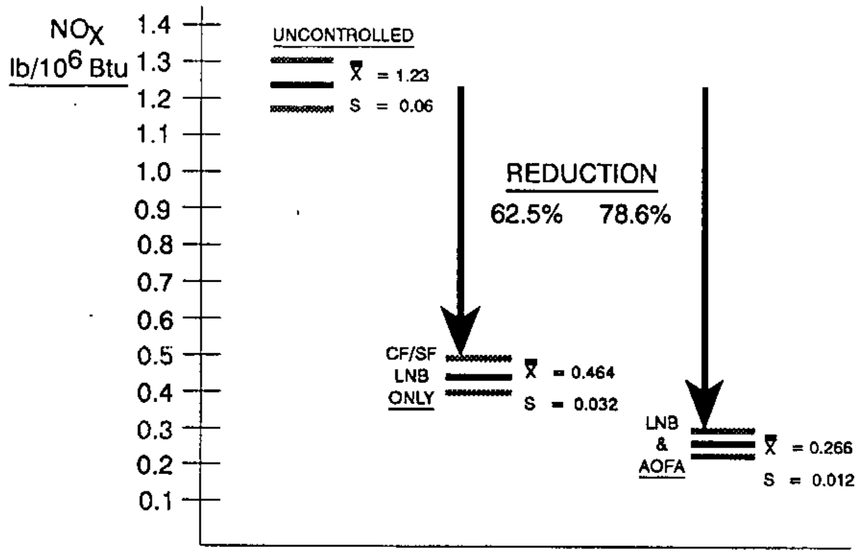


Fig 5. Advanced Low NO_x Retrofit 500 MW Unit Pressure Drop vs Load



CF/SF = Controlled Flow/Split-Flame
LNB = Low NO_x Burner
AOFA = Advanced Overfire Air
LOAD = 500 MW; O_2 = 3.5%

Fig 6. 500 MW Boiler NO_x Reduction

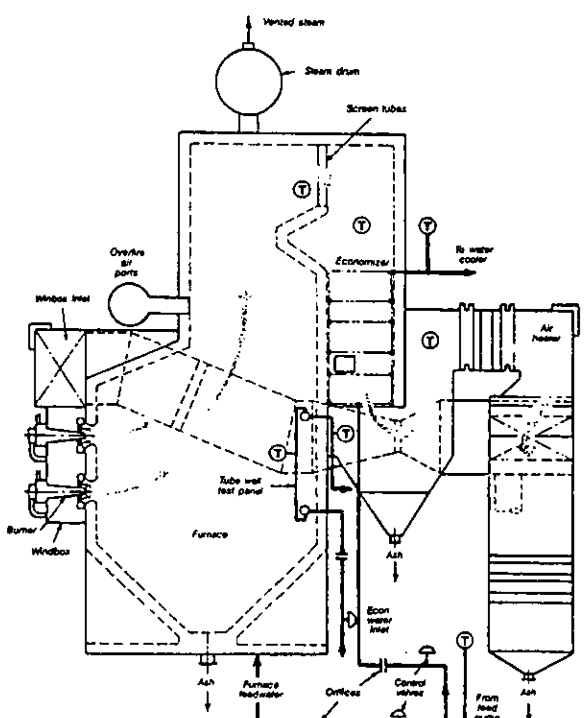


Fig 7. Combustion and Environmental Test Facility

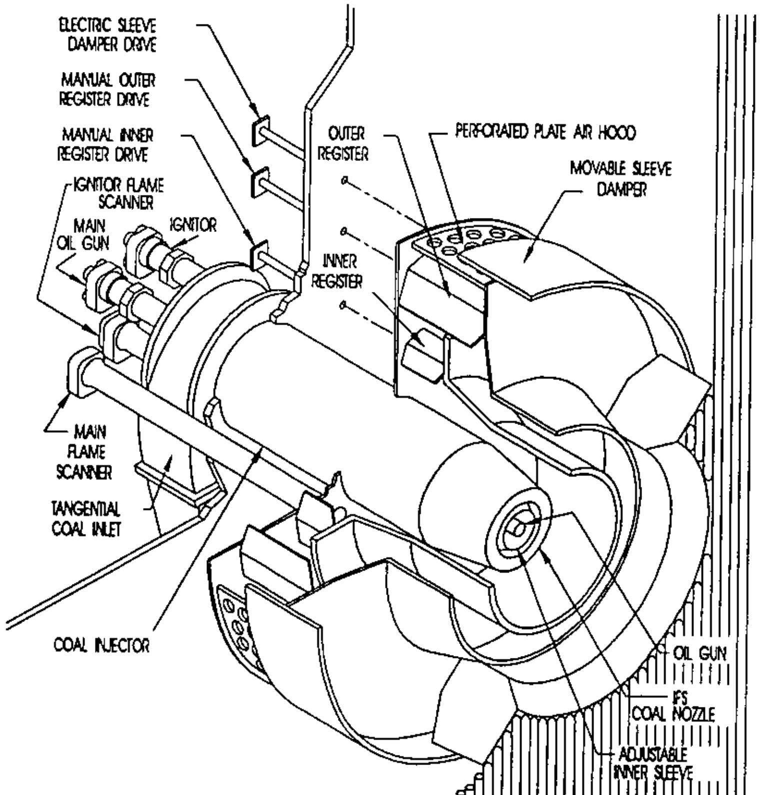
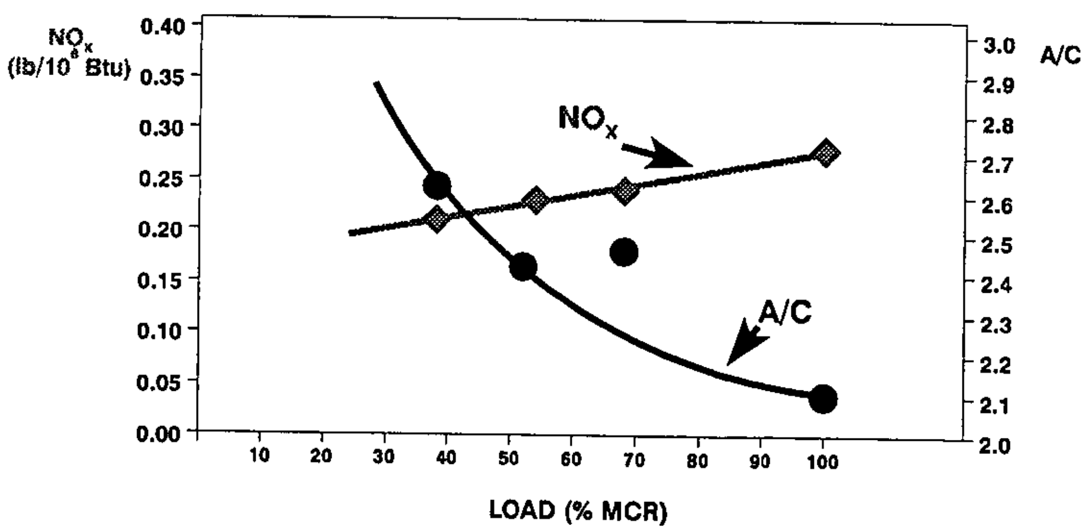


Fig 8. Internal Fuel Staged Low NO_X Burner™



For all test points: CO < 50 ppm ; O_2 = 3.4 - 3.6%
Δ P = 1.5" H_2O Maximum
No Overfire Air

Fig 9. CETF Testing Internal Fuel Staged Burner

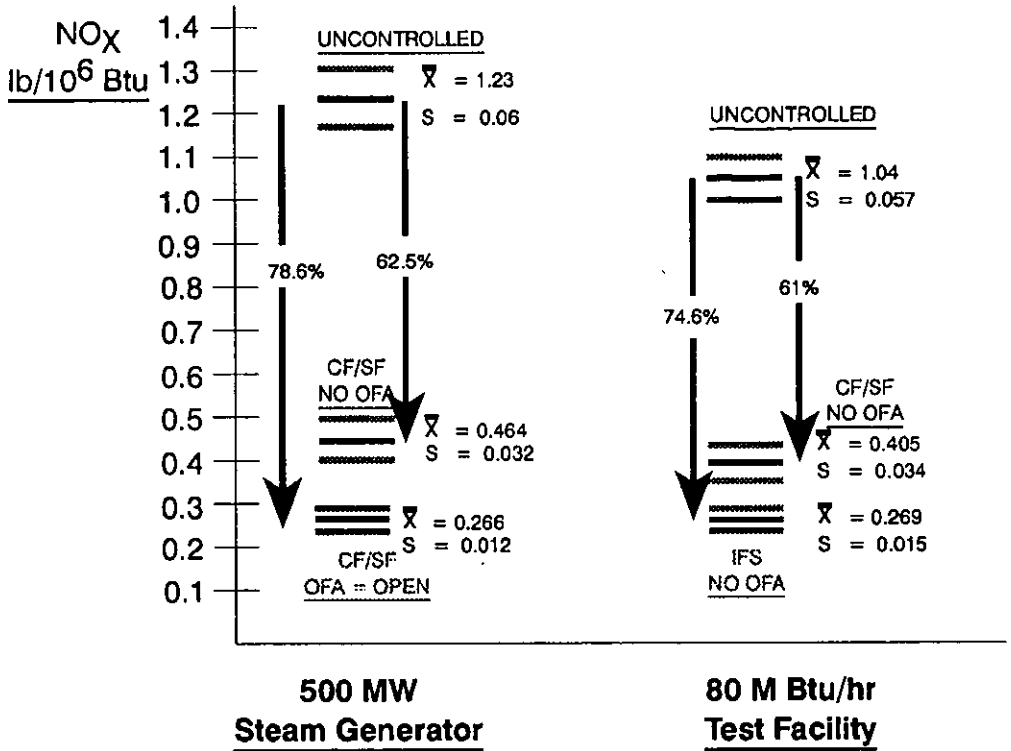


Fig 10. Low NO_x Burner Comparative Data
Controlled Flow/Split Flame vs Internal Fuel Staged

NOx REDUCTION SUMMARY
IFS vs. CF/SF

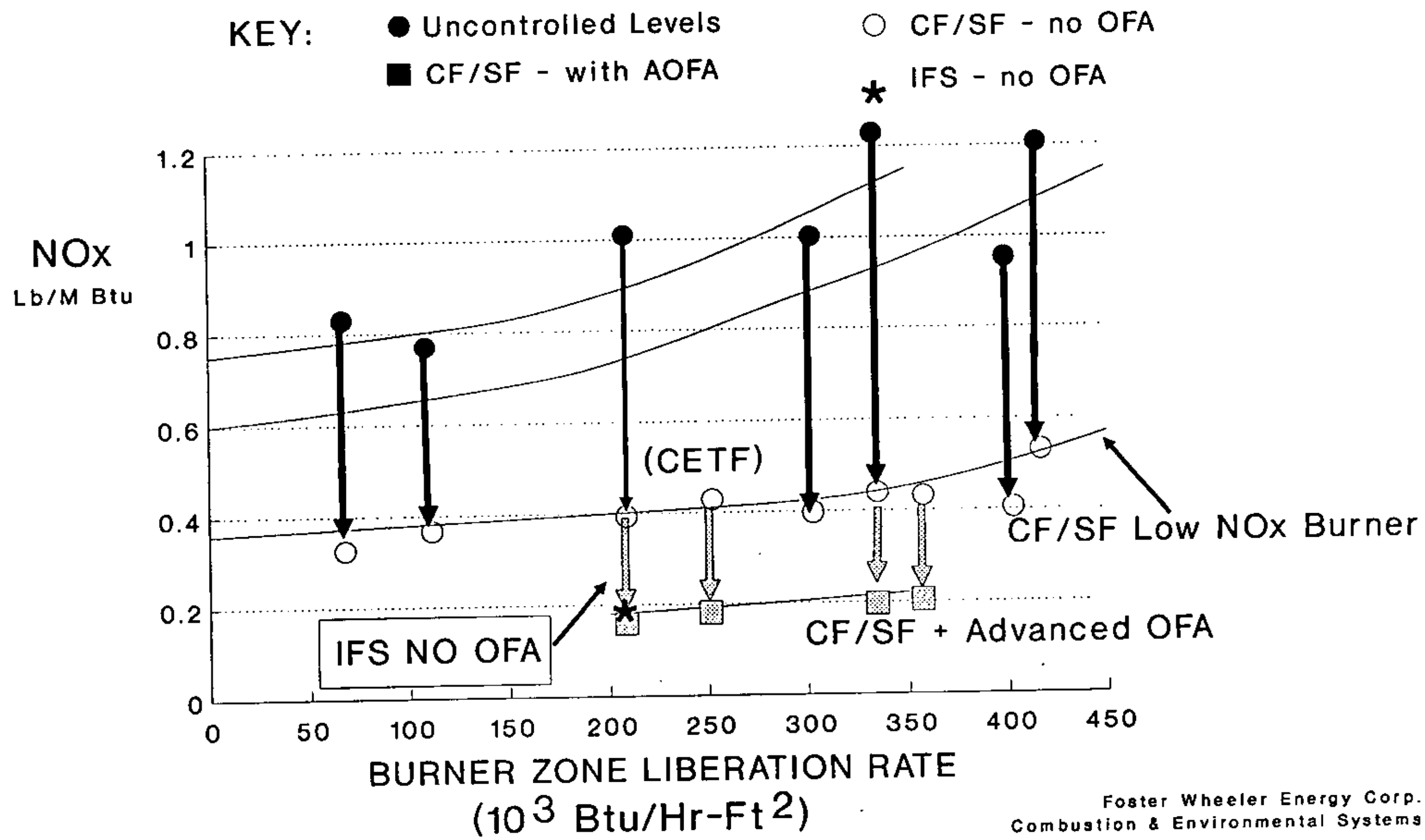


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Figure 11

1991 Joint Symposium on Stationary Combustion NO_x Control—EPA/EPRI

Volume 1: Sessions 1, 2, 3, 4A, and 4B

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