Demonstration of Coal Reburning for Cyclone Boiler NO_x Control

Final Project Report

Prepared by:

Babcock & Wilcox
a McDermott Company
Energy Services Division
20 South Van Buren Avenue
P.O. Box 351
Barberton, OH 44203-0351

Submitted by:

Babcock & Wilcox
Contract Research Division
1561 Beeson Street
Alliance, OH 44601

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ACRONYMS

ARC	Alliance Research Center
B&W	Babcock & Wilcox Co.
CCT-2	Clean Coal Technology Round 2
CEMS	Continuous Emissions Monitoring System
CRD	Contract Research Division (of Babcock & Wilcox)
DCS	Distributed Control System
DOE/PETC	Dept. of Energy/Pittsburgh Energy Technical Center
EPRI	Electric Power Research Institute
ESD	Energy Services Division (of Babcock & Wilcox)
ESP	Electrostatic Precipitator
FD	Forced Draft
FEGT	Furnace Exit Gas Temperature
FGR or GR	Flue Gas Recirculation
FPD	Fossil Power Division (of Babcock & Wilcox)
GR or FGR	Flue Gas Recirculation
GRI	Gas Research Institute
HAP	Hazardous Air Pollutant (Testing)
HVT	High Velocity Temperature (Probe)
K_f	Cleanliness Factor
kWh	Kilowatt Hour
%LOI	Percent Loss on Ignition
MBtu	Million Btu
MMD	Mass Mean Diameter (particle size measurement)
MW_e	Megawatt of Electricity (Net)
NFPA	National Fire Protection Association
NSPS	New Source Performance Standards
OFA	Overfire Air (Ports) (NO_x Ports)
PA	Primary Air
PC	Pulverized Coal
PRB	Powder River Basin (Coal)
R&DD	Research & Development Division (of Babcock & Wilcox)
RH	Reheater
RSH	Reheating Superheater
SBS	Small Boiler Simulator (Pilot Test Facility)
SCA	Specific Collection Area (ESP size parameter)
SCR	Selective Catalytic Reduction
SH	Superheater
SR	Stoichiometric Ratio
SSH	Secondary Superheater
TCR	Total Capital Requirement
T/R	Transformer/Rectifier (Electrostatic Precipitator)
U_{act}/U_{exp}	Actual Overall Conductance/Expected Overall Conductance
UBC	Unburned Carbon
UT	Ultrasonic Thickness
WP&L	Wisconsin Power & Light

1.0 Executive Summary

As part of the U.S. Department of Energy's (DOE's) Innovative Clean Coal Technology Program, under Round 2, a project for Full Scale Demonstration of Coal Reburning for Cyclone Boiler Nitrogen Oxide (NO_x) Control was selected. DOE sponsored The Babcock & Wilcox (B&W) Company, with Wisconsin Power & Light (WP&L) as the host utility, to demonstrate coal reburning technology at WP&L's 110 MW_e cyclone-fired Unit No. 2 at the Nelson Dewey Generating Station in Cassville, Wisconsin.

The driving force to demonstrate coal reburning technology is the existence of over 100 operating cyclone-fired boilers. Although these units represent about 15% of pre-New Source Performance Standards (NSPS) coal-fired generating capacity, they contribute approximately 21% of the NO_x formed by coal-fired pre-NSPS units. Their inherently turbulent, high-temperature combustion process is conducive to NO_x formation. No commercially demonstrated NO_x reduction combustion technology was available for cyclones, and typical modifications such as staged combustion were not applicable because they rely on a heavily oxygen deficient atmosphere. In a cyclone, this would increase the potential for tube corrosion which is a highly undesirable maintenance concern.

The coal reburning demonstration was justified based on two prior studies. An Electric Power Research Institute (EPRI) and B&W sponsored engineering feasibility study indicated that the majority of cyclone-equipped boilers could successfully apply reburning technology to reduce NO_x emissions by 50 to 70%. An EPRI/Gas Research Institute (GRI)/B&W pilot-scale evaluation substantiated this conclusion through pilot-scale testing in B&W's 6 million Btu/hr Small Boiler Simulator. Three different reburning fuels, natural gas, No. 6 oil, and pulverized coal were tested. This work showed that coal as a reburning fuel performs nearly as well as gas/oil without deleterious effects of combustion efficiency. Coal was selected for a full scale demonstration since it is available to all cyclone units and represents the highest level of technical difficulty in demonstrating the technology.

1.1 Definition of Reburning

Reburning is a process by which NO_x produced in the primary burner zone (the cyclone in this case) is chemically reduced by radical fragments to molecular nitrogen in the main furnace by injection of a secondary fuel. The secondary, or reburning, fuel is injected with a limited supply of air to create an oxygen-deficient region which decomposes the NO_x. See Figure 1-1. Because reburning can be applied while the cyclone operates under its normal oxidizing condition, it's effect on cyclone performance can be minimized.

The reburning process employs multiple combustion zones in the furnace, defined as the main combustion, reburn and burnout zones. The main combustion zone is typically operated at a stoichiometry of 1.1 to 1.2 (10 to 20% excess air) and combusts the majority of the fuel (70 to 80% heat input). The balance of fuel (20 to 30%) is introduced above the main combustion zone in the reburn zone through reburning burners. When the reburn fuel is coal, it is pulverized prior to delivery to the burners. These burners are operated in a similar fashion to standard wall-fired burners except that they are fired at extremely low stoichiometries (less than 0.6). The combustion gases from the reburn burners mix with combustion products from the cyclones to produce a furnace reburning zone stoichiometry in the range of 0.85 to 0.95. This stoichiometry is needed to achieve maximum NO_x reduction based on laboratory pilot-scale results. A sufficient furnace residence time within the reburn zone is required for flue gas mixing and NO_x reduction kinetics to occur.

The balance of the required combustion air totals 15 to 20% excess air at the economizer outlet, and is introduced through overfire air (OFA) ports. As with the reburn zone, a satisfactory residence time within this burnout zone is required for complete combustion.

1.2 Project Objective and Goals

The objective of the demonstration project was to evaluate the applicability of the technology for reducing NO_x emissions in full scale cyclone-fired boilers. The performance goals were:

1. Provide a technically and economically feasible means for cyclone boilers to achieve 50% or greater NO_x reduction at full load where one did not exist, using the present boiler fuel (coal) making supplemental fuels (oil, gas) unnecessary.

2. Achieve the NO_x reduction goal with no substantial adverse impact on other boiler emissions.

3. Provide a system that maintains boiler reliability, operability and steam production performance after retrofit.

This full-scale evaluation was designed to confirm pilot-scale results as well as resolve those technical issues that are not possible to fully address in an engineering study or in pilot-scale tests.

All goals of the cyclone coal reburning project have been achieved or exceeded. Greater than 50% NO_x reduction at full load was achieved on two fuels, a bituminous coal and a subbituminous Powder River Basin coal, with no apparent boiler operational problems. WP&L has accepted the system and continues to run it as part of Unit No. 2.

1.3 Project Approach

Consistent with the DOE Clean Coal Technology Program organization, the coal reburning project consisted of three phases: Phase I - Design & Permitting; Phase II - Procurement, Fabrication, Installation and Startup; and Phase III - Operation and Disposition.

Phase III of the project entailed all post-retrofit testing activities.

Phase I design activities included extensive design data development such as performance of pilot-scale combustion tests in the six million Btu per hour cyclone-equipped Small Boiler Simulator (SBS) located at B&W's Alliance Research Center using the demonstration test coal. This activity examined the effectiveness of reburning and its associated side effects such as fireside corrosion and deposition in the secondary superheater tube bank. Operating conditions at WP&L's Nelson Dewey Unit No. 2 were simulated in the SBS and the demonstration coal was used to realistically duplicate reburn operation. Information developed during this work provided guidance for reburn system start-up and operation at full scale.

Additional design data and development activity included both physical and three-dimensional numerical flow modeling of Nelson Dewey Unit No. 2. The basic modeling assumption was that maximum NO_x reduction and minimum unburned carbon impact would occur under conditions of complete mixing. Hence both a physical flow 1/12th scale Plexiglass model and a numerical model were developed and operated to identify optimal mixing conditions in the Nelson Dewey Unit. These tools helped to evaluate and optimize mixing between the combustion gases from the cyclones and those of the reburn burners, and ultimately mixing of reburn gases with overfire air.

To validate the results of modeling activities, a complete baseline test program was carried out at Nelson Dewey Unit No. 2 to benchmark pre-retrofit boiler operation, both from an emissions and a boiler performance viewpoint. In-furnace probing was performed to understand furnace gas flow patterns and temperature distribution. This information allowed the numerical model to be fine-tuned to guide design of the coal reburning system at Nelson Dewey. Good agreement between full-scale testing and both numerical and physical flow modeling results was obtained. The numerical model was, at one point, used to simulate the physical cold flow model to resolve areas of disagreement between numerical and cold flow predictions.

Ultimately, the tuned mathematical model, able to qualitatively predict full-scale baseline and 1/12 scale flow patterns, was used to evaluate placement of burners and overfire air ports. A large number of cases were run with the model, varying the number of burners and overfire air ports, the locations, the amount of reburn fuel to the burners, the level of gas recirculation to the burners, etc., until the optimal mixing case was determined. Optimal mixing is defined as maximizing the percentage of gas in the reburn zone containing less oxygen than that which is theoretically required to complete combustion. This concept was proven valid during pilot-scale SBS testing and subsequent modeling of the SBS. The Nelson Dewey case which exhibited maximum mixing was the best design recommendation.

Based on the mathematical modeling results, the detailed design of the coal reburning system for Nelson Dewey Unit No. 2, as shown in

Figure 1-2, included four reburn burners and four overfire air ports on the rear wall of the unit. Additionally, the system design included the capability to achieve flue gas recirculation to the burner, which the model predicted would provide flexibility for reburn flame penetration into the furnace gases.

The reburn system was installed at Nelson Dewey and was operable in November 1991. The specified test fuel was Illinois Basin Lamar bituminous coal. Parametric testing was done to understand the full range of performance capabilities of the coal reburning system. Cyclones were operated at 10% excess air at 65 to 80% of total heat input to the boiler, with crushed coal. The reburn system provided the balance of fuel as pulverized coal.

Coal reburning tests were performed to evaluate the effect of key parameters on NO_x reduction and to determine potential side effects. Key parameters included reburn zone stoichiometry, boiler load and level of gas recirculation to the reburn burners. Optimum reburn conditions for the long-term performance tests were developed using parametric test data.

Long-term performance testing was carried out with the reburn system in the fully automatic mode and the boiler following WP&L system dispatch load requirements. During this testing, operating information was collected continuously on a data acquisition system for boiler information and on a continuous emissions monitoring system (CEMS) for emissions data.

During all testing, baseline in Phase I and all Phase III activity, emissions were monitored both by a B&W grid at the economizer outlet and by the CEMS system at the outlet of the precipitator. The CEMS capability was supplied by Acurex Environmental Corporation as an independent third party testing contractor. This was done for quality assurance and control purposes to ensure the validity of test results.

Near the end of Phase III testing, the U.S. DOE and EPRI requested reburn system Hazardous Air Pollutant (HAP) testing on the bituminous demonstration coal. Additionally, B&W was requested to perform reburn parametric optimization testing on a subbituminous Powder River Basin (PRB) coal. Accordingly, HAP testing on the demonstration coal and a test program on PRB coal were completed prior to termination of testing activities.

1.4 Technical Results of Coal Reburning

The focus of the demonstration project testing program was to determine the maximum NO_x reduction capabilities of reburning without adversely impacting boiler performance, operation or maintenance between full load (110 MW_e) and 50% load (55 MW_e). The testing phases were designed not only to evaluate the most efficient operating conditions for the reburn system at Nelson Dewey, but also to provide sufficient data to confirm and expand upon the previously performed B&W SBS pilot-scale testing and engineering study results.

The testing program consisted of six separate test groups while firing two different coals: the demonstration fuel, Lamar bituminous (Illinois Basin) coal and a Western subbituminous PRB coal. Test groups consisted of initial tuning of the system; parametric testing to explore the full range of the technology's operating parameters; performance testing in full automatic at the beginning of long-term testing and again at the end of long-term testing, all on the Lamar coal; parametric testing with Western fuel; and HAP testing on the Lamar coal. The parameters explored to determine impact of the reburn technology included: boiler load, reburn system fuel input as a percentage of total fuel input to the furnace, reburn zone stoichiometry, gas recirculation rate and flue gas oxygen content at the economizer outlet.

1.4.1 Emissions Performance

NO_x

The most critical factor in reducing NO_x emission levels with the coal reburn technology was the reburn zone stoichiometry; lower stoichiometry provided greater NO_x reductions. In order to obtain 50% NO_x reduction at full load with Lamar bituminous coal, reburn zone stoichiometry needed to be about 0.89. The data also indicated that at the lowest reburn stoichiometry tested, 0.81, a NO_x reduction of 61.8% to 233 ppm (0.32 lb/10^6 Btu) was achieved.

Post-retrofit tests with reburning were performed over the boiler load range of 37 to 110 MW_e. Plant maximum output on Lamar coal is 118 MW_e but 110 MW_e is more representative of typical full load operation. Accordingly, no emissions data were gathered at 118 MW_e on Lamar coal. Emissions performance averages for NO_x are summarized in Table 1-1. Values in ppm are corrected to 3% O_2 content in the flue gas for comparison consistency.

TABLE 1-1
AVERAGE REBURN NO_x EMISSIONS VERSUS LOAD FOR LAMAR COAL

Load (MW_e)	NO_x ppm (lb/10^6 Btu)/% Reduction From Baseline
110	290 (0.39)/52.4
82	265 (0.36)/50.1
60	325 (0.44)/35.8
37 to 38	400 (0.54)/33.3

Post-retrofit tests with reburning were also performed over the boiler load range of 41 to 118 MW_e with subbituminous PRB fuel. Results with PRB fuel showed that 50% NO_x reduction could be achieved at a reburn zone stoichiometry of about 0.91, which results in a reducing environment which is not as aggressive as that needed with the Lamar coal. At the lowest reburn stoichiometry tested, 0.85, a NO_x reduction of 62.9% (0.28 lb/10^6 Btu) to 208 ppm was achieved. Table 1-2 summarizes average NO_x emissions performance with PRB coal.

TABLE 1-2
AVERAGE REBURN NO_x EMISSIONS VERSUS LOAD FOR PRB COAL

Load (MW_e)	NO_x ppm (lb/10^6 Btu)/% Reduction From Baseline
118	275 (0.37)/-
110	250 (0.34)/55.4
82	230 (0.31)/52.1
60	220 (0.30)/52.6
41	210 (0.28)/-

Because 118 MW_e on PRB fuel was not possible without reburn operation, no baseline and no percent reduction are available.

In general, Western fuel reburning operation resulted in improved reburn burner flame stability and a higher level of NO_x reduction as compared to that observed during the Lamar bituminous coal tests.

Carbon Monoxide Emissions

Typically, for the Lamar coal, carbon monoxide (CO) emissions levels experienced under baseline and reburn operating conditions were 50 to 60 ppm and 90 to 100 ppm, respectively. Although the CO emissions did increase slightly with reburn operation, all levels indicated were considered minimal and did not present a significant impact on operation.

With the PRB coal, baseline CO emissions over the load range for all tests ranged from 28 to 48 ppm. During reburn operation, the CO emission levels increased slightly to 45 to 84 ppm, again a minimal impact to operation.

Precipitator Performance

No change in opacity levels and minimal increase in precipitator outlet particulate loadings were observed during baseline versus optimized reburning operation while firing either the Lamar or the PRB coals. This is the result of no change in fly ash resistivity, slightly larger fly ash mean particle size distribution with reburning, improved precipitator efficiency in the bituminous coal case (no efficiency change for subbituminous), and lower overall particulate loadings with reburn in operation than specified in the original precipitator design.

1.4.2 Boiler Performance

Boiler Thermal Efficiency

An important impact on boiler efficiency is unburned carbon loss (UBCL). This parameter is directly affected by the amount of fly ash leaving the boiler and its carbon content. With the reburn system in operation at 110 MW_e on the Lamar coal, the fraction of total ash entering the boiler which leaves as fly ash increased from 23 to 37% because of the fineness of the reburn coal. Theoretically, with 30% of the total fuel to the boiler introduced through the reburn burners, the fly ash component could have reached 46% of the ash entering the boiler. The actual increase in fly ash indicates that about 60% of the reburn ash must be leaving as fly ash. At 75 and 50% loads, percent ash as fly ash increases from 26 to 36% and 47 to 57%, respectively, with reburn in service.

Combining the higher fly ash levels with changes in unburned carbon translated to higher unburned carbon losses due to reburn operation. At full load with Lamar coal, the unburned carbon component decreased boiler efficiency by 0.10% compared to baseline. At 75 and 50%, efficiency losses due to unburned carbon increased by 0.25 and 1.50%, respectively, operating on the Lamar coal. These values are considered to be the overall impact on boiler efficiency which would be expected on a typical 110 MW_e cyclone-fired unit.

At Nelson Dewey, because dry gas losses decreased as indicated by lower flue gas temperatures at the air heater outlet the overall boiler efficiency actually improved at full load with reburn. However, the improvement in dry gas losses cannot be attributed to reburn. They were the result of differences in operating conditions, including a cleaner economizer.

In general, a larger scatter in fly ash partition data (fly ash versus bottom ash) with reburn out of service was observed during PRB firing. Because the ash splits with reburn in service firing PRB coal were extremely close to those of the Lamar coal, it is reasonable to assume ash splits without reburn in service were also similar. Nevertheless, the unburned carbon in the ash was so low that the fly ash split had minor impact on unburned carbon loss.

With the PRB coal, at full load the efficiency loss due to unburned carbon was unchanged with reburn operation compared to baseline. At 75 and 50% load, the increases in unburned carbon losses were 0.2 and 0.3%, respectively; much improved over unburned carbon losses with Lamar bituminous coal. Overall boiler efficiency actually decreased more than unburned carbon losses indicated, but the additional losses were due to increased dry gas losses resulting from fouling in the economizer (because of inoperable sootblowers). As with the efficiency improvements with Lamar coal which could not be attributed to reburn, these losses could not be attributed to reburn. Unburned carbon loss is the only significant reburn-driven factor impacting overall unit efficiencies.

Furnace Exit Gas Temperature

At full load firing Lamar coal, the furnace exit gas temperature (FEGT) decreased by approximately 100 to 150°F with reburn in service. Of this, approximately 25°F was attributed to gas recirculation flow. There was no change in FEGT at 75% load and an increase of 50 to 75°F was noted at 50% load. With reburn in operation burning PRB coal at full load the FEGT dropped by 50°F, again 25°F of which was due to gas recirculation. There was no change at 75% load, but there was an increase of 75°F at 50% load with reburn in service.

Operation of the coal reburning system impacted absorption profiles within the furnace. Apparently, more heat was absorbed in the furnace itself due to possible changes in emissivities in the substoichiometric region. This was an unanticipated impact since preliminary engineering predictions indicated the possibility of increased FEGT. This is an advantage for the technology where FEGT is near the boiler's upper limit.

This phenomenon, if observed in all reburn applications, could potentially be beneficial to units where FEGT is at an upper limit at full load, or where slagging/fouling problems may be alleviated by a reduction in FEGT.

As a result of the lower FEGT with the Lamar coal, both the superheat and reheat attemperator spray flows were significantly lower than those experienced during baseline conditions. Because less of a FEGT depression was experienced while firing the PRB coal, the superheat/reheat attemperator spray flow quantities were very similar with and without reburn in service.

Slagging and Fouling

There was no indication of detrimental impact on unit cleanliness due to reburn operation with the Lamar coal. All boiler surface cleanliness factors stabilized within five hours after a sootblowing sequence. The component cleanliness decay rates were the same as those developed for pre-retrofit baseline testing.

With PRB coal, the surface cleanliness factors stabilized within three hours after sootblowing, indicating a quicker decay rate than with Lamar coal. The percent cleanliness reduction was about the same for the secondary inlet and outlet banks and the reheater. However, the primary superheater and economizer did not decay as much as was observed during the Lamar tests.

Overall, slagging and fouling were more fuel dependent than reburn dependent. Reburn operation compared to baseline conditions with a given fuel did not change slagging and fouling characteristics significantly.

Corrosion Potential

To investigate possible corrosion in the furnace at Nelson Dewey, ultrasonic thickness measurements (UT) were made throughout the furnace before and after one year of reburn operation at various conditions. No tube metal corrosion within the furnace was detectable. In addition, measurements near the boiler tube walls did not reveal the presence of hydrogen sulfide (H_2S), which would be an indication of corrosion potential.

Simulation of higher furnace tube metal temperatures, indicative of forced circulation-type boilers (universal pressure boilers), was carried out by installation of thicker wall tube panels throughout the furnace region prior to reburn startup. Furnace UT measurements of these panels and removal of one tube panel for laboratory investigation showed no apparent corrosion.

It is both B&W's and WP&L's intent to check the furnace by additional UT testing programs on a periodic basis during the next five years to assure detection of a corrosion problem should it exist.

1.4.3 Boiler Operation

Turndown

WP&L's typical pre-retrofit low load was about 30 MW_e. This level was unaffected by the reburn retrofit in that without reburn in operation the same low load limit of 30 MW_e applies. Because of flame stability issues and the need for cyclones to maintain a minimum firing rate, a new low load minimum of 37 MW_e was defined for operation with reburn in service. The resultant boiler turndown with reburn in service was still at 63%, exceeding the project goal of 50% turndown.

Full Load with Subbituminous Coal

Typically, an approximate 10 to 25% derate is experienced when cyclone boilers fire 100% PRB coal, when compared to the bituminous design coal. The derate is caused by the need to increase cyclone heat input and coal feed rate with PRB fuel to maintain load carrying capability, because of the inherently lower heating value and higher moisture content of PRB coal. Maximum allowable heat input and coal loading criteria for the cyclones therefore limit boiler load when firing the PRB coal.

The testing at Nelson Dewey indicated the maximum load achievable during day to day operation with the PRB coal was 108 to 110 MW_e without reburn in operation. The main limitations were cyclone coal loading concerns and furnace over pressure alarms. With the bituminous Lamar coal, maximum load was 118 MW_e, limited by the capability of the feedwater pumps.

Because the reburn system removes approximately 30% of the heat input from the cyclones, higher boiler loads were maintained during 100% PRB coal firing as compared to baseline conditions on the same fuel. The maximum load of 118 MW_e achieved burning Lamar coal was possible with the PRB coal only during reburn operation. Thus, reburn has the potential to minimize or even eliminate the derate problem when switching fuels by diverting a portion of unit heat demand away from the cyclones to the reburn burners. In this capacity, coal reburning could be viewed as a NO_x reduction strategy to compliment and enhance performance of a fuel switching SO_2 reduction strategy. Further, a reburn system possibly could be economically justified based on fuel cost savings and regained unit capacity when switching to a PRB coal.

1.5 Long-Term Operation and Implications for Future Application

The reburn system was operated by WP&L with Nelson Dewey Unit No. 2 in a dispatch load-following mode for a period of four months on Lamar bituminous coal. This period was shorter than originally planned due to the host's decision to switch to low sulfur Western coal because of state imposed limits on SO_2 emissions. The CEM recorded emissions during this operation. Long-term data was summarized for reburn in operation at greater than 100 MW_e, greater than 80 MW_e and all loads combined.

For reburn in operation at loads greater than 100 MW_e (108 MW_e average) an average NO_x reduction of 51.2% was achieved. For loads greater than 80 MW_e (97.9 MW_e average), an average reduction of 49.0% occurred and for all loads (74.1 MW_e average), the overall NO_x reduction was 40.0%. These values agreed quite closely with NO_x reductions achieved during the performance test sequences for corresponding loads in automatic control.

The implication of these results is that for a given reburn plant site, average NO_x reductions over the load range can be expected to approach demonstration performance testing results. Performance testing results were developed during system operation in a full automatic mode. Since coal type also influences system performance, the reburn control system must be set up for full automatic control based on performance testing information for the specific coal. Control should be by a state-of-the-art distributed control system to allow handling of complex relationships between many variables and quick response.

With the PRB coal, short-term NO_x reductions in excess of 50% were achieved at all loads. It would be expected that if there had been time for long-term testing with this fuel, the overall average reduction would have been 50% or greater, versus 40% with Lamar bituminous coal.

There was significant interest in the possibility of reburn operation on lignite and although testing at Nelson Dewey was not a possibility, a project sponsored by the North Dakota Lignite Board was carried out at the Alliance Research Center in the pilot-scale SBS. It was found the lignite achieved good results in reburn operation in the SBS and, accordingly, good results are expected at full scale. Appendix 3 summarizes the Lignite testing.

It should also be noted that under rigid test conditions in manual control, generally higher levels of NO_x reduction at a given load were possible. These results cannot be reproduced under full automatic control operation because automatic control must have a wider tolerance band to allow for variations in operating conditions.

1.6 Economics of Reburning

An economic analysis was performed using the EPRI Economic Premises, to develop total capital and levelized revenue requirements for a coal reburning retrofit for a 110 MW_e plant and for a 605 MW_e plant. These results are shown in Table 1.3. In addition, annualized costs per ton of NO_x removed for both the 110 MW_e case and the 605 MW_e case were developed for periods of 10 and 30 years. This information is also shown in Table 1-3.

TABLE 1-3 - REBURN TECHNOLOGY ECONOMICS

	Plant Size	
	110 MW_e	**605 MW_e**
Total Capital Cost ($/kW)	66	43
Levelized Busbar Power Cost (mills/kWh) (10 yr levelized/30 yr levelized)	2.4/2.3	1.6/1.5
Annualized Cost ($/ton removed) (10 yr/30 yr)	1075/692	408/263

These values assume typical retrofit conditions. Numerous site specific factors can greatly impact the cost of retrofitting a coal reburning system to an existing cyclone-equipped boiler. The most significant of these factors include the state of the existing control system in the plant, availability of flue gas recirculation; and space for location of the coal pulverizer(s), reburn burners and overfire air ports within the existing confines of the unit. Fuel handling equipment modifications and additions required to supply the reburn system are also a major cost factor. Additional site specific factors include sootblowing capacity and location, electrostatic precipitator or back-end gas cleanup capacity, boiler circulation considerations and steam temperature control capacities.

It should also be evident that the costs for a reburn retrofit can be reduced by savings incurred with the technology. Again, on a site-by-site basis, cost of the technology may be offset by savings in fuel cost when switching to a PRB coal. An expensive low sulfur, high Btu blend coal may no longer be needed to regain full load capabilities. These factors have not been included in the costs developed.

1.7 Other Requirements

Even with the positive results developed during the demonstration of coal reburning, there remain a number of technical issues which need to be considered for future reburn retrofits. Coal reburning technology is control intensive and a distributed control system (DCS) is necessary in a cyclone-fired boiler to integrate reburn parameters with those of the existing boiler system. The reburn technology requires accurate and responsive control of air and fuel flows to the various reburning zones. Upgrading controls, if not already at the DCS level, will be required.

Accurate control of cyclone air and fuel flow rates is critical to the protection of the cyclone furnaces as well as reburn system NO_x reduction performance. This requires tight control of reburn zone stoichiometry. Individual air control capability to each cyclone will need to be addressed on large open windbox cyclone boilers, because present air flow indications at each cyclone may not be adequate to control cyclone stoichiometry. Higher than desired air flow to a cyclone will increase stoichiometry of the reburn zone, reducing the ability to decompose NO_x. A lower than desired air rate could aggravate a cyclone corrosion problem.

Gas recirculation (GR) is required to consistently maintain high NO_x reductions while providing adequate cooling to the reburn burners; GR removes unnecessary oxygen from the reburn zone. This is accomplished either by allowing a trade off of air with GR at the reburn burners maintaining constant mass flow to allow flame penetration and/or by replacing cooling air requirements with GR, both reduce reburn zone stoichiometry by elimination of oxygen. The lower stoichiometry made possible by GR allows improved NO_x reduction to be achieved. A number of cyclone operating utilities have removed GR fans. For maximum NO_x reduction, new fans may need to be included in the final reburn system design.

Finally, the performance of reburn technology depends heavily upon effective in-furnace mixing of cyclone and reburn burner gas flows. Careful evaluation of mixing parameters will be necessary for each unit considering reburn technology as a NO_x reduction alternative in order to properly locate and size the burners and overfire air ports.

2.0 Introduction and Background

2.1 Introduction

The Department of Energy (DOE) under its Clean Coal Round 2 solicitation sponsored the Babcock & Wilcox Company (B&W) with the Wisconsin Power & Light Company (WP&L) to perform a full-scale demonstration of reburning technology for cyclone boiler NO_x emissions control. This full-scale evaluation was justified via a previous Electric Power Research Institute sponsored (Project: RP-1402-30) engineering feasibility study and EPRI/GRI (EPRI: RP-2154-11; GRI: 5087-254-1471) pilot-scale evaluation of reburning for cyclone boilers performed by B&W. The feasibility study indicated that this technology could be successfully applied to the majority of cyclone-equipped boilers to reduce NO_x emission levels by approximately 50 to 70%. The pilot tests evaluated the potential of natural gas, oil, and coal as reburning fuels in reducing NO_x emissions. The data obtained from the pilot-scale project substantiated the results predicted by the feasibility study. Though oil/gas reburning can play a role in reducing NO_x emissions from cyclone boilers, B&W coal reburning research showed that coal performs nearly as well as gas/oil without deleterious effects on combustion efficiency. This means that boilers using reburning for NO_x control can maintain 100% coal usage instead of switching to 20% gas/oil for reburning. As a result coal reburning technology advanced to the point where demonstration on a commercial scale was the next logical step.

Currently, 105 operating cyclone-equipped utility boilers exist, representing approximately 15% of pre-New Source Performance Standards (NSPS) coal-fired generating capacity (over 26,000 MW_e). These units contribute approximately 21% of the NO_x emitted because their inherent turbulent, high-temperature combustion process is conducive to NO_x formation. Although the majority of the cyclone units are 20 to 30 years old, utilities plan to operate many of these units for at least an additional 10 to 20 years. These units (located primarily in the Midwest) have been targeted for Phase II Federal Acid Rain NO_x emission limitations.

The coal reburning demonstration project for cyclone boiler NO_x control was carried out at WP&L's Nelson Dewey Station, Unit No. 2, in Cassville, Wisconsin. The unit is a B&W RB-type boiler with three cyclone furnaces. Unit No. 2 is small (nominal 100 MW_e) to limit project costs, but large enough to demonstrate that the reburning technology can be successfully applied to a full-scale cyclone-fired utility boiler. As part of the project, B&W's six million Btu/hr Small Boiler Simulator (SBS) pilot facility was used to duplicate the operating practices of WP&L's Nelson Dewey Unit No. 2. The coal that is fired at Nelson Dewey was fired in the SBS cyclone and also was used as the reburn fuel. During the field test phase at Nelson Dewey Station, emission and performance data were acquired and analyzed before the coal reburn conversion to serve as a baseline against which to determine the NO_x reduction and impact on boiler performance. Combining these combustion test results with physical and numerical modeling of the technology as applied to Dewey Unit No. 2 provided a comprehensive test program not only for successful application of WP&L's unit, but for the cyclone population as a whole.

From WP&L's perspective, involvement in this project was undertaken for several reasons. The State of Wisconsin enacted acid rain legislation in 1986, which was fully implemented in 1993. Federal acid rain legislation will require NO_x reductions from cyclone-fired boilers beginning in 1997. The state law requires significant reduction of SO_2 emissions and the study of potential reduction of NO_x emissions. Approximately 50% of WP&L's coal-fired capacity is generated from cyclone boilers installed between 1952 and 1969. These boilers are vital to meeting the electricity needs of WP&L's customers. However, of concern to WP&L is that these cyclone boilers produce about 75% of the NO_x emitted within the WP&L system. Environmental concerns have been complicated by the fact that no commercial combustion technologies exist for controlling NO_x emissions from cyclone boilers. Based upon WP&L's internal analyses of several advanced technologies, coal reburning surfaced as the least-cost retrofit alternative. With these reasons and a desire to promote cost-effective emission reduction technologies, WP&L accepted B&W's offer to participate and host this project.

This document which represents the Final Project Report for the Coal Reburning for Cyclone Boiler NO_x Control Demonstration project describes the activities and results of the work performed. Section 1, the Executive Summary condenses the results of the report, providing an overview. Section 2, the Introduction and Background summarizes the work on which this project was based and is provided for the sake of continuity of technology development. Also, the details of the project organization are provided. Section 3 summarizes baseline test results as a point of comparison for later reburn testing. Sections 4 and 5 summarizes the pilot-scale testing and mathematical/physical flow modeling studies performed at the Alliance Research Center to optimize the reburn system design. Section 6 describes the reburn system installed at Nelson Dewey, the operation of which allowed the compilation of data presented in Section 7, Coal Reburning Technical Impacts. Section 7, the heart of the report, summarizes overall performance and emissions impacts of the reburn technology on the cyclone fired boiler. Section 8 presents an economic assessment based on the information developed during Nelson Dewey engineering construction and testing. This work builds upon the economic study performed during the original feasibility and pilot-scale work as outlined in Section 2. Section 9, Application of the Technology validates the mathematical models as design tools by comparing predictions with full-scale results at Nelson Dewey. Section 10 provides the Conclusions and Recommendations developed during this full-scale demonstration project.

2.2 Description of Reburning Process Technology

The cyclone furnace consists of a cyclone burner connected to a horizontal water-cooled cylinder, commonly referred to as the cyclone barrel. Air and crushed coal are introduced through the cyclone burner into the cyclone barrel. The larger coal particles are thrust out to the barrel walls where they are captured and burned in the molten slag layer which is formed; the finer particles burn in suspension. The mineral matter melts, exits the cyclone furnace from a tap at the cyclone throat, and is dropped into a water-filled slag tank. The flue gases and remaining ash leave the cyclone and enter the main furnace.

No commercially-demonstrated combustion modifications have significantly reduced NO_x emissions without adversely affecting cyclone operation. Past tests with combustion air staging achieved 15 to 30% reductions. Cyclone tube corrosion concerns due to the resulting reducing conditions were not fully addressed because of the short duration of these tests. Further investigation of staging for cyclone NO_x control was halted due to the utility's corrosion concern.

The use of selective catalytic reduction (SCR) technology offers promise of controlling NO_x emissions from these units, but at high capital and operating costs. Further, significant uncertainties exist about catalyst life in this environment with medium and high sulfur U.S. coals. Reburning is, therefore, a promising alternative NO_x reduction approach for cyclone-equipped units with more reasonable capital and operating costs.

Reburning is a process by which NO_x produced in the cyclone is reduced (decomposed to molecular nitrogen) in the main furnace by the injection of a secondary fuel. The secondary (or reburning) fuel creates an oxygen-deficient (reducing) region which accomplishes decomposition of the NO_x. Because reburning can be applied while the cyclone operates under its normal oxidizing condition, its effects on cyclone performance can be minimized.

The reburning process employs multiple combustion zones in the furnace, defined as the main combustion, reburn, and burnout zones, as shown in Figure 2-1. The main combustion zone is operated at a reduced stoichiometry and has the majority of the fuel input (70 to 80% heat input). Most past investigations on natural gas-/oil-/coal-fired units have shown that the main combustion zone of the furnace should be operated at a stoichiometry of less than 1.0. This operating criteria is impractical for cyclone units due to the potential for highly corrosive conditions, because many cyclones burn high-sulfur, high-iron content bituminous coals. To avoid this situation and its potential consequences, the cyclone main combustion zone was defined to be operated at a stoichiometry of no less than 1.1 (2% excess O_2).

The balance of fuel (20 to 30%) is introduced above the main combustion zone (cyclones) in the reburn zone through reburning

Reburning Process

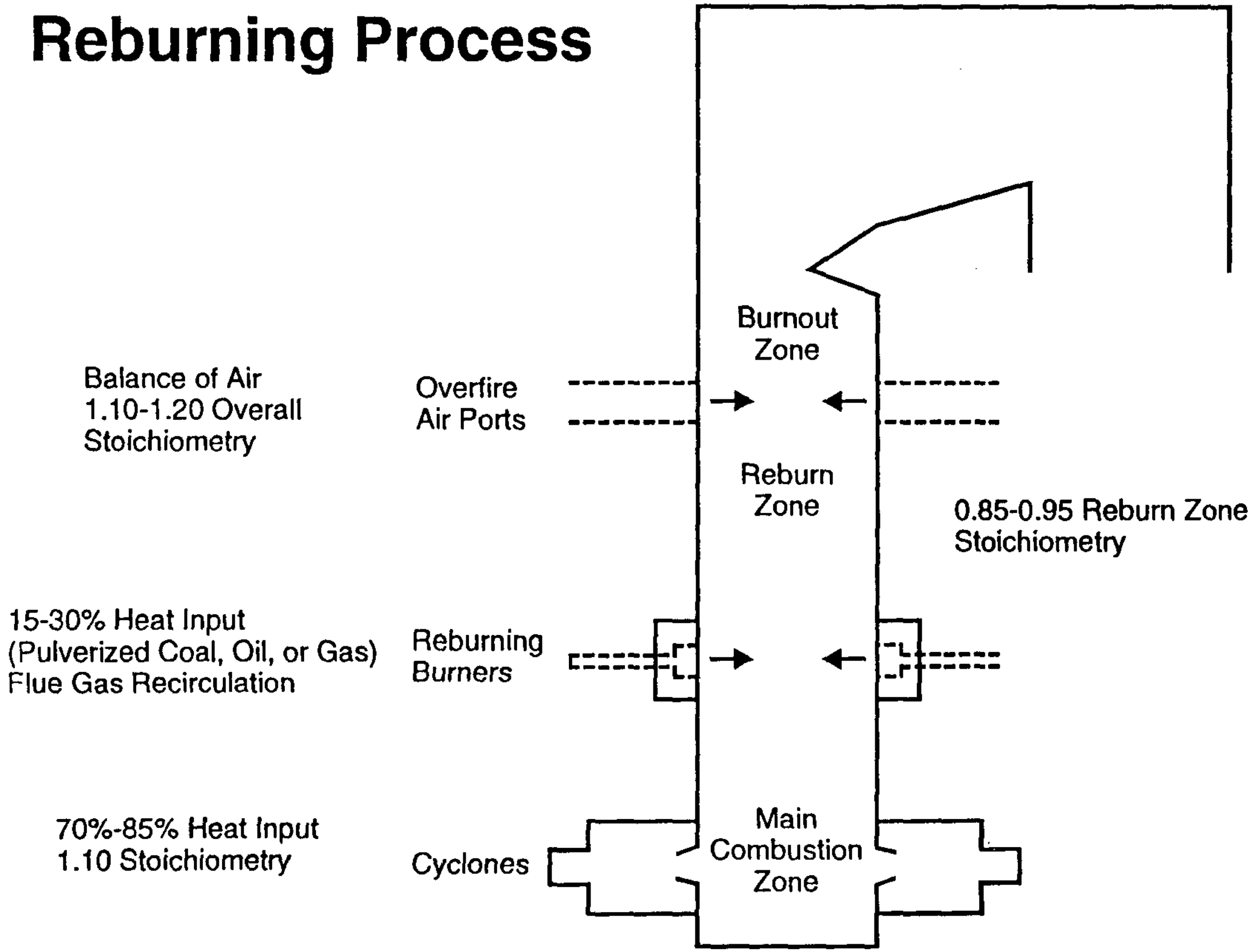


Figure 2.1

burners. To protect the tubes in the reburning zone from fireside corrosion, air is introduced through the reburning burners. They are operated in a similar fashion to a standard wall-fired burner except that they are fired at extremely low stoichiometries (less than 0.6). The furnace reburning zone is operated at stoichiometries in the range of 0.85 to 0.95 by controlling the burner stoichiometry, in order to achieve maximum NO_x reduction based on laboratory/actual boiler application results. A sufficient furnace residence time within the reburn zone is required for flue gas mixing and NO_x reduction kinetics to occur.

The balance of the required combustion air (totaling 15 to 20% excess air at the economizer outlet) is introduced through overfire air (OFA) ports. As with the reburn zone, a satisfactory residence time within this burnout zone is required for complete combustion. These ports were designed with adjustable air velocity controls to enable optimization of mixing for complete fuel burnout prior to exiting the furnace.

2.3 Previous Work

This full-scale demonstration of coal reburning technology builds on knowledge gained during execution of two earlier projects:

(1) An engineering feasibility study - sponsored by EPRI (Project RP-1402-30) which analyzed the population of cyclone boilers to determine candidates for the technology. Based on residence time results, the technology could potentially be applied to a majority of cyclone boilers and conceivably achieve a NO_x emission reduction of 50 to 70%. This assumes no site specific factors exist which would preclude installation of a reburning system.

(2) A pilot-scale evaluation of reburn technology was also performed under joint EPRI/Gas Research Institute (GRI) sponsorship (EPRI: RP-2154-11; GRI: 5087-254-1471). This work evaluated the use of natural gas, oil and coal as reburning fuels. Gas, oil, and coal were all found to perform well in achieving NO_x reductions without deleterious effects on combustion efficiency.

Summaries of each of these projects are given below to provide continuity of reburn process development from the study stage through pilot-scale testing.

2.3.1 Reburn Feasibility Study

2.3.1.1 Objectives

The objective of the feasibility study was to make a preliminary assessment of the applicability of reburning to cyclone units using available information on the reburning process design requirements and performance expectations. The study involved the following major elements:

(1) A survey of the cyclone boiler population to determine furnace gas residence time for various cyclone boiler designs and generating capacities.

(2) Specification of reburn design criteria which would be compatible with cyclone design and operation (residence times and stoichiometries).

(3) A design of a reburning system for two representative cyclone boilers and predictions of NO_x reductions.

(4) An assessment of cyclone/boiler reliability and operability while operated with a reburn system.

2.3.1.2 Results

As previously discussed the reburning process employs multiple combustion zones in the furnace. In the reburning and burnout zones, residence time is extremely important. For purposes of the feasibility study, minimum combustion gas residence times within the reburn and burnout zones, developed during pilot tests, were used to determine the applicability of the technology to the cyclone boiler population. This provided a conservative review with respect to the overall commercial practicality of cyclone reburning.

Boiler Design Survey

The cyclone boiler population was surveyed to assess the suitability of these units to retrofit of the reburning technology. The population was first categorized according to furnace arrangements (single and opposed wall-fired units) and generating capacities (40 to 1150 MW_e). Then specific representative units from each category were selected to perform a more detailed reburning application evaluation. The major criteria used to determine if the reburn technology could be successfully applied was the estimated furnace gas residence time. In addition, space availability at the anticipated reburn burners and overfire air locations was examined. Table 2-1 summarizes the eight categories of cyclone boilers that were evaluated.

TABLE 2-1 CYCLONE BOILER POPULATION SURVEY				
IDENTIFICATION	**FURNACE ARRANGEMENT**	**BURNER ARRANGEMENT**	**MW_e**	**INSTALLED**
2.1	Single Wall-Fired	2 Cyclones/1 Level	40	1959
2.2	Single Wall-Fired	3 Cyclones/1 Level	100	1960
2.3	Single Wall-Fired	4 Cyclones/2 Levels	150	1965
2.4	Opposed Wall-Fired	4 Cyclones/1 Level	190	1961
2.5	Opposed Wall-Fired	7 Cyclones/1 Level	330	1964
2.6	Opposed Wall-Fired	8 Cyclones/2 Levels	420	1968
2.7	Opposed Wall-Fired	14 Cyclones/2 Levels	700	1963
2.8	Opposed Wall-Fired	23 Cyclones/2 Levels	1150	1969

Original boiler design data was used to calculate the furnace gas residence times of the above units because actual unit operating data was unavailable. The process to determine residence times and evaluate their significance was three-fold:

(1) Predict furnace gas flow patterns via past B&W flow modeling experience to confirm the validity of the plug flow residence time calculation method used.

(2) Use unit design data and previously discussed cyclone reburn design criteria to compare available furnace height with the furnace height necessary to apply reburning (residence time criteria).

(3) Select two actual units to perform a more detailed engineering/cost analysis.

Furnace Gas Flow Patterns

Predicting furnace gas flow patterns for opposed wall-fired units was done using the results from two past B&W physical flow model test programs.[1][2] No directly pertinent data were available for single wall-fired units. The acrylic models used in the B&W flow tests were 1/70 and 1/32 scale and used water seeded with neutral buoyancy plastic particles as the working fluid. Physical observation and photographic views indicated that the furnace flow patterns were relatively uniform above the cyclone combustion zone in both of the opposed wall-fired models (with no noticeable areas of downward recirculation). No unusual furnace gas flow patterns were expected in the reburning zones. Thus, the residence time estimates using plug flow conditions appeared to be adequate.

Furnace Gas Residence Time

For each of the representative units listed in Table 2-1, calculations were made to determine if sufficient furnace height was available to accommodate the necessary reburning residence times identified earlier. The minimum required residence times in the reburn and overfire air zones were used. The location of the reburning burners was dictated by physical space limitations. Locating the reburn burners in close proximity to the cyclones does not inhibit the reburning performance because the majority of combustion occurs within the cyclone barrel.

Comparing the actual residence time available in the various units to the minimum required time, a difference between actual boiler furnace height versus necessary reburning boiler furnace height was determined. Thus, for screening purposes, this technique determined if the majority of cyclone units could apply the reburn technology. Table 2-2 summarizes these furnace height calculations for the eight units identified in Table 2-1. The base design specifications used to generate this table include:

Fuel Split Between Cyclone and Reburn Zone . . . 80/20
Reburning Fuel . . . . Natural Gas
Cyclone Stoichiometry 1.1

TABLE 2-2 REQUIRED FURNACE HEIGHT

Unit Identification	2.1	2.2	2.3	2.4	2.5	2.6	2.7	2.8
Total Number of Cyclones	2	3	4	4	7	8	14	23
Furnace Width (ft)	18	34	36	26	45	36	60	96
Furnace Depth (ft)	10	16	24	20	24	27	33	33
Elevation of Furnace Exit (ft)	609	703	106	115	305	159	528	541
Required Elevation of Furnace Exit (ft)	626.7	702.3	99.4	124.5	294.0	150.2	505.6	527.7
Difference Between Actual and Calculated Furnace Exit (ft)	17.7	-0.7	-6.6	9.5	-11.0	-8.8	-22.4	-13.3
% Increase in Furnace Zone Height Required	52.1%	-1.6%	-13.4%	12.7%	-15.7%	-9.5%	-23.1%	-14.5%

The difference between the actual (available full load residence time) and calculated (required reburn system residence time) furnace exit elevation is a key factor in determining whether the technology can be applied; A positive value signifies that additional furnace height is necessary a negative value indicates sufficient height is available.

The majority of cyclone units examined showed that sufficient furnace height (available gas residence time) exists to accommodate reburning. The only units which appear unsuitable are the small, single wall-fired boilers (less than 80 MW_e). Unit 2.1 in Table 2-2 typifies this category of units where an additional furnace height of 17.7 feet would be required. This corresponds to increasing the furnace height by over 50% which is impractical. These units represent less than approximately 7% of the cyclone generating capacity.

Unit 2.4 also requires an additional 9.5 feet, but this corresponds to an increase of only 12.7%. The reburning technology could still be applied to this unit if a reduction in residence times within the main, reburn and overfire air zones were incorporated. This would, however, lead to a lower expected NO_x reduction.

Retrofit Reburning Case Studies

Two boilers -- Unit 2.4 (200 MW_e) and Unit 2.7 (700 MW_e) -- were chosen to perform a more detailed technical and economic analysis. Unit 2.4 was selected because, although it was considered to be an acceptable candidate for the technology, non-ideal residence times exist and, therefore, it represents a worst case scenario. Unit 2.7 is indicative of the majority of the units reviewed because sufficient residence time to apply the technology was determined. The specific criteria which were varied to evaluate the best conditions available within these units to obtain maximum NO_x reduction include:

Fuel Split . . . . 75/25, 80/20, and 85/15
Reburn Fuel . . . . Gas/Oil/Coal

Calculations show that under any condition, the 200 MW_e unit possesses less furnace height than would be optimal to obtain maximum NO_x reduction. The required residence times could be achieved at about 85% of rated full load, but because a derate condition usually is unacceptable, NO_x emissions were predicted at both full and partial loads.

The 700 MW_e unit has about 22 feet additional furnace height that can be used to increase the reburn system residence times.

NO_x Predictions

At full-load conditions, NO_x reduction predictions for the two reburning applications were 49 and 62% for the 200 MW_e and 700 MW_e units, respectively. A 15% derate of the 200 MW_e facility would provide sufficient residence time within its furnace to achieve a predicted 63% NO_x reduction from full-load baseline conditions. Table 2-3 summarizes the prediction methodology:

TABLE 2-3
NO_x Emissions Predictions

Unit Size (MW_e)	200	700
Full Load - Baseline NO_x (ppm/lb/10^6 Btu)	985/1.34	1180/1.60
NO_x Reductions -		
• Due to reduced cyclone load (%)	15.7	23.7
• Further reduction due to reburn process (%)	40.0*	50
• Overall NO_x Reduction (%)	49.0	62
• Reburn NO_x Emission Level (ppm/lb/10^6 Btu)	498/0.68	450/0.61
15% Derate from Full Load - Baseline NO_x (ppm/lb/10^6 Btu)	870/1.18	-
NO_x Reductions -		
• Due to reduced cyclone load (%)	16.0	-
• Further reduction due to reburn process (%)	50.0	-
• Overall NO_x reduction (%)	58.0	-
• Reburn NO_x Emission Level (ppm/lb/10^6 Btu)	365/0.50	-

* reduced residence time for 200 MW_e case, full load

The baseline NO_x predictions were made using B&W design standards for cyclone boilers that are based on NO_x emission field data. The NO_x reduction capabilities of a reburning system were determined from data available from Babcock-Hitachi and other researchers.[1][2][3][4] Because no reburning pilot data simulating cyclone characteristics were available, this study assumed that the above referenced research was applicable to approximate NO_x reductions in cyclone boilers.

The NO_x reduction comes from two sources:

(1) Beginning with a baseline NO_x emission for full-load fuel input to the cyclones, an initial NO_x reduction is realized by diverting fuel to the reburn ports, therefore reducing total heat input (and NO_x) at the cyclones. This initial NO_x reduction ranges from 15 to 25% depending on the reduced input to the cyclones and the full-load cyclone heat input. This effect has been verified by B&W based on field data.

This estimate is based on standard B&W cyclone NO_x emission correlation curves.

(2) Tests performed with relatively high primary NO_x levels (>500 ppm) show that approximately 50 to 60% reduction can be achieved regardless of reburning fuel type (gas, oil, coal). Additionally, reburning zone stoichiometries of 0.85 to 0.95 show 35 to 60% reduction capabilities. In the case where reburn residence times are restricted, the overall NO_x reduction by reburning is substantially decreased.

Using this information, the reduction of NO_x emissions by the application of reburning to cyclones is a combined effect of the reburning process and lower heat input to the cyclones. Overall, approximately 20% reduction is realized by decreased heat input, and approximately 50% reduction (in NO_x from the cyclones) can be realized by reburning. The combined effect provides conservatively a 60 to 65% reduction from baseline NO_x emissions, if required residence times are available, and approximately 45 to 50% reduction if residence times are slightly reduced.

Operational Impacts

The 200 MW_e case study was used to perform a more detailed operational assessment of applying the reburning technology. Following a conceptual design of the reburn system (based on the stoichiometries and residence times determined earlier), the boiler performance and power plant impacts were addressed.

Standard heat transfer calculations were used to determine the effect of reburning on furnace absorption, furnace exit gas temperatures (FEGT), and unit efficiency. Because the unit's performance depends on the FEGT, a base-case FEGT for normal cyclone operating conditions was determined. The maximum increase of FEGT when applying various reburning combustion schemes (varying fuel type and furnace locations where combustion actually occurs) was 56°F. This increase is considered insignificant such that the unit's efficiency and existing metals in the convective pass should not be adversely affected.

The major uncertainties were the slagging/fouling potential, unburned combustible losses, and corrosion potential. These items had to be addressed during the pilot-scale evaluations.

Typically, existing cyclone operation does not incorporate precise control over air and fuel splits. For a given load, fuel and air are divided near-equally between the in-service cyclones, with some cooling air provided to out-of-service cyclones. For successful application of the reburning technology, more precise air and fuel control is required. Secondary air monitors for each cyclone, and gravimetric feeders are recommended to assure a balanced air and fuel distribution to each cyclone.

With the reburning technology, the cyclone itself is operated in a normal manner at all times: start-up, shutdown, emergencies, etc. When operating in a lower NO_x mode (reburning), the cyclone operates with reduced fuel input and reduced air levels. The addition of reburning equipment should not impact the operational range of the cyclone.

The reburn burners would be operated much like wall-fired burners. The equipment associated with them includes lighter/ignitor systems and flame detection devices. This equipment is conventional and used throughout the industry.

Using coal as the reburn fuel could potentially double the particulate loadings and thus adversely affect precipitator/baghouse performance. In addition, possible changes in particle size distribution and flue gas properties will need to be addressed. These issues are site-specific and will be determined on a retrofit-to-retrofit basis.

2.3.1.3 Conclusions and Recommendations of the Feasibility Study

Review of the cyclone boiler population showed that reburning technology to reduce NO_x emissions is applicable from the standpoint of furnace residence time availability. Only the small (<80 MW_e) single wall-fired units appear non-conducive to reburning.

Criteria for main, reburning, and overfire air zone residence times and stoichiometries were determined based on pilot scale data. For cyclone firing, stoichiometries are as follows:

Main Zone . . . . 1.1 stoichiometry
Reburning Zone . . . . 0.85 to 0.95 stoichiometry
Overfire Air Zone . . . . 1.16 to 1.2 stoichiometry

Nominal 50 to 60% NO_x reductions can be expected from existing cyclone-equipped boilers. Typical uncontrolled NO_x emissions from cyclones are 0.8 to 1.8 $lb/10^6$ Btu.

Corrosion potential within the cyclone barrel when applying this technology may be avoidable through recommended modifications to the coal/air flow control system. Additional protection may be necessary in the main furnace near the reburning ports if coal is the reburn fuel.

Although FEGT, deposition, unburned carbon, steam temperatures and boiler efficiencies are expected to be minimally impacted, pilot/full-scale testing was needed to validate these assumptions.

The study assumed all three fuels were comparable with respect to reducing NO_x. Pilot-scale tests were needed to confirm this, along with any associated detrimental boiler side effects. Thus, after this technical evaluation of the three reburn fuels was completed, a combined cost/technical evaluation was performed.

2.3.2 Pilot Scale Evaluation of Reburn Technology

As recommended under the feasibility study, pilot-scale evaluation of the reburn technology was the next logical step. A summary of the pilot testing follows.

2.3.2.1 Objectives

The technical objectives of the pilot scale tests were to demonstrate NO_x reductions of nominally 50 to 60% while maintaining acceptable cyclone/boiler operating conditions. Three reburning fuels were evaluated while operating under various simulated anticipated full-scale reburning conditions. Table 2-4 summarizes the various ranges of reburning criteria that were evaluated for NO_x reduction capability. Fuel splits for main cyclone/reburning burners, reburning fuel type, furnace stoichiometries, and furnace residence times were varied. Additional variables that were evaluated include mixing, corrosion potential, fireside deposition, and combustion efficiency.

TABLE 2-4
SUMMARY OF REBURNING CONDITIONS EVALUATED DURING PILOT TESTS

	Main Combustion (Primary) Zone	Reburning Zone	Burnout Zone
Fuel	Kittanning Coal	Natural Gas, No. 6 Fuel Oil, Kittanning Coal	---
Fuel Split	70 - 85%	15 - 30%	---
Stoichiometry	1.0 - 1.2	0.85 - 0.95	1.05 - 1.2
Residence Time (Assume Plug Flow)	0.1 second	0.5 - 0.8 second	0.6 - 0.9 second

The major areas of technical uncertainty that were identified in the feasibility case studies and were evaluated during the pilot tests for all reburning fuel types included:

- NO_x reduction potentials of the reburning fuels when operating in a cyclone boiler environment of high initial primary NO_x levels and low char carryover to the main furnace (high char carryover increases available, unconsumed oxygen in the reburning zone)
- Optimization of process parameters for cyclone application
- Effects on increased solids deposition with coal reburning in the upper furnace and convective section
- Corrosion throughout the furnace
- Unburned combustibles and FEGT changes

The work was conducted in B&W's six million Btu/hr Small Boiler Simulator (SBS) at the Alliance Research Center. The facility is described in Appendix 1.

2.3.2.2 Pilot-Scale Results

Pilot scale testing consisted of baseline tests, to serve as a benchmark for comparison, and reburn operation testing. Critical data collected for both the baseline and reburning tests included NO_x, CO, O_2 and unburned combustibles levels. Also, gas temperature profiles were measured throughout the furnace. Pennsylvania Kittanning seam coal was used as main cyclone fuel during all testing as well as reburn fuel for coal reburning investigations.

Baseline Tests

Figure 2-2 illustrates the NO_x emission levels obtained during the baseline tests. Operating the cyclone at six million Btu/hr resulted in a baseline NO_x level of 920 ppm at 3% excess O_2. NO_x emissions increased by approximately 40 ppm per each percentage point increase in excess O_2. Higher excess O_2 increases the availability of O_2 to form NO_x at high temperatures, as is indicated by this data. Reducing furnace load to 4.3 million Btu/hr decreased the NO_x emissions levels to 850 ppm at 3% excess O_2. As excess O_2 changed, the slope of the NO_x curve was the same as that observed at full load. Firing natural gas in the cyclone at six million Btu/hr resulted in NO_x emissions of 455 ppm at 2% excess O_2 (typical operating excess O_2). Reducing the oxygen to 1% resulted in the same NO_x level as that observed at 2% O_2 (455 ppm), but increasing the oxygen to

3% excess O_2 reduced the NO_x level to 392 ppm. These NO_x levels can be explained via the cyclone exit gas temperatures and the various mechanisms of NO_x formation.

Cyclone exit temperatures were measured using an optical pyrometer. At six million Btu/hr (coal firing), the temperatures changed from 2950° to 2850°F at 2 to 4% O_2, respectively. At 4.3 million Btu/hr, the same trend was observed at 2 to 4% O_2 (2800° to 2700°F). Natural gas firing at six million Btu/hr showed temperatures of 2640° to 2570°F from 1 to 3% O_2. Temperatures are lower with natural gas because of higher hydrogen content in gas than in coal and correspondingly higher moisture generation.

The various trends of NO_x emission levels versus excess oxygen can be explained by the different mechanisms of NO_x formation. During natural gas firing, thermal NO_x is the major mechanism of NO_x formation. Thus, NO_x levels decreased as the excess oxygen increased because the cyclone exit temperature was also observed to decrease. During coal firing, fuel NO_x, along with thermal NO_x also contributes to emission levels. Because fuel NO_x emissions increase with increasing excess oxygen, the overall NO_x levels were observed to increase with higher O_2.

Reburning Tests

The two reburning burners were located at the rear furnace wall of the SBS. Kittanning coal was fired in the cyclone during all test phases and the cyclone was operated at 65 to 85% of total load under excess air conditions. Reburning fuel provided the remaining 15 to 35% heat input. In order to obtain various in-furnace reburning zone stoichiometries (0.85 to 0.95), the reburning burners were operated at sub-stoichiometric conditions. The balance of air was then introduced through OFA ports located in the upper furnace. Under optimized test conditions, reburning burner stability was observed during each of the reburn fuel test phases. No indication of excessive CO levels (at the stack) or burner instability was observed during any of the optimum test conditions.

The reburning burners were first adjusted for optimum NO_x emission levels via burner hardware. Changing the swirl component exiting the burner (via spin vanes in the outer zone) had an effect on resulting NO_x levels. Reducing the amount of swirl provided more reburning fuel penetration and improved NO_x reduction. In addition, flue gas recirculation (FGR) could be introduced to the burner and an improvement in NO_x reduction was also observed under this condition. More than a 50% NO_x reduction was achieved with natural gas, oil, and coal reburning at optimum conditions. The optimum burner settings for each

Baseline NO_x Levels in SBS

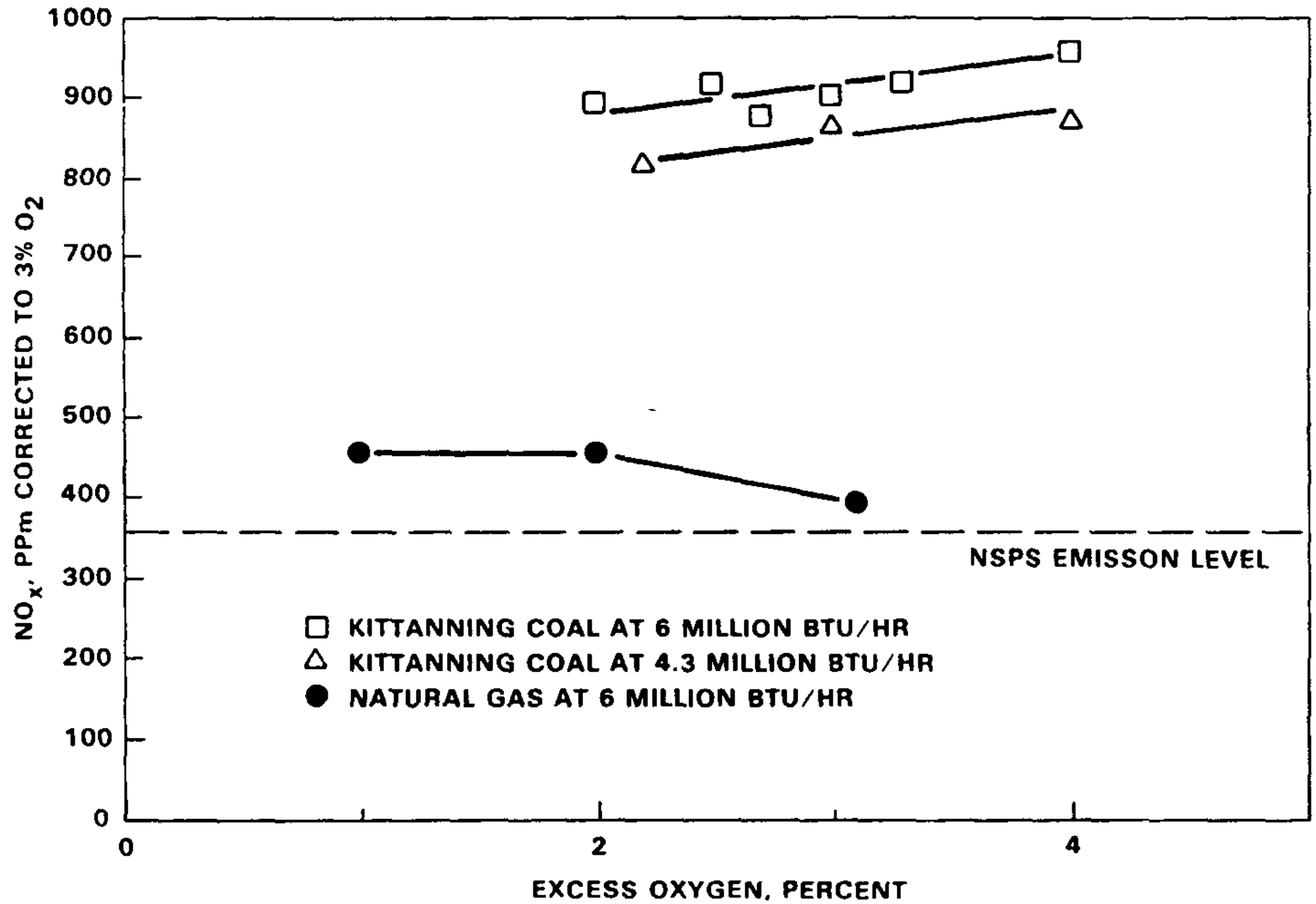


Figure 2-2 Baseline NO_x Emission Levels in the SBS

reburning fuel were determined based upon NO_x reduction capability, flame stability, and CO emission levels.

NO_x Emissions

A 40 to 75% NO_x reduction (from the baseline NO_x level) was achieved during reburning under various test conditions. These results are reported as overall reductions and consist of basically three components:

- NO_x reduction via lower heat input at the cyclone burner
- NO_x reduction via substitution of main combustion zone coal input with oil or natural gas, thus reducing the total fuel nitrogen content to the furnace (oil and gas reburning tests only)
- NO_x destruction via the reburning process

The following results are based upon the overall NO_x reductions obtained.

Reburning Zone Stoichiometries. Figure 2-3 shows that NO_x emissions decreased with decreasing reburning zone stoichiometry for the three reburning fuels tested. Varying the amount of natural gas and oil reburning fuels from 16 to 28% of total heat input changed the reburning zone stoichiometry from 0.95 to 0.85, respectively. While increasing fuel to the reburn burners, air was increased to maintain very low stoichiometry at the reburn burners, air and fuel to the cyclones decreased to maintain constant cyclone stoichiometry and air to the OFA ports increased to meet overall air requirements (3.0% O_2 in the flue gas). To achieve the same reburning zone stoichiometry during coal reburning tests, 22 to 36% reburning coal had to be introduced to the furnace. Nitrogen-free natural gas provided the best NO_x reduction. NO_x concentrations ranged from 420 to 235 ppm while varying the reburning zone stoichiometry from 0.95 to 0.85 during gas reburning operation. From the baseline NO_x emission level of 925 ppm, these NO_x emission levels corresponded to a 55 to 75% reduction. During No. 6 fuel oil reburning tests, NO_x reductions of 42 to 73% were achieved at reburning zone stoichiometries of 0.95 to 0.85. Pulverized coal reburning reduced the NO_x levels 40 to 68% for the same range of reburning zone stoichiometry. For a 50% NO_x reduction from baseline conditions, 15% natural gas or 25% coal was required.

Flue Gas Recirculation (FGR). Figure 2-4 shows that NO_x emissions decreased with FGR rate to the reburning burners. In these tests, cyclone and reburning burner stoichiometries and fuel fractions were constant.

NO_X Levels with Reburning

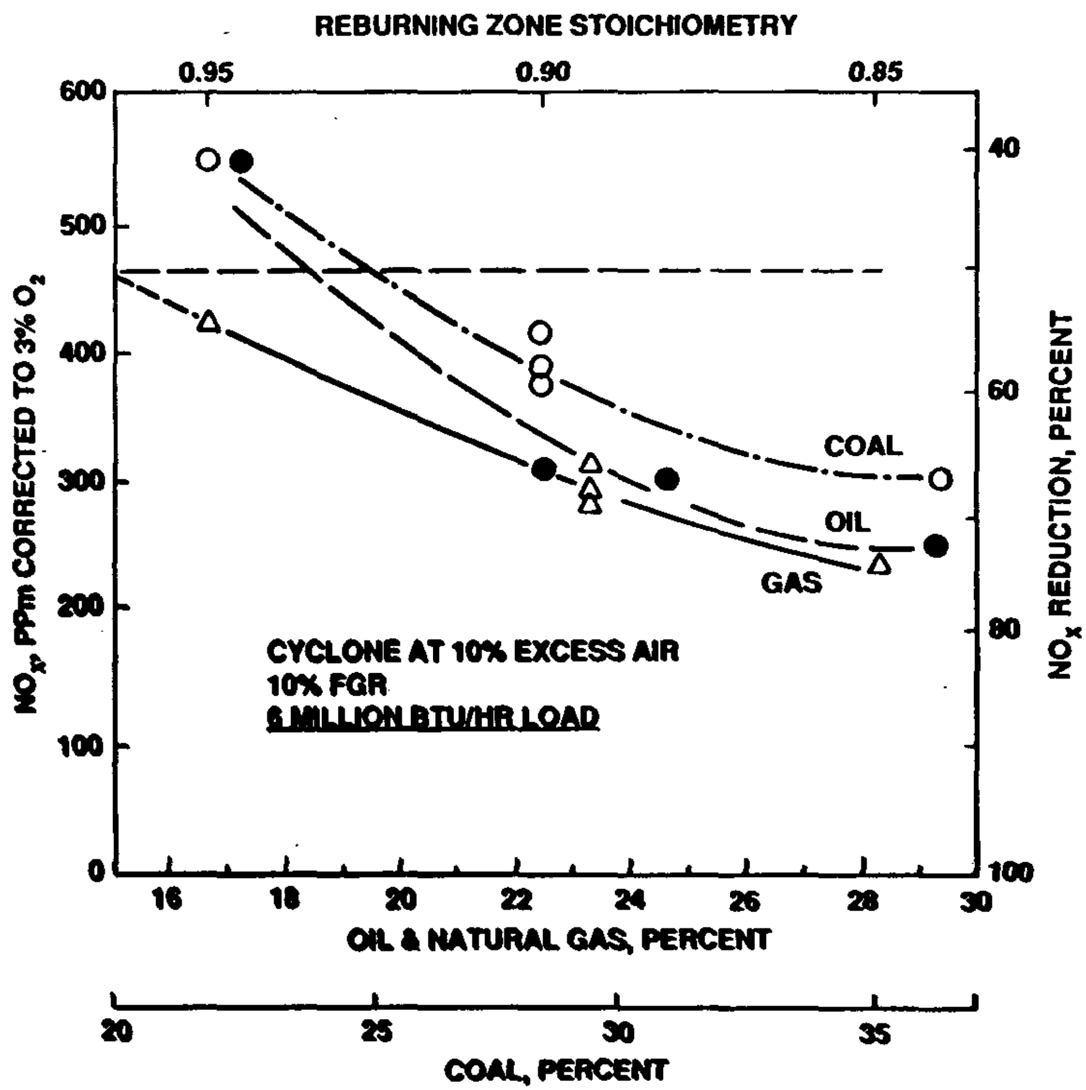


Figure 2-3 NO_X Emission Levels with Reburning

Reburning fuel fractions were 22% for natural gas or oil reburning and 28% for coal reburning. These reburning fuel fractions provided the reburning zone stoichiometry of 0.9. Addition of FGR helps to improve the mixing between furnace combustion gases and the reburning fuel. With coal reburning, NO_x emissions were more sensitive to FGR than natural gas and oil reburning. This could be due to the presence of coal nitrogen in the reburning coal. Without FGR, some NO_x is being formed through the volatile flame attached to the reburning burner. When FGR is added, in addition to improved mixing, NO_x formation by the volatile reburning flame may be reduced. Therefore, coal reburning is more sensitive to FGR flow rate. This hypothesis will be confirmed through future investigations.

Cyclone Burner Stoichiometry. The effects of varying the cyclone burner stoichiometry and percent reburning fuel were investigated; the results are plotted in Figure 2-5. Although B&W recommends that minimal cyclone operation changes be employed, various cyclone stoichiometries were tested during this project in order to complete the technology database. Figure 2-5 is based upon maintaining a constant reburning zone stoichiometry of 0.9. As the cyclone stoichiometries were varied between 1.0 to 1.2, the percentage of reburning fuel to the reburning burners (versus coal to the cyclone to keep a constant six million Btu/hr load) was changed accordingly to achieve the reburning zone stoichiometry of 0.9. The natural gas input varied between 13 to 31%. The figure shows that NO_x levels decreased from 420 to 260 ppm as the cyclone stoichiometry was increased from 1.0 to 1.2, respectively.

During coal reburning tests as the cyclone stoichiometry increased from 1 to 1.2, 17 to 37% coal had to be introduced to achieve the reburning zone stoichiometry of 0.9. The NO_x levels were almost insensitive to the cyclone stoichiometry. During pilot-scale coal reburning tests, the same coal was used at the cyclone and reburning burners, but with different grind size. Because the total heat input was constant at six million Btu/hr, the total fuel nitrogen input to the furnace was not changed at different cyclone stoichiometries. These results indicate that the reburning zone stoichiometry is the controlling parameter in NO_x reduction in the reburning zone.

In-furnace NO_x measurements were taken throughout the SBS (nine sampling ports are located on the side furnace wall) during both the baseline and reburning test phases. Baseline NO_x levels were uniform throughout the test facility, thus substantiating that all of the NO_x generation occurs within and/or immediately upon exiting the cyclone. Operating in the natural gas reburning mode (cyclone burner at 77% of load and 2% excess O_2; reburning

Effect of FGR on NO_X Levels

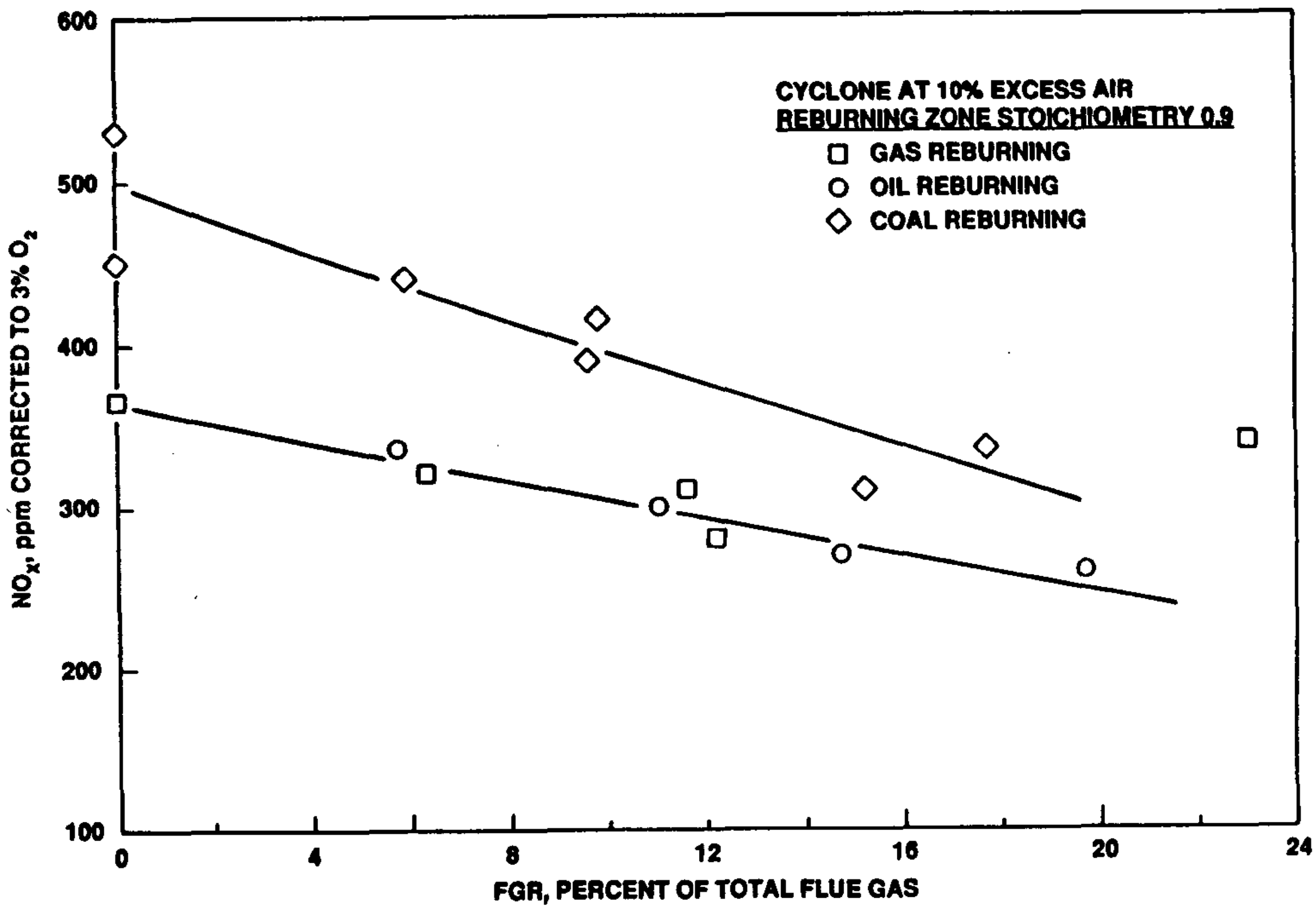


Figure 2-4 Effect of Flue Gas Recirculation (FGR) on NO_X Emission Levels

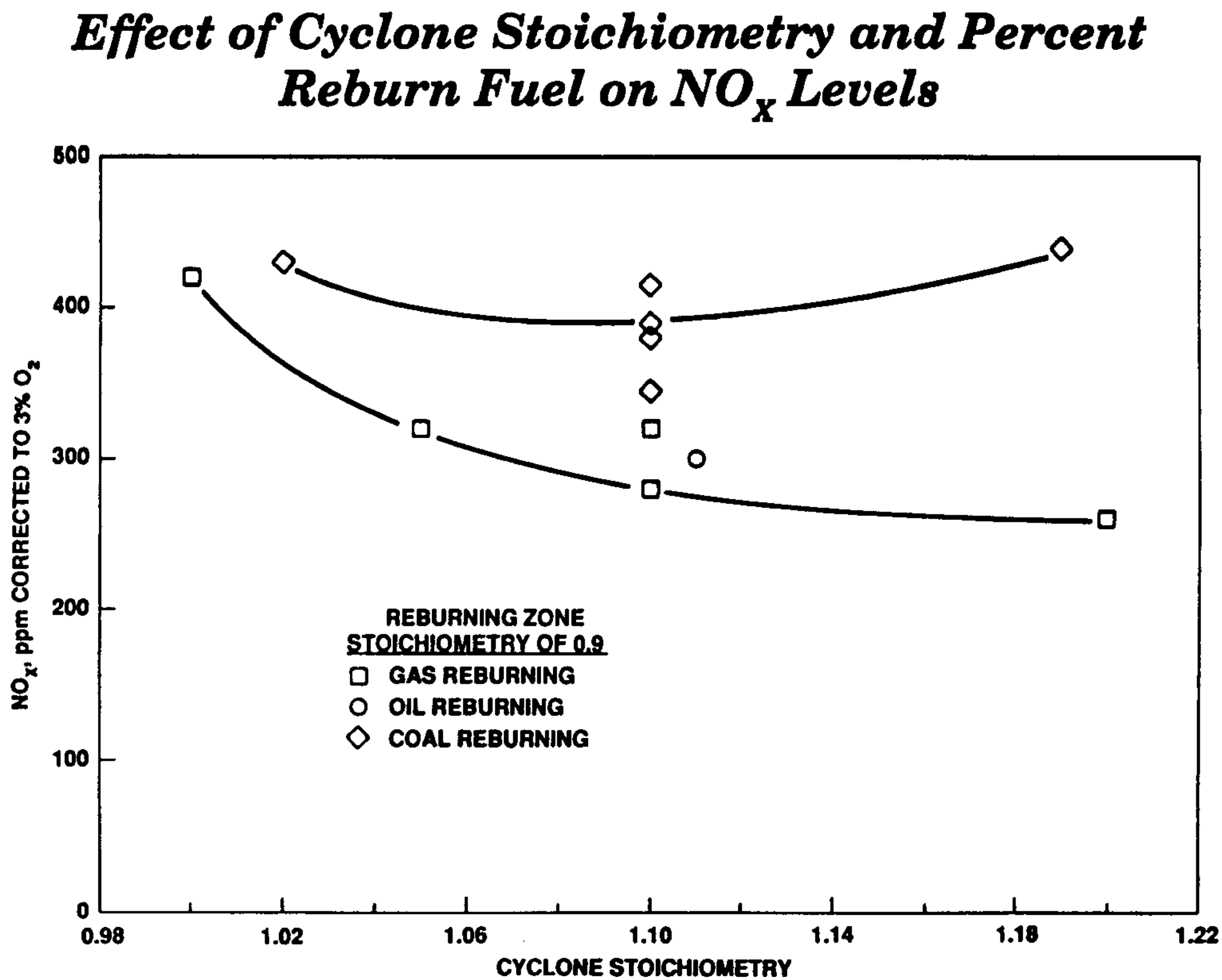


Figure 2-5 Effect of Cyclone Stoichiometry and Percent Reburning Fuel on NO_x Emission Levels

burners input at 23% of load), NO_x levels at an elevation between the cyclone exit and the burners were 900, 743, and 450 ppm at the right side, left side, and center of the furnace, respectively. While the right-side/left-side NO_x levels agree with the baseline results, the 450 ppm at the center port indicates that some of the reburning fuel is being recirculated below the reburning burners. During coal reburning (cyclone burner at 72% load and 2% O_2; reburning burners at 28% load), NO_x levels of 900, 860, and 830 ppm were measured and recirculation was not observed. Measuring the NO_x levels directly above the reburning burners showed that the majority of NO_x reduction had occurred. These results substantiate that good mixing between the reburning fuel and combustion gases existed.

Pilot Furnace Temperature Profile

SBS furnace temperatures were measured during both baseline and reburning phases. Figure 2-6 illustrates the resulting FEGTs under various operating conditions. The data indicate that while utilizing reburning, rear-wall OFA ports, a cyclone stoichiometry of 1.1, zero percent flue gas recirculation (FGR), and maintaining a constant six million Btu/hr furnace heat input, as approximate 50°F FEGT <u>increase</u> (from baseline) was observed. However, when 10% FGR was added to the reburning system, a temperature quenching phenomena occurred and a 50°F FEGT <u>decrease</u> (from baseline) resulted due to the quenching effect of FGR. A ±50°F variation in FEGT is considered to have a minimal (if any) impact on boiler performance.

The in-furnace probing showed no significant temperature variations between the baseline/reburning conditions, except that again a quenching effect occurred in the reburning zone when FGR was added.

Combustible Loss

Unburned carbon and CO emissions were measured at both the stack and throughout the furnace during the baseline and reburning phases. An inherent cyclone characteristic is that the majority of the combustion occurs within the cyclone itself. Because the cyclone will continue to be operated in an excess air mode, this combustion characteristic will not be altered. However, the amount of unburned char that does not burn within the cyclone will now enter a reducing environment in the reburning zone, with the remaining combustion air not to be introduced until the OFA ports. When coal and fuel oil are used for reburning, additional unburned carbon may result because the reburning fuels are introduced into the reducing environment of the reburning zone. Although they devolatilize and partially burn, final burnout will be

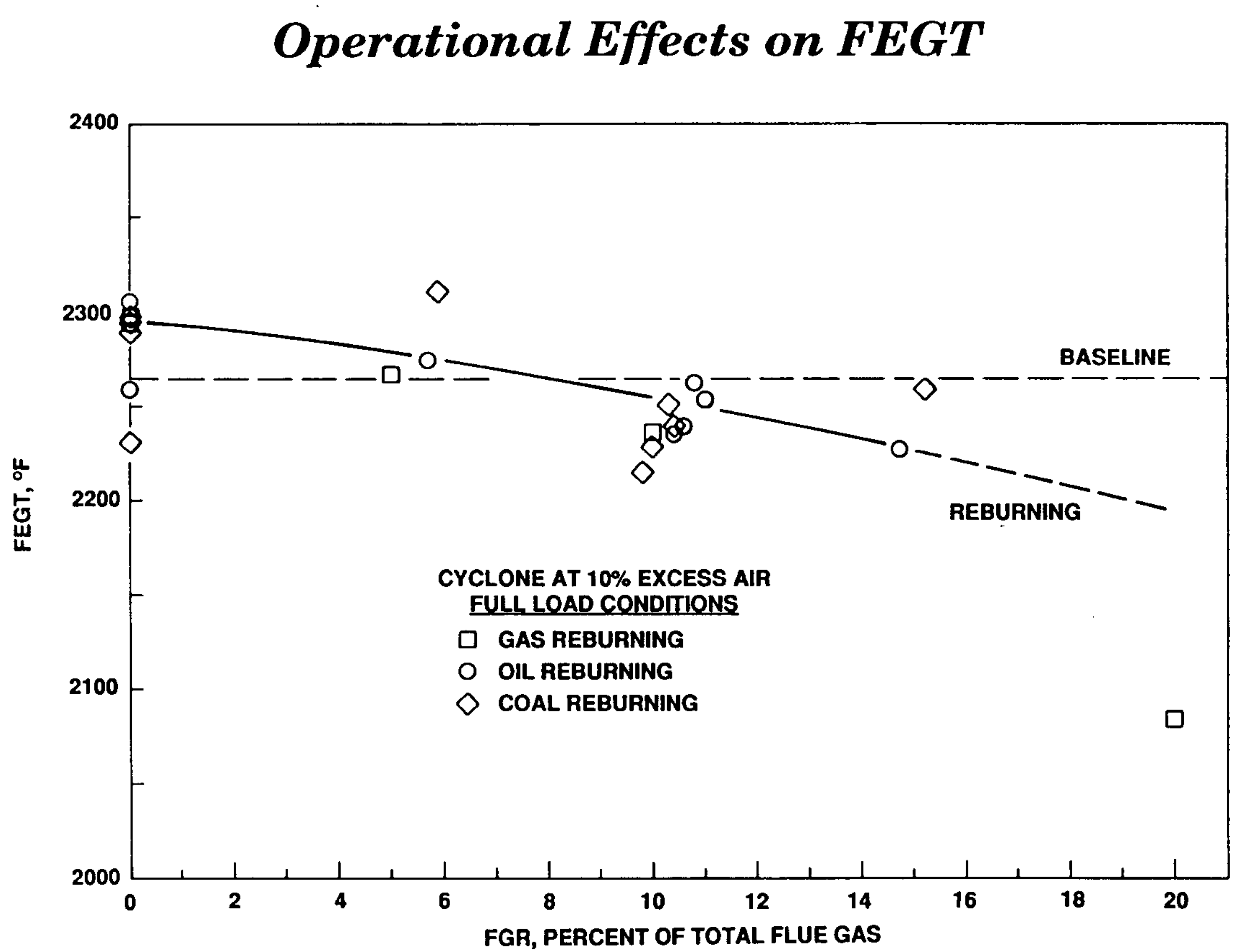


Figure 2-6 Operational Effects on Furnace Exit Gas Temperature (FEGT)

delayed until the burnout zone. If FGR is introduced, unburned combustible levels increase because the burnout zone residence time decreases due to increased mass loading through the furnace and the associated lower gas temperature profile within the reburn zone region. Efficient mixing of the air introduced through the OFA ports will help alleviate this concern and any potential CO emission problems.

Numerous measurements were taken to establish a database and to validate the trends of variation of unburned combustibles with different reburning zone parameters such as fuel split, FGR, and reburning fuel type. Table 2-5 illustrates the comparison of baseline and reburning tests at optimum conditions with and without FGR.

TABLE 2-5
COMPARISON OF COMBUSTION EFFICIENCIES

	Carbon, %	Ash, % in Convection Pass	Total Combustion Efficiency	Cyclone Fuel Burnout, %	Reburning Fuel Burnout, %
Baseline	0.3	18.2	99.99	99.99	N/A
Gas Reburn No FGR	2.3	14.2	99.96	99.95	100
Gas Reburn 10% FGR	4.5	14.2	99.92	99.90	100
Oil Reburn No FGR	3.0	14.2	99.95	99.95	99.95
Oil Reburn 10% FGR	5.4	14.2	99.91	99.90	99.93
Coal Reburn No FGR	1.6	32.7	99.94	99.95	99.91
Coal Reburn 10% FGR	3.4	32.7	99.87	99.90	99.79

Isokinetic samples of the fly ash were withdrawn from the stack of the SBS and analyzed for combustibles. In addition, total mass loadings of the fly ash were measured. Table 2-5 shows the carbon content of the fly ash and percentage of ash at the convection pass to the total ash input to the boiler at baseline conditions. During natural gas and oil reburning tests, the ash went down because these reburning fuels did not contain ash. On the other hand during coal reburning tests, ash loading almost doubled because ash from the reburning coal fraction was not removed as slag. Total combustion efficiencies were calculated from ash percent in the convection pass, carbon content of the fly ash, and coal analysis. The overall change of combustion efficiencies from the baseline condition is less than 0.1% for natural gas and oil reburning and 0.13% for coal reburning. This is a minimal impact and provides a strong justification that the unburned combustible potential associated with the reburning technology could be controlled to acceptable levels.

Further analyses were performed to calculate the individual combustion efficiencies of cyclone and reburning fuels. It was assumed that natural gas burns completely. Therefore, the cyclone fuel burnout was calculated from the total combustion efficiency and fuel split during natural gas reburning tests. Knowing the cyclone fuel burnout, then reburning fuel burnout could be calculated during oil reburning and coal reburning tests. The results indicate that up to 99.79% of the coal reburning fuel was burned.

CO levels were low (less than 30 ppm) at the stack during the baseline tests and there was no apparent increase when the reburning technology was applied. In-furnace probing at the reburning zone revealed areas of high CO (>1000 ppm) due to the sub-stoichiometric condition of this region. Upon introduction of OFA, the CO emissions were dramatically reduced - as stated above, less than 30 ppm CO was measured at the furnace exit. Thus, it is apparent that good mixing between the OFA and combustion gases existed.

Corrosion Potential

Because the reburning zone must be operated under substoichiometric conditions, corrosion potential within this region was investigated. By operating the cyclone in an excess air mode, the majority (if not all) of the sulfur from the coal in the main combustion zone is converted to SO_2. Due to the reducing atmosphere in the reburning zone, H_2S measurements were performed. High concentrations of H_2S can be conducive to increased rates of tube corrosion. H_2S concentrations at baseline and reburning conditions are illustrated in Table 2-6.

TABLE 2-6
REBURNING NO_X CONTROL FOR CYCLONE BOILERS
FIRESIDE CORROSION - H_2S CONCENTRATION
(ppm)

Measured	Baseline	Gas Reburn	Oil Reburn	Coal Reburn
Cyclone Outlet	0	---	---	98
Below Reburn	40-55	50	0	0-200
Reburn Zone	0-60	25-90	14-93	0-265

Multiple measurements were performed in the furnace, and results are presented in a range of H_2S concentrations. Up to 60 ppm of H_2S were measured at the SBS during baseline conditions. H_2S levels did increase up to 90 ppm during gas reburning where no additional sulfur was added with the reburning fuel. Fuel oil used for reburning contained 0.78% sulfur, and H_2S levels were compatible with those observed during gas reburning. When coal was utilized, however, up to 265 ppm of H_2S was measured. The impact of these levels of H_2S on tube wastage has yet to be determined. It is encouraging that only a small percentage of SO_2 from cyclone flue gases is converted to H_2S. In addition, when sulfur-bearing fuels were used for reburning, only a small fraction of the reburning fuel sulfur converted to H_2S. Up to 200 ppm of H_2S for oil reburning and 900 ppm of H_2S for coal reburning would be detected if all of the reburning fuel sulfur were converted to H_2S. Further evaluations will predict corrosion rates within the various furnace regions during reburn operation.

2.3.2.3 Full-Scale Utility Application Economics

An economic analysis was performed in order to estimate the total capital and levelized revenue requirements for retrofitting and operating a reburning system to reduce NO_x emissions from a base case 200 MW_e unit. Costs associated with this process included: acquisition and handling of the reburning fuels, installation and operation of the reburning system, and boiler impacts and counter-measures. Prime concern within this task was to evaluate the potential of this technology on a commercial scale based upon economics. There was a high priority placed on making cost comparisons between using various reburning fuels (gas, oil, or coal) in this process. The basis for the costs used in this evaluation were B&W cyclone reburning proposal cost estimates that have been prepared for numerous cyclone reburn proposed demonstration projects. These proposals have included use of each of the three reburn fuels.

The major equipment components used for each of the reburn fuels evaluated are as itemized below:

<u>Major Reburning Control System Components</u> --

<u>All Reburn Fuels</u>

- Reburn Burners
- Overfire Air (OFA) Ports
- Tube Wall Openings/Replacement Wall Panels
- Piping/Ductwork to Reburn Burners/OFA Ports
- Burner/Combustion Control System

- Cyclone Gravimetric Feeders
- Cyclone Secondary Air Monitors

<u>Coal Reburning</u>

- Pulverizer/Gravimetric Feeder
- Bucket Elevator
- Coal Silo
- Structural Steel/Pulverizer Enclosure
- Furnace Corrosion Protection

<u>Oil Reburning</u>

- Positive Displacement Pumps
- Oil Storage Tanks

<u>Gas Reburning</u>

- Assumed $3 Million Gas Pipeline *(if no pipeline* exists and a 10 mile long gas line is necessary)
- Gas Substation

The EPRI economic premises for electric power generating plants were used to develop the cost comparisons to address the above-stated objectives. Table 2-7 summarizes the economic evaluation per each reburning fuel type.

Capital costs and 10 year levelized busbar power costs were sensitive to reburn fuel type, fraction, and price. Approximately 70 to 90% of the associated 10 year levelized cost is attributable to the fuel cost. Variations in prices for gas, oil and coal in different demand regions will influence the economics of reburning with these alternative fuels. Price (1987 dollars), ranging from \$2.50 to \$3.50/10^6 Btu for gas \$3.00 to \$4.00/10^6 Btu for oil, and \$1.70/10^6 Btu for coal, were evaluated. Two gas availability scenarios were also considered - gas on-site and 10 mile tie-in to nearest pipeline at $300,000/mile.

The results presented in Table 2-7 give some indication of the variability in costs as key cost parameters are altered. For gas reburning, the installed capital costs range from $22/kW - if gas is available on-site - to about $44/kW - if the assumed $3 million gas-line cost is borne solely by the power plant. [Note: In many cases the gas supplier will extend gas service at no direct cost to the user, but will factor this cost into the contracted transportation charges (rate base). In this case, the capital cost would be the same as the gas on-site situation.]

TABLE 2-7 ECONOMIC EVALUATION FOR APPLYING REBURNING TO CYCLONE BOILERS*				
Reburning Fuel	**Fuel Cost ($/lb/10^6 Btu)**	**Main/Reburn Fuel Split**	**Total Estimated Capital Cost Required ($/kW)**	**10 Year Levelized Busbar Power Cost (mills/kWh)**
Gas	2.5	85/15	22	2.3
	3.5	85/15	22	4.1
	2.5	85/15	43**	3.1**
	3.5	85/15	44**	4.9**
Oil	3.0	81/19	28	3.3
	4.0	81/19	28	4.9
Coal (Same as Main Fuel)	1.7	75/25	41	1.7

* Based on 200 MW_e unit operating at 65% capacity with 50% reduction. Cyclone burner operates air-rich (1.1 stoichiometry) and reburn zone fuel-rich (0.93 to 0.97 stoichiometry).
** Assumes $3-million gas pipeline cost.

The 10 year levelized costs for 15% gas reburning were shown to increase from 2.3 mills/kWh at $2.50/10^6 Btu gas to 4.1 mills/kWh at $3.50/10^6 Btu gas. These prices translate into gas-oil price differentials of $0.80 and $1.80/10^6 Btu, respectively. The gas reburning busbar costs did not include any credits for reduced coal handling/inventory, ash disposal, or maintenance as a result of 15% gas substitution.

Oil reburning was projected to cost about $28/kW on the 200 MW_e plant with 10 year levelized costs ranging from 3.3 to 4.9 mills/kWh at assumed oil prices of $3.00/10^6 Btu and $4.00/10^6 Btu, respectively, and 19% oil firing.

Finally, capital costs for pulverized-coal reburning were estimated at $41/kW. Assuming the 25% reburn coal fraction is the same fuel as that currently fired in the cyclone burners, the 10 year incremental busbar cost was estimated at 1.7 mills/kWh.

These costs were based on information available at the time of the pilot-testing work. These are updated in Section 8.0 of this report to include knowledge gained in the full-scale demonstration.

2.3.2.4 Conclusions and Recommendations of the Pilot-Scale Work

A 40 to 75% overall NO_x emissions reduction is expected to be achievable in cyclone-equipped units via the reburning technology. This overall NO_x reduction is attributed to three different mechanisms: 1) NO_x destruction in the reducing environment of the reburning zone via reburning process, 2) during gas and oil reburning, secondary fuel input to the reburning zone contributes a small percentage of NO_x formation (little or no fuel-bound nitrogen in fuel), and 3) reduced load and oxygen level at the cyclone. Typical uncontrolled NO_x emission levels from cyclone units are 600 to 1400 ppm at 3% O_2.

For a 50% NO_x reduction, 15% natural gas or oil and 25% coal are required.

The lower in-furnace reburning zone stoichiometry (0.85 to 0.95 range) provided the best overall NO_x reduction.

FGR to the reburning burners improved mixing (turbulence) between the combustion gases and reburning gases, improving NO_x reduction. FGR was more effective during coal reburning than during natural gas or oil reburning. This tool could be beneficial in future applications.

CO emission levels were low (less than 30 ppm) throughout the various optimal test conditions and, thus, were of no concern during the reburning operation.

Total combustion efficiency decreased insignificantly, less than 0.1% for natural gas and oil reburning and 0.13% for coal reburning. This is a minimal impact.

Furnace exit gas temperatures (FEGTs) increased by less than 50°F during reburning operation.

The cyclone itself must be operated under excess air conditions in order to minimize corrosion potential within the cyclone barrel. Accurate air/fuel control is also essential to alleviate this potential concern.

H_2S concentrations in the reburning zone were 90 and 265 ppm for natural gas and coal reburning, respectively. Only a small portion of sulfur in the coal was converted to H_2S.

The nominal costs to apply reburning to a baseloaded 200 MW_e cyclone unit to achieve a 50% NO_x reduction with different reburning fuels are estimated, based on the pilot-scale work, as follows (total capital costs, 10-year busbar power cost):

- Gas (On-site or pipeline extension factored in rate base) - \$22/kW, 2.3 mils/kWh
- Oil - \$28 kW, 3.3 mils/kWh
- Coal - \$41/kW, 1.7 mils/kWh

The corresponding gas and oil fuel price differentials (compared to coal) used to determine these values are \$0.80 and \$1.30/lb/10^6 Btu, respectively. The coal reburn fuel was assumed to be the same as the main cyclone coal.

If the capital cost of a 10 mile tie-in to an existing pipeline is passed on directly to this plant, the capital and 10 year levelized power costs increase to about \$44/kW and 3.1 mils/kWh, respectively.

The reburning fuel choice has a major impact on the economics of this process. Site-specific consideration of the availability and price of alternative fuels, the availability of capital, and NO_x reduction target will influence the attractiveness of any one option.

The next logical step in development of reburn technology is a full-scale demonstration at a cyclone-fired utility boiler.

2.4 Host Site Characteristics

Both the feasibility study and pilot scale testing developed positive results regarding coal reburning technology. The next logical step in development was full-scale demonstration of coal reburning. The host site chosen under DOE's Clean Coal II Program was Wisconsin Power & Light's 100 MW_e Nelson Dewey Station Unit No. 2.

The following is a summary of pertinent information:

- UTILITY: Wisconsin Power & Light
- UNIT ID: Nelson Dewey Unit No. 2
- LOCATION: County Trunk VV, Cassville, Grant County, Wisconsin 53806
- NAME PLATE RATE: 100 MW_e
- TYPE: Steam Turbine
- PRIMARY FUEL: Bituminous Coal
- OPERATION DATE: October 1962 - Unit No. 2
- BOILER ID: B&W RB-369
- BOILER CAPACITY: Nominal 110 MW_e (Defined by WP&L operation)

- BOILER GENERAL CONDITION: Good
- BOILER MANUFACTURER: Babcock & Wilcox
- BOILER TYPE: Cyclone-Fired RB Boiler, Pressurized Unit
- REBURNING DEMONSTRATION FUEL: Indiana (Lamar) Bituminous Coal, Medium Sulfur
- BURNERS: Three B&W Vortex-Type Burners, Single wall-fired
- PARTICULATE CONTROL: Research Cottrell ESP
- BOILER AVAILABILITY: 75% Availability

Features of this host site offer additional benefits as a candidate for reburn technology demonstration:

(1) The unit is representative of the small and mid-sized cyclone boiler population (<300 MW_e) to which the technology would apply.

(2) Total costs for the modifications were expected to be lower than those of a large unit.

(3) Initial review of the unit showed adequate space to add the retrofit equipment.

(4) Furnace residence time as outlined in the feasibility study was adequate to support the requirements of coal reburning.

(5) The unit's primary fuel is bituminous coal.

Figure 2-7 is a sectional side view on Nelson Dewey Unit No. 2.

2.5 Project Organization

The Coal Reburning Project organization consists of the U.S. Department of Energy, The Babcock & Wilcox Company, Wisconsin Power & Light and the Electric Power Research Institute (EPRI). Team members from B&W represent the Research and Development Division (R&DD), the Fossil Power Division (FPD), the Energy Service Division (ESD) and the Contract Research Division (CRD).

Major subcontractors are Acurex Environmental Corporation and Sargent & Lundy Engineers. Acurex was designated to perform continuous emissions monitoring activities as well as various analytical requirements during the testing program. Sargent & Lundy performed balance of plant design activities pertaining to the system supplying coal to the pulverizer in addition to various structural steel and electrical design specification activities.

A summary of the overall project organization is as follows:

- Department of Energy - 46.5% funding co-sponsor
- Babcock & Wilcox - Prime contractor/project manager and funding co-sponsor
- Wisconsin Power & Light - Host site utility and funding co-sponsor
- EPRI - Technical advisor and funding co-sponsor
- State of Illinois (IDENR/ICCI) - Funding co-sponsor
- Acurex Corporation - Testing subcontractor
- Sargent & Lundy - Architect engineer subcontractor
- Utility funding co-sponsors

1. Allegheny Power System
2. Associated Electric Coop, Inc. (through the National Rural Electric Co-Op Association)
3. Atlantic Electric
4. Baltimore Gas & Electric
5. Basin Electric Power Coop
6. Iowa Public Service
7. Iowa Electric Light & Power Co.
8. Kansas City Power & Light
9. Kansas City Board of Public Utilities
10. Minnkota Power Coop, Inc.
11. Missouri Public Service
12. Montana-Dakota Utilities
13. Northern Indiana Public Service Co.
14. Tampa Electric Co.

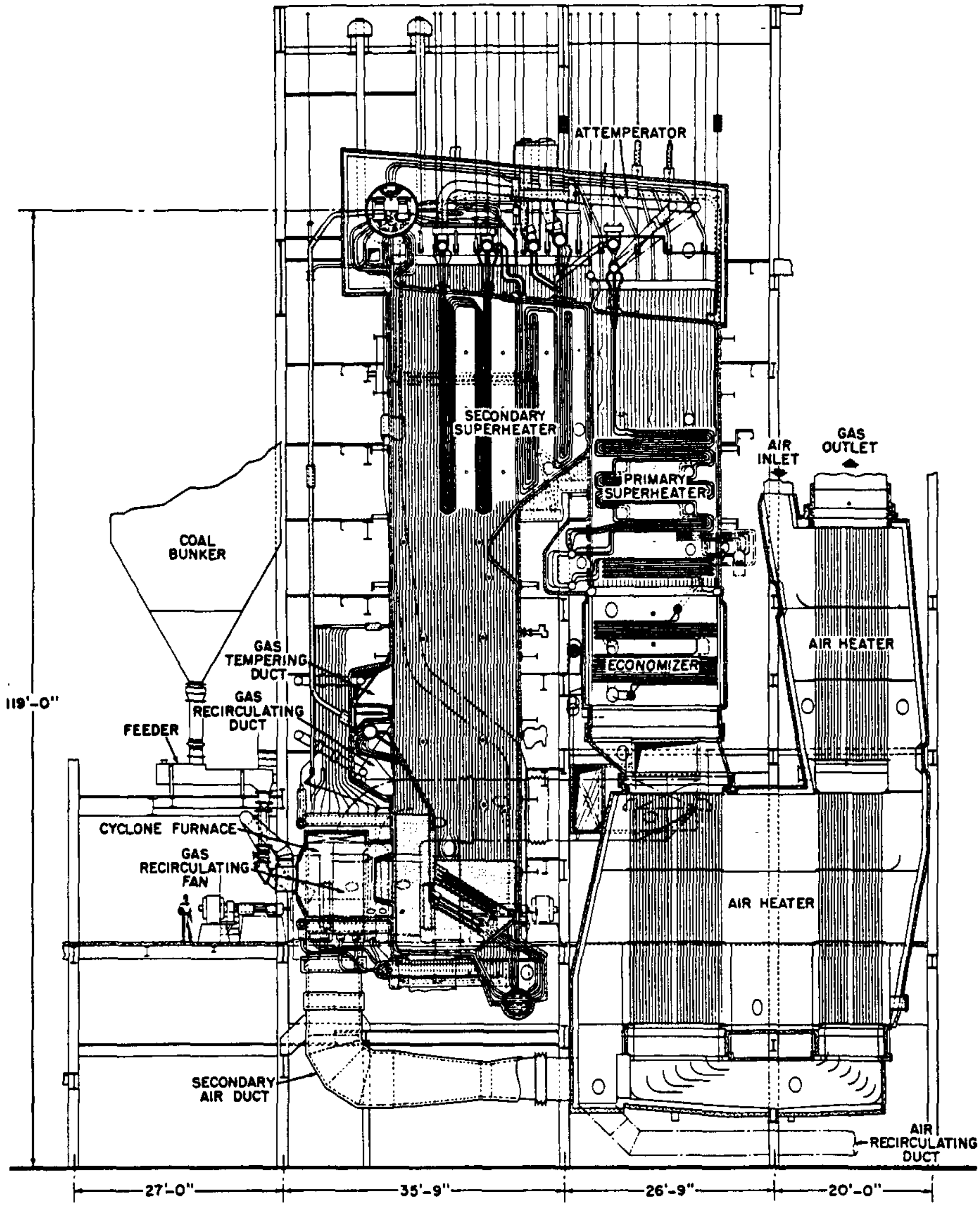
Figure 2-8 is an organizational chart for the project.

2.6 Project Phases and Schedule

Consistent with the DOE Clean Coal Program project organization, this project consisted of three phases: Phase I - Design & Permitting; Phase II - Procurement, Fabrication, Installation and Start-Up; and Phase III - Operation and Disposition. Phase II was divided to IIA and IIB to allow long-lead-time equipment to be ordered as part of budget period 1 (Phase I and IIA). Budget periods 2 and 3 consisted of Phase IIB and III respectively. Each Phase is outlined down to the task level in Appendix 2, Statement of Work.

Figure 2-9 presents the overall project schedule for the coal reburning project. Although the formal Cooperative Agreement with DOE was not executed until early 1990, Phase I activities such as modeling and pilot testing, as well as preparation for baseline testing at Nelson Dewey, were initiated in late 1989 as part of pre-award activities. This minimized schedule delays early in the project.

System design activities and Phase I in general were complete in early 1991 as was Phase IIA, Long-Lead-Time Item Procurement. As part of Phase IIA, the foundation at Nelson Dewey was installed to avoid spring thaw water problems. Phase IIB, Construction and



WISCONSIN POWER & LIGHT COMPANY
NELSON DEWEY STATION —UNIT NO. 2
CASSVILLE, WISCONSIN
B & W CONTRACT NO. RB-369

CY:RB-369-500

FIGURE 2-7 SECTIONAL SIDE VIEW

Start-Up was initiated in March 1991 with fabrication of the pulverizer and burners. General mechanical installation began as of June 1991 and was completed in early November 1991. Start-up activities were completed three months later in early February 1992.

Phase III, Operation and Disposition activities overlapped start-up by about one month and began in 1992 with parametric optimization testing. This testing was complete in May 1992 when long-term performance testing was started. As additions to the scope of the project, both Hazardous Air Pollutant (HAP) testing and performance testing on Western coal were performed. All testing was complete at Nelson Dewey by December 11, 1992. Title to the reburn system was transferred to WP&L in March 1993, completing disposition activities. The project completion date is October 1993 with approval of the final report for the project by DOE.

Project Organization

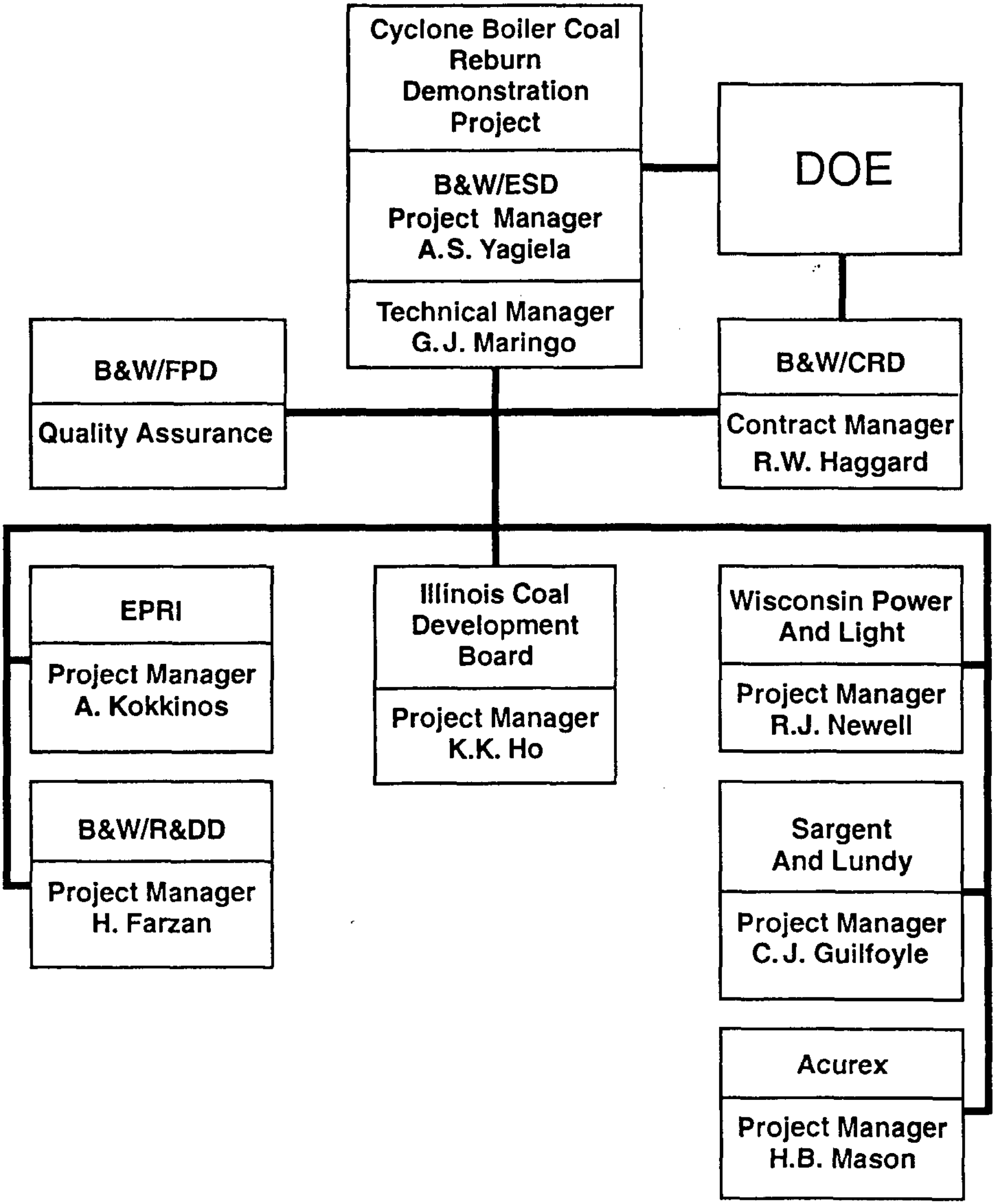


Figure 2.8

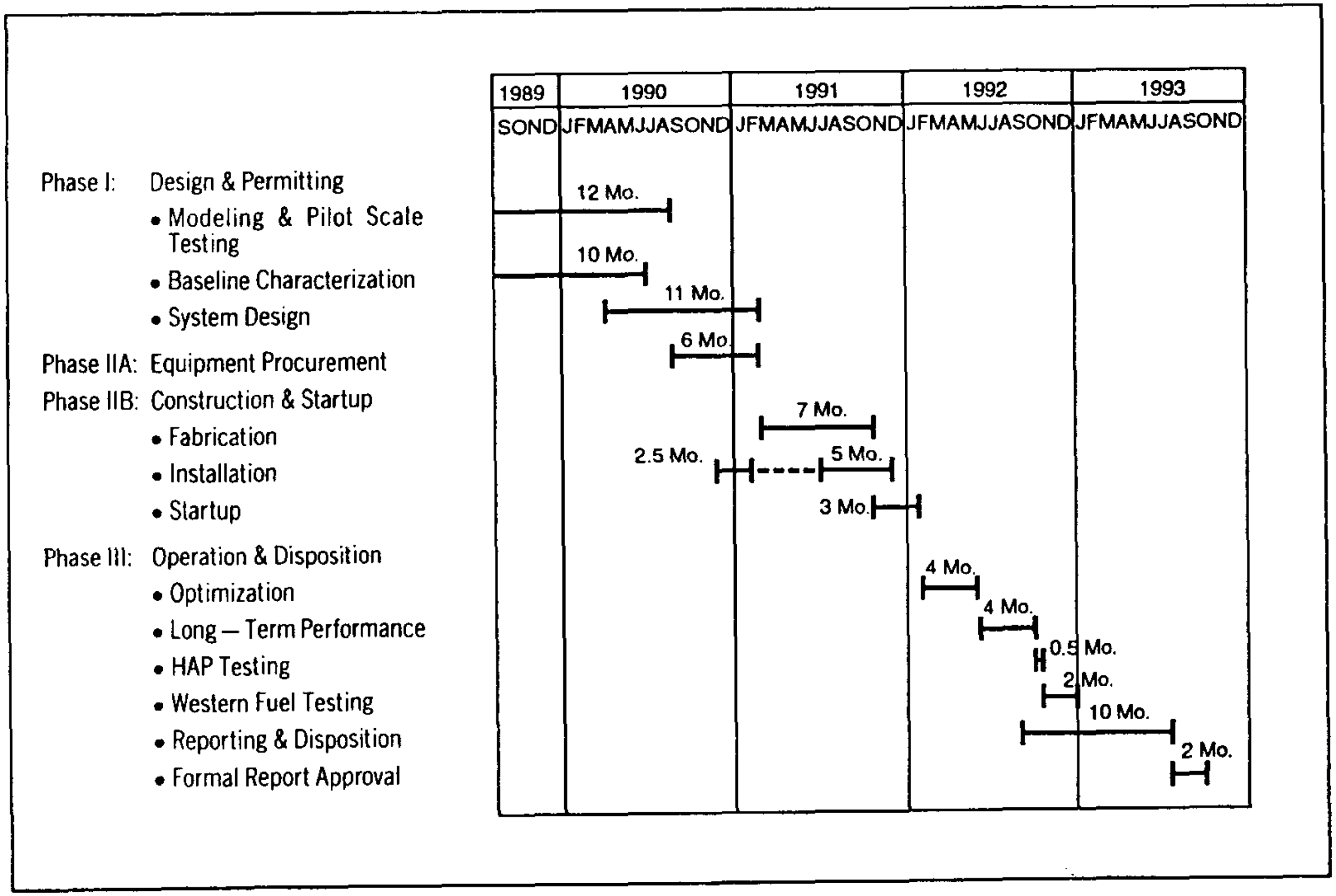


Figure 2.9 -- Coal reburning for cyclone boiler NO_x control project schedule.

3.0 Baseline Testing

Baseline tests were performed at Nelson Dewey Unit No. 2 prior to installation of the coal reburning system in order to provide the benchmark data to which subsequent reburning results were compared. The test sequence included collecting data at three load conditions--100%, 75%, and 50%--and at different excess air and flue gas recirculation levels. Thus, the baseline characterization not only identified normal or typical conditions for boiler operations/ performance, emissions characteristics, and electrostatic precipitator performance, but the test matrix was structured to identify changes in these parameters when excess air and flue gas recirculation rates were varied. This provided background data for coal reburning operation. For a detailed account of these baseline test results, refer to the Phase I - Baseline Test Report, DOE Agreement number DE-FC22-90PC89659.[9]

The bulk of testing was performed with Lamar coal, a medium sulfur bituminous coal, mined in Indiana. Table 3-1 provides an analysis of this coal. An additional series of baseline tests was performed with western fuel since this is WP&L's fuel of choice to meet SO_2 compliance requirements as of January 1, 1993. The western fuel analysis is also in Table 3-1. The baseline test matrix included Babcock & Wilcox collecting in-furnace gas velocity (under cold and hot conditions) and gas species (NO_x, CO, O_2, and H_2S) data within the furnace envelope. On-line boiler performance evaluations were also made in order to assess boiler efficiency and cleanliness. In addition, B&W set-up an economizer outlet gas grid to measure gaseous NO_x, O_2, CO, CO_2, and temperatures. The Acurex Corporation maintained a certified continuous emissions monitoring system (CEMS) at the precipitator (ESP) outlet measuring NO_x, O_2, CO, CO_2, and SO_x. Acurex also measured particulate loading/sizing at the ESP inlet/outlet, in-situ resistivity at the ESP inlet, trace metals, volatile/non-volatile organics at the precipitator outlet, unburned carbon, and ash toxicity.

The data were collected while operating at 100%, 75%, and 50% load conditions which corresponded to approximately 110 MW_e, 82 MW_e and 55 MW_e respectively. Original boiler design full load is 100 MW_e (700,000 #/hr steam flow), but based upon the past 20 plus years of operating experience, full load rating has been redefined as 110 MW_e (780,000 #/hr steam flow) within WP&L's system. No major operational problems are encountered by WP&L at this load.

In-furnace flue gas flow velocity measurements during cold and hot boiler conditions were performed to provide qualitative information to confirm the physical and numerical modeling predictions. Higher positive gas velocity along the boiler rear wall and low and/or negative flow (recirculation) near the boiler target wall was observed (as measured at boiler elevation 666', near the planned furnace reburn burner elevation of 664'6").

TABLE 3-1 TEST COAL ANALYSIS		
	Lamar Coal	**Western Coal**
HHV	11,326 Btu/lb	9,189 Btu/lb
C	63.64%	53.04%
H	4.35%	3.71%
S	1.15%	0.27%
O	7.92%	13.07%
N	1.24%	0.55%
H_2O	16.74%	25.85%
Ash	4.96%	3.51%

A total of 51 tests were performed to evaluate baseline boiler performance. Seventeen of these tests involved an independent testing company, the Acurex Corporation, to obtain numerous baseline emission levels.

3.1 NO_x and Percent Loss on Ignition (Unburned Carbon) Emission Levels

Figures 3-1 and 3-2 show the full load (110 MW_e) baseline stack NO_x emission levels (ppm, corrected to 3% O_2 for comparative consistency) and percent loss on ignition (LOI), respectively, as measured by Acurex versus various excess oxygen contents as measured at the economizer. All future NO_x emission values reported in ppm will be corrected to 3% O_2. Figure 3-1 reveals NO_x levels ranging from approximately 640 ppm to 700 ppm when economizer outlet O_2% was varied between about 2 and 4%, respectively. Since operating at 3% economizer outlet O_2 is considered typical, the normal baseline NO_x level is 661 ppm (0.90 million Btu). For the Western coal testing, the baseline NO_x level is 584 ppm (.79 million Btu). Figure 3-2 shows percent LOI varied from approximately 18% down to 9% while increasing excess O_2% from 2 to 4%, respectively for the Lamar coal.

Additionally, Figures 3-3 and 3-4 show the relationship between NO_x and percent LOI versus boiler load (MW_e) during typical boiler operation (3% economizer outlet O_2) with Lamar coal. As shown in Figure 3-3, varying the load from 55 MW_e to 110 MW_e resulted in NO_x levels of approximately 550 ppm to 661 ppm, respectively. Figure 3-4 reveals that percent LOI remained fairly constant over the load range (approximately 16 to 17% LOI).

NO_x was measured by Acurex at the point in the precipitator outlet duct which indicated the highest level of pollutant, as determined by point to point traversing. This is the accepted EPA method for continuous emissions monitoring. B&W's NO_x readings were obtained

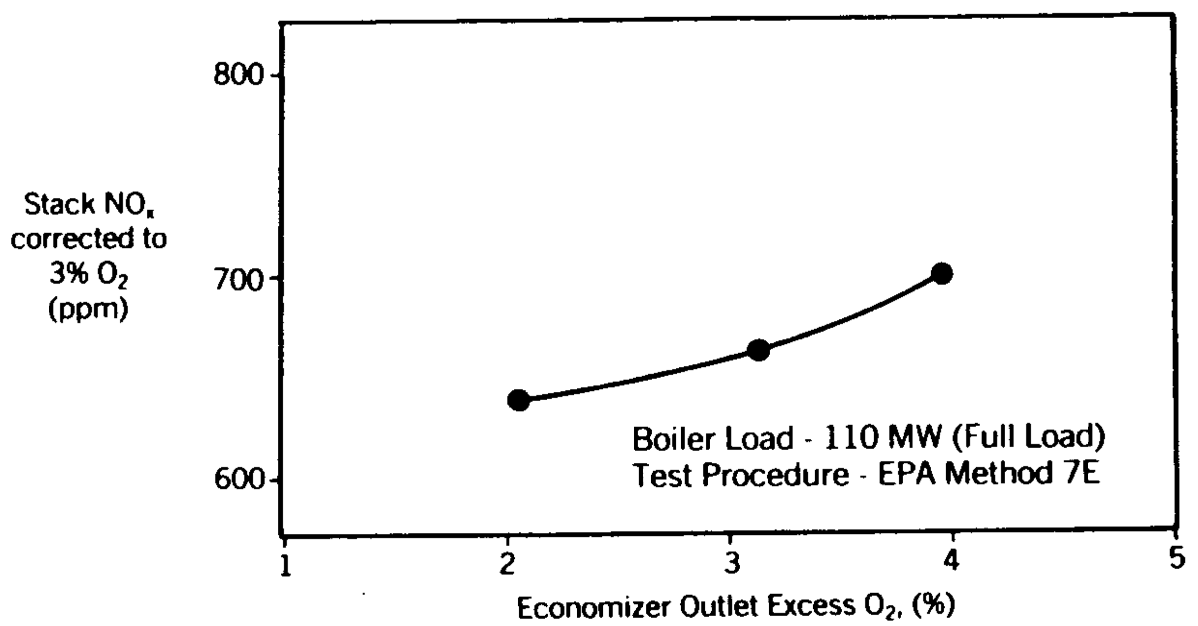


Figure 3.1 – Baseline NO_x emission levels vs. load. Nelson Dewey - Unit 2.

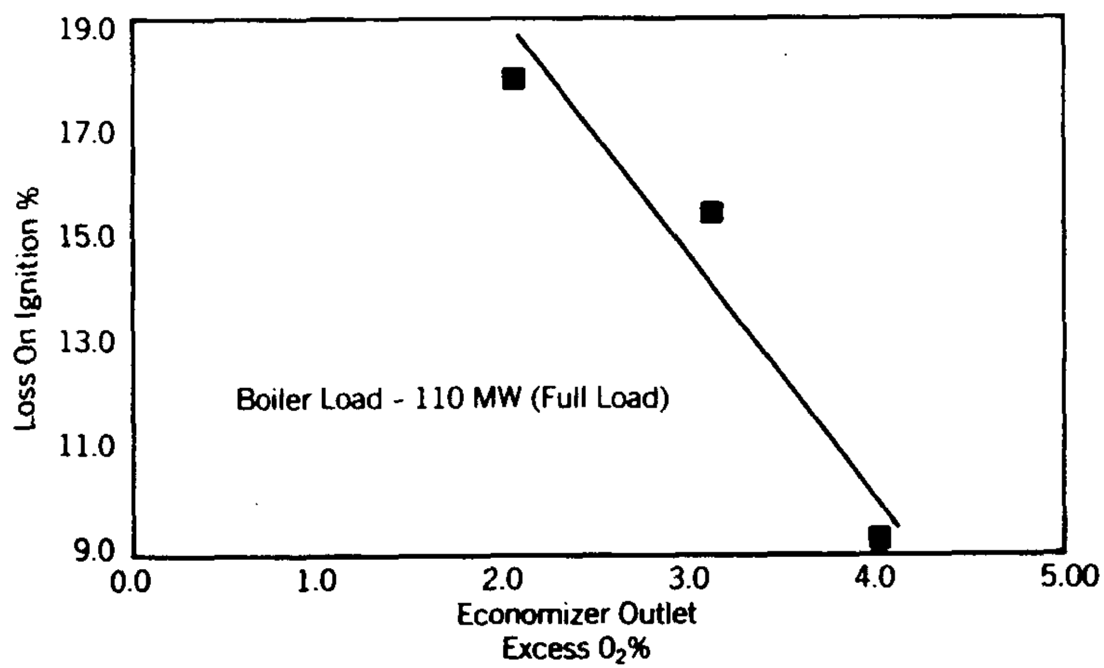


Figure 3.2 -- Baseline % LOI emissions levels vs. excess O_2%. Nelson Dewey - Unit 2.

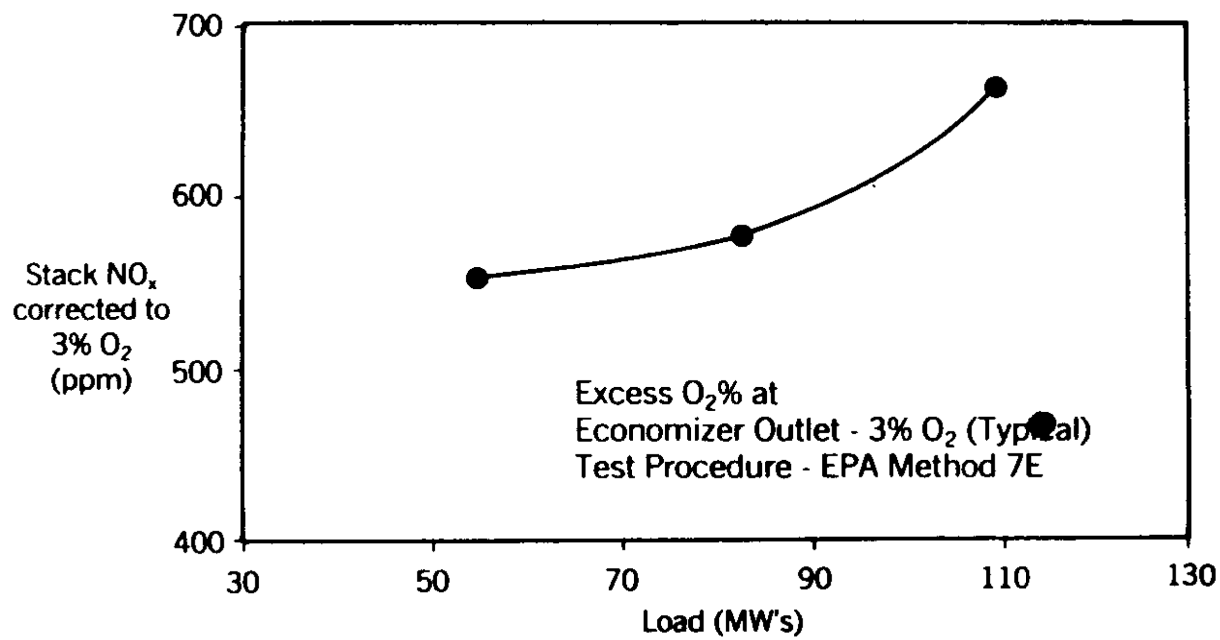


Figure 3. 3 **-- Baseline NO_x emission levels vs. excess O_2. Nelson Dewey - Unit 2.**

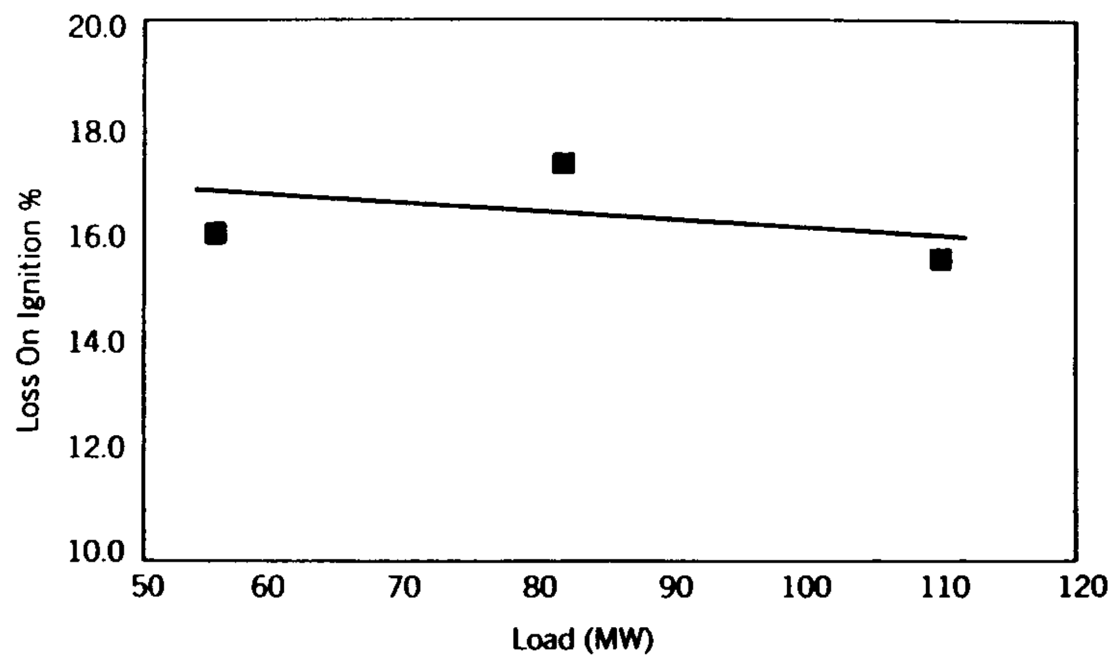


Figure 3.4 – Baseline % LOI emission levels vs. load. Nelson Dewey - Unit 2.

from a composite grid at the economizer gas outlet. The B&W values are consistently lower than the Acurex values, which would be expected when comparing an average value to a maximum value.

A summary of the comparison between the Acurex and B&W averaged test data results for the normal excess air/various load operating conditions during the Lamar coal firing are as follows:

Load	**Acurex NO_x Levels (ppm @ 3% O_2)**	**B&W NO_x Levels (ppm @ 3% O_2)**	**Delta NO_x (%)**
110	661	609	7.9
82	585	531	9.2
55	553	506	8.5

Thus, a consistent approximate 8-9% deviation over the load range is observed.

3.2 Particulate Emissions

The Acurex precipitator performance test data taken during Lamar coal firing showed particulate capture efficiencies ranging over a broad spectrum. Average precipitator performance under full load/normal excess air conditions is 93% collection efficiency. Tests at 82 MW_e and 55 MW_e showed averaged efficiencies of 88% and 93% respectively.

Full load precipitator inlet particulate loadings are questioned due to the magnitude of the results and these were equal to approximately 8-10% of the total available ash loading. Cyclone boilers of this vintage typically emit about 15-20% of the total ash to the boiler proper (thus, typically 80-85% ash capture within the slag). Due to the lower than anticipated precipitator inlet levels measured during the baseline tests, these tests were duplicated after the reburn system retrofit to confirm the baseline particulate levels. This is discussed in Section 7.3.2 Boiler Performance Results.

Baseline fly ash resistivity measurements during full load normal excess air/Lamar coal firing conditions ranged between 5.3 to 6.2 x 10^{10} OHM-CM. These levels correspond closely with the measured resistivities obtained during the SBS pilot-scale testing.

Plots of the Voltage versus Current relationships for the four transformer/rectifier (T/R) sets of Unit No. 2 precipitator during baseline testing were developed along with the theoretical curves. Only the inlet field of the precipitator agreed reasonably well with what is theoretically expected. The shapes of the curves indicated a high ash resistivity (5 x 10^{11} OHM-CM to 1 x 10^{12} OHM-CM). Predicted resistivity based on ash chemistry was on the order of 4 x 10^9 OHM-CM at the precipitator's operating temperature of approximately 500°F. The curves also indicated the possibility of excessively thick dust deposits on the discharge electrodes/collecting plates associated with two of the T/R sets.

Plant personnel indicated that a degradation in precipitator performance with time was noticed when switching to the Indiana Lamar coal. Many "hot-side" precipitators experience a similar degradation when burning coals having low sodium and/or high calcium content ashes which usually have moderate inherent resistivities (5 x 10^9 to 1 x 10^{10} OHM-CM). With time, the ash layer adjacent to the collecting plates experiences depletion of sodium ions (the primary current carrier) and the resistivity of the layer rises. If this layer is not removed by rapping, a degradation in performance could occur. Sodium depletion could be a problem with the Lamar coal (ash sodium = 0.5%, calcium = 8.5%).

3.3 In-Furnace Probing

B&W performed in-furnace probing at 4 different furnace elevations: 1. cyclone exit (elevation 658'), 2. reburn burner region (elevation 666'), 3. reburn zone area (elevation 676'), and 4. furnace exit (elevation 700'). See Figure 6-3, boiler sectional side view, for a relative indication of the elevations probed. Furnace velocity traverses and species/temperature measurements were carried out at various elevations. This information provided a qualitative verification of the numerical and physical flow model results.

Furnace Gas Velocity Traverse. Furnace gas velocity profiles were obtained at the approximate anticipated reburn burner elevation during cold and hot conditions. This information aided in determining the design of the reburn system. Cold flow data was collected utilizing a 4 wide anemometer grid system when operating FD fans only. These data were collected at Nelson Dewey #2 boiler elevation 666'. The cold flow test results at Nelson Dewey showed higher gas velocities along the rear wall and low and/or negative flow near the target wall (opposite the rear wall). Highest flows were indicated on the boiler right-hand side. The cold air velocity data were utilized to help verify the numerical and physical model results of Nelson Dewey #2.

After the cold air tests, furnace gas velocities at the same elevation were measured during hot conditions while firing oil in the cyclone burners to approximately 50 MW_e. The B&W water-cooled Fecheimer probe was utilized to obtain gas velocity data at the boiler elevation of 666'. The highest gas velocities were located near the boiler rear wall, about 90-95 ft/sec. Near the boiler centerline at the same elevation, velocities of 25-35 ft/sec were recorded. The hot flow data also indicated higher gas velocities on the boiler right hand side in agreement with the cold flow data.

Furnace Gas Species/Temperature Probing. In-furnace temperature/gas species were measured at three (3) furnace elevations utilizing water-cooled HVT probes. It should be noted that in-furnace probing (especially in the lower furnace region) is a difficult task due to the high temperature, turbulent and ash/slag rich conditions, conducive to probe plugging problems. Duplicate measurements were performed to verify the accuracy of these data at each of the various baseline combustion test conditions. The following summarizes the measurement locations/data collected:

- Reburn burner region (elevation 666') - Measure temperatures, O_2 (%), CO (ppm) at 41 locations.
- Reburn zone region (elevation 676') - Measure temperatures, NO_x (ppm), O_2 (%), CO (ppm) at 18 locations.
- Furnace exit (elevation 700') - Measure temperatures, O_2 (%), CO (ppm) at 26 locations.

In addition to the above measurements, in-furnace baseline H_2S levels were determined at the cyclone exit and at the reburn region furnace walls utilizing special water-cooled probes. The results of in-furnace data measurements are summarized in the Baseline Test Report[9] issued to DOE/PETC.

3.4 Boiler Performance

Unit performance was evaluated by B&W using Combustion and Unit Efficiency Program P-8475 and Heat Transfer Program P-140. The fifty-one (51) tests comprising the baseline test program were performed to establish operating characteristics. The critical parameters in evaluating the impact of the cyclone reburn system are superheat and reheat final steam temperatures, superheat and reheat spray flow quantities, furnace exit gas temperature (FEGT), surface cleanliness factors (Kf's), efficiency and unburned carbon. A more detailed description of the elevation tools used and the results obtained can be found in the Baseline Test Report[9].

3.4.1 Superheat/Reheat Steam Temperatures/Spray Flows

Final Superheat and Reheat Steam Temperature. For all tests performed at 70 MW_e's and above, the unit was capable of maintaining superheat and reheat steam temperature at 1005°F ± 5° by use of superheat and reheat attemperator sprays and flue gas biasing. At full load conditions, it is normal plant operating practice to bias more flue gas than is necessary to the reheat pass and allow some reheat spray in order to reduce the quantity of superheat spray. This prevents the superheat spray valves from being wide open, giving the operators control flexibility.

For the 50 MW_e tests, the unit was capable of operating in excess of the design superheat and reheat temperatures of 950°F. Superheat temperatures during these tests ranged from 975 - 992°F while reheat temperatures ranged from 950 - 983°F.

Superheat and Reheat Attemperator Spray Flow. For the normal economizer outlet O_2% full load operating conditions, the superheater spray was consistently around 50,000 lbs/hr, with reheat spray varying from 15,000 lbs/hr to 26,000 lbs/hr, depending upon the cleanliness of the various components. The maximum spray capabilities are 63,000 lbs/hr superheat spray and 26,000 lbs/hr reheat spray. For the high excess air tests at full load, both the superheat and reheat sprays were at maximum, while steam temperatures were near 1000°F. For the western coal firing tests at full load and normal excess air, both the superheat and reheat sprays were at maximum capacity with final steam temperatures of 999°F superheat and 1001°F reheat. Anticipating a potential increase in FEGT during coal reburning operation, made it necessary to consider upgrading the spray capacities of the unit.

3.4.2 Furnace Exit Gas Temperature

Under full load conditions, the furnace exit gas temperature averaged 2125°F with variations from 2065 to 2180°F depending on the cleanliness of the furnace and the level of excess air.

For the 110 MW_e tests, the FEGT averaged 2082°F with variations from 2060 to 2127°F. For the 82 MW_e tests, the FEGT averaged 1932°F with variations from 1910 to 1953°F. The 55 MW_e tests averaged 1640°F with variations from 1620 to 1680°F. There were five (5) tests during which HVT traverses of the furnace exit (El. 700) were conducted. Table 3-2 is a summary of the measured gas temperature versus the calculated gas temperature for these tests. The largest discrepancy between measured and calculated temperatures was 120°F during Test #7. The calculated gas temperature is an average gas temperature at the furnace exit plane, while the HVT traverses cover a finite number of points at a location slightly different than the vertical plane defined as the furnace exit. The scatter in the measured gas temperature versus the calculated gas temperatures (approximately 6%) is not excessive, and the calculated FEGT's are considered as the more representative value for the purpose of this evaluation.

TABLE 3-2 - HVT TEMPERATURE COMPARISON

Test No.	Load MW_e	Excess Air %	Measured FEGT (HVT)	Calculated FEGT (HVT)	Difference
1	111	24.3	2110	2110	0
4-2	111	12.2	2145	2115	30
7	111	17.2	2225	2105	120
10	81	16.7	1995	1915	80
13	53	15.9	1605	1680	-75

3.4.3 Surface Cleanliness

Utilizing the on-line boiler performance heat transfer models, the boiler heat transfer surface's cleanliness factors (Kf's) were determined. The component cleanliness factors varied significantly during the testing due to variations in sootblowing throughout the test program. Table 3-3 summarizes the average component cleanliness factors for both the Lamar and western coals and their variations for all of the full load tests.

TABLE 3-3 - AVERAGE CLEANLINESS FACTORS

Component	Lamar Coal			Western Coal		
	Avg Kf	Max Kf	Min Kf	Avg Kf	Max Kf	Min Kf
Sec SH In	0.94	1.07	0.82	0.86	0.90	0.80
Sec SH Out	0.85	0.94	0.75	0.78	0.80	0.77
Reheater	1.00	1.21	0.87	1.02	1.12	0.97
Pri SH	0.90	1.06	0.78	0.93	0.95	0.87
Economizer	0.81	0.90	0.72	0.75	0.79	0.72

All of the KF's stabilized within 5 hours of sootblowing in a given component. The cleanliness decay rates for each component are as follows:

Secondary SH Inlet Bank - The cleanliness factor decreased by 20% over a four hour period, with most of the decrease occurring in the first two hours.

Secondary SH Outlet Bank - The cleanliness factor decreased by 23% over a four hour period.

Primary Superheater - The cleanliness factor decreased by 20% over a five hour period.

Economizer - The cleanliness factor decreased by 12% over a five hour period.

The FEGT is the primary indicator of furnace cleanliness. During the baseline tests the FEGT would increase by 50°F within two hours of blowing the furnace IR sootblowers. After this initial increase, FEGT leveled off, indicating that the furnace cleanliness had stabilized. Any fluctuations in FEGT during the tests are a function of excess air and how quickly the tests were started after blowing the furnace blowers.

One of the constraints of the testing program was that no sootblowing could take place during the in-furnace probing. This severely limited the ability to blow sootblowers, since the daily afternoon testing involved furnace traversing. The unit demonstrated the ability to operate for prolonged periods of time (as much as sixteen hours) without blowing sootblowers in the convection pass. IR furnace blowers and the IK blowers at the leading edge of the secondary superheater were usually operated once or twice a day in between traverses.

As noted above, after five hours the component Kf's would stabilize and remain constant for the remainder of the test period.

3.4.4 Efficiency Calculations

The complete set of efficiency calculations were performed for all the 51 tests performed during baseline testing. These can be found in the Baseline Test Report[9]. The efficiencies were corrected for air heater performance and non-design fuel, air inlet temperature, and excess air. These corrections essentially normalize the results for direct comparison of the impact of the reburn system on unit efficiency. For the full load tests conducted burning Lamar coal, the average corrected efficiency was 88.16% with a maximum efficiency of 88.47% and a minimum efficiency of 87.46%. For the full loads tests burning western coal, the average corrected efficiency was 87.80% with a maximum efficiency of 87.94% and a minimum efficiency of 87.73%.

3.4.5 Unburned Combustible Losses

Unburned Carbon. The Acurex Corporation was responsible for obtaining the fly ash samples and analyzing them for carbon content. Carbon in the fly ash was measured for all tests that involved emissions testing by Acurex. Carbon in the cyclone slag was not measured during this test program. For this evaluation, the assumption was made that the carbon in the cyclone slag was equal to ten (10) percent of the carbon in the fly ash. The percent ash split between cyclone bottom ash and fly ash was obtained by calculating the amount of ash entering the precipitator. The calculations were based on the measured dust loading from Acurex and the calculated gas weights from the performance monitoring program.

For the Lamar coal tests, the maximum unburned carbon was .46 lb C/100 lb coal at 50% load, normal excess air and the minimum unburned carbon was .11 lb C/100 lb coal for full load, high excess air operation.

Carbon Monoxide. CO (ppm) levels were measured via the B&W gas grid system located at the economizer outlet. Throughout the test period there was a side to side imbalance in CO, with the right side of the unit showing consistently higher levels of

CO. The average CO (ppm) level during the Acurex test series for the full load typical excess air tests burning Lamar coal was 105 ppm. The left/right side averages during these tests were 66/143 ppm respectively. These levels were obtained following balancing air flows to each cyclone. A slightly higher O_2% is also associated with the higher CO (ppm) side which is inconsistent with normal combustion practices. The average CO for the tests conducted burning western coal was 166 ppm. The maximum averaged CO reading obtained throughout the testing was 570 ppm for Test 26. This test was part of the gas recirculation evaluation at full load, and is not representative of normal unit operation. For the full load tests without gas recirculation, the maximum CO reading was 340 ppm for Test 2.

4.0 Pilot-Scale Study

As a part of this project, B&W's 6 million Btu/hr Small Boiler Simulator (SBS) pilot-scale facility was used to duplicate the operating practices of the Nelson Dewey Unit No. 2. The coal that was fired at Nelson Dewey for the demonstration was fired in the SBS cyclone and also was utilized as the reburn fuel. The purpose of this pilot-scale study was to examine the effectiveness of reburning for NO_x reduction and to assess the potential side effects. In addition, the potential of a high-sulfur Illinois coal for cyclone reburning application was evaluated.

The Lamar demonstration test coal is a medium sulfur content fuel and not representative of sulfur levels in coals typically used by cyclone operators in the mid-west. Because of strict SO_2 regulations in Wisconsin, a higher sulfur test coal was not practical at Nelson Dewey. A variance to allow high sulfur coal testing was not possible particularly because emissions concentrate in the river valley which the plant and Cassville occupy.

High sulfur Illinois (Peabody) coal is more representative of mid-western cyclone boiler fuels. This fuel was tested in the SBS to correlate results with the Lamar coal and a western Powder River Basin (PRB) coal which were both tested at Nelson Dewey Unit No. 2. The objective was to predict expected full-scale reburn results using the Peabody coal. Of particular interest was to determine if unacceptable H_2S levels would be generated with high sulfur fuel in the reburning zone.

Supportive numerical modeling was used to assess the mixing performance in the SBS. The numerical flow predictions quantify the SBS reburning mixing performance. Based on pilot-scale and numerical modeling a methodology was developed for scale-up to the 110 MW_e Nelson Dewey Unit #2.

4.1 Experimental Facility

B&W's 6 million Btu/hr small boiler simulator (SBS) was utilized to perform the pilot-scale study (Figure 4-1). This facility is described in detail in Appendix 1. A short description of the facility pertinent to scale-up is presented here.

The SBS is fired by a single, scaled-down version of B&W's cyclone furnace. Coarse pulverized coal (44% through 200 mesh), carried by primary air, enters tangentially into the burner. Pulverized coal had to be utilized in the SBS instead of crushed coal to obtain complete combustion in this small cyclone. Preheated combustion (secondary) air at 600° to 800°F enters tangentially into the cyclone furnace.

The water-cooled furnace simulates the geometry of B&W's single-cyclone, front-wall fired cyclone boilers. The inside surface of the furnace is insulated to yield a furnace exit gas temperature (FEGT) of 2200-2300°F at the design heat input rate of

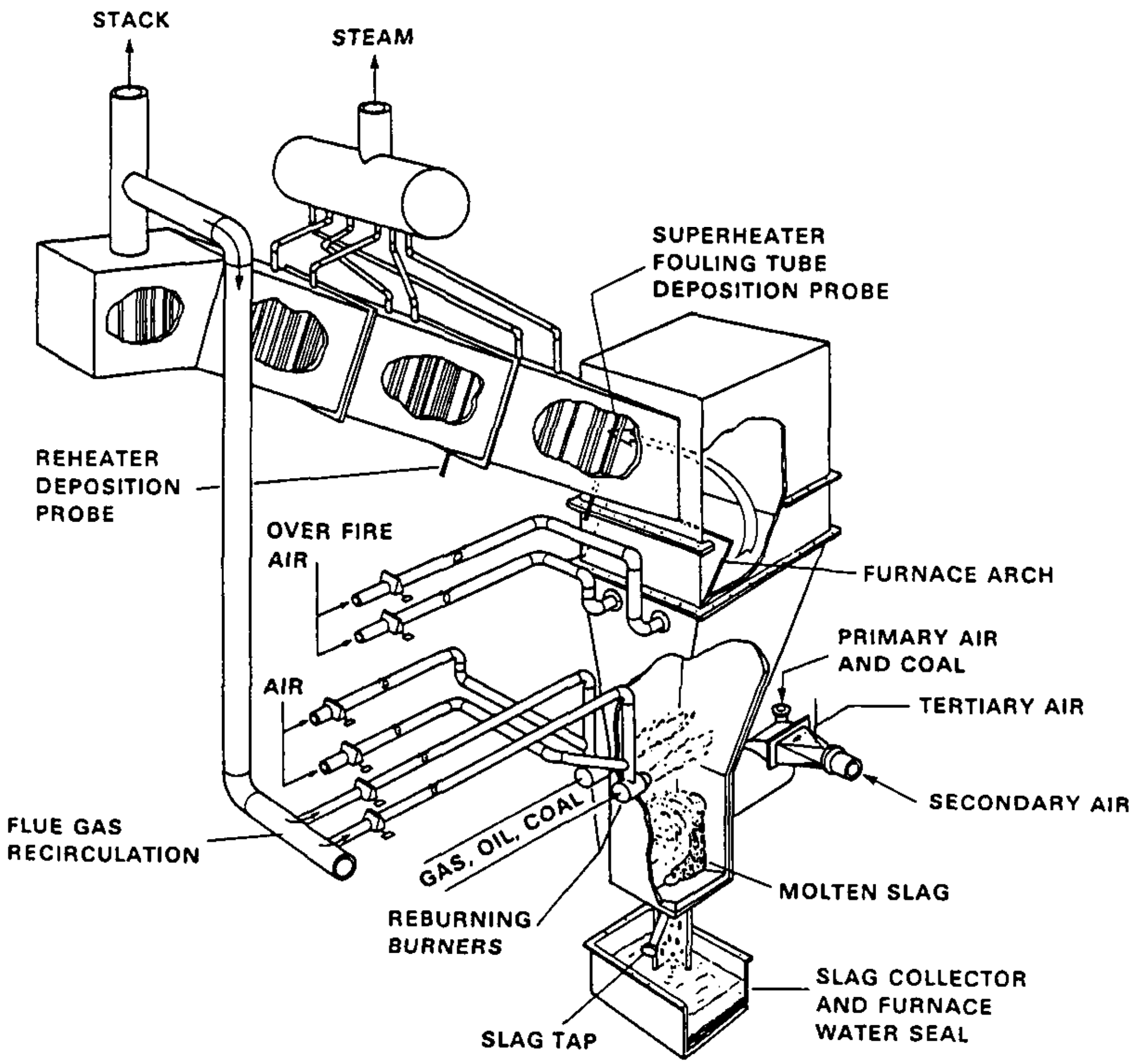


Figure 4-1 The Small Boiler Simulator (SBS) at the Alliance Research Center of B&W

6 million Btu/hr. This facility simulates furnace/convective pass gas temperature profiles and residence times, NO_x levels, cyclone slagging potential, ash retention within the resulting slag, unburned carbon, and fly ash particle size of typical full-scale cyclone units. A comparison of baseline conditions of these units is shown in Table 4-1.

TABLE 4-1
COMPARISON OF BASELINE CONDITIONS
FOR THE SBS FACILITY AND COMMERCIAL UNITS

	SBS	**Typical Cyclone-Boilers**
Cyclone Temperature	>3000°F	>3000°F
Residence Time seconds	1.4 seconds*	0.7 - 2
Furnace Exit Gas Temperature	2265°F	2150° - 2350°F
NO_x Level	900-1200 ppm	600 - 1400 ppm
Ash Retention	80 - 85%	60 - 80%
Unburned Carbon	<1% in ash	1 - 20%
Ash Particle Size (MMD; Bahco) microns	6 - 8 microns	6 - 11

* At full load

Two reburning burners were installed on the SBS furnace rear wall above the cyclone furnace. Each burner consists of two zones with the outer zone housing a set of spin vanes while the inner zone contains the reburning fuel components. Air and flue gas recirculation (FGR) can be introduced through the outer zone. Overfire air (OFA) ports are located on both the front and rear walls of the SBS at three elevations, with each elevation containing two ports.

An air-cooled deposition probe and a simulated commercial sootblower are available in the convective section (simulating secondary superheater tube) in order to allow fouling (deposition) studies to be performed.

4.2 Demonstration Coal Pilot-Scale Results

B&W's 6 million Btu/hr small boiler simulator (SBS) was used to duplicate the operating practices of Nelson Dewey Unit No. 2 (such as excess air, combustion air temperature, and boiler residence time). Baseline and coal reburning tests were performed using the Nelson Dewey demonstration coal (Lamar — a medium sulfur bituminous, coal from the Illinois Basin). Reburn coal fineness was varied from 63 to 90% through 200 mesh. During the reburning tests, the cyclone was fired at 10% excess air and at a coal flow rate equivalent to 66 to 80% of the total heat input. The remaining 20 to 34% of the heat input was introduced through reburning burners under substoichiometric conditions to obtain reburn zone air/fuel stoichiometries of 0.86 to 0.95. The balance of air was introduced through OFA ports to achieve an overall stoichiometry of 1.15 to 1.2. NO_x emissions and potential side effects were evaluated.

4.2.1 NO_x Emissions

Figure 4-2 shows NO_x emissions as a function of the reburn zone stoichiometry and reburn coal fineness at 6 million Btu/hr. During all reburning tests, the cyclone stoichiometry was held constant at 10% excess air in order to minimize impact on cyclone slagging and corrosion. The baseline NO_x level was 1025 ppm at 3% excess oxygen (furnace stoichiometry of 1.16). As expected, the NO_x concentrations decrease with decreasing reburn zone stoichiometry. A 49 to 73% NO_x reduction was achieved when varying the reburn zone stoichiometry from 0.95 to 0.86. NO_x levels were insensitive to reburn coal fineness, despite its wide variation (63, 78 , and 90% through 200 mesh).

Similar NO_x reductions were also achieved at 75% boiler load. When FGR was added into the reburning burner secondary air stream, the NO_x reduction improved slightly. However, FGR can be utilized more effectively in larger utility boiler retrofits to enhance mixing between reburn fuel and combustion flue gases.

As identified above, the SBS full load baseline NO_x level was 1025 ppm. The WP&L Nelson Dewey baseline NO_x emissions identified in Section 3.1 reveal full load levels of 609 to 661 ppm. This discrepancy is discussed in Section 4.2.7 SBS Scale-Up Methodology.

4.2.2 Combustible Loss

Unburned carbon and CO emissions were measured during the baseline and reburning phases. An inherent characteristic of cyclone furnaces is that combustion occurs mainly inside the cyclone furnace. Since cyclones will continue to be operated in an excess air mode, their combustion characteristics will not be altered. However, the amount of unburned char that does not burn within the cyclone will now enter a reducing environment in the reburning zone, with introduction of the remaining combustion air delayed until the OFA ports. During coal reburning, unburned carbon may increase since the reburning fuel is introduced into an oxygen deficient environment. Although the reburn coal devolatilizes and partially burns, complete burnout will be delayed until the burnout zone. If FGR is introduced, unburned combustible levels may also increase since the residence time in the burnout zone decreases due to increased mass loading through the furnace and the associated lower gas temperature profile

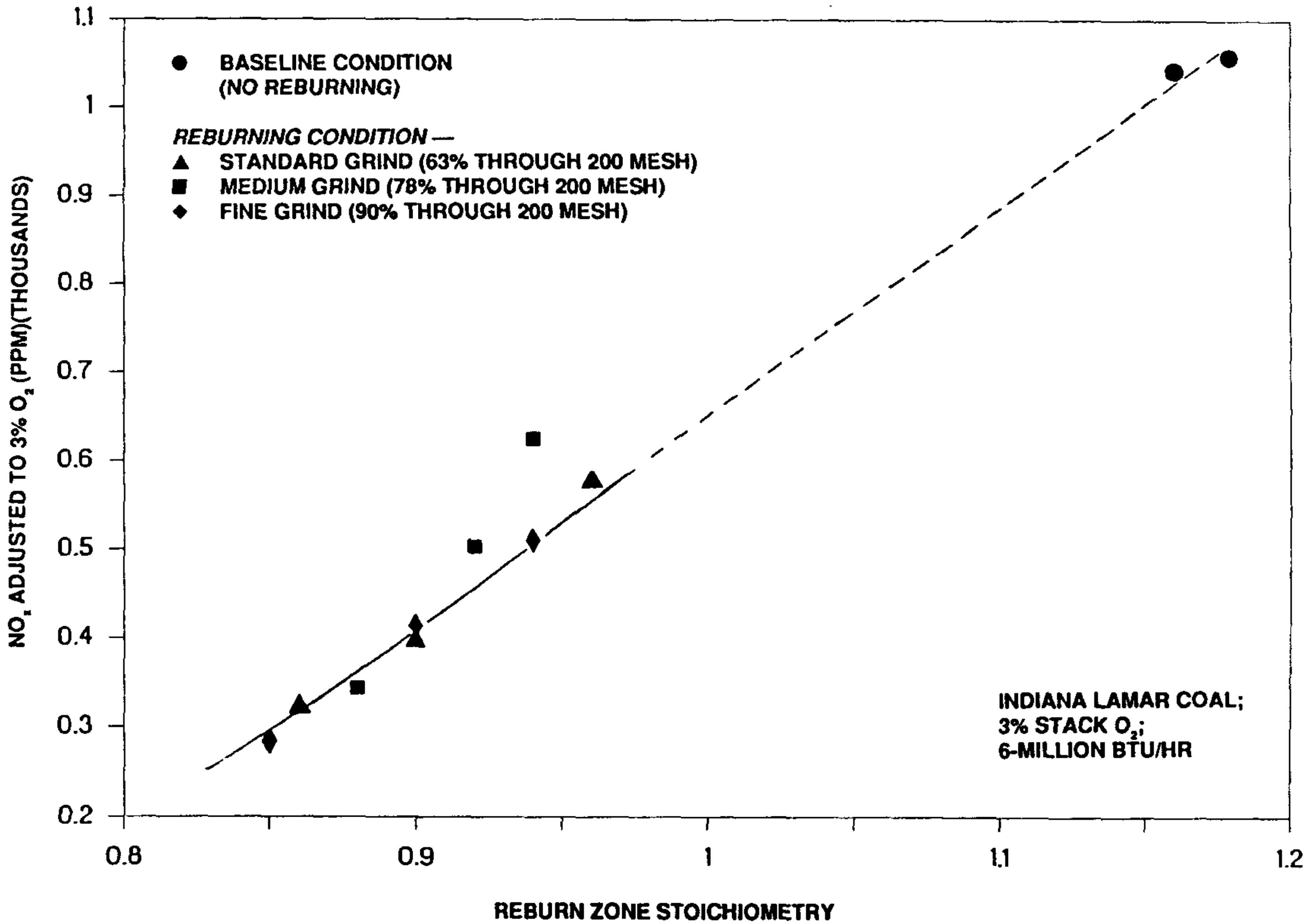


Figure 4-2 Pilot-Scale NO_x Emissions With Lamar Coal

within the reburn zone region. Efficient mixing of the air introduced through the OFA ports minimizes this concern and any potential CO emission problems.

Variation of unburned combustibles with reburn zone parameters such as coal fineness, fuel split, and FGR were determined by numerous measurements. Fly ash samples were withdrawn isokinetically from the stack and analyzed for combustibles. In addition, total mass loadings of the fly ash were measured in order to determine the combustion efficiencies for baseline and reburning conditions. Figure 4-3 shows the carbon content of the fly ash for baseline and reburning conditions. Unburned combustibles for the SBS baseline conditions are low (less than 1%). Operating under the reburning mode increases the fly ash carbon content to approximately 4 to 10% (depending on the reburn coal input and coal fineness). At a reburn zone stoichiometry of 0.9 and utilizing the fine grind coal, the unburned combustible content in the fly ash was approximately 5%. The combustion efficiencies were calculated from percent ash in the convection pass, carbon content of the fly ash, and coal analysis. The overall change of combustion efficiencies between the baseline condition and reburning with fine grind coal was only 0.05%.

Measured CO levels at the stack during the baseline tests were less than 30 ppm and no apparent increase during the reburning tests was observed. In summary, reburning had a minimal impact on the CO emission levels, but caused a moderate increase in unburned carbon.

4.2.3 Pilot-Scale Furnace Temperature Profile

SBS furnace temperatures were measured during both baseline and reburning phases to determine the technology's potential effect on temperature profiles. Figure 4-4 illustrates the furnace exit gas temperatures (FEGT) under various operating conditions. With reburning, no FGR, and maintaining a constant 6-lb/10^6 Btu/hr furnace heat input, FEGT increased from the baseline by approximately 40°F. However, when 10% FGR was added to the reburning system, a temperature quenching phenomena occurred, resulting in a 50°F FEGT drop from baseline. A 50°F variation in FEGT is considered to have a minimal impact to boiler performance. At 4.5 million Btu/hr, FEGT increases of up to 100°F were observed; this is not a major concern for low-load operation in full-scale boilers.

4.2.4 Corrosion Potential in the Reburn Zone

Since the reburn zone must be operated under substoichiometric conditions, corrosion potential within this region was investigated. By operating the cyclone in an excess air mode, most (if not all) of the sulfur from the coal in the main combustion zone is converted to SO_2. Due to the reducing atmosphere in the reburning zone, H_2S may evolve. High

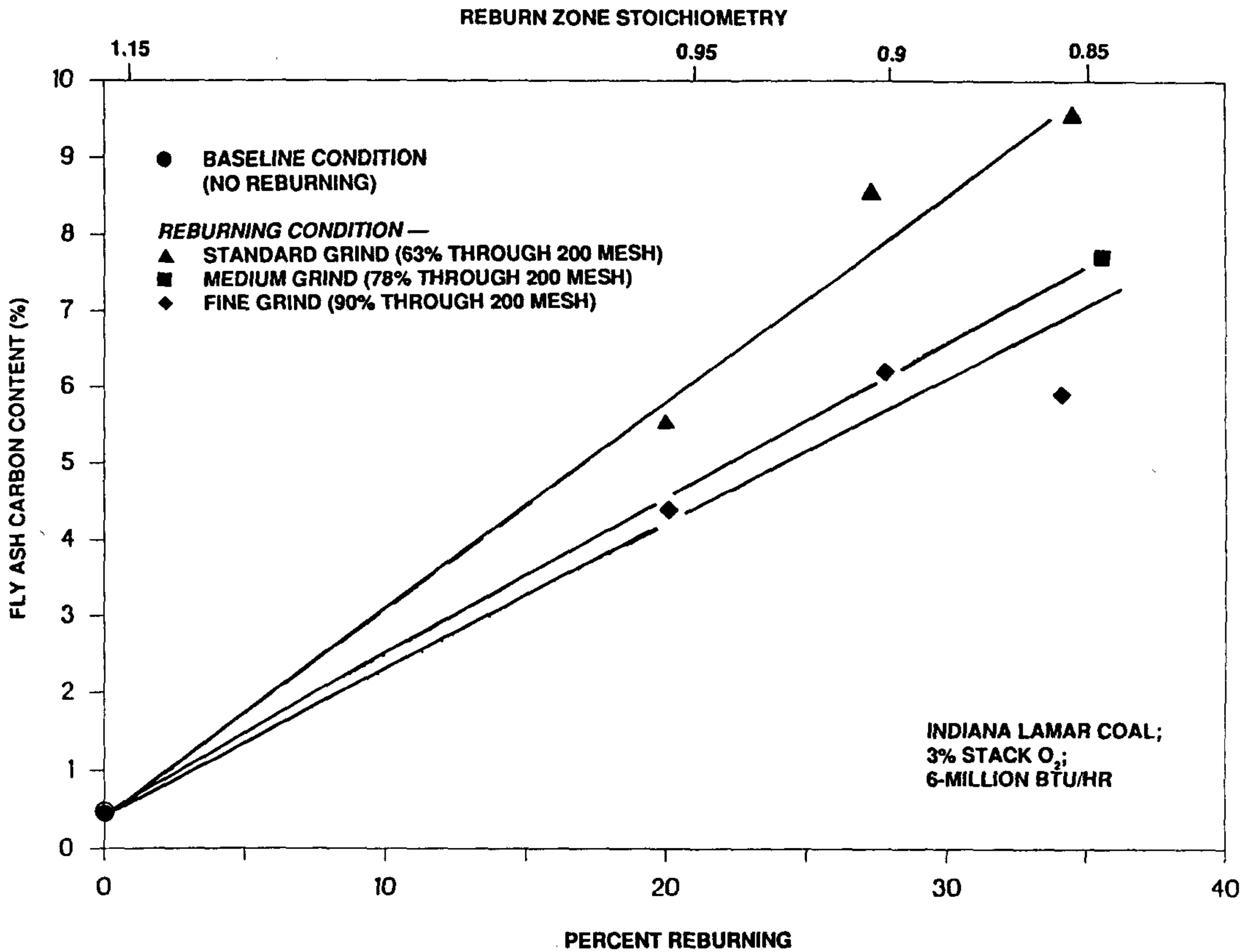


Figure 4-3 Pilot-Scale Combustible Losses With Lamar Coal

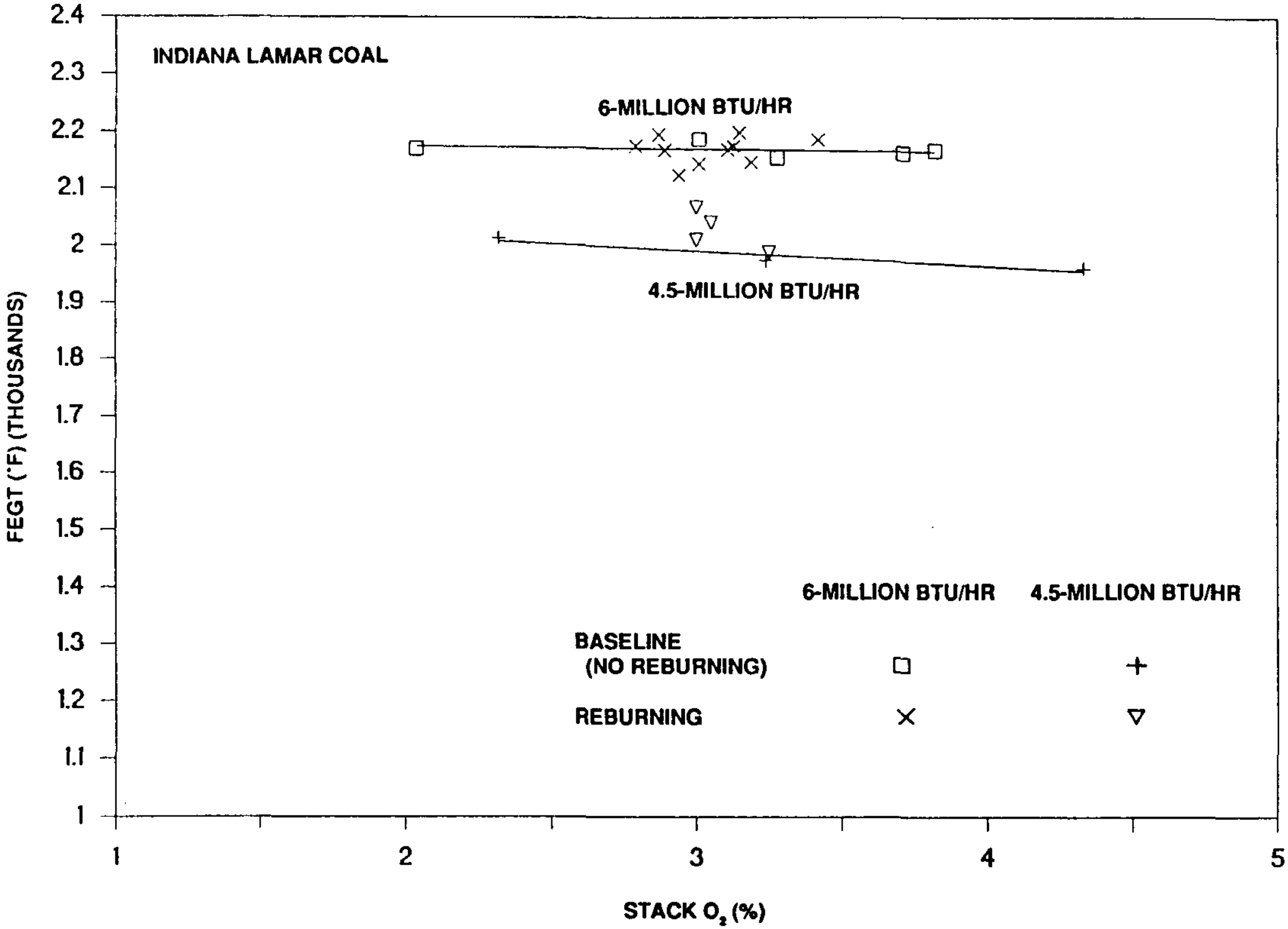


Figure 4-4 Pilot-Scale Furnace Exit Gas Temperature With Lamar Coal (No FGR)

concentrations of H_2S can be conducive to an increased rate of tube corrosion. Numerous H_2S measurements were performed within the upper furnace region with and without reburning. No H_2S was detected in the SBS during baseline conditions. Local H_2S levels increased up to 200 ppm during reburning operation. Maximum H_2S concentrations were observed between the two reburning burner flames and lower H_2S levels were measured near the boiler walls (12 to 16 ppm). Due to minimum contact of H_2S with the boiler walls, no major boiler corrosion via H_2S would be predicted for the full-scale retrofit. However, the corrosion rate in the reburn zone is expected to be a strong function of coal sulfur content and boiler type, and site-specific analysis is required for future retrofit applications.

Reburning burner(s) must be properly designed to prevent flame impingement with the boiler walls. This will be discussed in detail later in this report.

4.2.5 Other Investigations

The potential impacts of reburning on fireside deposition, electrostatic precipitator (ESP) performance, and reburning burner flame detection were studied. A brief summary of these studies is included in this report. Reference 10 documents those results in detail.

Convective surface ash deposition is a potential concern during operation of a reburning system. Since the combustion process is delayed in reburning, slightly lower/higher furnace exit gas temperatures (FEGT) could result. Also, diverting fuel away from the cyclone furnace to the reburn burners could result in higher mass loading and thus change the boiler deposition characteristics during reburning conditions. Therefore, fireside deposition was studied during two 48-hour baseline and reburn tests using a simulated superheater deposition probe. Time elapsed between sootblowing cycles was 7 to 10 hours for the baseline and 7 hours for reburning conditions. The superheater probe heat flux was recovered with sootblowing (using the same pressure which is within capabilities of commercial units) for baseline and reburning conditions. The chemical analysis of the probe deposits under coal reburning conditions showed that concentrations of sodium and potassium were less than baseline conditions on the superheater probe. In addition, fly ash loading increased by approximately 40%; however, sootblowing pressure requirements did not change. It was concluded that although fireside deposition changed slightly during reburn operation, it was not negatively affected beyond controllability.

Electrostatic Precipitator (ESP) performance is a potential concern during operation of a coal reburning system. The fly ash loading to the ESP increases since the ash from the coal reburning system is not removed as slag. The chemical analysis of ash and the ash particle size distributions can also be affected by reburn operation. The fly ash loading, fly ash particle size distribution, and fly ash resistivity were measured in the SBS. These data along with the baseline results from the Nelson Dewey station were used for a comprehensive ESP evaluation (section 7.3.1.3). During reburning conditions, fly ash loading increased by approximately 40% from the baseline conditions. The fly ash particle size during reburning was also coarser than at baseline conditions. The reburn fly ash contained less fine fly ash, e.g. 38% less than 2.3 microns for baseline versus 30.6% less than 2.3 microns for the reburning conditions. This is beneficial for ESP particulate removal. In-situ resistivity measurements showed that fly ash resistivity remains fairly constant around 2.4-5.9 x 10^{10} ohm-cm for baseline and the reburning conditions. The ESP evaluation was performed and is reported in section 7.3.1.3.

An important aspect of the reburn system is burner management capability. Since 20 to 30% of the total heat input to the furnace is introduced through the reburning burners, the National Fire Protection Association (NFPA) recommends installation of flame safety equipment to monitor the reburning burner flames. Commercial equipment is available for utility and industrial boiler management for various fuels. However, reburning burner throat stoichiometry is different from typical utility burners. A commercial infrared (IR) flicker type flame scanner was tested in the SBS. The flame scanner detected the flame during all conditions and was not sensitive to the background radiation. This scanner was recommended for use at the Nelson Dewey station.

4.2.6 Mixing Evaluation

Effective mixing between the reburn fuel and cyclone gases is needed to obtain acceptable NO_x reduction. In addition, good mixing between OFA and reburn zone gases is necessary to avoid unacceptable unburned combustible losses and high CO emissions. Furnace flow patterns and mixing performance were evaluated by in-furnace probing as well as three-dimensional mathematical simulation of the baseline and reburning flow conditions in the SBS.

The B&W FORCE numerical flow model solves the governing equations for conservation of mass and momentum to predict the three-dimensional turbulent flow in the furnace. Velocity predictions for the SBS were compared with velocity measurements at four elevations in the furnace. The predictions were in general agreement with the data. The predicted flow patterns are shown in Figure 4-5. The direction of the flow is indicated by the arrows; the length of the arrows is proportional to the magnitude of the velocity. Coal and air enter the furnace through the reburning burners on the rear wall. The flow turns upward and mixes with the cyclone

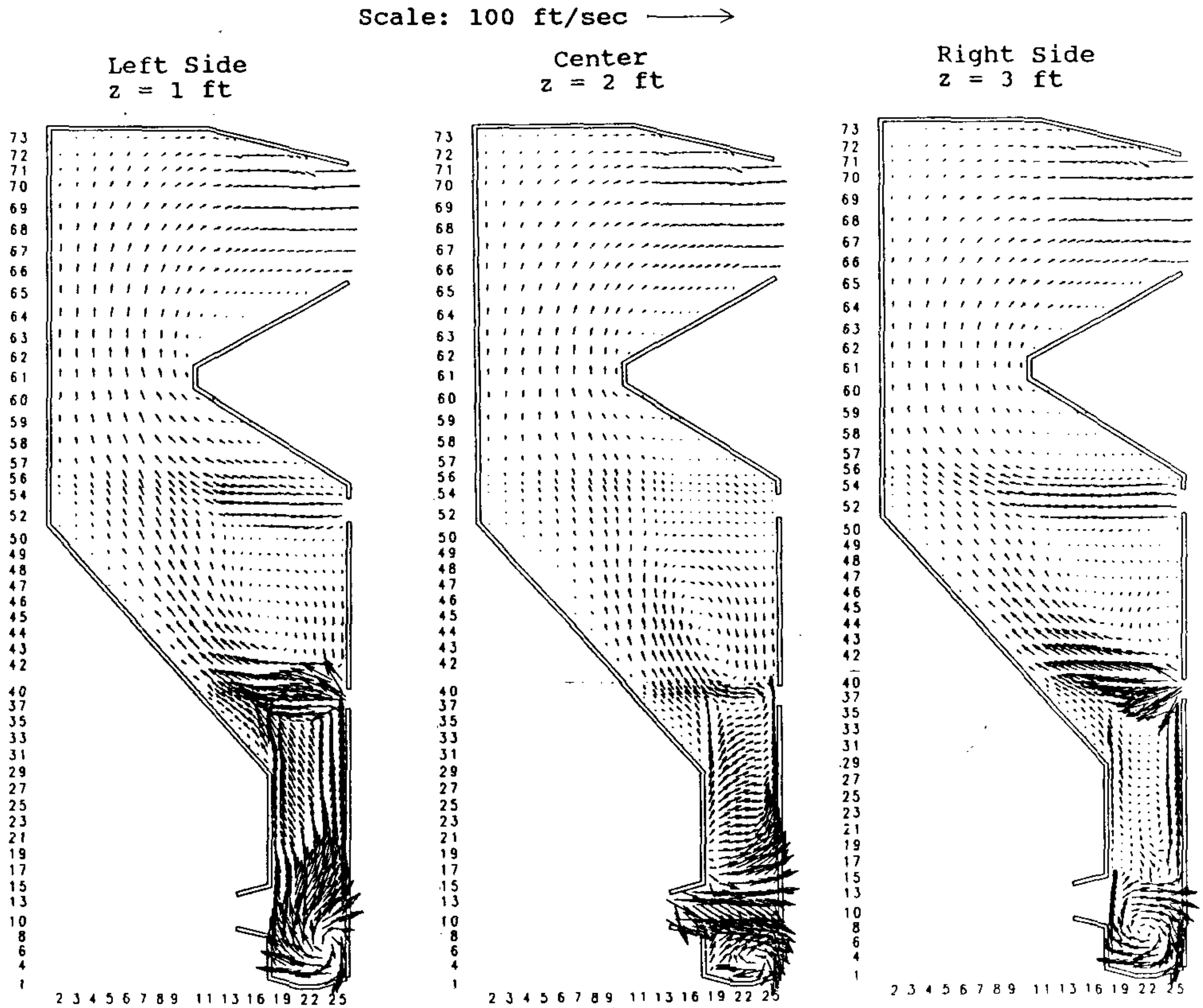


Figure 4-5 Predicted Flow Profiles for Pilot-Scale Reburning

gases flowing upward from the bottom of the furnace. A recirculation zone is formed above the reburning burners which circulates air downward from the OFA ports into the reburn zone. The recirculation zone is expected to improve carbon burnout; however, it may have a negative impact on overall NO_x reduction because of the reduced size of the reburn zone. The OFA flow enters the furnace and turns upward while mixing with the reburn zone combustion gases.

Predicted distributions of stoichiometric ratio (SR) were also used to evaluate mixing in the SBS. Figure 4-6 shows the comparison of in-furnace CO measurements with the predicted stoichiometries at four elevations in the SBS. In this comparison, only two regions of SR are shown with corresponding CO measurements. The shaded region is fuel-rich (SR<1); the unshaded regions are fuel-lean (SR>1). Generally, the higher CO concentrations correspond to predicted fuel-rich regions. Agreement is particularly good in the upper furnace. Some disparity exists in lower furnace presumably due to the delay of CO oxidation.

Figure 4-7 shows the mean stoichiometry and percentage of mass flow at reducing conditions predicted for each elevation in the SBS. The mean stoichiometry is 1.1, 0.9, 1.15 for the cyclone, the reburn zone, and the burnout zone, respectively. In the reburn zone, the amount of flow with SR<1 increases with elevation and approximately 80% of the flow achieves reducing conditions. In the burnout zone, the amount of flow with SR<1 decreases with elevation. Mixing in the burnout zone is complete, with all of the gases and particles achieving the oxidizing condition before leaving the furnace.

The numerical flow predictions quantify the SBS reburning system mixing performance that achieves over 50% NO_x reduction. Based on the results, a methodology was developed for scale-up to the 110 MW_e Nelson Dewey boiler using the pilot-scale data, and physical and numerical modeling results. Section 5.0 describes this methodology for modeling activities.

4.2.7 SBS Scale-Up Methodology

Comparison of the baseline conditions of the SBS and Nelson Dewey Station shows that the pilot-scale facility sufficiently simulates the full-scale conditions. Since the demonstration coal was tested in the SBS, the effect of coal properties is eliminated. The temperature profiles and the average furnace residence time in the SBS and Nelson Dewey were generally in agreement. The baseline NO_x level was higher for the SBS (1025 ppm) than for Nelson Dewey (661 ppm). The only apparent rationale for this difference is that 1) coal moisture content during the Nelson Dewey baseline tests was substantially higher than the baseline SBS tests (16.74% versus 3.79%) and 2) required inherent SBS design features due to surface-to-volume differences, e.g., higher secondary air temperature and smaller

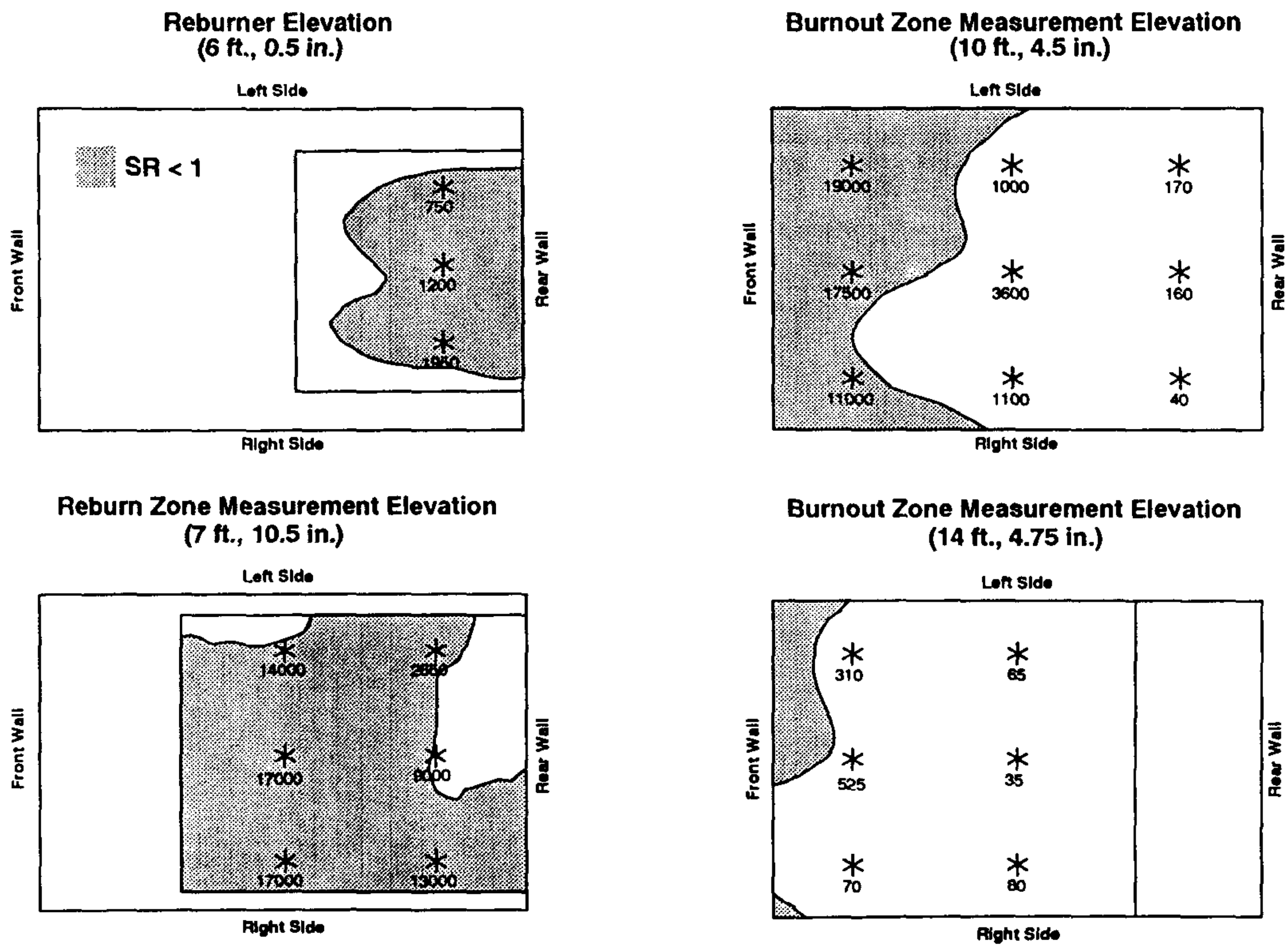


Figure 4-6 Comparison of Measured CO (ppm) and Predicted Regions of SR <1 in the SBS for Reburning Conditions

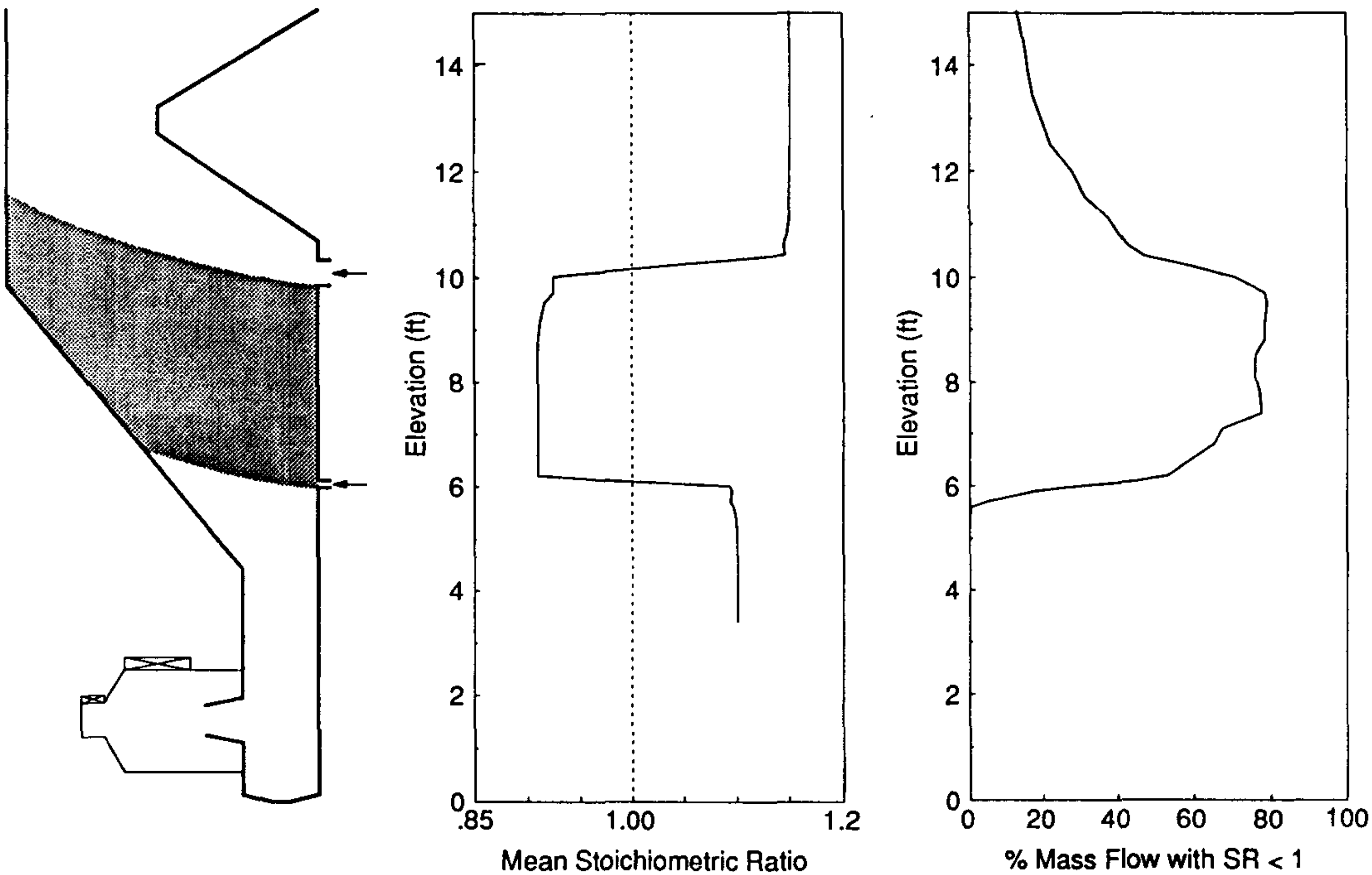


Figure 4-7 Predicted Mixing Performance for the SBS With Coal Reburning

coal particle sizes as compared to full-scale operation. Although this difference in the baseline NO_x concentrations is not completely understood, it is not defeating since the NO_x reduction effectiveness of reburning is not strongly sensitive to NO_x levels entering the reburn zone in the 500 to 1000 ppm range [11]. In addition, flexibility at the demonstration site provided the capability to allow a higher percentage of coal to be switched to the reburning burners if required. The carbon content of the fly ash was lower in the SBS than the Nelson Dewey station during the baseline conditions, presumably due to finer coal particles in the SBS cyclone. However, the combustion efficiency of the reburning coal (and, therefore, the impact on combustible loses) obtained in the SBS will be similar to that for full-scale since the reburn coal particle size distribution and the thermal and chemical environments of the two boilers are similar. It is in our best judgement that the Nelson Dewey's reburning system performance would be close to the performance of the SBS if the mixing in the reburn and burn-out zones of the two boilers are similar. This will be discussed in detail in section 5.0.

In-furnace flow measurement and physical flow modeling were used to benchmark the numerical flow model for the SBS and Nelson Dewey unit. Numerical models are based on a fundamental description of turbulent flow processes which are the same regardless of scale. Once validated with pilot-scale or physical flow modeling results, the numerical flow model can be used for quantitative evaluation and scale-up of the reburning process from the 6 million Btu/hr pilot-scale facility to the commercial-scale boiler.

4.2.8 Conclusions And Recommendations

Based on the pilot-scale study, the following conclusions and recommendations are derived:

- Nominal 50% NO_x reduction is feasible without major side effects on boiler operational conditions

- Pilot-scale simulation of the Nelson Dewey unit produced thermal and chemical environments close to those of full-scale. Differences are identified, but they are not defeating.

- Numerical models were validated for mixing evaluation. These tools could be used in future applications.

- The pulverizer design should be capable of providing a nominal 30% heat input with a fineness of 85% through 200 mesh

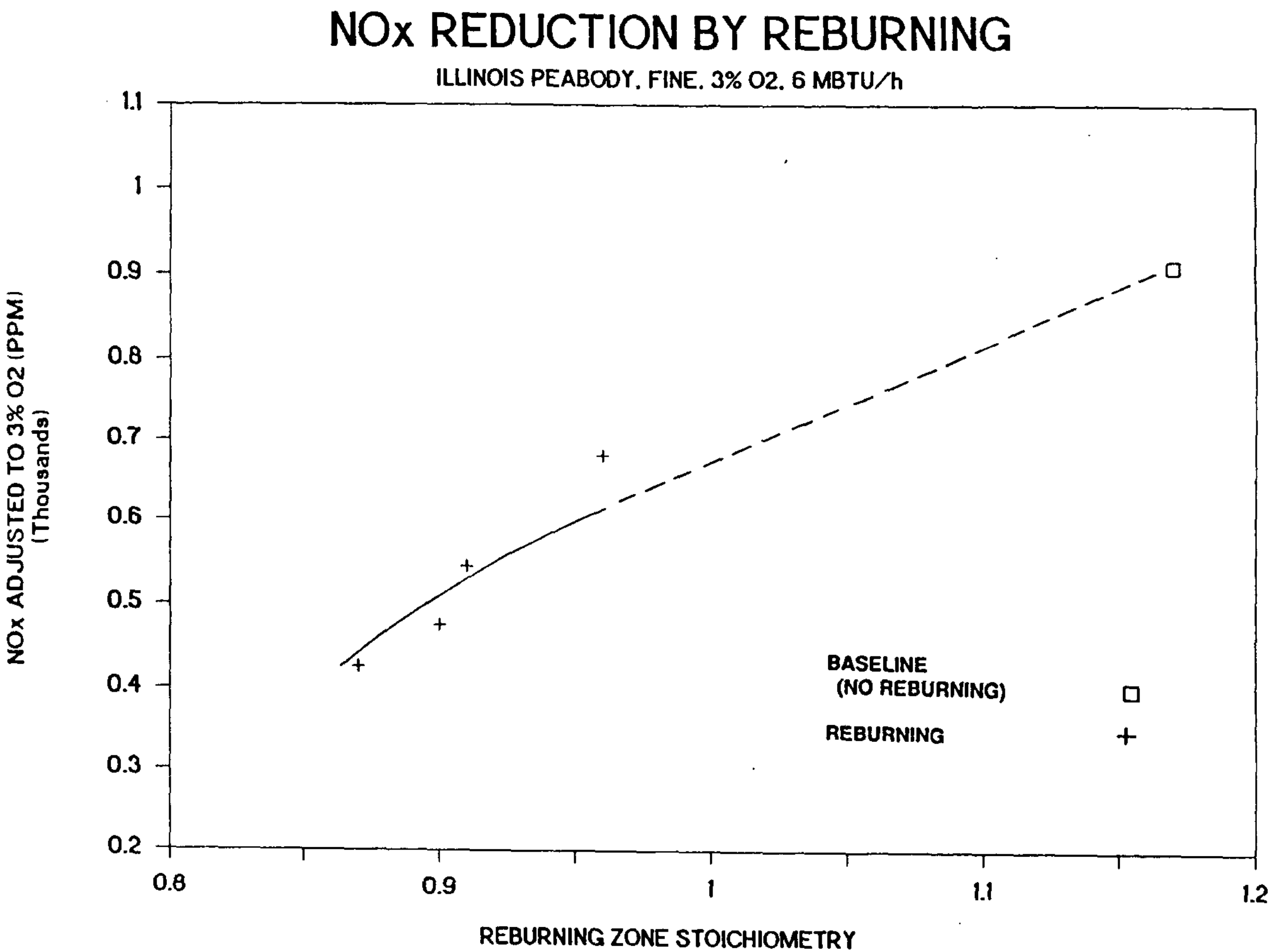


Figure 4-8 NO_x **Emissions With Peabody Coal**

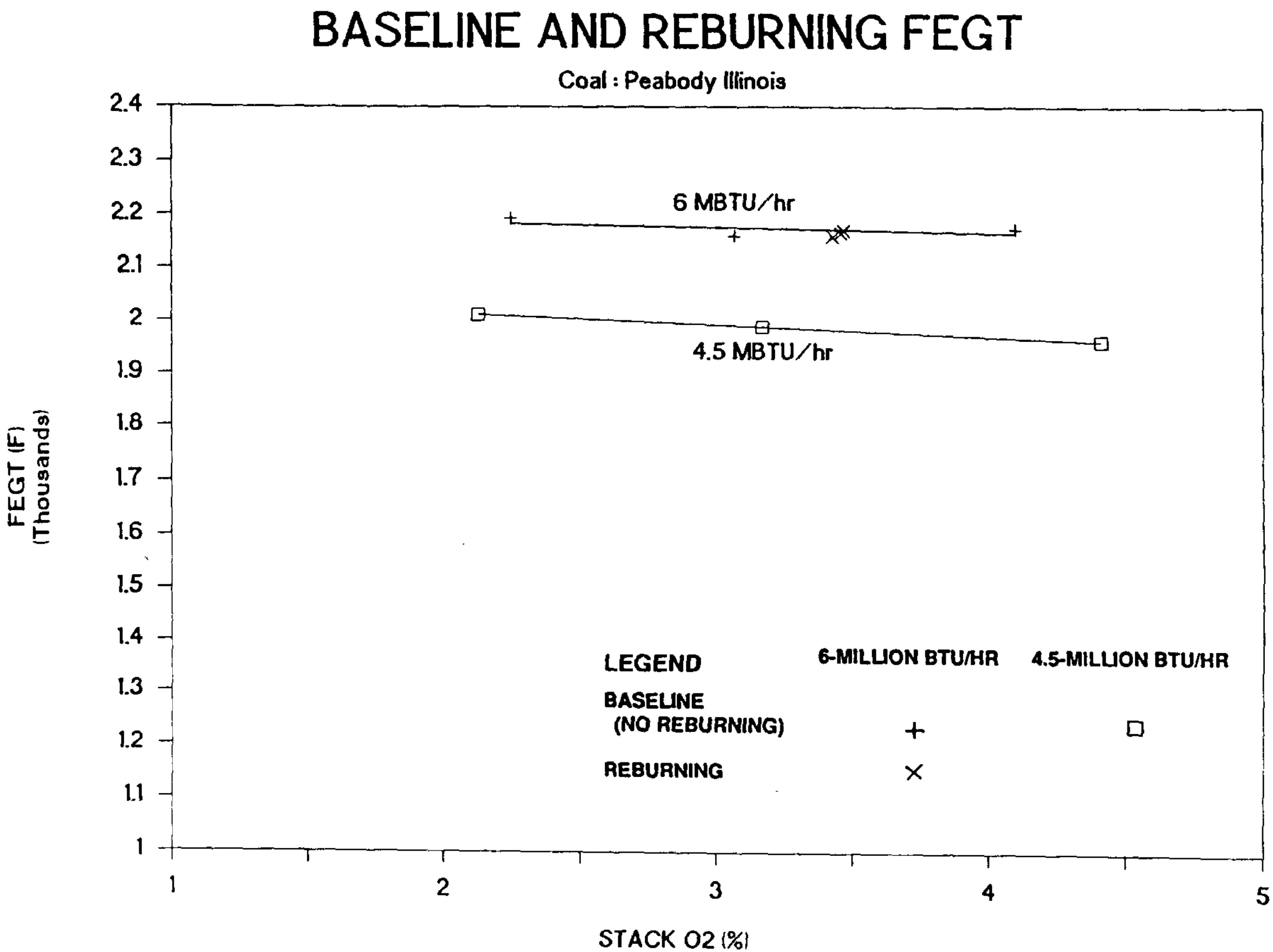


Figure 4-9 Effect of Reburning on FEGT With Peabody Coal (No FGR)

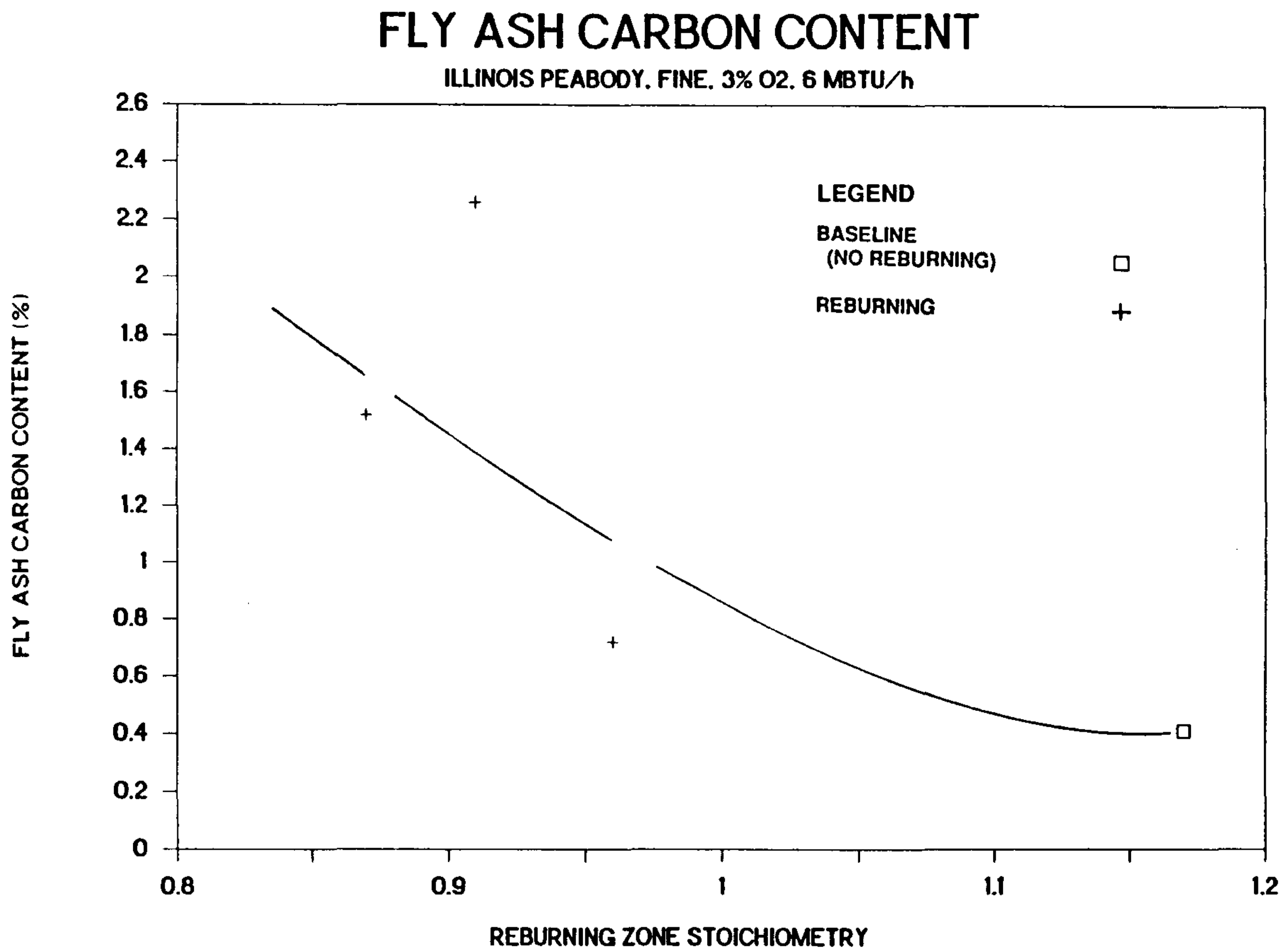


Figure 4-10 Reburning Combustible Losses With Peabody Coal

4.3 High Sulfur Illinois Coal Results

NO_x emission levels during high-sulfur Illinois (Peabody) coal firing tests are illustrated in Figure 4-8. At full-load (6 million Btu/hr), NO_x levels (adjusted to 3% O_2) increased from 884 to 989 ppm when varying stack excess oxygen from 2.25 to 4.1%. Since operating at 3% excess oxygen is considered typical, all subsequent reburning conditions are shown while maintaining an overall stack oxygen of 3%. The full-load baseline NO_x level at 3% excess O_2 was 935 ppm and all subsequent reburning NO_x levels will be compared to this condition. At 4.5 million Btu/hr, NO_x emissions were lower and ranged from 851 to 970 ppm, adjusted to 3% O_2 when varying excess oxygen from 2.1 to 4.4%, respectively. With the reburning system in operation, NO_x reductions of 30 to 54% from the baseline condition were achieved for the reburn zone stoichiometries of 0.96 to 0.87, respectively. In all tests, the cyclone stoichiometry was maintained at 1.1 due to potential corrosion/slag tapping concerns. A fine (90% through 200 mesh) grind pulverized coal was used for all reburning tests performed with Peabody coal. The reburn zone stoichiometry was varied by changing the amount of the heat input introduced at the reburning burners. The heat input to the reburning burners ranged from 20.8 to 34.9% of the total for reburn zone stoichiometries of 0.96 to 0.87, respectively.

In addition, the formation of N_2O during coal reburning was also investigated; the levels were 7 to 11 ppm at a reburn zone stoichiometry of 0.9. No baseline N_2O data was obtained during the pilot testing phase. The small magnitude of the measured N_2O levels during reburn operation indicates that any change would be insignificant.

4.3.1 Furnace Exit Gas Temperature (FEGT)

Furnace exit gas temperature (FEGT) did not change significantly between baseline and reburning conditions (+11°F). Figure 4-9 compares the FEGT for reburning and baseline operating conditions. Baseline FEGT was 2157°F at full load with 3% excess oxygen. The FEGT under reburning conditions ranged from 2156° to 2168°F for 20.8 to 34.9% reburn fuel, respectively. The FEGT changes shown during these tests are less sensitive than that observed during the Lamar coal testing (+11°F versus +40°F).

4.3.2 Combustion Efficiency

Figure 4-10 illustrates carbon content of the fly ash under the baseline and reburning conditions. In the majority of the baseline tests, low (less than 1.0%) combustibles were found in the fly ash with the Peabody coal. The highest level of combustibles during baseline testing was observed while operating at 70% load and 2% excess oxygen (approximately 1.4%). During reburning conditions while utilizing fine (90% through 200 mesh) pulverized coal, combustible losses ranged from 0.72 to 2.26% for 20.8 to 34.9% reburn fuel input.

Combustible losses are very small (less than 0.1% combustion efficiency) and are in agreement with the Lamar coal tests. But the percent carbon in the fly ash differs considerably from the Lamar coal mainly due to the variation in fly ash content which acts as a diluent for unburned combustibles. Peabody coal contains more ash than Lamar coal, 11.8 and 4.4%, respectively on a dry basis.

4.3.3 Corrosion Evaluation

Table 4-2 shows the H_2S levels during firing of the medium- and high-sulfur coals tested under baseline and reburning conditions. In the baseline conditions, 0 ppm H_2S was found with the Lamar coal and only a trace amount could be seen with the Peabody coal. The reburning system produced up to 200 and 300 ppm H_2S in the reburn zone with Lamar and Peabody coals, respectively. The maximum H_2S concentrations were found between the flames of the reburning burners, and H_2S levels near the boiler side walls were low. The highest sidewall measured level was 20 ppm during the higher sulfur Peabody coal test. Thus, minimum H_2S contact with the boiler walls was observed. If these low H_2S levels can be reproduced at the full-scale WP&L Nelson Dewey Station Unit No. 2 tube wastage will be negligible for this boiler type.

TABLE 4-2
H_2S CONCENTRATIONS IN REBURN ZONE

	Baseline	Reburning
Lamar Coal (1.87 % sulfur, dry)	0 ppm	0 to 200 ppm*
Peabody Coal (4.24% sulfur, dry)	0 to 2 ppm	0 to 300 ppm*

* 1) H_2S levels vary within the reburn zone.
2) Maximum H_2S levels were observed between the two reburning burner flames.
3) H_2S levels were low near the side walls.

4.4 Western Coal Results

4.4.1 NO_x Emission Levels

A series of pilot-scale tests were conducted using a western sub-bituminous PRB coal. Baseline NO_x emission levels adjusted to 3% O_2 ranged from 736 to 829 ppm while varying the stack O_2% from 2.2 to 4.1%, respectively, at 5 million Btu/hr. Since 3% stack O_2 is typical of Nelson Dewey station operation, all subsequent reburning conditions are shown while maintaining an overall stack O_2 of 3%. Thus, the referenced baseline NO_x level when operating at 3% O_2 is 769 ppm. Reducing the SBS load to 3.7 million Btu/hr reduced the NO_x level to 717 ppm. This was the minimum load achievable at the SBS based on cyclone slag tapping.

Operating the coal reburn system at the SBS on sub-bituminous fuel revealed NO_x reductions on the order of 48 to 68% from the baseline depending on reburn zone stoichiometry (0.93 to 0.85). Figure 4-11 shows the NO_x levels versus reburn zone stoichiometry.

Maintaining the cyclone furnace stoichiometry at 1.1 throughout the test sequence is critical due to the potential corrosion and operating (slag tapping) concerns in cyclones. The reburn zone stoichiometry is varied by increasing the amount of the heat input to the reburning burners and maintaining a constant burner stoichiometry. It is the increased amount of low constant stoichiometry reburn gases mixing with a decreased amount of constant stoichiometry cyclone gases which averages reburn zone stoichiometry downward. To obtain these NO_x reductions, the corresponding cyclone/reburning burner coal splits are approximately 79/21 (0.95 stoichiometry) and 65/35 (0.85 stoichiometry).

At a reburn zone stoichiometry of 0.9 (29% reburn fuel which is typical during full load Nelson Dewey operation) a NO_x emission level of 340 ppm was measured. This corresponds to 55.8% NO_x reduction from the baseline conditions. The datum point at 0.95 stoichiometry corresponds to a 30% NO_x reduction. The actual NO_x level at this stoichiometry falls above the least squares curve fit. This is attributed to difficulty in obtaining stable NO_x emissions at 0.95. This stoichiometry appears to be the transition point at which NO_x is extremely sensitive to slight variations in operating conditions. Figure 4-12 shows the baseline and reburning NO_x levels at different loads. The baseline NO_x level increased from 717 ppm to 769 ppm when the SBS load was increased from 3.7 to 5 million Btu/hr. The reburn NO_x levels increased from 270 to 429 ppm when SBS load increased from 4 to 5.8 million Btu/hr at a reburn zone stoichiometry of 0.9.

All of the aforementioned data corresponds to 0% flue gas recirculation (FGR) in the reburn burners. Adding FGR to the reburning burners increases the mass flow through the burner and thus results in higher burner velocities. When approximately 5 and 9% FGR were added to the reburn burners (at 5 million Btu/hr and reburn zone stoichiometry of 0.9), NO_x levels of 278 and 260 ppm were achieved respectively. With no FGR, at a stoichiometry of 0.9, 363 ppm NO_x was achieved.

4.4.2 Furnace Exit Gas Temperature (FEGT)

Furnace Exit Gas Temperature (FEGT) did not change significantly between baseline and reburning operation. Baseline FEGT at 5 million Btu/hr and 3% stack oxygen was 2003°F. Incorporating reburning revealed minimum FEGT effects within a range of +/- 50°F for the majority of test conditions. FEGT increased to 2132°F (approximately 130°F increase) at the reburn zone stoichiometry of 0.85. This corresponds to a 34.8%

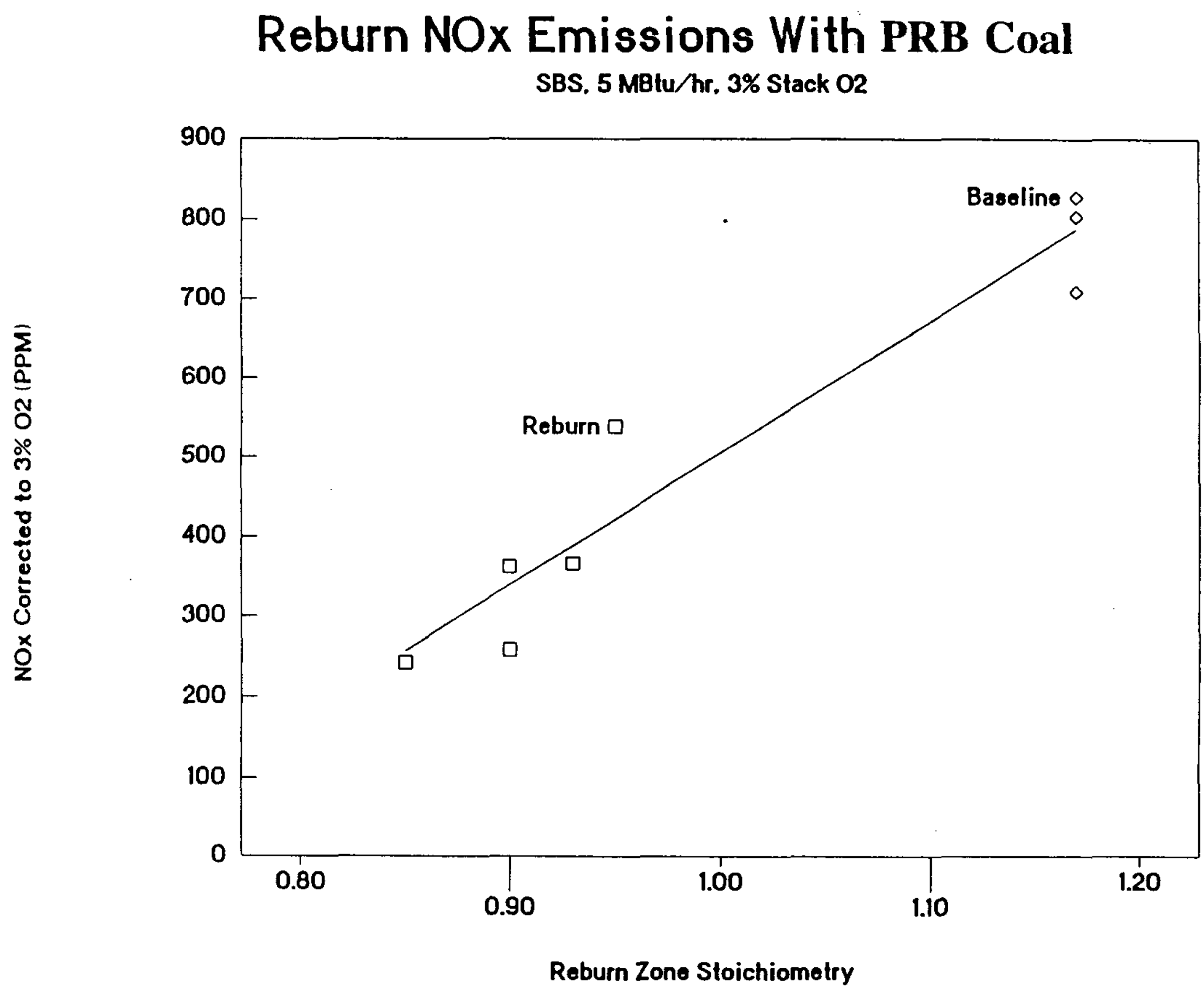


Figure 4-11 SBS NO_x Emissions With PRB Coal at 5 Million Btu/hr

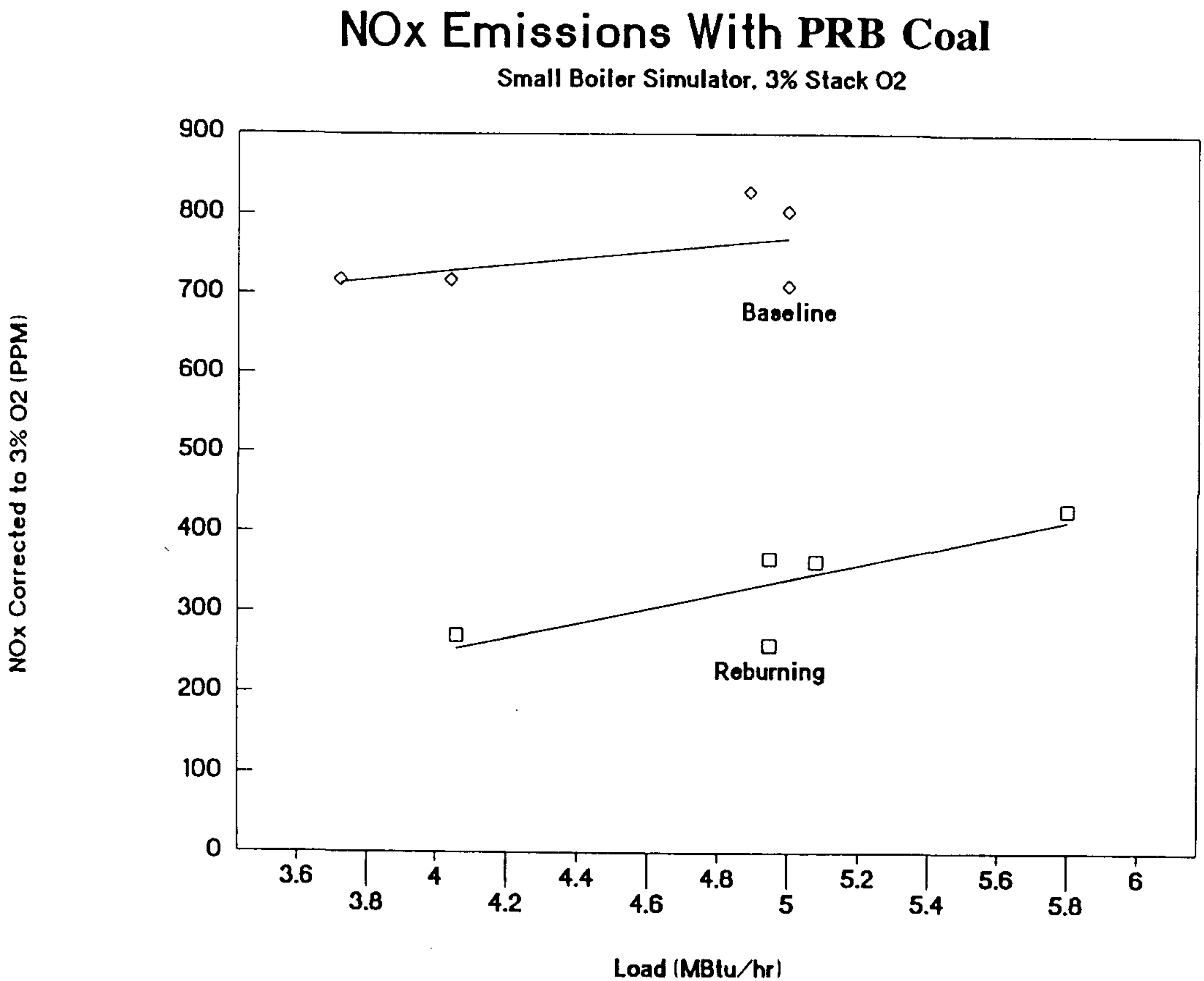


Figure 4-12 SBS NO_x Emissions at Different Firing Rates With PRB Coal

heat input to the reburn burners. FEGT decreased to 1934 when approximately 5% FGR was introduced into the reburn burners. Although changes in FEGT are low for most of the tests (with exception of high reburn fuel heat input), convection pass metal temperatures should be monitored in future full-scale retrofits to assure that no problems are encountered.

4.4.3 Combustion Efficiency

The unburned combustibles in the SBS were all very low during baseline and reburn conditions. Unburned combustibles in the fly ash were below 1% and did not increase with the reburn operation. These results were obtained with a fine grind reburn coal (84% through 200 mesh). The total ash output from the SBS increased, as expected, from approximately 20% of original coal ash for the baseline to 30% at reburning conditions. Although unburned carbon content of the fly ash did not change, the total ash loading at the stack increased. This would predict a slight increase in ash loading and unburned combustibles in the full-scale operation at the inlet to the precipitator.

4.5 Lignite Testing

Additional SBS testing was carried out using North Dakota lignite as both the cyclone and reburn fuel. This program was sponsored by the North Dakota Lignite Board and member utilities independent of the DOE Coal Reburning Project. Results indicate that lignite performs well as a reburn fuel. Appendix 3 is the report for the lignite reburn test work.

5.0 Numerical and Physical Flow Modeling

Both numerical and cold flow modeling were undertaken to provide tools for reburn system design. A numerical model could easily be used to study reburn applications simply by changing the model boundary conditions to simulate the boiler. The B&W FORCE code was used to evaluate flow patterns in the Nelson Dewey boiler under baseline and reburn conditions. The cold flow plexiglass model of Nelson Dewey was also constructed to study gas flow distribution with and without reburn. Baseline data at Nelson Dewey, in the form of boiler flow and temperature measurements, and baseline and reburn data at the Small Boiler Simulator pilot unit were used to tune and validate the numerical model. Cold flow analysis was also used to verify numerical modeling results. The combination of cold flow modeling, SBS data and baseline data at Nelson Dewey proved the usefulness of a numerical model as a design tool.

Numerical modeling as carried out in the initial design task consisted only of flow modeling. Section 9.0 of this report summarizes both numerical flow modeling (FORCE) and combustion modeling, incorporating B&W's FURMO model into the analysis. Actual data at Nelson Dewey was used to evaluate both flow and combustion modeling predictions.

5.1 Methodology

In the design phase of the project, furnace flow patterns and reburning system mixing performance were evaluated using physical and numerical flow models for the nominal 110 MW_e cyclone boiler at WP&L's Nelson Dewey Station, Unit No. 2.[12]

The first objective of the physical and numerical flow modeling was to characterize the flow patterns for the baseline configuration of the WP&L boiler and benchmark physical and numerical flow models with gas velocity measurements in the field unit. First, a series of field flow tests were conducted on Nelson Dewey Station Unit No. 2 at Cassville, Wisconsin. Next, a series of tests were performed on the 1/12-scale physical flow model at B&W's Alliance Research Center. Finally, numerical flow modeling was used to characterize the baseline flow patterns in the field unit.

The second objective of physical and numerical flow modeling was to simulate reburning conditions and to assist in the design of the reburning system. Modeling was used to help determine the size, number, and location of reburning burners and OFA ports required to control mixing in the reburning and burnout zones of the WP&L furnace. The reburning system was also evaluated to ensure proper reburning burner flame penetration into the furnace. Over-penetration or under-penetration of the reburning burner flame could cause tube wastage and flame stability problems.

The host site boiler was inspected for suitable burner and OFA locations. It was necessary to arrange the reburning burners on the rear wall to achieve uniform mixing across the width of the boiler, and at an elevation above the slagging zone to prevent slag buildup around the reburning burners. Due to the space limitations, a maximum of four reburning burners could be utilized.

Three configurations of reburning burners and OFA ports tested in the physical model and simulated with the numerical flow models are shown in Figure 5-1. The first is an arrangement of three reburning burners and three OFA ports on the rear wall of the furnace. This configuration is the minimum cost alternative because fewer penetrations of the furnace enclosure are required. The other two arrangements include an additional OFA port and/or reburning burner to improve mixing in the reburning and OFA zones, respectively.

Results of the mixing tests performed in the physical flow model were used first to benchmark and refine the predictive capability of the numerical model of the 1/12-scale physical flow model. The benchmarked numerical flow model was then applied to predict the performance of the full-size field unit.

Reburning combustion tests were conducted on B&W's 6 million Btu/hr SBS facility using the operating conditions of the WP&L boiler. Furnace flow patterns, mixing, and residence time were then evaluated using B&W's FORCE numerical flow model for baseline and coal reburning conditions tested in the SBS. Velocity predictions were compared with hot velocity traverse measurements in the SBS and were in general agreement with the measured data.

Predicted distributions of furnace stoichiometric ratio were used to evaluate mixing effectiveness for coal reburning tests in the SBS. Predicted mixing results for the SBS are described in section 4.0.

Full-scale performance will be similar to the performance of the SBS provided that the residence time in the reburning zone and mixing effectiveness among other variables (e.g., temperature, chemistry, etc.) are similar. The mixing results for the SBS are useful criteria for evaluation of reburning system mixing performance. These criteria are used to select the best reburning system design for the WP&L boiler.

5.2 Baseline Flow Patterns

Due to the critical importance of mixing, a comprehensive study was first performed for the baseline configuration of the boiler. Tests in the field unit consisted of cold flow tests and hot flow tests as described in section 3.3 In-Furnace probing. The cold tests were conducted with air at 100°F; the hot tests were conducted by operating the cyclones at approximately 50% load with No. 2 fuel oil and 49% flue gas recirculation (FGR) introduced above the cyclones. A rake of four vane-type anemometers was used between the right and left walls at the approximate reburning burner location (666-foot elevation) to measure the cold air velocities. For the hot flow tests, a Fecheimer probe was inserted through ports in the left, right, and rear walls at the same elevation. For both the cold flow and hot flow tests, the same Fecheimer probe was inserted through

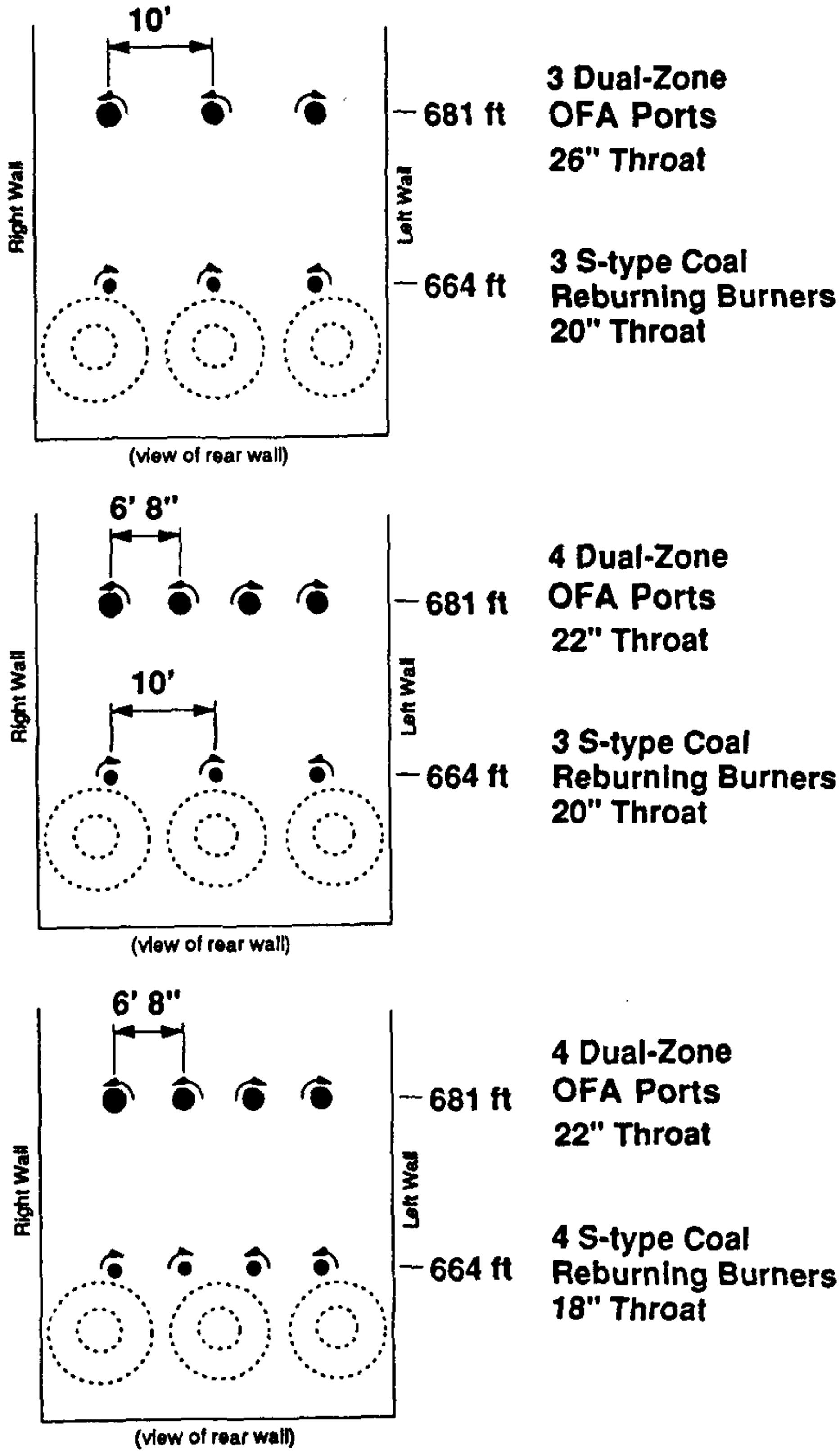


Figure 5-1 Specific Configurations of the Reburning System Design Tested by the Physical and Numerical Models

the port in left wall at the 584-foot elevation for measurements at the cyclone exit plane.

The physical flow model was a 1/12-scale geometrical model of Nelson Dewey furnace fabricated from transparent Lexan™ material. A photograph of the model that shows three simulated cyclones in the lower foreground and the furnace arch on the other side is shown in Figure 5-2. The baseline tests for the physical flow model consisted of: 1) measurement of air velocities at the reburning burner level, at the OFA port level, and at the furnace arch with cold air aspirated through all three cyclones, and 2) measurement of the air velocities at the reburning burner location with only one or two cyclones in service.

Babcock & Wilcox's FORCE numerical flow model was used to simulate turbulent flow in the baseline configuration of the WP&L boiler. This computer program solves the steady, Reynolds-averaged form of the Navier-Stokes equations for conservation of mass and momentum in three dimensions. The flow is modeled from the re-entrant throat of the cyclone to the furnace exit. Flow obstructions, such as the target wall, slag screen, and secondary superheater tubes, are modeled by placing flow resistances to simulate blockages and pressure drop. Axial and angular components of momentum at the throats of the cyclones are established based on conservation of mass, momentum, and energy for coal combustion in the cyclone furnace. These conditions are imposed at the re-entrant throat of the numerical flow model.

A comparison of numerical, physical, and field cold flow results is shown in Figure 5-3 and a comparison of numerical and field hot flow velocity profiles is shown in Figure 5-4. Predictions are in general agreement with the physical flow data and the field velocity measurements; thus, this information provides the means for validating the physical and numerical flow models. In all cases, the velocity is highest near the rear wall, and a recirculation zone exists in the main furnace with flow moving downward along the front wall and target wall.

Some disparities exist between data and predictions, however. The numerical model shows a bias in flow to the left side, due to the clockwise cyclone swirl, that could not be confirmed by the data. The velocity gradient from front to rear is also somewhat steeper at Nelson Dewey than for the numerical model (Figure 5-4). These differences are not significant, however. A sensitivity analysis was performed with the numerical model to ensure that the mixing results were not affected by these differences.

5.3 Reburning System Evaluation

The same physical flow model used for the baseline flow test was also used for the reburning system evaluation with the addition of reburning burners and OFA ports. Test variables for the reburning system in the physical flow model were the number and the location of reburning burners and OFA ports; the secondary variables are FGR

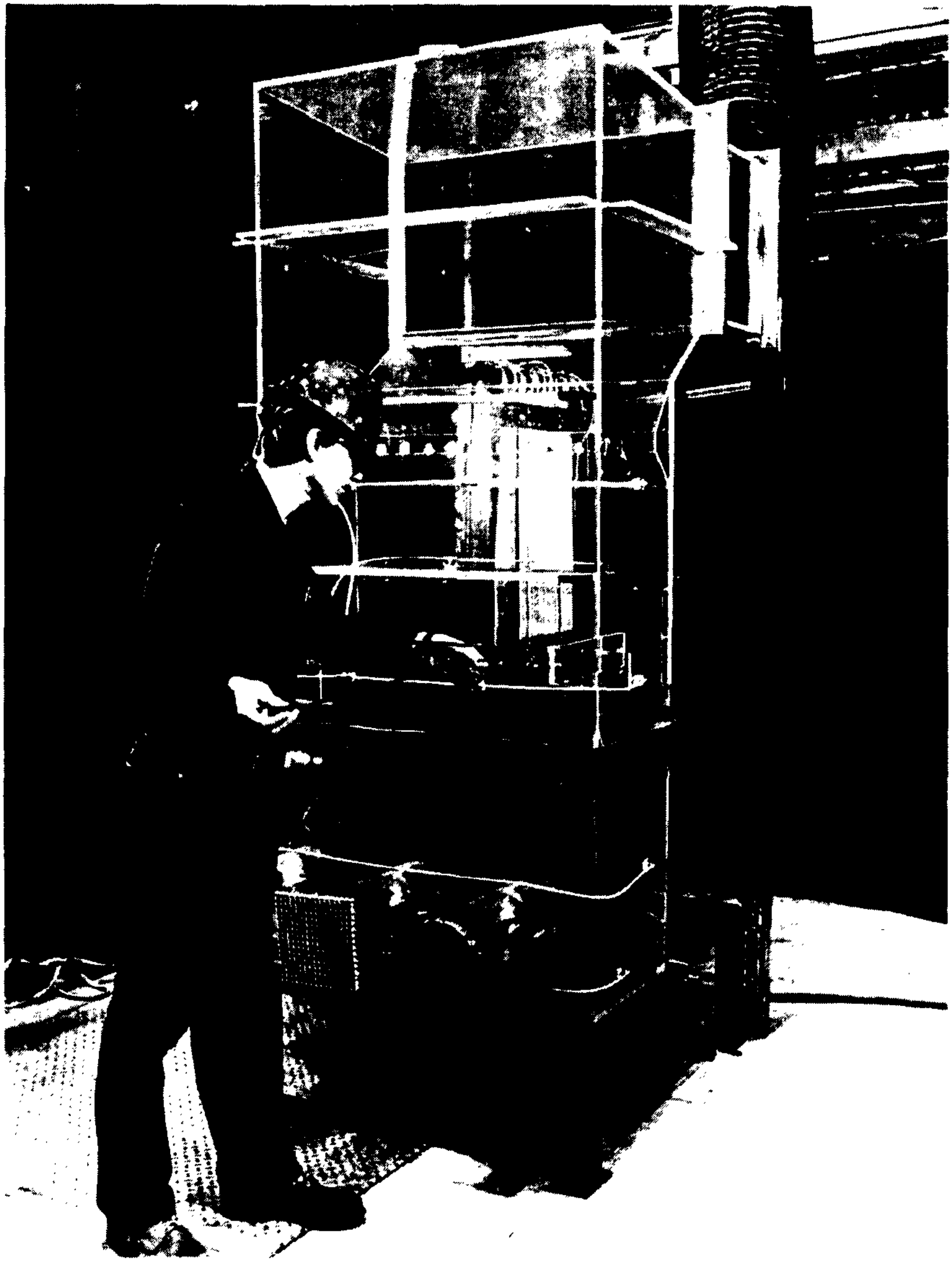


Figure 5-2 Photograph of the 1/12-Scale Physical Flow Model

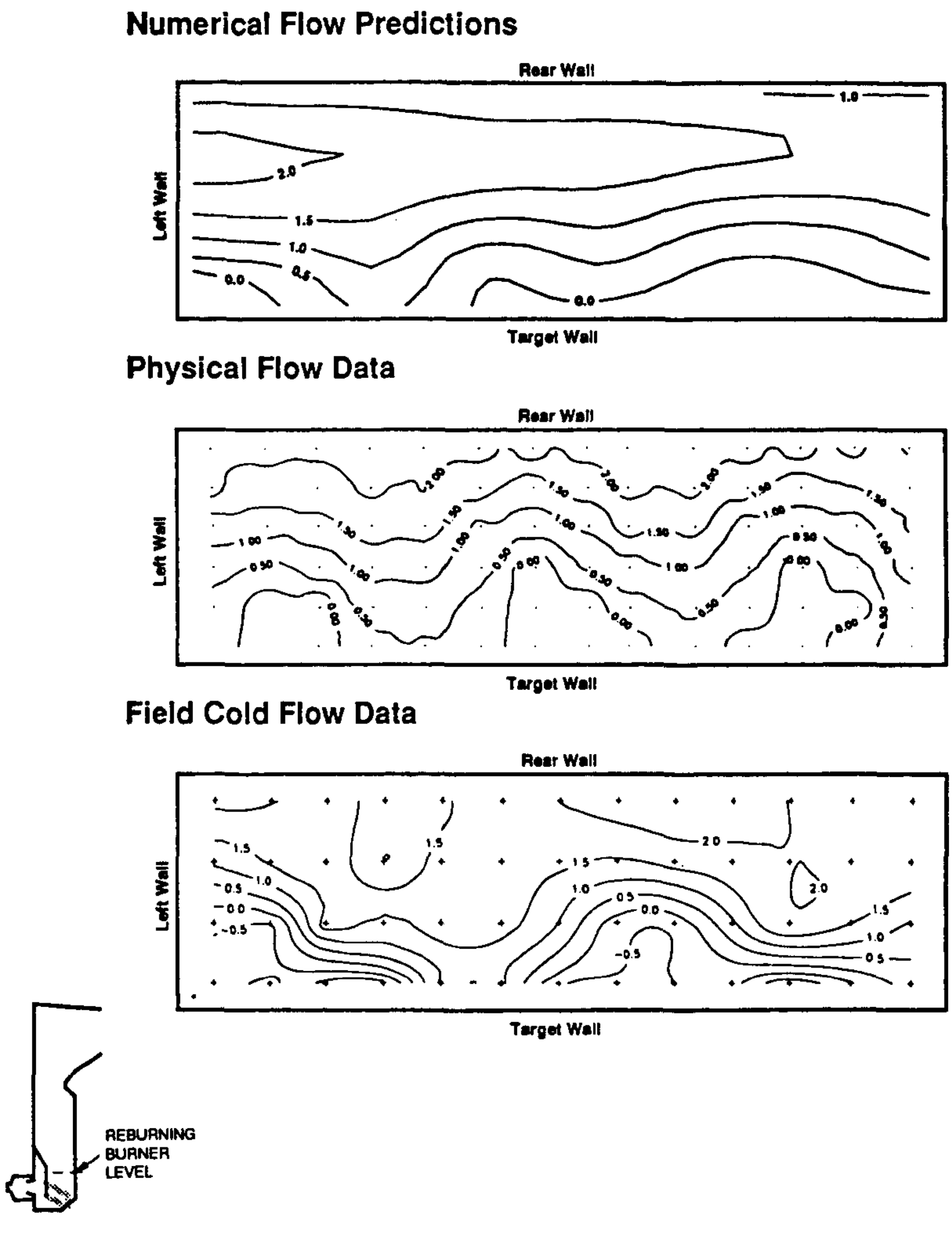


Figure 5-3 Comparison of Normalized Velocity Distributions at the Reburning Burner Level

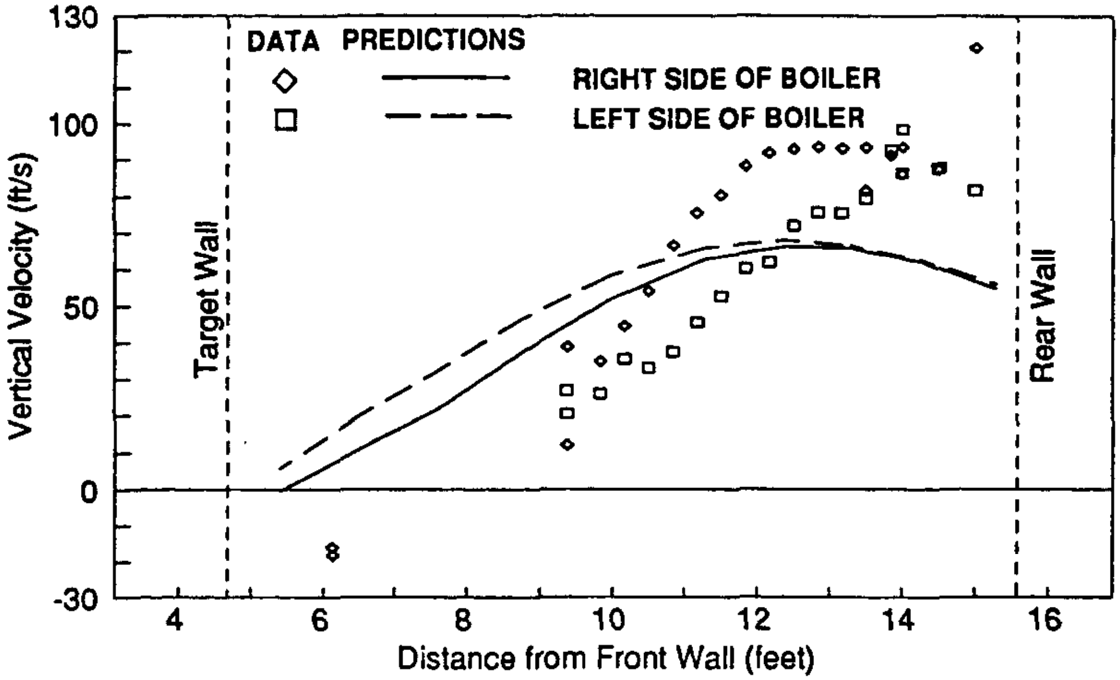


Figure 5-4 Comparison of Velocity Profiles at the Reburning Burner Level for the Numerical Flow Model and the Hot Flow Test in the Field Unit

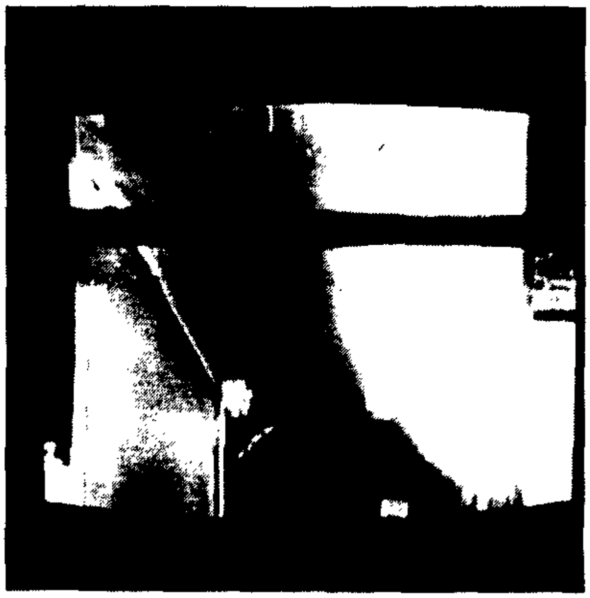
and cyclone/reburning burner fuel split. To evaluate the mixing performance of the reburning burners, cold air was aspirated through the cyclones and heated air was supplied through the primary and secondary flow passages in the reburning burners. Temperatures of the mixed air were measured at the OFA port level with the OFA ports out of service. To evaluate the mixing performance of the OFA ports, cold air was aspirated through the cyclones and the reburning burners and heated air was supplied through the OFA ports. Temperatures of the mixed air were measured at the furnace arch level.

The FORCE numerical flow model was used to simulate the flow patterns and evaluate mixing effectiveness for the reburning system in the WP&L boiler. In addition to equations for conservation of mass and momentum, FORCE predicts the distribution of scalar quantities such as temperature or stoichiometric ratio in the furnace. Three-dimensional distributions of stoichiometric ratio were statistically analyzed to determine the best configuration for mixing.

As mentioned earlier, numerical model predictions were in general agreement with the baseline results of the Nelson Dewey boiler measurements. In order to validate the numerical model for penetration from the reburning burners and OFA ports, numerical simulation of the physical model was performed. In this simulation, the measured velocity distribution approaching the reburning burner elevation was used as the inlet boundary conditions of the numerical model. This eliminated the uncertainties associated with differences between the numerical flow predictions and the steep velocity gradients of the physical flow measurements. Numerical model predictions of jet penetration were in qualitative agreement with flow visualization in the physical model using smoke injection, as shown in Figure 5-5.

The methodology used for numerical simulation of the physical model was used for the full-scale reburning system. The measured velocity profiles from the Nelson Dewey boiler were used as the inlet boundary condition of the numerical model. The predicted flow patterns and stoichiometry distribution in the furnace are shown in Figure 5-6. The shaded region is the reducing zone where NO_x destruction takes place. The recirculation zone that was present during baseline conditions was fortunately eliminated during reburning conditions. The reburning burner flow has adequate penetration without impinging on the target wall because the location of low stoichiometry is near the center of the furnace. Adequate reburning burner penetration will maintain flame stability and prevent tube wastage. The OFA flow also penetrates adequately and will be discussed later.

A complete numerical simulation of the reburning system, including cyclones and screen tubes, was performed. The purpose was to evaluate the effects of lower furnace velocity gradients computed by the model on the mixing performance. Similar mixing performance was achieved for the reburning burner penetration as the previous



PHOTOGRAPH
OF TEST 31

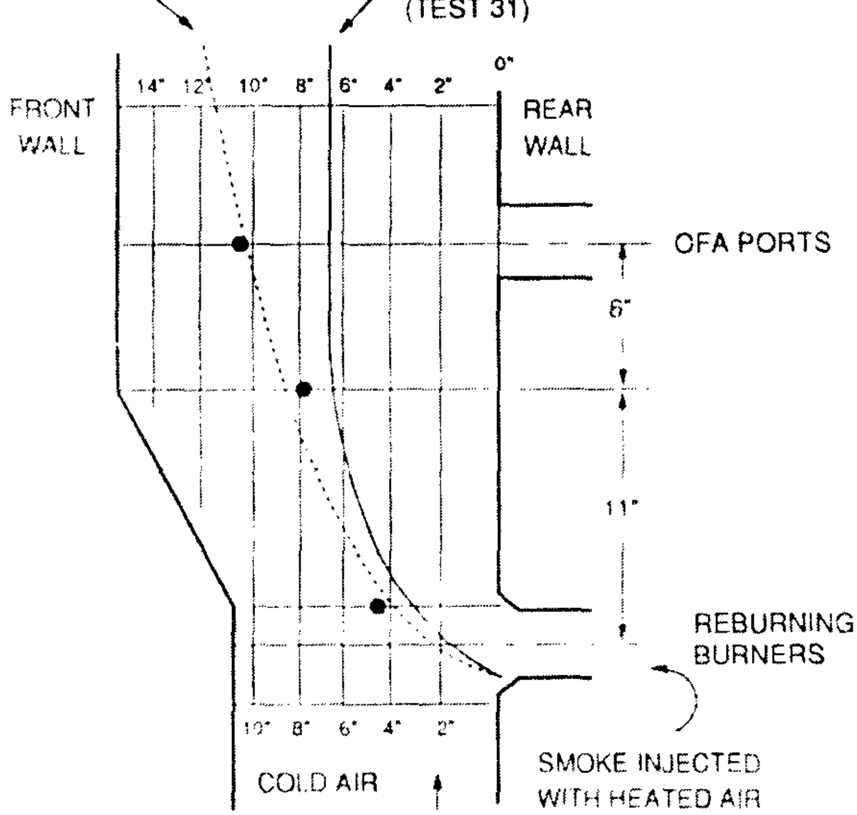


Figure 5-5 Visualization of Reburning Burner Penetration Using Smoke Injection

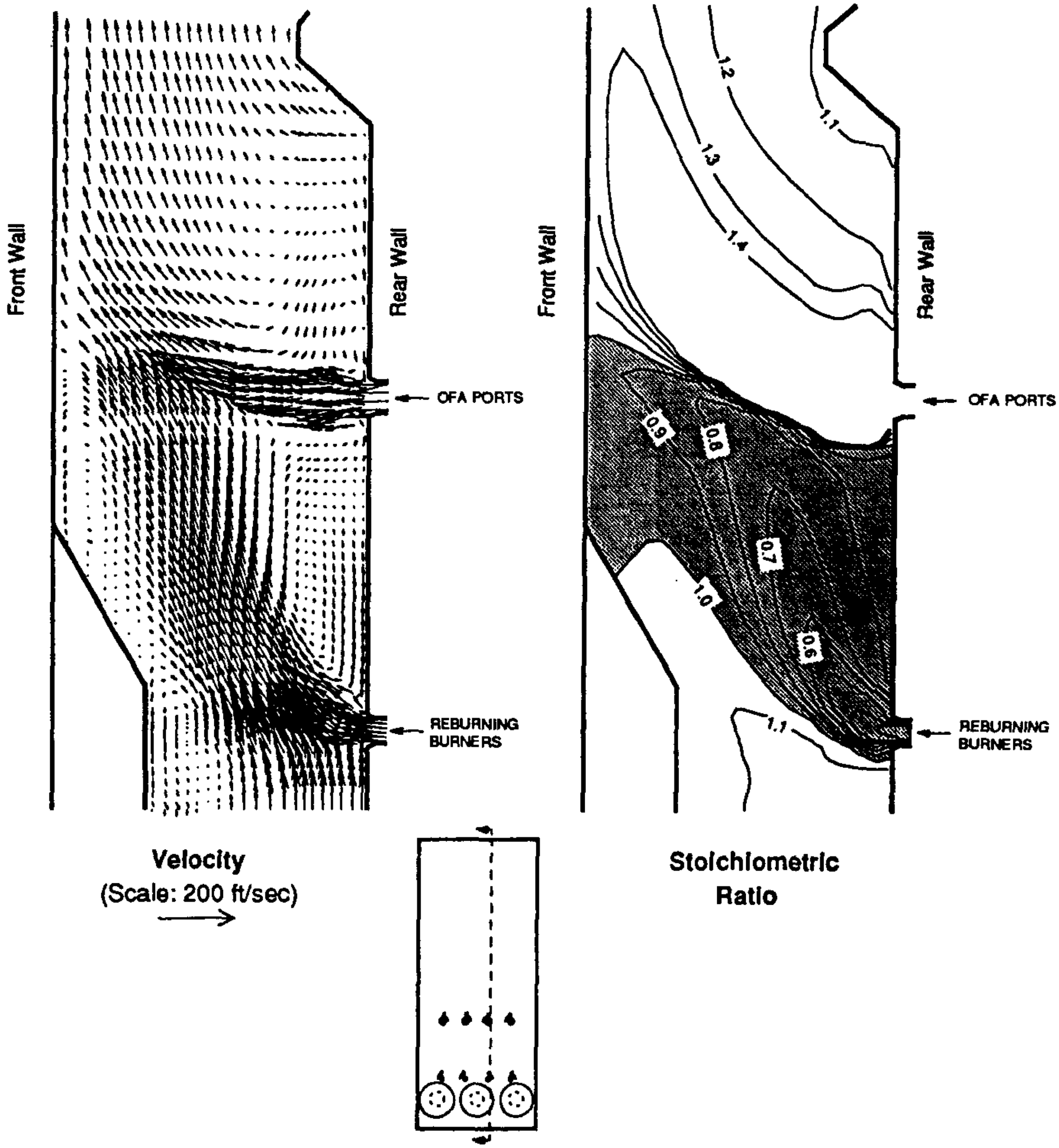


Figure 5-6 Flow Patterns and Stoichiometric Ratio Distribution Predicted by the Numerical Flow Model for Full-Scale With Four Reburning Burners 925% Fuel, 5% FGR) and Four OFA Ports

simulations utilizing measured velocities from the full-scale unit. The numerical model is capable of predicting the mixing and stoichiometry distributions. Detailed combustion and heat transfer predictions using B&W models were conducted later during this project, and results are presented in Section 9.0.

Numerous cases were studied using the validated model. These cases included the effects of size, number and location of the burners and OFA ports, and the addition of FGR on mixing. Figure 5-7 shows the mixing performance computations for three and four burners. When FGR was not used, mixing with three reburning burners was almost as good as that with four reburning burners, with approximately 60% of the flow reaching the reducing conditions. The maximum flow achieving reducing conditions was observed when four burners were used along with FGR. A total of 80% of the flow reached the reducing environment with four reburning burners in comparison to 62% for a three reburning burner system. The OFA mixing was also good in that all flow reached the oxidizing conditions before exiting the furnace. The predicted mixing performance of the Nelson Dewey boiler with four reburning burners/OFA ports was similar to that of the SBS. Therefore, four reburning burners were recommended for the reburn retrofit.

5.4 Conclusions and Recommendations

Based on physical and numerical flow modeling results, the proposed coal reburning retrofit for the WP&L boiler will achieve the expected flow and mixing performance conditions when the unit is operated and tested in the field. This conclusion is supported by the following:

- Physical and numerical models simulate the major features of furnace gas flow leaving the cyclones of the WP&L boiler. Field flow test data, and physical and numerical flow model results are in qualitative agreement for the baseline configuration.

- Physical and numerical flow model results are in qualitative agreement for the 1/12-scale model of the reburning system. Numerical models are based on a fundamental description of turbulent fluid dynamic processes which are the same regardless of scale. Therefore, the numerical model can be used for qualitative evaluation and scale-up of the reburning system design.

- Predicted performance for the full-scale reburning system achieves mixing objectives established by the pilot-scale combustion tests. Penetration of the reburning burner flow is acceptable. Greater than 80% of the flow in the reburning zone reaches substoichiometric conditions. All of the flow in the burnout zone reaches a stoichiometric ratio greater than 1.0 upstream of the furnace exit.

- Four reburning burners and four OFA ports provide the best mixing performance. Reburning burner flow penetration and

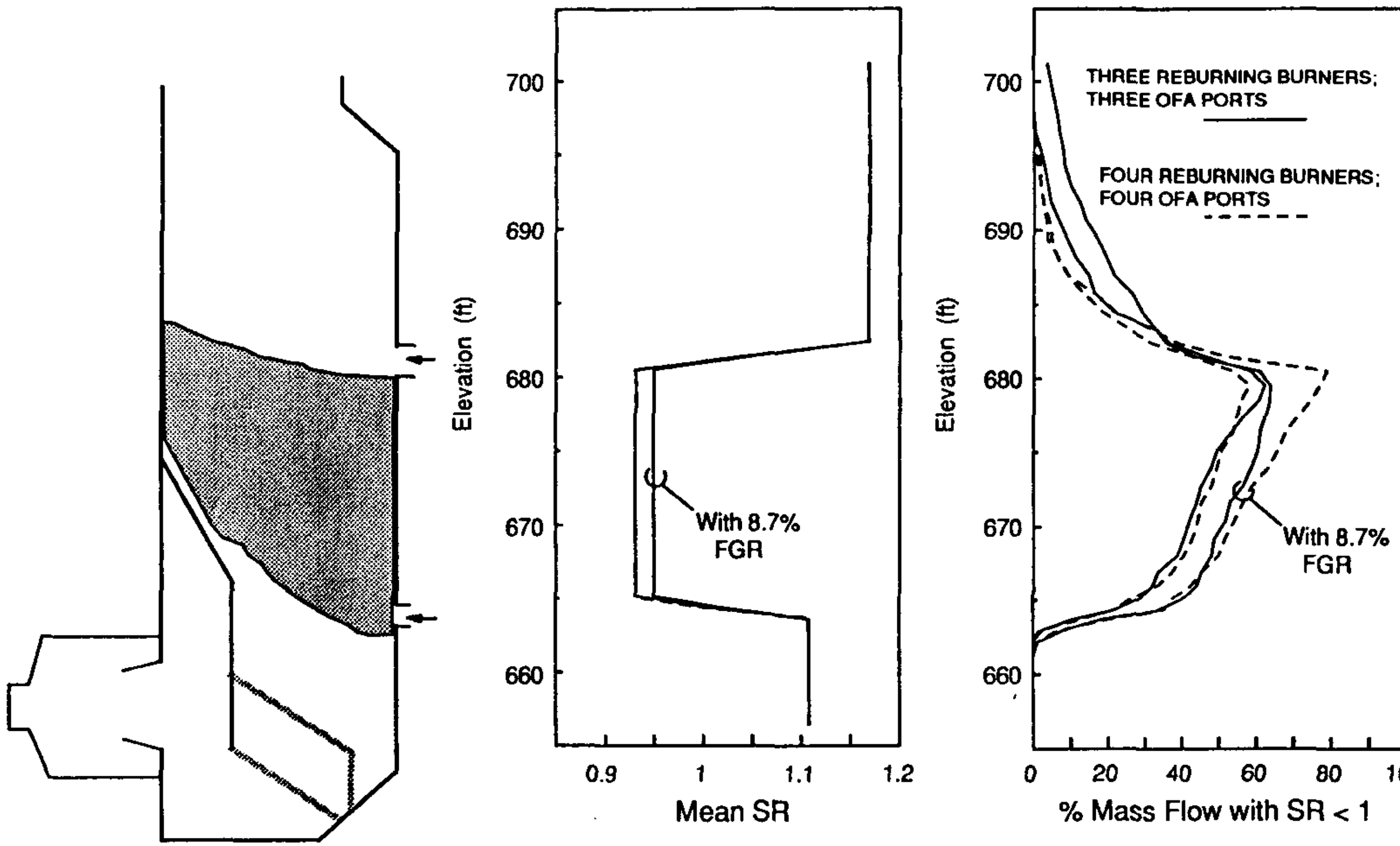


Figure 5-7 Effect of the Number of Reburning Burners and OFA Ports on Predicted Mixing Performance (25% Fuel to the Reburning Burners)

mixing performance improve with increasing amounts of FGR and fuel provided to the reburning burners. Thus, the coal reburning burner and OFA port designs will provide sufficient flexibility to ensure effective mixing.

The following reburning system design recommendations are made:

- Use four S-Type reburning burners at the 664-foot elevation.
- Use four dual-zone NO_x (OFA) ports at the 681-foot elevation.
- Include the capability to add 5 to 10% FGR to the reburning burners.
- Maintain the capability for 25 to 30% fuel to the reburning burners.

5.5 Modeling Support Via Full-Scale Utility Measurements

In order to support the modeling activities discussed above and also to subsequently improve future reburning scale-up practices for various unit configurations, in-furnace probing at WP&L's Nelson Dewey Unit #2 was performed. Both gas species and temperatures were measured at multiple furnace elevations during post-retrofit baseline and reburning conditions. The ultimate goal was to develop a tool for commercialization that will help locate/size reburn components to provide optimized mixing capabilities and also predict resulting emission levels.

The measurements that were obtained include O2 (%), CO (ppm), NO_x (ppm), and temperature (°F). These measurements were obtained at various furnace elevations. The critical elevations were at the furnace exit (elv. 700), within the reburn zone (elv. 676), and at the approximate reburn burner location (elv. 666). Two (2) observation port openings were probed at elevation 700 while only one (1) port was available at each of the other elevations. Each of these locations include a total of 10 to 11 furnace measurements across the width of the boiler. The B&W Results Department provided the manpower and equipment to obtain this data. The Baseline Test Report[9] describes the procedures used to perform these measurements.

Table 5-1 is a summary of the averaged baseline and reburning in-furnace probing data during operation at 110 MW_e load conditions. All the data presented in the table are averages of the 10 or 11 in-furnace measurements. At elevation 700, two (2) measurements are identified and these were obtained at the observation port openings located toward the rearwall/frontwall respectively. Appendix 4 contains plots of all the in-furnace data collected.

TABLE 5-1 FULL LOAD (110 MW_e) IN-FURNACE PROBING SUMMARY				
CONDITION/LOCATION	TEMPERATURE (°F)	O2 (%)	CO (ppm)	NO_x (ppm)
	(REAR/FRONT)	(R/F)	(R/F)	
BASELINE @ ELV 700	2246/2269	2.5/3.7	174/213	-
REBURN @ ELV 700: #20T	2087/2190	5.1/2.8	653/1481	-
REBURN @ ELV 700: #8P	2203/2217	2.7/4.0	1320/246	-
BASELINE @ ELV 676	2260	3.7	239	490
REBURN @ ELV 676: #20T	2658	0.50	6639	443
REBURNING @ ELV 666	-	1.96	364	-

Table 5-1 compares the post-retrofit baseline tests with reburn tests #20T and #8P. The difference between these 2 reburning tests is that a burner modification had occurred and the resulting furnace gas flow patterns were affected. This modification will be discussed in more detail in later sections of this report. The main issue of concern for this evaluation is the fact that the #20T test was performed with a reburn burner flame length that was longer and more narrow than that observed during the #8P test. Thus, more penetration of the fuel rich reburn stream should be observed during the #20T test as compared with test #8P.

Since the fuel rich stream in test #20T penetrates the furnace to a greater degree, the O2% is correspondingly lower toward the front wall of the boiler (2.8% O2 vs 5.1% O2). Likewise, the CO emission levels are higher at the front wall side (1481 ppm vs 653 ppm). As expected, the opposite results are observed in test #8P since less penetration is seen. The higher % O2 is now at the front side of the boiler (4.0% vs 2.7% O2) and the corresponding CO emissions are lower (246 ppm vs 1320 ppm).

Although the CO emission levels shown at elevation 700 are higher than ideal, the resulting economizer outlet levels are well below critical. The average economizer outlet CO levels for the baseline, #20T, and #8P tests were 70 ppm, 77 ppm, and 81 ppm respectively. The overfire air ports were optimized to minimize the CO emissions at the economizer outlet.

Temperatures at elevation 700 showed that the average baseline values are higher than those observed during either of the reburning tests identified. These results were also confirmed throughout all of the boiler performance calculations and will be extensively reviewed in section 7.0 of this report. At this point, it suffices to say that these results are all consistent with those identified throughout the entire project and that these measurements can be utilized to benchmark future modeling activities.

Moving down the furnace height to the reburn zone (elv. 676) provided interesting information as to the reburning process itself. As anticipated, the average % O2 level was low at 0.50 % and the corresponding CO emissions high at 6639 ppm. Baseline data at this elevation showed O2 and CO values of 3.7% O2 and 239 ppm CO respectively. Increased temperatures were also seen during the reburn operation and this is due to the reburn coal combustion occurring higher in the furnace region.

NO_x emissions were also measured at this lower elevation and the baseline versus reburning NO_x levels were not significantly different. This unexpected result revealed that only about a 9.6% NO_x reduction had occurred between the averaged data for each of these cases. The economizer outlet NO_x emissions during these baseline and reburn tests were 603 ppm and 270 ppm corrected to 3% respectively, and this corresponds to a 55% NO_x reduction. Thus, this result would lead one to believe that the NO_x reduction kinetics were not yet complete at the one small region measured, or that the mixing between the reburn/cyclone streams had not yet been achieved. Observing the low %O2 and the high CO data at this location shows that the mixing had occurred. Further investigation is required to fully understand these results.

Finally, O2 and CO measurements were taken at elevation 666 during reburning operation to help assure that the cyclones were operating at the specified conditions. Since the cyclones were set up to run at about 2% O2 or a 1.1 stoichiometry, the 1.96% O2 shown in Table 5-1 proves that the required air/fuel relationship was being accurately maintained. In addition, the 364 ppm CO emission level is in line with the baseline levels, and this shows that no fuel rich reburn flow is recirculating down below the reburn burner elevation.

Similar data is obtained at 82 MW_e and the same trends observed with the 110 MW_e data presented above are apparent. The post-retrofit baseline data is compared with reburning test #47T. As with the 110 MW_e reburn test #20T, 47T was performed while utilizing the burner arrangement that resulted in a greater fuel rich penetration condition. Table 5-2 shows the averaged baseline versus reburning data for the in-furnace probing. Appendix 4 contains plots of all the in-furnace data collected.

TABLE 5-2 MEDIUM LOAD (82 MW_e) IN-FURNACE PROBING SUMMARY				
CONDITION/LOCATION	TEMPERATURE (°F)	O2 (%)	CO (ppm)	NO_x (ppm)
	(REAR/FRONT)	(R/F)	(R/F)	
BASELINE @ ELV 700	2119/2089	3.5/3.0	42/3	-
REBURN @ ELV 700: #47T	1989/2120	6.2/3.2	96/2175	-
BASELINE @ ELV 676	1952	3.40	48	480
REBURN @ ELV 676 :#47T	2489	0.40	6156	358

All the same trends described for the full load tests are apparent at this reduced load condition. One interesting note is that the NO_x emissions reveal a 25.4% reduction at this load versus only a 9.6% change at the higher load. Thus, either an improvement in mixing occurred, or the longer reburn zone residence time at the reduced load condition resulted in better reburn efficiency. Although improved, the economizer outlet NO_x emission levels at the 82 MW_e baseline and reburn tests were 535 ppm and 237 ppm respectively and this corresponds to a 55.7% reduction.

Based upon all the in-furnace probing data obtained throughout this project, B&W mathematical modeling activities can be improved to reflect actual field measurements. Future modeling work can be accomplished to aid reburn system scale-up designs and predictions of resultant emission levels.

6.0 Coal Reburning System for Nelson Dewey Unit No. 2

6.1 Implementation of Modeling Results

The reburning system design philosophy included using physical and numerical modeling along with B&W low NO_x burner/overfire air port design experience. Questions which had to be answered pertained to the size, number, and location of reburn burners and OFA ports. The goal--to obtain good mixing at the reburn burner elevation and OFA ports--is essential for NO_x reduction and combustible burn-out. In addition, proper penetration of the reburn burners fuel streams into the hot flue gas is important since over-penetration or under-penetration would cause tube wastage in the boiler, along with potential burner flame instability problems.

Simultaneous modeling of the cyclone, reburn burners and OFA ports within one system is a new and unique procedure. Development of a modeling methodology to assess mixing and penetration results was required. The following plan was developed to meet the above stated goals:

- Develop a procedure to simulate cyclone boiler flue gas flow in cold flow and numerical models. Compare (validate) these results with actual baseline flow measurements obtained at Nelson Dewey.

- Use the validated cold flow model to simulate the reburn system conditions using fundamental laws of aerodynamic similarity.

- Use the validated numerical model to simulate the reburn system conditions using B&W's FORCE and CYCLONE model computer codes.

Utilizing the conclusions/recommendations from the physical/numerical modeling as outlined in section 5.0, along with B&W's low NO_x system design experience, the reburn system design was determined. A flow schematic and an isometric view of the overall system design are shown in Figures 6-1 and 6-2, respectively.

Figure 6-2 shows a general overview of the reburning system and how it compares to the existing boiler arrangement. The pulverizer (and associated equipment) are located in a new building enclosure adjacent to the existing building. The hot primary air (PA) supply is taken off the left side of the air heater and ducted to the PA fan inlet. Tempering air is fed to the PA prior to the PA fan inlet in order to control pulverizer air inlet temperatures. Automatic dampers have been installed in each of these ducts. In addition, an isolation damper (automatic) is located just prior to the PA fan inlet to allow maintenance on the fan/pulverizer when the boiler is operating. An air measuring device is located just prior to the pulverizer inlet to measure total primary air flow.

Secondary air to the reburning burners is also supplied from an air heater outlet takeoff point located at the center bottom of the air heater. An automatic damper and air monitor are located within this

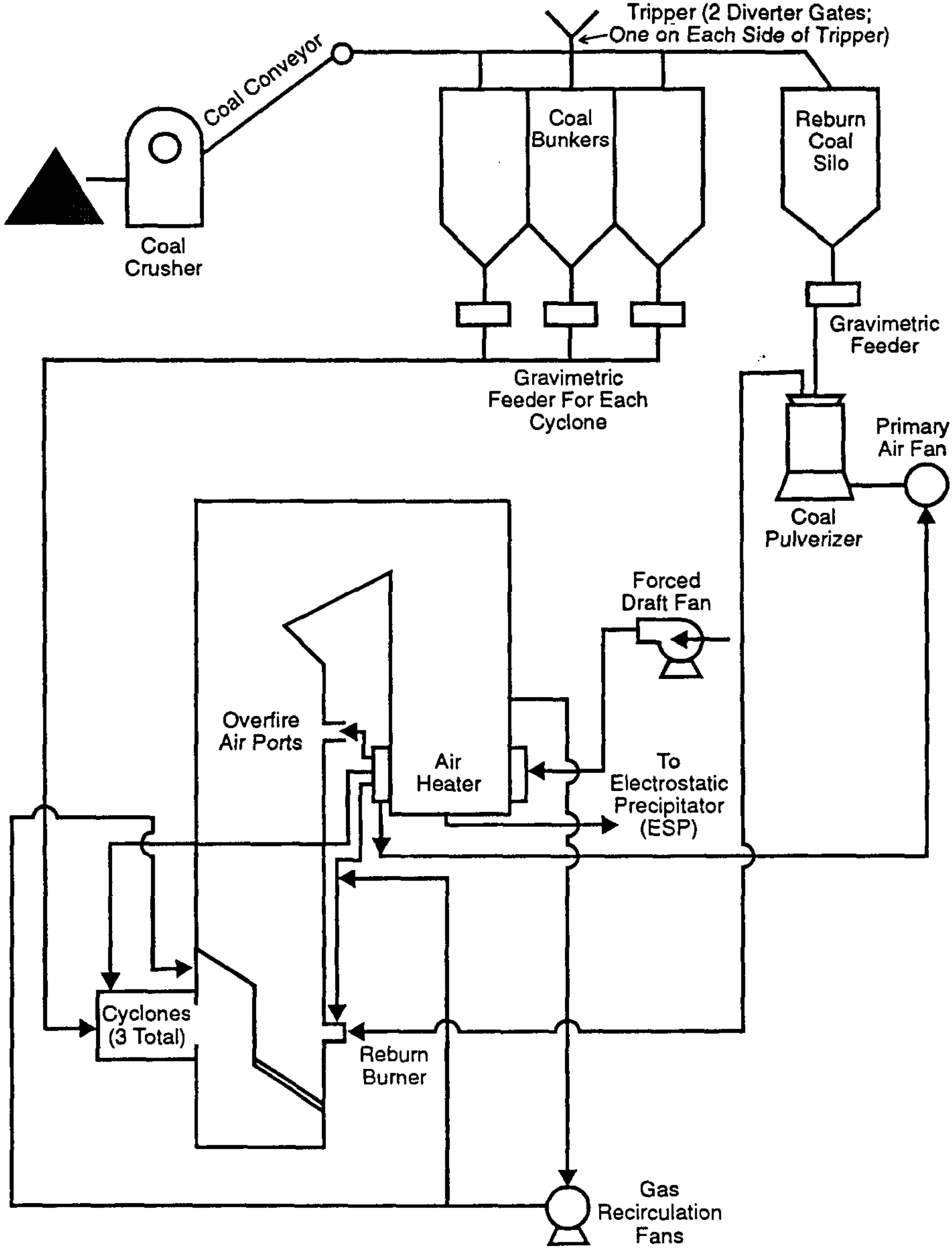


Figure 6.1 – Reburn System Flow Schematic

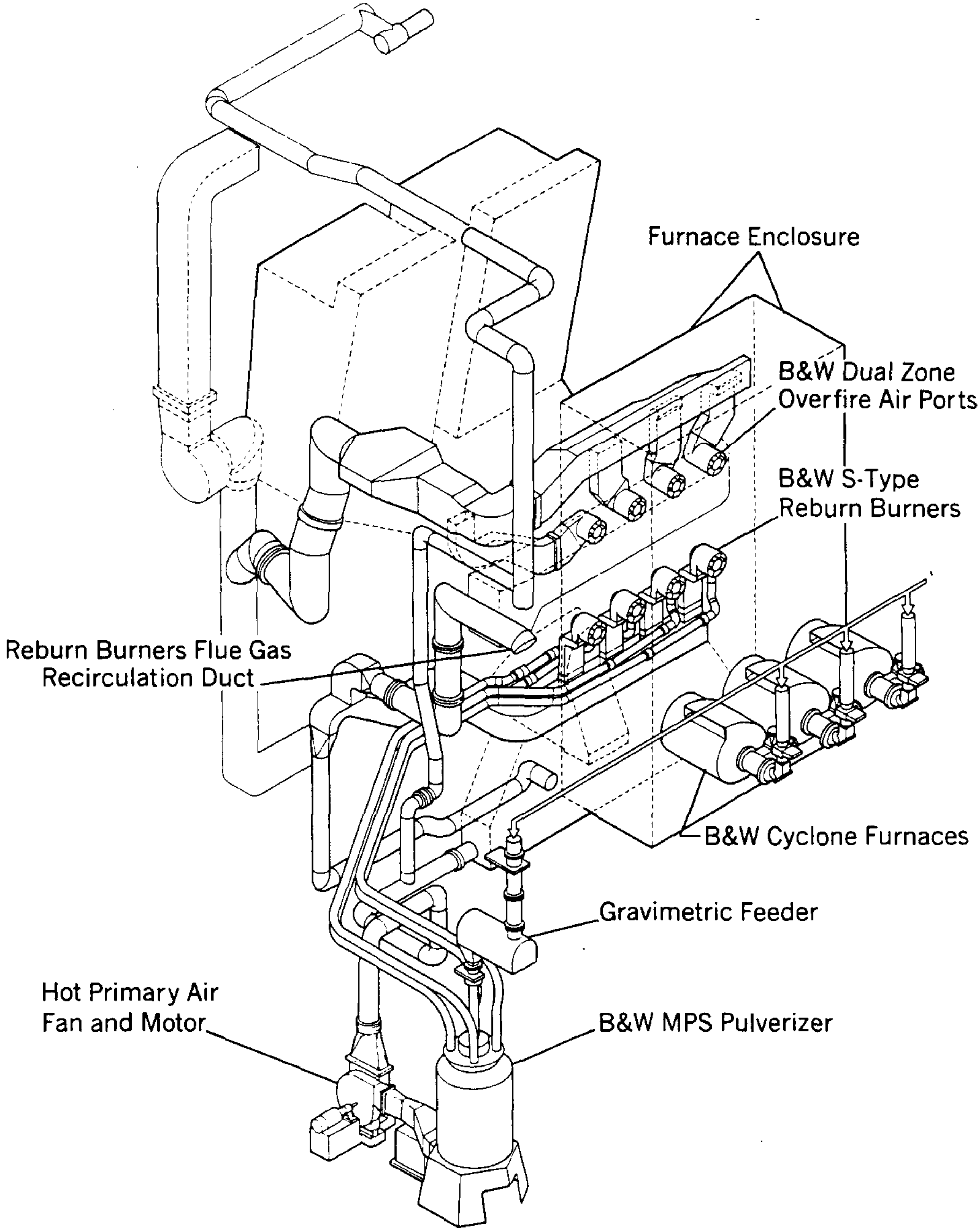


Figure 6-2 The Coal Reburning System Installed at WP&L's Nelson Dewey Unit No. 2

line to control and measure total secondary air flow to the burners. Gas recirculation is introduced into this system to vary the total mass flow through the burners. The gas recirculation (GR) takeoff is located after the existing system's GR fans and is tied into the secondary air duct prior to the burner splits. An automatic damper and monitor are installed in this flue to control and measure flow. Finally, this air/gas to the burner subsystem contains four manually adjustable dampers, one in each of the lines leading to the individual burners. These dampers were utilized during system commissioning to balance flows to each burner in case an imbalance exists.

The OFA system is supplied from the existing boiler's hot air recirculation system. The hot air recirculation system is available to take air from the air heater outlet to the FD fan discharge (basically an air preheat system originally designed to help protect against cold end air heater corrosion). The OFA takeoff is upstream to a booster fan in this system. The duct work which leads to the four OFA ports includes an automatic damper/air monitor to control and measure total air flow to the OFA system.

Location of the burners and OFA ports are also shown relative to the boiler in Figure 6-3, a boiler sectional side view. A complete description of each segment of the system follows.

6.2 Combustion Hardware

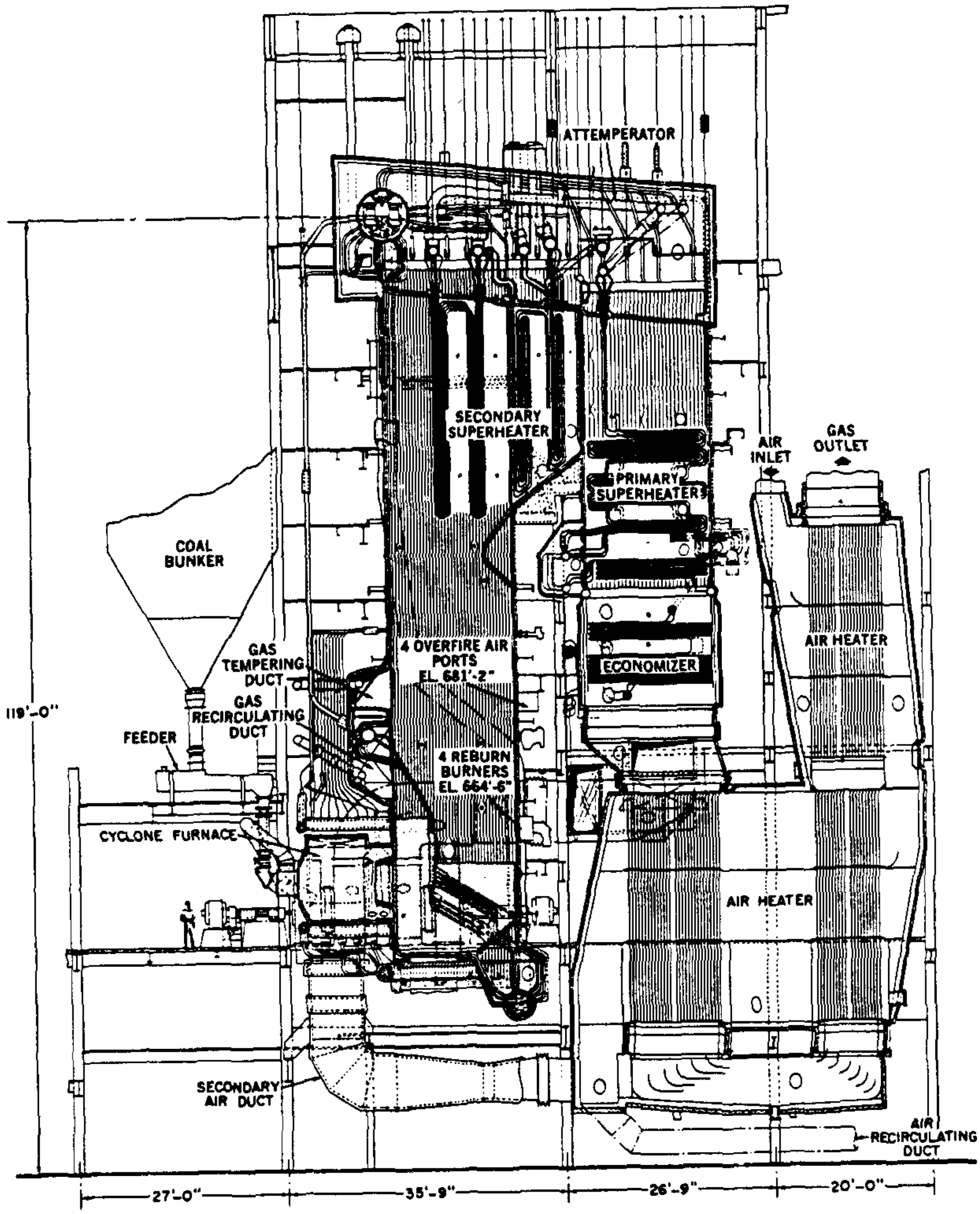
6.2.1 Cyclones (Existing Equipment)

Unit #2 at Nelson Dewey Station is equipped with three (3) cyclone furnaces/vortex-type burners oriented along the boiler front wall. Crushed coal and air is introduced through the cyclone burner into the cyclone barrel. This main combustion zone is operated with 70-75% of the required fuel heat input. The cyclone burners are operated at an approximate minimum stoichiometry of 1.1 (10% excess air).

Physically the original cyclone equipment did not require modification for the cyclone reburn process. The current gravimetric coal feeders provide adequate coal flow measurement and control needed to maintain the stringent stoichiometric operating parameters within the cyclone. In addition, each cyclone presently contains its own individual air flow measurement capability since each cyclone has its own secondary air duct.

6.2.2 Reburn Burners

Four (4) B&W S-Type Burners were installed on the rear furnace wall at boiler elevation 664'- 6", and are spaced side to side on approximate seven foot centers. The burner characteristics include a coal nozzle with a manually adjustable impeller (with capability to deflect coal/air direction), one (1) single outer air zone with manually adjustable spin vanes, individual burner air measuring device (in order to balance air/gas flows) and



Wisconsin Power & Light Company
Nelson Dewey Station - Unit No. 2 (RB-369)
Cassville, Wisconsin
Cyclone Reburn Project

Figure 6-3

each burner contains its own individual windbox (part of the burner assembly). Figure 6-4 is a sectional burner assembly drawing for the burners.

Four (4) coal pipes convey the coal/ primary air mixture from the MPS coal pulverizer to the burners. Each coal pipe includes two valves, one dust tight automatic valve at the pulverizer, and one manually operated isolation valve at each burner. Manually operated seal air is also available between these valves when pulverizer maintenance is required during boiler operation. The total combustion air to the reburn burners includes the primary air flow, secondary air flow, and any gas recirculation flow to the burners. The secondary air source is from the existing air heater outlet via a 26" diameter duct. Regulation of the secondary air flow is accomplished by a single damper, positioned at elevation 624'-0", immediately downstream of the air heater. An air flow monitor located downstream of the damper measures the secondary air flow. The gas recirculation duct, which ties into the secondary air duct at elevation 659', sources gas from the existing gas recirculation system at elevation 683'- 1". A control damper/air monitor, located in the 40" diameter gas recirculation duct, regulates and measures the gas flow to the secondary air and gas recirculation junction.

The use of gas recirculation serves the function of promoting increased penetration of the fuel/ air mixture into the furnace, if required, thus maximizing the flexibility to vary mixing potential and improve NO_x reduction. A manual biasing damper located just upstream of each burner allows for the balancing of air flow (differential pressure) to each burner.

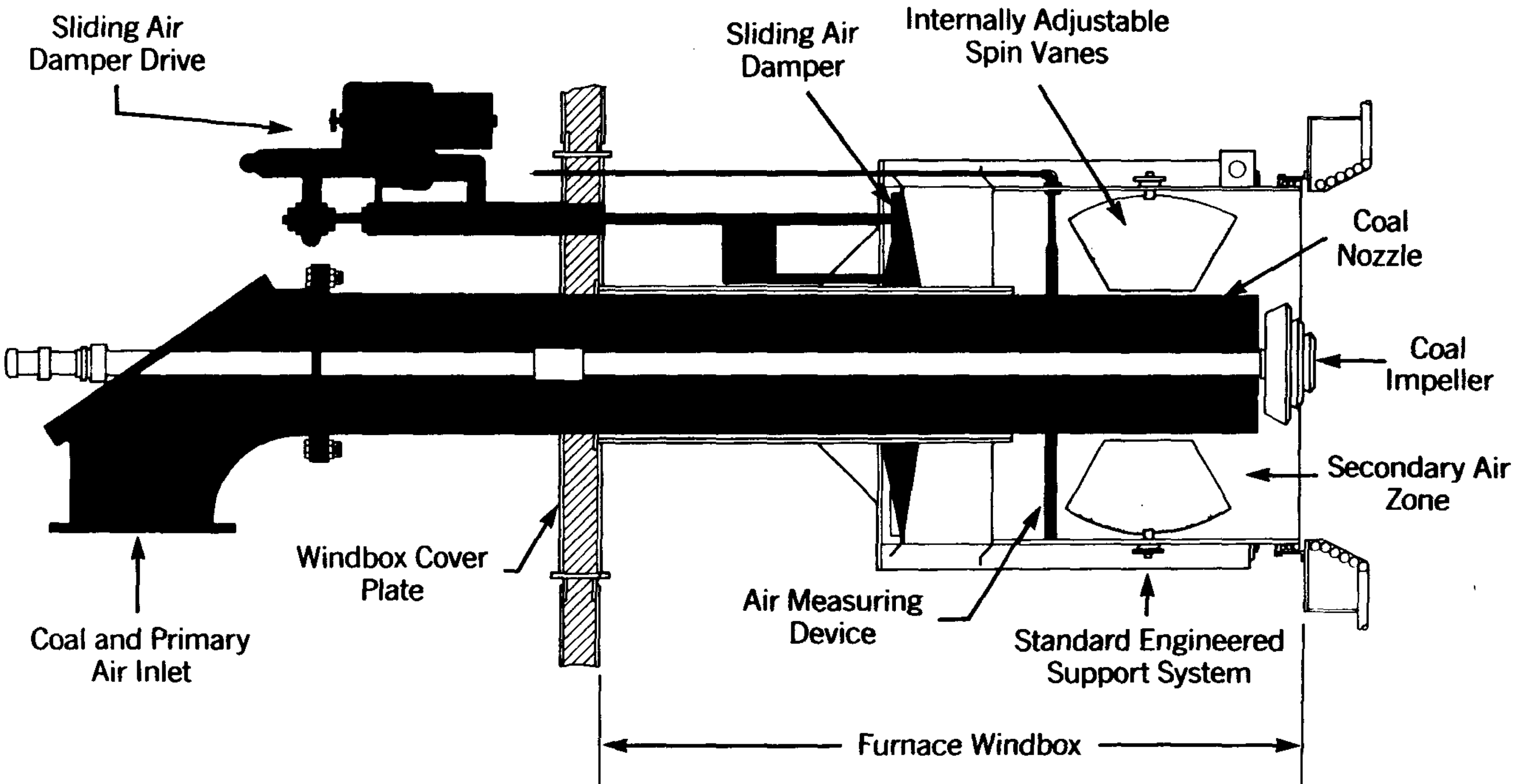
Each burner is equipped with a single No. 2 fuel oil non-retractable lighter with a retractable high energy spark source. A shop fabricated B&W PLC-150 Ignitor Control Package with valve rack assembly, controls the ignitor, high energy spark system, oil, and atomizing/ purge medium. The fuel oil and atomizing/purge medium is supplied from existing plant sources.

The burners are operated such that all four (4) burners are in service at the same time. Provisions in the control system, however, allows for one (1) burner to be out-of-service at any given time. This option will be utilized on a test basis only, and will not be considered a full time option. Flame scanning logic permits operation (avoiding a reburn fuel system trip) with a minimum of two (2) burner flames detected. The Detector Electronic flame scanners contain the flexibility to remotely adjust the gain settings if required.

6.2.3 Overfire Air (OFA) Ports

Four (4) B&W Dual-Air Overfire Air Ports were installed on the furnace rear wall at boiler elevation 681'- 2". The OFA ports

S-Type Burner
P. C. Fired



Babcock & Wilcox
a McDermott company
October 1990
feq04A2/1

Figure 6-4

provide the balance of combustion air to bring the total boiler air flow to a stoichiometry of approximately 1.16. The OFA ports consist of two (2) air zones. The inner zone contains a manual sliding disk control in order to vary the air penetration capability of the port. The outer zone houses manually adjustable spin vanes in order to vary the side to side mixing capability. As with the S-Type burner, each OFA port assembly contains its own windbox. Figure 6-5 is a sectional OFA port assembly drawing.

The overfire air source is from the existing air heater, hot air recirculation duct, with the tie-in point at elevation 659'- 6". A 58" diameter duct directs the overfire air through a control damper up to the OFA port take-off ducts located at elevation 689'- 1". The total overfire air flow is measured by an air monitor positioned between the control damper and OFA port take-off. Each OFA port is equipped with an air measurement device (a pitot tube arrangement) allowing for the balancing of air flow through each port.

6.3 Coal Preparation & Handling

6.3.1 Coal Conveyor System

To accommodate the new coal reburn fuel preparation equipment, and the location of the new 150-ton silo, the existing coal conveyor system had to be modified. Tripper conveyor D-1 was revised such that coal from the main conveyor can be diverted to the tripper conveyor for supplying the new silo. The basic objective of the conveyor system modification was to extend tripper conveyor D-1, and provide the necessary hardware to be able to provide a satisfactory and reliable coal supply for the reburn process. The basic hardware includes:

- Two (2) power-operated diverter gates
- Loading chutes
- Idlers
- Skirtboards
- Inspection doors
- Additional belting
- Conveyor extension enclosure

General electrical equipment includes:

- Diverter chute push button (P.B.) station
- Inching P.B. station
- Emergency stop P.B. station
- Emergency stop cable switch
- Over-travel limit switch
- Chute heating pads
- Chute control thermostat
- Chute alarm thermostat
- Plugged chute detector

Overfire Air Port Assembly
(Dual Air Zone)

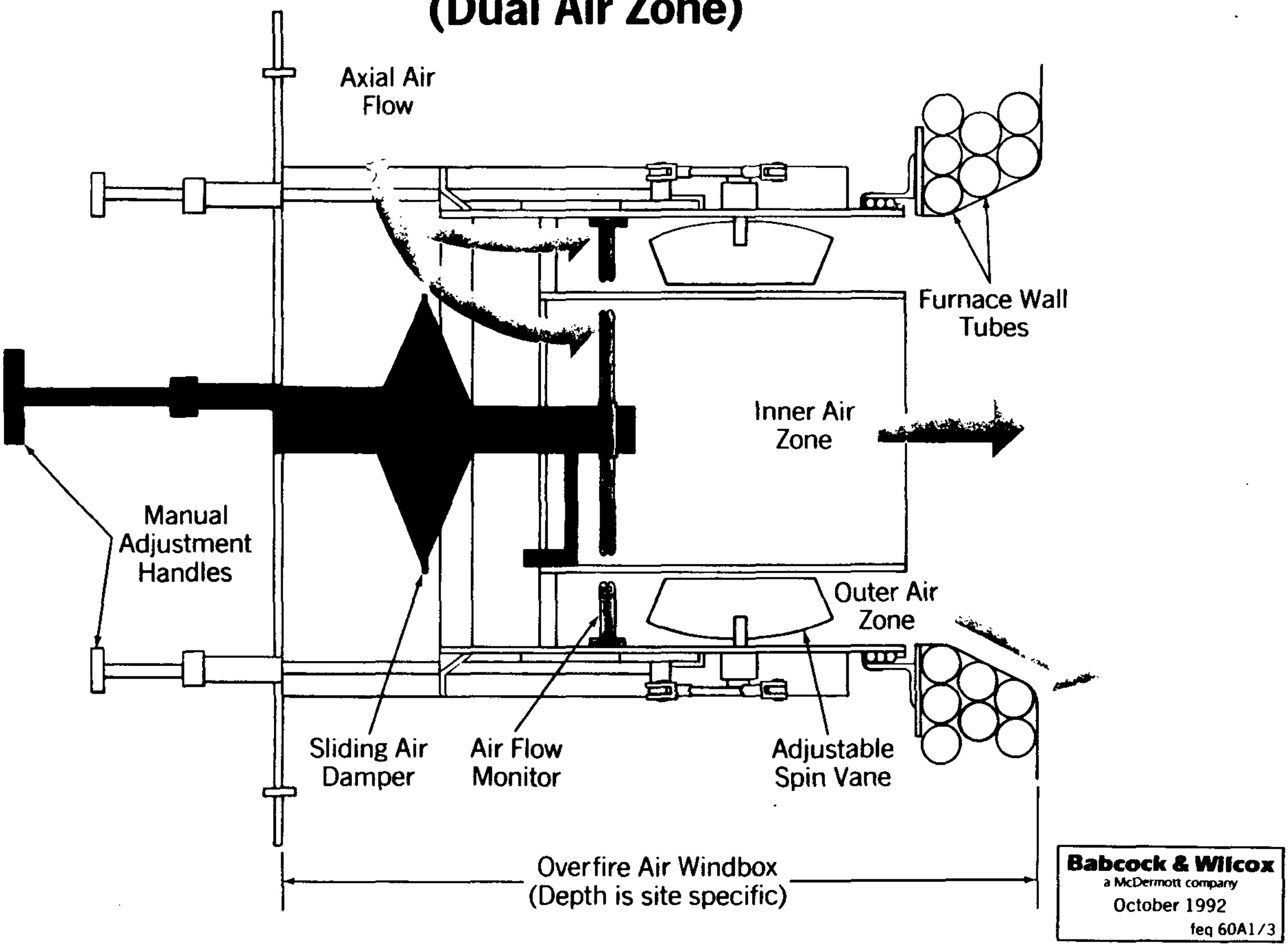


Figure 6-5

6.3.2 Coal Silo

One 150-ton coal silo (or bunker) provides the storage for the coal prior to its introduction to the coal feeder. The existing coal conveying system for the plant was modified so that coal can be fed into the coal silo.

6.3.3 Coal Feeder

One (1) gravimetric feeder and associated equipment, provides the means necessary to accurately measure and regulate the coal flow to the pulverizer. The feeder supply scope also includes the coal bunker outlet gate and feeder outlet gate valves. The feeder was installed at elevation 662'- 0" within the confines of the pulverizer building enclosure.

6.3.4 Pulverizer

To provide a fine-grind coal to the four reburn burners, one (1) B&W MPS-67 Pulverizer is adequate. The coal is ground to meet the desired 88-90% fineness through a 200 mesh. To achieve this fineness, the pulverizer is equipped with a rotating classifier, and a hydraulic drive unit which can vary the classifier's rotational speed. The loading portion of the hydraulic system can also vary the loading of the pulverizer's pressure frame, thus providing the required coal fineness under various coal and pulverizer conditions. The rotating classifier promotes increased coal recirculation within the pulverizer, and the pressure frame loading is optimized based on the coal feed rate to the mill. Coal sampling ports to check coal fineness are located on each coal pipe with access from the top of the pulverizer.

The pulverizer supplied by B&W includes the gear box, motor, lube oil set, and a hydraulic oil skid which will hydraulically drive the rotating classifier, and hydraulically pressurize the loading frame.

Pyrite Removal System

The pyrite removal system, an integral component of the coal pulverizer, allows for the removal of pulverizer rejects, which include such items as coarse coal, tramp iron, and rocks. Rejects from the pulverizer which accumulate in the pulverizer pyrites box, can be evacuated via the sluice system. The sluice water required for the pyrites removal system is supplied by a 4" sluice water pipe, which sources water from an existing 12" diameter High Pressure Service Water line located within the boiler house. The rejects are transported to the boiler slag tank through the pyrites discharge piping.

Inerting System

The pulverizer is equipped with a locally operated inerting and clearing system. Whenever the pulverizer is shutdown with coal remaining within it, the inerting and clearing procedure must be used to remove the coal. Inerting is accomplished by the direct injection of steam into the pulverizer. Once the inerting process is complete, the pulverizer is locally started and flushed clean by the introduction of water into the pulverizer windbox area via water wash nozzles located in the primary air duct. The coal/water mixture is subsequently flushed into the pyrites box and evacuated to the boiler slag tank via the pyrites removal (sluice) system. Once the clearing procedure is complete, the pulverizer can be returned to service.

Pulverizer Hydraulic Loading System

A skid mounted hydraulic system serves two purposes; to drive the pulverizer's rotating classifier, and to provide variable pressure to the pressure frame of the pulverizer. The location of the hydraulic loading system is at the base of the pulverizer.

6.3.5 Primary Air Fan

The variable speed primary air (PA) fan provides the necessary air requirements for the transporting of the fine-grind coal to the reburn burners. Upstream of the primary air fan, hot and cold (tempering) air are mixed to provide the necessary temperature to properly dry the coal within the pulverizer.

The hot air source is from the existing air heater via a 30" diameter duct connection at elevation 631'- 3". Tempering air is supplied by way of a 22" diameter duct which is connected to a newly installed 30" cooling air duct at elevation 689'- 4". The forced draft fan discharge is the ultimate source of the tempering air. The hot air and tempering air ducts tie in at elevation 641'- 6" within the pulverizer building enclosure.

Hot and tempering primary air flows are integrally regulated by their respective dampers to achieve the desired pulverizer outlet temperature. Primary air flow requirements are established by direct control of the primary air fan speed. Total air flow, which includes the mixture of hot and tempering air, is measured by a venturi/pitot tube arrangement, situated in the primary air duct between the PA fan outlet and pulverizer windbox inlet.

Appendix 5 summarizes the balance of plant details.

7.0 Coal Reburning Technical Impacts

7.1 Parametric Optimization/Performance Testing Overview

7.1.1 Objectives

The focus of this demonstration project's testing program was to determine the maximum NO_x reduction capabilities without adversely impacting boiler performance, operation or maintenance between full load (110 MW_e) and 50% load (55 MW_e). The goal was to achieve a greater than 50% NO_x reduction at full load. Incorporating the optimized test results obtained during the parametric/performance testing into the Nelson Dewey Unit #2 boiler controls then provided WP&L a reburn system that could operate in a fully automated condition. The testing phases were designed to not only evaluate the most efficient conditions to operate the reburn system at Nelson Dewey, but to also provide sufficient data to confirm and expand upon the previously performed B&W SBS pilot scale testing and engineering study results. Utilizing this information will enhance the design considerations for future applications.

The parametric/performance testing program was divided into a group of six (6) separate series while firing a total of two (2) different coal types. The primary demonstration coal was an Illinois Basin bituminous coal (Lamar) and the majority of the testing was performed while firing this fuel. Following the bituminous coal testing, sub-bituminous western coal, Powder River Basin coal, tests were performed to evaluate the effect of coal switching on reburn operation. WP&L's future strategy to meet sulfur emission limitations is to fire low sulfur coal, thus the reburn system had to be re-optimized to handle this fuel switching alternative. The following sections summarize all the testing results obtained throughout the post-reburning retrofit phases. The six (6) test series are:

1. Initial Reburn Tuning Tests (B&W emission testing) - **"T" Series**
2. Reburn Parametric Tests (B&W/ACUREX emission testing) - **"A" Series**
3. Initial Performance Tests (B&W/ACUREX emission testing) - **"P" Series**
4. Final Performance Tests (B&W/ACUREX emission testing) - **"F" Series**
5. Western Fuel Tests (B&W emission testing) - **"W" Series**
6. Hazardous Air Pollutant Tests (ACUREX emission tests) - **"HAP" Series**

The fuel analyses for these tests are provided in Table 7-7 of Section 7.3.2.2, Calculation Methodology. One of the major objectives of the bituminous coal firing phases was to provide sufficient information in order to incorporate a fully operational coal reburning system at Nelson Dewey Unit #2. Long-term performance evaluation of this fully automated/load following system was required to help assess the commercialization potential of this technology. This long-term operation occurred between the "P" and "F" Series. Thus, the objective of this portion of the project was to evaluate the long-term effects of reburning on boiler performance, emissions, and corrosion.

7.1.2 Test Parameters

Numerous variables are associated with the reburn system and a test matrix had to be established in order to proceed from one parameter to another during the optimization testing. The official Test Plans were developed prior to the original 1990 Baseline testing and the subsequent post-reburn retrofit testing.[13,14] Based on WP&L's day-to-day boiler requirements, the specific test matrices were modified on-site to accommodate WP&L's energy demands while maintaining the reburn program's initiatives. The test variables included in the matrix along with the approximate ranges tested are:

- Boiler load (37 - 118 MW_e)
- Reburn system percent of total boiler heat input (~25 - 40%)
- Reburn zone stoichiometry (~0.83 - 0.96)
- Reburn burner stoichiometry (~0.35 - 0.70)
- Reburn burner pulverized coal fineness (80 - 98% thru 200 mesh)
- Gas recirculation rates to reburn burners (0 - 5% of total boiler gas flow)
- Reburn burner spin vane and impeller/swirler adjustments
- Overfire air (OFA) port spin vane/sliding disk adjustments
- Economizer outlet O_2% (2 - 4%)

The number of cyclones in operation was changed to maintain acceptable cyclone operating characteristics during testing at lower loads. The number of cyclones normally operated in a given load range both for baseline and reburn operation are as follows:

LOAD RANGE		
No. of Cyclones Operating	**Without Reburn**	**With Reburn**
3	80 - 110	90 - 110
2	50 - 80	60 - 90
1	30 - 50	37 - 60

The above parameters were investigated for both the bituminous and the western sub-bituminous coals. Babcock & Wilcox and the Acurex Corporation installed separate boiler performance/emission systems to evaluate the tested variables. The subsequent sections discuss the information collected throughout these parametric evaluations.

7.1.3 Continuous Emissions Monitoring System

Emissions monitoring is accomplished via two (2) separate systems in order to assure accuracy in addition to obtaining measurements in two independent locations. Babcock & Wilcox located an emission monitoring grid at the economizer outlet to evaluate the boiler combustion performance while Acurex set-up at the precipitator outlet to obtain stack emissions.

The B&W test system measured NO_x, O_2, CO, and CO_2 in a 60 point total test grid. The average emissions for the boiler left versus right sides were measured to evaluate any air/fuel imbalances within the furnace combustion region. This information was obtained during all the start-up, optimization, and performance testing. Thus, the B&W system was in operation during the following test series: "T", "A", "P", "F", and "W". The B&W equipment is described in the Coal Reburning Test Plan - Phase III Operation.[14]

Acurex installed a Continuous Emission Monitoring System (CEMS) at the precipitator outlet to continuously measure NO_x, O_2, CO, CO_2, and SO_2. This system was installed after B&W completed the "T" test series in March 1992 and was operational until the completion of the project. Thus, the Acurex CEMS was utilized during the following test sequences: "A", "P", "F", "W", and "HAP" plus the long-term performance test series. The Acurex emission data was saved via their own software and also sent to WP&L's on-line boiler performance monitor which allowed the boiler operators to identify the real time emission values. Based upon these results, long-term emission data can be reviewed and correlated. The Acurex equipment is described in the Coal Reburning Baseline Test Report[9] and again in the final Test Report included as Appendix 6.

The Acurex CEM system was an integral tool in obtaining the emissions data during the long-term performance tests that occurred between series "P" and "F". The purpose of this phase was to evaluate the coal reburning technology with respect to operation during normal boiler load-following conditions. Since no test personnel were on-site during this approximate four (4) month time period, the Acurex CEM system collected all the required emission data in order to fully assess the technology's potential.

7.1.4 Boiler Performance Characteristics

B&W test equipment to determine on-line boiler performance was available to help evaluate the effects of reburning versus non-reburning operation. Also, a permanent on-line boiler performance system was maintained. The permanent system was installed by Black & Veatch to continuously monitor all boiler functions. B&W installed its boiler heat transfer module into the Black & Veatch system to provide boiler cleanliness (heat transfer calculations) and critical reburn system information and calculations for such parameters as various stoichiometries and reburn % heat input. Thus, since the B&W and Black & Veatch systems were available, a verification of the data could be maintained, similar to the verification that was available for the emissions data described earlier.

In order to completely evaluate boiler performance, numerous physical measurements are required. The Acurex Corporation and Babcock & Wilcox were responsible to perform these tests. Acurex performed the majority of these tests and they included: precipitator inlet/outlet particulate loadings, precipitator inlet particle size distribution and resistivity measurements, volatile/non-volatile organic compounds, and metals. Unburned carbon (UBC) determinations were made using the fly ash obtained from the isokenetic particulate loading tests. A complete description of the Acurex test procedures is available in Appendix 6. In addition, UBC analyses of the cyclone slag was measured for each of the tests performed. Using the UBC results with the particulate loading data (which determined the fly ash split to the cyclone slag versus the furnace), combustion efficiency could be determined to help evaluate overall boiler efficiency. Additional investigation with the above data allowed evaluation of the overall precipitator performance.

Long-term boiler operation was evaluated by comparing the "P" and "F" series test results since these test series were considered the initial and final performance tests. Boiler performance and corrosion evaluations were reviewed between these phases. The boiler performance determinations were made using the above specified informational tools while the corrosion evaluation was made via two (2) approaches. First, H_2S measurements were made throughout the furnace regions at areas near the furnace tube walls during baseline and reburning operations. Second, ultrasonic tube thickness (UT) measurements were done throughout the furnace envelope before and after long-term reburning. Comparing these data will then provide information to help determine if any corrosion concerns are apparent.

7.2 Testing Chronology

7.2.1 Test Dates

Because of the magnitude of tests performed throughout this program, the following Table 7-1 is provided to summarize the test dates associated with each of the series.

TABLE 7-1 TESTING CHRONOLOGY		
TEST DESCRIPTION	**NUMBER OF OFFICIAL TESTS**	**TEST DATE**
Initial Reburn Tuning - "T" series	50	2/12/92 - 3/5/92
B&W/ACUREX Optimization - "A" series	30	3/31/92 - 5/1/92
Initial Performance Tests - "P" series	9	5/16/92 - 5/20/92
Final Performance Tests - "F" series	19	9/28/92 - 10/5/92
Hazardous Air Pollutant - "HAP" series	6	11/2/92 - 11/6/92
Western Fuel Firing Tests - "W" series	30	11/15/92 - 12/10/92

Although Table 7-1 identifies the total number of official tests performed, numerous additional mini-tests were done to fully address the optimization of the reburn system. These tests incorporated measuring various parameters described above such as particulate loadings and UBC. Additional mini-tests varying reburn burner spin vanes/impeller or swirler positions, OFA port settings, and gas recirculation rates were completed and evaluated based upon NO_x and CO emission levels. Optimized conditions were then utilized to run the official tests per the test matrix.

Finally, various reburn burner design modifications were done within the overall test program to help improve reburn operation. The main purpose of these modifications was to improve burner flame stability at low loads. The first modification was performed after the "A" Test Series on 5/3/92 and it included adding fixed spin vanes in the burner outer air zone (replaces the adjustable spin vanes and minimizes air flow leakage around the vanes) and switched the adjustable conical impeller with a swirler arrangement (increased the swirl component of the primary air/coal flow). Reduction of NO_x at full load suffered with this revision but flame stability at low load was improved. The second modification was to replace the original swirler with another swirler design that contains less of a swirl component, hopefully to regain NO_x performance at full load while maintaining adequate stability at low load.

This was accomplished prior to the "F" Test Series on August 25, 1992. The last change was to reinstall the original swirler due to operational problems with the second swirler which suffered heat damage due to its longer geometry.

7.2.2 Summary of Tests Performed

7.2.2.1 Initial Tuning Tests - "T" Series

The "T" series was initiated after the start-up activities had been completed. B&W test personnel were available to perform all the required testing throughout this phase. The 50 official tests performed included investigating the following:

- Baseline tests with no reburn @ loads: 55 to 110 MW_e
- Varying reburn zone stoichiometries: 0.83 to 0.97
- Varying reburn system % heat input: 25 to 39%
- Varying gas recirculation rates to reburn burners: 0 to 5%

The associated results obtained within this phase included economizer outlet emissions, particulate loadings at the precipitator inlet/outlet, and fly ash and slag UBC. An official test lasted about two hours after the test condition had been set-up. This time constraint was based upon the requirement for particulate loading since sufficient fly ash catch is required to assure accurate results and to assure satisfactory quantities for later % UBC measurements. Reburn burner and OFA port adjustments were also made within this phase to optimize flame stability via CO emission levels and flame scanner intensity at loads of 55-110 MW_e.

In addition, in-furnace probing for temperatures and gas species was performed during reburning operation to compare to the baseline test results. This data will aid the modeling activities such that improved scale-up to various unit sizes and different configurations can be confidently accomplished. Thus, commercialization work will include the ability to model not only the optimized locations for the reburn equipment from a mixing standpoint, but also predictions of the resulting NO_x emissions.

7.2.2.2 B&W/Acurex Optimization Tests - "A" Series

Following the initial tuning tests using B&W test personnel, a similar test matrix was performed to duplicate conditions while an independent third party test firm (Acurex Corp.) provided confirmation of the B&W test results. The Acurex CEM system was debugged at the start of this test phase and remained operational throughout the rest of the program. A single point probe was installed at the precipitator outlet to sample the flue gas for the Acurex system analysis. The single point was chosen based upon performing duct stratification tests per EPA guidelines. In addition, Acurex personnel set up equipment at the precipitator inlet/outlet to measure particulate loadings, etc. The 30 official tests performed included investigation of the following:

- Baseline tests with no reburn @ loads: 55 - 110 MW_e
- Varying reburn zone stoichiometries: 0.81 - 0.97
- Varying reburn system % heat input: 25 - 33%
- Varying gas recirculation rates to reburn burners: 0 - 4%
- Varying pulverizer rotating classifier speed: 100 - 160 rpm
- Increasing overall excess oxygen: 2.5 - 4.5 $\%O_2$

In addition to the Acurex test equipment, B&W's economizer outlet grid was also available to measure emissions. An official Acurex test would last about 2 1/2 hours after B&W had set-up the test condition. This time constraint was again based upon the requirement for sufficient fly ash catch.

Based upon the data results from series "T" and "A", optimized reburn system control curves were generated and incorporated into the boiler's automatic microprocessor control system. Thus, WP&L could operate the unit in a fully automated mode under normal load following demand with reburning and achieve reduced NO_x emissions with no major boiler operational problems.

At the end of series "A", the first reburn burner modification was incorporated to help low load flame stability. As stated earlier, this modification included fixed spin vanes and a swirler to replace the adjustable conical impeller.

7.2.2.3 Initial Performance Testing - "P" Series

Since the optimized reburn control curves had been incorporated after series "A", the initial official performance tests could then be performed. The "P" series included operating the boiler with reburn in operation and the controls in a complete automatic mode. The test matrix consisted of nine (9) total tests. Three (3) loads were tested (110 MW_e, 82 MW_e, and 60 MW_e) and three (3) duplicate tests were completed at each load condition. During one (1) of the tests at each load, sootblowing was performed to assess its effect on the measured parameters. The following list summarizes the measured variables and included participation from both Acurex and B&W:

- Precipitator/economizer outlets emissions data (NO_x, O_2, CO, CO_2, SO_2)
- Precipitator inlet/outlet particulate loadings
- Precipitator inlet resistivity/particle size distribution
- Precipitator outlet metals/volatile/non-volatile organic compounds
- Cyclone slag and precipitator fly ash unburned carbon
- Fly ash toxicity

The objective of the initial performance tests was to provide a reburning baseline from which subsequent final performance tests could be compared to assess if any degradation had occurred over time. Following the series "P" tests, long-term performance operation began. Original project intentions were that this phase would last approximately nine (9) months. Due to start-up delays, the addition of western fuel firing tests, and an exhausted supply of Lamar coal, the resultant actual long-term test duration was about four (4) months.

7.2.2.4 Final Performance Testing - "F" Series

Based upon a complete analysis of all the previous testing, a sufficient amount of data scatter was observed with respect to the particulate loadings and % UBC results to necessitate additional baseline tests be performed. The test matrix for series "F" included a total of 19 tests as compared to the 9 test "P" series. The added baseline tests were performed to better determine the resultant fly ash loading and % UBC levels being generated via the cyclone operation alone. Fluctuations in data were thought to be attributed to cyclone operation and not necessarily the reburn system. Thus, cyclone loads which were defined to remain constant whether reburn was in operation or not were identified and tested to eliminate the effects of cyclone load swings.

In addition to the added baseline tests, lower loads with reburning in operation were also tested. These tests were performed to improve the data base with respect to low load operation and thus provide modified operational curves.

Prior to initiation of the "F" series testing, the second generation reburn burner modification was installed. As stated earlier, this modification included replacing the original swirler with a new swirler that would create less turbulent conditions.

The test variables for the "F" series testing, including participation from both Acurex and B&W, is summarized as follows:

- Precipitator/economizer outlets emissions data (NO_x, O_2, CO, CO_2, SO_2)
- Precipitator inlet/outlet particulate loadings
- Cyclone slag and precipitator fly ash unburned carbon

Utilizing all the data collected within series "F", an improved understanding of the overall process was accomplished and a direct comparison between the "P" and "F" series could be performed.

7.2.2.5 Hazardous Air Pollutant Tests - "HAP" Phase

After the "F" series tests were completed, the amount of Indiana bituminous coal that remained on-site was low. The "HAP" series testing was performed just prior to completely running out of the coal. The "HAP" test matrix included performing a total of six (6) tests at full load conditions (3 baseline and 3 reburning tests). The Acurex Corporation obtained all required measurements. Section 7.3.3 identifies all parameters that were measured throughout this series.

7.2.2.6 Western Fuel Firing Testing - "W" Series

The western sub-bituminous coal firing investigation was performed to obtain a direct comparison of reburn performance as a function of coal type. In addition, sufficient data was collected in order to allow optimized reburning performance curves to be generated and incorporated into the boiler control system at Nelson Dewey Unit #2. Similar tests to those performed earlier in series "T", "A", "P", and "F" were done throughout series "W". B&W test crews were available to obtain the data required to accomplish the above stated goals. A total of 30 official tests were performed.

Prior to initiating the "W" series, the final reburn burner modification, which consisted of reinstalling the original swirler was completed. It was decided to return to these swirlers for two reasons: 1. Some blade burn back was noted on the current swirlers. These swirlers were slightly longer than previous models and accordingly were inserted further into the furnace. Not retracting them during non-reburn operation aggravated the overheating problem. 2. No apparent improvement in flame stability at low loads was achieved with the current swirlers and no major change in emission levels resulted.

7.2.3 Evaluation Methodology

Evaluation of the coal reburning technology involved review of the test results with respect to emission levels, boiler performance and operations, and precipitator performance. The methodology used throughout the testing phases was to determine the optimum conditions at which the coal reburning system should be operated. As discussed in the previous sections, numerous tests were organized to encompass a comprehensive matrix that would provide sufficient data to allow a complete evaluation. B&W and Acurex test personnel performed simultaneously to assure data accuracy and completeness while maintaining cost control.

In accordance with the stated methodology, the testing could be divided into official and non-official tests. The non-official tests involved the optimization of burner flame stability and OFA port effectiveness. The tests involved modifying the parameter in question and identifying any change in flame scanner intensity, flame appearance, NO_x and CO emission levels, O_2% balance at the economizer outlet, and boiler controls response. These tests would normally last approximately 15 - 30 minutes and were intended to provide relatively quick information in order to set-up the conditions from which the official tests would be operated. As stated earlier, the following variables were investigated during these non-official tests:

- reburn burner spin vane direction and impeller/swirler position
- gas recirculation flow rates to the boiler/reburn burners
- primary air versus coal flow rates
- reburn burner pressure drops
- cyclone stoichiometries
- OFA ports spin vane direction and sliding disk position

Based upon the optimum results observed from these non-official tests, the official tests evaluated the following variables:

- reburn zone stoichiometry
- % reburn heat input
- coal fineness
- gas recirculation rate to reburn burners
- economizer outlet % O_2

The data obtained from each of the official tests was evaluated based upon emission levels and boiler performance. Thus, all the curves generated in the subsequent sections are based upon these test series.

Numerous baseline tests were performed throughout the various series in order help determine the actual effects of reburning. Pre-retrofit baseline tests were performed in 1990. Although these tests provided valuable information aiding in the reburn system design and providing good baseline NO_x, CO, O_2, and CO_2 emission levels, the boiler fly ash loading and percent UBC levels obtained were questionable. Thus, to assure a true indication of baseline versus reburn operation, the post-retrofit baseline versus reburn comparison should be used.

These post-retrofit baseline tests include about 0.6-0.8% higher excess O_2% due to the cooling air requirements for the reburn burners/OFA ports, but this data is corrected back to normal excess air conditions for boiler performance/efficiency calculations.

7.3 Coal Reburning Performance Results

7.3.1 Environmental Effects of Reburning

Application of coal reburning to a cyclone-equipped boiler will affect various unit emission levels due to the inherent nature of the technology. First, NO_x emission levels will be decreased since the technology is geared toward creating a substoichiometric furnace region to generate hydrocarbon radicals that will react with NO_x molecules produced in the main combustion zone to form molecular nitrogen. Carbon monoxide emission levels will be increased due to the substoichiometric (reducing/fuel rich) zone created to reduce the NO_x emissions, but will then be decreased to normal levels after the remaining combustion air is introduced through the OFA ports. Higher fly ash loadings to the furnace will be realized since the ash in the pulverized coal feed to the reburn burners will not be trapped within the cyclone slag as is presently occurring under cyclone only firing. Thus, the higher loading and potentially different size ash could affect precipitator performance. The following section will discuss the effects of various cyclone coal reburning operational parameters on these emission levels.

7.3.1.1 NO_x and CO Emission Levels

Numerous test data points are available to evaluate the coal reburning impact on NO_x and CO emission levels. All the test series addressed earlier involve changing specific reburning variables and identifying the resultant NO_x and CO emission levels. The first section herein reports the results during utilization of the demonstration Lamar bituminous coal. A summary of all the tests performed and the associated results for the "T", "A", and "P"/"F" series are shown in Tables 1, 2 and 3, respectively in Appendix 7. The data within these tables are the basis for all the following figures that will be presented. Subsequent sections will discuss the data with respect to the western fuel firing tests. In addition, Table 4 of Appendix 7 shows a summary of all the coal samples analyzed throughout both the bituminous and sub-bituminous coal testing phases.

Babcock & Wilcox and Acurex data were collected during the "A", "P", "F", and "W" series and were compared for consistency. Generally speaking, comparison of data between the two sources was good throughout all test phases. When a discrepancy does exist, the Acurex NO_x

levels show a consistently higher level of approximately 20 ppm. This discrepancy is explained by the fact that B&W values are based on a 60 point test grid while Acurex values are a single or double point indication. Although there is some small amount of stratification at the precipitator outlet (where Acurex measurements were made), the variation is relatively insignificant and remained constant, thus evaluation of the data can be made utilizing either of the data bases.

The following results show the effect of reburning zone stoichiometry, % reburn heat input, % of gas recirculation, and load on both NO_x and CO emission levels. Within these figures, comparisons between the B&W and Acurex data is included to verify the consistency of the two measurements.

All subsequent NO_x emission values are reported in ppm (parts per million) corrected to 3% O_2 and lb/10^6 Btu. CO emission levels are also reported in ppm corrected to 3% O_2. In addition, all the data reported were collected while maintaining a cyclone stoichiometry at as close to 1.10 as possible (typically 1.06 - 1.13).

7.3.1.1.1 Reburn Zone Stoichiometry Impact

Varying reburn zone stoichiometry is the most critical factor in changing NO_x emission levels during coal reburning operation. The reburn zone stoichiometry can be varied via altering the air flow quantities (oxygen availability) to the reburn burners, the % reburn heat input, the gas recirculation flow rate, or the cyclone stoichiometry. The following series of figures reveal NO_x emission levels versus reburn zone stoichiometry at various load conditions.

Figure 7-1 represents B&W economizer outlet NO_x emissions in ppm corrected to 3% O_2 and lb/10^6 Btu versus reburn zone stoichiometry at full load conditions (110 MW_e). The data base used in this figure is comprised of series "T", "A", "P", and "F" and show a range of reburn zone stoichiometries from 1.14 (baseline - no reburning) to 0.81 (lowest stoichiometry tested w/reburning). All data for the four series of tests are combined since the same reburn zone stoichiometries were achieved in all tests series regardless of method (i.e., more coal to the reburn burners, less air/more gas recirculation). All other factors are secondary to reburn zone stoichiometry with respect to their impact on NO_x reduction. The average B&W baseline NO_x level identified during the 1990 Baseline Tests is 609 ppm (0.826 lb/10^6 Btu) and Figure 7-1 shows

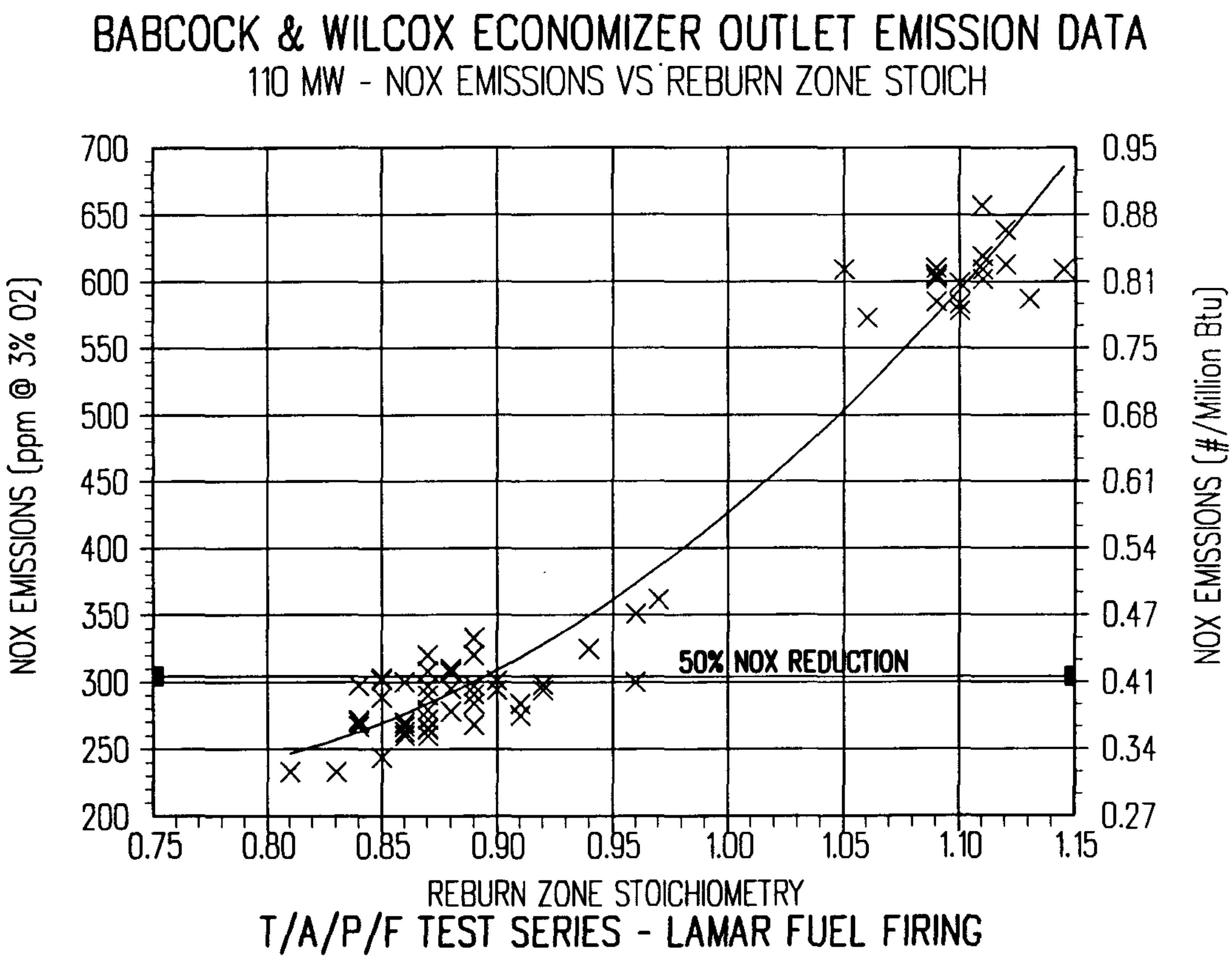
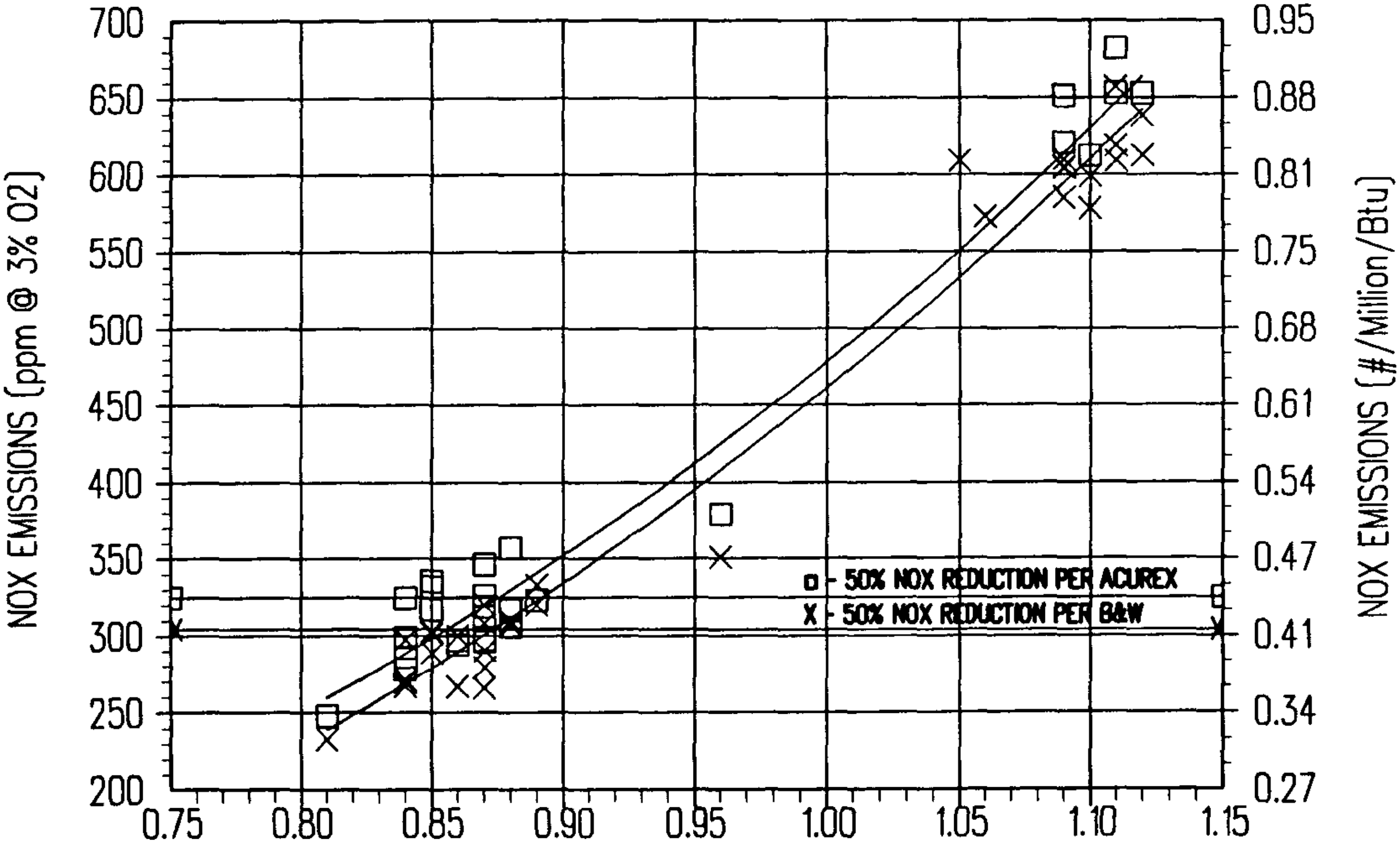

BABCOCK & WILCOX ECONOMIZER OUTLET EMISSION DATA
110 MW - NOX EMISSIONS VS REBURN ZONE STOICH
NOX EMISSIONS (ppm @ 3% O2)
700
650
600
550
500
450
400
350
300
250
200
NOX EMISSIONS (#/Million Btu)
0.95
0.88
0.81
0.75
0.68
0.61
0.54
0.47
0.41
0.34
0.27
50% NOX REDUCTION
0.75
0.80
0.85
0.90
0.95
1.00
1.05
1.10
1.15
REBURN ZONE STOICHIOMETRY
T/A/P/F TEST SERIES - LAMAR FUEL FIRING

FIGURE 7-1

ACUREX VS BABCOCK & WILCOX EMISSIONS DATA
110 MW - NOX EMISSIONS VS REBURN ZONE STOICH



A/P/F TEST SERIES - LAMAR FUEL FIRING

FIGURE 7-2

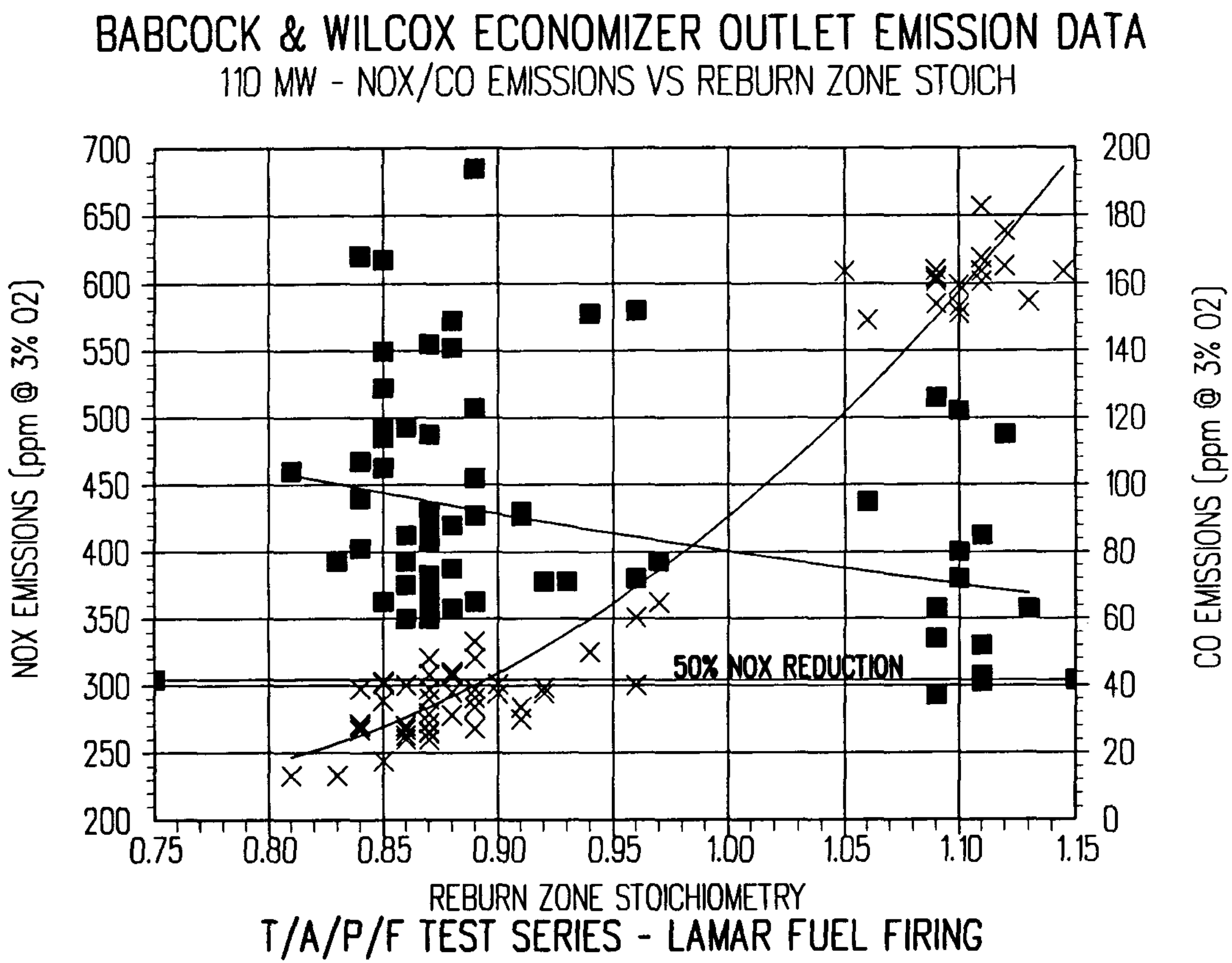
that the post-retrofit baseline NO_x is approximately the same. In order to obtain the required goal of 50% NO_x reduction (305 ppm or 0.413 lb/10^6 Btu), Figure 7-1 reveals that the reburn zone stoichiometry must be at about 0.895. In addition, the data shows that the lowest reburn stoichiometry tested at 0.81 would yield a corresponding NO_x level of 233 ppm (0.32 lb/10^6 Btu) or a 61.8% NO_x reduction.

Comparing the B&W economizer outlet and Acurex precipitator outlet data at the above specified conditions is shown in Figure 7-2. The Acurex data is consistently 20 ppm higher at this 110 MW_e load as compared to the B&W data during tests conducted in series "A", "P", and "F" (only B&W tests are done in series "T"). As described earlier, the main reason for this discrepancy is due to the large grid arrangement that B&W had installed at the economizer outlet versus the single or double point extraction system that Acurex had on-site at the precipitator outlet.

The other interesting issue observed on Figure 7-2 is while removing the "T" series tests from the B&W data, the reburn zone stoichiometry to achieve a 50% reduction changes from the earlier reported 0.895 (based upon Figure 7-1) to approximately 0.875 in Figure 7-2. The explanation for this difference is the fact that a reburn burner modification occurred between the "T"/"A" and the "P"/"F" series which slightly altered the mixing characteristics. A slightly higher NO_x emission level resulted after this modification. It is believed that the more turbulent and shorter flame length provided less overall mixing within the reburn zone and thus higher NO_x emissions. Therefore, the data base after the modification reveals that lower reburn zone stoichiometries are required to meet the 50% reduction target.

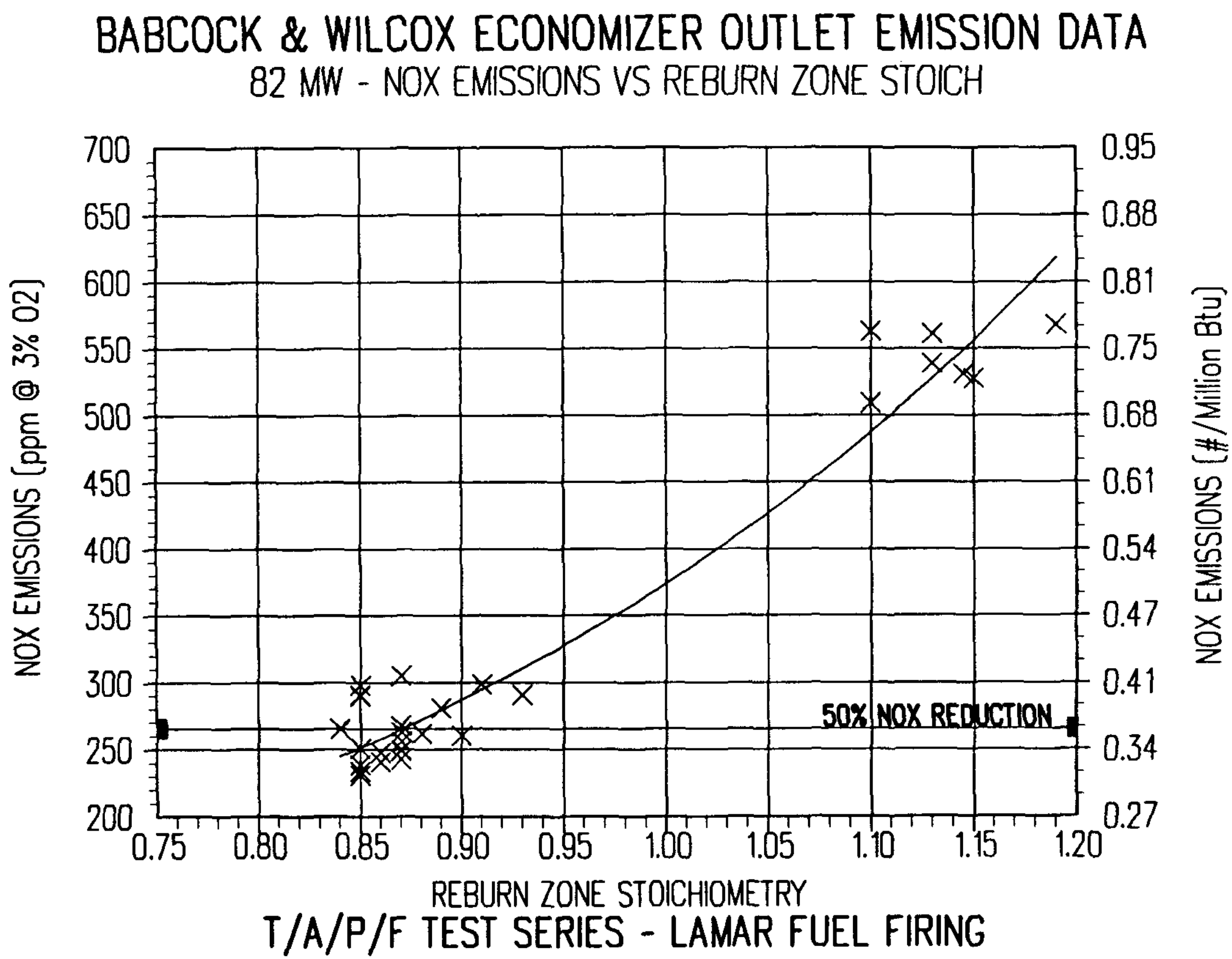
The resultant positive note to the burner modification #1 is the fact that a more stable flame was apparent over the boiler load range allowing the reburn system to be operated at lower loads without any concern for flame out and reburn trip sequences.

The CO emission levels (ppm @ 3% O_2) and NO_x emission levels versus reburn zone stoichiometry at the 110 MW_e load condition during test series "T", "A", "P", and "F" are shown in Figure 7-3. Although CO emission data scatter exists, the average baseline and reburn operation CO emission levels increased from about 70 ppm to 100 ppm. Figure 7-3 shows that



BABCOCK & WILCOX ECONOMIZER OUTLET EMISSION DATA
110 MW - NOX/CO EMISSIONS VS REBURN ZONE STOICH
NOX EMISSIONS (ppm @ 3% O2)
CO EMISSIONS (ppm @ 3% O2)
700
650
600
550
500
450
400
350
300
250
200
200
180
160
140
120
100
80
60
40
20
0
0.75
0.80
0.85
0.90
0.95
1.00
1.05
1.10
1.15
50% NOX REDUCTION
REBURN ZONE STOICHIOMETRY
T/A/P/F TEST SERIES - LAMAR FUEL FIRING

Figure 7-3



BABCOCK & WILCOX ECONOMIZER OUTLET EMISSION DATA
82 MW - NOX EMISSIONS VS REBURN ZONE STOICH
NOX EMISSIONS (ppm @ 3% O2)
700
650
600
550
500
450
400
350
300
250
200
NOX EMISSIONS (#/Million Btu)
0.95
0.88
0.81
0.75
0.68
0.61
0.54
0.47
0.41
0.34
0.27
50% NOX REDUCTION
0.75
0.80
0.85
0.90
0.95
1.00
1.05
1.10
1.15
1.20
REBURN ZONE STOICHIOMETRY
T/A/P/F TEST SERIES - LAMAR FUEL FIRING

Figure 7-4

the reburn system is maintaining a 50% reduction at about a 0.895 reburn zone stoichiometry, the average CO emission level during reburning operation is 92 ppm. As can be seen in Figure 7-3, no significant correlation is directly apparent except that a slight increase in CO (ppm) emissions occur as the NO_x emission levels are decreased via reducing the reburn zone stoichiometry.

All the above information was obtained during full load operation (110 MW_e). The same data was gathered at reduced loads of 82 MW_e and 60 MW_e. Figure 7-4 is a plot of all the data collected throughout the Lamar coal test series at 82 MW_e for NO_x emission levels versus reburn zone stoichiometry. The B&W 1990 Baseline Test NO_x emission level at 82 MW_e was 531 ppm (0.72 lb/10^6 Btu) and Figure 7-4 shows that the post-retrofit baseline level is also approximately the same. Varying the reburn zone stoichiometry from 1.13 to 0.85 results in NO_x emissions from 531 ppm to 250 ppm (0.34 lb/10^6 Btu). In order to achieve a 50% reduction, Figure 7-4 shows that a reburn zone stoichiometry of 0.87 is required. Operating at the lower 0.85 reburn zone stoichiometry would correspond to a 52.9% NO_x reduction.

Similar to the 110 MW_e case, the "T"/"A" series only data at 82 MW_e shows that the NO_x emissions versus reburn zone stoichiometry relationship was altered due to the reburn burner modification #1. The data shows that before the modification, a higher reburn zone stoichiometry of 0.885 could be utilized to achieve a 50% NO_x reduction instead of the 0.87 required per Figure 7-4. Comparing the B&W versus Acurex NO_x emission data at 82 MW_e showed an extremely close correlation.

CO emission (ppm @ 3% O_2) and NO_x emission levels versus reburn zone stoichiometry at the 82 MW_e load condition during test series "T", "A", "P", and "F" is revealed in Figure 7-5. The average baseline versus reburn operation CO emission levels increased from about 70 ppm to 100 ppm (which is the same as that observed at 110 MW_e). Figure 7-5 shows that the reburn system is maintaining a 50% NO_x reduction at about 0.87 reburn zone stoichiometry and the average CO emission level during reburn operation is 98 ppm. This result is typical for day to day baseline and reburning operation.

The 60 MW_e test results for NO_x emissions versus reburn zone stoichiometry for all the Lamar fuel test series is shown in Figure 7-6 and reveals that

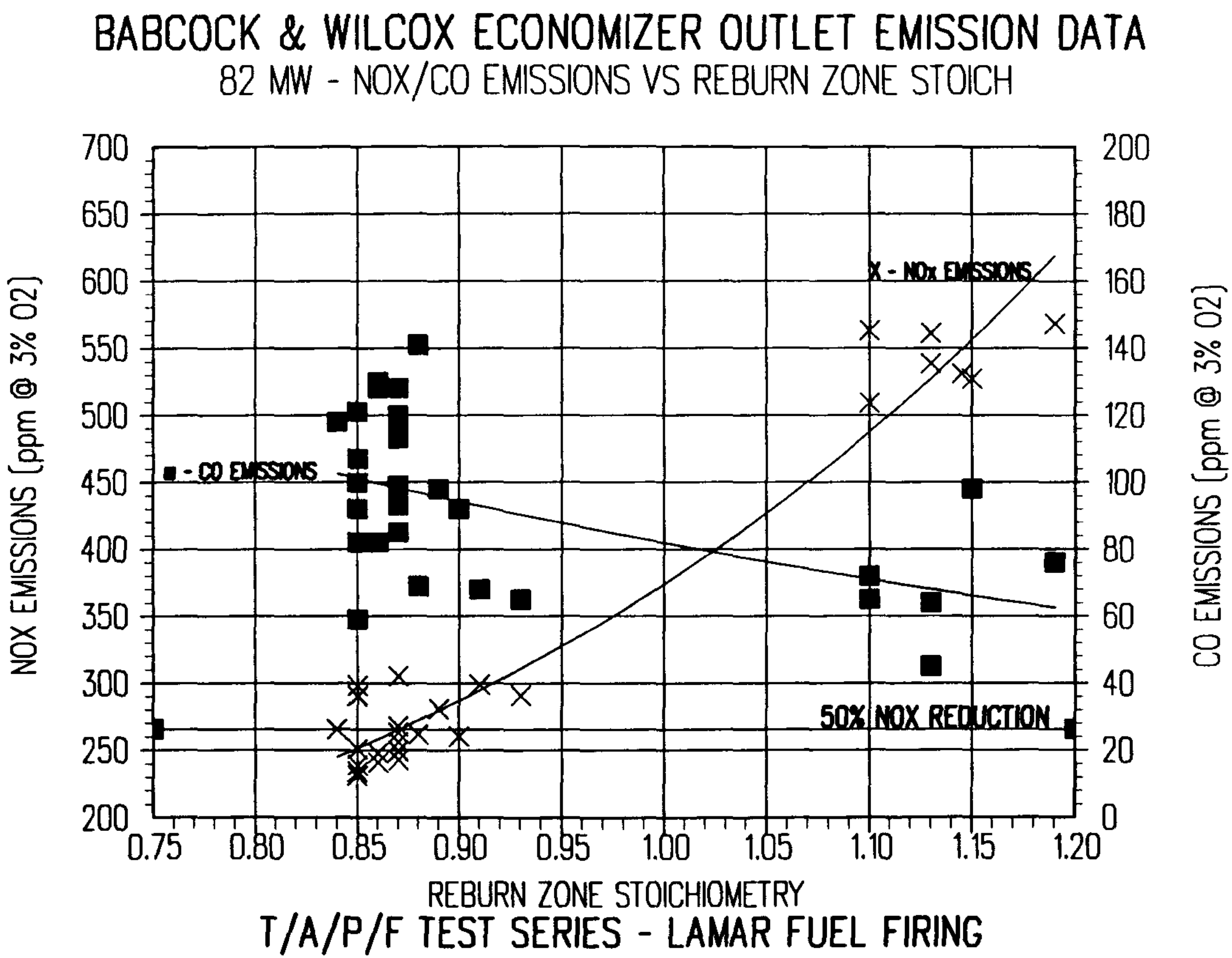

BABCOCK & WILCOX ECONOMIZER OUTLET EMISSION DATA
82 MW - NOX/CO EMISSIONS VS REBURN ZONE STOICH
NOX EMISSIONS (ppm @ 3% O2)
CO EMISSIONS (ppm @ 3% O2)
700
650
600
550
500
450
400
350
300
250
200
200
180
160
140
120
100
80
60
40
20
0
0.75
0.80
0.85
0.90
0.95
1.00
1.05
1.10
1.15
1.20
X - NOx EMISSIONS
■ - CO EMISSIONS
50% NOX REDUCTION
REBURN ZONE STOICHIOMETRY
T/A/P/F TEST SERIES - LAMAR FUEL FIRING

FIGURE 7-5

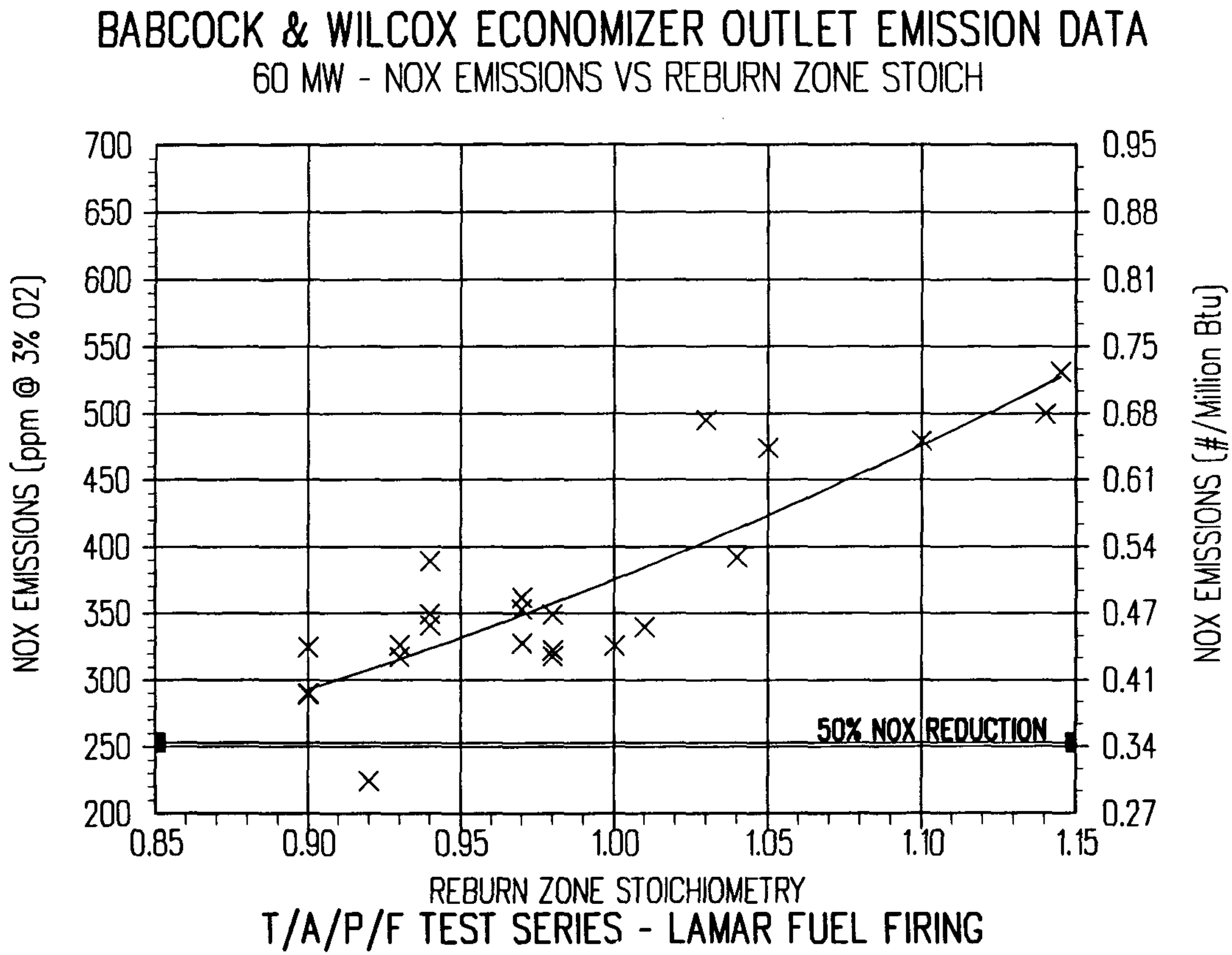

BABCOCK & WILCOX ECONOMIZER OUTLET EMISSION DATA
60 MW - NOX EMISSIONS VS REBURN ZONE STOICH
NOX EMISSIONS (ppm @ 3% O2)
700
650
600
550
500
450
400
350
300
250
200
0.85
0.90
0.95
1.00
1.05
1.10
1.15
0.95
0.88
0.81
0.75
0.68
0.61
0.54
0.47
0.41
0.34
0.27
NOX EMISSIONS (#/Million Btu)
50% NOX REDUCTION
REBURN ZONE STOICHIOMETRY
T/A/P/F TEST SERIES - LAMAR FUEL FIRING

Figure 7-6

a 50% reduction at this low load is not obtainable. The 1990 B&W economizer outlet Baseline Test Data indicates that the baseline NO_x level at 60 MW_e's is 506 ppm (0.69 lb/10^6 Btu) and Figure 7-6 shows that the post-retrofit baseline results are similar. Thus, varying the reburn zone stoichiometry from 1.13 to 0.90 results in NO_x emission levels of 506 ppm to 290 ppm (0.39 lb/10^6 Btu). Operating at the lower 0.90 stoichiometry corresponds to an approximate 42.7% NO_x reduction.

A reduction of 50% is not obtainable at this load because flame stability problems are encountered starting at about 70 MW_e and below. In order to maintain a strong flame intensity signal from the scanners, higher secondary air flow to the reburn burners (and thus higher reburn zone stoichiometry) is required. As shown in all the previous NO_x versus reburn zone stoichiometry curves, the higher the stoichiometry, the higher the NO_x emissions. In addition, no major cyclone slag tapping problems were encountered at this load condition.

Reviewing the NO_x emission versus reburn zone stoichiometry data obtained prior to the reburn burner modification #1 (series "T" and "A") and the results of Figure 7-6, the average NO_x levels at 60 MW_e and a 0.90 reburn zone stoichiometry were approximately 312 ppm versus 294 ppm respectively. Thus, although the higher load data reveals that the burner modification had a slight negative impact on NO_x emissions, the low load operation shows that the opposite was true and a slight improvement in NO_x emissions resulted after the burner #1 modification.

The B&W versus Acurex NO_x emission data at 60 MW_e is similar to that observed at 110 MW_e where an approximate 15-30 ppm higher Acurex reading is seen over the reburn zone stoichiometric range.

CO emission (ppm @ 3% O_2) and NO_x emission levels versus reburn zone stoichiometry at the 60 MW_e load condition during test series "T", "A", "P", and "F" are revealed in Figure 7-7. The average baseline versus reburn operation CO emission levels increased from about 80 ppm to 110 ppm (which is similar to that observed at 82 and 110 MW_e). This result is typical as found in day to day baseline and reburning operation.

7.3.1.1.2 Reburn % Heat Input Impact

Altering the % reburn heat input affects the reburn zone stoichiometry and the following section

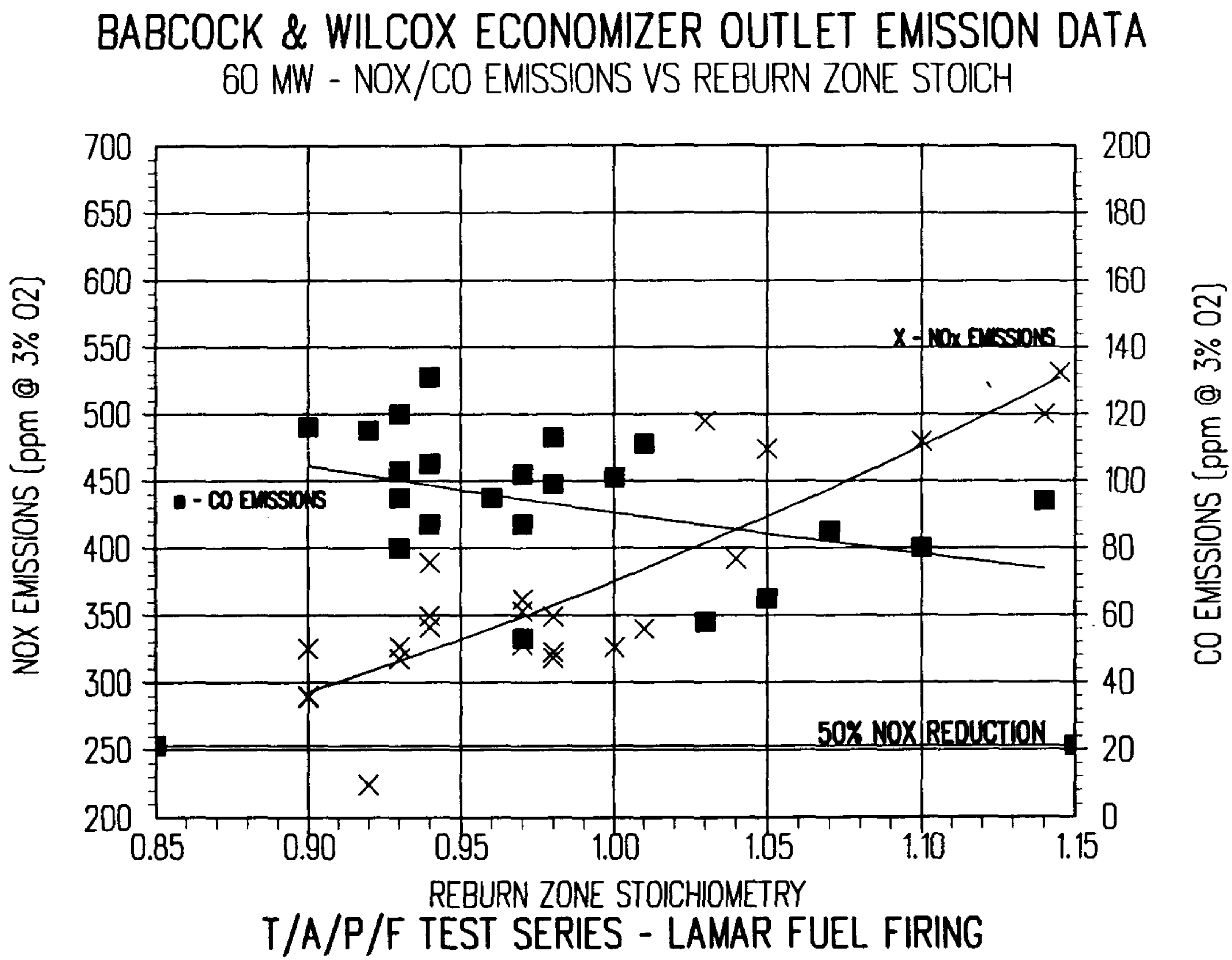

BABCOCK & WILCOX ECONOMIZER OUTLET EMISSION DATA
60 MW - NOX/CO EMISSIONS VS REBURN ZONE STOICH
NOX EMISSIONS (ppm @ 3% O2)
CO EMISSIONS (ppm @ 3% O2)
700
650
600
550
500
450
400
350
300
250
200
180
160
140
120
100
80
60
40
20
0
0.85
0.90
0.95
1.00
1.05
1.10
1.15
X - NOx EMISSIONS
■ - CO EMISSIONS
50% NOX REDUCTION
REBURN ZONE STOICHIOMETRY
T/A/P/F TEST SERIES - LAMAR FUEL FIRING

FIGURE 7.7

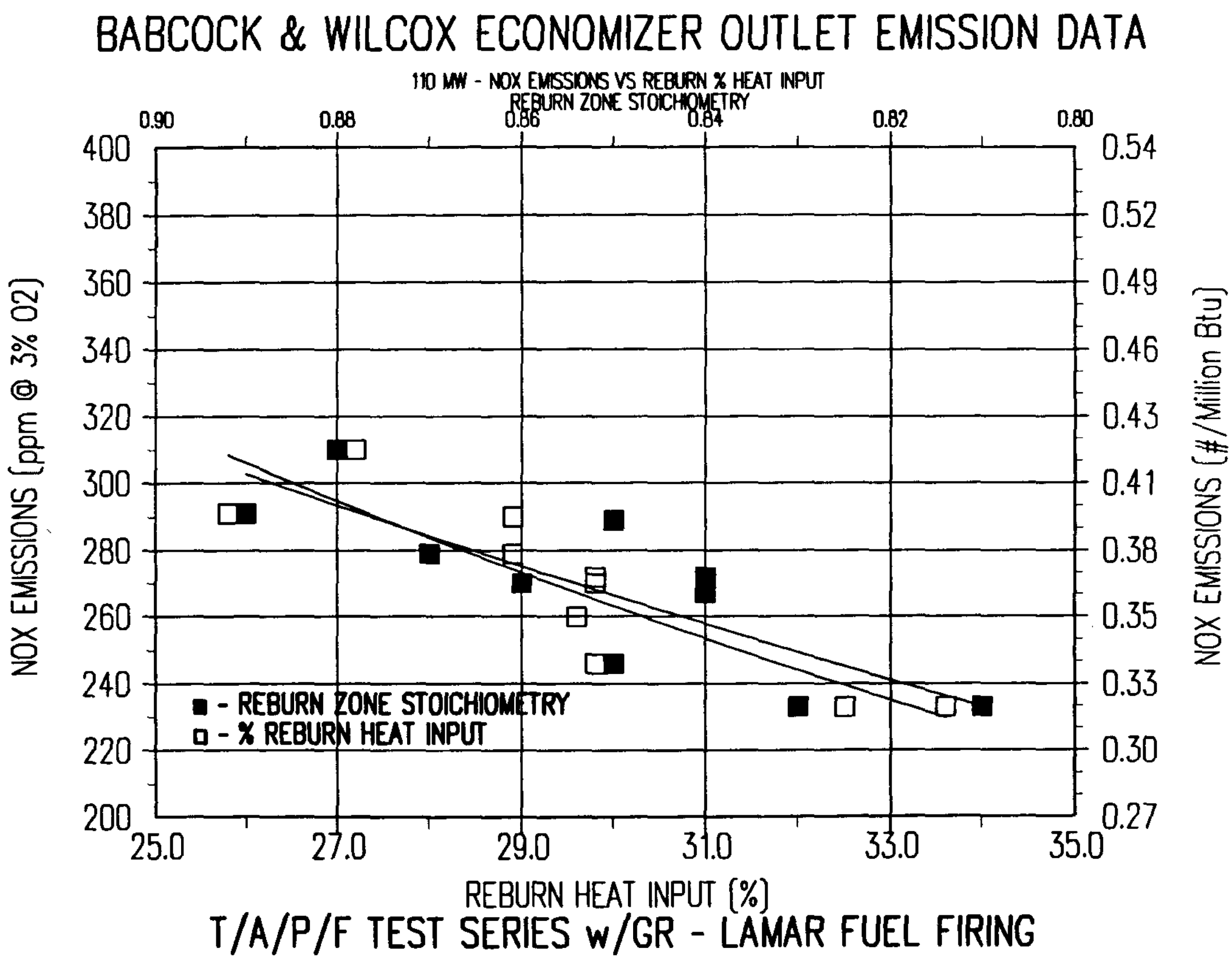
describes the results of varying this parameter and the resultant NO_x emission levels. In addition, the total amount of fuel to the reburn burners will affect the total ash loading to the furnace region. Obtaining the lowest NO_x emission level with the lowest amount of reburn fuel is a high priority in setting up the optimized reburn control scheme over the boiler load range.

Figures 7-8, 7-9, and 7-10 show results from the "T", "A", "P" and "F" series tests of NO_x emissions versus reburn % heat input and associated reburn zone stoichiometry for loads 110, 82 and 60 MW_e's respectively. The two curves of each figure show the direct relationship that exists between the % reburn heat input and the reburn zone stoichiometry variables. Although ideally the curves should be identical, variations in cyclone stoichiometry, reburn secondary air flow and gas recirculation rates between each of these tests result in the slight deviations observed.

Figure 7-8 reveals that varying reburn % heat input from 26 to 33.5% changed NO_x emissions from approximately 310 ppm (0.42 lb/10^6 Btu) to 232 ppm (0.32 lb/10^6 Btu) at 110 MW_e. Based upon the goal of the project to achieve 50% reduction at the least amount of reburn fuel heat input, the majority of tests are performed at the 29 - 30% heat input region.

Figure 7-9 reveals that varying reburn % heat input from 29 to 37% changed NO_x emissions from approximately 292 ppm (0.40 lb/10^6 Btu) to 232 ppm (0.32 lb/10^6 Btu) at 82 MW_e. As with the 110 MW_e case, based upon the goal of the project to achieve 50% reduction at the least amount of reburn fuel heat input, the majority of tests are performed at the 32 - 34% heat input region.

Figure 7-10 reveals that varying reburn % heat input from 31 to 35.5% did not change NO_x emissions significantly (about 347 - 337 ppm) at 60 MW_e. Raising reburn % heat input to higher levels at low loads is limited by minimum required cyclone coal flow rates. Increasing the reburn pulverizer coal output must accompany a corresponding cyclone coal feed reduction and this is not possible once the minimum cyclone loading is reached. Thus, the only means of significantly varying the reburn zone stoichiometry at the lower loads is to reduce secondary air to the reburn burners. Unfortunately, this practice causes flame instability leading to a less than ideal set of reburn system conditions at



BABCOCK & WILCOX ECONOMIZER OUTLET EMISSION DATA
110 MW - NOX EMISSIONS VS REBURN % HEAT INPUT
REBURN ZONE STOICHIOMETRY
0.90
0.88
0.86
0.84
0.82
0.80
400
380
360
340
320
300
280
260
240
220
200
0.54
0.52
0.49
0.46
0.43
0.41
0.38
0.35
0.33
0.30
0.27
NOX EMISSIONS (ppm @ 3% O2)
NOX EMISSIONS (#/Million Btu)
■ - REBURN ZONE STOICHIOMETRY
□ - % REBURN HEAT INPUT
25.0
27.0
29.0
31.0
33.0
35.0
REBURN HEAT INPUT (%)
T/A/P/F TEST SERIES w/GR - LAMAR FUEL FIRING

Figure 7-8

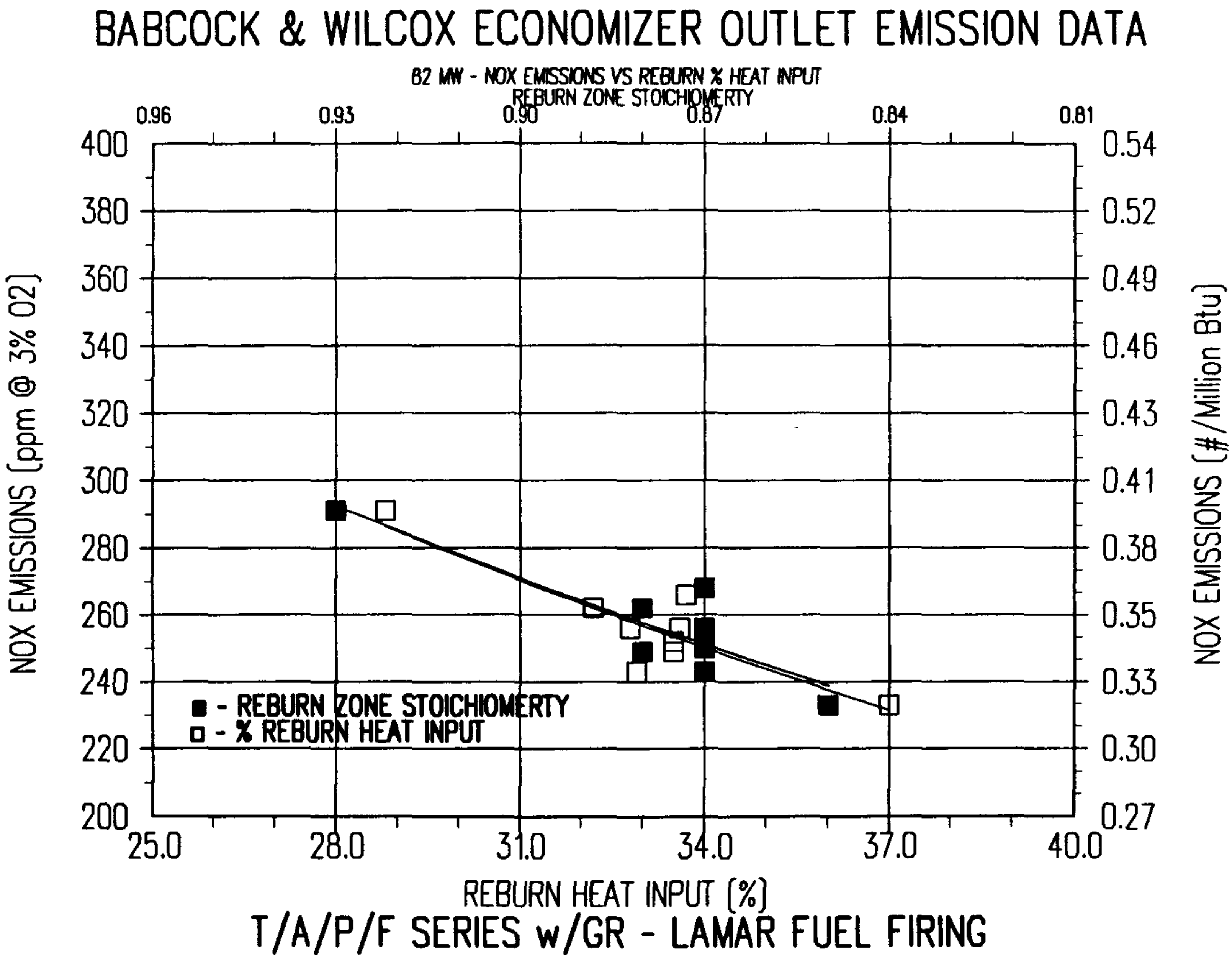

BABCOCK & WILCOX ECONOMIZER OUTLET EMISSION DATA
82 MW - NOX EMISSIONS VS REBURN % HEAT INPUT
REBURN ZONE STOICHIOMERTY
0.96
0.93
0.90
0.87
0.84
0.81
400
380
360
340
320
300
280
260
240
220
200
0.54
0.52
0.49
0.46
0.43
0.41
0.38
0.35
0.33
0.30
0.27
NOX EMISSIONS (ppm @ 3% O2)
NOX EMISSIONS (#/Million Btu)
■ - REBURN ZONE STOICHIOMERTY
□ - % REBURN HEAT INPUT
25.0
28.0
31.0
34.0
37.0
40.0
REBURN HEAT INPUT (%)
T/A/P/F SERIES w/GR - LAMAR FUEL FIRING

Figure 7-9

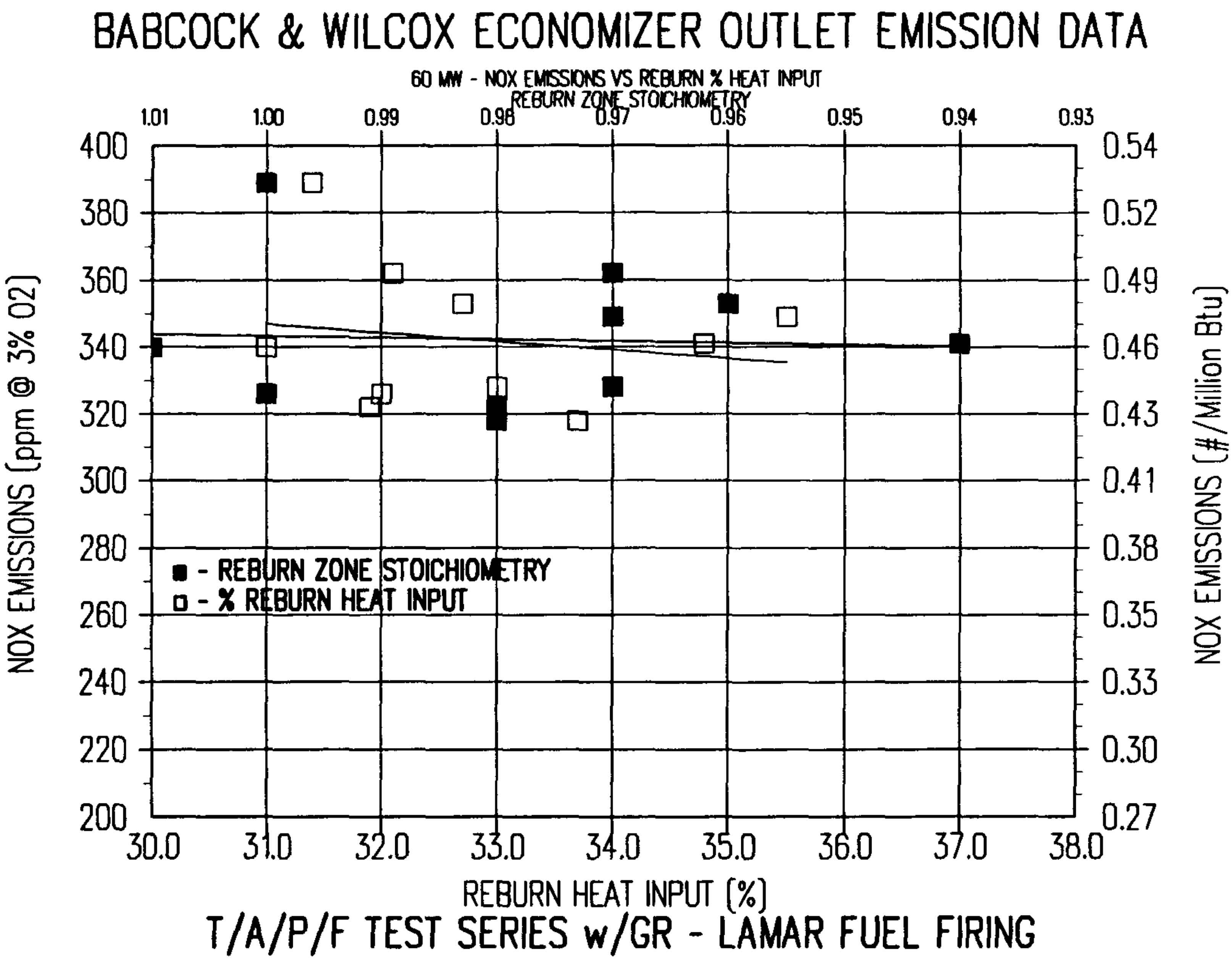

BABCOCK & WILCOX ECONOMIZER OUTLET EMISSION DATA
60 MW - NOX EMISSIONS VS REBURN % HEAT INPUT
REBURN ZONE STOICHIOMETRY
1.01
1.00
0.99
0.98
0.97
0.96
0.95
0.94
0.93
400
380
360
340
320
300
280
260
240
220
200
0.54
0.52
0.49
0.46
0.43
0.41
0.38
0.35
0.33
0.30
0.27
NOX EMISSIONS (ppm @ 3% O2)
NOX EMISSIONS (#/Million Btu)
■ - REBURN ZONE STOICHIOMETRY
□ - % REBURN HEAT INPUT
30.0
31.0
32.0
33.0
34.0
35.0
36.0
37.0
38.0
REBURN HEAT INPUT (%)
T/A/P/F TEST SERIES w/GR - LAMAR FUEL FIRING

Figure 7-10

lower loads. In addition, the data scatter in Figure 7-10 reveals that the boiler control at 60 MW_e is less stable.

7.3.1.1.3 Gas Recirculation Rate Impact

Gas recirculation (FGR) plays two key roles in the reburn system operation. First, the existing gas recirculation ports are located in an area that requires the FGR flow to pass by the cyclones prior to entering the main furnace. When the FGR fans are off, seal air must be provided to seal and cool the port openings. Since this air is not considered cyclone combustion air, it simply adds to the overall reburn zone stoichiometry and detracts from the % NO_x reduction capabilities. Therefore, operating the FGR fan allows seal air to be shut off and the reburn zone stoichiometry is not negatively affected. Secondly, the addition of FGR flow to the reburn burners makes possible the reduction of secondary air to the burners while maintaining acceptable burner velocity/pressure drop/mixing capability. Reducing the secondary air lowers the reburn zone stoichiometry and thus lowers NO_x emission levels.

When the boiler FGR fans are operating, opening the reburn system FGR damper allows a portion of the FGR to be mixed with the secondary air to the reburn burners. The amount of FGR to these burners is measured by an air monitor located within the FGR flue prior to the secondary air mix point. This flow is also calculated from the resultant O_2% measurement (taken downstream of the mix point) and the known secondary air flow rate. Due to fly ash pluggage problems at the FGR flow monitor, inconsistent flow indications were observed. This necessitated operation of the FGR system controls based upon the calculated flow rate.

The maximum amount of FGR flow that could be delivered to the reburn burners at full load operation is about 55,000 #/hr (approximately 5% of total boiler flow). The following discusses the results of operating with and without the FGR fans and the effects of varying FGR flow to the burners.

Table 7-2 shows the results of operating with and without the FGR fans at full load (110 MW_e) conditions.

TABLE 7-2 GAS RECIRCULATION EFFECT DURING LAMAR FUEL FIRING				
Condition	**B&W NO_x ppm @ 3% O_2**	**Reburn Zone Stoichiometry**	**% Reburn Heat Input**	**% Change**
Reburning - no FGR fan	298	0.93	29.6	-
Reburning - w/FGR fan: no FGR to burners	284	0.91	29.1	4.7
Reburning - w/FGR fan: FGR to burners	260	0.86	29.6	12.8

As shown in Table 7-2, reburn operation with the FGR fan off resulted in a NO_x level of 298 ppm. Operation of the FGR fan without adding any FGR to the reburn burners resulted in a 4.7% change in NO_x levels or 284 ppm NO_x. This reduction occurred due to the fact that by turning the FGR fan on, the seal air to the FGR ports is deleted and thus, a lower reburn zone stoichiometry is realized. Operating with about 1.0% FGR to the reburn burners and reducing the reburn burner stoichiometry resulted in an overall 12.8% lower NO_x level from the reburn/no FGR fan case. The significance of these changes are all related to the earlier described single most important parameter, reburn zone stoichiometry. Although typical 110 MW_e boiler operation does not require FGR flow, the above shows the significance of operating the FGR fans. In addition, no negative boiler effects are observed due to this operational change in philosophy.

Although FGR is an important variable, Figure 7-11 shows that at a constant reburn zone stoichiometry (about 0.90), varying the amount of FGR flow to the reburn burners did not substantially change the NO_x reduction capability. By maintaining approximately the same reburn zone stoichiometry, the resultant change in NO_x emissions would be directly impacted by any change in mixing characteristics. Figure 7-11 reveals that by increasing the % FGR flow to the reburn burners from approximately 0.13 to 5.50% (of the total boiler gas flow) results in NO_x emissions of 297 ppm to 294 ppm and thus, no change is observed.

As discussed earlier, the most critical parameter in reducing NO_x emissions during the cyclone coal reburning project is associated with the reburn zone stoichiometry. Maintaining the capability to add

FGR flow provides sufficient flexibility to help alter this variable without any major impact on burner performance.

7.3.1.1.4 Pulverizer Coal Fineness Impact

Changing the rotating classifier speed on the reburn pulverizer will affect the coal fineness to the reburn burners. Initial reburn design considerations dictated the potential to achieve at least a 90% through 200 mesh coal fineness. Full load pulverizer results showed that by changing the rotating classifier speed from 100 to 160 RPM provided coal fineness of about 81 to 82% and 97 to 98% through 200 mesh, respectively. Thus, higher fineness than originally specified was achieved. Since the reburn burners are introducing about 30% of the boiler's heat input higher in the furnace as compared to normal cyclone only operation, increasing coal fineness to these burners was critical to help control any potential impact on unburned carbon in the ash.

To determine coal fineness, pulverized coal samples were obtained at sampling taps in the vertical coal piping leaving the B&W MPS mill. Samples were obtained isokinetically and sent to B&W's Alliance Research Center for particle size distribution evaluation. ASTM D-197 fineness sampling and analysis procedures were followed.

Figure 7-12 shows results obtained during the "T" and "A" series tests of NO_x and unburned carbon (%) versus pulverizer classifier speed. The data was obtained during operation of the reburn zone at a stoichiometry of about 0.88. The NO_x emission levels are fairly consistent over the range of classifier speeds tested (approximately 300 ppm). This was expected based upon the SBS pilot scale test results that showed no impact of coal fineness on NO_x emissions. The major impact is observed in the resulting UBC levels when changing the classifier speed from 100 to 140 rpm. The % UBC was reduced from approximately 20% at 100 rpm to a range of 6 to 12% at 140 rpm. This reduction in UBC is directly attributed to the improved coal fineness. Increasing the classifier speed to 160 rpm did not show any additional improvement in UBC. Changing the classifier speed from 140 to 160 rpm increases the fineness from 94 to 96 % to 97 to 98% through 200 mesh.

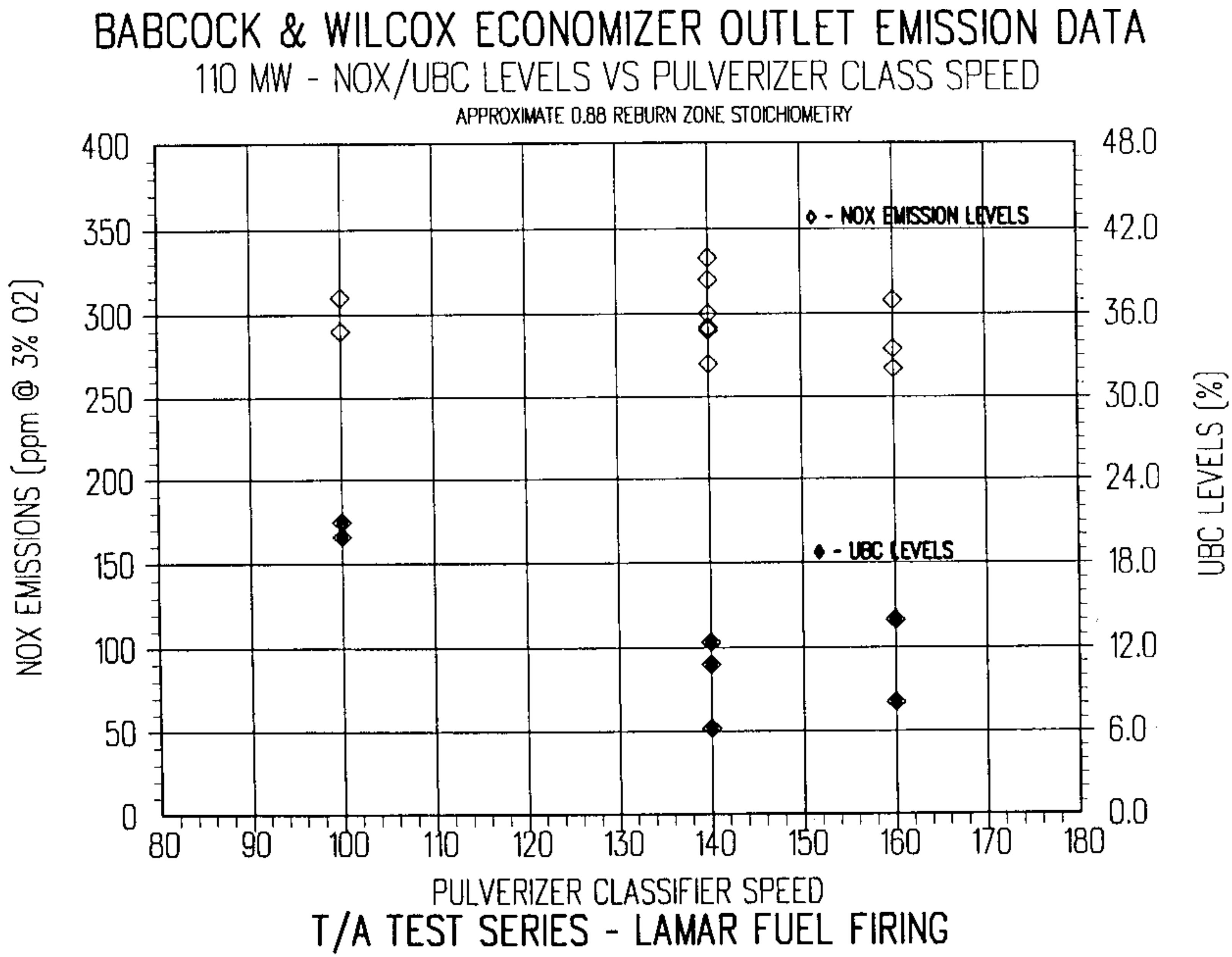

BABCOCK & WILCOX ECONOMIZER OUTLET EMISSION DATA
110 MW - NOX/UBC LEVELS VS PULVERIZER CLASS SPEED
APPROXIMATE 0.88 REBURN ZONE STOICHIOMETRY
◇ - NOX EMISSION LEVELS
◆ - UBC LEVELS
NOX EMISSIONS (ppm @ 3% O2)
UBC LEVELS (%)
400
350
300
250
200
150
100
50
0
48.0
42.0
36.0
30.0
24.0
18.0
12.0
6.0
0.0
80
90
100
110
120
130
140
150
160
170
180
PULVERIZER CLASSIFIER SPEED
T/A TEST SERIES - LAMAR FUEL FIRING

Figure 7-12

7.3.1.1.5 Reburning's Effect on Unit Load

Post-retrofit baseline and reburning tests were performed over the boiler load range of 37 - 110 MW_e. WP&L's typical pre-retrofit low load was about 30 MW_e and without reburn in operation this level was not affected after the retrofit. Due to reburn flame stability issues and the fact that the cyclones have to maintain a minimum firing rate, this 30 MW_e low load condition had to be increased to 37 MW_e. Although not ideal, the resultant boiler turndown was 66% with reburn in operation, exceeding the project's goal of 50% turndown. The following discussion describes the results in terms of load versus NO_x emissions, % NO_x reductions, and CO emissions for the various test series.

Figure 7-13 shows the data from all the Lamar bituminous test series for load versus NO_x emissions under baseline and reburning conditions. The baseline data is from all the post-retrofit testing and the average curve representing this data is within 5 to 10 ppm of data obtained during the 1990 Baseline Test Phase.

Although the average post-retrofit baseline NO_x emissions reveal a good correlation with the pre-retrofit values, day to day variations are observed. The largest variations are seen at 110 MW_e's where the baseline levels range between 573 to 657 ppm. This variation is typical and is due to changes in boiler conditions (boiler cleanliness, temperatures, air flows, etc.) and coal analyses (% nitrogen contents).

Additional baseline tests were performed at 37-38 MW_e during the post-retrofit tests and Figure 7-13 shows that the NO_x levels increase up to 600 ppm at these load conditions. The NO_x level increase is due to the fact that the boiler goes to single cyclone operation. Operating in this mode results in an increased heat input for the operating cyclone which represents close to full load cyclone capacity. In addition to the higher cyclone capacity (thus higher localized temperatures and higher resultant NO_x levels), the cooling air flow to the idle cyclones also increases the overall boiler oxygen content which is conducive to higher NO_x emission levels.

Table 7-3 shows the average baseline and reburn operation NO_x emission levels along with the associated % NO_x reductions at various tested loads.

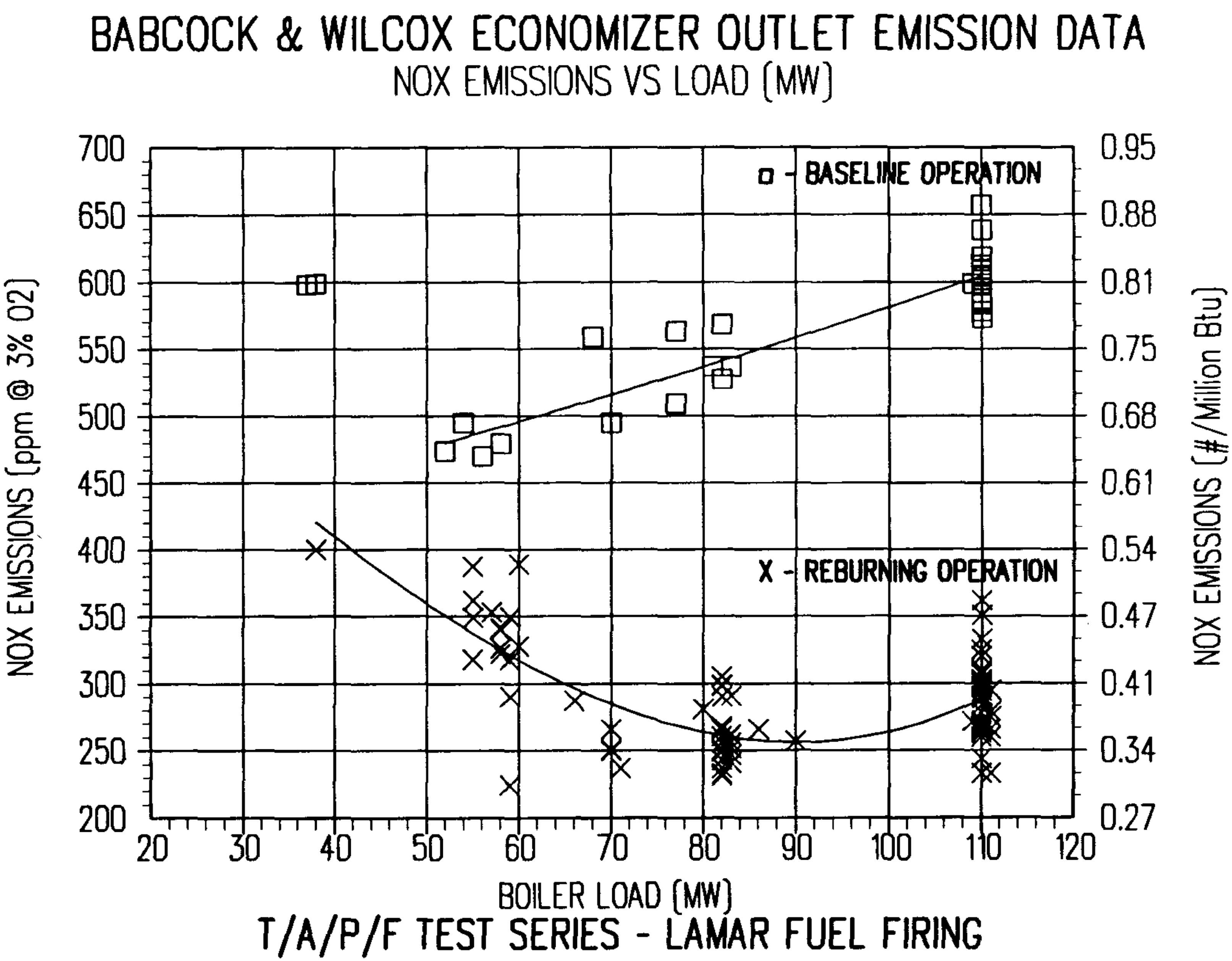

BABCOCK & WILCOX ECONOMIZER OUTLET EMISSION DATA
NOX EMISSIONS VS LOAD (MW)
NOX EMISSIONS (ppm @ 3% O2)
700
650
600
550
500
450
400
350
300
250
200
NOX EMISSIONS (#/Million Btu)
0.95
0.88
0.81
0.75
0.68
0.61
0.54
0.47
0.41
0.34
0.27
□ - BASELINE OPERATION
X - REBURNING OPERATION
20
30
40
50
60
70
80
90
100
110
120
BOILER LOAD (MW)
T/A/P/F TEST SERIES - LAMAR FUEL FIRING

Figure 7-13

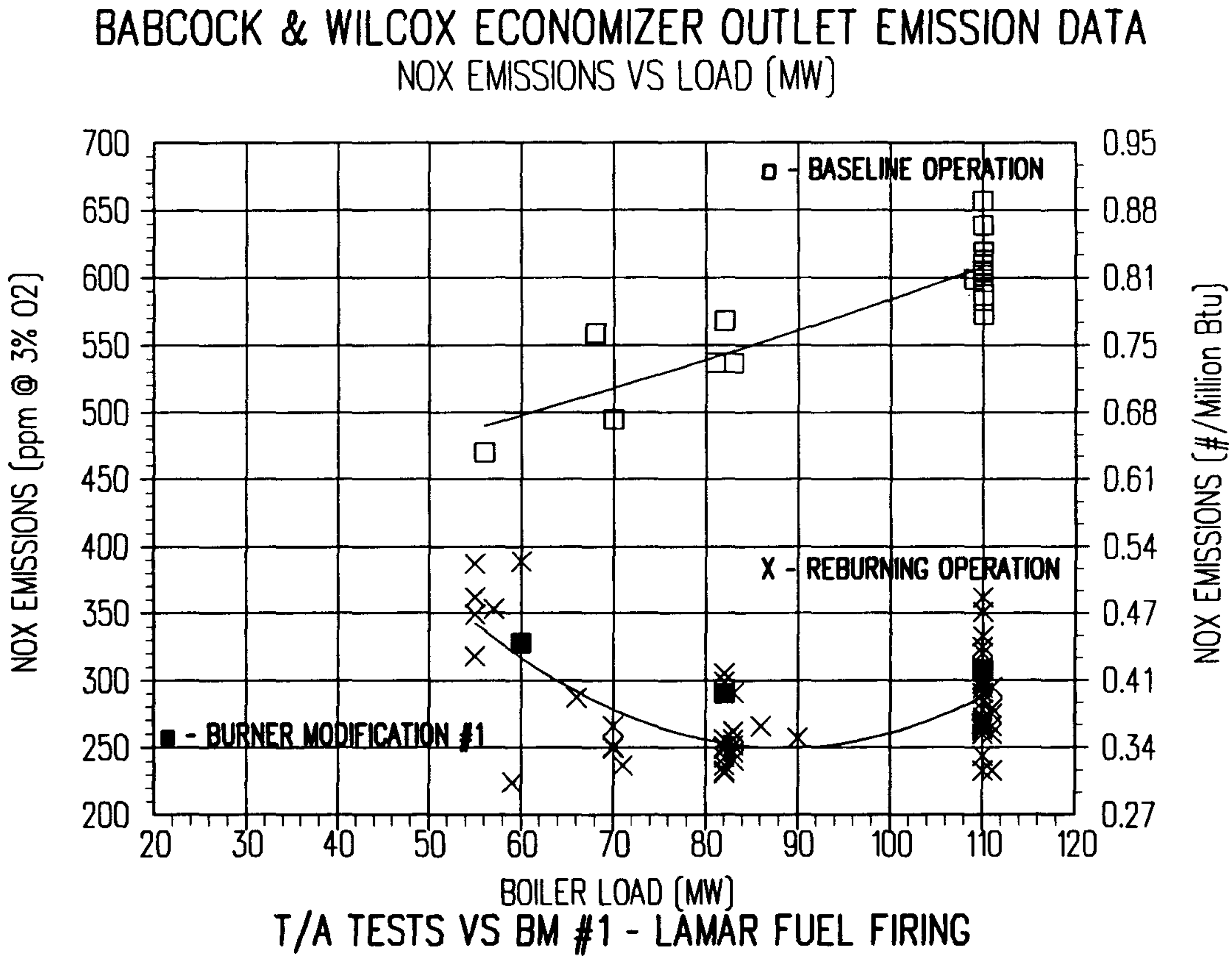
TABLE 7-3 PARAMETRIC TESTING AVERAGE % NO_x REDUCTION RESULTS			
Load (MW_e)	**Baseline NO_x (ppm @ 3% O_2)**	**Reburn NO_x (ppm @ 3% O_2)**	**% Reduction**
110	609	290	52.4
82	531	265	50.1
60	506	325	35.8
37-38	600	400	33.3

Figure 7-14 shows the load versus NO_x emission results for test series "T"/"A" and identifies three (3) test data points to compare the effect of the burner modification #1 (this is also discussed in section 7.3.1.1.1). As determined earlier, the effect of changing the burner swirler/spin vanes resulted in slightly higher NO_x emissions (5-30 ppm). The largest effect can be observed at the 82 MW_e load. Based upon these slightly higher NO_x levels, and in order to regain the lower NO_x values, the reburn control system was set-up to operate at lower reburn zone stoichiometries to provide the same % NO_x reduction capability as observed prior to the modification.

CO emission levels over the load range for all the test series is shown in Figure 7-15. Although a large data scatter is apparent, the overall baseline versus reburn operation CO emission results provide a good correlation of day to day activity. The average baseline data from 110 to 37 MW_e remains very constant at approximately 66 ppm while the reburn operation shows a range of 92 to 100 ppm. Reviewing the CO emission results presented earlier, this minimal impact between baseline and reburning operation is very typical.

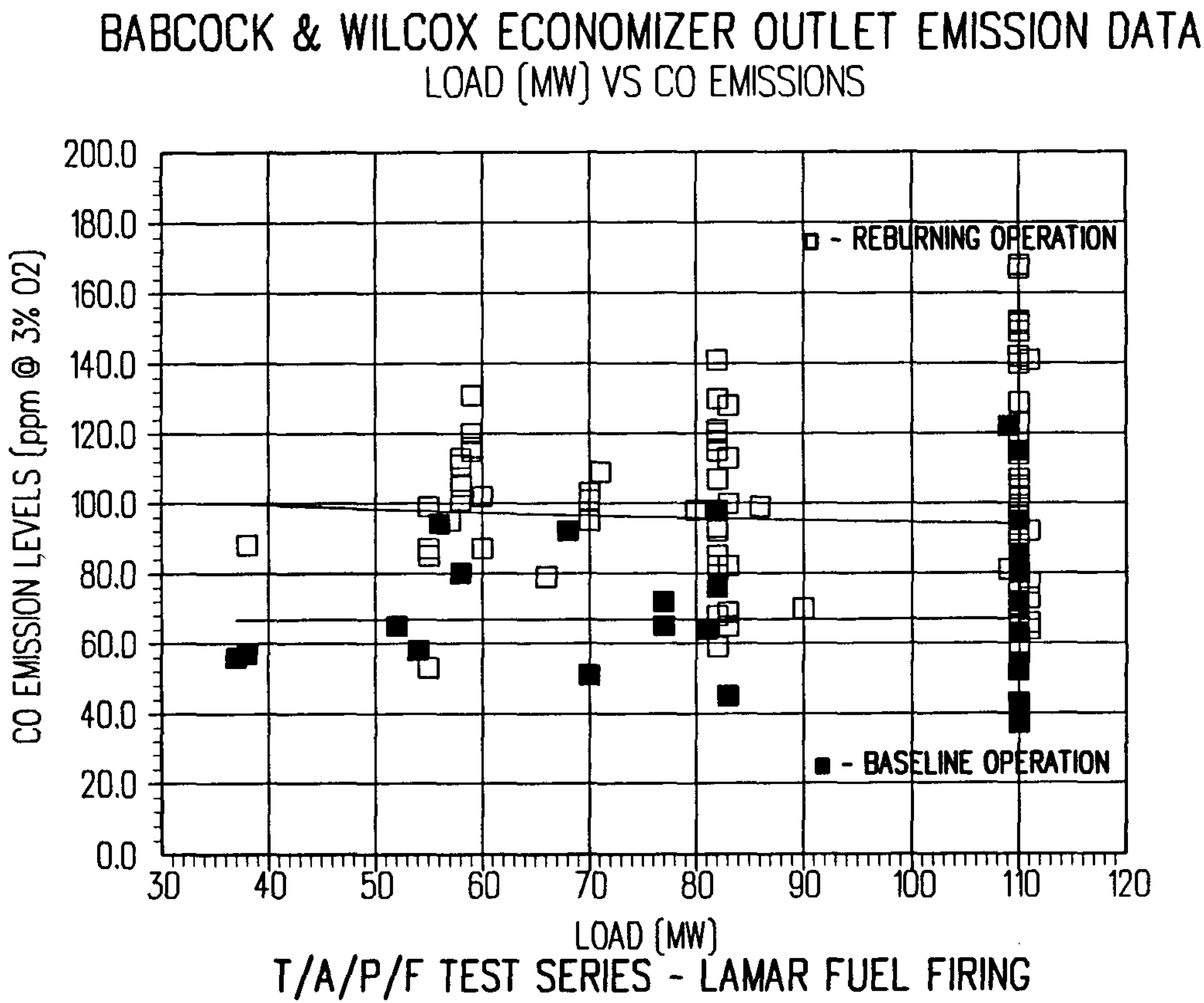
Figure 7-16 shows the same CO versus load curve except that it consists entirely of Acurex precipitator outlet data. The Acurex baseline CO levels remained constant over the load range at about 24-30 ppm. During reburn operation the Acurex CO indications ranged from about 40 ppm at full load to 60 ppm at 60 MW_e. The variation in B&W and Acurex data is again due to the grid versus single/double point sample extraction methods utilized.

Series "P" and "F" were performed to officially test the optimized reburning operation at the start and



BABCOCK & WILCOX ECONOMIZER OUTLET EMISSION DATA
NOX EMISSIONS VS LOAD (MW)
NOX EMISSIONS (ppm @ 3% O2)
NOX EMISSIONS (#/Million Btu)
□ - BASELINE OPERATION
X - REBURNING OPERATION
■ - BURNER MODIFICATION #1
700
650
600
550
500
450
400
350
300
250
200
0.95
0.88
0.81
0.75
0.68
0.61
0.54
0.47
0.41
0.34
0.27
20
30
40
50
60
70
80
90
100
110
120
BOILER LOAD (MW)
T/A TESTS VS BM #1 - LAMAR FUEL FIRING

Figure 7-14



BABCOCK & WILCOX ECONOMIZER OUTLET EMISSION DATA
LOAD (MW) VS CO EMISSIONS
CO EMISSION LEVELS (ppm @ 3% O2)
200.0
180.0
160.0
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
30
40
50
60
70
80
90
100
110
120
LOAD (MW)
□ - REBURNING OPERATION
■ - BASELINE OPERATION
T/A/P/F TEST SERIES - LAMAR FUEL FIRING

Figure 7-15

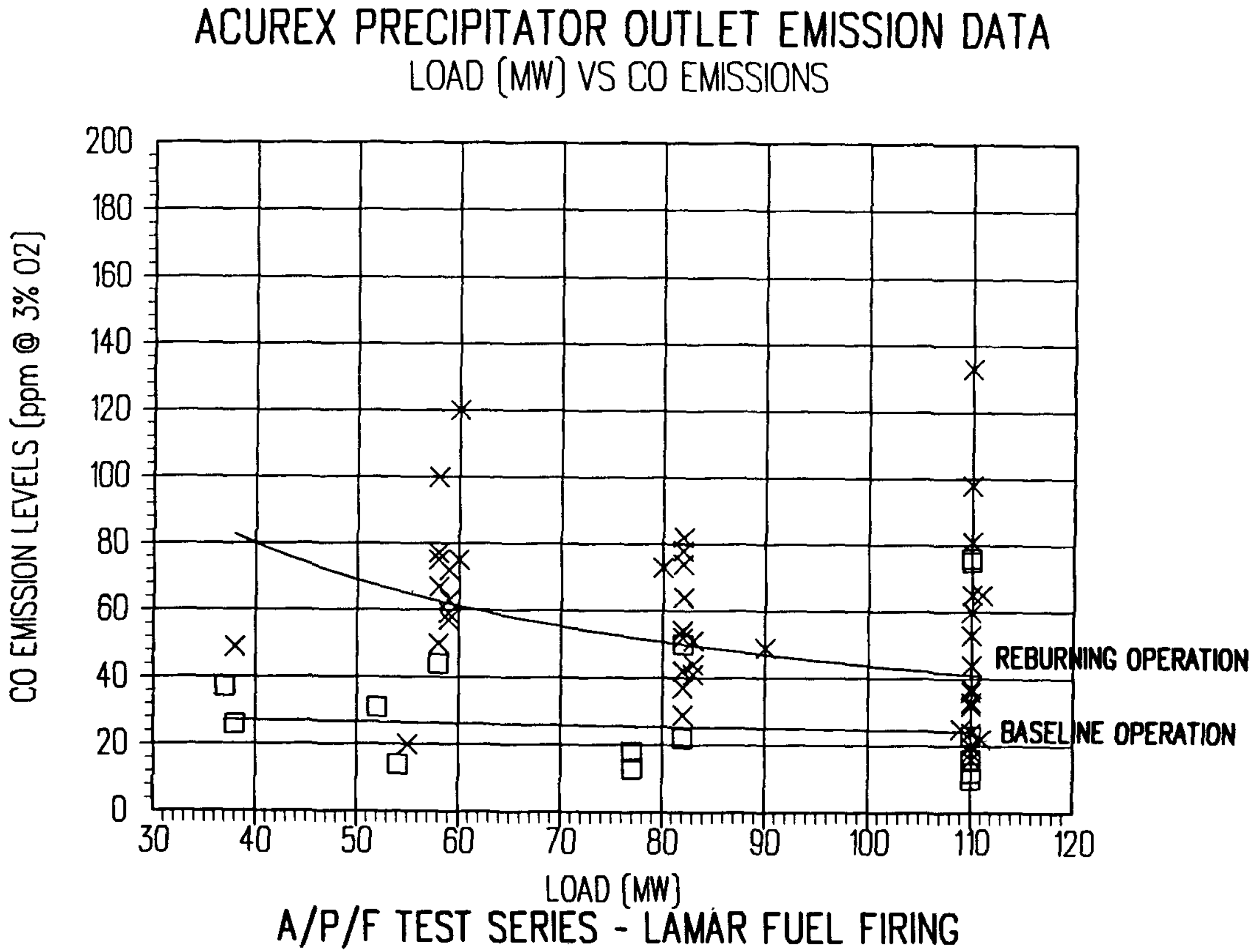

ACUREX PRECIPITATOR OUTLET EMISSION DATA
LOAD (MW) VS CO EMISSIONS
CO EMISSION LEVELS (ppm @ 3% O2)
200
180
160
140
120
100
80
60
40
20
0
30
40
50
60
70
80
90
100
110
120
LOAD (MW)
REBURNING OPERATION
BASELINE OPERATION
A/P/F TEST SERIES - LAMAR FUEL FIRING

Figure 7-16

finish of the long-term performance phase. Three (3) duplicate reburning tests were completed at each of the three (3) load conditions, giving a total of nine (9) tests. Figure 7-17 displays the initial/final performance tests for load versus NO_x emission levels. The data show that the NO_x results between the two phases is fairly consistent, although the final phase does reveal a slightly higher NO_x level at the 110 and 82 MW_e loads.

Figure 7-18 shows the average % NO_x reductions from both the "P" and "F" series tests. At 110, 82, and 60 MW_e's, the resultant % NO_x reductions for the initial performance tests are 54.7%, 49.2%, and 35.0% respectively. The final performance tests reveal % reductions of 50.6%, 46.3%, and 35.2% for the 110, 82, and 60 MW_e's respectively. The original project goal of achieving a 50% reduction at full load was achieved as demonstrated by these results.

The only modification that is apparent between the 2 test series is the fact that a second burner modification had occurred to help burner stability. Unfortunately, the results reveal that a slight degradation in NO_x reduction efficiency became apparent with no corresponding improvement in burner stability. This modification #2 is described earlier in sections 7.2.2.4 and 7.2.2.6. Based upon the observed non-improvement, the burner modification #1 was re-installed before the HAP test series.

Although no immediate NO_x emission test data was obtained to directly compare between burner modifications, the subsequent HAP testing results can be used to determine if the % NO_x reduction capability was altered. Using the baseline NO_x levels of 609 ppm (Initial Performance Tests) and 585 ppm during HAP testing revealed overall reburning % NO_x reductions of 54.7 and 53.2% respectively. Therefore, restoring the coal impeller prior to the HAP testing to that used during the initial performance tests confirmed that similar higher % reductions were again achieved. This provides justification for the earlier stated claim that the burner modification caused the % NO_x reduction degradation between the "P" and "F" series testing.

7.3.1.2 Western Fuel Firing Results

The western sub-bituminous coal firing tests were done to obtain a direct comparison of reburn performance for two different coal types. In addition, sufficient data were

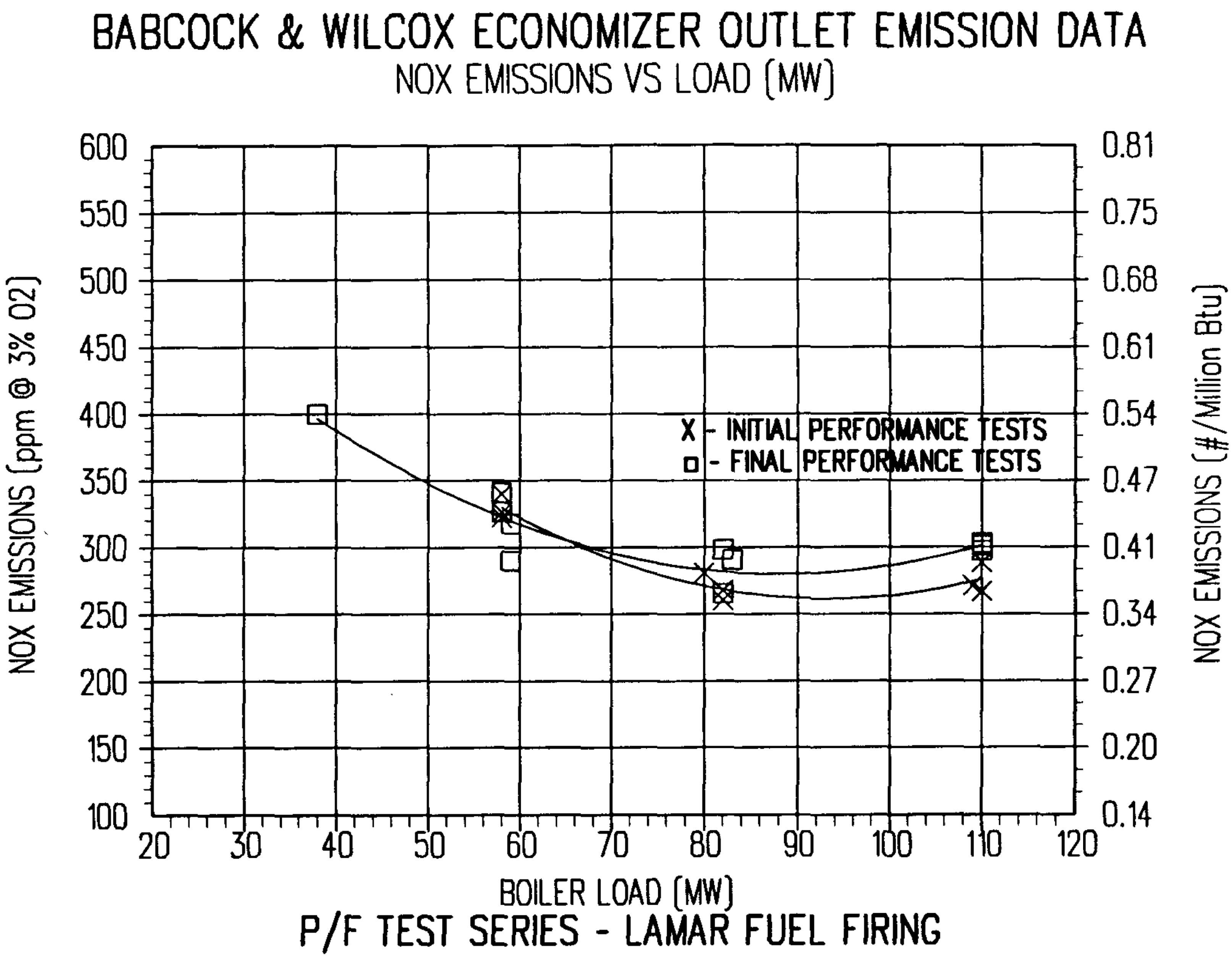

BABCOCK & WILCOX ECONOMIZER OUTLET EMISSION DATA
NOX EMISSIONS VS LOAD (MW)
NOX EMISSIONS (ppm @ 3% O2)
600
550
500
450
400
350
300
250
200
150
100
0.81
0.75
0.68
0.61
0.54
0.47
0.41
0.34
0.27
0.20
0.14
NOX EMISSIONS (#/Million Btu)
X - INITIAL PERFORMANCE TESTS
□ - FINAL PERFORMANCE TESTS
20
30
40
50
60
70
80
90
100
110
120
BOILER LOAD (MW)
P/F TEST SERIES - LAMAR FUEL FIRING

Figure 7-17

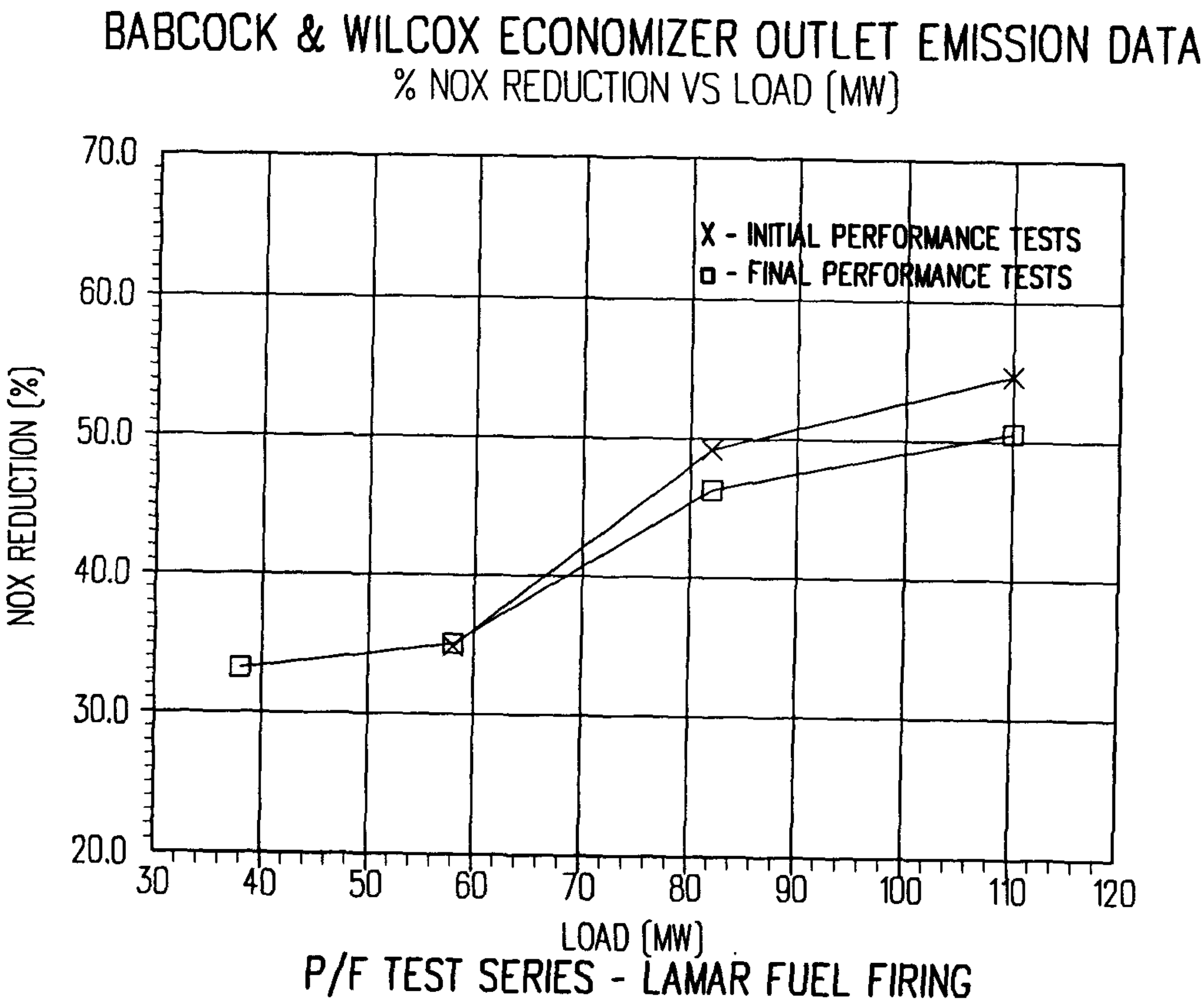

BABCOCK & WILCOX ECONOMIZER OUTLET EMISSION DATA
% NOX REDUCTION VS LOAD (MW)
NOX REDUCTION (%)
70.0
60.0
50.0
40.0
30.0
20.0
30
40
50
60
70
80
90
100
110
120
LOAD (MW)
X - INITIAL PERFORMANCE TESTS
□ - FINAL PERFORMANCE TESTS
P/F TEST SERIES - LAMAR FUEL FIRING

Figure 7-18

collected in order to allow optimized reburning performance curves to be generated and incorporated into the boiler control system at Nelson Dewey Unit #2. Similar tests to those performed earlier in series "T", "A", "P", and "F" were carried out within series "W". A total of 30 official tests were performed.

Babcock & Wilcox collected the majority of the test data obtained during the "W" series, but the Acurex CEM system also remained operational. Table 5 in Appendix 7 is a summary of all the tests performed within the "W" series and the associated results. The following information shows the effect of reburning zone stoichiometry, % reburn heat input, % of gas recirculation, and load on both NO_x and CO emission levels. Within these figures, comparisons between the B&W and Acurex emission data are included to verify the consistency of the two measurements. Finally, a direct comparison between the coal reburning results from the Lamar bituminous and western sub-bituminous tests is provided.

7.3.1.2.1 Reburn Zone Stoichiometry Impact

As shown in the results from the Lamar bituminous testing, varying the reburn zone stoichiometry is the most critical factor in changing NO_x emission levels during coal reburning operation. The reburn zone stoichiometry can be varied via altering the air flow quantities (oxygen availability) to the reburn burners, the % reburn heat input, the gas recirculation flow rate, or the cyclone stoichiometry. The following series of figures reveal NO_x emission levels versus reburn zone stoichiometry at various load conditions.

Figure 7-19 represents B&W economizer outlet NO_x emissions versus reburn zone stoichiometry at full load conditions (110 MW_e). The average baseline NO_x level identified is 560 ppm (0.75 lb/10^6 Btu). In order to obtain the required goal of 50% NO_x reduction (280 ppm or 0.375 lb/10^6 Btu), the reburn zone stoichiometry must be at about 0.91. In addition, the data shows that the lowest reburn stoichiometry tested at 0.85 would yield a corresponding NO_x level of 208 ppm (0.28 lb/10^6 Btu) or a 62.9% NO_x reduction.

The B&W economizer outlet and Acurex precipitator outlet data are extremely consistent over the entire reburn zone stoichiometric range at 110 MW_e. Although the comparison between these two independent emission measurements was good during the Lamar bituminous coal testing, the entire "W" series had the benefit of a two (2) probe gas

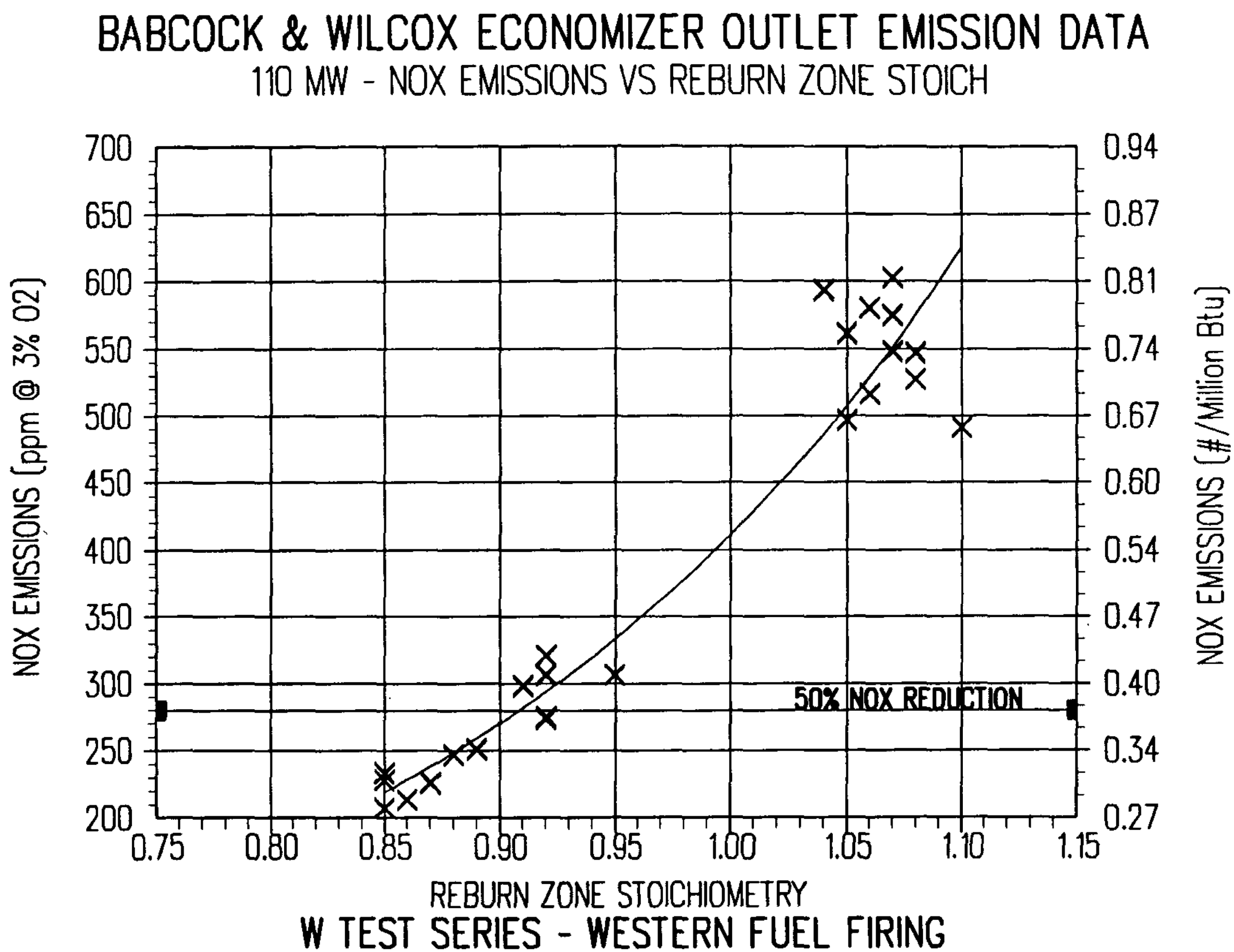

BABCOCK & WILCOX ECONOMIZER OUTLET EMISSION DATA
110 MW - NOX EMISSIONS VS REBURN ZONE STOICH
NOX EMISSIONS (ppm @ 3% O2)
700
650
600
550
500
450
400
350
300
250
200
0.75
0.80
0.85
0.90
0.95
1.00
1.05
1.10
1.15
0.94
0.87
0.81
0.74
0.67
0.60
0.54
0.47
0.40
0.34
0.27
NOX EMISSIONS (#/Million Btu)
50% NOX REDUCTION
REBURN ZONE STOICHIOMETRY
W TEST SERIES - WESTERN FUEL FIRING

Figure 7-19

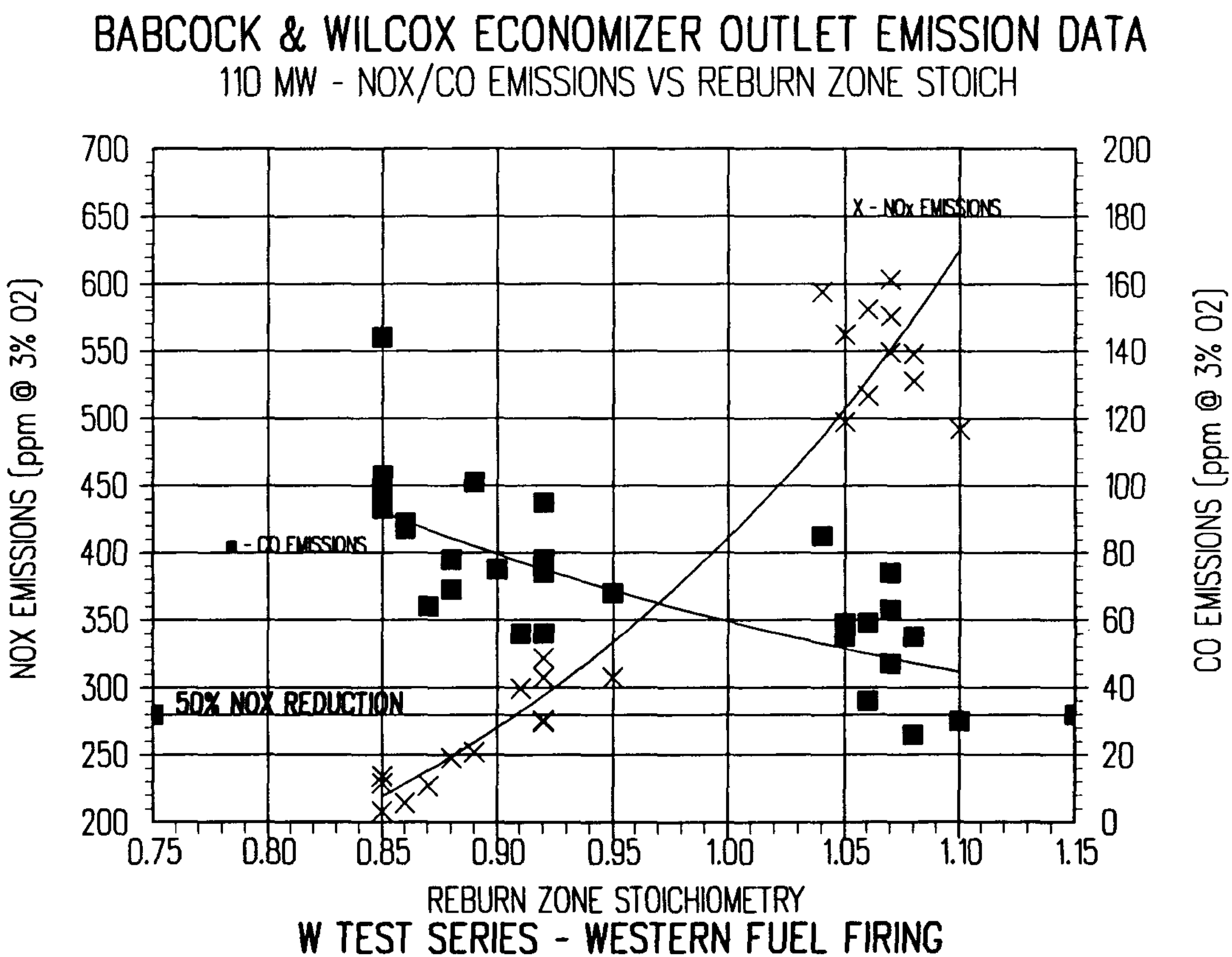

BABCOCK & WILCOX ECONOMIZER OUTLET EMISSION DATA
110 MW - NOX/CO EMISSIONS VS REBURN ZONE STOICH
NOX EMISSIONS (ppm @ 3% O2)
CO EMISSIONS (ppm @ 3% O2)
700
650
600
550
500
450
400
350
300
250
200
200
180
160
140
120
100
80
60
40
20
0
X - NOx EMISSIONS
■ - CO EMISSIONS
50% NOX REDUCTION
0.75
0.80
0.85
0.90
0.95
1.00
1.05
1.10
1.15
REBURN ZONE STOICHIOMETRY
W TEST SERIES - WESTERN FUEL FIRING

Figure 7-20

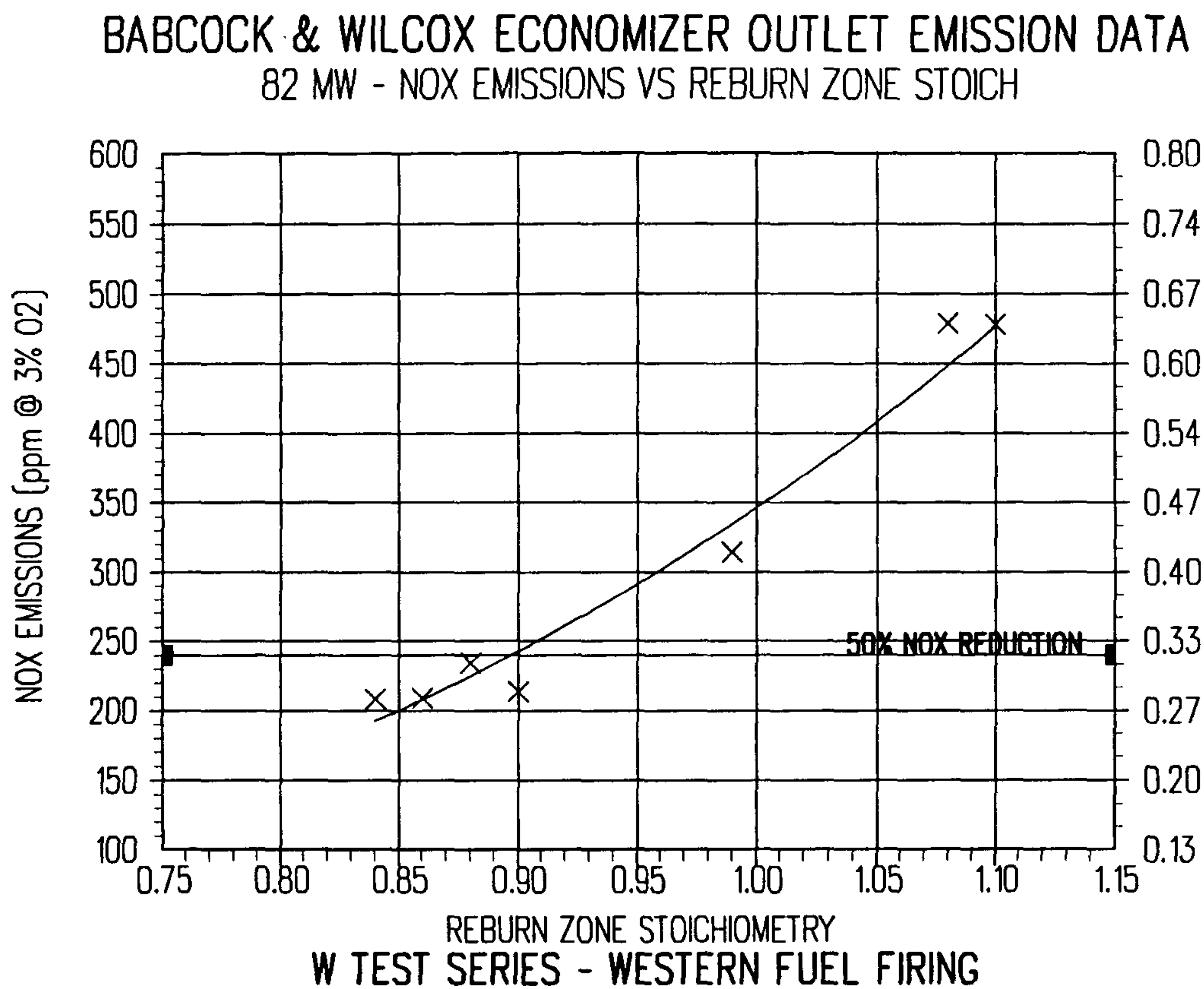

BABCOCK & WILCOX ECONOMIZER OUTLET EMISSION DATA
82 MW - NOX EMISSIONS VS REBURN ZONE STOICH
NOX EMISSIONS (ppm @ 3% O2)
600
550
500
450
400
350
300
250
200
150
100
0.80
0.74
0.67
0.60
0.54
0.47
0.40
0.33
0.27
0.20
0.13
50% NOX REDUCTION
0.75
0.80
0.85
0.90
0.95
1.00
1.05
1.10
1.15
REBURN ZONE STOICHIOMETRY
W TEST SERIES - WESTERN FUEL FIRING

Figure 7-21

extraction Acurex system (instead of the single probe system used for a portion of the Lamar fuel testing) and thus a better overall average was realized.

CO and NO_x emission levels versus reburn zone stoichiometry at the 110 MW_e load condition during the "W" test series is revealed in Figure 7-20. The average baseline versus reburn operation CO emission levels increased from about 44 ppm to 92 ppm. Assuming the reburn system is maintaining a 50% reduction at about a 0.91 reburn zone stoichiometry, the average CO emission level during reburning operation was 78 ppm. As expected, reducing NO_x emissions via lowering the reburn zone stoichiometry results in increasing the CO emission levels. Less CO emission data scatter is apparent during the western fuel firing tests as compared to that observed during the Lamar tests (see Figure 7-3).

Figure 7-21 is a plot of the data collected during the "W" series at 82 MW_e for NO_x emission levels versus reburn zone stoichiometry. The figure shows a baseline NO_x level of 480 ppm (0.64 $lb/10^6$ Btu). Varying the reburn zone stoichiometry from 1.10 to 0.84 results in NO_x emissions from the 480 ppm baseline level to 205 ppm (0.275 $lb/10^6$ Btu). In order to achieve a 50% reduction, Figure 7-27 shows that a reburn zone stoichiometry of about 0.90 is required. Operating at the lower 0.84 reburn zone stoichiometry would result in a corresponding 57.3% NO_x reduction.

As stated above for the 110 MW_e condition, an extremely good correlation between the B&W and Acurex emission values at the 82 MW_e load for the reburn zone stoichiometry versus NO_x emission level was also seen.

CO and NO_x emission levels versus reburn zone stoichiometry at the 82 MW_e load condition during the "W" test series is shown in Figure 7-22. The average baseline versus reburn operation CO emission levels increased from about 20 ppm to 56 ppm. Assuming the reburn system is maintaining a 50% reduction at about a 0.90 reburn zone stoichiometry, the average CO emission level during reburn operation was 45 ppm. This result is typical as observed in day to day baseline and reburning operation.

60 MW_e test results for NO_x emissions versus reburn zone stoichiometry for the "W" test series is shown in Figure 7-23 and reveals that a 50% reduction can

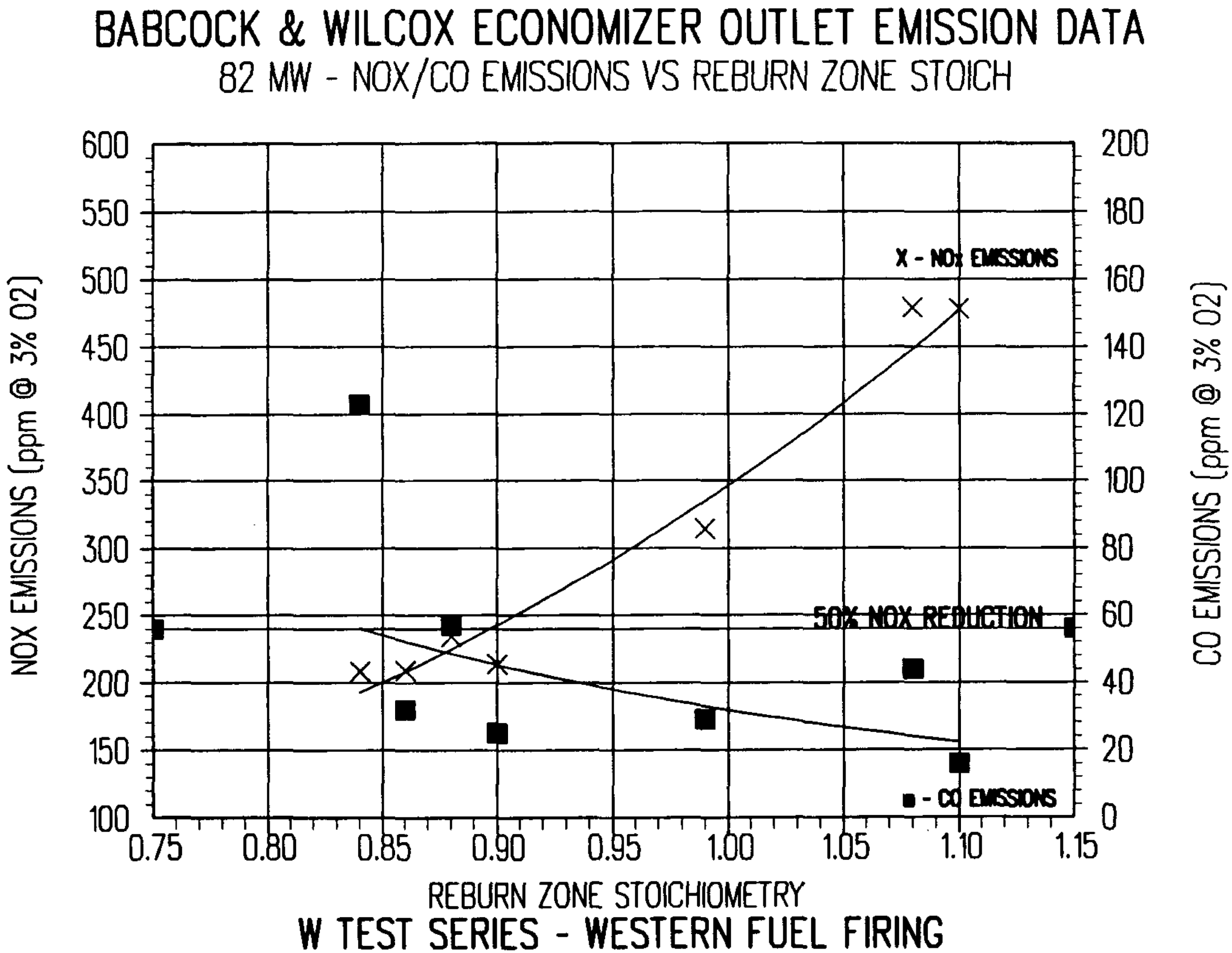
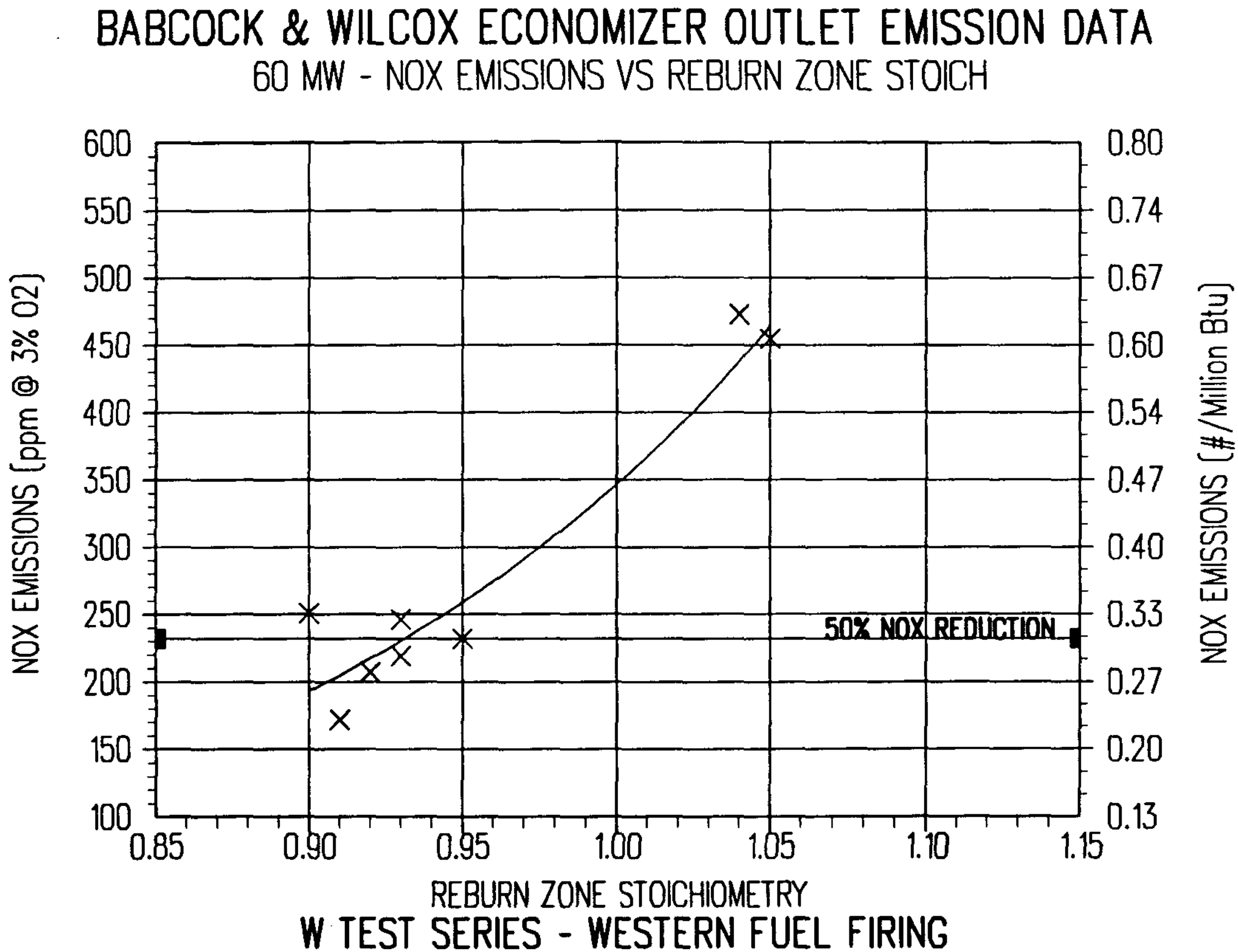

BABCOCK & WILCOX ECONOMIZER OUTLET EMISSION DATA
82 MW - NOX/CO EMISSIONS VS REBURN ZONE STOICH
NOX EMISSIONS (ppm @ 3% O2)
CO EMISSIONS (ppm @ 3% O2)
600
550
500
450
400
350
300
250
200
150
100
200
180
160
140
120
100
80
60
40
20
0
X - NOx EMISSIONS
50% NOX REDUCTION
■ - CO EMISSIONS
0.75
0.80
0.85
0.90
0.95
1.00
1.05
1.10
1.15
REBURN ZONE STOICHIOMETRY
W TEST SERIES - WESTERN FUEL FIRING

Figure 7-22



BABCOCK & WILCOX ECONOMIZER OUTLET EMISSION DATA
60 MW - NOX EMISSIONS VS REBURN ZONE STOICH
NOX EMISSIONS (ppm @ 3% O2)
600
550
500
450
400
350
300
250
200
150
100
0.80
0.74
0.67
0.60
0.54
0.47
0.40
0.33
0.27
0.20
0.13
NOX EMISSIONS (#/Million Btu)
50% NOX REDUCTION
0.85
0.90
0.95
1.00
1.05
1.10
1.15
REBURN ZONE STOICHIOMETRY
W TEST SERIES - WESTERN FUEL FIRING

Figure 7-23

be achieved at a reburn zone stoichiometry of 0.93. This was not the case with the Lamar coal since the 50% reduction goal could not be obtained at this lower load. The B&W economizer outlet data indicated that the average baseline NO_x level at 60 MW_e's is 464 ppm (0.62 lb/10^6 Btu). Figure 7-23 shows that varying the reburn zone stoichiometry from 1.05 to 0.90 results in NO_x emission levels of 464 ppm to about 195 ppm (0.26 lb/10^6 Btu). Reducing the reburn zone stoichiometry to the 0.90 case results in a 58.0% NO_x reduction.

At 60 MW_e, the comparison between the B&W and Acurex data is similar to that observed at 110 MW_e and 60 MW_e during the Lamar coal tests where an approximate 20 ppm higher Acurex reading is seen over the reburn zone stoichiometric range. As observed with that data, the consistency between the two measurements over the stoichiometric range provides a good indication of the accuracy of results and simply shows that a small gas flow stratification occurs at this load.

CO emission (ppm @ 3% O_2) and NO_x emission levels versus reburn zone stoichiometry at the 60 MW_e load condition during this "W" test series is shown in Figure 7-24. The average baseline versus reburn operation CO emission levels increased from about 32 ppm to 54 ppm over a reburn zone stoichiometric range of 1.05 to 0.90. At the reburn zone stoichiometry at which a 50% NO_x reduction was achieved (0.93), an average CO emission level of 48 ppm was observed. This result was typical as observed in day to day baseline and reburning operation.

7.3.1.2.2 Impact of Reburn Heat Input

Altering the % reburn heat input affects the reburn zone stoichiometry. The following section describes the results of varying this parameter and the resultant NO_x emission levels during western coal firing. The subsequent figures show the results from series "W" at various loads for NO_x emissions versus reburn % heat input and reburn zone stoichiometry. As stated earlier, although the curves should be ideally the same, variations in cyclone stoichiometry, reburn burner secondary air flow and gas recirculation rates between each of the tests result in the slight variations.

Figure 7-25 reveals that varying reburn % heat input from 25.5 to 32% changed NO_x emissions from approximately 299 ppm (0.40 lb/10^6 Btu) to 227 ppm

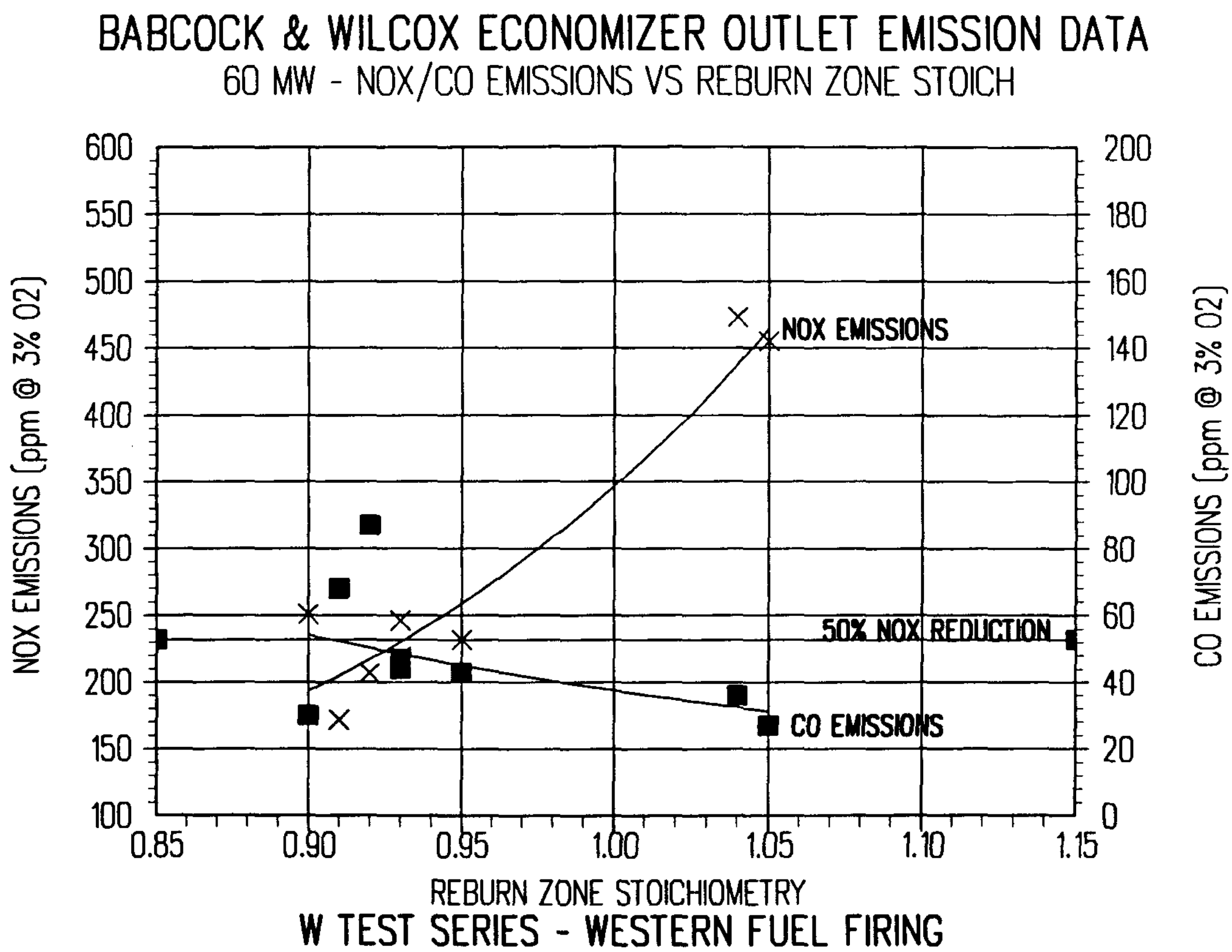
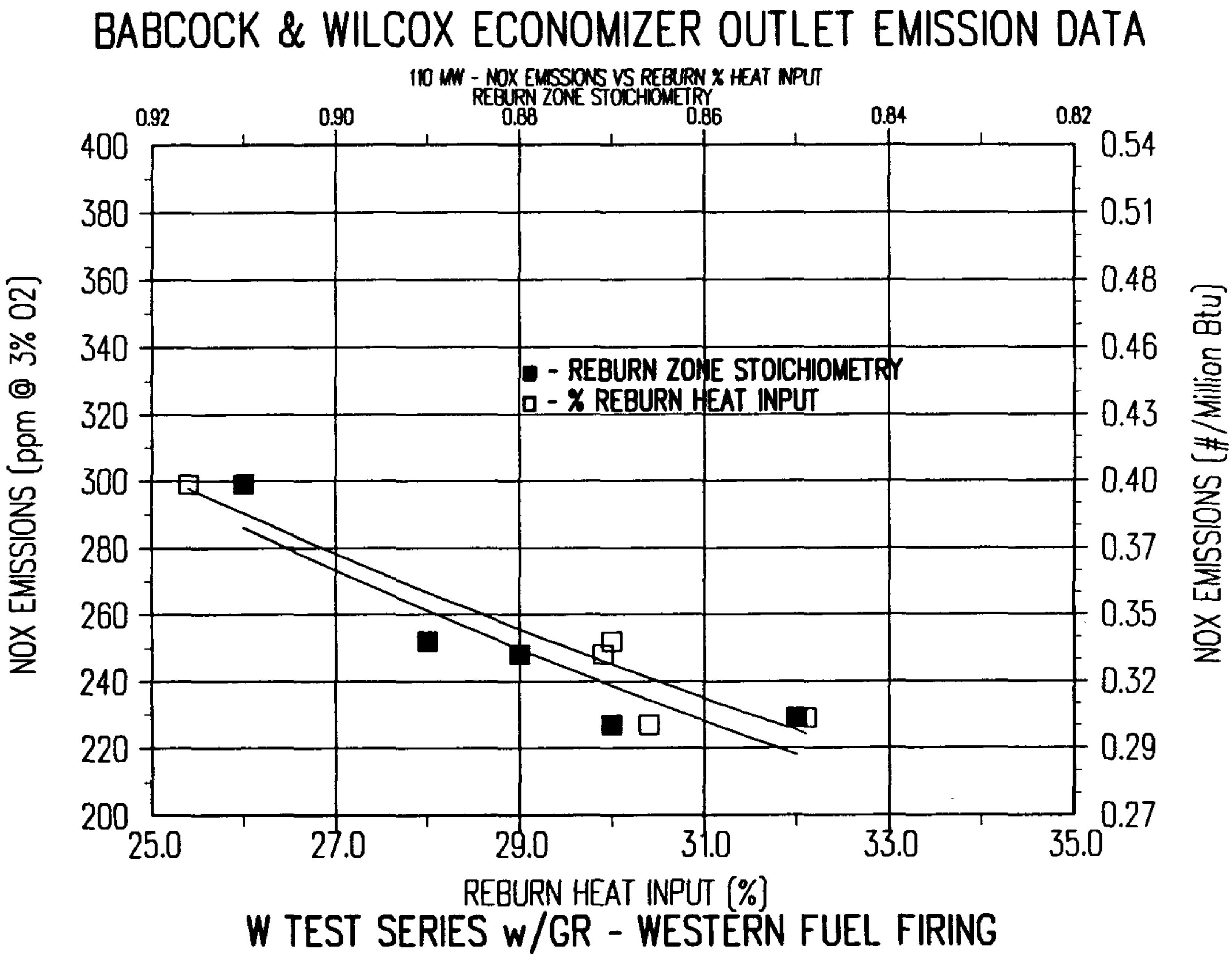

BABCOCK & WILCOX ECONOMIZER OUTLET EMISSION DATA
60 MW - NOX/CO EMISSIONS VS REBURN ZONE STOICH
NOX EMISSIONS (ppm @ 3% O2)
600
550
500
450
400
350
300
250
200
150
100
CO EMISSIONS (ppm @ 3% O2)
200
180
160
140
120
100
80
60
40
20
0
NOX EMISSIONS
50% NOX REDUCTION
CO EMISSIONS
0.85
0.90
0.95
1.00
1.05
1.10
1.15
REBURN ZONE STOICHIOMETRY
W TEST SERIES - WESTERN FUEL FIRING

Figure 7-24



BABCOCK & WILCOX ECONOMIZER OUTLET EMISSION DATA
110 MW - NOX EMISSIONS VS REBURN % HEAT INPUT
REBURN ZONE STOICHIOMETRY
0.92
0.90
0.88
0.86
0.84
0.82
400
380
360
340
320
300
280
260
240
220
200
0.54
0.51
0.48
0.46
0.43
0.40
0.37
0.35
0.32
0.29
0.27
- REBURN ZONE STOICHIOMETRY
- % REBURN HEAT INPUT
NOX EMISSIONS (ppm @ 3% O2)
NOX EMISSIONS (#/Million Btu)
25.0
27.0
29.0
31.0
33.0
35.0
REBURN HEAT INPUT (%)
W TEST SERIES w/GR - WESTERN FUEL FIRING

Figure 7-25

(0.30 lb/10^6 Btu) at 110 MW_e. Based upon the desire to achieve greater than 50% reduction at the least amount of reburn fuel heat input, the majority of tests were performed at the 29 - 30% heat input region.

Figure 7-26 reveals that varying reburn % heat input from 26 to 34% changed NO_x emissions from 312 ppm (0.42 lb/10^6 Btu) to about 207 ppm (0.28 lb/10^6 Btu) at 82 MW_e. As with the 110 MW_e case, based upon the goal of the project to achieve greater than 50% reduction at the least amount of reburn fuel heat input, the majority of tests are performed at the 32 - 33% heat input region.

Figure 7-27 reveals that varying reburn % heat input from 33.5 to 41% at 60 MW_e changed NO_x emissions from approximately 235 ppm (0.32 lb/10^6 Btu) to 208 ppm (0.28 lb/10^6 Btu). Due to the lower heating value of the western fuel (as compared to the Lamar bituminous coal), the minimum coal flow rate to the cyclones, which were identified as a problem during the low load reburn Lamar testing was less apparent while operating with the western fuel. Thus, increasing reburn % heat input to higher levels at low loads was slightly more feasible during the "W" series.

7.3.1.2.3 Gas Recirculation Rate Impact

As discussed earlier in the Lamar bituminous gas recirculation section (7.3.1.1.3), FGR is an extremely useful tool in the reburning system. The FGR system design at Nelson Dewey Unit #2 provides the capability to add FGR to the FGR ports, minimize the seal air entering the boiler, and/or to introduce FGR to the reburn burners.

The following discussions reveal the results of operating with and without the FGR fans during reburning and also the effects when varying the amount to the reburn burners during western fuel firing. Table 7-4 shows the results of operating with and without the FGR fans at full load (110 MW_e) conditions.

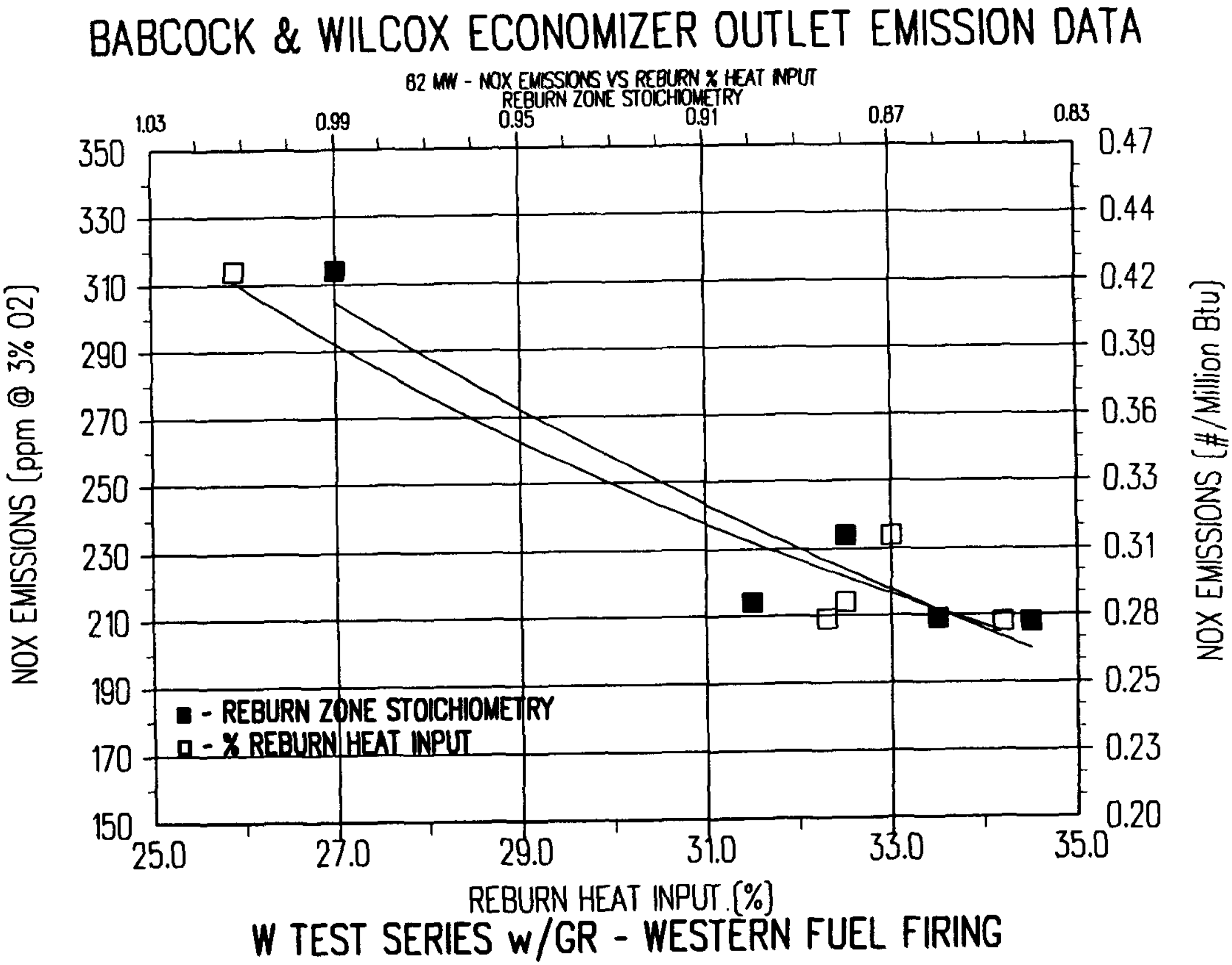
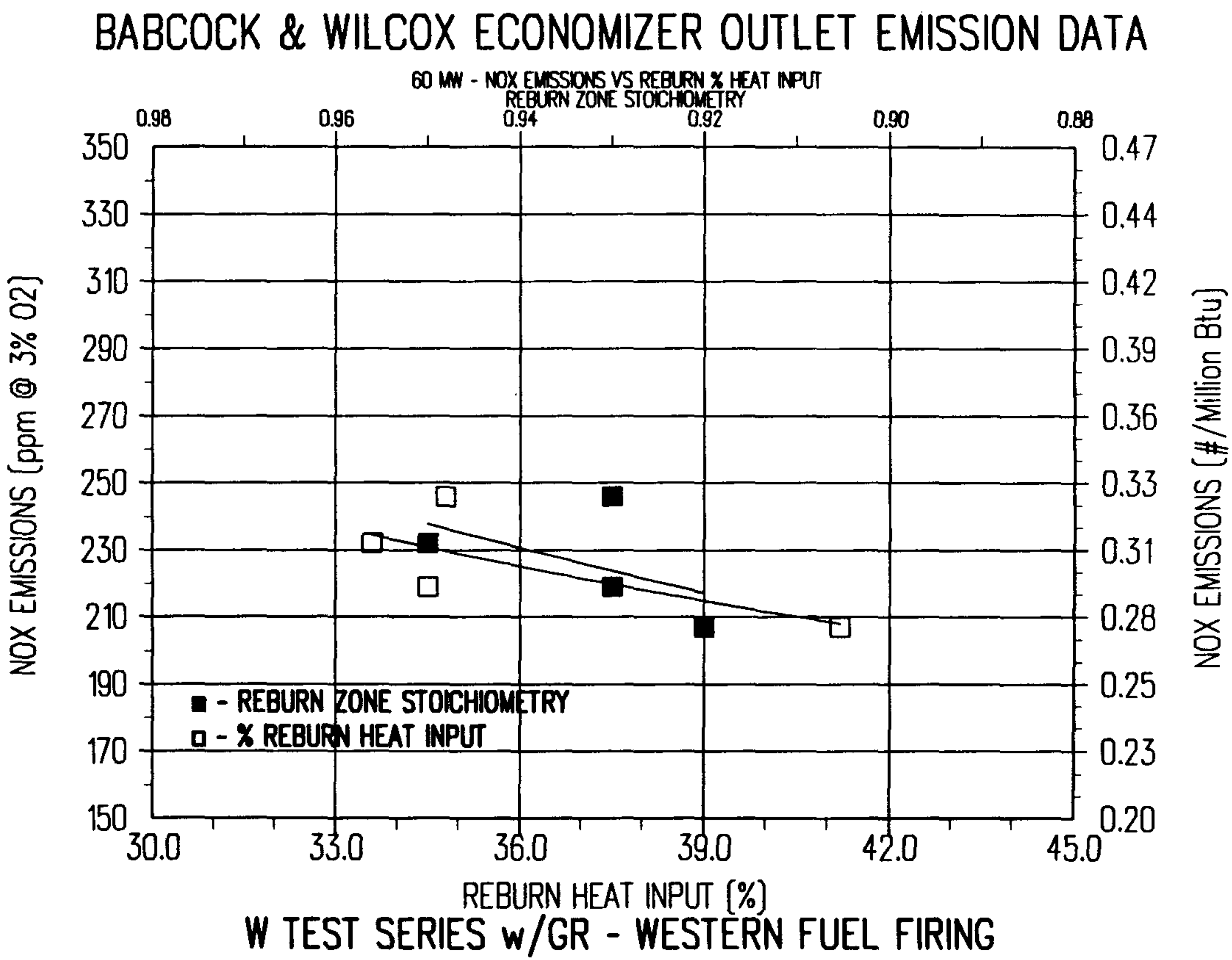

BABCOCK & WILCOX ECONOMIZER OUTLET EMISSION DATA
82 MW - NOX EMISSIONS VS REBURN % HEAT INPUT
REBURN ZONE STOICHIOMETRY
1.03
0.99
0.95
0.91
0.87
0.83
350
330
310
290
270
250
230
210
190
170
150
0.47
0.44
0.42
0.39
0.36
0.33
0.31
0.28
0.25
0.23
0.20
NOX EMISSIONS (ppm @ 3% O2)
NOX EMISSIONS (#/Million Btu)
■ - REBURN ZONE STOICHIOMETRY
□ - % REBURN HEAT INPUT
25.0
27.0
29.0
31.0
33.0
35.0
REBURN HEAT INPUT (%)
W TEST SERIES w/GR - WESTERN FUEL FIRING

Figure 7-26



BABCOCK & WILCOX ECONOMIZER OUTLET EMISSION DATA
60 MW - NOX EMISSIONS VS REBURN % HEAT INPUT
REBURN ZONE STOICHIOMETRY
0.98
0.96
0.94
0.92
0.90
0.88
NOX EMISSIONS (ppm @ 3% O2)
350
330
310
290
270
250
230
210
190
170
150
NOX EMISSIONS (#/Million Btu)
0.47
0.44
0.42
0.39
0.36
0.33
0.31
0.28
0.25
0.23
0.20
■ - REBURN ZONE STOICHIOMETRY
□ - % REBURN HEAT INPUT
30.0
33.0
36.0
39.0
42.0
45.0
REBURN HEAT INPUT (%)
W TEST SERIES w/GR - WESTERN FUEL FIRING

Figure 7-27

TABLE 7-4 GAS RECIRCULATION EFFECT DURING WESTERN FUEL FIRING		
Condition	**B&W NO_x ppm @ 3% O_2**	**% Change**
Reburning - No FGR Fan	307	-
Reburning - w/FGR Fan: No FGR to Burners	282	8.1%
Reburning - w/FGR Fan: FGR to Burners	252	17.9%

As shown in Table 7-4, reburn operation with the FGR fan off resulted in a NO_x level of 307 ppm. Operation of the FGR fan without adding any FGR to the reburn burners resulted in an 8.1% change in NO_x levels or an associated 282 ppm NO_x level. This reduction occurred due to elimination of seal air to the FGR ports when the FGR fan is on. Thus, a lower reburn zone stoichiometry is realized. Operating with about 2.3% FGR to the reburn burners and reducing the reburn burner stoichiometry resulted in a 17.9% lower NO_x level from the reburn/no FGR fan case. The significance of these changes are all related to the earlier described single most important parameter, reburn zone stoichiometry. Although typical 110 MW_e boiler operation does not require FGR flow, the above shows the significance of operating the FGR fans. In addition, no negative boiler effects are observed due to this operational change in philosophy.

Figure 7-28 shows the effect of adding various amounts of FGR to the reburn burners without changing reburning stoichiometries (thus identifying the effect of altering the burner/furnace flow mixing patterns). Varying the flow from approximately 11,000 lb/hr to 55,000 lb/hr revealed that the NO_x emission levels changed from 235 ppm to 219 ppm, or a 6.8% improvement. Finally, the benefits of a slightly improved NO_x reduction capability must be weighed against the associated potential side affects such as burner flame instability, higher power consumption, and higher ash flows through the associated flue and ductwork. The increases in fly ash flows through the ductwork are not significant, but some ash build-up within the flues/ducts was apparent due to the numerous bends required in the routing of these systems. Thus, minimizing the FGR flow would reduce any ash collection within the flues/ducts (WP&L cleans the

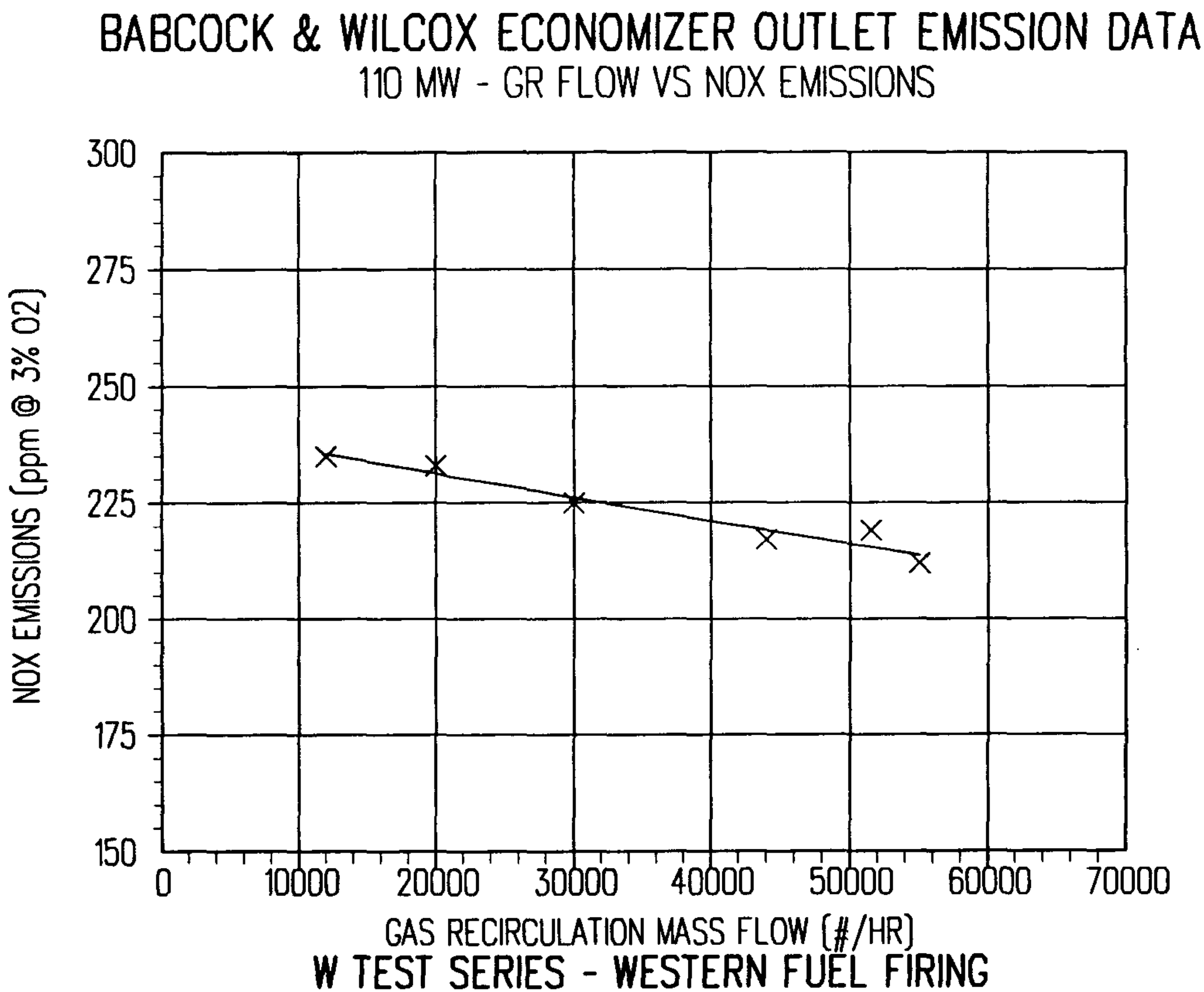

BABCOCK & WILCOX ECONOMIZER OUTLET EMISSION DATA
110 MW - GR FLOW VS NOX EMISSIONS
NOX EMISSIONS (ppm @ 3% O2)
300
275
250
225
200
175
150
0
10000
20000
30000
40000
50000
60000
70000
GAS RECIRCULATION MASS FLOW (#/HR)
W TEST SERIES - WESTERN FUEL FIRING

Figure 7-28

ash from these ducts periodically just as is typical for all coal fired FGR systems).

Although a slight improvement is observed while increasing the % FGR flow to the burners during the western fuel testing, no apparent improvement was noted while firing the Lamar fuel. No specific rational is apparent for this result except that the mixing capability may be improving during the western fuel firing tests when additional FGR is introduced.

7.3.1.2.4 Effect of Unit Load on Reburning Performance

Post-retrofit baseline and reburning tests were performed over the boiler load range of 41 - 118 MW_e during the western fuel firing tests. The following discussion describes the results in terms of load versus NO_x emissions, % NO_x reductions, and CO emissions for the "W" test series. In addition, comparisons between the Lamar bituminous and western sub-bituminous tests are reviewed.

Figure 7-29 shows the data results from all the western sub-bituminous tests for load versus NO_x emissions under baseline and reburning conditions. As observed with the Lamar testing results, operating the coal reburn system over the load range resulted in obtaining different NO_x reduction levels at various load conditions. The average NO_x emission levels during baseline and reburn operation and the associated % NO_x reduction varied as follows:

Load (MW_e)	Baseline NO_x, ppm	Reburn NO_x, ppm	% Reduction
110	560	250	55.4
82	480	230	52.1
60	464	220	52.6

The 41-42 MW_e results revealed a NO_x level with reburning of 210 ppm (0.28 lb/10^6 Btu). No baseline data was obtained at these loads during the "W" series. Finally, higher loads than tested during the Lamar coal firing phase were also evaluated. The maximum load tested was 118 MW_e and the limiting factor at that point was that the feedwater pumps were at maximum capacity. The associated NO_x emission level at 118 MW_e's was 275 ppm (0.37 lb/10^6 Btu).

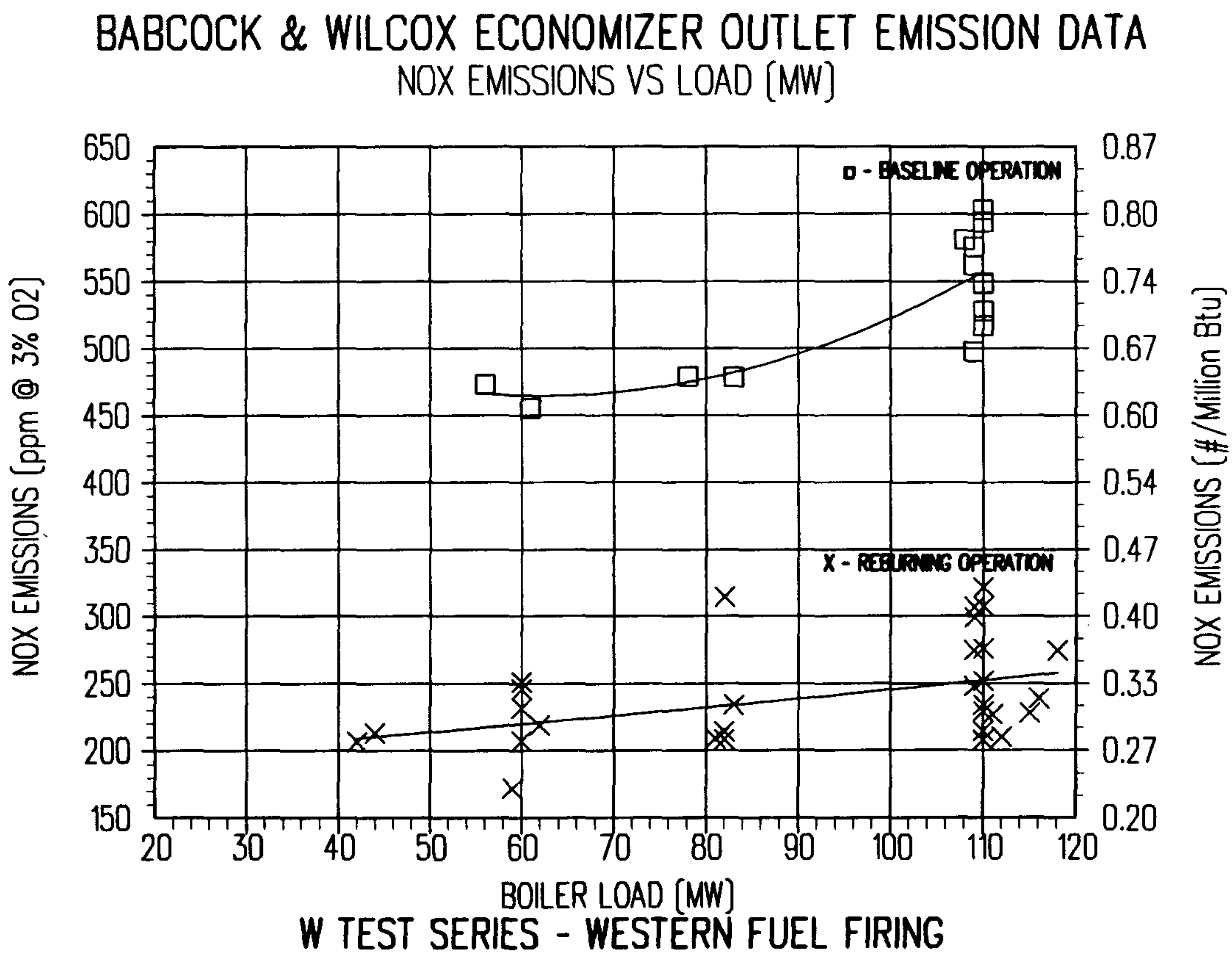

BABCOCK & WILCOX ECONOMIZER OUTLET EMISSION DATA
NOX EMISSIONS VS LOAD (MW)
NOX EMISSIONS (ppm @ 3% O2)
650
600
550
500
450
400
350
300
250
200
150
NOX EMISSIONS (#/Million Btu)
0.87
0.80
0.74
0.67
0.60
0.54
0.47
0.40
0.33
0.27
0.20
20
30
40
50
60
70
80
90
100
110
120
BOILER LOAD (MW)
□ - BASELINE OPERATION
X - REBURNING OPERATION
W TEST SERIES - WESTERN FUEL FIRING

Figure 7-29

CO emission levels over the load range for all the tests are shown in Figure 7-30. The average baseline data from 110 to 60 MW_e varied from approximately 48 to 28 ppm respectively. The reburn operation between the load range 118 to 41 MW_e shows a range of 84 to 45 ppm respectively. Based upon these results and reviewing the CO emission results presented earlier, this minimal impact between baseline and reburning operation is very typical.

Comparisons between the western sub-bituminous ("W" series) and the Lamar bituminous ("P"/"F" series) coal tests for load versus NO_x emissions are shown in Figure 7-31. The western fuel firing reburn operation achieved lower overall NO_x emission levels. Two factors contribute to the lower NO_x emissions. First, the primary baseline NO_x levels are approximately 10% less during the western fuel firing due to the inherent fuel characteristics such as the following in order of importance:

- lower % nitrogen (0.6 to 0.7 versus 1.1 to 1.3)
- higher moisture content (25 to 28% versus 15 to 18%)
- lower fixed carbon/volatile ratio (1.2 to 1.3 versus 1.3 to 1.5)

Secondly, a higher % reduction is realized during reburn operation. This is probably due to the higher western fuel volatile content and thus higher concentrations of hydrocarbon radicals being developed in the substoichiometric region of the furnace. In addition, a change in overall mixing is a possible explanation. The final interesting observation from Figure 7-31 is that the NO_x emissions could be maintained at a constant level over the 110 to 41 MW_e load range.

The direct comparison between the western and Lamar coal ("F" series) tests showed that the resultant NO_x emissions were about 301 ppm versus 234 ppm at 110 MW_e, 285 ppm versus 234 ppm at 82 MW_e, and 328 ppm versus 232 ppm at 60 MW_e for Lamar and western fuel, respectively. This direct comparison is based upon operating the reburn system under similar conditions such as the same reburn % heat input and reburn zone stoichiometries. Optimizing the western fuel firing resulted in a further improvement in the overall NO_x emission levels. The NO_x emission levels ranged from about 208 ppm to 220 ppm over the 110 to 41 MW_e load

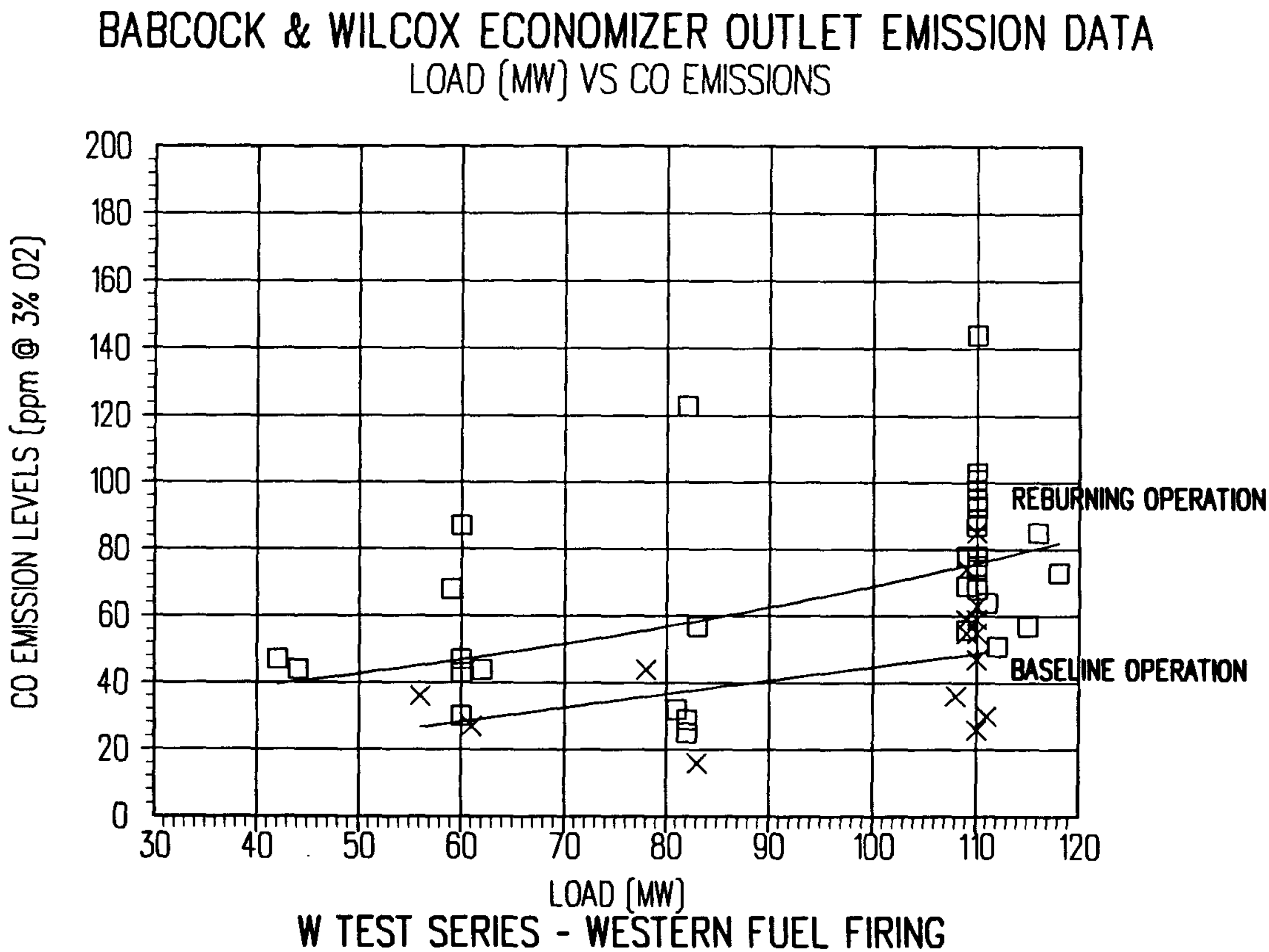

BABCOCK & WILCOX ECONOMIZER OUTLET EMISSION DATA
LOAD (MW) VS CO EMISSIONS
CO EMISSION LEVELS (ppm @ 3% 02)
200
180
160
140
120
100
80
60
40
20
0
30
40
50
60
70
80
90
100
110
120
REBURNING OPERATION
BASELINE OPERATION
LOAD (MW)
W TEST SERIES - WESTERN FUEL FIRING

Figure 7-30

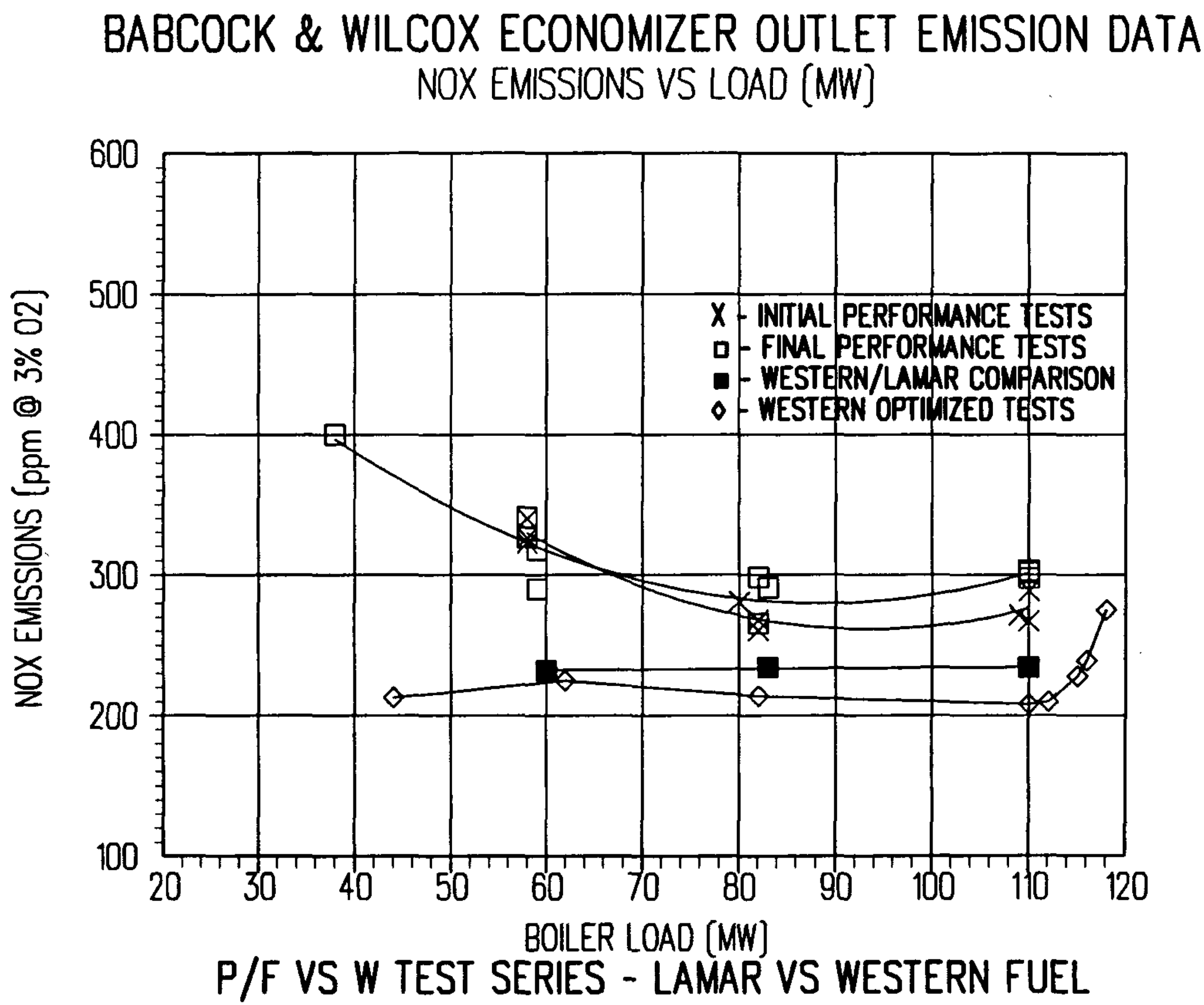

BABCOCK & WILCOX ECONOMIZER OUTLET EMISSION DATA
NOX EMISSIONS VS LOAD (MW)
NOX EMISSIONS (ppm @ 3% O2)
600
500
400
300
200
100
20
30
40
50
60
70
80
90
100
110
120
X - INITIAL PERFORMANCE TESTS
□ - FINAL PERFORMANCE TESTS
■ - WESTERN/LAMAR COMPARISON
◇ - WESTERN OPTIMIZED TESTS
BOILER LOAD (MW)
P/F VS W TEST SERIES - LAMAR VS WESTERN FUEL

Figure 7-31

conditions. Increasing load above 110 MW_e resulted in higher NO_x emissions. At 118 MW_e, the resultant NO_x level was 275 ppm. This increase in NO_x level was due to the fact that less % reburn heat input could be supplied as a result of reburn feeder limitations. Also, the baseline NO_x emission levels increased at this higher load.

The baseline NO_x emission levels utilized to calculate the % NO_x reductions at higher than 110 MW_e loads were based upon extrapolating the baseline curve identified in Figure 7-29. This was done since no actual baseline testing was possible with western fuel at higher than 110 MW_e.

The information of Figure 7-31 is plotted as % NO_x reduction in Figure 7-32 to compensate for western fuel's inherent lower NO_x characteristics, allowing a direct comparison between the Lamar and western fuel. The improved NO_x reduction capability when firing the sub-bituminous coal is apparent, particularly maintaining high NO_x reductions at low loads. In addition, Figure 7-32 shows the % NO_x reductions for the optimized western fuel reburning conditions. A summary of the % NO_x reductions for the Lamar "F" series, the western fuel direct comparison, and the western fuel optimized conditions are presented in Table 7-5.

TABLE 7-5
WESTERN VS. LAMAR FUEL % NO_X REDUCTION SUMMARY

Load Condition (MW_e)	Lamar "F" Series (% Reduction)	Western Direct Comparison (% Reduction)	Western Optimized (% Reduction)
110	51%	58%	62%
82	47%	51%	55%
60	35%	50%	53%

The western fuel reburning operation resulted in both an improved overall NO_x emission level and greater % NO_x reduction as compared to the Lamar bituminous reburn testing results. In addition to better NO_x reduction, the reburn burner flame stability was improved during the western fuel firing as well as more stable CO emissions and unburned carbon levels.

It should be pointed out that although no testing was carried out at Nelson Dewey with lignite coal, good reburning results were obtained while firing

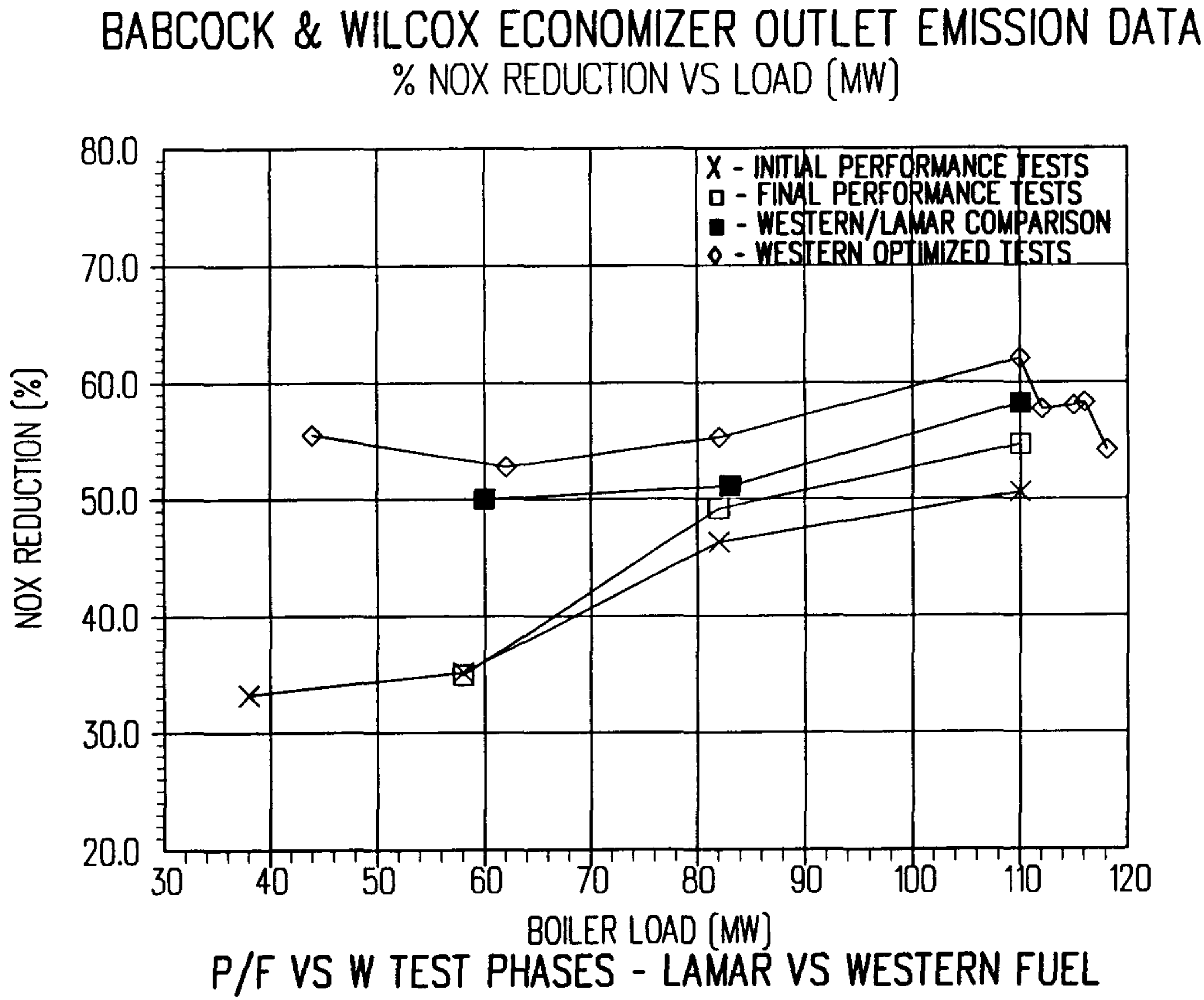

BABCOCK & WILCOX ECONOMIZER OUTLET EMISSION DATA
% NOX REDUCTION VS LOAD (MW)
NOX REDUCTION (%)
80.0
70.0
60.0
50.0
40.0
30.0
20.0
30
40
50
60
70
80
90
100
110
120
BOILER LOAD (MW)
X - INITIAL PERFORMANCE TESTS
□ - FINAL PERFORMANCE TESTS
■ - WESTERN/LAMAR COMPARISON
◇ - WESTERN OPTIMIZED TESTS
P/F VS W TEST PHASES - LAMAR VS WESTERN FUEL

Figure 7-32

lignite coal in the Small Boiler Simulator at the Alliance Research Center. These results are summarized in Appendix 3.

7.3.1.3 Particulate Emission/Precipitator Performance

The coal reburning technology to reduce NO_x emissions from cyclone boilers will impact the total particulate loading to the furnace and thus the resultant downstream fly ash removal equipment may be affected. Initial calculations to determine the increase of particulate loading during reburn operation utilized typical cyclone fly ash loading data and assumed a worst case scenario that 100% of the reburn coal ash would be entrained with the furnace gas. Using these assumptions, a predicted increase in ash loading to the precipitator of about 45% was estimated. In addition, fly ash from cyclone boilers typically has a small mass median diameter and contains a large number of fine particles which reduces precipitator performance. It was felt that the use of pulverized coal burners would increase the MMD of the ash exiting the boiler and reduce the percentage of fine particles and thus benefit precipitator performance. No change in the temperature profile at the precipitator inlet was anticipated.

Based upon these initial assumptions and the pilot scale results obtained in the SBS facility at the Alliance Research Center (fly ash size distribution and constituents and also ash resistivities with/without reburn), an independent research evaluation was completed.

APCO Services, Inc. modeled the predicted performance of the Nelson Dewey Unit #2 precipitator prior to the boiler modifications to determine baseline versus reburning operation implications. Specifically, initial projections were made using the following: 1. Reburn data gathered at the SBS Combustor facility at the B&W Alliance Research Center; 2. Baseline performance test data collected at the Nelson Dewey Unit #2 by the Acurex Corporation; 3. Precipitator electrical readings taken during the baseline testing; 4. Precipitator design data; and 5. Predicted reburn operating conditions. Finally, post-retrofit reburning test results were used to determine the accuracy of the precipitator model projections. Data was available while firing both the bituminous and subbituminous coals.

This precipitator evaluation section thus describes all the preliminary baseline precipitator performance, initial coal reburning projections and actual reburning versus modeling results. Appendix 8 - "APCO Research Reports on Precipitator Performance" contains the detailed reports submitted by APCO describing their evaluation of the Nelson Dewey precipitator results.

7.3.1.3.1 Nelson Dewey Precipitator Specifications

The Nelson Dewey Station precipitator was supplied by Research Cottrell and operates under positive pressure at a design temperature of 550 F. It has two chambers, each having three mechanical fields in the direction of the gas flow. The center mechanical field is split into two electrical fields such that a total of four electrical fields are available. The first and last field lengths are 9 foot while the middle two fields are 4.5 feet long. The mechanical sections are rapped on the leading and the trailing edges of the plates.

Additional unique design features of the Dewey unit #2 precipitator include the following:

Volume flow = 487,000 ACFM
SCA = 272 ft^2/kACFM
Design Efficiency = 99.5%
Number of gas lanes per chamber = 41
Plate Dimensions = 4.5 feet long; 30 feet high
Collecting Plate Type = Opzel
Discharge Electrode Type = weighted wire
Discharge Electrode Dimensions = 0.109" diameter
Plate to Plate Spacing = 9.0"
Wire to Wire Spacing = 9.0"

7.3.1.3.2 Computer Model Description

Predictions of precipitator performance were made using a mathematical model developed at Southern Research Institute[15],[16] with the sponsorship of EPA. A flow diagram of the model showing important input parameters and some of the output information is available in Appendix 8 - APCO Reports on Precipitator Performance.

The mathematical model is based on the exponential Deutsch-Anderson equation. It is structured so that the precipitator is divided into small incremental lengths in the direction of gas flow. In each increment, calculations are made for each particle size band contained per the inlet particle size distribution. Also calculated for each incremental length are the following: the electric field at the plate, the particle charge for each particle size band, the migration velocities of the particles toward the plate, and collection efficiencies for each particle size band. The particulate matter which is not collected in a given increment becomes the inlet loading for the succeeding increment. The incremental structure of the model is required to allow for the changing conditions present along the length of a precipitator and to insure that the assumptions made in the Deutsch-Anderson equation are met.

The model computes length-averaged migration velocity as a function of particle size, and the overall mass collection efficiency by summation over the fractional collection efficiencies. In addition, the model uses empirical expressions to adjust the length-averaged migration velocities for non-ideal effects such as gas bypassing a collector section (sneakage, S) and variations in the gas velocity distribution (%RMS deviation, σg). A sneakage of 10% per baffled section and σg of 25% are typically required to match measured performance with modeled results for older precipitators. For newer units, S = 5% and σg = 15% are usually more representative.

The model is very sensitive to changes in the electrical conditions within each collecting field, the inlet particle size distribution, the gas volume flow rate, the electrical properties of the gas, the electrical properties of the particles, rapping re-entrainment, and non-ideal effects.

If the particle size distribution does not change, variations in the inlet mass loading cause minor variations in the overall collection efficiency for inlet loadings less than 3-4 gr/acf, but the resultant opacity predictions are very sensitive to changes in the mass loading.

7.3.1.3.3 Pre-Retrofit Precipitator Evaluation

The measured baseline collection efficiency identified during the Acurex testing while burning Lamar coal had been 82.6% (17.4% penetration) for a boiler load of 110 MW_e. Earlier data obtained while firing a different coal had indicated a collection efficiency of 92.9%. Model projections indicated a collection efficiency of 83.8% (16.2% penetration) as baseline performance. This represents a difference of 7% between measured and predicted performance in terms of penetration; which was considered to be good agreement. Measured and predicted collection efficiencies are significantly less than design due to changes on fuel characteristics and maintenance needs which became apparent to WP&L on reviewing test results.

The above model projections were based on a particle size distribution having an MMD of 3.10 μm and a standard deviation of 2.46 (measured distribution for the SBS combustor). The gas flow rate of 475,000 acfm was a measured value. The inlet mass loading of 0.0855 gr/acf (0.35 lb/MBTU) and the electrical conditions used were also measured values. The non-ideal parameters which gave the best agreement between measured and modeled performance were a standard deviation in gas-flow distribution of 25% and a sneakage per baffled section of

10%. The values of these last two parameters were adjusted to obtain the best fit and are typical for older precipitators.

The model was next used to predict precipitator performance during reburning operation. Three gas flow rates were considered: the measured value as stated above, 475,000 acfm; a calculated value of 440,000 acfm based upon an excess air of 30%, and 416,700 acfm which was calculated assuming 3.0% O2 at the economizer outlet. Also, the electrical conditions for the precipitator fields were varied to determine how the precipitator would react to an improvement in electrical conditions and how it would respond to changes in fly ash resistivity. Finally, model runs were made by assuming no change in the inlet particle size distribution, and also by assuming a size distribution having a larger MMD with a smaller percentage of fine particles.

The general model projections of precipitator performance with reburn indicated the following:

- If no improvement in the electrical operating conditions was seen, the performance of the unit would be marginal (increased particulate loading and opacity) for the increased inlet mass loading associated with reburning, assuming the size distribution shifted toward a larger MMD with a smaller percentage of fine particles.

- If no improvement in the electrical operating conditions was seen, and the particle size distribution did not change with reburning, the unit would be out of compliance with emission standards.

- Improving electrical operating conditions to the level one would anticipate while firing the Lamar Coal ash would improve precipitator performance significantly. It was felt that the unit would remain in compliance even under the worst condition stated above (assuming the size distribution of the particulate at the ESP inlet remained constant).

Following the boiler modifications to accommodate the reburning system, the performance of the precipitator was determined via extensive testing for both the Lamar coal and a western coal.

7.3.1.3.4 Post-Retrofit Precipitator Evaluation

Following the reburning system retrofit, various testing was performed to collect data during both baseline and reburning operation. The following summarizes the various tests that will be used in this study:

1. 1990 Baseline Data (bituminous coal)
2. 1992 HAP Baseline Data (bituminous coal)
3. Western Fuel Baseline Test # 1W (sub-bituminous coal)
4. Initial Performance Reburn Test # 6P (bituminous coal)
5. Western Fuel Reburn Test # 1W (sub-bituminous coal)
6. 1992 HAP Reburn Data (bituminous coal)

The data which was obtained throughout these tests include precipitator inlet particle size distribution, particle mass loading, and fly ash resistivity. The following discusses the results of the testing in addition to the application of the data to the precipitator model. Appendix 8 contains an additional detailed report describing the model predictions supplied by APCO.

7.3.1.3.5 Post Retrofit Precipitator Data

The bituminous coal was fired during the majority of the testing. The moisture content was 15.68% and the ash content was 6.4%. This ash level represented an ash content of approximately 5.8 lb/MMBtu. Inlet mass loadings measured for the baseline cases averaged approximately 1.35 lb/MMBtu. This corresponds to 23% of the ash being converted to fly ash. With reburn, the average inlet mass loading was approximately 2.52 $lb/10^6Btu$ which would represent 44% of the ash appearing as fly ash.

No change in fly ash resistivity was apparent between the baseline and reburning cases at the tested loads. The following shows the precipitator inlet ash resistivity results that the Acurex corporation collected throughout the bituminous coal test series:

Load (MW_e)	**Baseline Resistivity (OHM-CM)**	**Reburn Resistivity (OHM-CM)**
110	5.70×10^{10}	5.85×10^{10}
82	5.60×10^{10}	3.74×10^{10}
55	5.80×10^{10}	2.25×10^{10}

The average collection efficiency of the precipitator for the baseline case was 97.3% while the average collection efficiency during the reburn case was 99.2%. Significant improvement in collection efficiencies over pre-retrofit values was the result of WP&L efforts to renovate the precipitator to achieve original design performance. Using these efficiencies and the above inlet mass loadings and resistivity results, one would estimate that the emissions for the baseline case would have been 0.036 $lb/10^6Btu$ and 0.020 $lb/10^6Btu$ for the reburn case. The outlet emissions in terms of lb/hr ranged from 25 lb/hr to 41 lb/hr for the three baseline tests and 7.5 lb/hr to 37 lb/hr for the reburn tests.

Based upon the fact that the emission data ranges overlap for the baseline versus reburn test conditions, one would be led to question the validity of making a statement about the average reburn emissions being lower than the average baseline emissions. In order to see if this difference was statistically meaningful, earlier performance data were reviewed.

Minimum data are available for the baseline only condition. The 1990 baseline results indicated an average emission rate of 0.061 $lb/10^6Btu$ and post-retrofit tests showed baseline emission rates of approximately 0.14, 0.15, and 0.041 $lb/10^6Btu$ respectively. Averaging these four tests gives an emission rate for the baseline case of 0.098 ± 0.048 $lb/10^6Btu$.

Fourteen reburn tests were used to determine the average reburn emissions. The average emissions for these tests was 0.024 ± 0.015 $lb/10^6Btu$. The average collection efficiency for these 14 tests was $97.6 \pm 2.1\%$.

Collection efficiencies for baseline runs ranged from 82% to 98.6%. Average emissions from these tests would indicate that the reburn emissions are statistically lower than emissions during baseline conditions. But again, the limited number of baseline tests and the large spread in their results should make one cautious about making such a statement.

Assuming the emissions are actually lower while using the reburn technology, one must ask what changes in precipitator performance could lead to this conclusion. The inlet mass loading is higher with reburn and the collection efficiency is higher. The mass loadings measured for both boiler firing conditions are such that they should not significantly impact performance. One would expect a change in particle size distribution for the inlet mass in the reburn case. The baseline data indicates that 43% of the mass has a particle diameter smaller than 2 μm under no reburn conditions. During reburn operation the data reveals that an average of 27% of the mass has particle diameters smaller than 2 μm.

Precipitator collection efficiency is low for particle diameters in the range of 0.2 to 2 μm with the minimum efficiency occurring at approximately 0.6 to 0.7 μm. The greater number of fine particles with baseline firing conditions most likely contributes to the higher emission rates for this firing condition.

The outlet particulate emissions with reburn was well below 0.1 $lb/10^6Btu$. While it was possible to obtain emissions below this limit for the baseline case, some tests indicated baseline emissions above this level. Thus, from the standpoint of precipitator performance, reburn firing is as good or better than cyclone-only firing.

Finally, the average opacity levels were unchanged between baseline and coal reburning operation cases, Typically, full load baseline opacity levels during bituminous coal firing ranged from 7-12% and after reburn was initiated, the same 7-12 % opacity levels were maintained.

7.3.1.3.6 Post-Retrofit Precipitator Modeling Results

All of the precipitator data that was collected throughout the test program was reviewed in terms of the ability to model the precipitator's performance. Table 7-6 summarizes the full load (110 MW_e) results of this review.

TABLE 7-6
SUMMARY OF THE COMPARISON OF MEASURED PRECIPITATOR PERFORMANCE WITH MODELED PRECIPITATOR PERFORMANCE FOR NELSON DEWEY UNIT #2.

TEST	MEASURED EFFICIENCY (%)	MODELED EFFICIENCY (%)	MEASURED OPACITY (%)	MODELED OPACITY (%)
1990 Baseline	82.6-92.3	83.8	10-15	11.6
Nov. 92 Baseline	97.3	97.8	7-12	11.2
1W (Baseline)	97.3	97.3	9-13	4.4
6P (Reburn)	99.3	97.8	7-12	11.1
3W (Reburn)	98.2	98.2	9-13	6.7
Nov. 92 Reburn	99.2	98.5	7-12	13.9

During the 1990 baseline tests, only 8-10% of the ash appeared as fly ash. It is felt that this produced a finer inlet particle size distribution and that this was the primary contributor to the low collection efficiencies measured during these tests. Subsequent baseline tests indicated that approximately 25% of the ash was converted to fly ash. Thus, one would expect a smaller percentage of fine particles.

Electrical conditions were not available for modeling the November 1992 tests. Flue gas volumes and gas temperatures were also not available. The electrical conditions were calculated assuming an ash resistivity of 2.0×10^{10} ohm-cm and flue gas volumes were calculated from coal chemistry by assuming a boiler input of 1,020 MMBtu/hr. In all cases except Initial Performance Test 6P, the non-ideal parameters used to obtain the model results were a sneakage per baffle section of 10% and a standard deviation in gas flow distribution of 25%.

It is concluded that in general the model does an adequate job of predicting precipitator performance and that the knowledge gained from this project can be used to estimate performance of precipitators for future projects.

7.3.2 Boiler Performance Results

7.3.2.1 Introduction

Performance and emissions tests were conducted on this unit during 1991 and 1992. The objective of this test program was to tune and optimize the reburn system, and to evaluate the impact of the reburn system on overall unit performance.

A total of 89 T and A series tuning and optimization tests were conducted to evaluate the impact of individual parameters on unit performance, flame stability, NO_x reduction, CO and unburned carbon generation, etc. All parameters having an impact on overall reburn performance were optimized during this period. Because of this optimization process, there is a large scatter in the data and results from these tests. All of the data from these tests is included in this report. However, most of the discussion regarding boiler performance will focus on the P and F series tests, which were conducted at optimum conditions.

A total of 9 P series performance tests were conducted to define unit performance at optimum conditions. Three tests each were conducted at 100 %, 75 %, and 50 % load (110 MW_e, 82 MW_e, and 55 MW_e). One test at each load was conducted with sootblowers in operation to comply with EPA emissions testing procedures.

A total of 19 F series final performance tests were conducted, after the unit had operated with reburn for an extended period, to determine any long term impact of reburn operation.

A total of 30 W series western fuel tests were conducted to tune controls and evaluate unit performance while burning the western fuel that WP&L intends to fire on a regular basis.

Appendix 9 contains a summary of pertinent performance information and a listing of all data obtained during the T and A series tests. Appendix 10 contains the same information for the P and F series tests, and Appendix 11 contains the same information for the W series tests.

7.3.2.2 Calculation Methodology

Unit performance was evaluated using B&W performance programs P-8475 -Combustion & Unit Efficiency Program and P-140 - Heat Transfer Program. Gas recirculation quantities were calculated using a curve fit developed from flow traverse data obtained during the tuning tests. This will be discussed in detail in section 7.3.2.3 - Discussion of 1990 Baseline Data.

The air heater of Nelson Dewey Unit No. 2 is a tubular type with two gas passes and two air passes. The gas leaving the hot end of the air heater goes to the hot precipitator and is returned to the cold end of the air heater. End temperature is controlled with a hot air recirculation system and a cold air by-pass between the inlet and center of the second air pass.

The effectiveness of the air heater is totally dependent upon how the hot air recirculation and especially the cold air bypass systems are operated. Inconsistent air heater performance causes inconsistent boiler efficiencies that do not reflect operation of the boiler. In order to obtain meaningful efficiency information, the test results were normalized to a known set of conditions. Test 9A from the 1990 Baseline Tests was selected as the base air heater performance test because the excess air and the air heater air inlet temperature for this test were the same as for the original design values. The results of test 9A were used as input to an air heater performance model to define the boundary conditions of the air heater. For all other tests the following data was supplied to the model:

- Gas flow to the air heater
- Gas inlet temperature
- Air flow from the air heater
- Air inlet temperature
- Air heater leakage

The air heater model would then predict the air and gas outlet temperatures that would have occurred if the air heater had been operating under the same conditions as test 9A. This gas outlet temperature was used in the corrected efficiency calculations to obtain an efficiency normalized to the test 9A air heater conditions. A summary of these calculations is contained in Appendix 12.

In addition to correcting efficiency to the test 9A air heater performance, the efficiency was also corrected to the original design fuel analysis, air temperature entering the air heater (126 °F), and excess air (17 %) per ASME PTC 4.1 Steam Generating Units. Air and gas weights were calculated stoichiometrically from measured O_2 and fuel analysis in accordance with ASME PTC 19.10 Flue And Exhaust Gas Analysis. Table 7-7 shows the original design (summary sheet) fuel analysis and the fuel analyses used for the actual test conditions.

TABLE 7-7
SUMMARY OF FUEL ANALYSES

DESCRIPTION OF TESTS	HHV	C	H	S	O	N	H2O	ASH
Summary Sheet	10,440	57.70	3.90	4.80	7.30	.80	12.70	12.80
T Series Tests	10,848	60.24	4.39	1.29	7.53	1.08	19.32	6.15
A Series Tests	11,169	62.62	4.30	1.52	7.63	1.29	16.56	6.08
Tests P1, P2	11,210	64.46	3.44	1.42	7.04	1.18	16.22	6.24
Tests P3, P4	11,023	61.81	4.17	1.39	8.14	1.10	16.80	6.59
Tests P5,P6,P7	11,232	62.43	4.23	1.32	8.20	1.19	16.32	6.31
Tests P8,P9	11,151	64.62	3.44	1.36	6.33	1.23	16.89	6.13
Tests F1,F2,F3	10,928	60.51	4.18	1.41	8.47	1.12	17.66	6.65
Tests F4,F5	10,996	61.23	3.93	1.36	8.64	1.12	17.24	6.48
Tests F6,F7,F8	11,003	61.22	4.27	1.37	8.20	1.08	17.46	6.40
Tests F9,F10	11,173	62.17	4.28	1.38	7.93	1.17	17.14	5.93
Tests F11-F14	11,111	61.58	4.14	1.42	8.43	1.13	16.94	6.36
Tests F15-F19	11,061	61.65	4.29	1.42	7.63	1.10	17.37	6.54
Test W1	9,541	54.74	3.4	.49	11.17	.74	24.83	4.63
Test W2	9,403	53.59	3.46	.43	11.97	.71	25.32	4.52
Test W3	9,321	54.39	3.26	.40	10.76	.78	25.98	4.43
Test W4	9,177	52.30	3.18	.39	12.60	.70	26.58	4.25
Test W5	9,150	51.89	3.76	.34	12.12	.66	27.15	4.08
Test W6	9,000	51.70	3.53	.33	11.88	.65	27.48	4.43
Test W7	9,030	51.81	3.64	.30	11.59	.65	27.98	4.03
Test W8	8,928	51.07	3.45	.29	12.20	.64	28.51	3.84
Test W9	9,194	52.71	3.46	.37	11.78	.69	26.72	4.27
Test W10	9,108	52.04	2.71	.32	13.77	.67	26.39	4.10
Test W11	9,132	52.13	3.19	.33	13.06	.62	26.60	4.07
Tests W12,W13	9,123	52.44	3.26	.32	12.52	.63	26.81	4.02
Tests W14,W15	9,122	52.28	3.27	.34	12.65	.67	26.69	4.10
Test W16	9,123	52.42	3.21	.38	12.01	.71	27.00	4.27

TABLE 7-7 SUMMARY OF FUEL ANALYSES								
DESCRIPTION OF TESTS	HHV	C	H	S	O	N	H2O	ASH
Test W17	9,125	52.41	3.20	.39	12.08	.70	26.89	4.33
Tests W18-W21	9,254	53.77	3.26	.43	11.08	.73	26.21	4.52
Tests W22-W28	9,266	52.80	3.10	.47	11.88	.70	26.45	4.60
Test W29	9,304	53.58	3.15	.53	11.37	.69	25.94	4.74
Test W30	9,382	53.16	3.32	.54	11.74	.68	25.85	4.71

The furnace exit gas temperature (FEGT) was calculated by heat balance based on the measured steam/water side absorption of each component, starting from the measured economizer gas outlet temperature. Utilizing the calculated gas weight, calculated gas temperatures entering and leaving each component and measured steam/water side temperatures, the actual overall conductance (Uact) and expected overall conductance (Uexp) can be calculated. The effectiveness or surface cleanliness (K_f) of each component is the ratio of the actual to expected conductance, Uact/Uexp.

Unburned carbon and fly ash splits were measured for all of the P and F series tests. For the T, A, and W series tests where unburned carbon was not measured, an average value from similar tests was used.

7.3.2.3 Discussion of 1990 Baseline Data

The baseline performance test data from 1990 was evaluated assuming a gas recirculation flow of fifty percent of the flow from the original fan curve. This assumption was used to address inconsistencies in boiler performance calculations when the original GR fan curve was used during low load operation. The major indicator of these inconsistencies was the boiler cleanliness factors at low loads. Based upon initial model review, modifying the expected GR flow curve appeared to address the problem. During the initial phases of the tuning tests, several flow traverses were conducted at the GR fan outlet to determine the actual gas recirculation flow. The results of these tests indicated a gas recirculation flow slightly higher than the flow from the original GR fan curve. Figure 7-33 shows the new gas recirculation flow curve, as well as the original fan curve and the assumed curve used to evaluate the baseline data. As a result of this change, all of the baseline data was re-evaluated using the new gas recirculation flows. The results impacted by this change are the furnace exit gas temperature (FEGT) and the component cleanliness factors (K_f's) for those tests where the GR fan was running. A summary of the

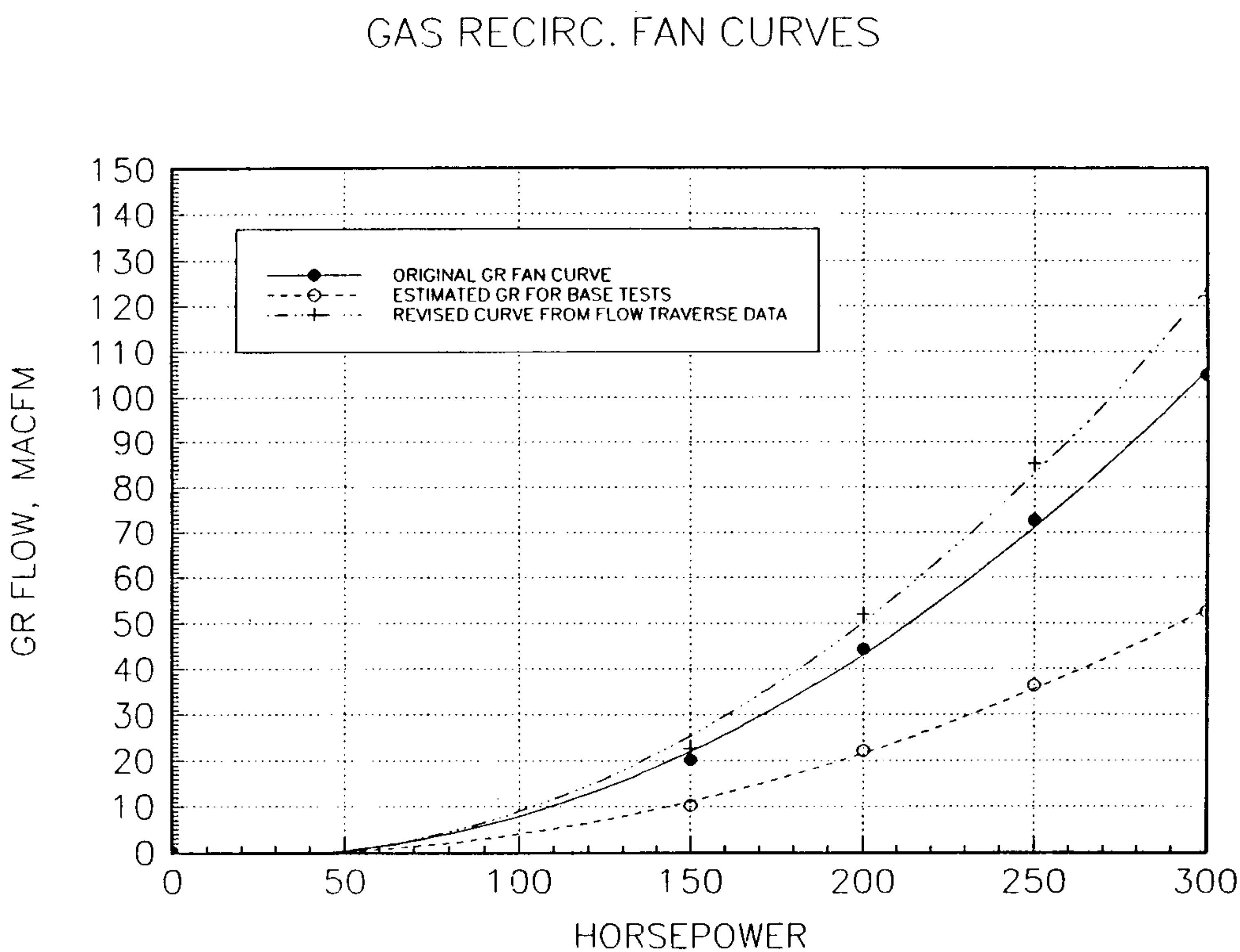

GAS RECIRC. FAN CURVES
ORIGINAL GR FAN CURVE
ESTIMATED GR FOR BASE TESTS
REVISED CURVE FROM FLOW TRAVERSE DATA
GR FLOW, MACFM
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
0
50
100
150
200
250
300
HORSEPOWER

Figure 7-33

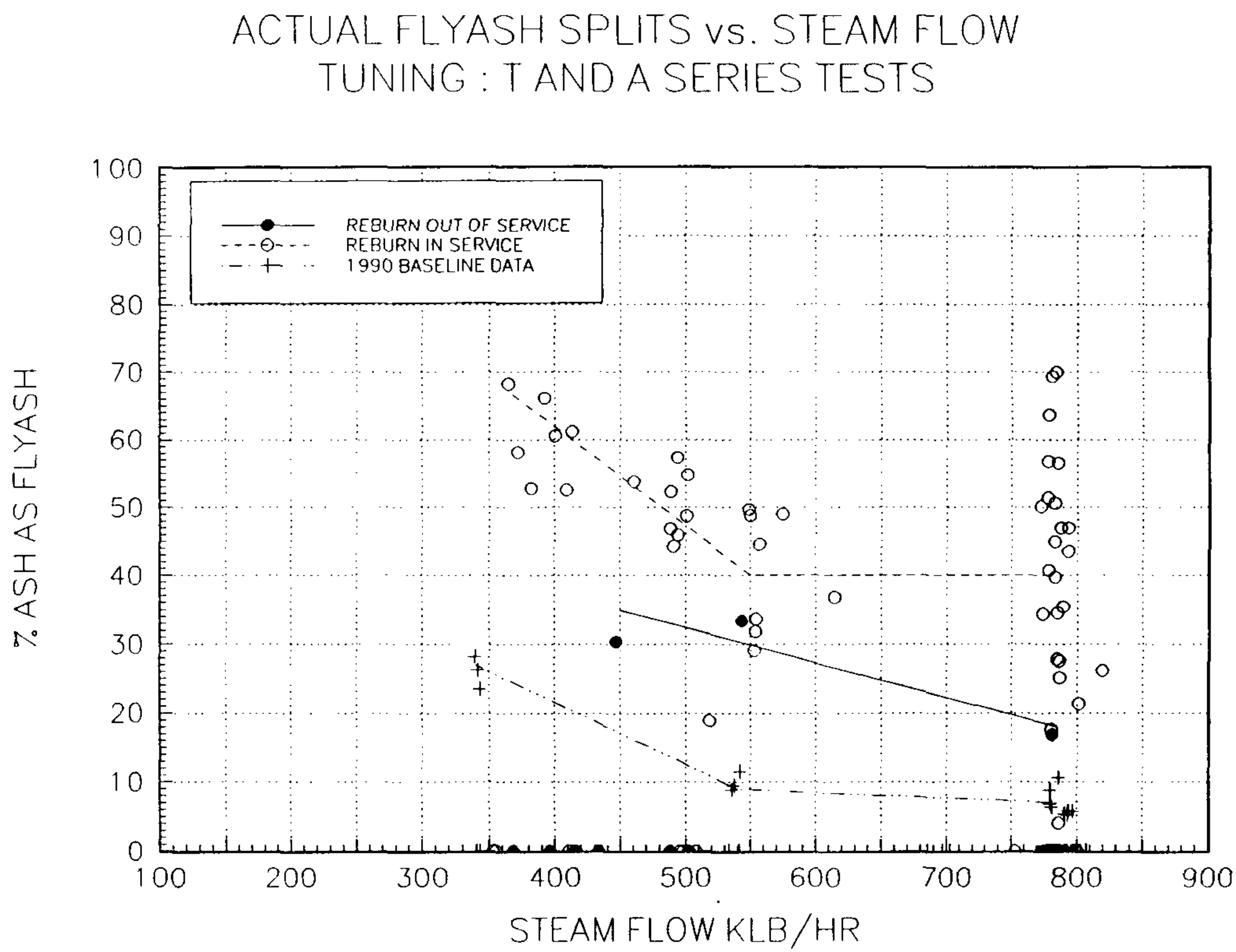

ACTUAL FLYASH SPLITS vs. STEAM FLOW
TUNING : T AND A SERIES TESTS
REBURN OUT OF SERVICE
REBURN IN SERVICE
1990 BASELINE DATA
% ASH AS FLYASH
STEAM FLOW KLB/HR
100
90
80
70
60
50
40
30
20
10
0
100
200
300
400
500
600
700
800
900

Figure 7-34

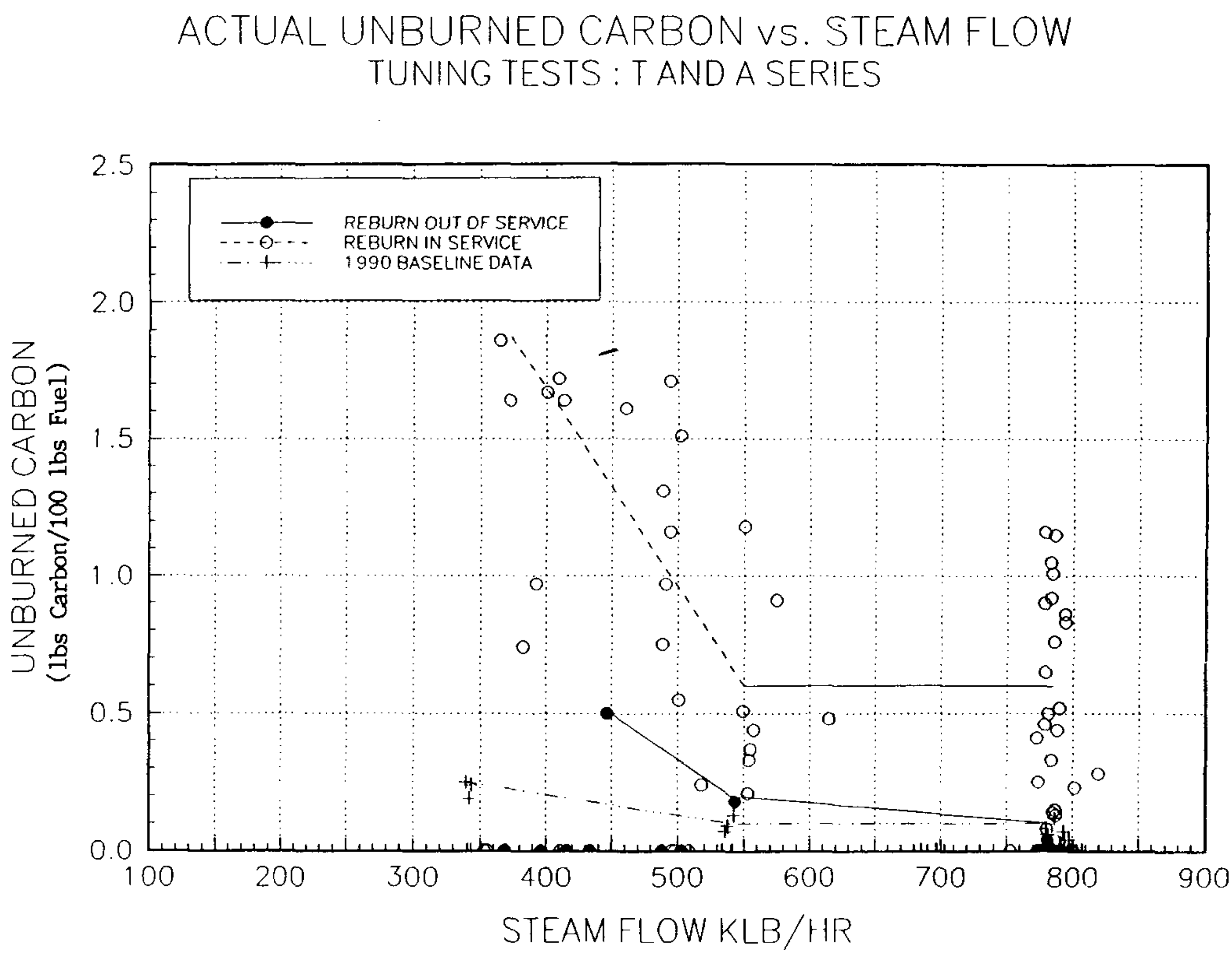

ACTUAL UNBURNED CARBON vs. STEAM FLOW
TUNING TESTS : T AND A SERIES
REBURN OUT OF SERVICE
REBURN IN SERVICE
1990 BASELINE DATA
UNBURNED CARBON
(lbs Carbon/100 lbs Fuel)
2.5
2.0
1.5
1.0
0.5
0.0
100
200
300
400
500
600
700
800
900
STEAM FLOW KLB/HR

Figure 7-35

While evaluating the data from the tuning tests (T and A series) and the performance tests (P series) it became apparent that the cyclones were not performing as they had during the baseline tests. During this period, there were only three tests conducted with reburn out of service where particulate loadings were obtained to determine ash splits and unburned carbon. However, the fly ash splits and unburned carbon results from these three tests were significantly different from the baseline data. Figure 7-34 shows the increase in percent of ash as fly ash between the baseline data and these three tests. Figure 7-35 shows the difference in unburned carbon (lb carbon/ 100 lb of fuel) between these three tests and the baseline data. Based on these results, the schedule for the final performance tests was revised to include additional tests with reburn out of service. Due to this large discrepancy between the baseline test results and the final performance test results with reburn out of service, the decision was made to compare reburn operation with the reburn out of service data rather than the baseline test data. The baseline data is included in all pertinent graphs for information.

7.3.2.4 Discussion of Test Results for Bituminous Coal (LAMAR)

The critical parameters in evaluating the impact of the reburn system on unit performance are superheat and reheat final steam temperatures, superheat and reheat spray flow quantities, furnace exit gas temperature (FEGT), surface cleanliness factors (K_f's), efficiency, unburned carbon, fly ash splits, NO_x emissions, and CO emissions. The NO_x and CO emissions were discussed in section 7.3.1 and will not be addressed here. The remaining items shall be discussed individually in this section.

7.3.2.4.1 Percent of Ash as Fly Ash (Fly Ash Split)

Figure 7-36 shows the actual percent fly ash for each of the P and F series tests. The three tests conducted while sootblowing are shown, but were not considered in the analysis. Summaries of the calculations for percent fly ash and unburned carbon for all tests can be found in Appendix 14. Appendix 15 contains the laboratory reports for all fuel and ash samples obtained. The results of four of the tests (1P, 5P, F13, and F14) were significantly different than the other tests conducted at the same loads. For the purpose of evaluating fly ash splits and unburned carbon, the results of these four tests were set equal to the average of the other tests at the same load.

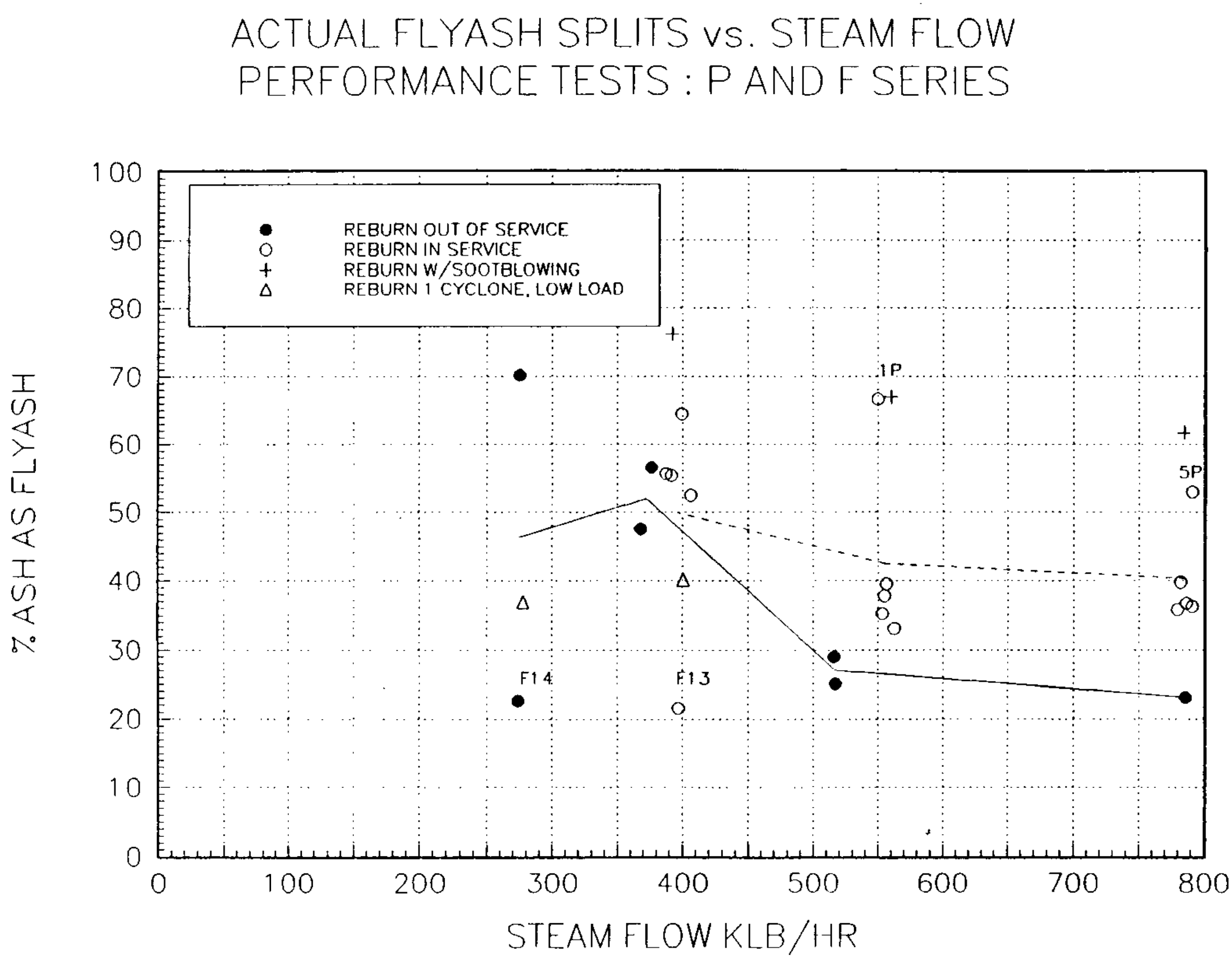

ACTUAL FLYASH SPLITS vs. STEAM FLOW
PERFORMANCE TESTS : P AND F SERIES
REBURN OUT OF SERVICE
REBURN IN SERVICE
REBURN W/SOOTBLOWING
REBURN 1 CYCLONE, LOW LOAD
1P
5P
F14
F13
% ASH AS FLYASH
STEAM FLOW KLB/HR
0
10
20
30
40
50
60
70
80
90
100
0
100
200
300
400
500
600
700
800

Figure 7-36

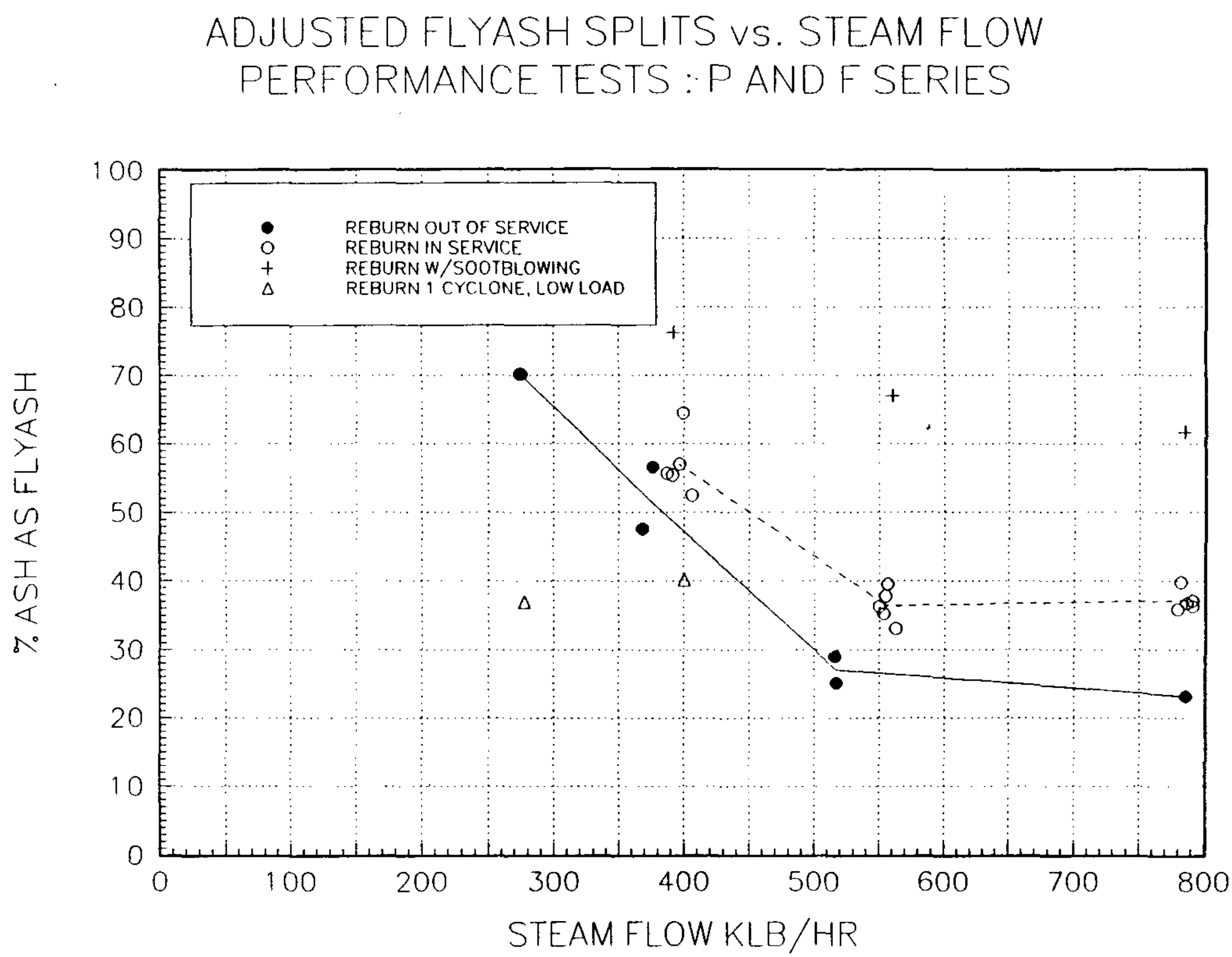

ADJUSTED FLYASH SPLITS vs. STEAM FLOW
PERFORMANCE TESTS : P AND F SERIES
REBURN OUT OF SERVICE
REBURN IN SERVICE
REBURN W/SOOTBLOWING
REBURN 1 CYCLONE, LOW LOAD
% ASH AS FLYASH
STEAM FLOW KLB/HR
0
10
20
30
40
50
60
70
80
90
100
0
100
200
300
400
500
600
700
800

Figure 7-37

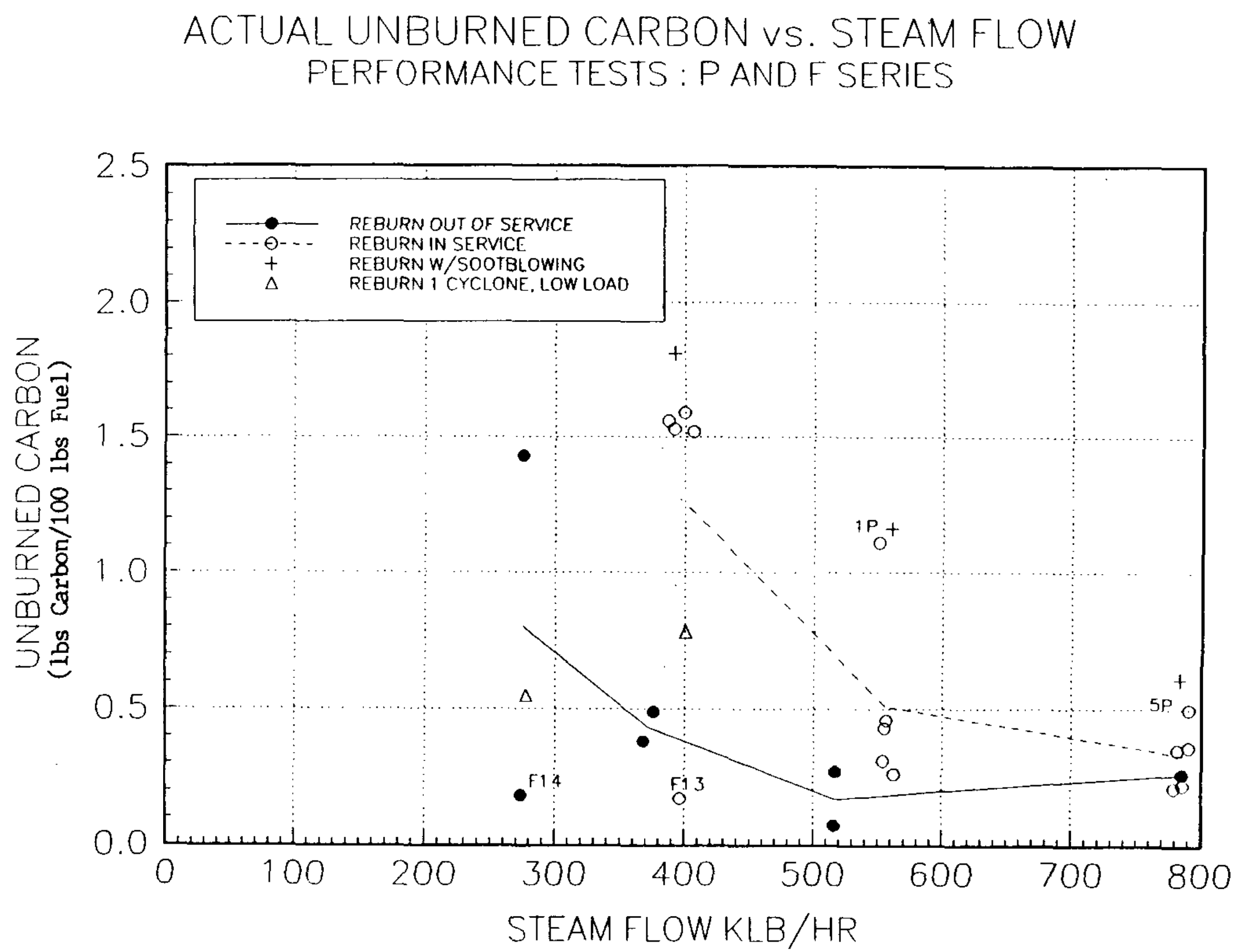
Figure 7-37 shows the percent fly ash as a function of load after adjusting these four tests. At 100% load (110 MW_e), percent of ash as fly ash increases from 23% baseline to 37% with reburn in service. With 30 percent of the fuel input to the reburn burners, the percent fly ash could have been as high as 46% if all of the ash to the reburn system were to leave the unit as fly ash. The above test results indicate that approximately 60% of the reburn ash is leaving the unit as fly ash, or some higher percentage of the reburn ash is leaving the unit and the reburn combustion process is minimizing some of the fly ash generated by the cyclones. Hypothetically, a portion of the cyclone ash or the reburn ash could be knocked back down into the lower refractory walled furnace and captured within the slag layer that exists within this region.

At 75% load (82 MW_e), the percent of ash as fly ash increases from 26% to 36% with reburn in service. And at 50% load (55 MW_e), the percent of ash as fly ash increases from 47% to 57% with reburn in service. The increase in fly ash percent is fairly constant over the load range.

7.3.2.4.2 Unburned Carbon (UBC)

Figure 7-38 shows the actual unburned carbon, on a lb/100 lb of fuel basis, as calculated from the fly ash splits, carbon in fly ash, and carbon in cyclone slag for the F and P series performance tests. Since the percent fly ash data was questionable for tests 1P, 5P, F13, and F14, these unburned carbon values were set equal to the average of the other tests at the same load. Figure 7-39 shows the unburned carbon vs. steam flow after adjusting these four tests. At full load the increase in unburned carbon with reburn in service is negligible (0.05 lb/100 lb fuel). At 75% load, the increase in unburned carbon with reburn in service is 0.2 lb/100 lb fuel. However, at 50% load the unburned carbon with reburn in service increases by 1.1 lb/100 lb fuel, from 0.44 lb/100 lb fuel to 1.55 lb/100 lb fuel.

Note that the two tests conducted at low load, with one cyclone in service show significantly lower unburned carbon values than the tests conducted at the same load with two cyclones in service. These two tests, and the increase in unburned carbon at lower loads without reburn in service, would indicate that a large portion of the unburned carbon increase with reburn in service is being caused by the cyclones operating at low input rates. Figure



ACTUAL UNBURNED CARBON vs. STEAM FLOW
PERFORMANCE TESTS : P AND F SERIES
REBURN OUT OF SERVICE
REBURN IN SERVICE
REBURN W/SOOTBLOWING
REBURN 1 CYCLONE, LOW LOAD
UNBURNED CARBON
(lbs Carbon/100 lbs Fuel)
STEAM FLOW KLB/HR
0.0
0.5
1.0
1.5
2.0
2.5
0
100
200
300
400
500
600
700
800
F14
F13
1P
5P

Figure 7-38

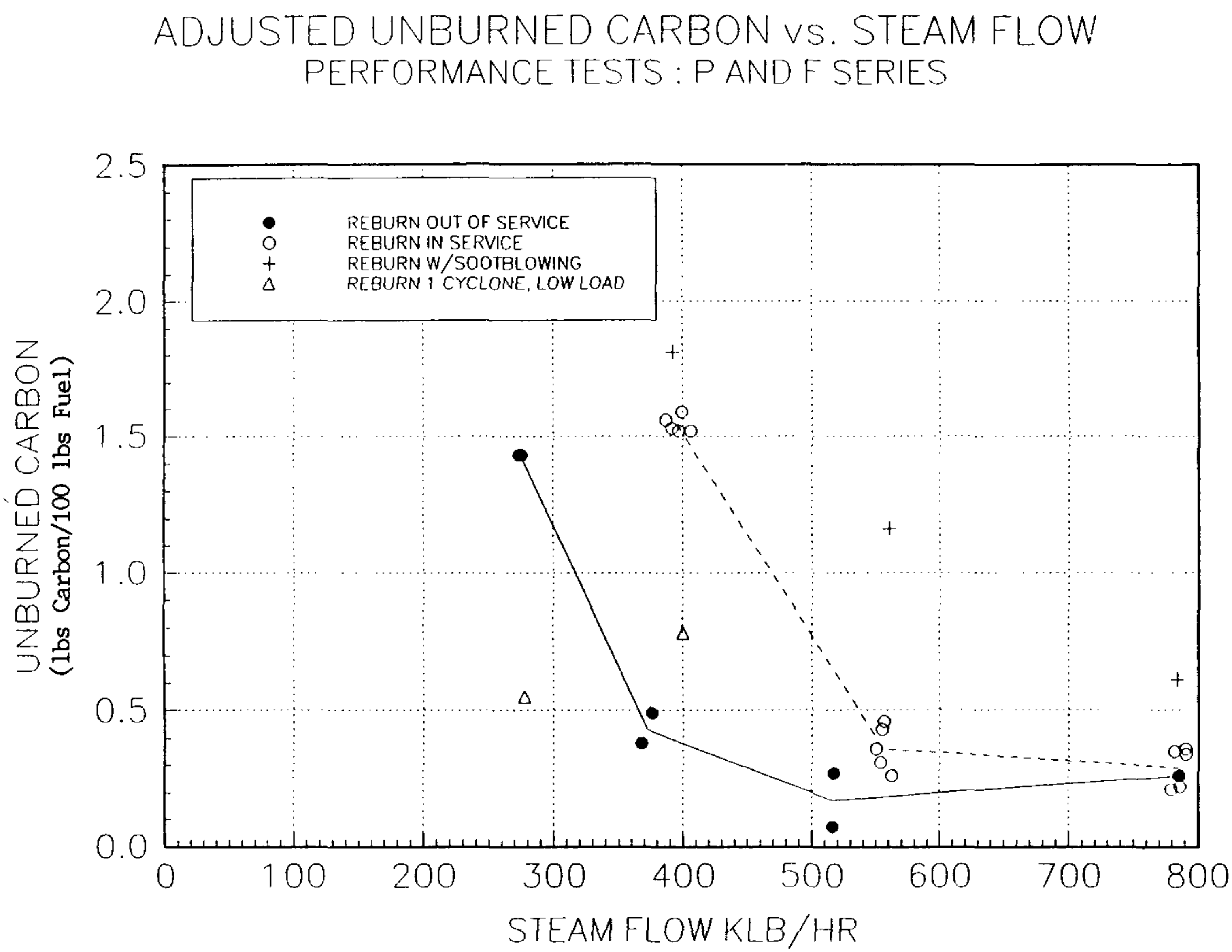

ADJUSTED UNBURNED CARBON vs. STEAM FLOW
PERFORMANCE TESTS : P AND F SERIES
REBURN OUT OF SERVICE
REBURN IN SERVICE
REBURN W/SOOTBLOWING
REBURN 1 CYCLONE, LOW LOAD
UNBURNED CARBON
(lbs Carbon/100 lbs Fuel)
STEAM FLOW KLB/HR
0.0
0.5
1.0
1.5
2.0
2.5
0
100
200
300
400
500
600
700
800

Figure 7-39

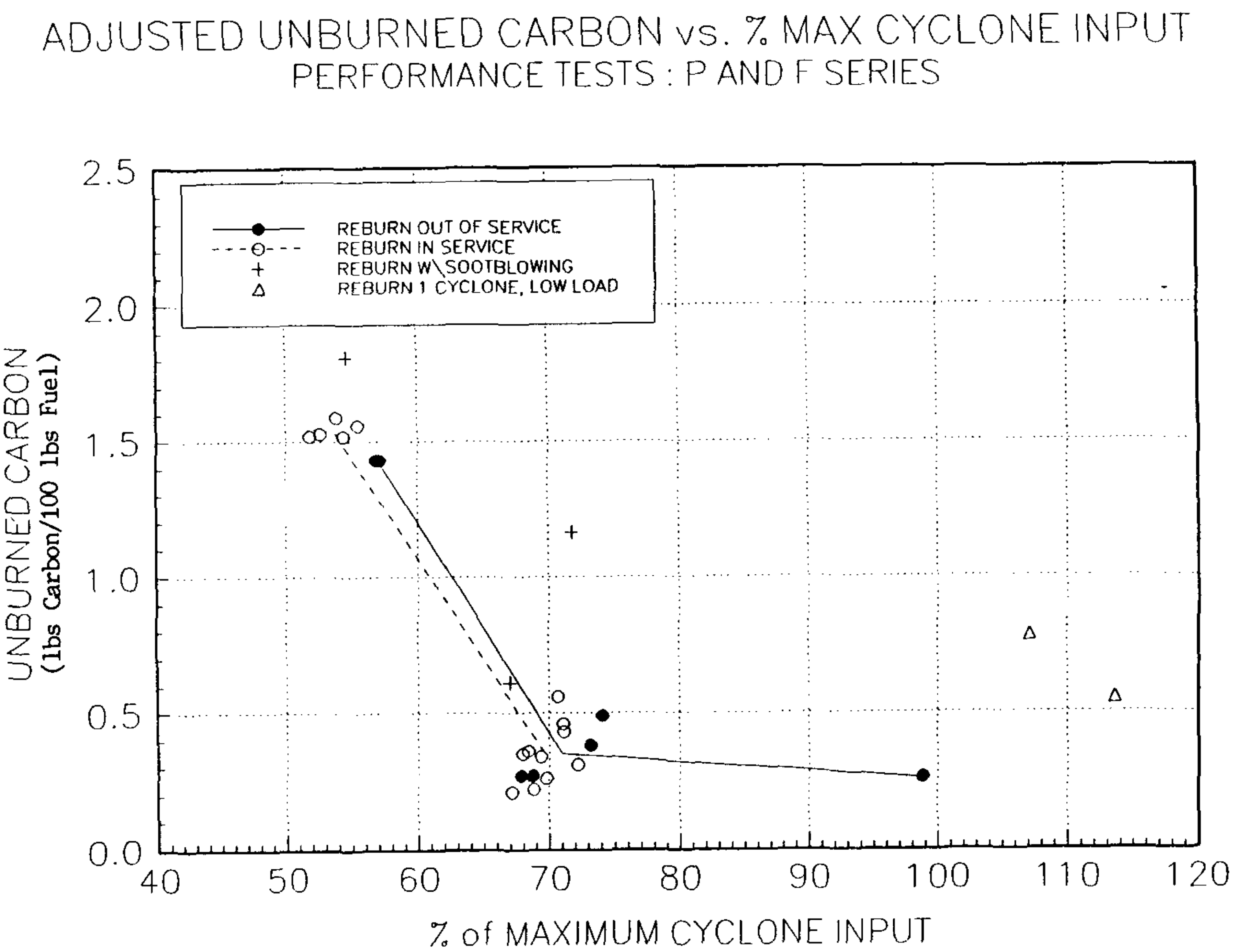

ADJUSTED UNBURNED CARBON vs. % MAX CYCLONE INPUT
PERFORMANCE TESTS : P AND F SERIES
REBURN OUT OF SERVICE
REBURN IN SERVICE
REBURN W\SOOTBLOWING
REBURN 1 CYCLONE, LOW LOAD
UNBURNED CARBON
(lbs Carbon/100 lbs Fuel)
2.5
2.0
1.5
1.0
0.5
0.0
40
50
60
70
80
90
100
110
120
% of MAXIMUM CYCLONE INPUT

Figure 7-40

7-40 shows the same data as Figure 7-39 plotted against percent of maximum cyclone input rather than steam flow. This plot shows that at equivalent cyclone loadings there is virtually no change in unburned carbon as a result of operating the reburn burners. This would imply that for units with a greater number of cyclones, and the ability to operate at lower loads with higher cyclone input to fewer cyclones, the reburn system would have a negligible impact on unburned carbon. However, since this unit does not have that operating flexibility, and must maintain two cyclones in service even with the reburn system operating (at loads greater than about 400,000 lb/hr steam flow), the reburn system does cause an increase in efficiency loss from unburned carbon at lower loads.

Figure 7-41 is a plot of the efficiency loss due to unburned carbon (UBCL) versus steam flow. At full load the UBCL with reburn is 0.1% higher than the UBCL with reburn out of service. The increase in UBCL at 75 percent load is 0.25% efficiency loss, and at 50 percent load the UBCL increase is 1.5% efficiency loss.

7.3.2.4.3 Unit Efficiency

Appendix 16 contains a summary of the efficiency calculations for all tests conducted. The right hand column in these summaries is the as tested efficiency. The center column is the efficiency corrected as discussed in the calculation methodology section. Appendix 17 contains summary sheets for the unit output calculations for all tests conducted. As discussed previously, the efficiencies were corrected for air heater performance and off-design fuel, air inlet temperature, and excess air. These corrections essentially normalize the results for direct comparison of the impact of the reburn system on unit efficiency.

Figure 7-42 shows efficiency versus steam flow for all of the tuning and optimization tests (T and A series). Unburned carbon was not measured for many of these tests, and the efficiency shown was calculated using assumed values based upon past similar test results. Figure 7-43 contains the efficiency versus steam flow for the P and F series performance tests. At full load the efficiency of the unit actually increases by 0.2% with reburn in service. This is caused by a decrease in the dry gas loss of 0.3% which compensates for the increase in the unburned carbon loss of 0.1%. At 75 percent

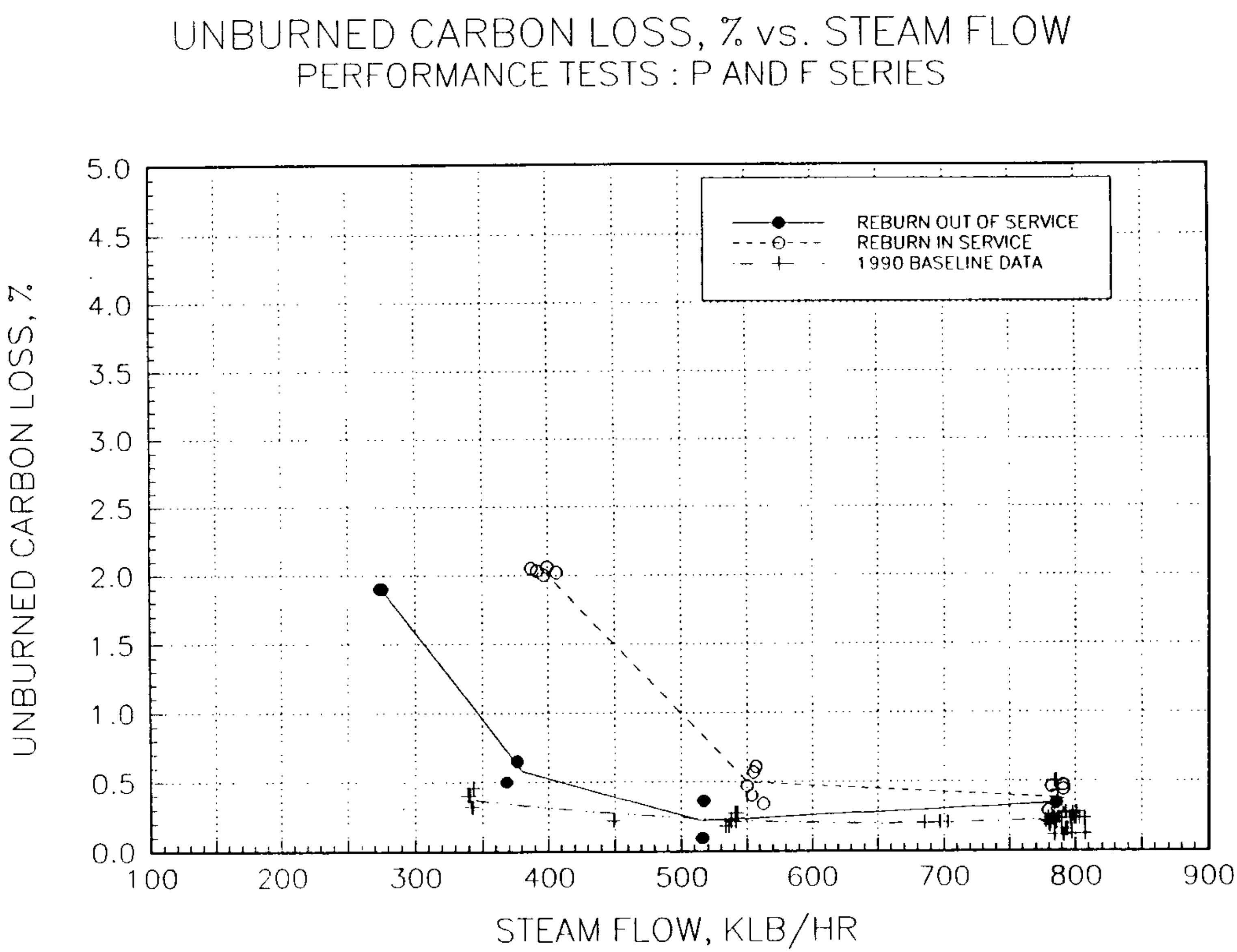

UNBURNED CARBON LOSS, % vs. STEAM FLOW
PERFORMANCE TESTS : P AND F SERIES
REBURN OUT OF SERVICE
REBURN IN SERVICE
1990 BASELINE DATA
UNBURNED CARBON LOSS, %
STEAM FLOW, KLB/HR
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
100
200
300
400
500
600
700
800
900

Figure 7-41

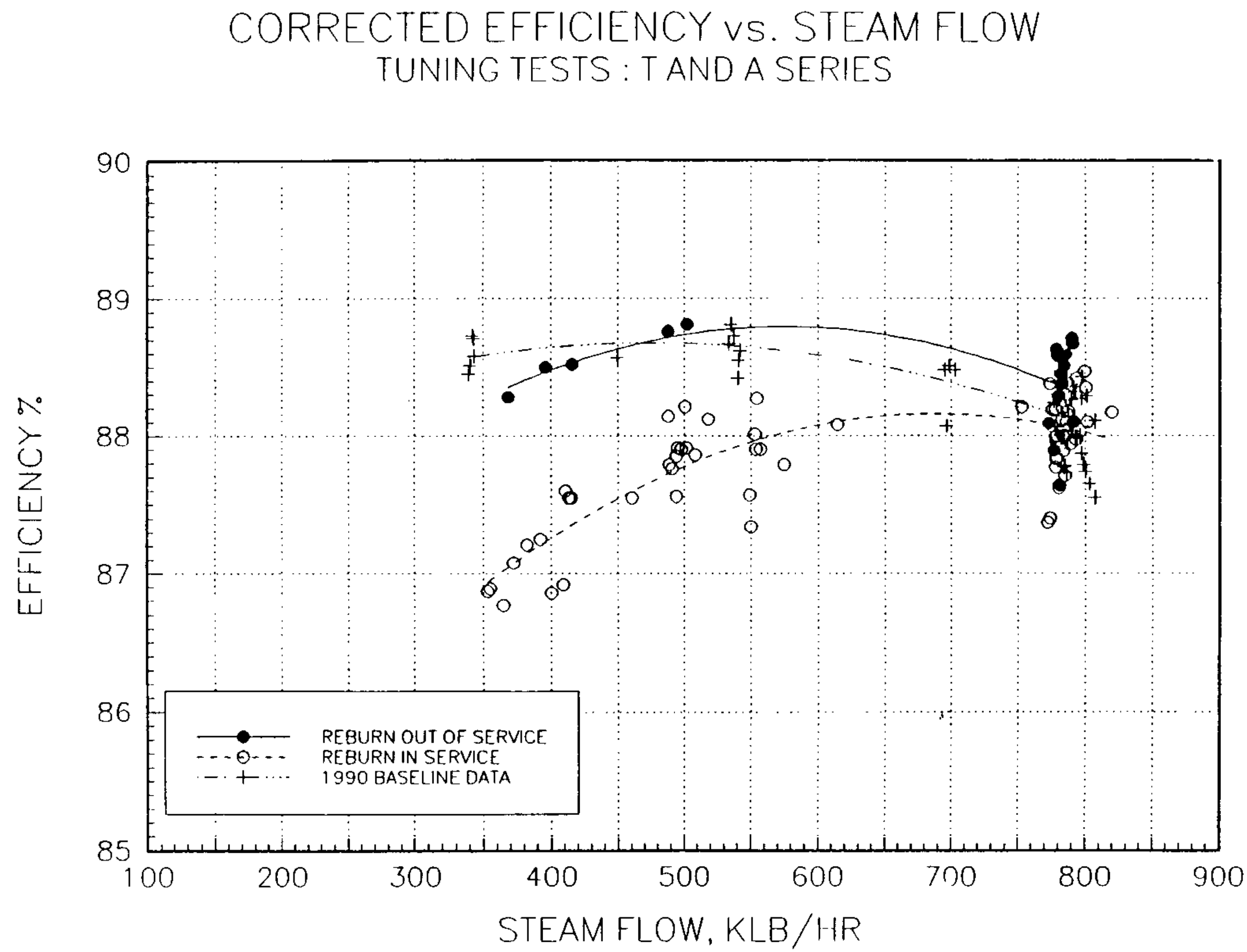

CORRECTED EFFICIENCY vs. STEAM FLOW
TUNING TESTS : T AND A SERIES
EFFICIENCY %
90
89
88
87
86
85
100
200
300
400
500
600
700
800
900
STEAM FLOW, KLB/HR
REBURN OUT OF SERVICE
REBURN IN SERVICE
1990 BASELINE DATA

Figure 7-42

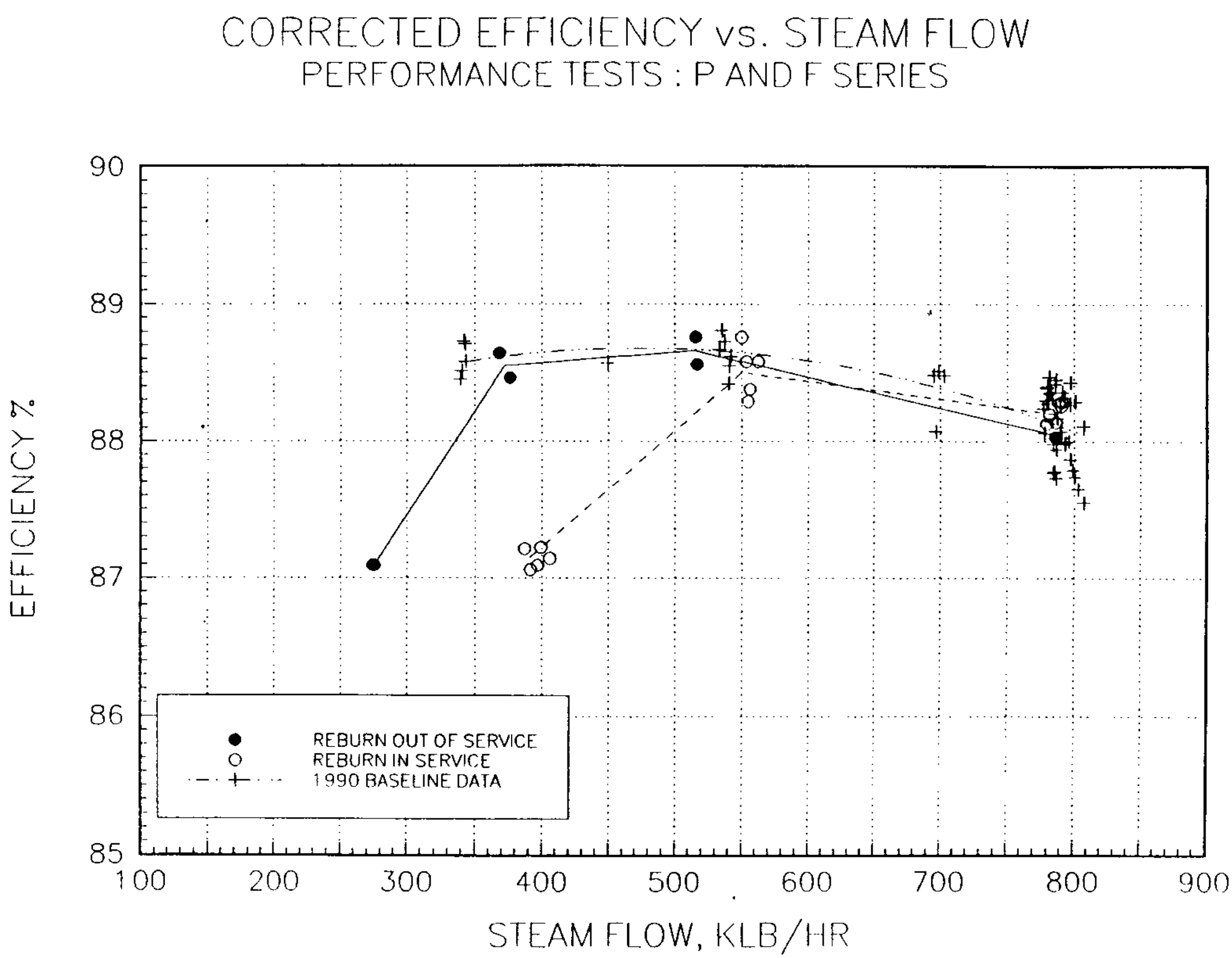

CORRECTED EFFICIENCY vs. STEAM FLOW
PERFORMANCE TESTS : P AND F SERIES
EFFICIENCY %
90
89
88
87
86
85
100
200
300
400
500
600
700
800
900
STEAM FLOW, KLB/HR
REBURN OUT OF SERVICE
REBURN IN SERVICE
1990 BASELINE DATA

Figure 7-43

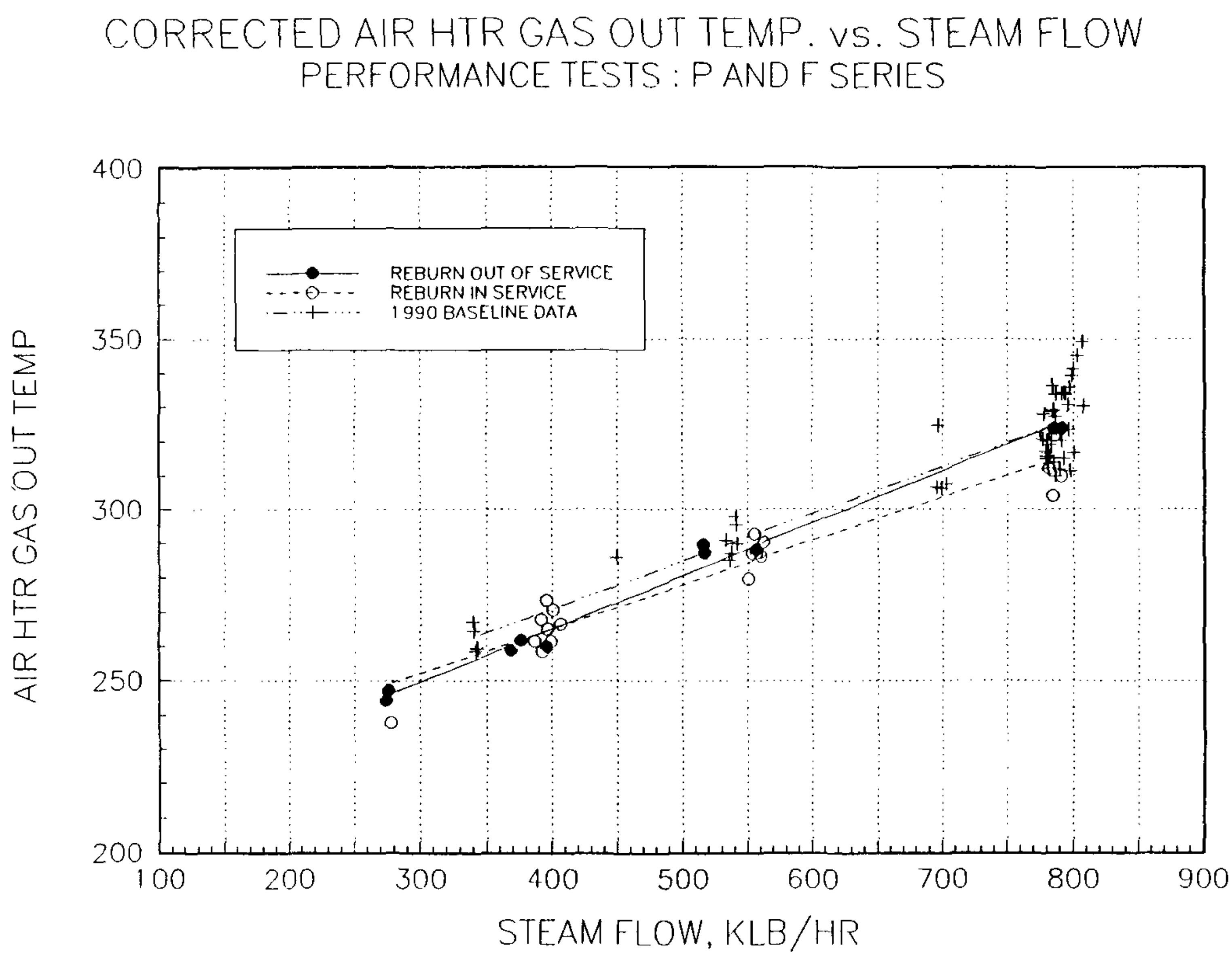

CORRECTED AIR HTR GAS OUT TEMP. vs. STEAM FLOW
PERFORMANCE TESTS : P AND F SERIES
REBURN OUT OF SERVICE
REBURN IN SERVICE
1990 BASELINE DATA
AIR HTR GAS OUT TEMP
400
350
300
250
200
100
200
300
400
500
600
700
800
900
STEAM FLOW, KLB/HR

Figure 7-44

load, unit efficiency decreases by 0.1% with reburn in service. Once again, the dry gas loss decreased by 0.15% to partially offset the 0.25% increase in unburned carbon loss. At 50 percent load the unit efficiency decreases by 1.5%. There is no change in dry gas loss.

The decrease in dry gas loss at full load and 75 percent load with reburn in service is caused by a lower air heater gas outlet temperature. Figure 7-44 is a plot of corrected air heater gas outlet temperature versus steam flow for the P and F series tests. Figure 7-45 shows the dry gas loss versus steam flow for the same tests. Figure 7-46 shows the economizer gas outlet temperature versus steam flow for the P and F series tests. The decrease in air heater gas outlet temperature is a result of the decreased air heater gas inlet temperature. The lower air heater gas inlet temperature is caused by differences in operating conditions. These include the operation of the gas recirculation fan, which changes the gas split between the primary superheater and the reheater, and a higher economizer cleanliness factor for the tests conducted with reburn in service. This benefit cannot be attributed to the reburn system as a credit. Therefore, the impact of the reburn system on unit efficiency is the increase in unburned carbon loss.

7.3.2.4.4 Furnace Exit Gas Temperature (FEGT)

The furnace exit is defined as the plane entering the first bank of pendant superheater, including the small horizontal plane under the pendant that is not shielded by the furnace arch. The furnace exit gas temperatures reported in this section were calculated by heat balance as described in paragraph 7.3.2.2, Calculation Methodology.

Figure 7-47 is a plot of FEGT versus steam flow for the T and A series tests. These tests were conducted with the original burner impellers installed. These impellers were changed prior to the P and F series tests, in an effort to promote better mixing in the combustion zone and reduce CO emissions at the furnace exit. With the original impellers, the FEGT at full load decreased by approximately 150 °F with reburn in service. At 50 % and 75 % loads there were no changes in FEGT with reburn in service. The gas recirculation fan was in service for the full load tests with reburn. Gas recirculation was required to maintain superheat and reheat steam temperatures with the reduced FEGT. In addition, flow traverses of the GR fan showed

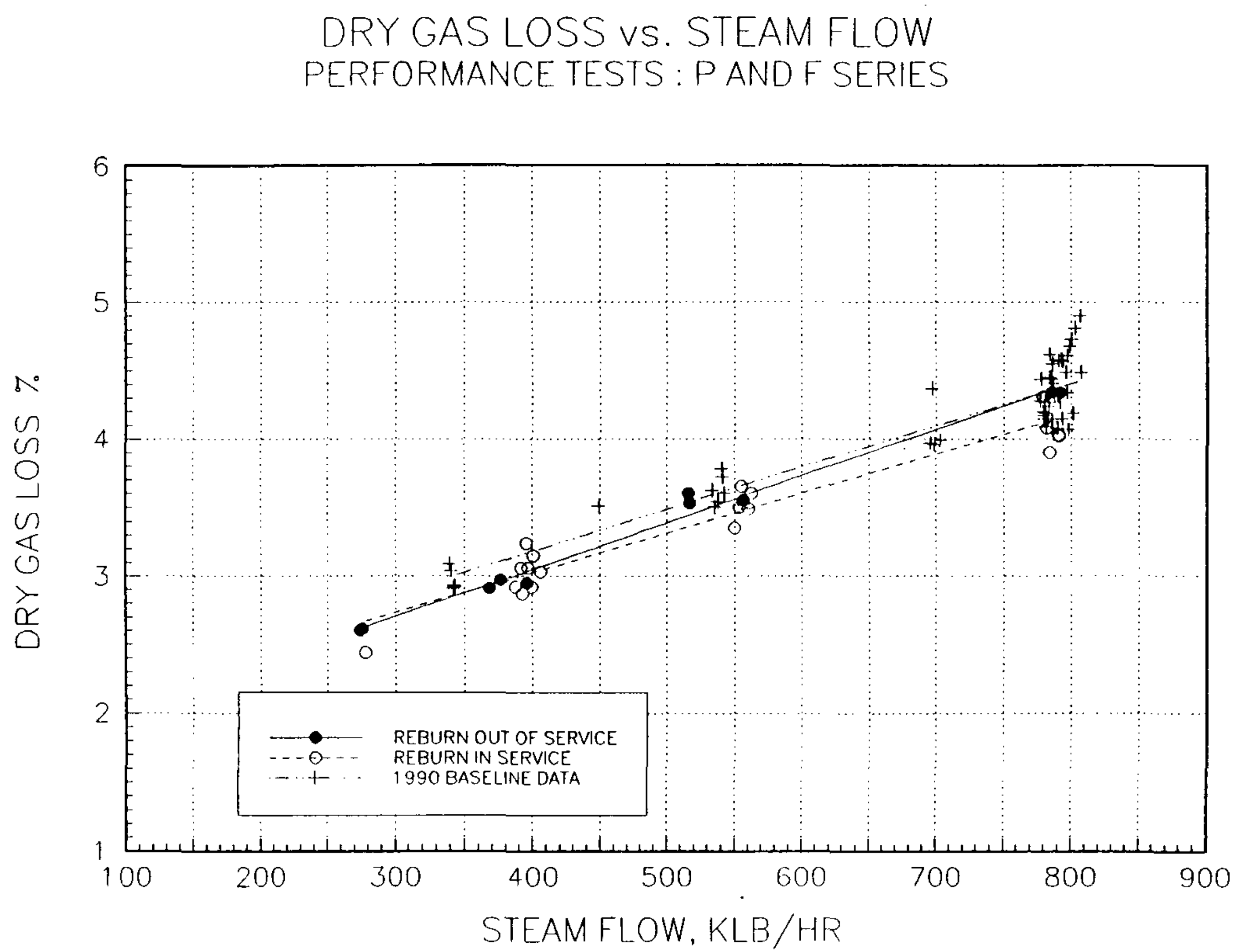

DRY GAS LOSS vs. STEAM FLOW
PERFORMANCE TESTS : P AND F SERIES
DRY GAS LOSS %
STEAM FLOW, KLB/HR
REBURN OUT OF SERVICE
REBURN IN SERVICE
1990 BASELINE DATA
6
5
4
3
2
1
100
200
300
400
500
600
700
800
900

Figure 7-45

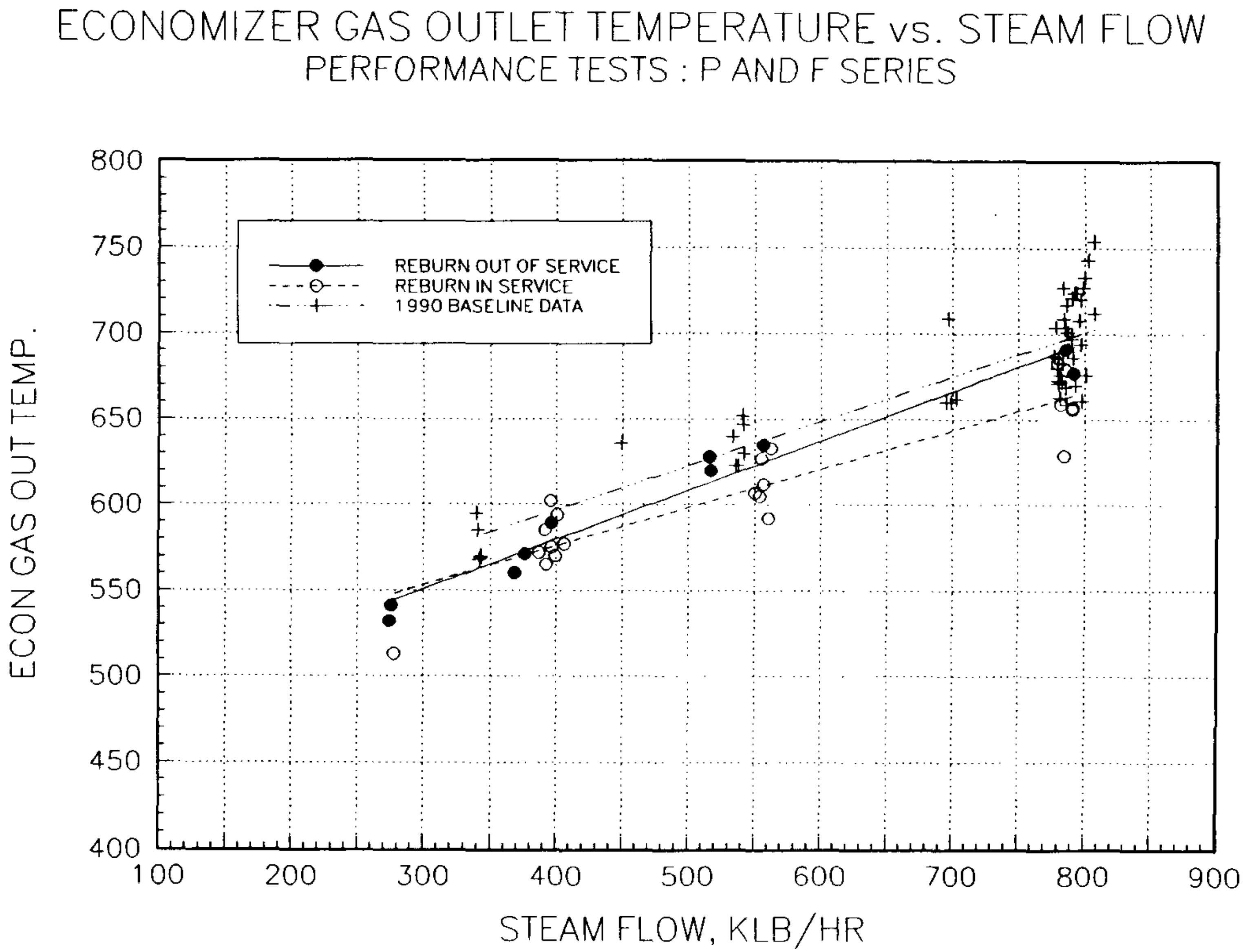

ECONOMIZER GAS OUTLET TEMPERATURE vs. STEAM FLOW
PERFORMANCE TESTS : P AND F SERIES
REBURN OUT OF SERVICE
REBURN IN SERVICE
1990 BASELINE DATA
ECON GAS OUT TEMP.
STEAM FLOW, KLB/HR
800
750
700
650
600
550
500
450
400
100
200
300
400
500
600
700
800
900

Figure 7-46

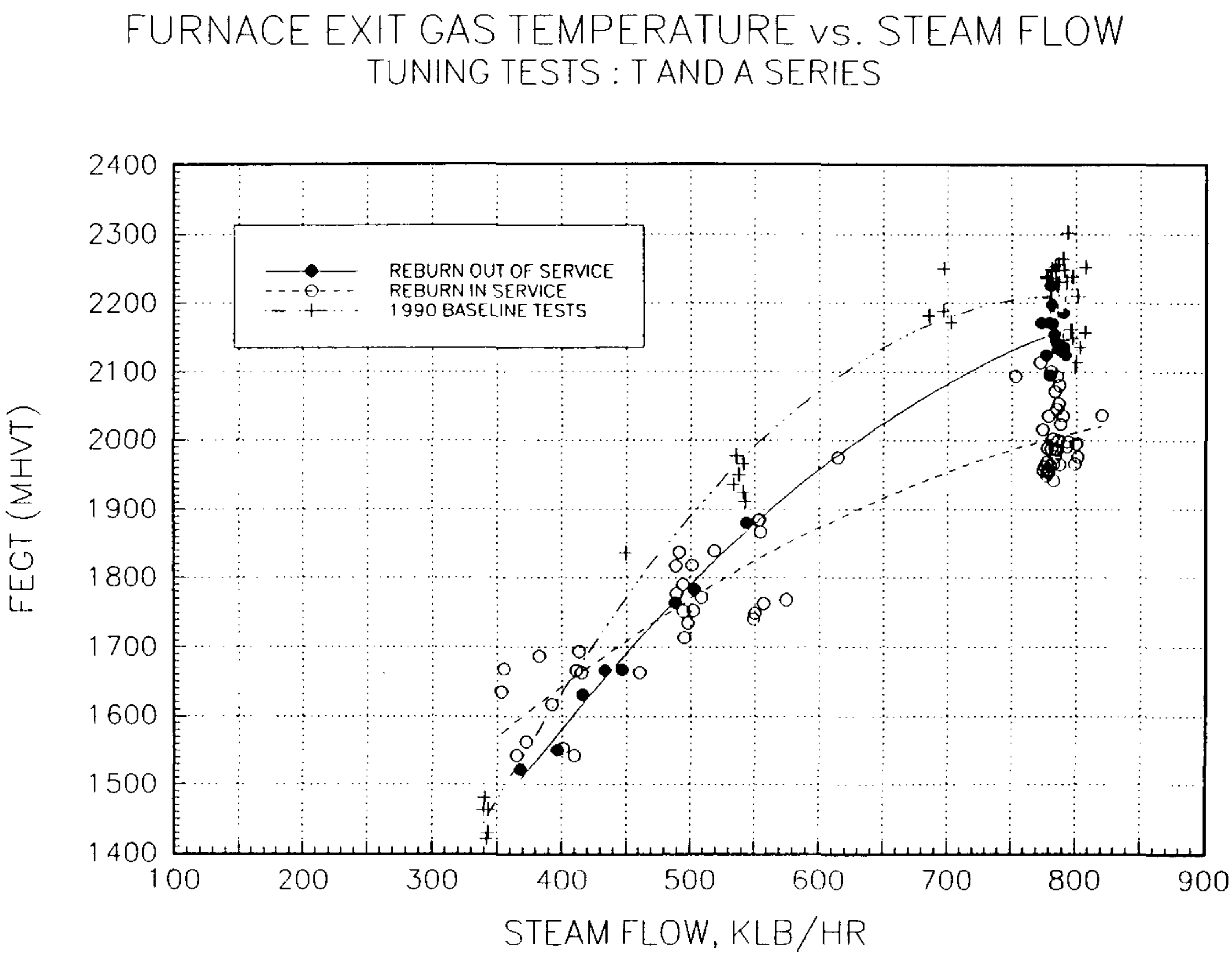

FURNACE EXIT GAS TEMPERATURE vs. STEAM FLOW
TUNING TESTS : T AND A SERIES
REBURN OUT OF SERVICE
REBURN IN SERVICE
1990 BASELINE TESTS
FEGT (MHVT)
2400
2300
2200
2100
2000
1900
1800
1700
1600
1500
1400
100
200
300
400
500
600
700
800
900
STEAM FLOW, KLB/HR

Figure 7-47

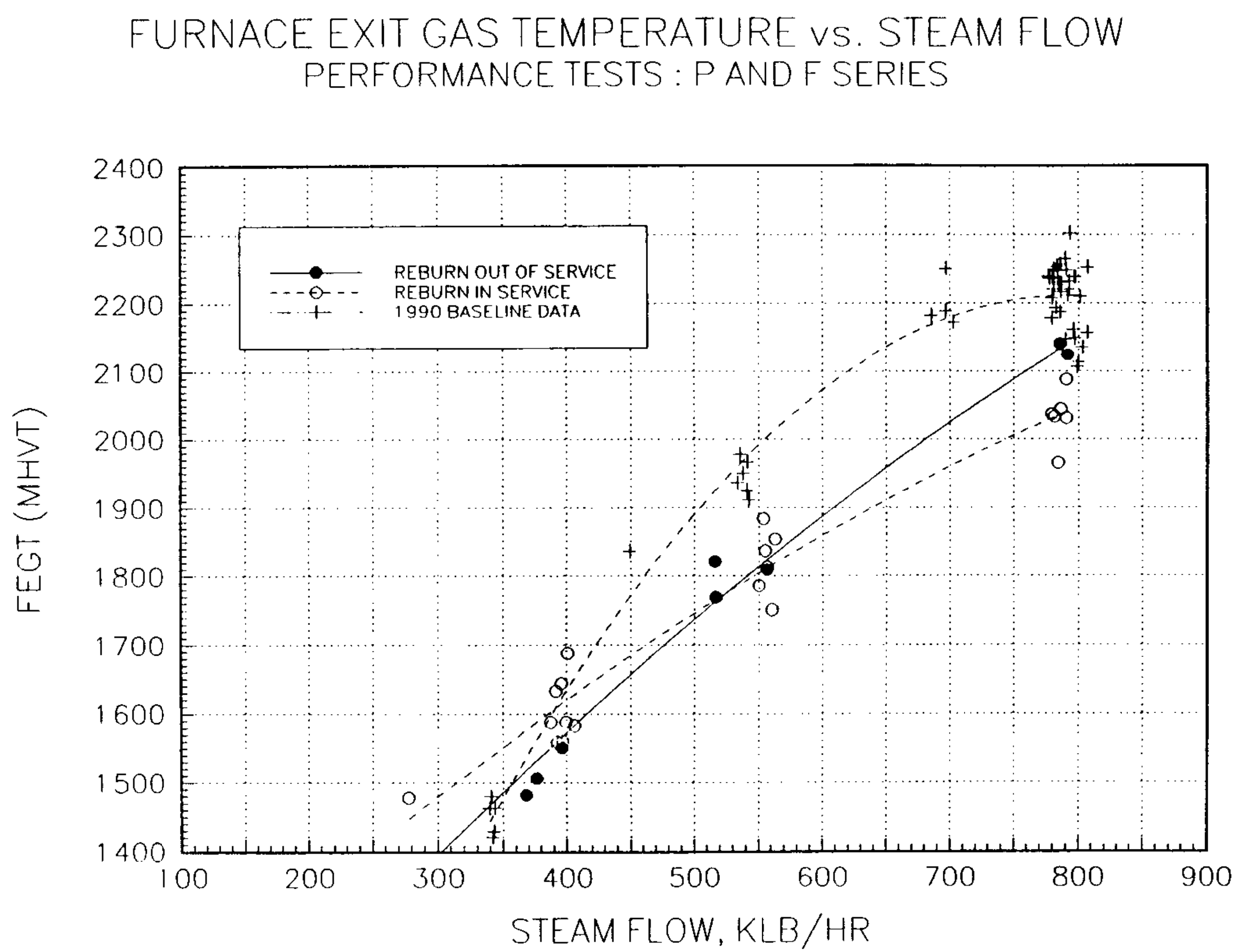

FURNACE EXIT GAS TEMPERATURE vs. STEAM FLOW
PERFORMANCE TESTS : P AND F SERIES
REBURN OUT OF SERVICE
REBURN IN SERVICE
1990 BASELINE DATA
FEGT (MHVT)
2400
2300
2200
2100
2000
1900
1800
1700
1600
1500
1400
100
200
300
400
500
600
700
800
900
STEAM FLOW, KLB/HR

Figure 7-48

quantities of seal air as high as 4 percent excess air. This quantity of air made it impossible to obtain the reburn zone stoichiometries required for NO_x reduction with the gas recirculation system out of service. The gas recirculation flow would be expected to decrease the FEGT by approximately 25 °F at full load.

The P and F series tests were conducted with the new impellers installed. Figure 7-48 shows the FEGT with and without reburn in service for these tests. At full load, the FEGT decreased by approximately 100°F with reburn in service. Once again, the gas recirculation flow with reburn in service would be expected to decrease the FEGT by approximately 25°F of this change. There was no change in FEGT at 75% load with reburn in service, and an increase of 50 to 75°F at 50% load with reburn in service.

7.3.2.4.5 Surface Cleanliness Factors (K_f's)

The component cleanliness factors (K_f's) varied significantly during testing as a result of variations in sootblowing throughout the test program. All components were significantly cleaner than they were during the baseline testing of 1990. This is a result of the unit being cleaned during the outage to install the reburn system. Table 7-8 shows the average, maximum, and minimum K_fs for all tests conducted at full load. Appendix 18 contains Figures 1 thru 5 which show individual component K_fs, over the load range, for the T and A series tests. In addition, Figures 6 thru 10 show the individual component K_fs for the P and F series tests.

TABLE 7-8 SUMMARY OF COMPONENT CLEANLINESS FACTORS					
	SSH IN	SSH OUT	PRI SH	REHEATER	ECON
1990 BASE DATA					
AVG	1.01	0.85	0.91	1.00	0.79
MAX	1.15	0.94	1.05	1.22	0.87
MIN	0.87	0.81	0.81	0.89	0.69
T AND A SERIES					
NO REBURN					
AVG	1.22	1.15	0.95	1.29	0.73
MAX	1.38	1.34	1.04	1.55	0.91
MIN	0.99	1.03	0.82	0.93	0.55
WITH REBURN					
AVG	1.22	1.16	0.98	1.30	0.84
MAX	1.42	1.28	1.16	1.58	0.99
MIN	0.97	1.03	0.80	1.09	0.54
P AND F SERIES					
NO REBURN					
AVG	1.08	1.09	0.89	1.08	0.78
MAX	1.13	1.13	0.90	1.12	0.79
MIN	0.99	1.04	0.88	1.04	0.77
WITH REBURN					
AVG	1.09	1.15	1.00	1.22	0.84
MAX	1.14	1.38	1.09	1.47	0.92
MIN	1.02	1.05	0.88	1.08	0.71

All components were cleaner with reburn in service than with reburn out of service. This is not a benefit created by the presence of the reburn system, but a result of the majority of the reburn tests being conducted closer to periods of sootblowing. The important conclusion is that there is no detrimental impact on unit cleanliness from operation of the reburn system.

All component K_f's stabilized within 5 hours of sootblowing in that component. In general, the component cleanliness decay rates were the same as for the 1990 baseline tests. The cleanliness decay rates for each component are as follows:

- Sec. SH Inlet Bank - The cleanliness factor decreased by 16 % over a four hour period, as compared to 20 % during the baseline tests.

- Sec. SH Outlet Bank - The cleanliness factor decreased by 15 % over a four hour period, as compared to 17 % during the baseline tests.

- Reheater - The cleanliness factor decreased by 25 % over a four hour period, as compared to 23 % during the baseline tests.

- Primary Superheater - The cleanliness factor decreased by 18 % over a four hour period, as compared to 20 % during the baseline tests.

- Economizer - The cleanliness factor decreased by 15 % over a four hour period, as compared to 12 % during the baseline tests.

The change in FEGT is the primary indicator of furnace cleanliness. During these tests, the FEGT increased gradually by 100 °F over an eight hour period, with or without reburn in service. During the baseline tests, the FEGT would increase by 50 °F during the first two hours after sootblowing, and then level off. This difference is probably the result of the furnace being in a generally cleaner condition than it was during the baseline tests. This is supported by the fact that the FEGT with reburn out of service was 50 °F lower at full load than it was for the baseline testing.

As was the case during the baseline testing, the unit operated for prolonged periods of time (up to twelve hours) with no sootblowing in the convection pass. Cleanliness factors for all components would stabilize after four or five hours, and the sootblowers were able to restore the components to their original state of cleanliness.

7.3.2.4.6 Superheat and Reheat Final Steam Temperatures

Evaluating the impact of reburn on final steam temperatures is difficult, due to the impact of several other variables. The variables having the largest impact are the introduction of gas recirculation, the change in flue gas biasing between the primary superheater and reheater caused by changes in FEGT, and over or under spraying in the superheater or reheater. Figures 7-49 and 7-50 show final superheat steam temperatures for the T and A series tests, and the P and F series tests. Figures 7-51 and 7-52 show final reheat steam temperatures for the T and A series tests and the P and F series tests. During the T and A series, several tests were conducted at full load with reburn in service and no gas recirculation. The unit was not capable of making superheat or reheat temperature as a result of the FEGT being 150°F lower with reburn in service. Superheat temperatures went as low as 955°F, while reheat temperatures dropped as low as 960°F. With the gas recirculation fan in service, the unit was capable of maintaining 1005°F superheat and reheat steam temperatures with reburn in service. Figures 7-53 and 7-54 show gas recirculation flow versus steam flow for the T and A series tests, and the P and F series tests respectively.

Evaluating the percent of required total absorption of the superheater and reheater effectively normalizes the impact of the variables described above, and gives a more accurate indication of changes in unit operation. Figures 7-55 and 7-56 show the percent of total required absorption (SHact+RHact)/(SHreq+RHreq) for the T and A series tests and the P and F series tests respectively. The baseline test data is also shown for comparison. For the T and A series tests, the actual total absorption without reburn in service was 115 percent of required absorption, which was very close to the baseline data. With reburn in service, the actual total absorption decreased to 103 percent of required absorption, with some tests actually dipping below 100 percent of required absorption. For the P and F series tests, the actual total absorption without reburn in service was 108 percent of required absorption. With reburn in service the actual total absorption dropped to 104% of required absorption. At 75 percent load and 50 percent load the percent of required absorption was essentially the same as the baseline data, for both the no reburn and with reburn tests.

The reburn system does reduce total absorption at full load due to the decrease in FEGT. At 75 percent load, the total absorption is maintainable with increased gas recirculation. At fifty percent load the total absorption is maintainable with the same gas recirculation flow because the FEGT increases with reburn in service.

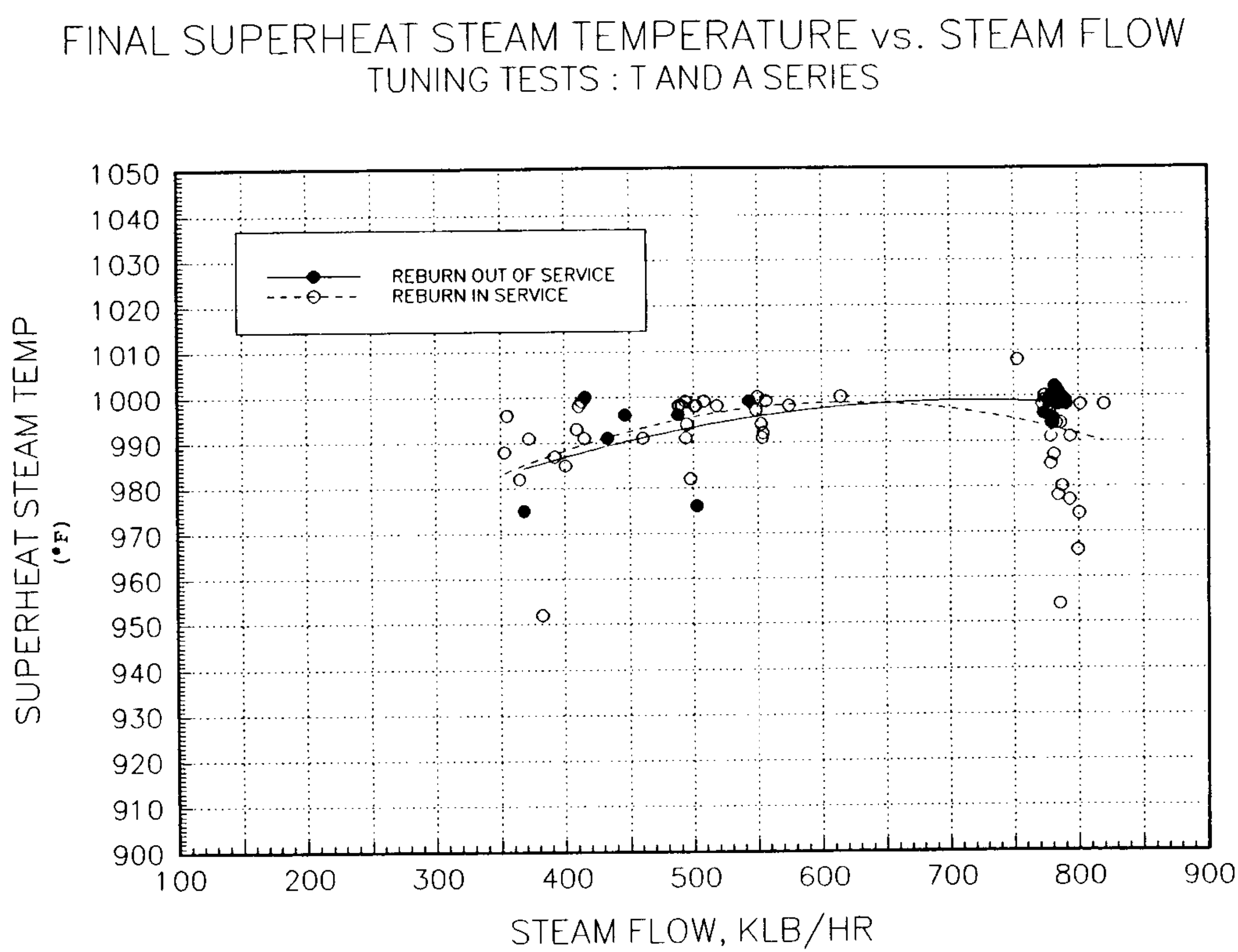

FINAL SUPERHEAT STEAM TEMPERATURE vs. STEAM FLOW
TUNING TESTS : T AND A SERIES
REBURN OUT OF SERVICE
REBURN IN SERVICE
SUPERHEAT STEAM TEMP (°F)
1050
1040
1030
1020
1010
1000
990
980
970
960
950
940
930
920
910
900
100
200
300
400
500
600
700
800
900
STEAM FLOW, KLB/HR

Figure 7-49

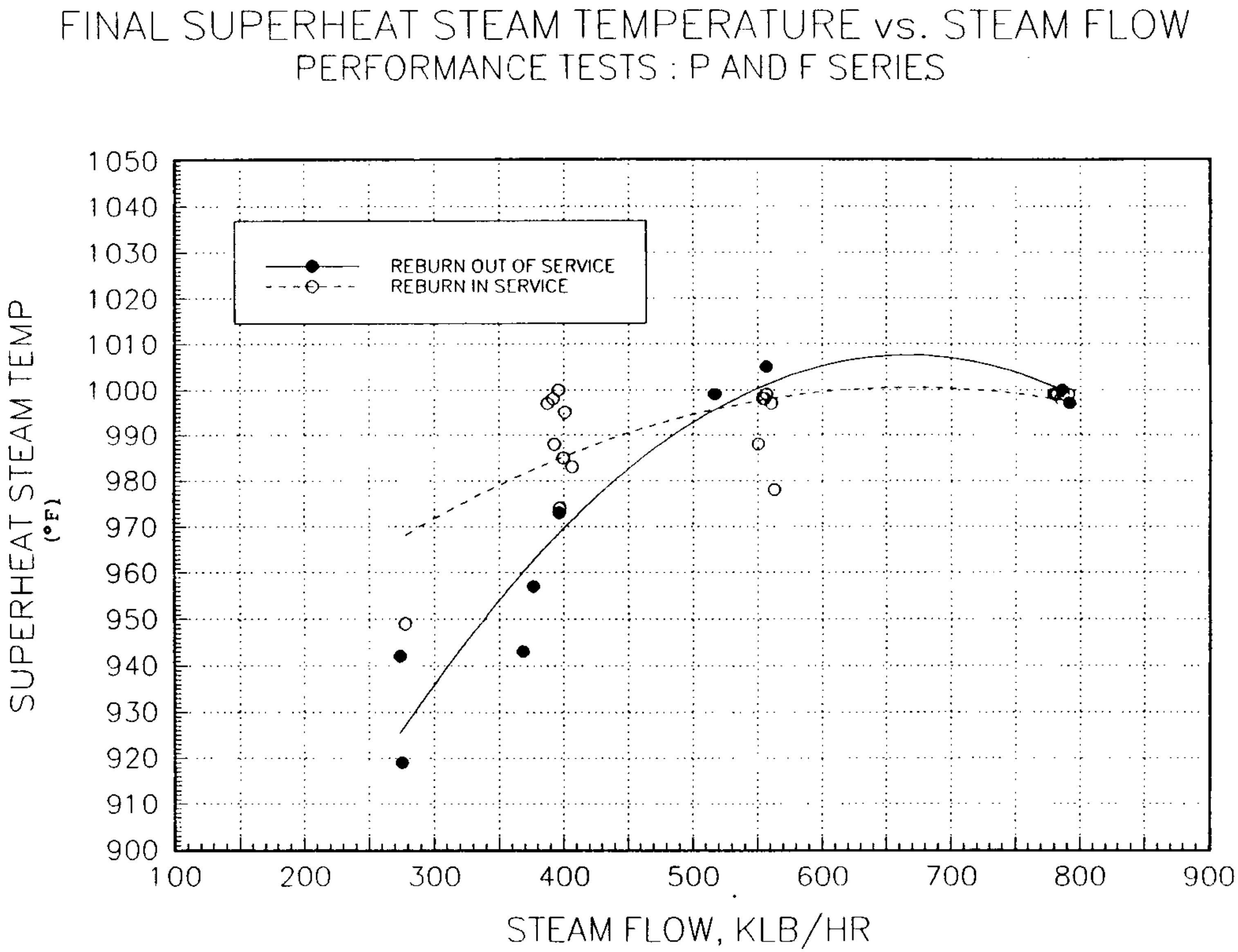

FINAL SUPERHEAT STEAM TEMPERATURE vs. STEAM FLOW
PERFORMANCE TESTS : P AND F SERIES
REBURN OUT OF SERVICE
REBURN IN SERVICE
SUPERHEAT STEAM TEMP (°F)
1050
1040
1030
1020
1010
1000
990
980
970
960
950
940
930
920
910
900
100
200
300
400
500
600
700
800
900
STEAM FLOW, KLB/HR

Figure 7-50

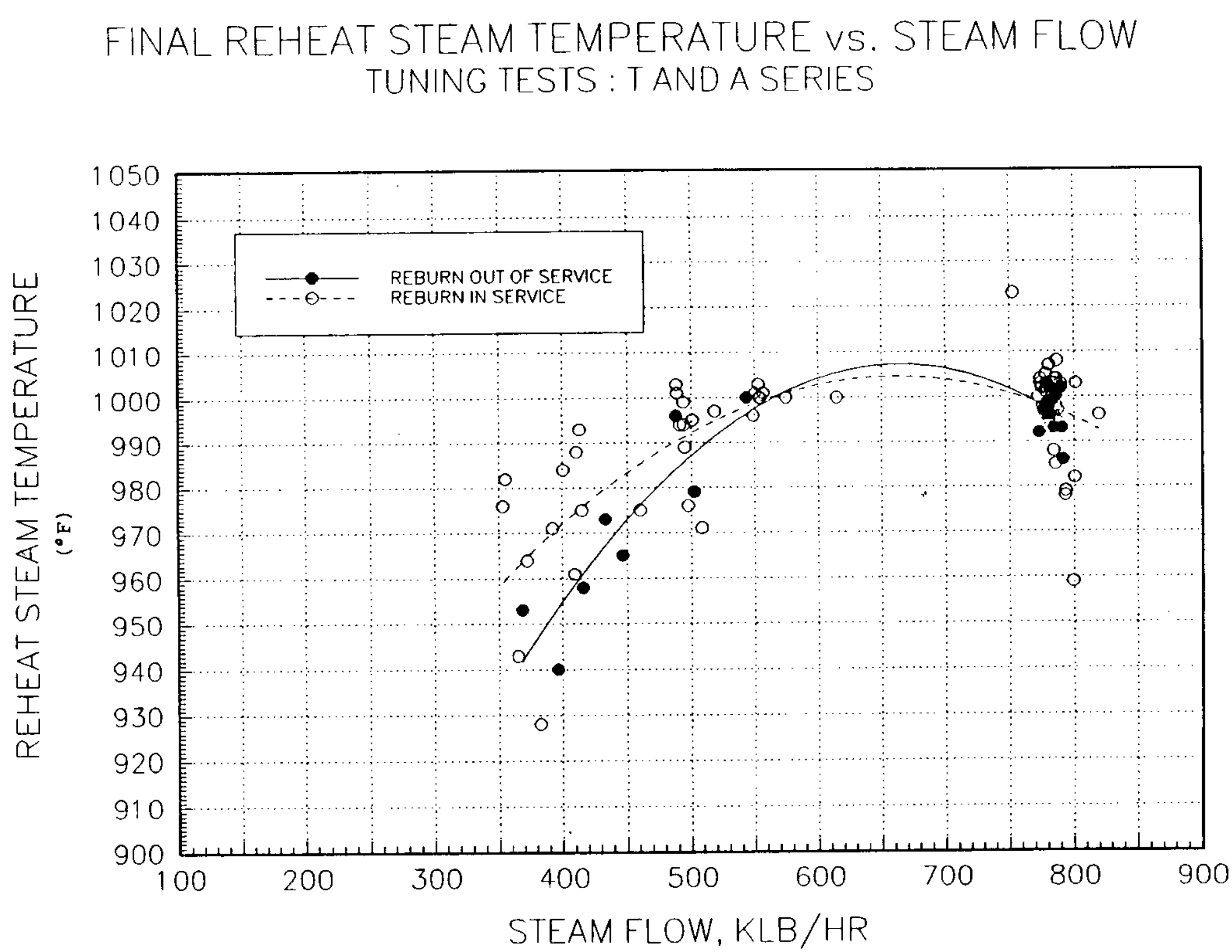

FINAL REHEAT STEAM TEMPERATURE vs. STEAM FLOW
TUNING TESTS : T AND A SERIES
REBURN OUT OF SERVICE
REBURN IN SERVICE
REHEAT STEAM TEMPERATURE
(°F)
1050
1040
1030
1020
1010
1000
990
980
970
960
950
940
930
920
910
900
100
200
300
400
500
600
700
800
900
STEAM FLOW, KLB/HR

Figure 7-51

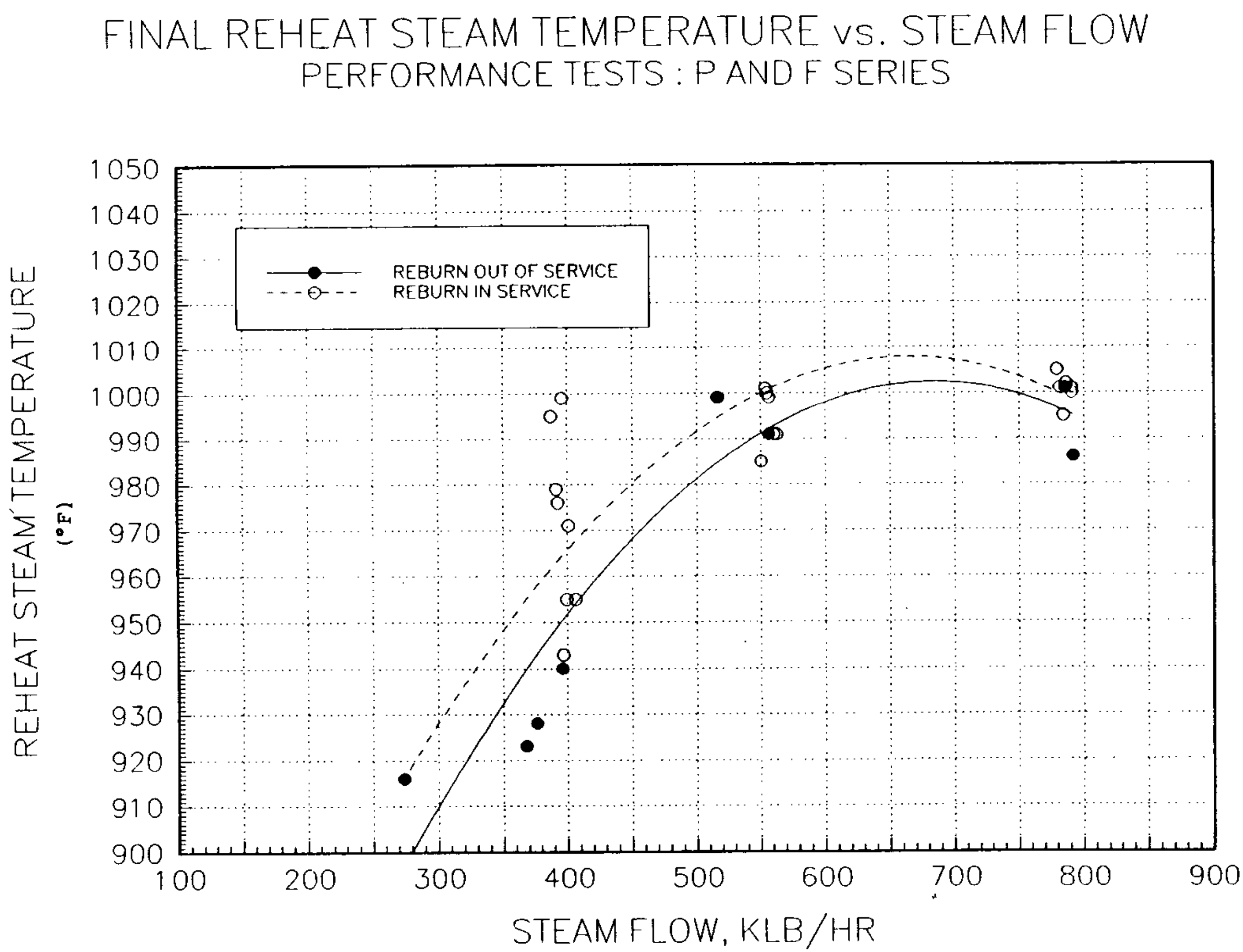
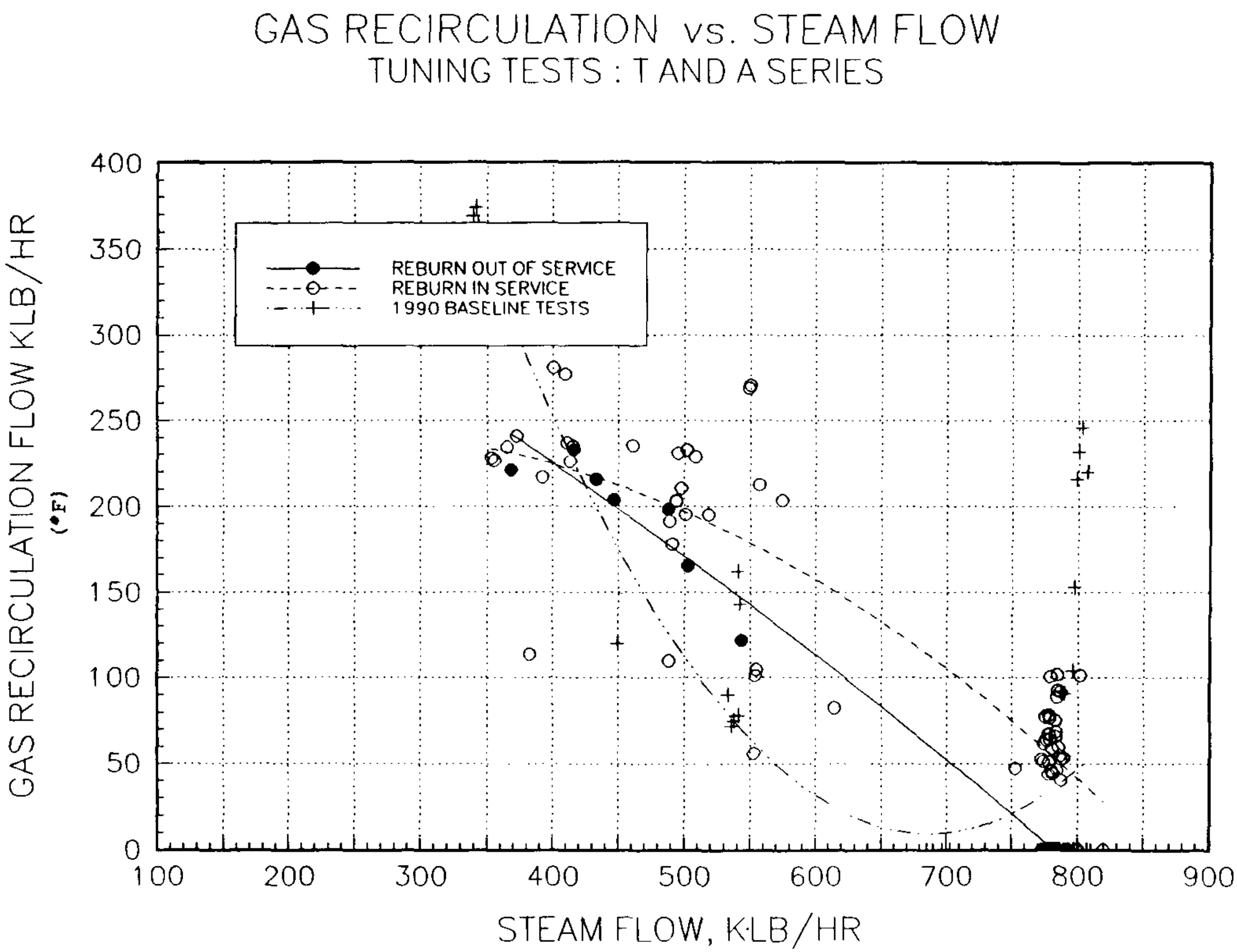
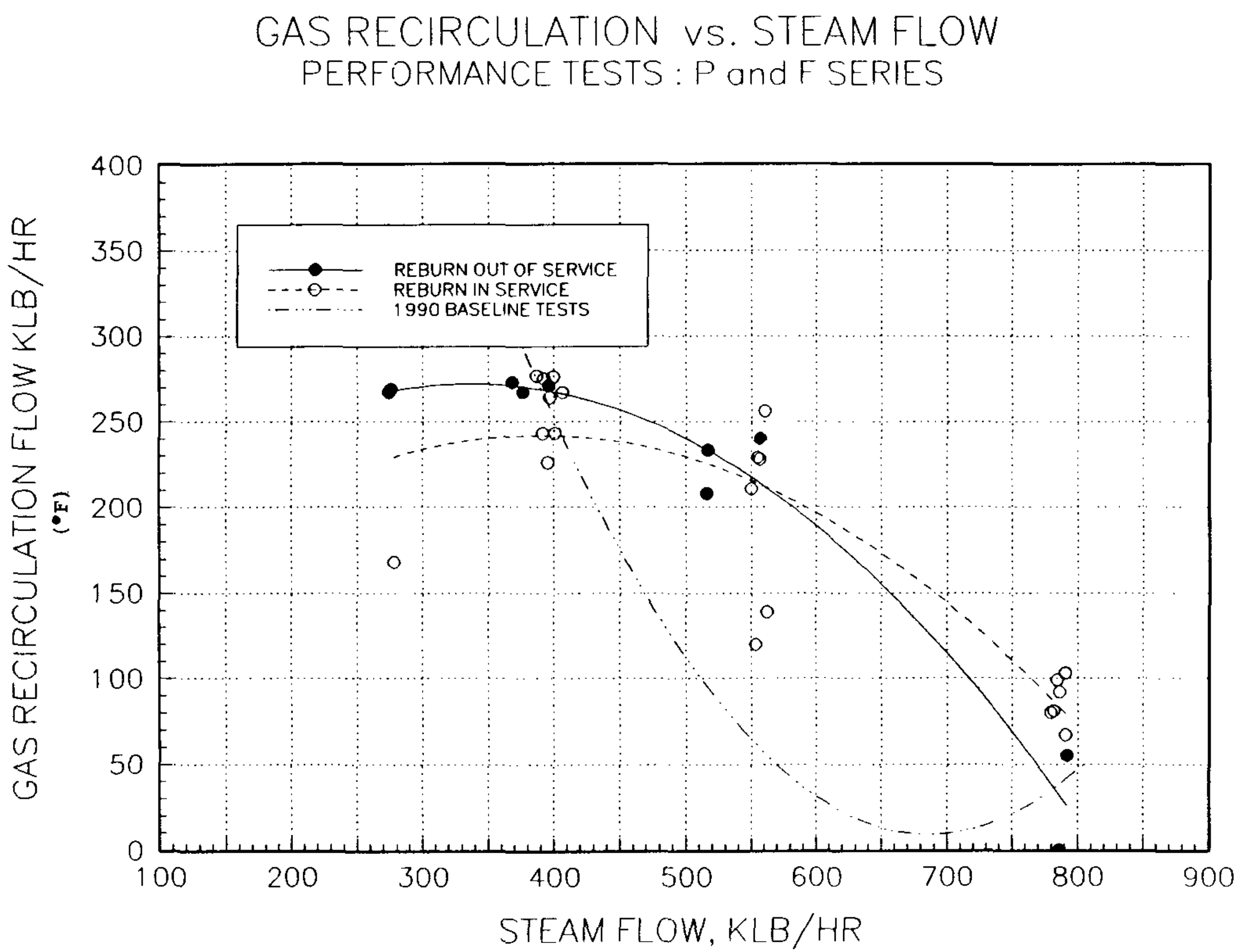

FINAL REHEAT STEAM TEMPERATURE vs. STEAM FLOW
PERFORMANCE TESTS : P AND F SERIES
REBURN OUT OF SERVICE
REBURN IN SERVICE
REHEAT STEAM TEMPERATURE
(°F)
1050
1040
1030
1020
1010
1000
990
980
970
960
950
940
930
920
910
900
100
200
300
400
500
600
700
800
900
STEAM FLOW, KLB/HR

Figure 7-52



GAS RECIRCULATION vs. STEAM FLOW
TUNING TESTS : T AND A SERIES
REBURN OUT OF SERVICE
REBURN IN SERVICE
1990 BASELINE TESTS
GAS RECIRCULATION FLOW KLB/HR
(°F)
STEAM FLOW, KLB/HR
0
50
100
150
200
250
300
350
400
100
200
300
400
500
600
700
800
900

Figure 7-53



GAS RECIRCULATION vs. STEAM FLOW
PERFORMANCE TESTS : P and F SERIES
REBURN OUT OF SERVICE
REBURN IN SERVICE
1990 BASELINE TESTS
GAS RECIRCULATION FLOW KLB/HR
(°F)
STEAM FLOW, KLB/HR
0
50
100
150
200
250
300
350
400
100
200
300
400
500
600
700
800
900

Figure 7-54

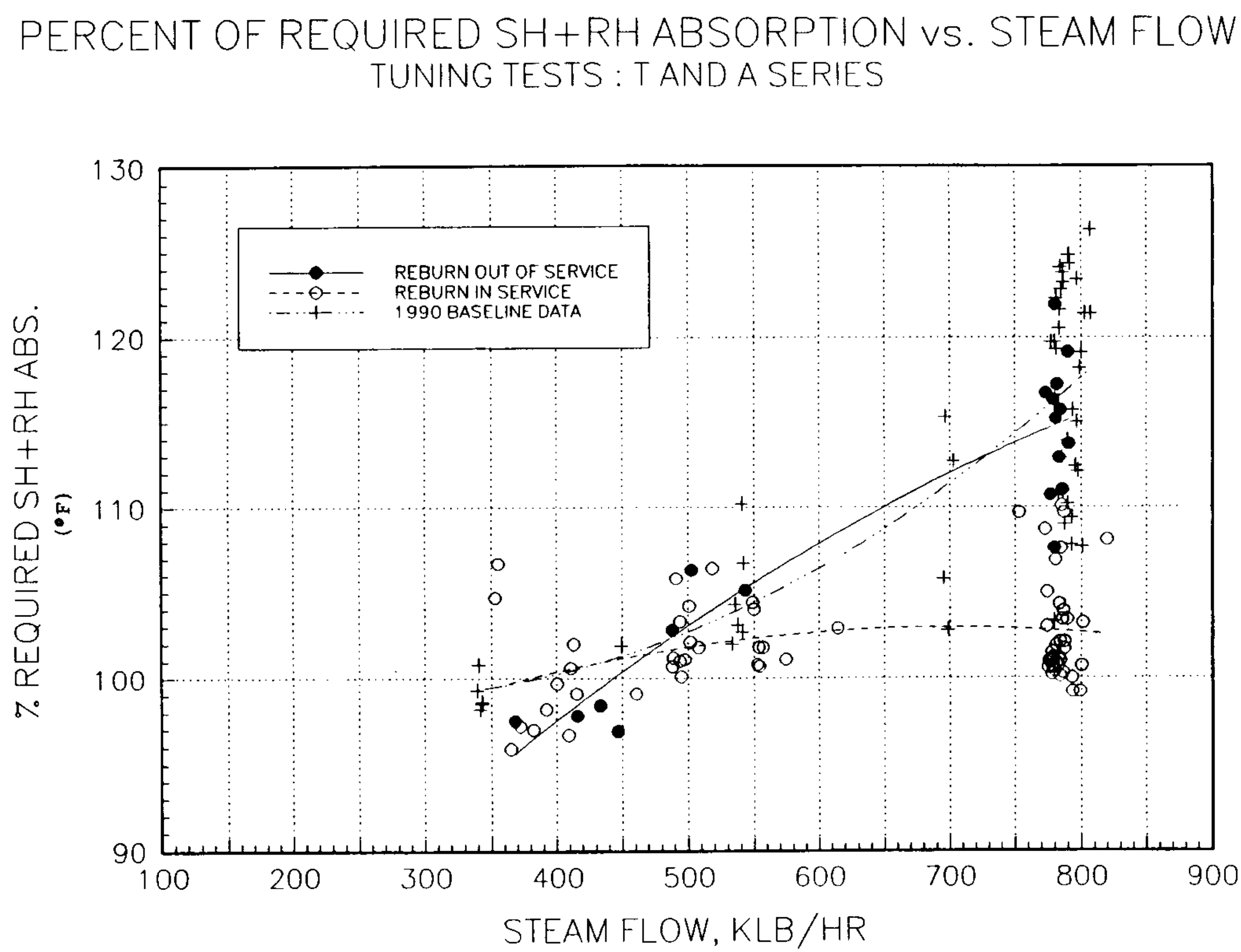
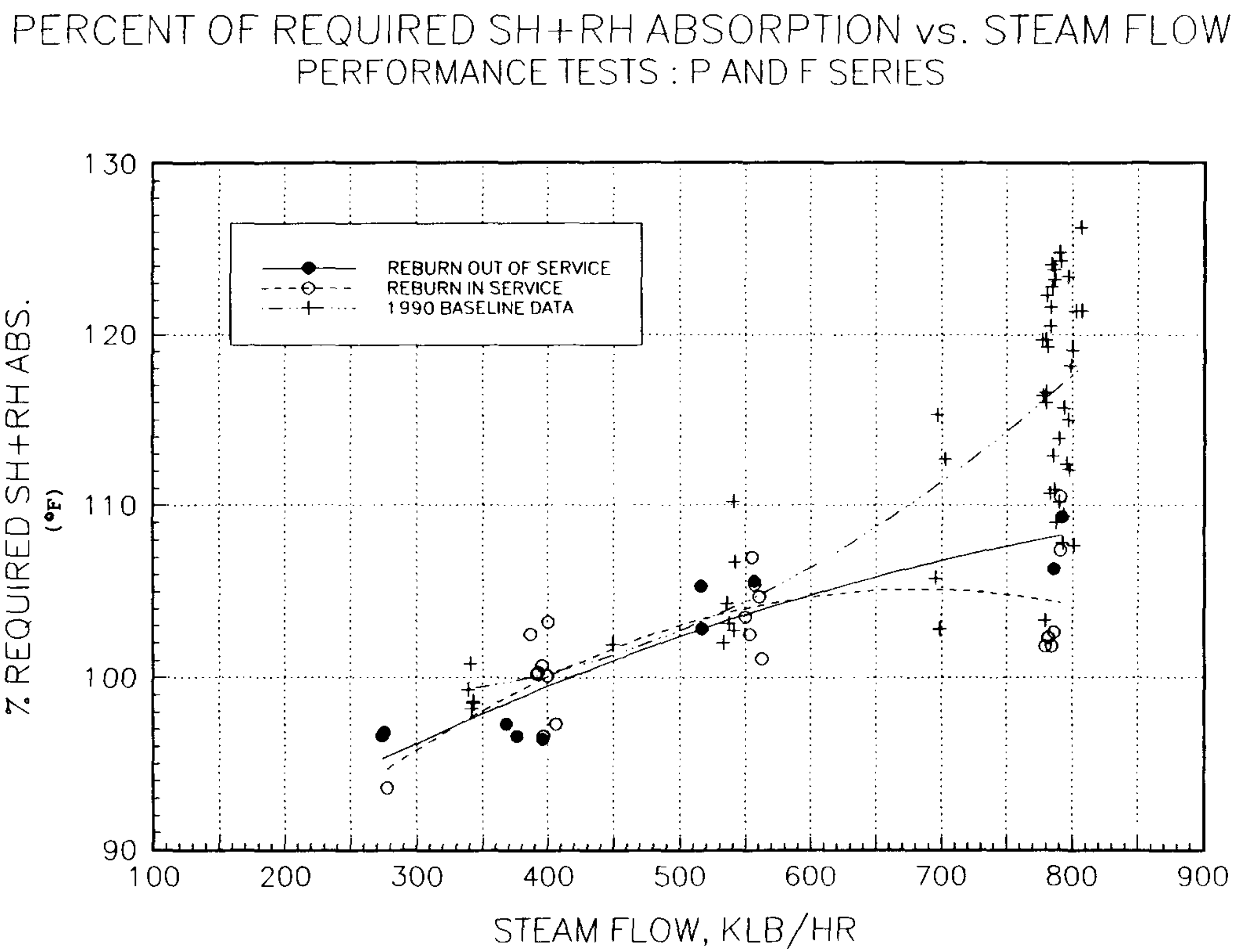

PERCENT OF REQUIRED SH+RH ABSORPTION vs. STEAM FLOW
TUNING TESTS : T AND A SERIES
REBURN OUT OF SERVICE
REBURN IN SERVICE
1990 BASELINE DATA
% REQUIRED SH+RH ABS.
(°F)
130
120
110
100
90
100
200
300
400
500
600
700
800
900
STEAM FLOW, KLB/HR

Figure 7-55



PERCENT OF REQUIRED SH+RH ABSORPTION vs. STEAM FLOW
PERFORMANCE TESTS : P AND F SERIES
REBURN OUT OF SERVICE
REBURN IN SERVICE
1990 BASELINE DATA
% REQUIRED SH+RH ABS. (°F)
130
120
110
100
90
100
200
300
400
500
600
700
800
900
STEAM FLOW, KLB/HR

Figure 7-56

7.3.2.4.7 Superheat and Reheat Spray Flow Quantities

Figures 7-57 and 7-58 show superheat spray flow quantities for the T and A series tests and the P and F series tests. Figures 7-59 and 7-60 show reheat spray flow quantities for the T and A series tests and the P and F series tests. During the T and A series tests with reburn out of service, the superheat spray flow was slightly higher than the spray flows from the 1990 baseline data, while the reheat spray flow was lower than the baseline values. This is the result of not biasing flue gas to the reheater, which was normal operating procedure during the baseline tests. For all tests with reburn in service, the spray quantities are minimal due to the lower FEGT. As discussed above, the percent of required total absorption is a more practical method of evaluating the changes in performance.

7.3.2.5 Discussion of Test Results for Western Coal

The W series tests were conducted to evaluate unit performance, and to tune the reburn combustion controls for western sub-bituminous coal firing. The same performance parameters that were evaluated for Lamar coal are discussed in this section.

7.3.2.5.1 Percent of Ash as Fly Ash (Fly Ash Split)

Figure 7-61 shows the actual percent fly ash for each of the W series tests. Because the purpose of this test program was to tune the reburn controls and the time schedule was rather compressed, there was little opportunity to repeat tests. There is a large scatter in the ash split data with reburn out of service. However, since the ash splits for the reburn in service tests are extremely close to the Lamar coal test results, it is a reasonable assumption that the ash splits without reburn in service are also similar to the Lamar coal test results. The unburned carbon in the ash was so low for these tests, that the fly ash split has very little impact on the unburned carbon loss. For this reason, the fly ash split was not considered as a critical parameter in this evaluation.

7.3.2.5.2 *Unburned Carbon (UBC)*

Figure 7-62 shows the actual unburned carbon, on a lb/100 lb of fuel basis, as calculated from the fly ash splits, carbon in fly ash, and carbon in cyclone slag for the W series tests. At full load, the increase in unburned carbon with reburn in service is negligible. At 75% load, the increase in unburned carbon with reburn in service is 0.15 lb/100 lb fuel. At 50% load, the unburned carbon with reburn in service increases by 0.2 lb/100 lb fuel.

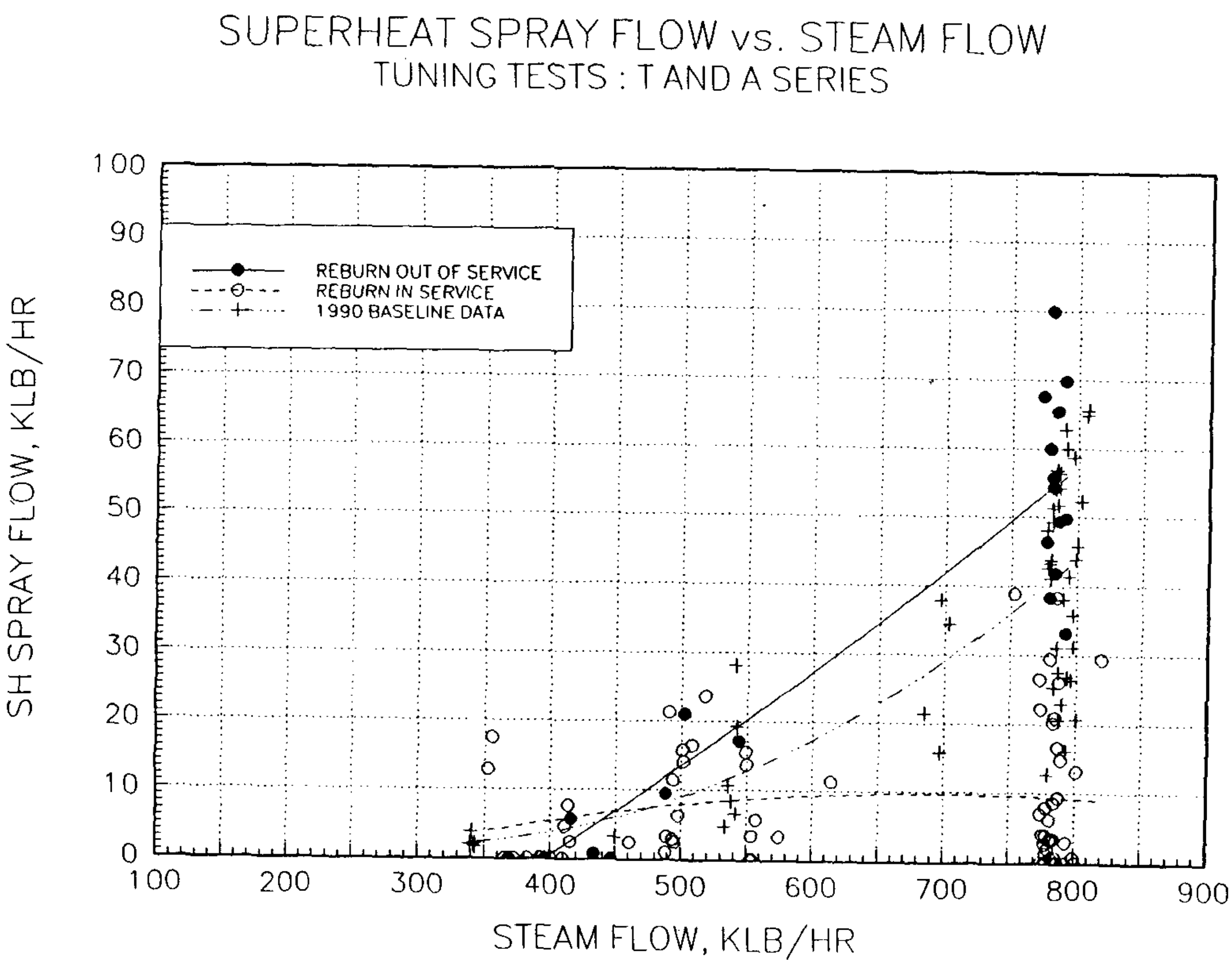

SUPERHEAT SPRAY FLOW vs. STEAM FLOW
TUNING TESTS : T AND A SERIES
REBURN OUT OF SERVICE
REBURN IN SERVICE
1990 BASELINE DATA
SH SPRAY FLOW, KLB/HR
STEAM FLOW, KLB/HR
0
10
20
30
40
50
60
70
80
90
100
100
200
300
400
500
600
700
800
900

Figure 7-57

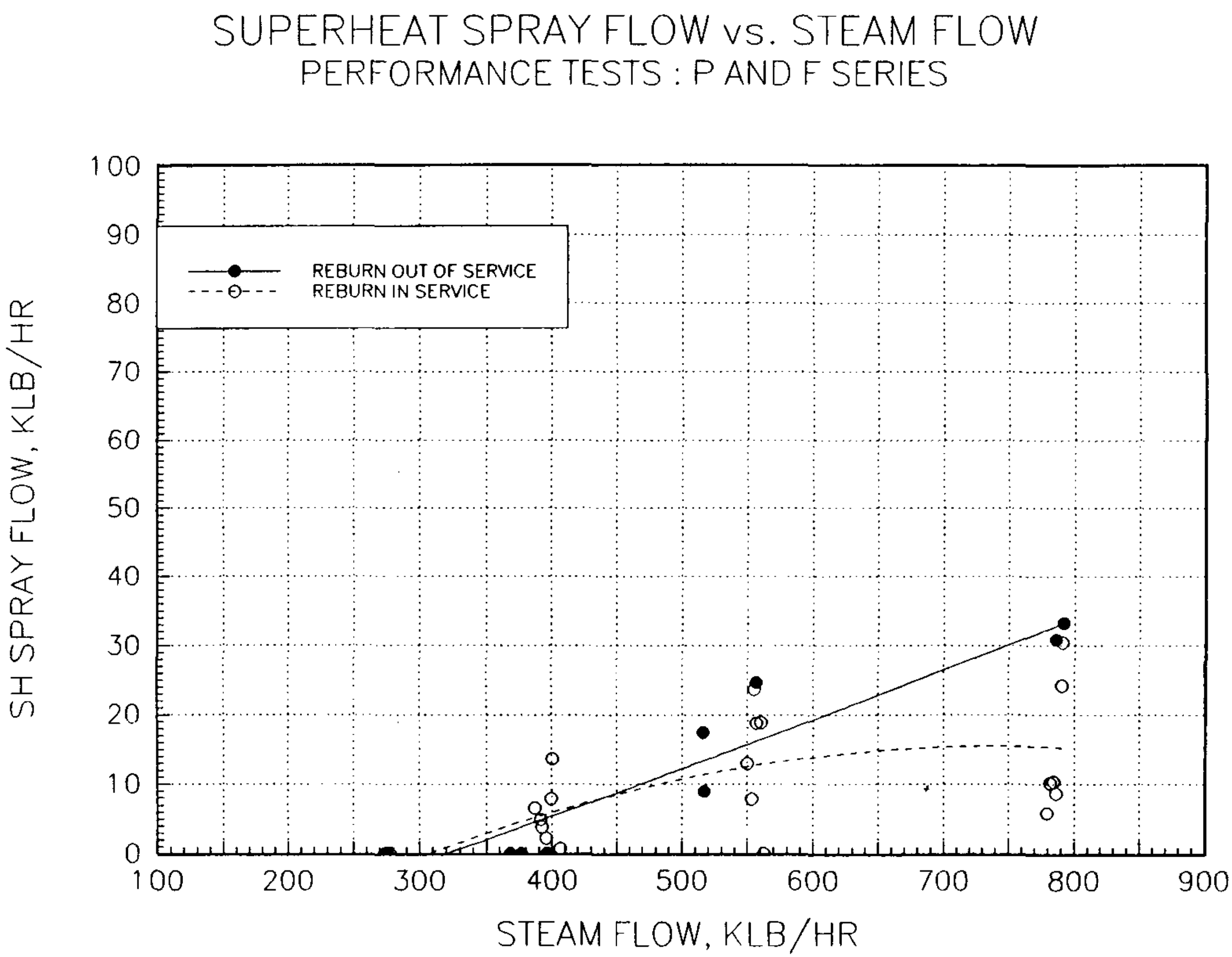
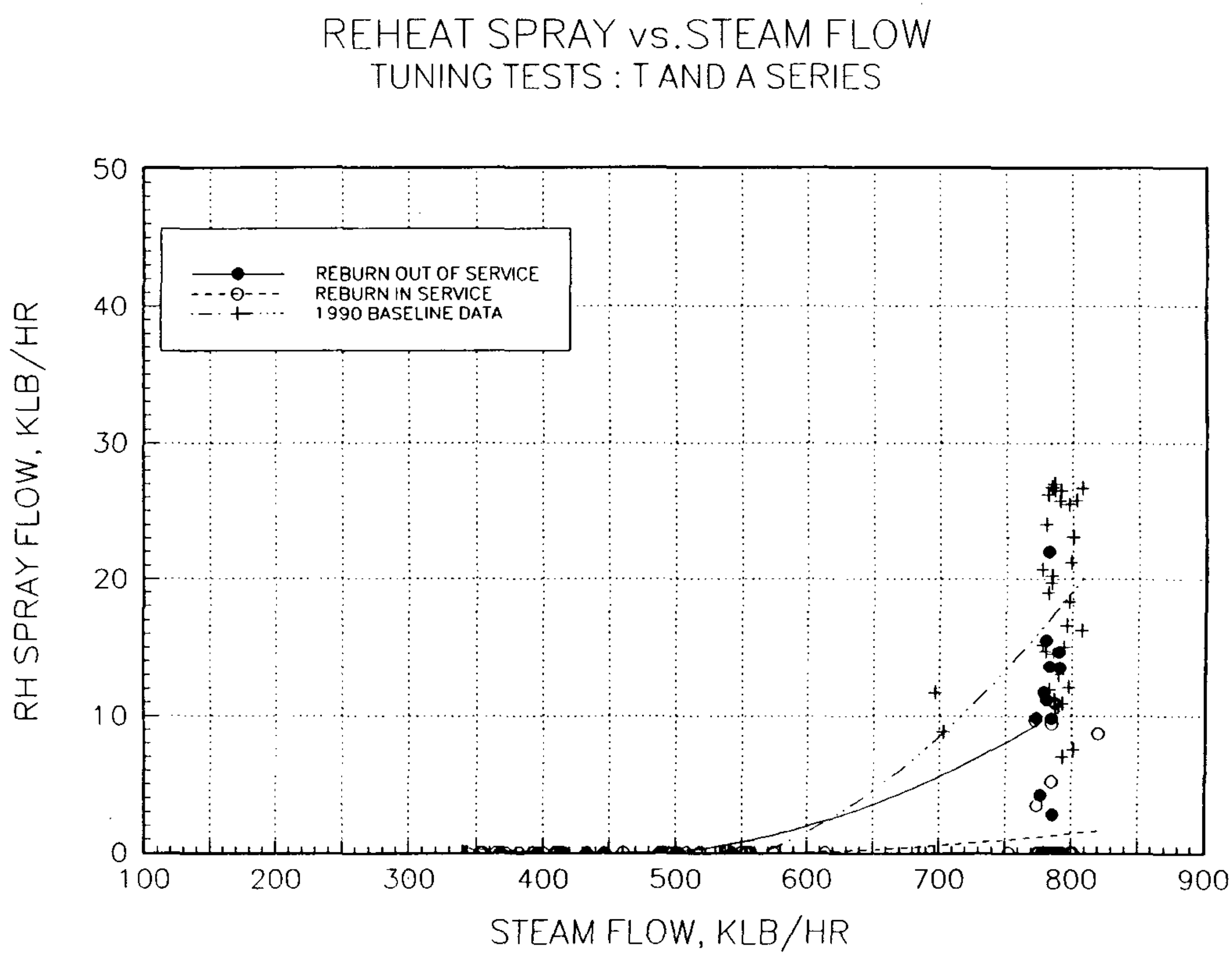

SUPERHEAT SPRAY FLOW vs. STEAM FLOW
PERFORMANCE TESTS : P AND F SERIES
REBURN OUT OF SERVICE
REBURN IN SERVICE
SH SPRAY FLOW, KLB/HR
STEAM FLOW, KLB/HR
0
10
20
30
40
50
60
70
80
90
100
200
300
400
500
600
700
800
900

Figure 7-58



REHEAT SPRAY vs.STEAM FLOW
TUNING TESTS : T AND A SERIES
REBURN OUT OF SERVICE
REBURN IN SERVICE
1990 BASELINE DATA
RH SPRAY FLOW, KLB/HR
STEAM FLOW, KLB/HR
0
10
20
30
40
50
100
200
300
400
500
600
700
800
900

Figure 7-59

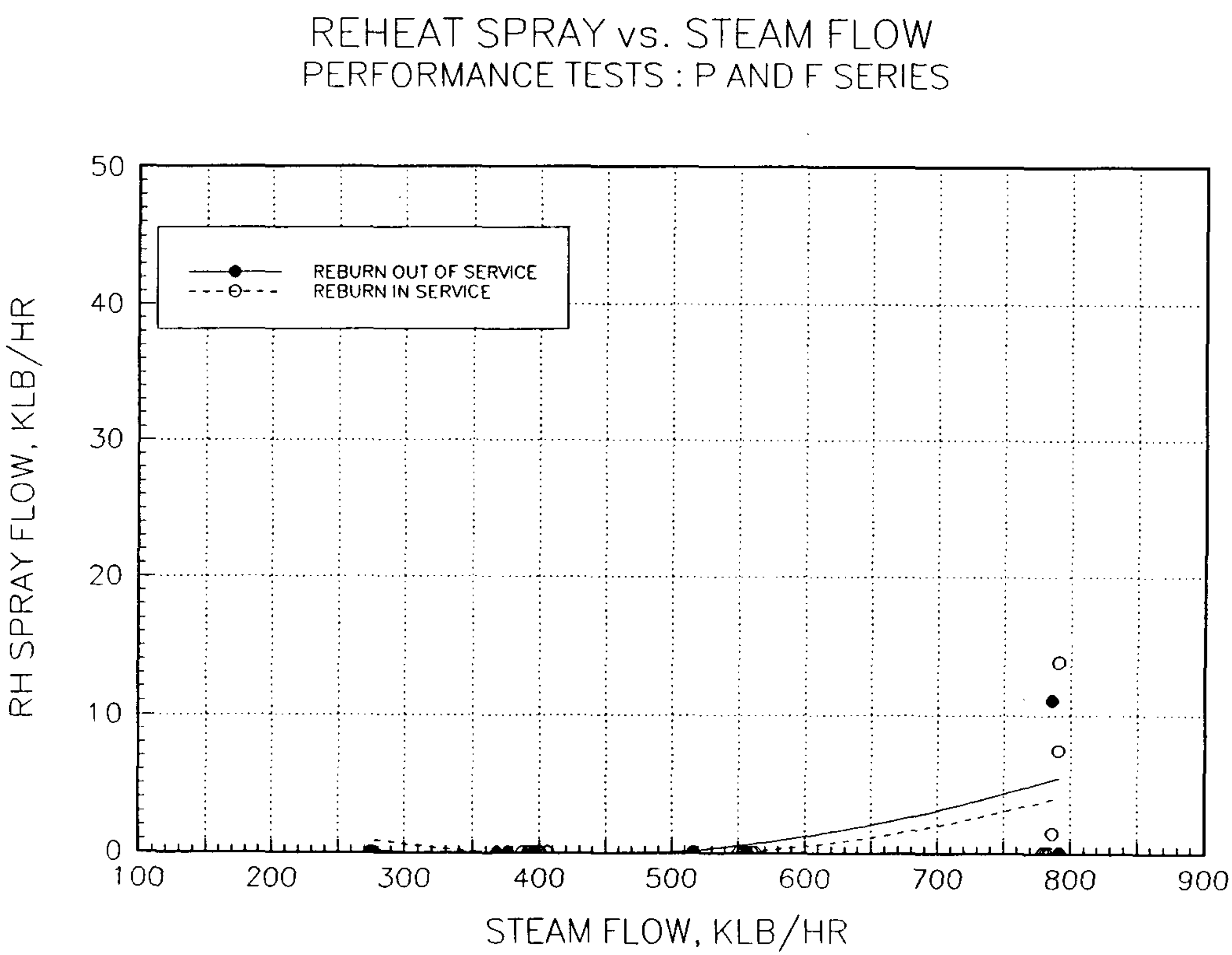

REHEAT SPRAY vs. STEAM FLOW
PERFORMANCE TESTS : P AND F SERIES
REBURN OUT OF SERVICE
REBURN IN SERVICE
RH SPRAY FLOW, KLB/HR
STEAM FLOW, KLB/HR
0
10
20
30
40
50
100
200
300
400
500
600
700
800
900

Figure 7-60

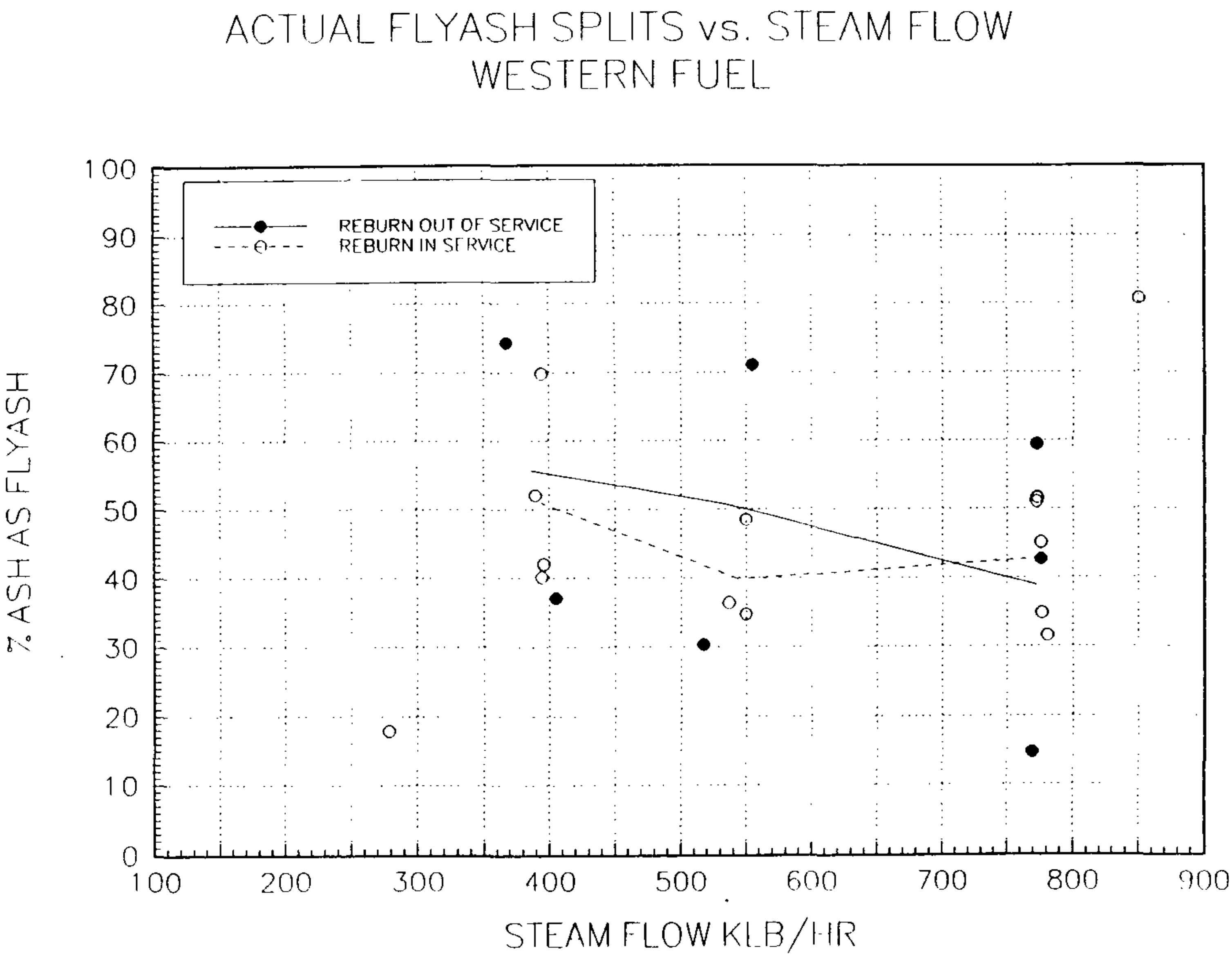

ACTUAL FLYASH SPLITS vs. STEAM FLOW
WESTERN FUEL
REBURN OUT OF SERVICE
REBURN IN SERVICE
% ASH AS FLYASH
100
90
80
70
60
50
40
30
20
10
0
100
200
300
400
500
600
700
800
900
STEAM FLOW KLB/HR

Figure 7-61

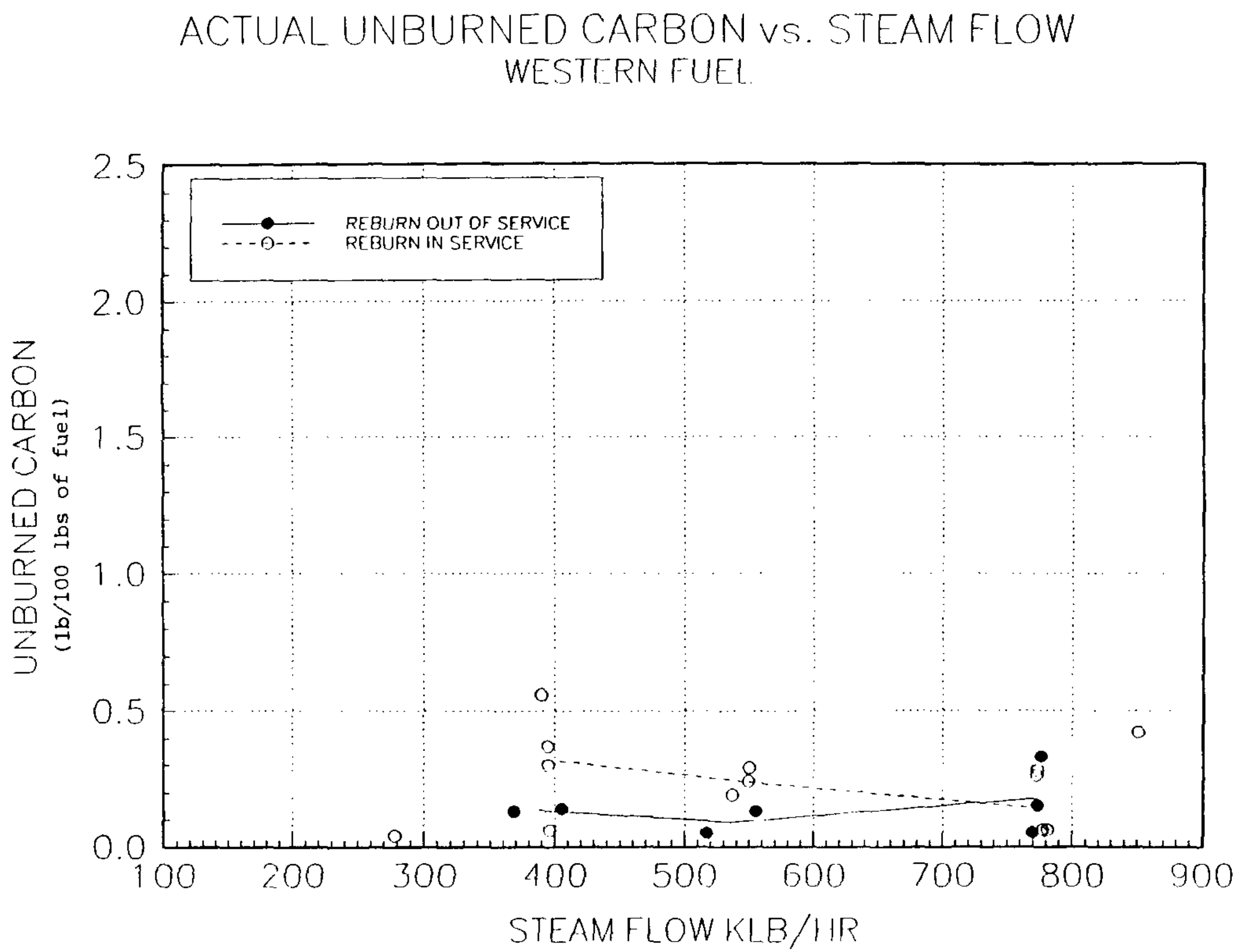

ACTUAL UNBURNED CARBON vs. STEAM FLOW
WESTERN FUEL
REBURN OUT OF SERVICE
REBURN IN SERVICE
UNBURNED CARBON
(lb/100 lbs of fuel)
2.5
2.0
1.5
1.0
0.5
0.0
100
200
300
400
500
600
700
800
900
STEAM FLOW KLB/HR

Figure 7-62

Figure 7-63 is a plot of the efficiency loss due to unburned carbon (UBCL) versus steam flow. At full load the UBCL with reburn is the same as the UBCL with reburn out of service. The increase in UBCL at 75 percent load is 0.2% efficiency loss, and at 50 percent load the UBCL increase is 0.3% efficiency loss.

7.3.2.5.3 Unit Efficiency

Figure 7-64 shows efficiency versus steam flow for all of the W series tests. At full load, the efficiency of the unit is 0.2% lower with reburn in service. This is caused by an increase in the dry gas loss of 0.2%. At 75 percent load, unit efficiency decreases by 0.3% with reburn in service. Once again, the dry gas loss increased by 0.1% in addition to the 0.2% loss from unburned carbon. At 50 percent load, the unit efficiency decreases by 0.35%. There is a slight increase in dry gas loss.

The increase in dry gas loss with reburn in service is caused by a higher air heater gas outlet temperature. Figure 7-65 is a plot of corrected air heater gas outlet temperature versus steam flow for the W series tests. Figure 7-66 shows the economizer gas outlet temperature versus steam flow. Figure 7-67 shows the dry gas loss versus steam flow for the same tests. The increase in gas temperature with reburn in service is caused by a lower K_f for the economizer. The lower economizer K_f should not be attributed to the reburn system being in service. Since the majority of the reburn tests were normally run after a lengthy period of non-sootblowing operation (which attributed to the lower K_f's). Individual test results show that if sootblowing in the economizer region was performed, higher gas temperatures would not be observed and thus, no change in K_f valves. Therefore, the impact of the reburn system on unit efficiency is the increase in unburned carbon loss.

7.3.2.5.4 Furnace Exit Gas Temperature (FEGT)

Figure 7-68 is a plot of FEGT versus steam flow for the W series tests. At full load, the FEGT decreased by approximately 50°F with reburn in service. Once again, the gas recirculation flow with reburn in service would account for approximately 25°F of this change. There was no change in FEGT at 75% load with reburn in service, and an increase of 75°F at 50% load with reburn in service. Figure 7-69 shows the FEGT for the western coal tests compared to the baseline tests and the P and F series tests. This plot shows that the FEGT, at full load, for western fuel with reburn in service is the same as the FEGT for bituminous coal without reburn in service.

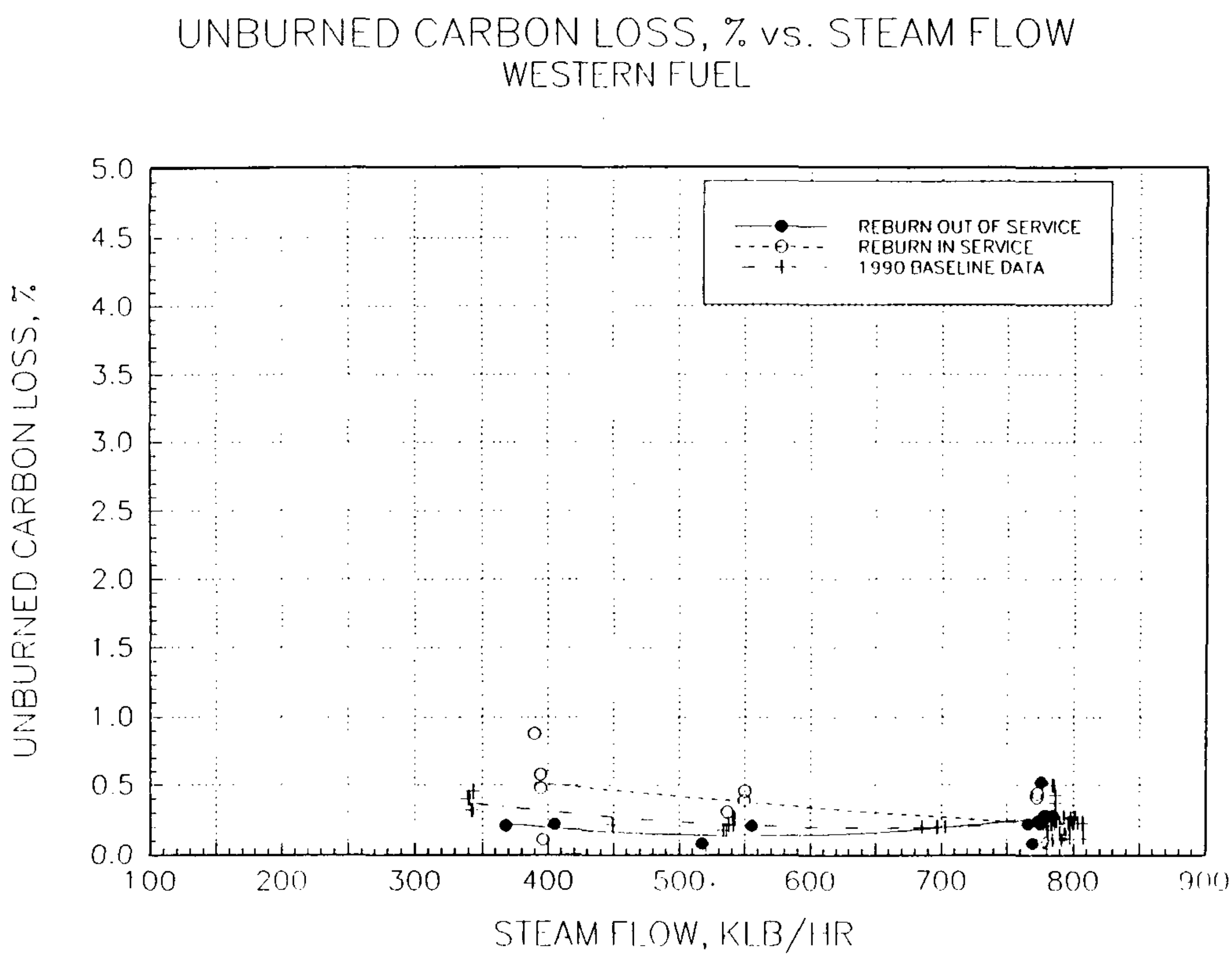

UNBURNED CARBON LOSS, % vs. STEAM FLOW
WESTERN FUEL
UNBURNED CARBON LOSS, %
STEAM FLOW, KLB/HR
REBURN OUT OF SERVICE
REBURN IN SERVICE
1990 BASELINE DATA
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
100
200
300
400
500
600
700
800
900

Figure 7-63

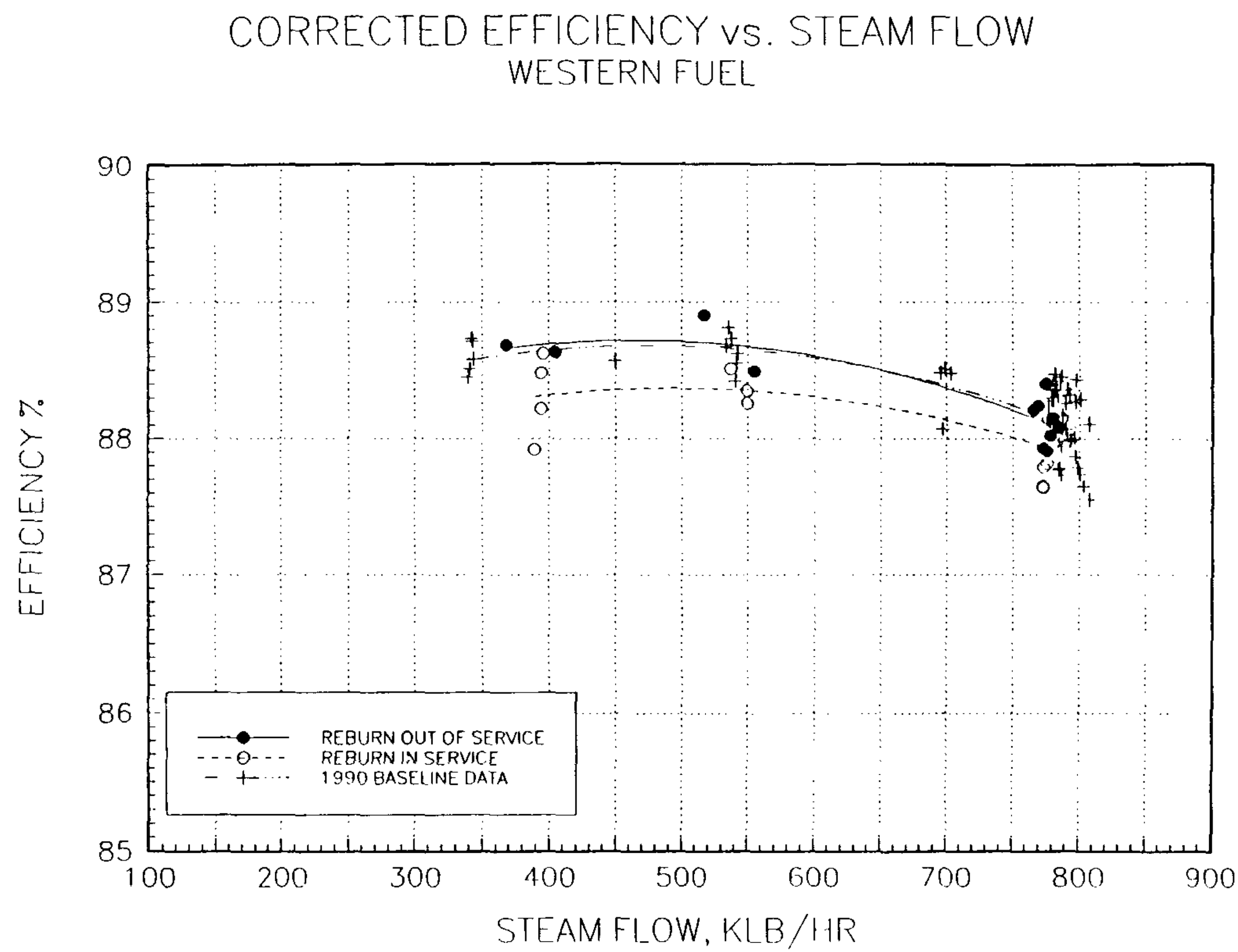

CORRECTED EFFICIENCY vs. STEAM FLOW
WESTERN FUEL
EFFICIENCY %
90
89
88
87
86
85
100
200
300
400
500
600
700
800
900
STEAM FLOW, KLB/HR
REBURN OUT OF SERVICE
REBURN IN SERVICE
1990 BASELINE DATA

Figure 7-64

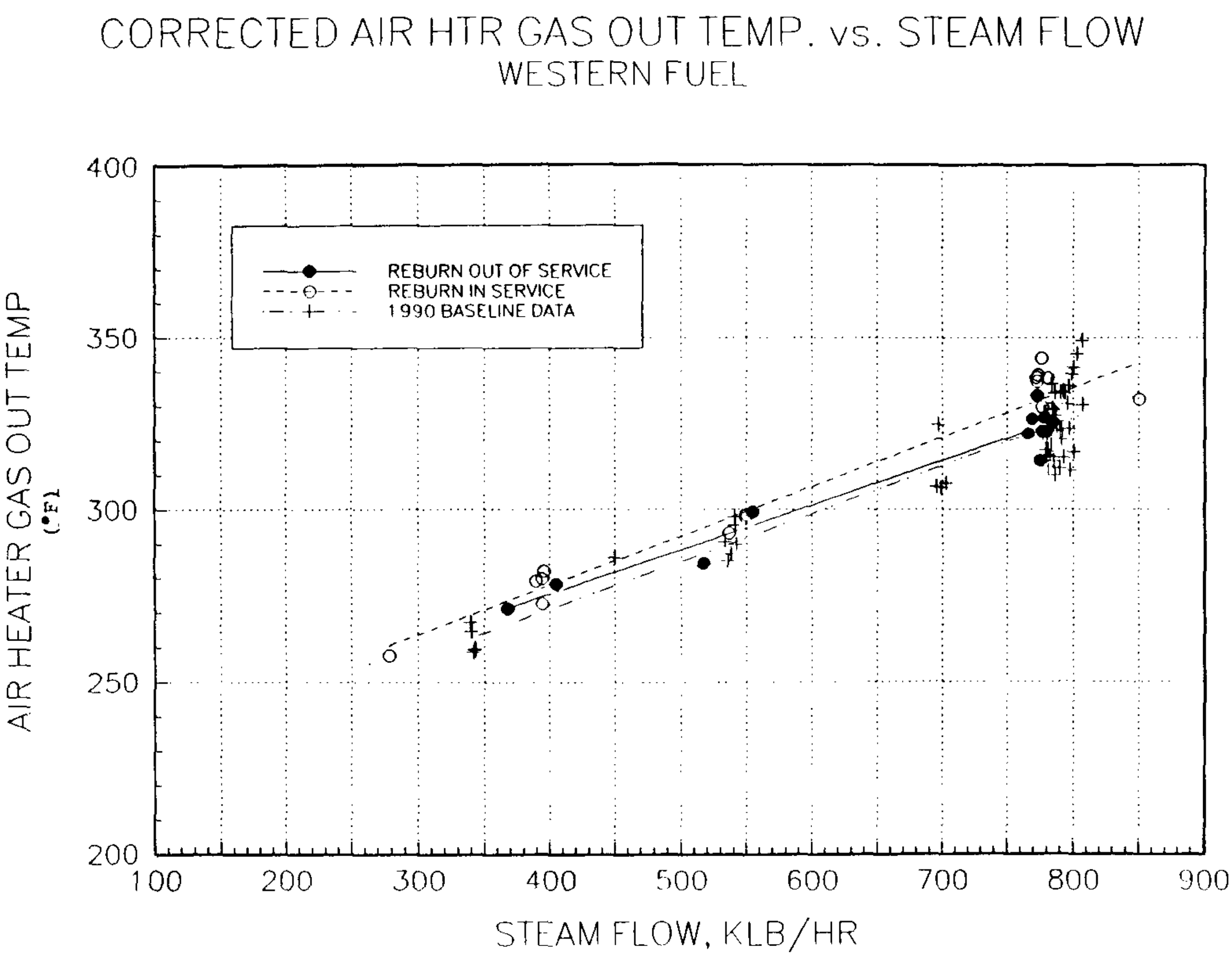
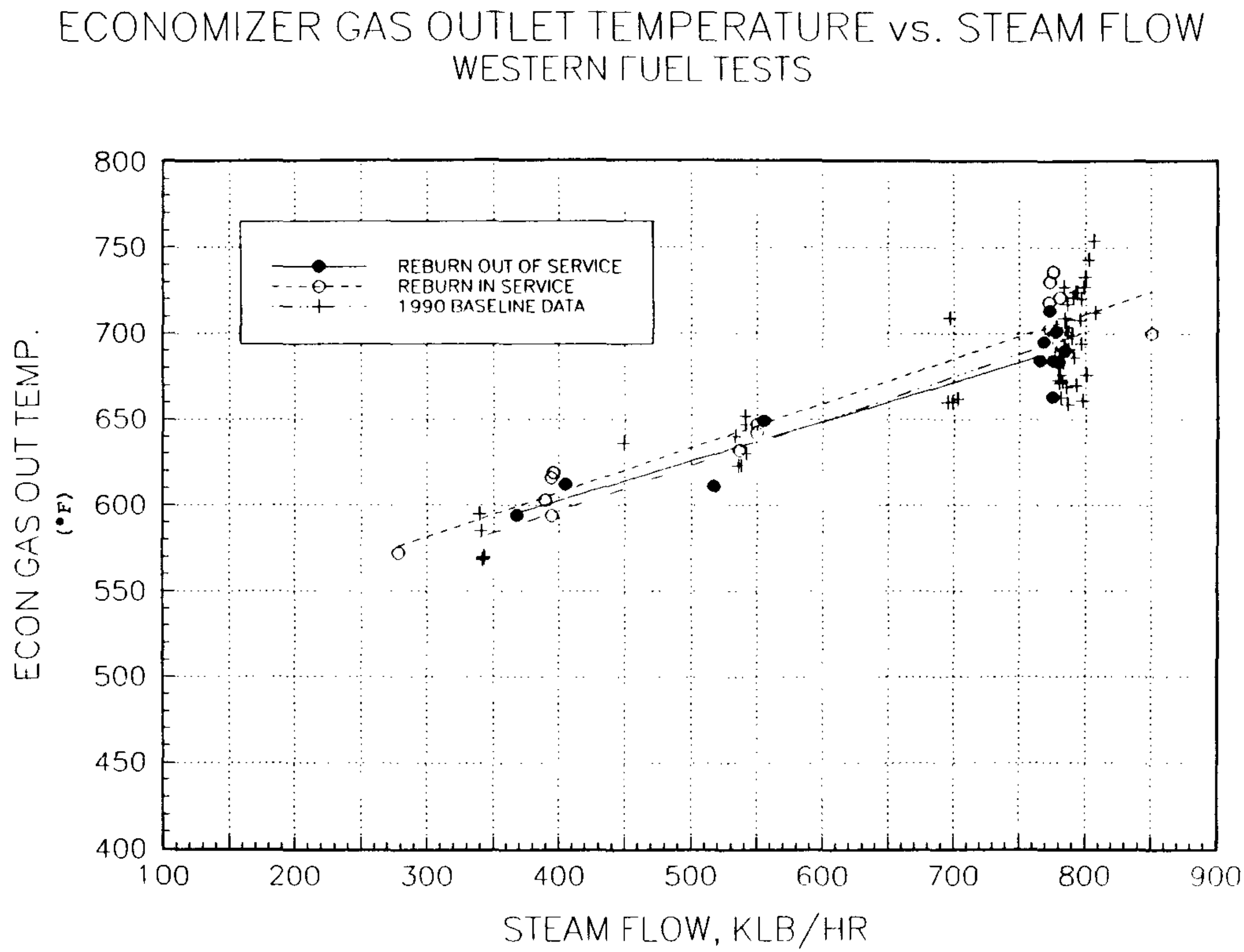

CORRECTED AIR HTR GAS OUT TEMP. vs. STEAM FLOW
WESTERN FUEL
REBURN OUT OF SERVICE
REBURN IN SERVICE
1990 BASELINE DATA
AIR HEATER GAS OUT TEMP (°F)
STEAM FLOW, KLB/HR
400
350
300
250
200
100
200
300
400
500
600
700
800
900

Figure 7-65



ECONOMIZER GAS OUTLET TEMPERATURE vs. STEAM FLOW
WESTERN FUEL TESTS
REBURN OUT OF SERVICE
REBURN IN SERVICE
1990 BASELINE DATA
ECON GAS OUT TEMP. (°F)
800
750
700
650
600
550
500
450
400
100
200
300
400
500
600
700
800
900
STEAM FLOW, KLB/HR

Figure 7-66

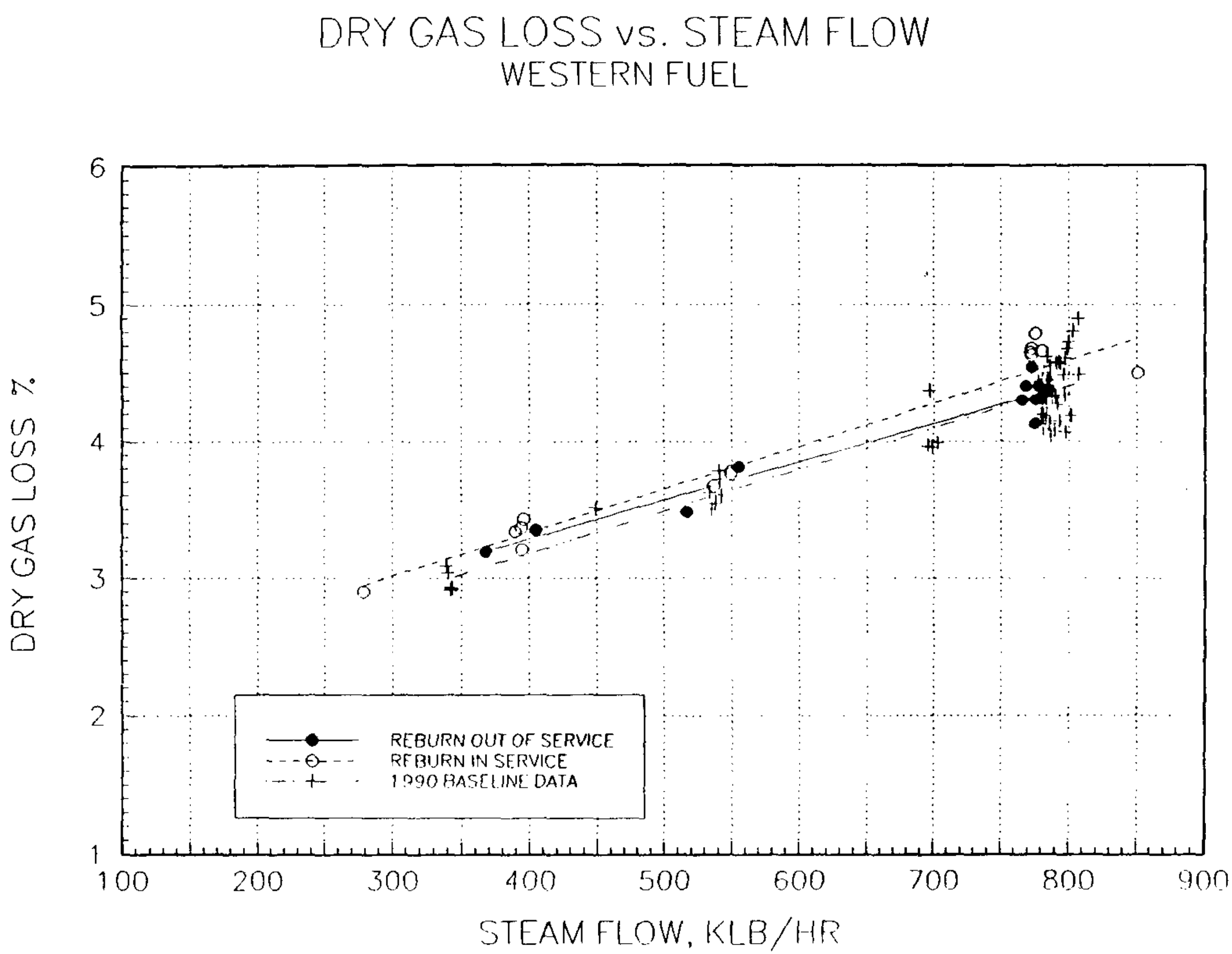

DRY GAS LOSS vs. STEAM FLOW
WESTERN FUEL
DRY GAS LOSS %
STEAM FLOW, KLB/HR
1
2
3
4
5
6
100
200
300
400
500
600
700
800
900
REBURN OUT OF SERVICE
REBURN IN SERVICE
1990 BASELINE DATA

Figure 7-67

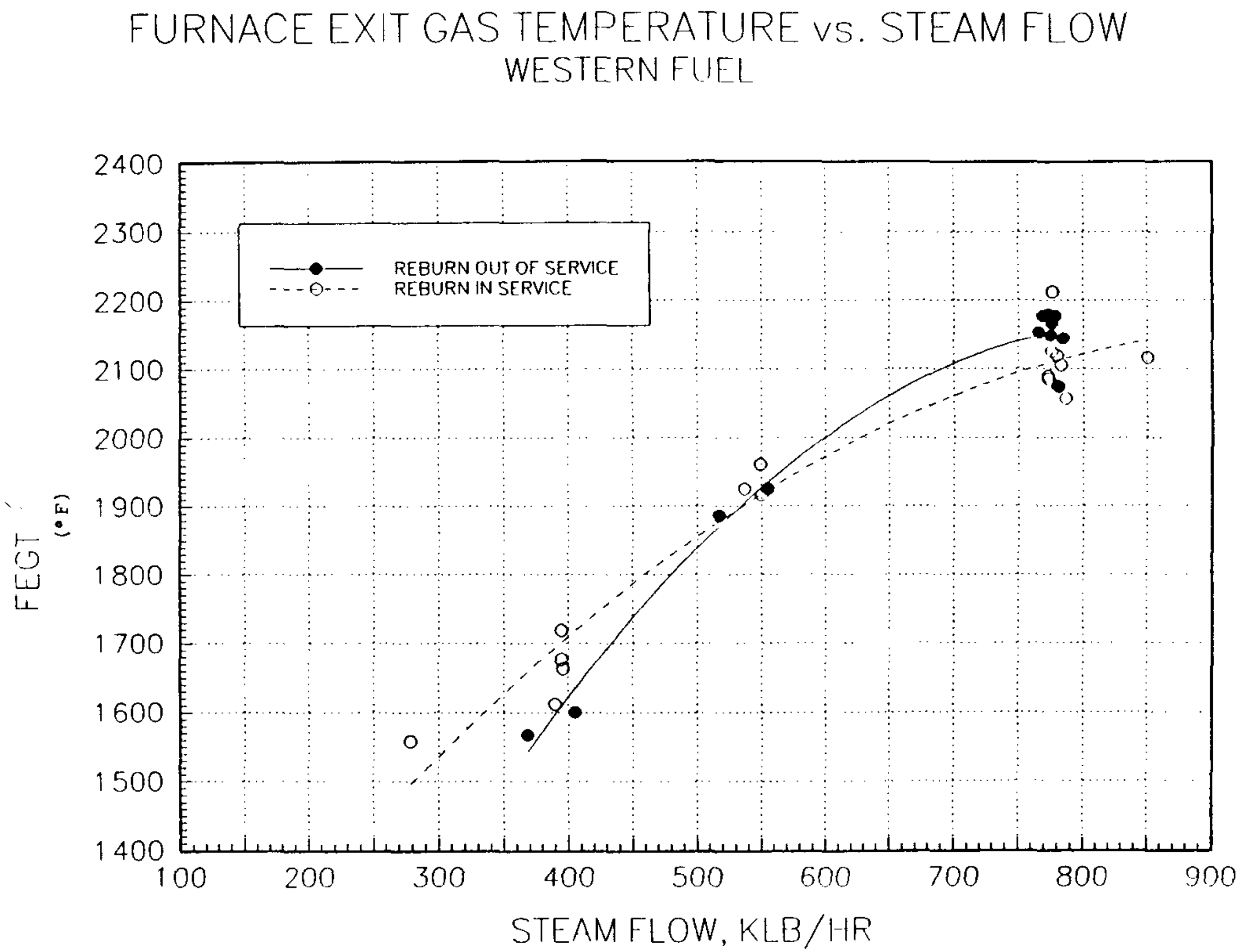

FURNACE EXIT GAS TEMPERATURE vs. STEAM FLOW
WESTERN FUEL
REBURN OUT OF SERVICE
REBURN IN SERVICE
FEGT (°F)
2400
2300
2200
2100
2000
1900
1800
1700
1600
1500
1400
100
200
300
400
500
600
700
800
900
STEAM FLOW, KLB/HR

Figure 7-68

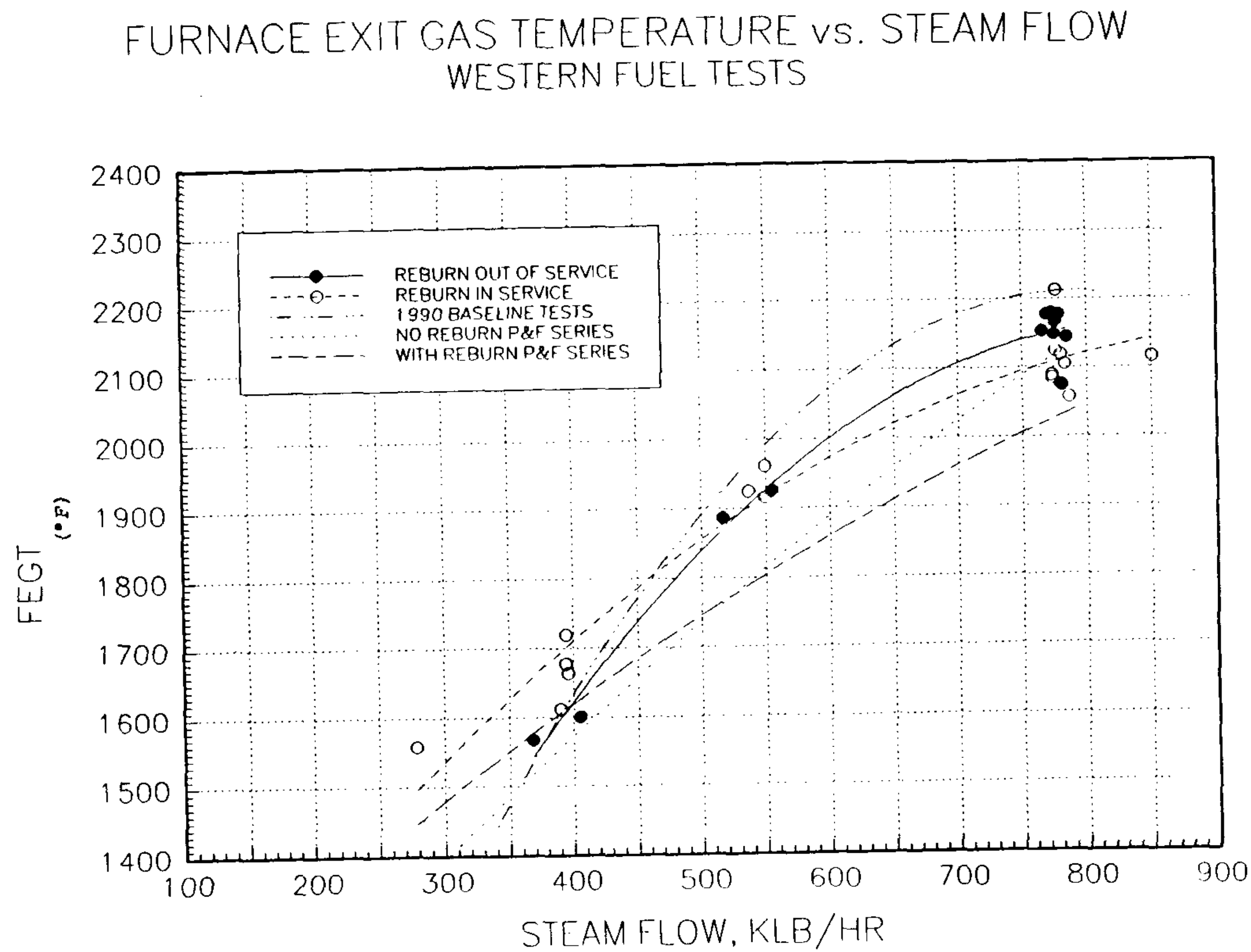

FURNACE EXIT GAS TEMPERATURE vs. STEAM FLOW
WESTERN FUEL TESTS
REBURN OUT OF SERVICE
REBURN IN SERVICE
1990 BASELINE TESTS
NO REBURN P&F SERIES
WITH REBURN P&F SERIES
FEGT (°F)
2400
2300
2200
2100
2000
1900
1800
1700
1600
1500
1400
100
200
300
400
500
600
700
800
900
STEAM FLOW, KLB/HR

Figure 7-69

7.3.2.5.5 Surface Cleanliness Factors (K_f's)

The component cleanliness factors (K_f's) varied significantly during testing as a result of variations in sootblowing throughout the test program. Table 7-9 shows the average, maximum, and minimum K_f's for all tests conducted at full load. Appendix 18 contains Figures 11 thru 15 which show the individual component K_f's for the W series tests.

TABLE 7-9
SUMMARY OF COMPONENT CLEANLINESS FACTORS FOR WESTERN FUEL

	SEC SH IN	SEC SH OUT	PRIMARY SH	REHEATER	ECON
NO REBURN					
AVG	0.97	1.00	0.94	1.15	0.78
MAX	1.10	1.08	1.01	1.35	0.90
MIN	0.87	0.90	0.91	0.99	0.72
WITH REBURN					
AVG	0.88	0.98	0.93	1.15	0.72
MAX	0.95	1.05	1.01	1.21	0.80
MIN	0.81	0.88	0.86	1.02	0.65

The secondary superheater inlet bank and the economizer had lower K_f's with reburn in service, while the other components showed very little change from the tests with no reburn. There is nothing unusual to indicate any detrimental impact on unit cleanliness from operation of the reburn system.

All component K_f's stabilized within 3 hours of sootblowing in that component. The decay rate was faster for all components than it was burning the Lamar coal, but the percent cleanliness reduction was about the same for the secondary inlet and outlet banks and the reheater. However, the primary superheater and economizer did not decay as much as they did during the Lamar coal tests. The cleanliness decay rates for each component are as follows:

- Sec. SH Inlet Bank - The cleanliness factor decreased by 22 % over a three hour period.
- Sec. SH Outlet Bank - The cleanliness factor decreased by 16 % over a three hour period.
- Reheater - The cleanliness factor decreased by 17 % over a three hour period.

- Primary Superheater - The cleanliness factor decreased by 13 % over a three hour period.
- Economizer - The cleanliness factor decreased by 7 % over a two hour period.

The change in FEGT is the primary indicator of furnace cleanliness. For the periods that data was recorded, the FEGT showed no trend either up or down. Sootblowing was usually conducted in the morning before raising load. By the time full load was reached and data was being collected, the FEGT had already stabilized.

7.3.2.5.6 Superheat and Final Reheat Steam Temperatures

Figure 7-70 shows final superheat steam temperatures for the W series tests. Figure 7-71 shows final reheat steam temperatures for the W series tests. Final superheat steam temperature was maintained at 1000°F down to 50 percent load. Final reheat steam temperature was maintained at 1000°F from full load down to 75% load, and was well above the design value of 950°F at 50% load. Four tests were conducted at full load with reburn in service and no gas recirculation. Because the FEGT only decreased 50°F with reburn in service, the unit was able to maintain final superheat and reheat temperatures without the use of gas recirculation. Figure 7-72 shows the percent of required total absorption versus steam flow. Figure 7-73 shows gas recirculation flow versus steam flow. The gas fan was operated to maintain lower furnace stoichiometries with the reburn system in service. As a result, the percent of required absorption is higher for all tests with reburn in service.

7.3.2.5.7 Superheat and Reheat Spray Flow Quantities

Figure 7-74 shows superheat spray flow quantities for the W series tests. Figure 7-75 shows reheat spray flow quantities for the W series tests. The spray flow quantities are very similar with and without reburn in service, and are significantly higher than the Lamar coal tests due to the higher FEGT.

7.3.2.6 Quality of Data

For all of the P and F series tests, a precision error was calculated for each data point. Appendix 19 contains listings of all of the data for each test, and a corresponding precision error. For all tests conducted, the precision error of the controllable critical parameters was within the guidelines set forth in the quality assurance procedures for this project. Items considered as non-controllable are air temperature and flue gas constituents. Non-controllable items also include those items which are allowed to change to maintain steady boiler conditions, such

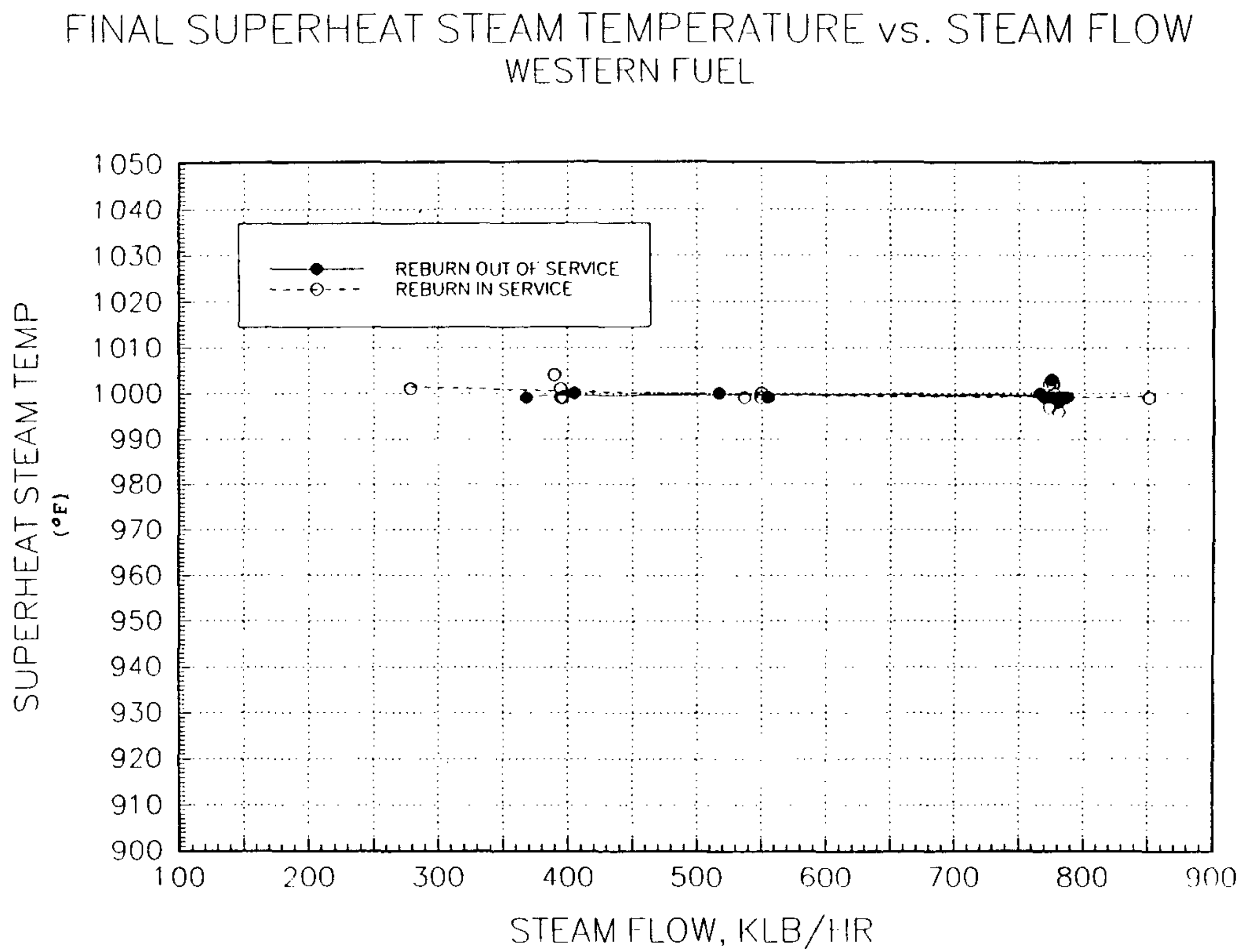

FINAL SUPERHEAT STEAM TEMPERATURE vs. STEAM FLOW
WESTERN FUEL
REBURN OUT OF SERVICE
REBURN IN SERVICE
SUPERHEAT STEAM TEMP (°F)
1050
1040
1030
1020
1010
1000
990
980
970
960
950
940
930
920
910
900
100
200
300
400
500
600
700
800
900
STEAM FLOW, KLB/HR

Figure 7-70

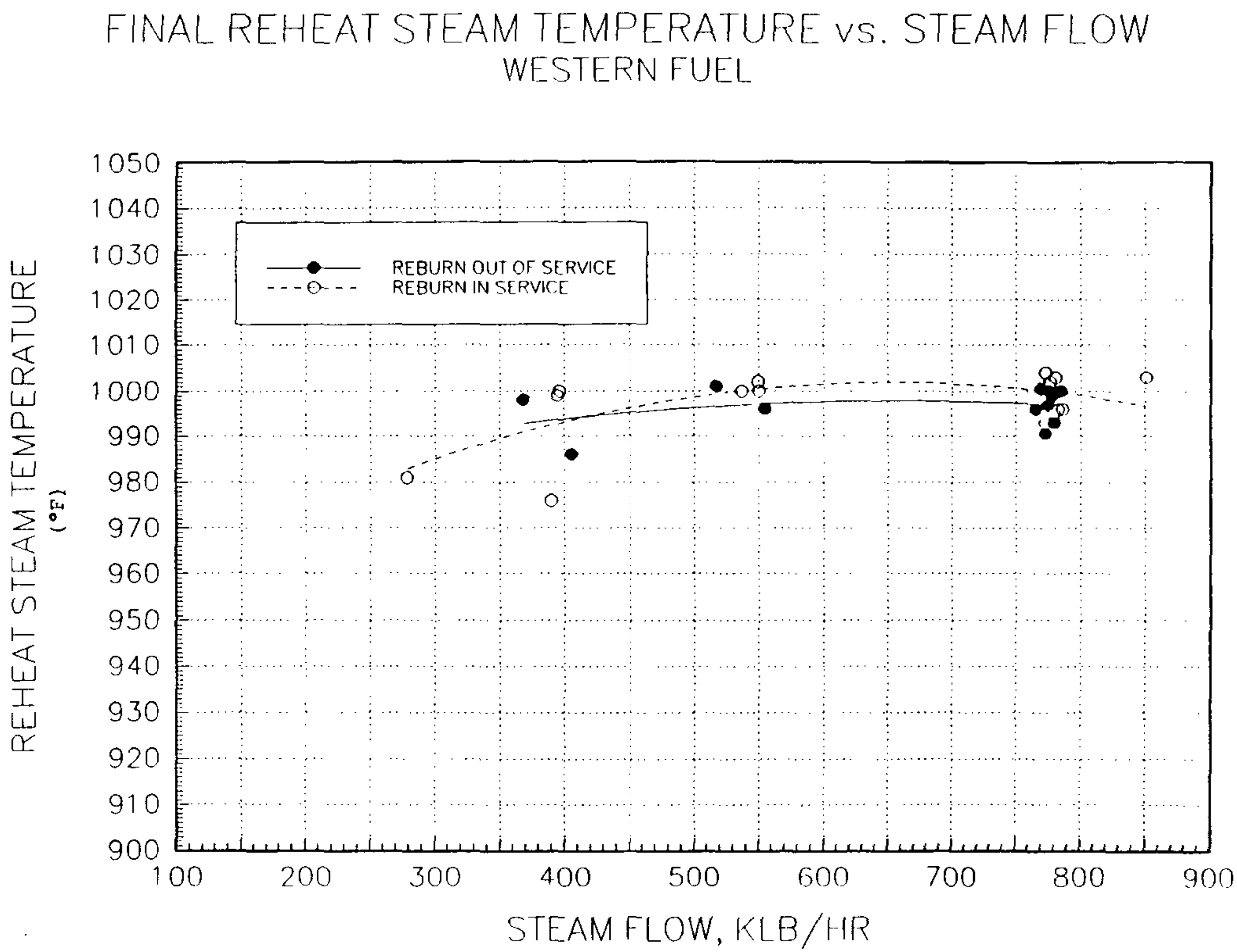

FINAL REHEAT STEAM TEMPERATURE vs. STEAM FLOW
WESTERN FUEL
REBURN OUT OF SERVICE
REBURN IN SERVICE
REHEAT STEAM TEMPERATURE (°F)
1050
1040
1030
1020
1010
1000
990
980
970
960
950
940
930
920
910
900
100
200
300
400
500
600
700
800
900
STEAM FLOW, KLB/HR

Figure 7-71

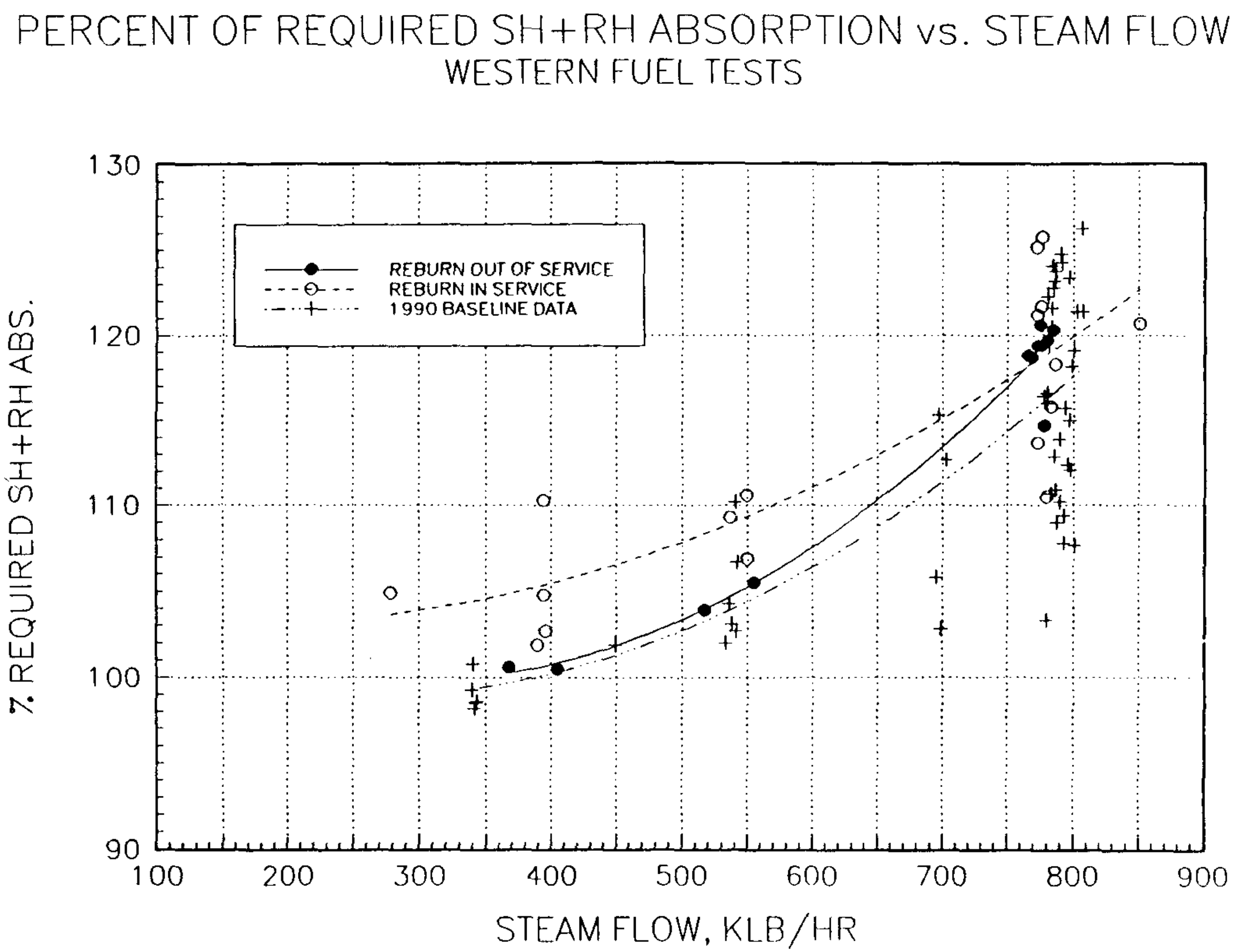

PERCENT OF REQUIRED SH+RH ABSORPTION vs. STEAM FLOW
WESTERN FUEL TESTS
REBURN OUT OF SERVICE
REBURN IN SERVICE
1990 BASELINE DATA
% REQUIRED SH+RH ABS.
130
120
110
100
90
100
200
300
400
500
600
700
800
900
STEAM FLOW, KLB/HR

Figure 7-72

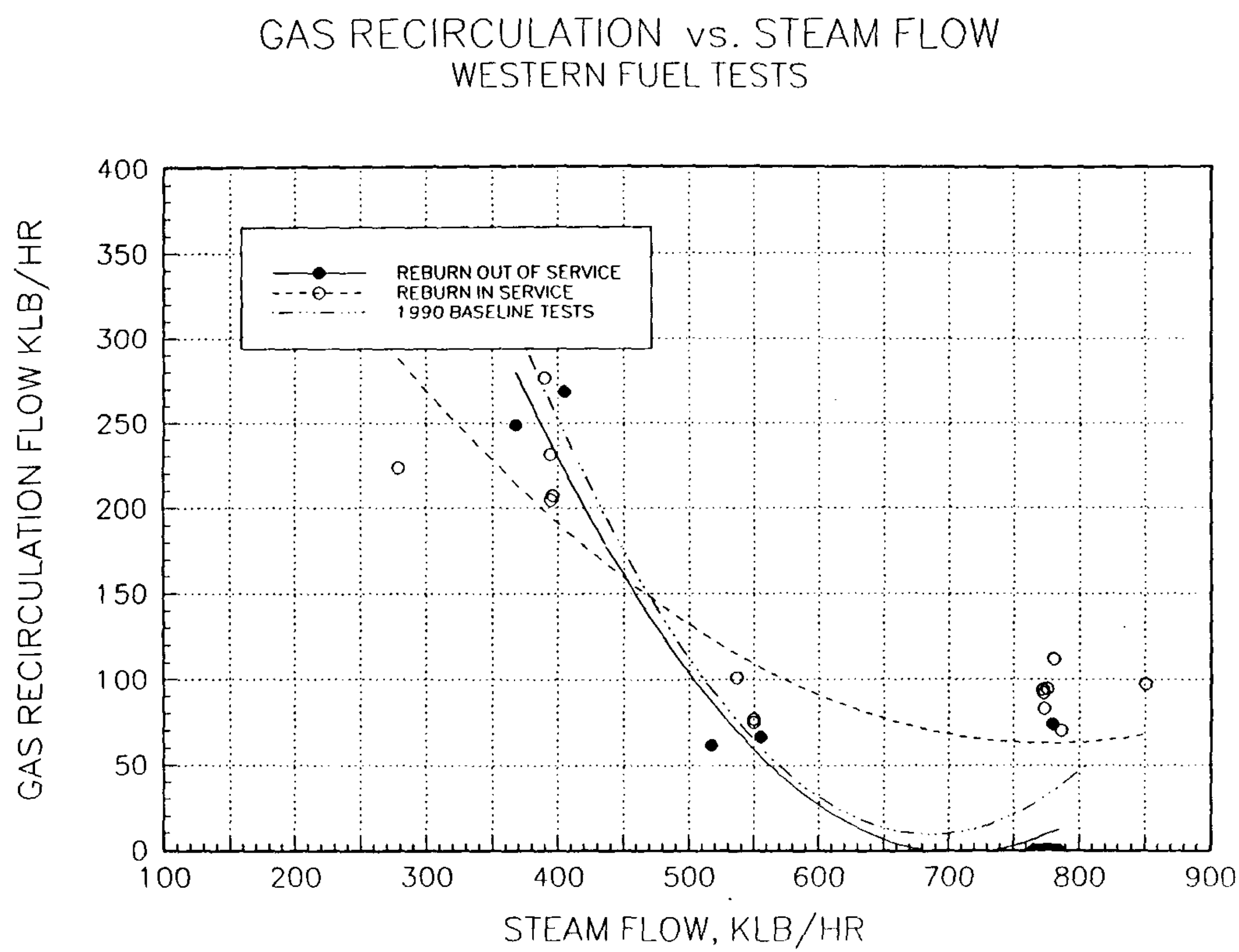

GAS RECIRCULATION vs. STEAM FLOW
WESTERN FUEL TESTS
REBURN OUT OF SERVICE
REBURN IN SERVICE
1990 BASELINE TESTS
GAS RECIRCULATION FLOW KLB/HR
STEAM FLOW, KLB/HR
0
50
100
150
200
250
300
350
400
100
200
300
400
500
600
700
800
900

Figure 7-73

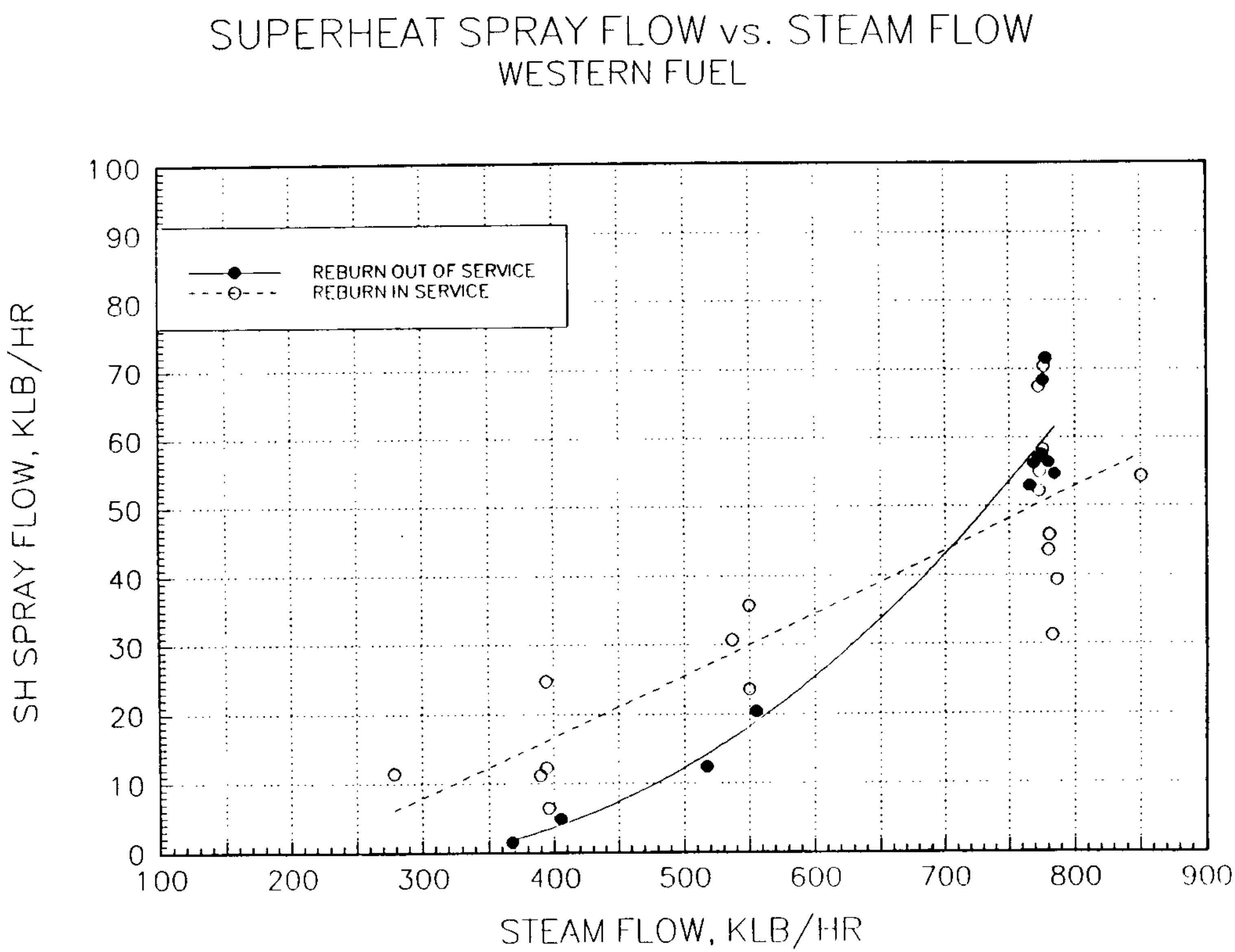

SUPERHEAT SPRAY FLOW vs. STEAM FLOW
WESTERN FUEL
REBURN OUT OF SERVICE
REBURN IN SERVICE
SH SPRAY FLOW, KLB/HR
STEAM FLOW, KLB/HR
100
90
80
70
60
50
40
30
20
10
0
100
200
300
400
500
600
700
800
900

Figure 7-74

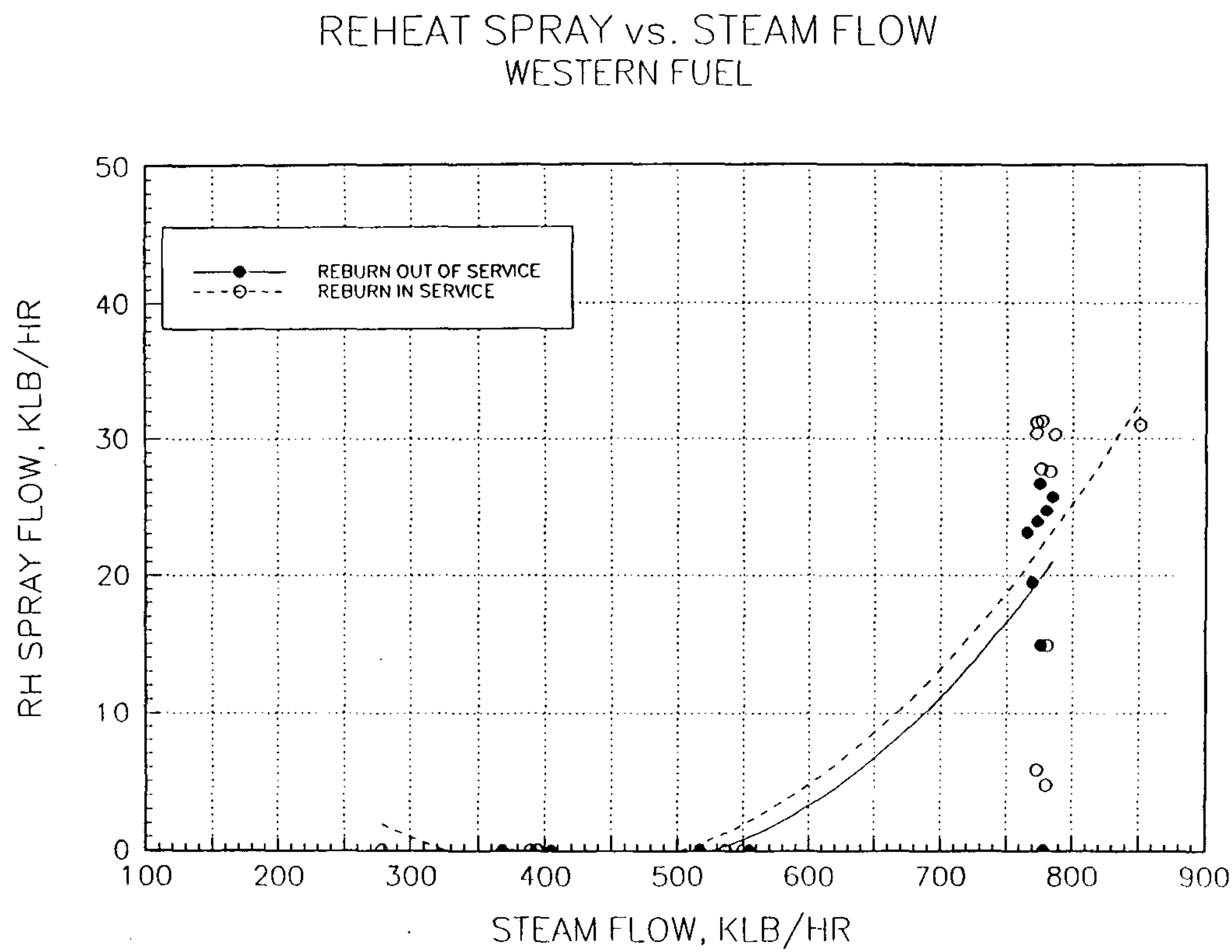

REHEAT SPRAY vs. STEAM FLOW
WESTERN FUEL
REBURN OUT OF SERVICE
REBURN IN SERVICE
RH SPRAY FLOW, KLB/HR
0
10
20
30
40
50
100
200
300
400
500
600
700
800
900
STEAM FLOW, KLB/HR

Figure 7-75

as reheat pass and primary superheater pass dampers, and superheat and reheat spray quantities.

7.3.3 Cyclone Reburning Western Fuel Firing Benefits

Since the reburn system removes approximately 30% of the heat input (coal flow) from the cyclones, higher boiler loads were maintained during 100% western fuel firing as compared to normal cyclone only (no reburning) operation. Typically, an approximate 10-25% derate is experienced when cyclone boilers fire 100% western fuel as compared to their normal design fuel. A major reason for this derate condition is that cyclone heat input and coal feed have to be increased with western fuel to maintain the same load carrying capability. This is due to the inherent higher moisture content and lower heating value of the western fuel. Maximum design heat input and coal flow loadings to the cyclones will limit boiler load. Thus, reburn operation minimizes or eliminates this derate impact when switching fuels by diverting a portion of the cyclone heat input and coal flow to the reburn system.

7.3.4 Environmental Monitoring

Compliance and supplemental monitoring of emissions was carried out during reburn testing as required by DOE. An Environmental Monitoring Plan was submitted along with environmental monitoring quarterly reports during testing Phase III. A final summary of performance and environmental test results as a function of boiler loads, reburn stoichiometries, etc. was also prepared. This report is included as Appendix 6 and it summarizes the following data:

- Continuous Emissions Monitoring data for O_2, CO_2, CO, NO_x and SO_2
- Particulate loading and particle sizing upstream and downstream of the ESP
- Trace metals emissions downstream of the ESP
- Unburned hydrocarbons and carbon in the fly ash
- Fly ash resistivity at the ESP inlet
- Fly ash leachable results

In general, the conclusions are that the reburn technology has no significant impact on:

- trace metals
- sulfates
- hydrocarbon emissions
- leachate toxicity
- fly ash resistivity

Reburn does significantly impact:

- NO_x emissions (reduced by at least 50% at full load)
- Particulate loading at the precipitator inlet increases

- Particle size of the fly ash increase
- Unburned carbon in the fly ash increases

Although more ash reaches the precipitator, that ash has a larger particle size and is easier to collect. With no change in fly ash resistivity, no significant increase in fly ash loading at the precipitator outlet was observed.

As outlined previously, fly ash generation increased from 10 to 14% above baseline condition depending on boiler load. Carbon content of the ash also increased to some extent. Accordingly, fly ash disposal facilities will experience an impact due to higher volumes of ash to be disposed. Changes in carbon content are insignificant from an environmental point of view. Also, fly ash leachate toxicity did not change for the metals tested, and all levels were well below RCRA toxicity characteristic leachate procedure (TCLP) threshold limits, indicating no need for concern.

7.3.5 Hazardous Air Pollutant Testing (HAP) Results

The United States Department of Energy is collaborating with the Electric Power Research Institute, the United States Environmental Protection Agency (EPA), and the Utility Air Regulatory Group (UARG) to develop a more complete data base for the emissions of hazardous air pollutants (air toxics or HAPs) from utility boilers. The Clean Air Act Amendments of 1990 identified 189 such substances, and charged the EPA with determining the need for emissions control regulations for each substance. The air toxics data base will be used by the EPA, in conjunction with the results of studies of the impacts of these emissions on public health, to promulgate air toxics emissions control regulations, as required. Development work on the data base is being supported by DOE's Pittsburgh Energy Technology Center, Office of Project Management, and by EPRI under its Power Plant Integrated Systems: Chemical Emissions Study (PISCES) project.

The DOE, in the development and commercialization of a wide variety of power plant-related technologies under its Innovative Clean Coal Technology Program, has determined that air toxics data for these projects is imperative to a complete evaluation. These projects are aimed at the environmentally-sound use of coal. As such, environmental monitoring is an important aspect of each project -- both to demonstrate compliance with project operating permits (compliance monitoring), and to facilitate assessment of the subject technology with respect to its potential environmental performance and impacts (supplemental monitoring). In keeping with this philosophy the DOE issued guidelines for extending the supplemental environmental monitoring being conducted under the various clean coal projects to include the monitoring of air toxics. This is to be accomplished through the development and implementation of a site-specific air toxics monitoring plan for each project.

Title III of the 1990 Clean Air Act Amendments listed 189 HAP compounds or substances of possible concern in air toxics control. These substances span the range of trace metals, other inorganics, organics, pesticides, and radionuclides. In utility boilers, only a fraction of the listed substances would be emitted in significant concentrations. Which substances are of most concern in utility boilers depends on fuel composition, boiler type, operating philosophy, and on the efficiency of emissions controls. In boilers, most of the inorganic compounds are directly related to mineral matter in the fuel. Organics formation is strongly affected by combustion conditions. Once formed, the partitioning of both inorganic and organic compounds among the possible gaseous and solid boiler effluent streams depends on the downstream boiler air pollution control equipment.

Studies by EPRI, DOE, and the EPA have identified the following classes of substances as high priority based on expected probability of occurrence and risk:

1. Trace metal emissions and particularly, the partitioning of metals into gaseous and solid streams.

2. Flue gas emission of semi-volatile organics, primarily polynuclear aromatics (PNA).

3. Flue gas emission of volatile organics, primarily benzene and toluene.

4. Flue gas emission of aldehydes.

5. Flue gas emission of total acid gases (chlorides and fluorides).

Hazardous Air Pollutant (HAP) testing was performed from November 2 through 9, 1992 at Nelson Dewey Unit No. 2 while operating on the Indiana Lamar bituminous coal. The test plan explored both baseline and reburn operation all at full load in triplicate (six tests, three baseline and three reburn). Acurex was the testing contractor during performance of the HAP tests.

The purpose of these tests was to obtain HAP emissions data for Nelson Dewey Unit No. 2 coal-fired cyclone boiler in the baseline, uncontrolled NO_x emission mode and in the coal-reburn low NO_x mode. The test matrix was developed to sample the following streams:

a_1. Crushed coal from the cyclone gravimetric feeders,
a_2. Reburn coal pulverizer outlet,
b. Furnace molten slag,
c. Flue gas sampling ports at the ESP inlet,
d. Flue gas sampling ports at the ESP outlet,
e. ESP hopper ash.

Table 7-10 shows the streams tested as well as the test analyses performed on each of the streams. Trace elements analyzed were arsenic, beryllium, cadmium, chromium, lead, nickel, manganese, selenium, and mercury. Volatile organics consisted of benzene and toluene. Acid gases were analyzed are hydrogen fluoride and hydrogen chloride.

Results of the testing indicated very low organics loadings in both the baseline and reburn operating modes for the cyclone fired boiler. No significant emission of semi-volatile target compounds were observed during baseline or reburn operation. Table 7.11 summarizes both volatile and semi-volatile organics results. The primary volatile target compounds detected were toluene and benzene. Traces of xylene appeared in several of the chromatograms. The detection limit for toluene and benzene was in the 0.2 ppb range, indicating the emission levels experienced were not greatly above the detection limit. Regarding aldehydes, none of the samples taken indicated any levels of aldehydes (formaldehyde and acetaldehyde) down to a detection limit of 5 ppb. The general observation from these data is that the cyclone appears to be an efficient combustor for volatile and semi-volatile organics and the reburn technology does not compromise this capability. These results as well as the metals partitioning results are discussed in detail in the HAP testing summary report prepared by Acurex, Appendix 20.

TABLE 7.10
TESTING PERFORMED AT EACH STREAM

Test Analysis Required	(a) Coal Feed	(b) Slag	(c) ESP Inlet	(d) ESP Outlet	(e) ESP Ash
HHV	✓				
Proximate	✓				
Ultimate	✓				
UBC					✓
Trace Element Total	✓	✓	✓	✓	✓
Particulate Loading			✓	✓	
Volatile Organics[1]				✓	
Semi-Vol. Organics[2]				✓	
Formaldehyde				✓	
Acid Gases				✓	

✓ = Required

1 Benzene/Toluene
2 Polycyclic organics especially benzo(a)pyrene

TABLE 7.11
ORGANICS RESULTS AT ESP OUTLET

Run	Volatiles		Semivolatiles
	Toluene ppb	Benzene ppb	PNA ppb
Baseline A	0.27	1.14	<1.18
Baseline B	0.37	1.00	<1.16
Baseline C	0.50	0.37	<1.22
Reburn A	0.51	0.26	<2.02
Reburn B	0.52	0.28	<1.61
Reburn C	0.30	0.22	<1.18

7.3.6 Long-Term Operational Summary

In order to fully assess the coal reburning technology and promote commercialization, long-term operation of the system is required. The long-term test phase was performed while firing the Lamar bituminous coal and it occurred between the "P" and "F" series. During this approximate four (4) month time period, WP&L operated Nelson Dewey Unit #2 per its normal load-following mode. The following section describes the comparison between the results from the "P" and "F" series with respect to boiler performance and emissions. In addition, since the Acurex CEM system was operational throughout this phase, averaged emissions data will also be identified. Finally, the corrosion evaluation will be reviewed based on the furnace tube ultrasonic thickness (UT) testing performed before and after the long-term testing.

7.3.6.1 Boiler Performance

Comparing the boiler performance data from the "P" and "F" series tests showed that long-term reburning operation did not have an effect on boiler operation. The critical factors reviewed to determine that no change was apparent include the following:

- Percent (%) Fly ash Loading
- Unburned Carbon (% UBC)
- Overall unit efficiency
- Furnace exit gas temperatures (FEGT)
- Boiler component cleanliness factors (Kf's)
- Ability to maintain final superheat and reheat temperatures
- Total boiler absorption profiles
- Superheat/Reheat spray flow quantities

Although only a four month long test period was available, it is believed that this duration is acceptable to evaluate the long-term coal reburning operational concerns with respect to the above stated issues. No significant changes were observed and thus continued long-term operation is expected to reflect the same positive indications. This will be verified periodically with Wisconsin Power & Light via their yearly heat rate determinations.

7.3.6.2 Emissions Summary

Series "P" and "F" were performed to officially test the optimized reburning operation at the start and finish of the long-term performance phase. As described earlier, Figure 7-17 displays the initial and final performance tests for load versus NO_x emission levels.

The data shows that the NO_x results between the two test series are fairly consistent, although the final series does reveal a slightly higher NO_x level at the 110 and 82 MW_e loads. Figure 7-18 showed the average % NO_x reductions. At 110, 82, and 60 MW_e's, the resultant % NO_x reductions for the initial performance tests are 54.7%, 49.2%, and 35.0% respectively. The final performance tests reveal that 50.6%, 46.3%, and 35.2% for the 110, 82, and 60 MW_e's respectively.

The only modification that is apparent between the two test series is the fact that a second burner modification had occurred to help burner stability. Unfortunately, the results reveal that a slight degradation in NO_x reduction efficiency became apparent with no corresponding improvement in burner stability. This modification #2 is described earlier in sections 7.2.2.4 and 7.2.2.6. Based upon the observed non-improvement, the burner modification #1 was re-installed.

In addition to the "P" and "F" series emission summary, the CEM system that Acurex maintained in operation can also be reviewed. The data collected with the CEM during long-term testing is presented in Table 7-12. The average overall load during the long-term test series was approximately 71 MW_e. During this period, the average for no reburning load conditions were 68MW_e. Reburning operation load conditions averaged 74 MW_e. The percent of time spent at the various load conditions is as follows: 19.9% of the time was at loads greater than 100 MW_e, 38.1% of the time was at loads between 80 and 100 MW_e, and 42.0% of the time was spent at 80 MW_e or less.

TABLE 7-12
LONG-TERM OPERATIONAL EMISSION SUMMARY

Condition	Avg Load (MW_e)	Avg NO_x (ppm)	Avg O_2 (%)	Avg CO (ppm)	Avg NO_x Per Test Series	% NO_x Red
Reburning - Operation > 100 MW_e	108.0	293	2.97	51	280	51.2
Reburning - Operation > 80 MW_e	97.9	296	3.08	43	270	49.0
Reburning - Operation @ All MW_e	74.1	309	3.57	53	285	40.0

Operating at loads greater than 100 MW_e during the long-term phase showed that the average reburning load was at 108.0 MW_e and the corresponding average NO_x emission was 293 ppm corrected to 3% O_2. The average baseline NO_x level observed during the numerous Lamar test series ("T", "A", "P", and "F") as shown in Figure 7-13 is 600 ppm corrected to 3%O_2.

Test data per this figure shows that the average expected reburning NO_x at the corresponding 108 MW_e load was 280 ppm @ 3% O_2. Thus, the comparisons between the long-term phase and the optimization/performance test series results is fairly consistent at loads greater than 100 MW_e. Using the original baseline NO_x emissions data from Figure 7-13 and the reburning results from the long-term operation, a % NO_x reduction of 51.2% results.

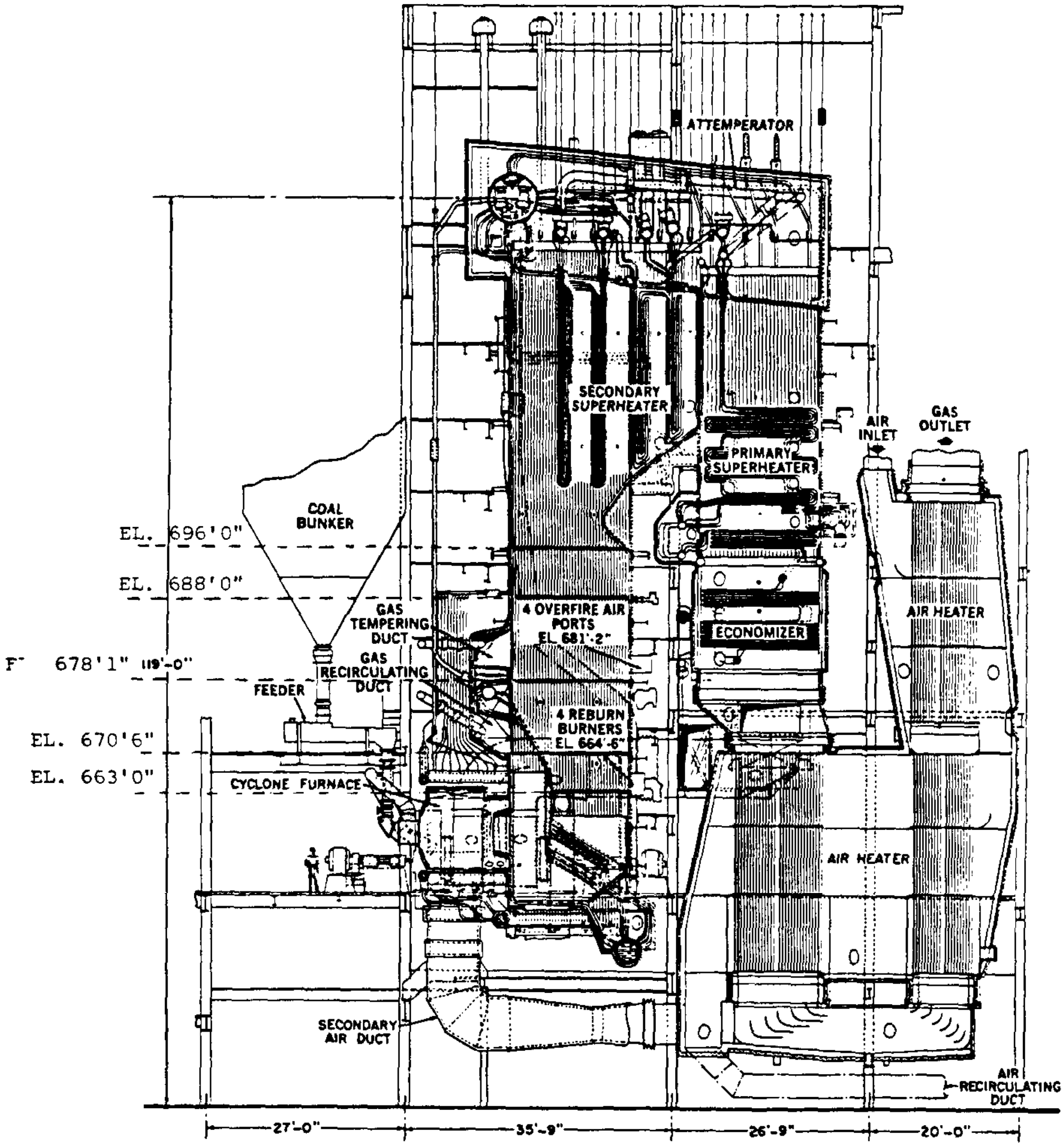
A summary of the same criteria at loads greater than 80 MW_e during the long-term testing is also shown in Table 7-12. The average load and NO_x emission levels during this case were 97.9 MW_e and 296 ppm @ 3% O_2 respectively. As observed with the greater than 100 MW_e case, the parametric/ optimization/performance testing reburn results at 98 MW_e is lower (290 ppm) than the long-term phase data. Utilizing the original baseline NO_x emissions data from Figure 7-13 (580 ppm) and the reburning data from the long-term operational phase gives a % NO_x reduction of 49.0%.

Finally, the last set of conditions which is reviewed contains all the data from the long-term test phase. During reburning operation, the average load and NO_x emission level during the four month long-term tests were 74 MW_e and 309 ppm respectively. The test results from the parametric/ optimization/performance series shown in Figure 7-13 reveal that at 74 MW_e the NO_x emission level is again lower than that observed during the long-term tests (285 ppm @ 3% O_2). The average baseline NO_x emission level obtained during the "T", "A", "P", and "F" series tests is 515 ppm @ 3% O_2. A 40% NO_x reduction is thus realized when comparing the long-term NO_x emission results to the baseline emission data.

Summarizing the above, the % NO_x reductions achieved during the long-term performance phase correlated well with the optimization and performance series test results. Although not exact, the data does fall into the range of data scatter observed throughout all of the testing series.

7.3.6.3 Corrosion Evaluation

At the inception of the coal reburning project, there was concern regarding the possibility of tube corrosion in the furnace area where sub-stoichiometric reburn conditions occur. Accordingly, ultrasonic tube thickness testing as a baseline was carried out in October of 1991 during the outage for reburn installation. Five (5) separate bands around the furnace were tested. These are at elevations 663'-0", 670'-6", 678'-1", 688'-0" and 696'-0" as shown in Figure 7-76. The cross sectional area of the boiler is shown in the figure with UT testing locations marked. The bands were sandblasted clean prior to UT testing.



Wisconsin Power & Light Company
Nelson Dewey Station - Unit No. 2 (RB-369)
Cassville, Wisconsin
Cyclone Reburn Project

Ultrasonic Thickness Testing Furnace Elevations

Figure 7-76

Based on the testing results, the furnace walls had not experienced wall thinning. Less than 1% of the inspected tubes fell below the specified original wall thickness. None of the tubes were below the Babcock & Wilcox wall thickness guidelines for required repair (70% of original specified thickness for water cooled tubes).

In October of 1992, one year after reburn installation at Nelson Dewey Unit No. 2, a similar series of UT testing was performed. Bands were sandblasted at the original locations and measurements were taken. Comparisons of the original 1991 data with 1992 data showed a series of inconsistencies, implying areas of both severe tube wall loss as well as wall thickening. The inconsistencies mandated another UT testing excursion to the plant which fortunately had a short outage in February, 1993. This time window allowed only enough time to retest the areas of the most questionable readings, the upper elevations on the left and right side walls.

Table 7-13 summarizes both the 1992 data, which is considered questionable and the February 1993 data for the upper three side wall elevations. As can be seen from the table, the 1992 data indicates an average loss of from 14 to 19 mils, which would be significant if the values are valid. However, the range of differences between baseline 1991 and 1992 data for these three side wall elevations is anywhere from a loss of 40 mils to a gain of 120 mils. These same data indicate a total of 49 tubes below specification thickness of 0.200 inches.

TABLE 7-13
ULTRASONIC THICKNESS TESTING RESULTS

Wall	Elevation	1992 (Questionable) Average Loss (mils)	1992 (Questionable) Range (mils)	1993 (Verification) Average Loss (mils)	1993 Tubes Below Spec Thickness*
Left	678'-1"	17	+95 to -30	3	0
	688'-0"	15	+40 to -30	3	0
	696'-0"	17	+10 to -35	5	0
Right	678'-1"	14	0 to -30	0	0
	688'-0"	14	+5 to -30	-3	0
	696'-0"	19	+120 to -40	4	0

* Tube Spec. (OD x thickness) = 2.969" x 0.200"

The 1993 verification data is also shown in Table 7-13 for the top three elevations of the side walls. The average differences were from a gain of 3 mils to a loss of 5 mils; within the error range of the UT instruments, indicating no significant corrosion has taken place. This data also showed that no tube thicknesses were below the specification thickness of .200 inches.

Additional rationale for questioning the validity of the 1992 data is:

1. The most severe problems highlighted by the 1992 data were in the upper regions of the furnace side walls, well above the overfire air port injection elevation of 681'2" in an oxidizing atmosphere. It would be expected that a corrosion problem with reburn would be manifested in the reburn region between the burners and overfire air ports (from elevation 664'6" to 681'2") and particularly at the rear wall which in closest to the reburn burner flames. There was no indication of problems in the rear wall at any elevation.

2. In order to simulate supercritical boiler operation with higher tube wall temperatures, a panel consisting of two thicker walled (0.420 in. minimum wall) tubes, each three feet in length was installed in the rear wall between the burner and overfire air elevations. One tube consisted of the normal steel tube material while the other was clad with approximately .060 inches of 304 stainless steel for corrosion protection. The 1992 UT test data indicated .075 inches wall loss for both tubes. To verify the measurements, the tube panel was removed during the February 1993 outage and submitted to B&W Alliance Research Center for analysis. The final report on these analyses is presented in Appendix 21. Wall thicknesses for both tubes are well above the 0.420 inches minimum wall thickness, indicating no corrosion wall thinning was apparent.

It is both WP&L's and B&W's intent to investigate furnace tube condition over the next five (5) years to assure that any corrosion problems are not left undetected. These UT investigations will be carried out on a yearly basis during a boiler outage of WP&L's choice.

8.0 Economic Assessment of Reburning Technology

An economic analysis was prepared in order to evaluate total capital and levelized revenue requirements for retrofitting and operating a reburning system to reduce nitrogen emissions using pulverized coal as the reburning fuel. Costs associated with this process include: preparation and handling of the coal reburning fuel, installation and operation of the reburning system, and any boiler impacts and countermeasures resulting in deviations in operating costs from baseline operation. This economic analysis evaluates cost practicality of the reburn technology on a commercial scale.

Although previous engineering studies have reported reburning economics, the specific commercial scale capital and operating requirements derived herein are from costs incurred during implementation of the cyclone coal reburning system at Wisconsin Power & Light's 110 MW_e Nelson Dewey Unit #2. Total capital and levelized revenue requirements are then estimated for a hypothetical application of coal reburning technology to a larger 605 MW_e commercial plant. Design considerations developed for the 110 MW_e retrofit were used to design a reburn system for a 605 MW_e unit. The key component was maintaining system capability to operate at 30% reburn heat input at full load to reflect conditions for 50% NO_x reduction observed at Nelson Dewey. This evaluation reveals the economy of scale apparent when reviewing the coal reburn technology at various boiler sizes. Appendix 22 contains additional detail to supplement the following discussion.

8.1 Economic Methodology and Assumptions

8.1.1 Methodology

The EPRI Economic Premises for Electric Power Generating Plants was used for all cost analyses. The cost analyses are based on implementation of reburning technology on a commercial scale with pulverized coal as the reburning fuel. Numerous assumptions are made within the context of this economic evaluation. The following details each of the assumptions made throughout the economic evaluation.

8.1.2 Assumptions

A. Fuel Storage - The reburning fuel for this cost analysis is assumed to be pulverized coal that is obtained from the same source as that fired in the cyclones. Therefore, no additional costs for fuel transportation or main outside storage facilities are included.

B. Combustion System Process Capital - In order to apply the reburning technology to cyclone equipped units, the following major equipment additions or plant modifications are required and are included within the process capital portion of this cost estimate:

- Pulverizer & pulverizer auxiliaries
- Reburn coal feeder
- Modification of existing coal handling/new coal silo
- Demolition & rerouting of existing plant piping
- Reburn burners & lighters
- Overfire air ports
- Additional dampers & drives
- Instrumentation & controls
- Addition of tube wall panel openings
- Additional air measuring equipment
- Flues/ducts/expansion joints
- MCC/transformers/wiring
- Pulverizer building enclosure & foundation
- Additional platforms & support steel
- Reburn coal piping
- Insulation/lagging

C. **Process Capital Cost Estimates** - The process capital cost estimates for the reburning equipment listed above include all general facility, home office, and engineering fees. The cost of installing a reburn control system is included in this analysis. It is assumed that a proposed site would already include a distributed control system (DCS) into which the reburn controls would be integrated. The cost of control modifications required by a reburn system is very site specific, depending on the state of the existing controls.

D. **Project Contingency** - Class 4 of the available EPRI project contingencies was chosen due to the finalized nature of the design of the reburn system. Based upon the #4 classification, a five percent contingency factor was selected for this cost estimate.

E. **Process Contingency** - The state of the coal reburning technology for a cyclone fired unit similar in size to Nelson Dewey Unit #2 is considered commercially available. Therefore, it was assumed that there is no process contingency costs per this economic evaluation.

F. **Sales Tax** - A 6.5 percent sales tax on all manufactured goods is included in this analysis.

G. **Operating & Maintenance Cost** - No additional labor is required for operation or maintenance of a coal reburning system based upon the retrofit experience at WP&L's Nelson Dewey Unit #2, thus no costs are included in this study under this category.

H. **Annual Maintenance Cost** - An annual maintenance factor of 2.0 was selected from a (1.5-3.0) range under the steam/ electrical systems category of the EPRI Economical Premises.

I. Power Consumption - Retrofitting the coal reburn system includes the addition of numerous components that require additional power consumption above that normally utilized. The major equipment included in this category is as follows: 1. Pulverizer motor, 2. Pulverizer auxiliary equipment motors, 3. Primary air fan motor, and 4. Seal air fan motor. In addition, the added gas recirculation flow required for the reburn system increased the power consumption associated with the GR fans and this was included. Finally, since the plant FD fan power was reduced during reburn operation, a decreased power factor was used to account for this improvement.

J. Fuel Consumption - Total fuel to the boiler when maintaining a specific load is slightly different during no reburning (baseline) versus reburning conditions. Using the results from the boiler performance efficiency calculations, additional fuel consumption during reburning operation is required. Based upon an approximate 0.2% efficiency loss at 82 MW_e, the cost of the additional coal required to maintain steam flow was added into the operating costs calculations.

K. Levelization Factors - The following levelization factors and carrying charges are used for all levelized cost estimates.

	Levelization Factors	
	30 Year	**10 Year**
Carrying Charges	0.165	0.1380
Fuel Charges	1.920	1.380
O & M Charges	1.750	1.320

8.2 Economic Analysis of the Nelson Dewey Retrofit

Table 8-1 summarizes the cost estimates based on the total project scope of retrofitting cyclone coal reburn at Nelson Dewey Unit 2. The estimate is not based upon the complete actual costs associated with the DOE Clean Coal project, but instead filters out the costs that are included due to the nature of a demonstration program. Thus, Table 8-1 is a true indication of what a commercial cost would be for the Nelson Dewey Unit #2 coal reburn retrofit. Based upon using the EPRI Economic Premises, the estimated Total Capital Requirement (TCR) for retrofitting a coal reburn system on a nominal 110 MW_e cyclone-equipped boiler is 66.5 $/kW.

TABLE 8-1

BABCOCK & WILCOX ECONOMIC EVALUATION
OF EQUIPMENT RETROFITS TO UTILITY STEAM GENERATORS

Based on EPRI Economic Premises for Electric Power Generating Plants

CUSTOMER : WISCONSIN POWER & LIGHT
STATION : NELSON DEWEY - UNIT 2
UNIT NO. : RB-369

PROJECT : CYCLONE COAL REBURN TECHNOLOGY - SITE SPECIFIC ANALYSIS

CAPITAL INVESTMENT

Process Capital		60.88 $/kW
Project Contingency		3.04 $/kW
Process Contingency		0.00 $/kW
Sales Tax		1.12 $/kW
Total Plant Cost		**65.04 $/kW**
Preproduction Costs :		
	One Month FOM	15,827 $
	One Month VOM	7,034 $
	2% of TPC	133,930 $
	Total	156,792 $
Total Preproduction Costs		1.43 $/kW
Total Capital Requirements		**66.46 $/kW**

OPERATING & MAINTENANCE (O&M) COSTS (1st Year)

Operating Costs	0.72 $/kW-Yr
Maintenance Labor	0.49 $/kW-Yr
Maintenance Materials	0.73 $/kW-Yr
Administrative & Support Labor	0.36 $/kW-Yr
Total O&M	**2.30 $/kW-Yr**
Fixed O&M	1.73 $/kW-Yr
Variable O&M	0.09 mills/kWh

LEVELIZED O&M COSTS :

	10 - Year	30 - Year
Levelized Fixed O&M	2.28 $/kW-Yr	3.02 $/kW-Yr
Levelized Variable O&M	0.12 mills/kWh	0.15 mills/kWh
Levelized Carrying Charges	12.76 $/kW-Yr	10.97 $/kW-Yr
Levelized Busbar Cost of Power @ Levelized Capacity Factor (CF)	**2.40** mills/kWh	**2.28** mills/kWh

* - Assumes actual retrofit construction of less than 1 year

In addition, levelized Busbar Power costs for 10 and 30 year periods are 2.40 mills/kWh and 2.28 mills/kWh, respectively. The 10 and 30 year time periods were chosen to bracket the anticipated life expectancies of the cyclone boiler population.

8.3 Economic Analysis of Hypothetical Plant

An economic analysis of a hypothetical coal reburning application for a commercial 605 MW_e cyclone fired unit was prepared for evaluation purposes on a larger scale. Assuming a 50% NO_x reduction requirement, the reburn system was designed using an operating 30% reburn heat input. Based upon this % heat input, all the coal handling and flues/ductwork sizes were developed for costing purposes. Table 8-2 summarizes the estimated costs with this retrofit and similar to the above 110 MW_e Nelson Dewey coal reburn retrofit, the values associated with this estimate are considered commercial. The Total Capital Requirement (TCR) for retrofitting a coal reburn system on a nominal 605 MW_e cyclone-equipped boiler is 43.1 $/kW. The capital cost requirement on a $/kW basis is substantially less for the larger facility as compared to the 110 MW_e case and this shows the economy of scale factor associated with the reburn technology.

In addition, levelized Busbar Power costs for 10 and 30 year periods are 1.61 mills/kWh and 1.55 mills/kWh respectively. The levelized costs for the 605 MW_e versus 110 MW_e cases also reflect the improved costs for the larger unit retrofit.

8.4 Site Specific Factors

Numerous site specific factors can greatly impact the cost of retrofitting a PC cyclone reburn system to an existing unit. The most significant of these factors include the state of the existing controls, availability of flue gas recirculation, availability of space to locate pulverizer(s)/reburn burners/OFA ports within existing structures, and the scope of coal handling equipment modifications/additions required to supply the reburn system with fuel. Additional site specific factors include sootblowing capacity/coverage, boiler tube corrosion potential, back-end boiler clean-up equipment capacity, boiler circulation, and steam temperature capabilities.

Low NO_x reburn technology control requirements dictate that a digital control system (DCS) should be available to effectively operate both the existing boiler and reburn systems. The reburn technology involves accurate and responsive control of air and fuel flow rates to various regions of the furnace. Updating existing controls will be a site specific factor depending upon the state of the utilities control system but, based upon the typical age of cyclone units, a controls improvement will most likely be necessary.

Gas recirculation to the reburn burners is required to consistently maintain greater than 50% NO_x reduction and thus the existing boiler GR fans will need to be reviewed. Numerous cyclone utilities have

TABLE 8-2

BABCOCK & WILCOX ECONOMIC EVALUATION
OF EQUIPMENT RETROFITS TO UTILITY STEAM GENERATORS

Based on EPRI Economic Premises for Electric Power Generating Plants

CUSTOMER : HYPOTHETICAL 605 MW CYCLONE EQUIPPED POWER PLANT

PROJECT : CYCLONE COAL REBURN TECHNOLOGY

CAPITAL INVESTMENT

Process Capital	39.08	$/kW
Project Contingency	1.95	$/kW
Process Contingency	0.00	$/kW
Sales Tax	1.10	$/kW
Total Plant Cost	**42.14**	$/kW
Preproduction Costs :		
One Month FOM	66,604	$
One Month VOM	29,602	$
2% of TPC	472,832	$
Total	569,037	$
Total Preproduction Costs	0.94	$/kW
Total Capital Requirements	**43.08**	$/kW

OPERATING & MAINTENANCE (O&M) COSTS (1st Year)

Operating Costs	0.68	$/kW-Yr
Maintenance Labor	0.31	$/kW-Yr
Maintenance Materials	0.47	$/kW-Yr
Administrative & Support Labor	0.30	$/kW-Yr
Total O&M	**1.76**	$/kW-Yr
Fixed O&M	1.32	$/kW-Yr
Variable O&M	0.07	mills/kWh

LEVELIZED O&M COSTS :

	10 - Year		30 - Year	
Levelized Fixed O&M	1.74	$/kW-Yr	2.31	$/kW-Yr
Levelized Variable O&M	0.09	mills/kWh	0.12	mills/kWh
Levelized Carrying Charges	8.27	$/kW-Yr	7.11	$/kW-Yr
Levelized Busbar Cost of Power @ Levelized Capacity Factor (CF)	**1.61**	mills/kWh	**1.55**	mills/kWh

* - Assumes actual retrofit construction of less than 1 year

removed their GR fans and this could potentially require that new fans be included into the cost estimates.

Space availability is a site specific variable which cannot be fully determined prior to a unit site visit. A large capital cost discrepancy could be observed depending upon the difficulty of locating the pulverizer(s) and the reburn burners/OFA ports for each specific coal reburn application.

The coal handling system would include an additional coal bunker and associated support steel along with modifications to the existing conveyor system or potentially tieing into an existing coal bunker arrangement. Site specific issues identifying the most economical arrangement will affect the final cost analysis.

8.5 NO_x Removed Economics

Table 8-3 is a summary of economic information for both the 110 MW_e case (including two different coal types) and the 605 MW_e case for 10 and 30 year levelized cost scenarios. This table presents annualized costs per ton NO_x removed. Identification numbers 1 and 1A show the WP&L 110 MW_e case while firing the demonstration Lamar bituminous coal. Case numbers 2 and 2A reveal the same conditions except while firing the western subbituminous fuel. Finally, identification numbers 3 and 3A show the economic review for the larger 605 MW_e hypothetical unit while firing a standard cyclone bituminous fuel.

Numerous operating data are identified in Table 8-3. Typical operating boiler capability factors were utilized to evaluate the \$/ton NO_x removed (75% and 70% for the WP&L Dewey Station and larger utility station unit respectively). Thus, the resultant baseline and reburning NO_x emission levels at the normalized load (based upon the capacity factor) were used to determine the yearly NO_x removed. In addition, a 90% reburn capacity level was included to reflect the high availability of the reburn system. The goal of this table is to show the comparison between various boiler sizes, fuel switching, and levelized time durations with respect to a \$/ton of NO_x removed.

The major difference between the WP&L Lamar versus western coal analysis is the lower initial primary NO_x level of the western fuel. This results in a slightly higher actual \$/ton removed value for the western coal. Thus, although the % NO_x reduction is greater for the western coal reburn operation, the overall yearly tons removed is slightly less than that achieved during the Lamar coal testing.

Finally, the economy of scale factor is observed when comparing the smaller 110 MW_e versus the larger 605 MW_e cases. A substantial reduction in \$/ton NO_x removed is realized when reviewing the 605 MW_e unit (greater than 50% lower costs).

TABLE 8-3. NOx REMOVAL ECONOMIC SUMMARY *

IDENTIFICATION CUSTOMER		(1) WP&L	(1A) WP&L	(2) WP&L	(2A) WP&L	(3) UTILITY	(3A) UTILITY
Levelized Duration	Years	10 yr	30 yr	10 yr	30 yr	10 yr	30 yr
Load Gross	MW	110	110	110	110	605	605
Auxiliary Power	%	5	5	5	5	10	10
Load Net	MW	104.5	104.5	104.5	104.5	544.5	544.5
Fuel HHV	Btu/lb	11,200	11,200	9,200	9,200	10,700	10,700
Fuel Flow	Klbs/hr	93.3	93.3	113.6	113.6	548.6	548.6
Boiler Capacity Factor (CF)	%	0.75	0.75	0.75	0.75	0.7	0.7
Adj. Fuel Input per CF	MBtu/hr	783.8	783.8	783.8	783.8	4,109.0	4,109.0
Base Boiler Efficiency	%	88.7	88.7	88.6	88.6	89.1	89.1
Adj. Fuel Output	MBtu/hr	695.2	695.2	694.4	694.4	3,661.1	3,661.1
Pre Retrofit Conditions							
NOx Emissions	lbs/MBtu	0.72	0.72	0.64	0.64	1.20	1.20
Unburned Carbon in Ash	%	10.0	10.0	5.0	5.0	8.0	8.0
Unburned Carbon Loss	% heat loss	0.23	0.23	0.12	0.12	0.52	0.52
Post Retrofit Conditions							
NOx Emissions	lbs/MBtu	0.37	0.37	0.29	0.29	0.57	0.57
Unburned Carbon in Ash	%	14.3	14.3	8.6	8.6	10.0	10.0
Unburned Carbon Loss	% heat loss	0.48	0.48	0.32	0.32	0.99	0.99
Reburn Capacity Factor	%	0.90	0.90	0.90	0.90	0.90	0.90
Results							
Percent NOx Reduction	%	49.17	49.17	54.90	54.90	52.50	52.50
Boiler Efficiency	%	88.45	88.45	88.41	88.41	88.63	88.63
Actual NOx Removed	tons/yr	1,090.5	1,090.5	1,088.6	1,088.6	10,155.2	10,155.2
Retrofit Cost	$1000's	7,300	7,300	7,300	7,300	25,800	25,800
Retrofit Cost	$/gross Kw	66	66	66	66	43	43
Capital Recovery Factor	10/30 yrs	0.1606	0.1034	0.1606	0.1034	0.1606	0.1034
Levelized Cost $/year	$1000's	1,172	755	1,172	755	4,143	2,668
Annualized $/ton Removed		1,075	692	1,077	693	408	263

* – BASED UPON USING THE EPRI ECONOMIC EVAULATION TO DETERMINE THE CAPITAL COSTS

1 – WP&L NELSON DEWEY, LAMAR COAL 10-YR LEVELIZATION
1A – WP&L NELSON DEWEY, LAMAR COAL 30-YR LEVELIZATION
2 – WP&L NELSON DEWEY, WESTERN COAL 10-YR LEVELIZATION
2A – WP&L NELSON DEWEY, WESTERN COAL 30-YR LEVELIZATION
3 – LARGE UTILITY FORCED CICULATION BOILER, BITUMINOUS COAL 10-YR LEVELIZATION
3A – LARGE UTILITY FORCED CICULATION BOILER, BITUMINOUS COAL 30-YR LEVELIZATION

9.0 Mathematical Flow and Combustion Modeling

9.1 Introduction

The objective is to demonstrate and validate mathematical flow and combustion models as a tool for evaluating the performance of coal reburning in cyclone boilers. These models are needed as a reliable and cost effective method for analyzing the performance of existing reburning units and for evaluating future commercial reburning installations.

Babcock & Wilcox's furnace models FORCE and FURMO were used to predict the combustion and heat transfer performance of the WP&L boiler. FORCE is a general purpose code for three dimensional turbulent flow. The computation of the flow field was described in Section 5.0. FURMO interacts with FORCE to predict steady-state three-dimensional combustion and heat transfer in the furnace.

9.2 Methodology

To utilize the FORCE and FURMO programs, the furnace volume is subdivided into subvolumes called control volumes. The furnace geometry and computational grid used in the numerical combustion and heat transfer modeling is shown in Figure 9-1. The grid lines of the computational grid used in FURMO coincide with grid lines used in the FORCE computational grid. However due to the greater computational requirements of FURMO, fewer control volumes are used in FURMO than in FORCE. The furnace is modeled from the cyclone re-entrant throat to the boiler screen tubes. The computational grid is finer in the reburning zone where high gradients of density and species concentration exist. Slag screens and pendent superheaters are modeled as porous media with convective surface heat transfer and modified radiation absorption and scattering properties. The target wall and furnace enclosure are modeled with convective surface heat transfer and constant emissivity. The net heat absorbed through the furnace walls, slag screens and pendent superheaters can be adjusted by modifying the overall thermal boundary condition to allow for uncertainties in the thickness and thermal conductivity of furnace slag or tube bank fouling.

Furnace heat transfer performance data from Baseline Test 9 were used to adjust the thermal boundary conditions for heat transfer surfaces to compensate for uncertainty in furnace slagging and fouling conditions. The heat transfer and gas temperature predictions from FURMO were compared to measurements and field data from Baseline Test 9. The thermal conductance was modified for the various heat transfer surfaces until a reasonable match to field data was achieved. The heat transfer boundary conditions were then assumed to remain constant for the post-retrofit models. The operating conditions for the combustion and heat transfer modeling

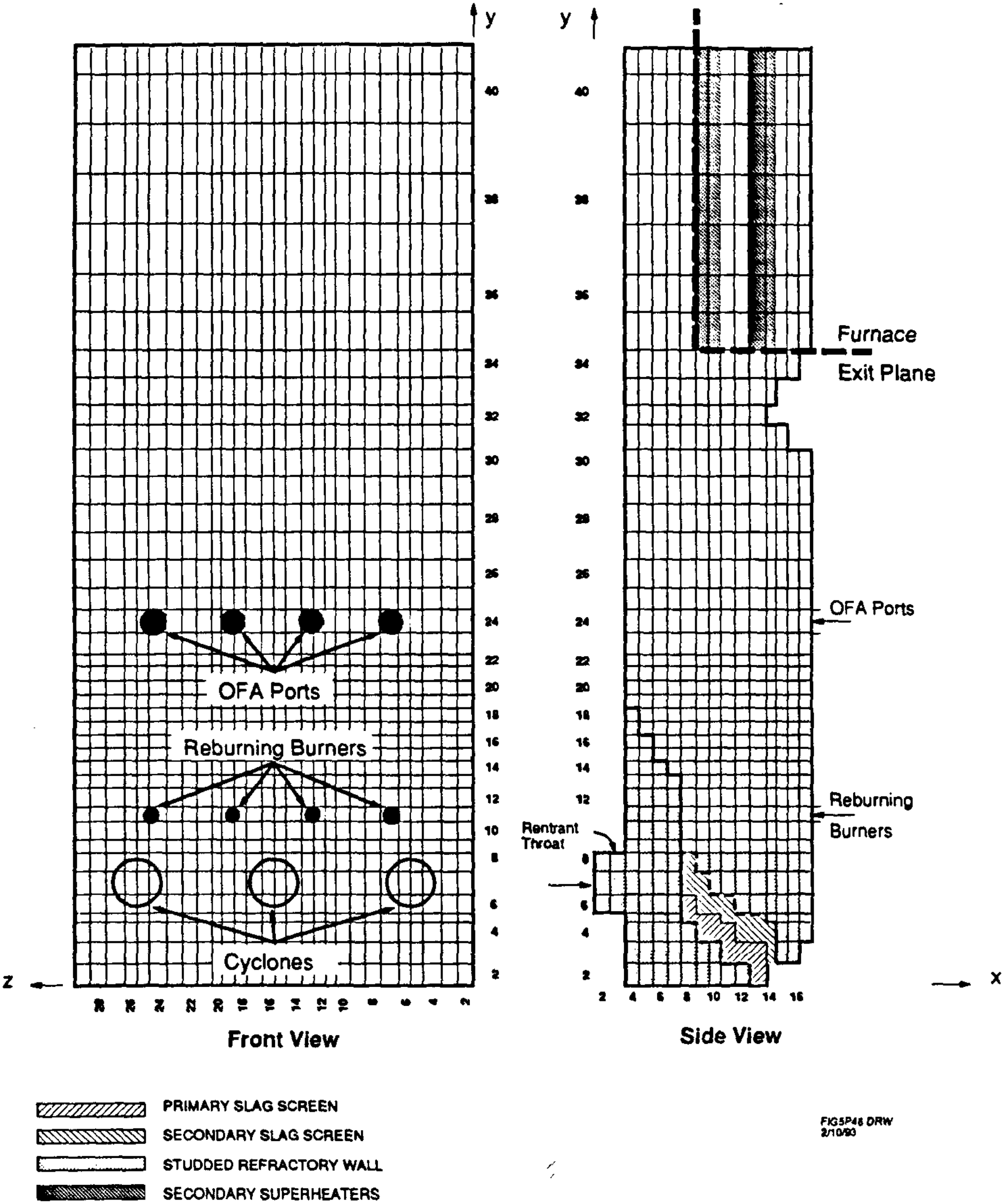


Figure 9-1 Numerical Combustion Model for Reburning Configuration

are summarized in Table 9-1 and described in more detail in Table 9-2. Both conditions modeled were at the maximum unit capacity of 110 MW_e. The modeling of reburning test 8P will be discussed in detail and compared to the baseline case.

TABLE 9-1
MODELED OPERATING CONDITIONS

Case No.	Operating Condition	Comments
Baseline	17% Excess Air, NO FGR, Reburning zone Stoichiometry 1.14	No reburning, cooling air to reburning burners and OFA ports.
Reburning with FGR	14.4% Excess Air, FGR, Reburning Zone Stoichiometry 0.85	Optimum reburning conditions, with FGR

TABLE 9.2
COAL REBURNING, WISCONSIN POWER & LIGHT MODELED OPERATING CONDITIONS

	Baseline	Reburning with FGR
Total Coal Flow (lbm/hr)	92,460	92,460
Total Air Flow (lbm/hr)	915,403	895,062
Total Furnace Flow (lbm/hr)	1,007,863	1,086,672
Cyclone Coal Flow (lbm/hr)	92,460	64,320
Primary Air Flow (lbm/hr)	82,633	56,927
Primary Air Temperature (F)	533	533
Secondary Air Flow (lbm/hr)	743,698	512,345
Secondary Air Temperature (F)	533	533
Flue Gas Recirculation Flow (lbm/hr)	0	88,100
Flue Gas Port Air Flow (lbm/hr)	35,000	0
Flue Gas Recirculation Temperature (F)	N/A	629

TABLE 9.2 (Continued)
COAL REBURNING, WISCONSIN POWER & LIGHT MODELED OPERATING CONDITIONS

	Baseline	Reburning with FGR
Reburning Burner Coal Flow (lbm/hr)	0	28,140
Reburning Burner Primary Air Flow (lbm/hr)	0	59,900
Reburning Burner Primary Air Temperature (F)	164	164
Reburning Burner Secondary Air Flow (lbm/hr)	27,071	29,990
Reburning Burner Secondary Air Temperature (F)	526	526
Flue Gas Recirculation	0	11,050
Overfire Air Flow (lbm/hr) (.56 Primary, .44 Secondary)	27,000	235,900
Overfire Air Temperature (F)	518	518
Reburning Burners	Off	On
Cyclone Stoichiometry	1.06	1.05
Reburning Burner Stoichiometry	N/A	0.41
Reburning Zone Stoichiometry	1.14	0.85
Furnace Stoichiometry	1.17	1.15

Reburning is modeled as a full load (110 MW_e) operating condition with low reburning zone stoichiometry (0.85) to give the optimum reduction in NO_x emission. The coal flow is split 70% to the cyclones and 30% to the reburning burners. The air flow is divided with 64% to the cyclones, 10% to the reburning burners and 26% to the overfire air ports. In addition, 9% total to the flue gas is recirculated with 8% to the existing gas recirculation ports and 1% to the reburning burners. The cyclone stoichiometry is 1.05, the reburning burner stoichiometry is 0.41, the reburning zone stoichiometry is 0.85, and the overall furnace stoichiometry is 1.15.

9.3 Results and Discussion

Flow/Mixing

The predicted flow patterns for the WP&L boiler for one of the reburn conditions modeled is shown in Figure 9-2. Shown are sectional side views through a vertical plane of the furnace including the left side cyclone, reburning burner and OFA port. The direction of flow is indicated by the arrows, with arrow length being proportional to the magnitude of velocity. The dominant flow pattern in the baseline case, as discussed in Section 5.2 Baseline Flow Patterns, is characterized by a strong column of gas travelling upward from the slag screens along the rear wall, turning past the arch and leaving the furnace along the arch. There is a recirculation region along the front wall above the target wall. The velocity is very non-uniform, with much of the flow bypassing the first bank of the secondary superheater at the furnace exit. In the reburning case of Figure 9-2, the reburning burner and the OFA port jets disrupt and redistribute the column of gas travelling upward from the slag screens, resulting in a more uniform flow in the upper furnace. The recirculation zone that existed on the front wall, and the strong flow up the rear wall in the baseline case are no longer present. The change in the flow patterns with reburning has a significant effect on heat transfer and gas temperature in the upper furnace.

Heat Transfer

The combustion and heat transfer predictions are summarized in Table 9-3. The heat release predictions are shown in Figure 9-3. This figure shows cumulative heat release versus elevation. The effect of reburning heat release is clearly shown at furnace elevations between 666 ft. and 681 ft. For the baseline case (no reburning) 86% of the heat is released in the cyclones. The remainder of the heat is released in the lower furnace and combustion completed near the reburning burner elevation (664 ft.). For the case with optimum reburning zone stoichiometry and FGR (70% coal to the cyclones) 59% of the heat is released in the cyclones. The combustion continues up to the reburning burner elevation where it is limited by low oxygen concentration. The combustion resumes when more air is added to the furnace at the OFA ports (681 ft). Comparing the two curves shows that the combustion process is delayed with reburning, resulting in a larger percent of the heat release at higher furnace elevations. The combustion is not complete until past the furnace arch elevation (700 ft), with 20% of the heat release occurring above the OFA ports.

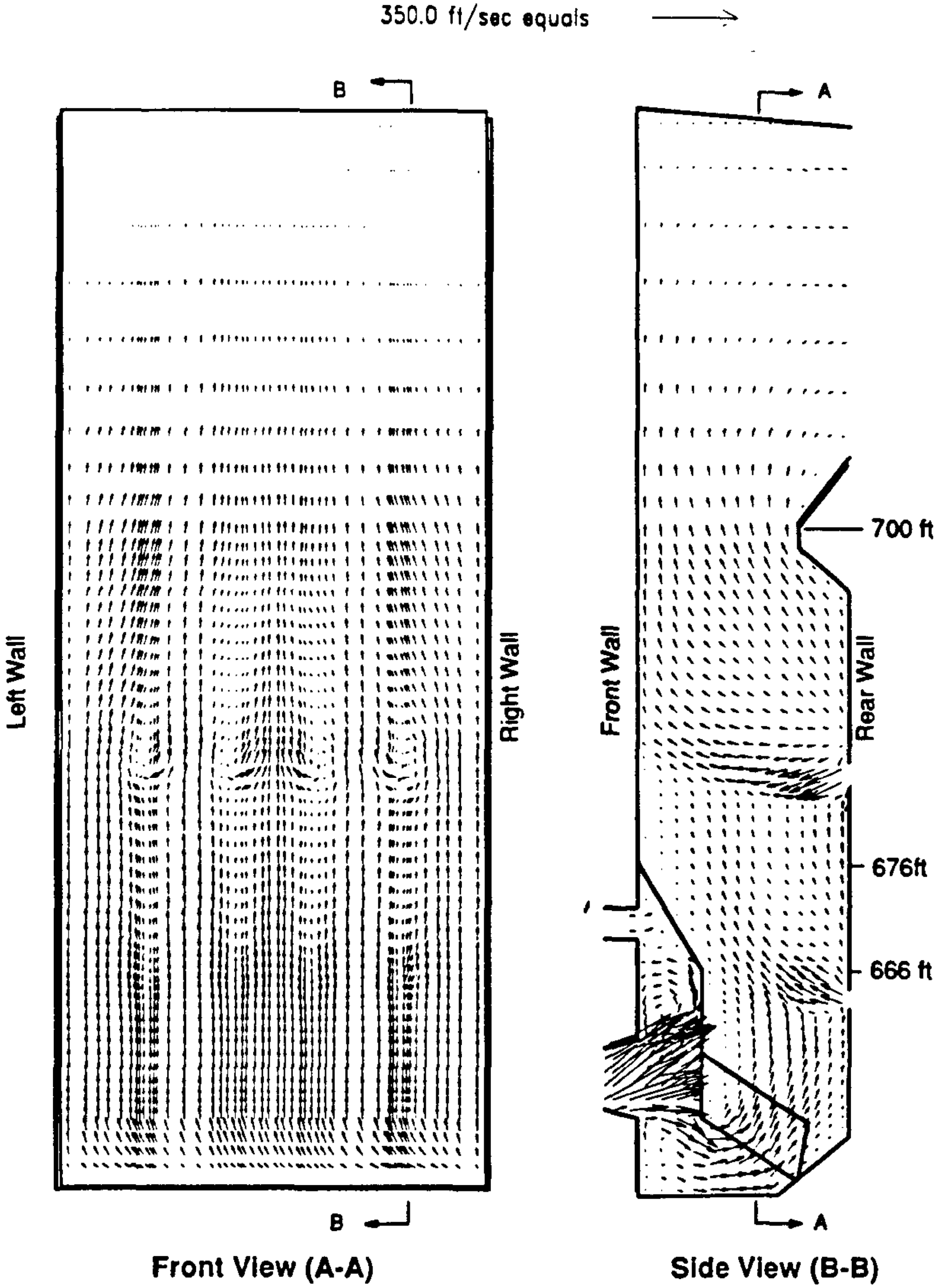


Figure 9-2 Predicted Flow Patterns for Reburning Test 8P

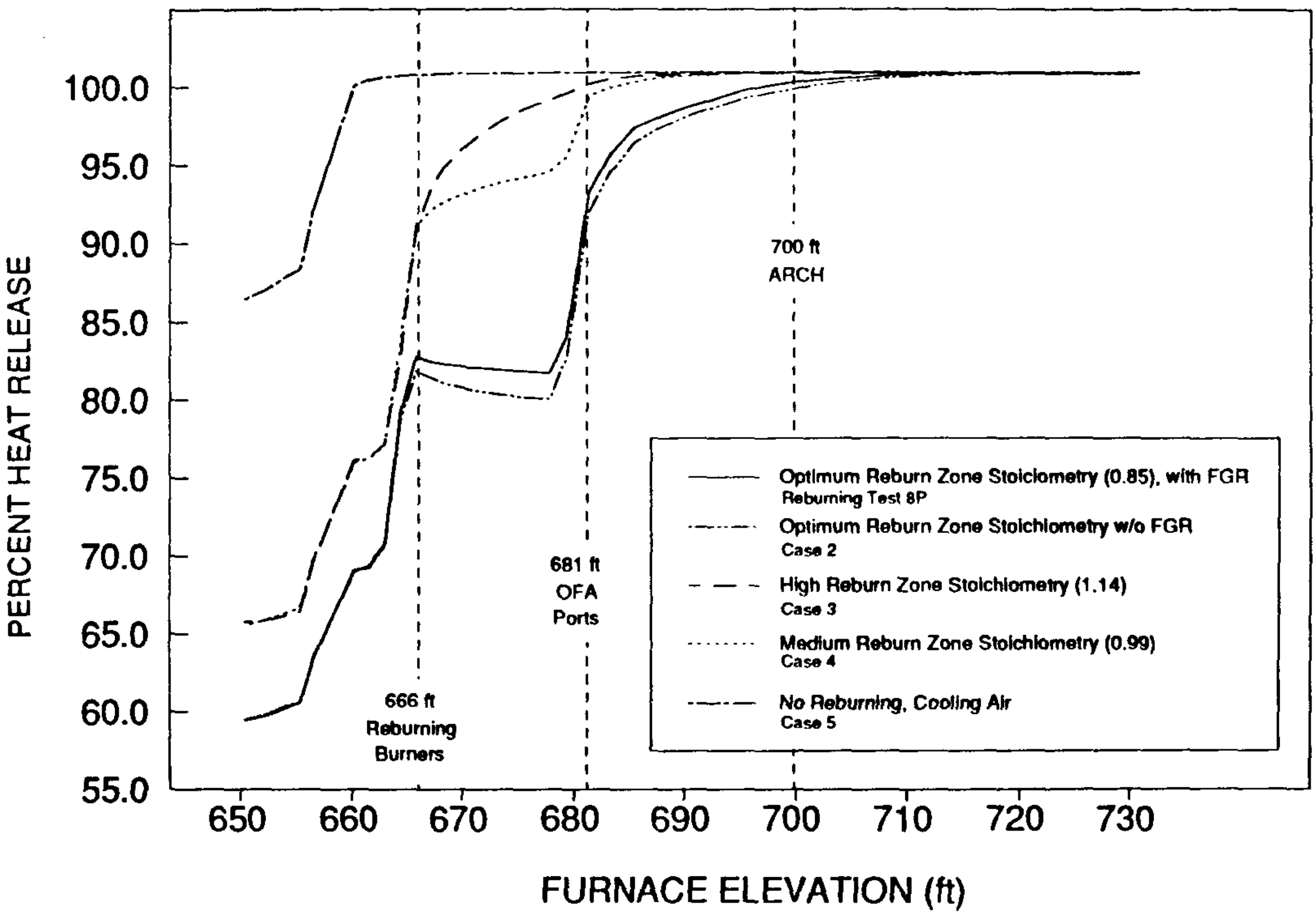


Figure 9-3 Predicted Heat Release

TABLE 9-3 SUMMARY OF PREDICTED FURNACE PERFORMANCE		
	Baseline	**Reburning with FGR**
FGR	NO	YES
Reburning	NO	YES
Reburning Zone SR	1.14	0.84
Furnace SR	1.17	1.15
Predicted Furnace Exit Gas Temperature (F)	2108F	2068F
Oxygen (%)	2.82	2.54
CO (ppm)	1 ppm	53 ppm
Ash Loading (%)	12.3	42.1
UBCA (%)	4.7	1.6
UBCL (%)	0.391	0.130
Predicted Heat Absorption in the Furnace (MBtu/hr)	400.6	375.6
Predicted Heat Absorption in the cyclone (MBtu/hr)	87.4	83.7
Effective Gas Emissivity		
Elevation 664	0.304	0.329
676	0.318	0.396
686	0.326	0.348
700	0.337	0.342
Average	0.321	0.354

The heat transfer predictions for the modeled conditions are shown in Figure 9-4. The cases have approximately 100 MBtu/hr of heat absorbed by the cyclones, and approximately 50% of the heat is absorbed before the reburning burner elevation (666 ft). Heat is absorbed at a nearly constant rate from the reburning burner elevation until above the arch (700 ft), where heat absorption increases due to the superheater banks.

Gas Temperature Distribution

Figure 9-5 shows measured and predicted temperatures at the furnace arch (elevation 700 ft). The MHVT measurements indicate that FURMO slightly underpredicts temperatures near the center of the furnace but the average temperature predicted at that plane is quite close to the measured values.

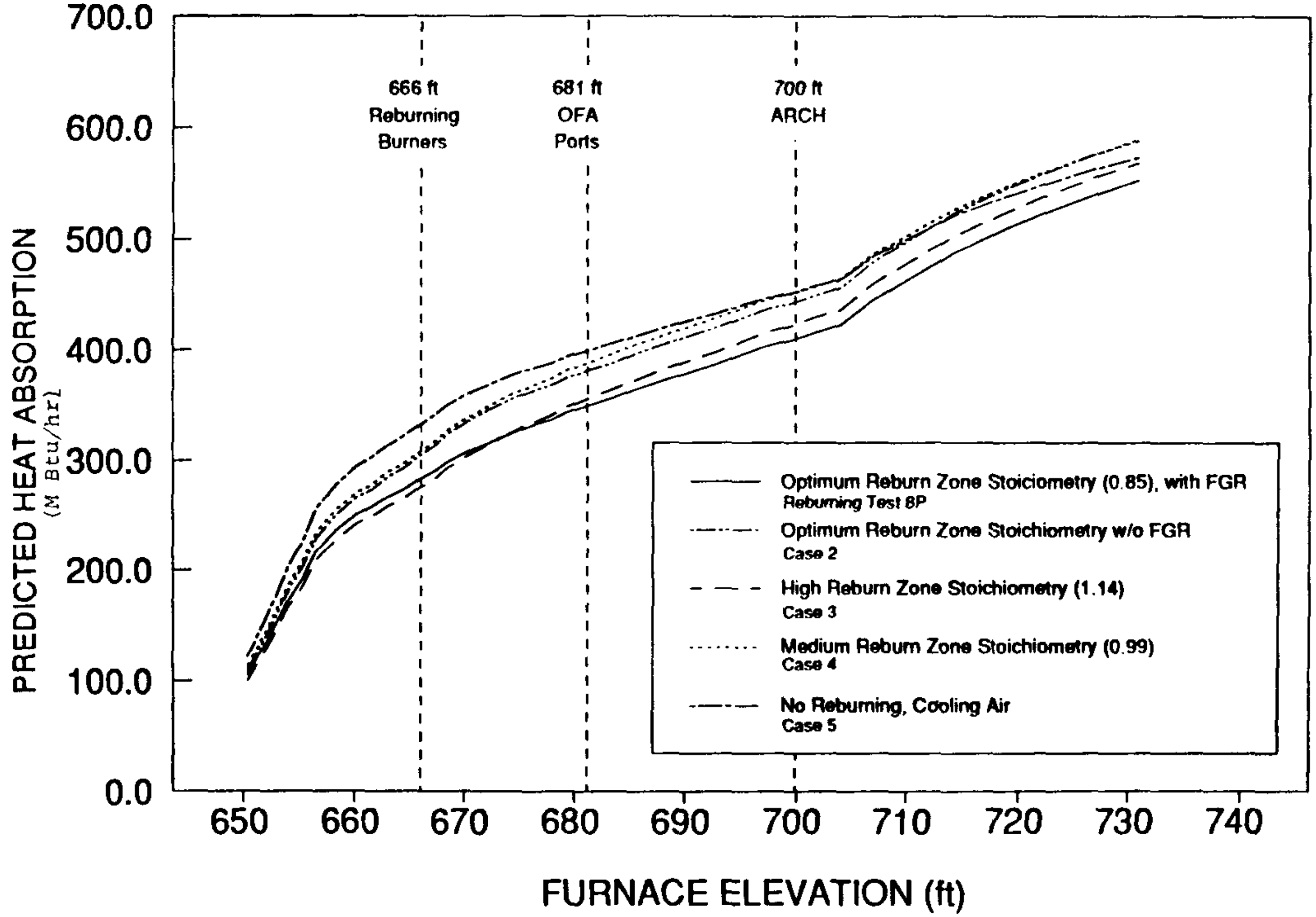
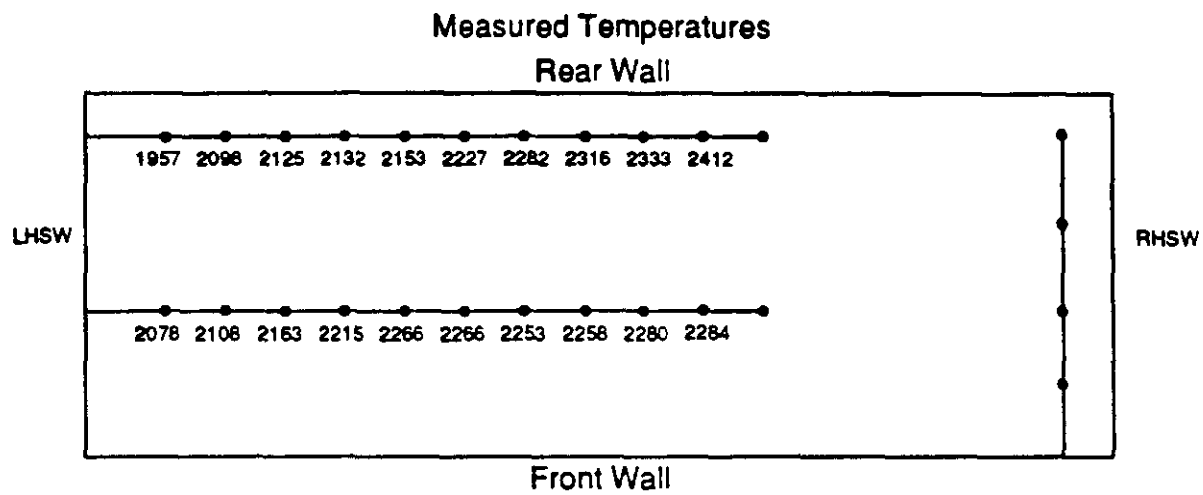


Figure 9-4 Predicted Heat Absorption



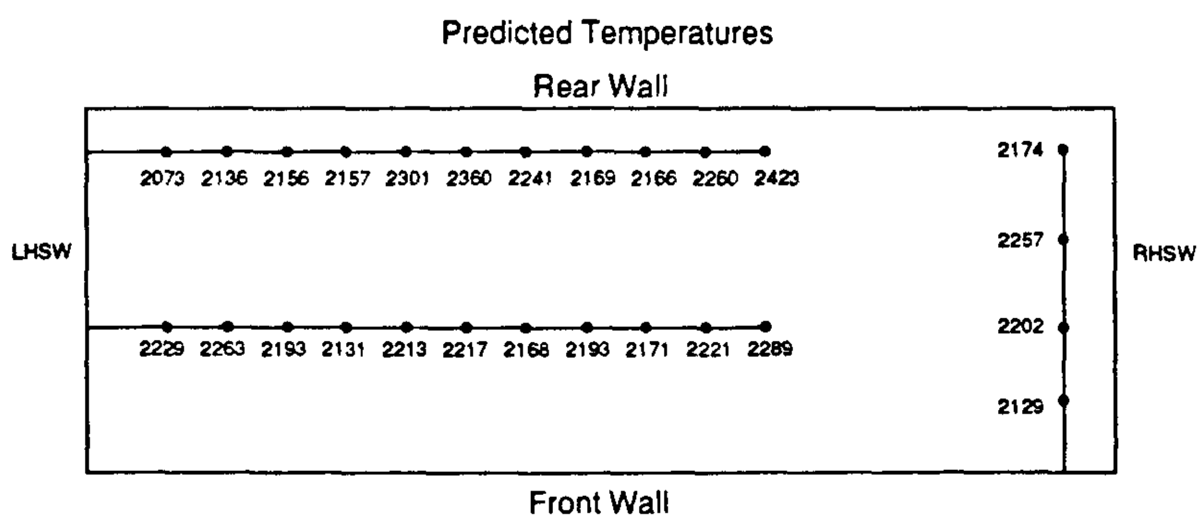


Figure 9-5 Measured and Predicted Temperatures at the Furnace Arch (elevation 700 ft.) for Reburning Test 8P.

Predictions of FEGT and furnace heat absorption for the modeled conditions are shown in Table 9-3. In the reburning case flue gas recirculation dilutes the combustion gas and reduces the gas temperature resulting in lower heat absorption in the furnace. This is partly offset by the higher emissivity of the gas/particle mixture increasing the heat absorption in the reburning zone. Reburning resulted in lower predicted heat absorption and a 40F lower FEGT than the baseline condition.

CO/Stoichiometry Distribution

Stoichiometry distribution for two vertical planes through the furnace is shown in Figure 9-6. The first view (Section A-A) is a front view of the stoichiometry distribution between the target and rear walls of the furnace. This view shows a region of low stoichiometry extending above each reburning burner to the OFA port. Also shown in this view is a region of substoichiometric flow along each side wall near the OFA ports. The second view (Section B-B) is a side view through a cyclone, reburning burner and OFA port. This view shows a region of low stoichiometry on the rear wall near the furnace arch that was not previously predicted by physical or numerical flow modeling. The regions of low stoichiometry on the side and rear walls indicate incomplete mixing of the OFA with the gas flow. OFA ports may be located too far from the side walls. However, additional swirl to the OFA ports (by shifting air from the core to the outer zone of the dual zone NO_x ports) may increase the spreading and reduce penetration for better mixing near the walls.

CO distribution for the same two vertical planes through the furnace is shown Figure 9-7. As expected, the regions of high CO correspond with regions of low stoichiometry. Figure 9-8 shows measured and predicted CO concentrations at the furnace arch (elevation 700 ft). FURMO underpredicts CO concentration at this plane, however the qualitative trends are correct. The high CO concentrations are of the same order of magnitude as the measurements, but slightly shifted in location due to inaccuracies in the predicted flow field. High CO concentrations are also predicted on the right side of the furnace but there was no data to confirm this. The exit plane values of CO in Table 9-3 are lower than expected. Therefore, FURMO overpredicts the CO oxidation rate for lower temperature regions with oxidizing conditions in the upper furnace and convection pass. This is a limitation of the global reaction kinetics used for CO oxidation.

UBC

The predictions for unburned carbon loss (UBCL) and unburned carbon in ash (UBCA) are included in Table 9-3. There is uncertainty in UBC for both measurements and predictions due to assumptions of ash carryover from the cyclones. The general trend is to have lower predicted UBCL and UBCA for reburning conditions than without reburning, which is the opposite of field observations. The cyclones have larger size particles than the reburning burners. Of the large particles that escape from the cyclone, most are probably

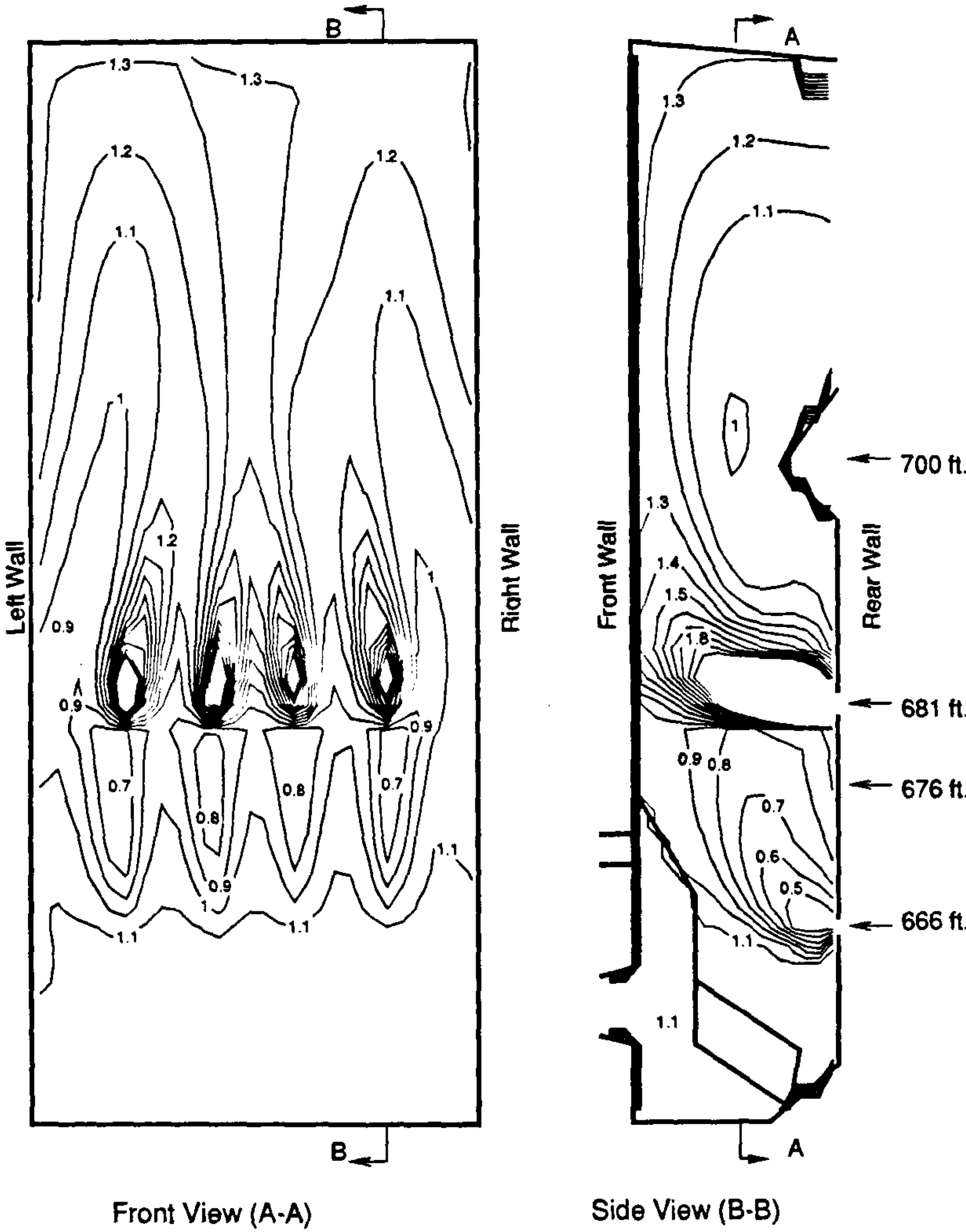


Figure 9-6 Predicted Stoichiometry Distribution Reburning Test 8P

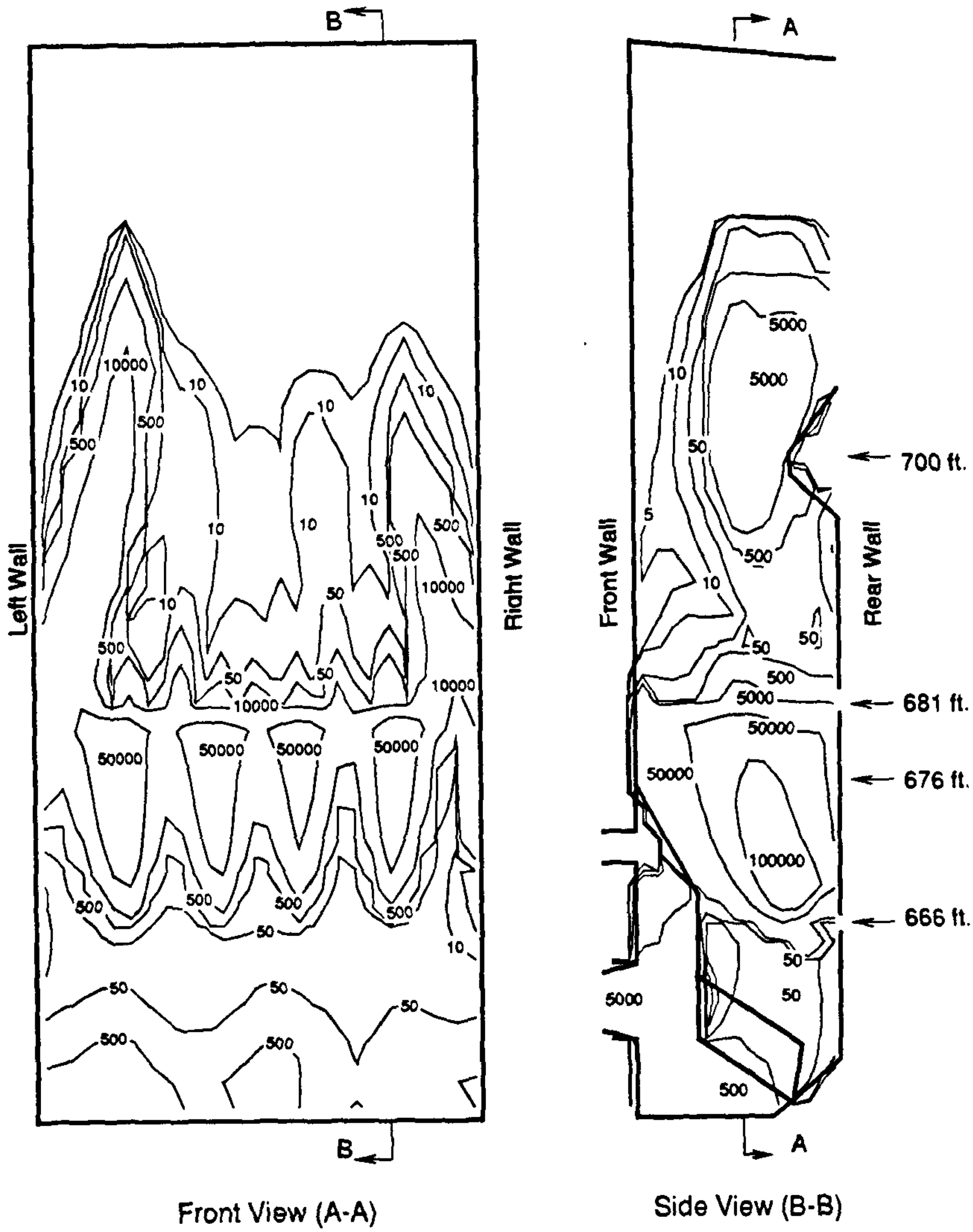


Figure 9-7 Predicted CO Distribution (ppm) for Reburning Test 8P

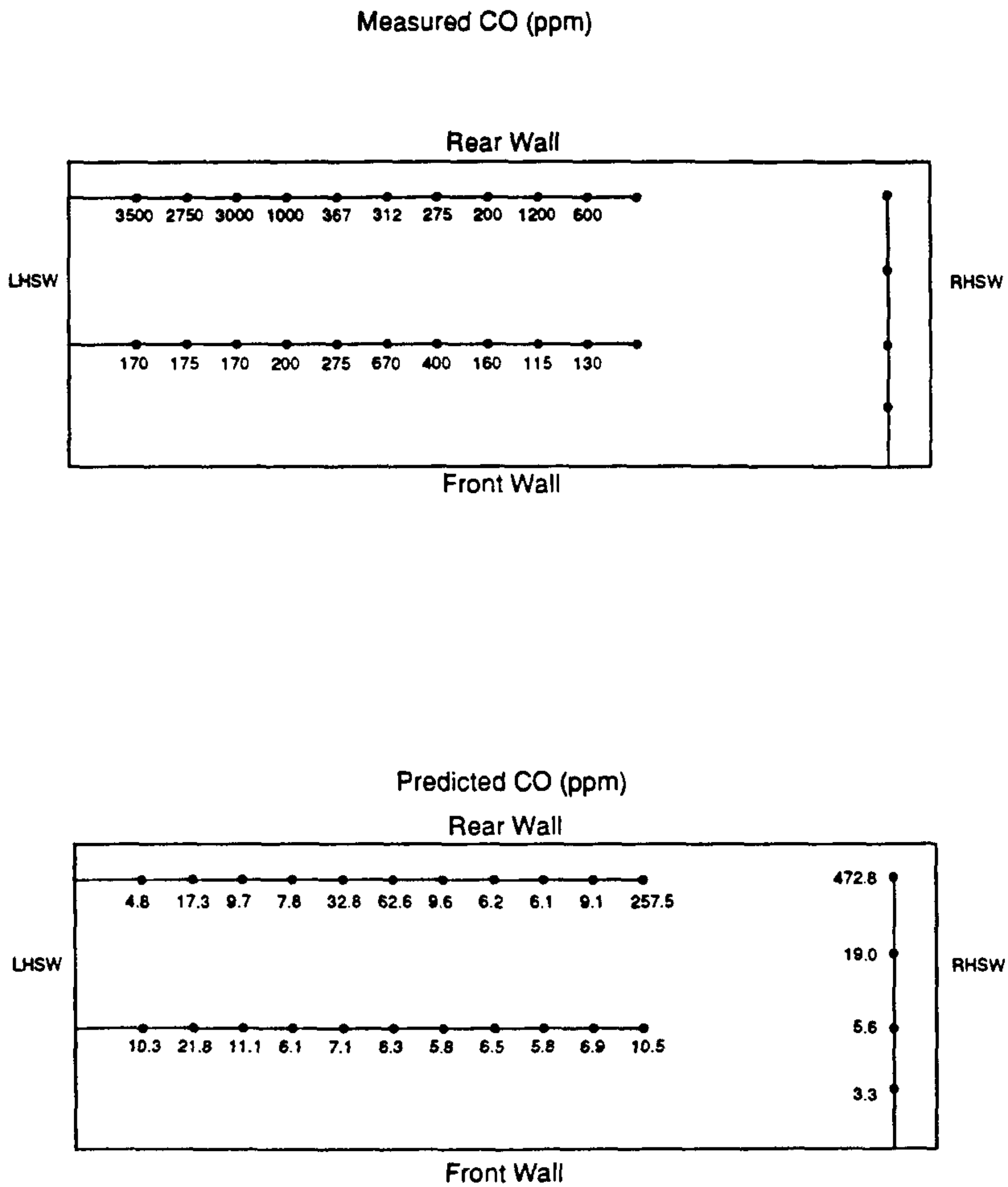


Figure 9-8 Measured and Predicted CO Concentration (ppm) at the Furnace Arch (elevation 700 ft.) for Reburning Test 8P.

deposited on the target wall and slag screens in the furnace. FURMO has no mechanism to model deposition of char particles on refractory walls and slag screens. Large size particles from the cyclones contribute a high percentage of the carbon loss predicted by FURMO, and therefore lower fuel flow to the cyclones (with reburning) results in a lower predicted carbon loss.

FURMO also underpredicts UBC from the coal introduced at the reburning burners. Higher temperature devolatilization, with lower char yields, and smaller particle size distribution both contribute to this result.

9.4 Status of Model Development

Flow/Mixing

Mathematical flow modeling can be used to qualitatively predict the flow patterns in the furnace (see Section 5.0). Flow modeling is a cost effective and efficient method of parametrically evaluating the size, number and location of reburning burners and OFA ports. The predicted stoichiometry distribution using FORCE (flow modeling only) is similar to stoichiometry using FORCE and FURMO (flow and combustion modeling). Therefore, combustion has little effect on predicted reburning burner and OFA penetration and mixing effectiveness. However, combustion effects may be important on other units, and should continue to be evaluated.

Heat Transfer

Combustion and heat transfer modeling predicts the correct trends in FEGT with reburning fuel split and stoichiometry. The effect of load on FEGT was not evaluated. The model requires the assignment of heat transfer boundary conditions for boiler walls and tube banks which are adjusted to account for uncertainties in slagging or fouling on furnace heat transfer. However, boundary conditions are then fixed for subsequent cases. Other factors affecting heat transfer such as flow patterns and mixing, gas temperature, species concentrations and flame emissivity are based on fundamental physical principles which are free of empiricism.

CO/Stoichiometry Distribution

Flow and combustion modeling predicts the correct qualitative trends in furnace stoichiometry distribution. A region of low stoichiometry near the furnace arch was predicted with FURMO which was not predicted with FORCE (flow modeling only). The low stoichiometry was confirmed by high CO measurements in the same region, and is caused by incomplete mixing of the OFA with the reburning burner flow. Regions of low stoichiometry may lead to tube corrosion problems due to the potential for increased H_2S. High CO concentrations predicted in the reburning zone were not confirmed because measurements were not made in that region.

FURMO predicts the correct qualitative trends in the distribution of CO concentration in the furnace. However, FURMO overpredicts the CO oxidation rate in lower temperature regions with oxidizing conditions in the upper furnace and convection pass. Therefore, CO concentration predictions in oxidizing regions should be viewed with caution. Further development of CO oxidation kinetics is needed to improve predictions for CO emissions.

NO_x

The development of a numerical model for predicting NO_x was not completed on company sponsored work for use in this project. The NO_x model is planned to be implemented into FURMO during 1993. An additional reburning mechanism for NO_x reduction may be required which is not included in the NO_x model. When the model has been implemented, NO_x predictions for the baseline and reburning cases should be performed and results should be validated with field measurements.

UBC

UBC predictions are sensitive to particle size, stoichiometry, residence time, and temperature. The low oxygen concentrations in the reburning zone are dependant upon CO kinetics. The models for UBC and CO are therefore strongly coupled in these regions. Further development of the CO model should also consider the effects on UBC. Addition of a mechanism for large char and ash particle deposition on enclosure walls and slag screens and reevaluation of char kinetics for reburning fuel is recommended to improve UBC predictions. More data is needed for UBC and ash carryover with coal reburning to verify model predictions.

10.0 Conclusions and Recommendations

10.1 Conclusions

The conclusions are sub-divided into sub-sections of general, emissions oriented, improved operational flexibility, power plant efficiency, long-term operation and economics.

10.1.1 General

- All goals of the cyclone coal reburning project have been achieved. Greater than 50% NO_x reduction at full load and no major boiler operational problems are apparent from both the optimization and long term performance test results.

- Varying the reburn zone stoichiometry is the most critical factor in changing NO_x emission levels during coal reburning operation.

- A good emissions comparison between the B&W 60-point economizer outlet grid and the Acurex 2-point extraction system at the precipitator outlet was observed.

- The demonstration showed the value of minor reburn burner design modifications and provided the opportunity to incorporate them within the test program to improve reburn operation. The main purpose was to improve reburn burner flame stability indications at low loads. The final design changes that achieved this goal included adding fixed spin vanes at the outer air zone to replace the adjustable spin vanes and minimize air flow leakage around the vanes. Also, the adjustable conical impeller was replaced with a swirler to increase the swirl component of the primary air/coal flow.

- Gas recirculation (GR) played two vital roles in the reburn system operation: 1. cooling and sealing the existing GR ports without negatively affecting the reburn zone stoichiometry and 2. replaces secondary air to the reburn burners and hence, reduces the reburn burner stoichiometry while maintaining acceptable burner velocity, pressure drop, and mixing capability.

- Full load pulverizer results showed that higher fineness is achievable than originally anticipated (97-98% versus 90% thru 200 mesh). Changing the rotating classifier speed from 100 to 160 RPM provided coal fineness of about 81 to 82% and 97 to 98% through 200 mesh, respectively.

- The optimized % heat input to the reburn burners over the boiler's load range to obtain the best reburn operating conditions for both the Lamar bituminous and western sub-bituminous coal firing are:

Load (MW_e)	% Reburn Heat Input
110	29-30
82	33-34
55	33-35

- The acceptable resultant boiler turndown capability during reburning operation is about 66% (from 110 MW_e to 37 MW_e), exceeding the project's goal of 50% turndown.

- Opacity levels and precipitator performance were not affected by reburning with either coal due to: 1. no change in flyash resistivity; 2. slightly larger flyash mean particle size distribution with reburning (about 5 versus 3 microns); 3. particulate loadings to the precipitator remained low enough to allow the precipitator to maintain opacity levels.

- Reburning precipitator efficiency improved during bituminous coal firing (about 98.8% reburn versus 97.4% baseline at full load) and no change was apparent while using sub-bituminous coal.

- Western fuel firing reburning operation resulted in improved reburn burner flame stability and a better % NO_x reduction capability as compared to that observed during the Lamar bituminous coal tests.

10.1.2 Emissions Review

10.1.2.1 Lamar Coal Firing Emission Summary

- The average B&W baseline NO_x levels identified at various loads during the 1990 Baseline Tests and also during the post-retrofit baseline tests are lower than expected from a typical cyclone and are as follows:

Load (MW_e)	NO_x Emissions ppm @ 3% O_2 (lb/10^6 Btu)
110	609 (0.83)
82	531 (0.72)
60	506 (0.69)
37	600 (0.81)

- Reburn zone stoichiometry affects the resultant NO_x emissions during the optimization testing as determined at various loads and stoichiometries:

Load (MW_e)	**Reburn Zone Stoichiometry**	**NO_x (ppm @ 3% O_2)**	**% Reduction**
110	0.95	365	40.0
110	0.89	305	50.0
110	0.81	233	61.8
82	0.93	310	41.6
82	0.87	266	50.0
82	0.85	250	52.9
60	1.00	375	25.9
60	0.90	290	42.7

- Typical CO emission levels at each of the load conditions tested for baseline and reburn operation are 50-60 ppm and 90-100 ppm @ 3% O2 respectively. Although the CO emissions did slightly increase during reburn operation, all the levels identified above are considered minimal and well below acceptable industry standards.

- Operating the GR fan eliminates the seal air to the GR ports and permits lower secondary air flow to be introduced to the reburn burner, thus lowering the reburn zone stoichiometry. Reburning NO_x emissions were reduced from 298 ppm to 263 ppm (11.7% change) by running the GR fan.

- Although GR is a key variable, increasing the % GR flow to the reburn burners from approximately 0.13 to 5.50% (of the total boiler gas flow) while maintaining a constant reburn zone stoichiometry lowered NO_x emissions from 297 to 294 ppm, which is not significant.

- UBC levels reduced from about 20% in the ash to 6-12% while varying the reburn burner coal fineness from 81-82% to 94-96% thru 200 mesh. No major changes in NO_x emissions were observed during this variation.

- Operating the coal reburn system over the load range during the performance test series, in the full automatic control mode, resulted in various NO_x

reductions. The average NO_x emissions which resulted are as follows:

Load (MW_e)	NO_x Emissions ppm @ 3% O_2 (lb/10^6 Btu)	% Reduction
110	290 (0.39)	52.4
82	265 (0.36)	50.1
60	325 (0.44)	35.8
37-38	400 (0.54)	33.3

10.1.2.2 Western Coal Firing Emission Summary

- During western coal firing, the average NO_x emission levels over the load range (118 MW_e to 41 MW_e) for baseline and optimized reburn operation varied as follows:

Load (MW_e)	Baseline NO_x, ppm (lb/10^6 Btu)	Reburn NO_x, ppm (lb/10^6 Btu)	% Reduction
118	-	275 (0.37)	-
110	560 (0.75)	250 (0.34)	55.4
82	480 (0.64)	230 (0.31)	52.1
60	464 (0.62)	220 (0.30)	52.6
41	-	210 (0.28)	-

- Baseline CO emission levels over the load range for all the tests averaged from approximately 28 to 48 ppm @ 3% O2. During reburn operation the CO emission levels increased slightly to 45-84 ppm @ 3% O2. Based upon these results, minimal impact between baseline and reburning operation was observed.

10.1.3 Improved Operational Flexibility

- The reburn system redirects approximately 30% of the heat input (coal flow) away from the cyclones, minimizing or eliminating an approximate 10-25% derate typically experienced when cyclone boilers fire 100% western fuel as compared to normal design fuel. Higher boiler loads are maintainable with reburn during 100% western fuel firing because reburn expands total volumetric fuel delivery capacity to the boiler allowing a higher quantity of lower Btu fuel to be burned, maintaining required heat input.

10.1.4 Power Plant Efficiency

There are three primary items relating to unit performance that are impacted by the coal reburn system. These are efficiency loss from unburned carbon (UBCL), the use of the gas recirculation system at full load, and the furnace exit gas temperature (FEGT).

10.1.4.1 Lamar Coal Firing Boiler Performance Summary

- At 100% load (110 MW_e), percent of ash as flyash increases from 23% to 37% with reburn in service. At 75% and 50% loads (82 and 55 MW_e's), the percent of ash as flyash increases from 26% to 36% and 47% to 57% respectively with reburn in service. The increase in flyash percent is fairly constant over the load range.

- Unburned carbon as efficiency loss (UBCL) versus load at 110 MW_e, 82 MW_e, and 55 MW_e is 0.1%, 0.25%, and 1.5% higher, respectively, with reburn in service. The increase in unburned carbon loss is the single significant impact of the reburn system on unit efficiency.

- The FEGT at full load decreased by approximately 100-150°F with reburn in service. There is no change in FEGT at 75% load with reburn in service, and an increase of 50 to 75°F at 50% load with reburn in service. The gas recirculation flow alone would be expected to decrease the FEGT by approximately 25°F at full load.

- The reburn system reduces overall boiler absorption at full load due to the decrease in FEGT. At 75 percent load, the total absorption is maintainable with increased gas recirculation. At fifty percent load the total absorption is maintainable with the same gas recirculation flow because the FEGT increases with reburn in service. Superheat and reheat final steam temperatures are not negatively affected with reburn in service.

- All boiler surface cleanliness factors (K_f) stabilized within 5 hours of sootblowing a given component. In general, the component cleanliness decay rates are the same as for the 1990 baseline tests. There is no detrimental impact on unit cleanliness from operation of the reburn system.

10.1.4.2 Western Coal Firing Boiler Performance Summary

- A large scatter in the ash split data with reburn out of service was observed during western fuel firing. Since the ash splits for the reburn in service tests are extremely close to the Lamar coal test results, it is assumed that the ash splits without reburn in service are also similar to the Lamar coal test results. The unburned carbon in the ash is so low for these tests, that the flyash split has very little impact on the unburned carbon loss.

- At full load the UBCL with reburn was the same as the UBCL with reburn out of service. The increase in UBCL at 75 percent load was 0.2% efficiency loss, and at 50 percent load the UBCL increase was 0.3% efficiency loss. The impact of the reburn system on unit efficiency was the increase in unburned carbon loss only.

- At full load, the FEGT decreased by approximately 50°F with reburn in service. The gas recirculation flow alone would account for approximately 25°F of this change. There was no change in FEGT at 75% load with reburn in service, and an increase of 75°F at 50% load with reburn in service.

- All component K_f's stabilized within 3 hours of sootblowing in that component. The decay rate was faster for all components than it was when burning the Lamar coal, but the percent cleanliness reduction remained about the same for the secondary inlet and outlet banks and the reheater. However, the primary superheater and economizer did not decay as much as they did during the Lamar coal tests.

- Final superheat steam temperature was maintained at 1000°F down to 50 percent load. Final reheat steam temperature was maintained at 1000°F from full load down to 75% load, and was well above the design value of 950°F at 50% load.

- The superheat/reheat spray flow quantities were very similar with and without reburn in service, and were significantly higher than the Lamar coal tests due to the higher FEGT experienced with the western fuel.

10.1.5 Long-Term Reburn Operation

- Long-term (four months) reburning operation did not have a negative affect on boiler operation. This will continue to be verified periodically by Wisconsin Power & Light via their yearly heat rate determinations.

- The % NO_x reductions achieved during the long term performance series with Lamar coal correlated well with the optimization series test results (within the range of data scatter observed throughout all the tests). The following summarizes the long-term NO_x emissions during reburn operation and the associated % reductions:

Load (MW_e)	**NO_x ppm @ 3% O_2 (lb/10^6 Btu)**	**% Reduction**
>100 MW_e, Avg = 108	290 (0.39)	51.2
>80 MW_e, Avg = 98	296 (0.40)	49.0
All loads, Avg = 74	285 (0.39)	40.0

- Ultrasonic tube thickness (UT) measurements throughout the furnace before and after long term reburning showed no loss of metal thickness. In addition, gas measurements near the boiler tube walls did not reveal any measurable quantities of H_2S.

10.1.6 Economics of Coal Reburning

- Estimated Total Capital Requirement (TCR) for retrofitting a coal reburn system on a nominal 110 MW_e cyclone-equipped boiler is 66.5 $/kw; and levelized Busbar Power costs for 10 and 30 year periods are 2.40 mills/kw and 2.28 mills/kw, respectively.

- For a hypothetical coal reburning application to a 605 MW_e cyclone fired unit, the TCR is estimated to be 43.1 $/kw; and levelized Busbar Power costs for 10 and 30 year periods are 1.61 mills/kw and 1.55 mills/kw respectively.

- Numerous site specific factors can greatly impact the cost of retrofitting a PC cyclone reburn system to an existing unit. The most significant of these factors include the state of the existing controls, availability of flue gas recirculation, availability of space to locate pulverizer(s)/reburn burners/OFA ports within existing structures, and the scope of coal handling equipment modifications/additions required to supply the reburn system with fuel. Additional site specific factors include sootblowing capacity/coverage, boiler tube corrosion potential, back-end boiler clean-up equipment capacity, boiler circulation, and steam temperature capabilities.

- A summary of annualized costs per ton NO_x removed for both the 110 MW_e case (while firing 2 different coal types) and the 605 MW_e case for 10 and 30 year levelized cost scenarios are:

ANNUALIZED COST CHART ($ per ton NO_x removed)		
Unit Size	**Levelized Period**	
	10-Year	**30-Year**
110 MW_e Bituminous Coal	1075	692
110 MW_e Western Coal	1077	693
605 MW_e Design Coal	408	263

10.2 RECOMMENDATIONS

- Low NO_x reburn technology control requirements dictate that a digital control system (DCS) should be available to effectively operate both the existing boiler and reburn systems. The reburn technology involves accurate and responsive control of air and fuel flow rates to various regions of the furnace.

- Gas recirculation to the reburn burners is required to consistently maintain high NO_x reduction levels. Numerous cyclone utilities have removed GR fans and this may require that new fans be included in the cost estimates.

- Accurate cyclone air/fuel measurement and controllability is critical to maintaining acceptable cyclone operation and reburning zone stoichiometry. Specifically, large open windbox cyclone boilers need to address this area of concern to a greater extent since present air flow indications on an individual cyclone basis may not be satisfactory.

- Because application of the cyclone reburning technology is site specific, each potential retrofit will require both engineering and economic studies to determine the reburn applicability.

- Effective in-furnace mixing between the cyclone and reburn burner flows is a key factor in obtaining optimized reburn operation. Numerical modeling is an extremely useful tool to help in this determination.

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