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INTEGRATED NOx REDUCTION PLAN TO MEET STAGED SCAQMD REQUIREMENTS FOR STEAM ELECTRIC POWER PLANTS

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I. ABSTRACT

The NO_x reduction regulations currently promulgated in California by the South Coast Air Quality Management District (SCAQMD) are the most stringent in the nation. As improved air quality is mandated elsewhere, it is reasonable to predict that current SCAQMD regulations in Southern California will spread across the country. The recently enacted Clean Air Act Amendments also mandate NO_x reductions from utility boilers.

In mid-1989, SCAQMD mandated drastic NO_x reductions for all of utility steam generating units within their jurisdiction. This SCAQMD mandate (Rule 1135) requires reduction from the 1989 average of 2.68 lb NO_x per MWh to 0.25 lb NO_x per MWh in 1999 (over 90% reduction).

This paper discusses in detail the many NO_x reduction techniques contemplated--low NO_x burners, flue-gas recirculation, single and multiple urea injection, selective catalytic reduction (SCR) baskets installed in Lungstom-type air heaters, and others. It will cover the interactions of these NO_x reduction steps and their cumulative effects.

Since this NO_x reduction program to meet SCAQMD Rule 1135 requirements is thought to be a precursor of future requirements elsewhere including the new Clean Air Legislation, this discussion should be of vital interest to generation operators across the country.

II. INTRODUCTION

The South Coast Air Quality Management District (SCAQMD) is the regulatory body mandated with improving the ambient air quality in the Los Angeles metropolitan area. Their jurisdiction area includes Los Angeles and Orange Counties, as well as parts of Riverside and San Bernardino Counties, collectively known as the South Coast Air Basin (SCAB).

In August of 1989 the SCAQMD enacted rule 1135 "NO_x Emissions From Utility Boilers." The rule dictates NO_x reduction in excess of 90% for all 5 utilities located within SCAB. This rule, which will be implemented over a ten year period, includes increasingly stringent increments of compliance.

In order to demonstrate compliance with each increment as well as the final emission limit of 0.25 lb NO_x per net MWh the affected utilities were required to submit "Emission Control Plans" to the SCAQMD. The development of this plan and the compliance strategy it represented involved a detailed technical and economic analysis of the NO_x reduction techniques available. The utilities, and their consultants, selected technologies which alone or in combination will achieve system wide compliance. As consultants, Chas. T. Main, Inc. and Applied Utility Systems, Inc. have been involved with NO_x emission compliance for all five utilities. This paper will first examine the technologies available presenting advantages and disadvantages for each. It will then explore how these technologies can be applied to achieve compliance, with particular emphasis on how complementary technologies can work in harmony to achieve greater NO_x reduction. Finally, the paper will review the economic considerations such as capital costs, operating costs, present worth and cost effectiveness.

III. NOx REDUCTION TECHNOLOGIES

NO_x reduction technologies can be divided into two broad categories, combustion-based technologies and post-combustion technologies. NO_x is formed in the combustion zone of fossil fuel fired boilers. The quantity formed is based on the nitrogen content of the fuel as well as combustion conditions such as temperature, air to fuel stoichiometry and degree of air and fuel mixing. Combustion based technologies regulate these conditions to minimize the formation of NO_x. Post combustion technologies, on the other hand, reduce NO_x emissions by chemical conversion of NO_x to molecular nitrogen (N_2) and water (H_2O).

A. Combustion-Based Technologies

There are numerous combustion-based technologies available for control of NO_x formation. Some of these, such as low NO_x burners, could require significant modifications to the existing boiler. Others, such as burner out of service, require changes to the method of burner operation, but no physical modifications to the boiler. Table 1 presents several combustion based technologies with advantages and disadvantages of each.

B. Post-Combustion Technologies

The variety of post-combustion technologies is nearly as great as combustion based technologies. Although these technologies differ greatly in cost, complexity and effectiveness, they all involve the same basic chemical reaction:

$$NH_3 + NO_x \rightarrow N_2 + H_2O$$

In selective catalytic reduction (SCR), the reaction takes place in the presence of a catalyst, improving performance. Noncatalytic systems rely on a direct reaction, usually at higher temperatures, to remove NO_x. Although removal efficiencies are lower, noncatalytic systems are typically less complex and often significantly less costly. Table 2 presents various catalytic and noncatalytic post-combustion technologies including advantages and disadvantages for each.

IV. COMPLIANCE STRATEGIES

The only single commercially available technology which can achieve the mandated 90% NO_x reduction is conventional SCR. However, other technologies when implemented together or in succession can achieve 90% reduction, often at a significant savings in capital and operating costs. Furthermore, the increasingly stringent increments of compliance make it practical to implement technologies in a staged approach to spread the compliance costs over the ten year program. Conventional SCR will play a role in achieving compliance with SCAQMD Rule 1135; however, for many boilers other strategies will prove more cost effective and practical. Below we will present two strategies which utilize complimentary technologies to achieve NO_x reductions in excess of 90%.

A. STRATEGY 1

The first strategy depends on both combustion-based and post-combustion technologies. Three technologies are implemented in succession. The technologies, as well as the order of implementation, were selected to minimize cost and maintain reliability.

Step 1 - Flue Gas Recirculation (FGR)

Flue gas recirculation was selected as the first technology because of moderate cost, relatively high NO_x reduction potential and low technological risk. The capital and operating costs for FGR, although not low, are significantly below many other alternatives. (See Section V for details) The NO_x reduction potential for FGR is boiler specific, ranging from 30 to 70%. A typical value for utility boilers without low NO_x burners is 50%.

FGR is considered a low technological risk for two reasons. First it has been tested and successfully implemented on many utility boilers. Second its function is not necessary for boiler operation. If problems occur during start-up, the FGR system can be shut down without interrupting boiler operation. The problem within the FGR system can often be corrected while the boiler is on-line. Many other systems will require a boiler outage to repair problems.

Step 2 - Low NOx Burners (LNB)

The second technology in this strategy is low NO_x burners (LNB). The staged combustion and enhanced control of fuel/air mixing available from LNB complement FGR. The resulting NO_x reduction of the two technologies is dependent on furnace geometry, heat release rate, and the design of the burner being replaced. Total reductions of 60-85% are possible with FGR and LNB.

Step 3 - Urea Injection

The third technology in this strategy is urea injection. As the final technology, it will be applied when the NO_x emissions are relatively low. This will decrease the cost of implementation. The injection rate of urea is dependent on the NO_x concentration and required removal efficiency. Therefore the storage and pumping requirements are smaller than if urea injection was applied as the first technology.

There is a strong technical advantage to applying urea injection after the combustion based technologies in Steps 1 and 2. FGR and particularly LNB will significantly alter the temperature profile of the boiler. The optimum urea injection point is very temperature dependent. If urea injection was applied

COMBUSTION BASED NOx REDUCTION TECHNOLOGIES

TECHNIQUE	DESCRIPTION	ADVANTAGES	DISADVANTAGES
1 Burner Out Of Service (BOOS)	Staged Combustion achieved by shutting off fuel flow from one or more burners while maintaining airflow. This creates fuel rich and fuel lean zones.	• No capital equipment required • Moderate NOx reductions • Low operating cost	• Typically some sacrifice in efficiency (higher excess air, high CO) • BOOS is a discrete event operability is limited at variable loads
2 Fuel Biasing	Staged combustion achieved by increasing the fuel flow to the lower burners and decreasing the fuel flow to the upper burners.	• Low capital costs – fuel flow control valves • Moderate NOx reductions • Variable control enhances operability over BOOS • Low operating cost	• Some efficiency penality but less than BOOS
3 Over Fire Air	Injectection of 10-20% of the combustion air above the combustion zone. This makes the combustion zone fuel rich decreasing NOx formation.	• Low operating cost	• Requires pressure part changes (additional penetrations) • Location and mixing of OFA critical to maintain efficient combustion • NOx verus efficiency, opacity tradeoffs
4 Reburning	Injection of fuel (usually natural gas) in upper furnace. This consumes remaining O_2 and converts NOx to N_2. Additional air is added downstream to consume remaining fuel.	• Potential for high NOx reduction • Low operating cost if primary fuel is natural gas	• High capital cost • Impact on boiler heat distribution • Effect on combustion efficiency
5 Low excess air operation	Decrease air flow to burners. This decreases the amount of excess O_2 available, thus decreasing NOx formation.	• Minimal capital cost • Efficiency improvements	• Limited NOx reduction • May require additional controls & monitors to insure safe operation
6 Flue Gas Recirculation (FGR)	Up to 20% of flue gas is recirculated and mixed with the combustion air. This dilutes the flame decreasing temperature and availability of O_2.	• High NOx reduction potential, especially effective for natural gas firing	• Moderately high capital cost • Moderately high operating costs • Affects heat distribution due to increased throughput
7 Low NOx Burners (LNB)	Control of fuel/air mixing creates larger, "bushier" flame. This decreases peak flame temperature decreasing NOx. Also reduces amount of O_2 available in hottest part of flame.	• Low operating costs • Moderate NOx reduction levels, increased when combined with FGR	• High capital cost for burner retrofit • Must be adapted to physical constraints of burner or major rework of burner front required
8 Water/steam injection	Injection of steam or water at burner to dilute flame. Decreases flame temperature and NOx formation.	• Moderate capital costs • Moderate NOx reductions	• Efficiency penalty due to additional water vapor loss and fan HP for increased mass flow
9 Reduced air preheat with HRSG	Elimination of air heater reduces combustion air temp. and NOx formation. Addition of HRSG captures heat previously captured in air heater.	• Possible efficiency benefit • Reduced cost of conventional SCR • Potential to achieve ultra low NOx levels	• High Capital costs

TABLE 1

POST COMBUSTION NOx REDUCTION TECHNOLOGIES

TECHNIQUE	DESCRIPTION	ADVANTAGES	DISADVANTAGES
1 Urea injection	Injection of urea into furnace to react with NOx to form N2 and H2O.	• Low capital cost • Relatively simple system • Moderate NOx removal (30-60%) • Non-toxic chemical • Typically, low energy injection sufficient	• Temperature dependent • Design must consider boiler operating conditions and design • Reduction may decrease at lower loads
2 Ammonia injection (Thermal-DeNOx)	Injection of ammonia into furnace to react with NOx to form N2 and H2O.	• Low operating cost • Moderate NOx removal (30-60%)	• Moderatly high capital cost • Ammonia handling, storage, vaporization and injection systems required (Ammonia is a toxic chemical)
3 Air Heater SCR (AH-SCR)	Air heater baskets replaced with catalyst coated baskets. Catalyst promotes reaction of ammonia with NOx.	• Moderate NOx removal (40-65%) • Moderate capital cost • No additional ductwork or reactor required • Low pressure drop • Can use urea as ammonia feedstock • Rotating air heater assists mixing, contact with catalyst	• Design must address pressure drop, maintain heat transfer • Due to rotation of air heater only 50% of catalyst is active at any time
4 Duct SCR	A smaller version of conventional SCR is placed in existing ductwork.	• Moderate capital cost • Moderate NOx removal (30%) • No additional ductwork required	• Duct location unit specfic temperature, access dependent • Some pressure drop must be accommodated
5 Activated Carbon SCR	Activated carbon catalyst, installed downstream of air heater, promotes reaction of ammonia with NOx at low temperature.	• Active at low temperature • High surface area reduces reactor size • Low cost of catalyst • Can use urea as ammonia feedstock • Activated carbon is non-hazardous material • SOx removal as well as NOx removal	• High pressure drop • Not a fully commercial technology
6 Conventional SCR	Catalyst located in flue gas stream (usually upstream of air heater) promotes reaction of ammonia with NOx.	• High NOx removal (90%)	• Very high capital cost • High operating cost • Extensive ductwork to/from reactor • Large volume reactor must be sited • Increased pressure drop may require ID fan or larger FD fan • Reduced efficiency • Ammonia sulfate removal equipment for air heater • Water treatment of air heater wash

TABLE 2

prior to FGR and LNB additional injection points might be required to insure the proper temperature window is available.

Urea injection alone can achieve NO_x reduction in the range of 30-60%. When all three technologies are applied in this sequence, a total reduction in excess of 90% is possible.

B. STRATEGY 2

The second strategy utilizes only two technologies, both of which are post-combustion. This strategy, although applicable to nearly all boilers, is particularly advantageous on units which can not be easily or cost effectively converted to low NO_x burners.

Step 1 - Urea Injection

As the first technology urea injection offers a high NO_x reduction at a reasonable cost. It has a relatively low technological risk as it can be shut down for repairs without taking the boiler off-line. NO_x reductions of 30-60% from baseline conditions are possible.

Step 2 - Air Heater Selective Catalytic Reduction

Air Heater Selective Catalytic Reduction (AH-SCR) was selected as the second technology because of its improved performance at lower NO_x levels. It also works with urea injection in a unique and very complementary way. The AH-SCR requires ammonia to remove NO_x. A side effect to urea injection is called ammonia breakthrough. This is a result of incomplete reaction of the urea and is dependent on the stoichiometric ratio of urea injected to the initial NO_x. If this ratio is increased the ammonia breakthrough increases. This ammonia breakthrough can be used as the ammonia supply for the AH-SCR. There are two advantages to this arrangement. First is the elimination of the hazardous ammonia storage, vaporization and injection system. This represents a significant cost savings. The second advantage is that improved NO_x reduction from the urea system is possible. The increased stoichiometric ratio will improve NO_x reduction as well as provide ammonia for the AH-SCR. This ratio is usually limited to minimize ammonia emissions due to breakthrough. Total NO_x reductions of up to 90% are possible with this strategy.

V. ECONOMIC ANALYSIS

The cost of complying with SCAQMD Rule 1135 or any strict NO_x emission regulation will be high. Reducing this cost through creative technology selection or improved design will decrease the impact on rate payers and improve the competitiveness of the utility. The economic analysis is an important step in determining the optimum compliance strategy. The first step is to estimate the capital and operating costs of the various technologies. These costs are then used to project the present worth cost and cost effectiveness ($/Ton NOx removed) of various strategies.

A. Capital Costs

There are three major components to the capital cost of a project similar to these. The first, engineering and design costs, is dependent on the technology selected, the specific design of the plant to be modified, and the availability of existing plant drawings and design data. This is estimated based on the applicable technology, plant visits, meetings with operations and maintenance personnel and review of existing drawings. The second component is equipment cost. This requires a preliminary design based on the plant conditions. Budget prices can be obtained from equipment vendors based on the sizing data from the preliminary design.

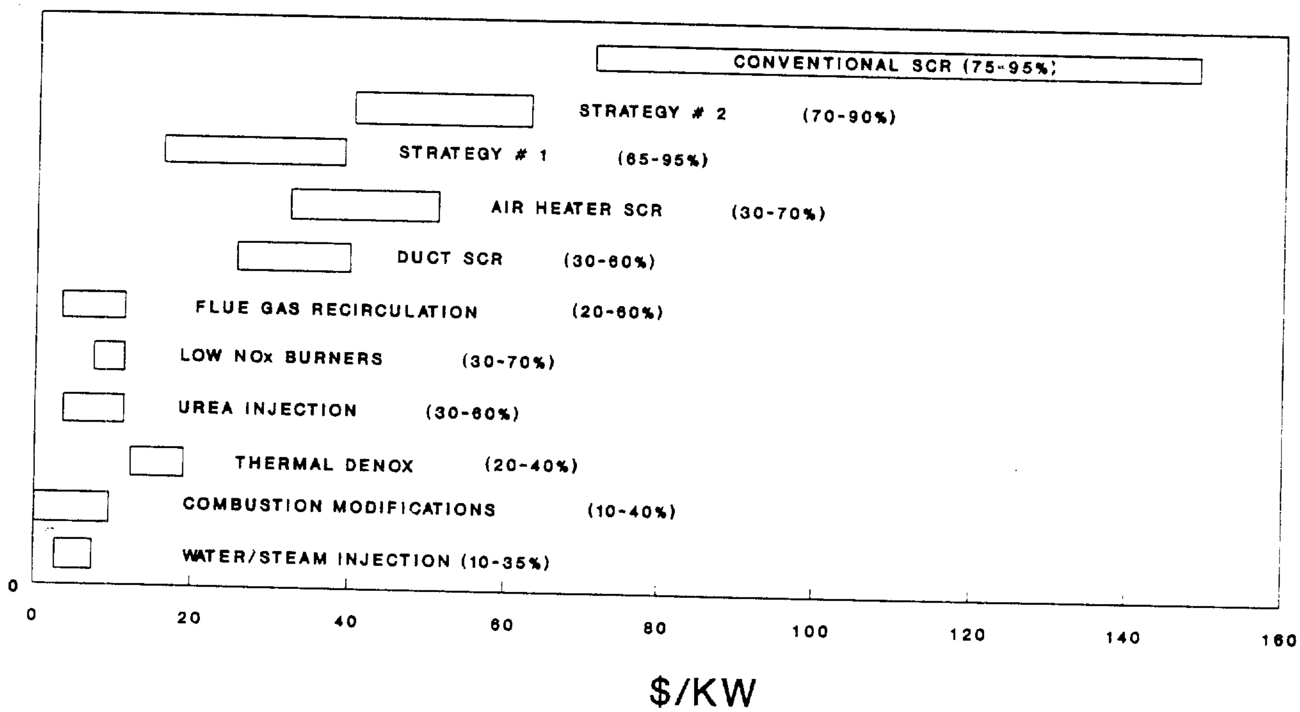
The final component of the capital cost is the installation. This requires an in depth analysis of the existing plant conditions. The installation cost varies significantly on retrofit projects and is almost always greater than an installation in a new plant. Many older plants contain asbestos insulation. Although it was not within the scope of a NOx reduction project to conduct an asbestos abatement program, many technologies require boiler or duct penetrations in areas containing asbestos. This will increase construction costs and schedule durations. Other factors which effect construction costs are unit layout and accessibility.

In order to compare technologies it is convenient to present capital costs in $/KW. Figure 1 shows typical capital cost ranges for the technologies presented in Section 3. As depicted in the above explanation capital costs are very unit specific. Therefore, any detailed study must include an analysis of the physical plant constraints.

B. Operating Costs

The operating cost associated with NOx reduction technologies are categorized as fixed costs or variable costs. Fixed costs are independent of unit load or hours of operation. Variable costs are a function of unit operation and load. Variable costs include such expenses as electricity consumption for operation of pumps, fans, or heaters, reagent costs for ammonia or urea injection, and catalyst replacement costs. Due to the variation in operating mode (base load vs. load following) and the desired level of

CAPITAL COST RANGE



NOTES: STRATEGY # 1 IS FGR, LNB, AND UREA INJECTION
STRATEGY # 2 IS UREA INJECTION AND AIR HEATER SCR

FIGURE 1

reduction, it is not practical to present operating cost ranges for NOx reduction technologies.

C. <u>Present Worth and Cost Effectiveness</u>

The capital and operating cost estimates are only the first step in a detailed economic analysis. A true economic comparison between technologies or strategies should be based on a present worth evaluation and/or a cost effectiveness calculation. The results are very unit specific, and therefore it is not practical to include ranges or typical values in this paper. We have included a general discussion of the methods used in these evaluations and the importance of these results in developing a compliance strategy.

A present worth calculation includes capital costs as well as operating costs for the projected life of the unit. Projected unit load and hours of operation are required to estimate future operating costs. The equivalent present worth of the projected operating costs are calculated based on the time cost of money. In a present worth comparison, technologies with low operating costs will fare better on base loaded units and technologies with lower capital costs will be fare better on load following or peaking units.

The present worth analysis will also demonstrate a significant advantage for staged implementation of several technologies over a single technology. As stated earlier the SCAQMD Rule 1135 includes increasingly stringent increments of compliance. If compliance is to be achieved with a single technology it must be applied to meet the first compliance date. This will require a large outlay of capital. The staged implementation of several technologies will spread the capital cost over the entire compliance period, while still meeting each increment of compliance. Due to the time cost of money this represents a significant savings.

Another way to compare technologies or compliance strategies is cost effectiveness (measured in $/Ton NOx removed). This is calculated based on annual cost and projected NO_x reduction. Annual costs are a combination of operating costs and capital recovery, which is based on total capital cost, projected unit life and the time cost of capital. NO_x reduction in tons/year is calculated from planned unit operations (hours and load), expected percent reduction and baseline NO_x emissions. The cost effectiveness varies widely with the technology selected as well as the specific unit being modified. The incremental cost effectiveness of technologies implemented in a staged approach generally increases for later technologies. This is due to the lower initial NO_x levels for the later technologies.

Cost effectiveness is useful in comparing costs between units, among utilities or even with other industries. It is very helpful for a regulating body which is attempting to reduce area wide emissions at the least possible cost. A utility should use cost effectiveness as part of the evaluation of various strategies. However, the final strategy must also insure system reliability. Although it may be more cost effective to modify only one unit to achieve a system average emission rate, this would require operation of that unit to achieve compliance. Therefore, it is often necessary to implement modifications with a higher $/Ton NO_x to insure the system can remain in compliance during various dispatch scenarios as well as during scheduled and unscheduled outages. This is particularly prevalent for utility systems with a limited number of operating units.

VI. SUMMARY

The numerous technologies described in this paper will all play a role in the compliance plans being developed to meet new NO_x emission regulations including the new Clean Air Act Amendments. The selection of an optimum NO_x reduction strategy requires a detailed technical and economic analysis.

Plant specific factors such as boiler design, layout and age will make some technologies more feasible than others. Projected mode of operation (baseload, load following or peaking) will influence the economic analysis. These considerations, when weighed with the required level of emission reduction and scheduling constraints, will determine the optimum compliance strategy for each individual unit or the entire utility system.