

# THERMAL DeNO<sub>x</sub> EFFECTIVENESS DEMONSTRATED IN A WOOD-FIRED BOILER

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## ABSTRACT

The THERMAL DeNO<sub>x</sub> process has been successfully applied to a wood-fired, fluidized bed combustor/boiler at Pacific-Ultrapower, Chinese Station, California. NO<sub>x</sub> reductions up to 80% have been achieved with no residual NH<sub>3</sub> emissions. This paper will describe the deNO<sub>x</sub> facilities, provide an assessment of deNO<sub>x</sub> performance and provide details of the cost effectiveness of this deNO<sub>x</sub> installation.

## BACKGROUND

The Pacific-Ultrapower plant is located at Chinese Station, Tuolumne County, California. The plant has a rated electrical output of 25 MWe. The waste wood fuel is comprised of a mixture of wood chips, mill waste and orchard prunings.

Figure 1 is a schematic showing the major components of the boiler and flue gas treatment facilities. The boiler system consists of a fixed fluidized bed combustor supplied by Energy Products of Idaho (EPI). The boiler produces 210,000 lb/hr (90,719 kg/h) of 1250 psig, 950°F (8.62 MPa, 510°C) steam, and is designed to operate an average of 350 days per year.

In order to maintain the desired project schedule, it was necessary for all emission criteria to be within the limits established for PSD permitting. At the time of this project development, this required no emissions

component to exceed 250 tons/year (227 t/year). With a major portion of the fuel supply to include agricultural waste, notably almond tree prunings, the inherent fuel-bound nitrogen levels of approximately 0.3 wt% were significantly higher than the normal 0.07 wt% for wood waste. The NO<sub>x</sub> levels, uncontrolled, were determined to exceed the PSD limits. For this reason, use of the THERMAL DeNO<sub>x</sub> process was considered.

When addition of the NO<sub>x</sub> reduction process was first being considered, many significant advantages became apparent with the fluid bed design. First, the boiler system was primarily a heat recovery unit, with an adiabatic combustor and heat exchange surface located downstream of the fluid bed combustor outlet. Second, being a fluid bed, the operating temperatures could be controlled very uniformly in the combustor. Finally, the potential residence time of flue gases, at temperature, between the combustion zone and the boiler surface could be set simply by increasing the height of the combustor vessel. The result of this was the ability to provide a residence time for NH<sub>3</sub>/NO<sub>x</sub> reaction well in excess of 1 sec. For these reasons, it was possible to use low pressure, fluidizing air as the conveyance medium for ammonia injection.

In addition to the THERMAL DeNO<sub>x</sub> system for controlling the NO<sub>x</sub> emissions, the boiler system is equipped with other types of emission abatement equipment. Particulate removal is accomplished by a

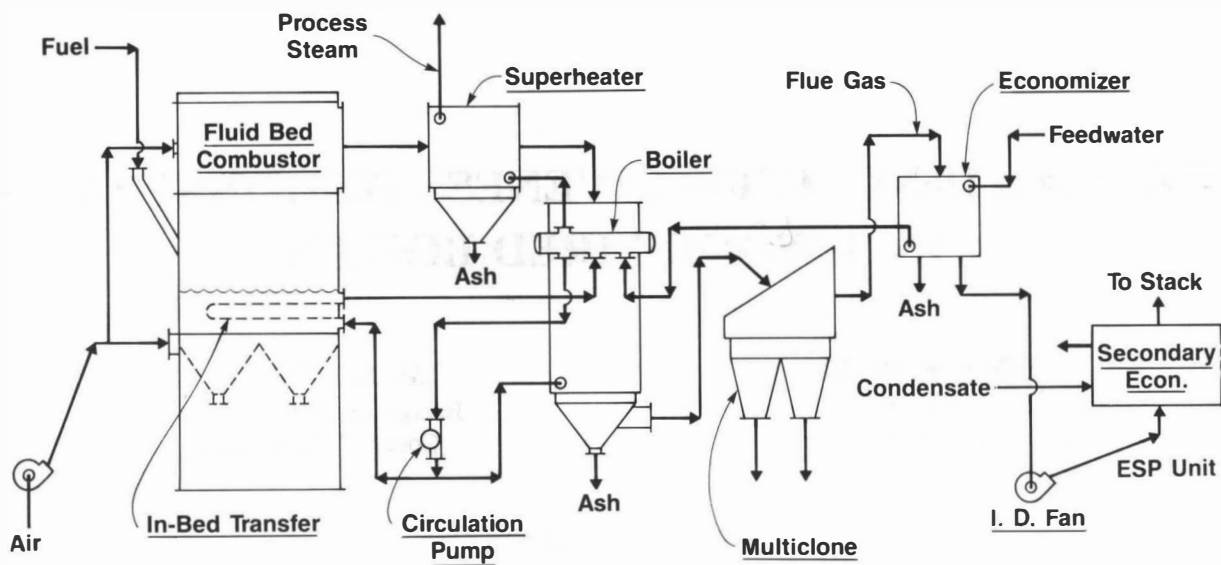


FIG. 1 SCHEMATIC — BOILER AND FLUE GAS TREATMENT FACILITIES  
(Pacific-Ultrapower, Chinese Station, California)

multiclone situated ahead of the primary economizer and an electrostatic precipitator situated ahead of the secondary economizer.

## INTRODUCTION

The THERMAL DeNO<sub>x</sub> process is a selective non-catalytic process involving the injection of NH<sub>3</sub> into high temperature flue gas, whereby NO<sub>x</sub> is reduced to N<sub>2</sub> and H<sub>2</sub>O. This reaction can proceed favorably over a wide temperature range extending from under 1600°F (870°C) up to 2200°F (1204°C). The basic equilibrium reaction involves the following constituents:



The actual reactions total approximately 31 and involve radical chemistry, principally OH<sup>-</sup>, H<sup>+</sup>, O and NH<sub>2</sub>. At the upper end of the temperature range, the deNO<sub>x</sub> reaction is superceded by the oxidation of NH<sub>3</sub> to form additional NO<sub>x</sub>. Thus, if injection occurs at too high a temperature, the addition of NH<sub>3</sub> becomes counterproductive. Conversely, if NH<sub>3</sub> is injected at temperatures below the reaction threshold, NH<sub>3</sub> will simply pass through without reaction with NO<sub>x</sub>. In cases where only low temperature flue gas below 1600°F (870°C) can be treated, it is possible to extend the deNO<sub>x</sub> reaction down to below 1300°F (700°C) by the simultaneous injection of H<sub>2</sub> and NH<sub>3</sub>.

TABLE 1 THERMAL DeNO<sub>x</sub> EXPERIENCE SUMMARY

	Installed	Design/ Construction
Japanese Industrial Boilers	4	
Japanese Utility Boilers	5	
Japanese Petroleum Heaters	4	
Japanese Municipal Incinerator	1	
USA Flat Glass Melting Furnaces	2	1
USA Petroleum Heaters	30	
USA Utility Boiler	1	
USA Industrial Boilers	3	1
USA Incinerators	6	14
USA Oil Field Steamers	6	
USA Wood-Fired Boilers	3	5
German Coal-Fired Utility Boilers	2	2
German Incinerators		1

Experience with this process is extensive, including over 80 installations to date, as shown in Table 1. Included are two additional wood-fired units, both equipped with grate type combustors. Both of these installations have achieved successful NO<sub>x</sub> reductions to meet permit requirements.

For this installation, the NO<sub>x</sub> emission limitation of 250 tons/year (227 t/year) equates to approximately 0.15 lb/MBtu (0.07 kg/GJ) or 85 vppm. Based on a predicted uncontrolled NO<sub>x</sub> concentration in the flue

TABLE 2 THERMAL DeNO<sub>x</sub> DESIGN BASIS

Case	Fuel Moisture, wt%	Flue Gas Rate, lb/hr	Flue Gas Temp, °F	Excess O <sub>2</sub> , vol%	H <sub>2</sub> O, vol%	Untreated NO <sub>x</sub> , vppm
1	51	467,192	1720	5	26	200
2	38	475,825	1830	7	22	200
3	--	495,802	1590	5	26	200
4	--	495,802	1960	5	26	200

1 kg/hr = 2.2046 US lb/hr  
 °F=1.8°C + 32

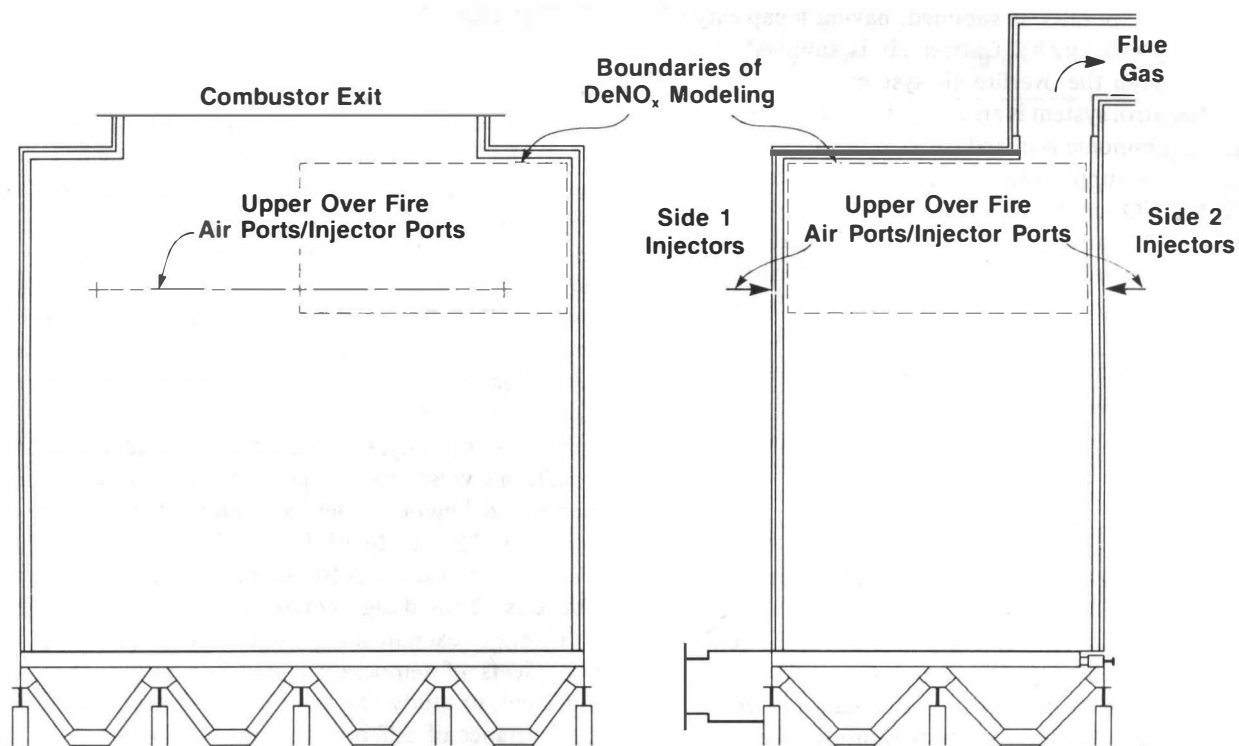


FIG. 2 COMBUSTOR CROSS-SECTION SHOWING DeNO<sub>x</sub> MODELING LOCATION (Pacific-Ultrapower, Chinese Station, California)

gas of 180 vppm (max.), the THERMAL DeNO<sub>x</sub> system would be required to achieve 53% reduction. In order to insure sufficient deNO<sub>x</sub> capability to meet the NO<sub>x</sub> target, the actual design basis was expanded by increasing the uncontrolled NO<sub>x</sub> to 200 vppm and reducing the outlet target NO<sub>x</sub> to 75 vppm. These data, as well as other design basis data, are found in Table 2.

### DeNO<sub>x</sub> FACILITIES

The NH<sub>3</sub> injection facilities for this installation consist of two sets of injectors, one each on opposite sidewalls of the combustor at the position indicated on Fig. 2. Each of the zones have separate controls for the carrier air and NH<sub>3</sub>. Ammonia is stored in a 12,000 gal (45.4 m<sup>3</sup>) storage tank. One electrically heated

TABLE 3 PREDICTED THERMAL DeNO<sub>x</sub> PERFORMANCE BASED ON TABLE 2 CONDITIONS

Case	Untreated NO <sub>x</sub> , vppm	Outlet (Treated) NO <sub>x</sub> , vppm	deNO <sub>x</sub> , %	Average NH <sub>3</sub> /NO <sub>x</sub> (mole ratio)	NH <sub>3</sub> Breakthrough, vppm
1	200	75	62.5	1.5	65
2	200	75	62.5	2.0	45
3	200	122	39.0	1.0	65
4	200	125	37.5	3.0	5

ammonia evaporator is supplied, having a capacity of 150 lb/hr (68 kg/h). Carrier air is supplied at low pressure from the overfire air system.

The control system is an analog semi-automatic type. Gaseous ammonia is mixed with carrier air fed through appropriate supply lines to the injectors, and mixed with the NO<sub>x</sub>-containing flue gas. Ammonia and carrier air rates are the manipulated variables. The independent variables, flue gas flow rate and initial NO<sub>x</sub>, are indirectly determined by measuring combustor load parameters (i.e., combustor air flow rate, steam flow rate, fuel flow rate) and outlet flue gas parameters (i.e., NO<sub>x</sub>, NH<sub>3</sub>, excess O<sub>2</sub>).

### PREDICTED PERFORMANCE

Predicted deNO<sub>x</sub> system performance data for four cases are shown in Table 3. Cases 1 and 2 are actual design cases for two different fuel moisture contents where 62.5% deNO<sub>x</sub> is predicted. Cases 3 and 4 show the adverse effect on deNO<sub>x</sub> performance of reducing or increasing the flue gas temperature in the reaction zone.

These results were obtained by a combination of three-dimensional flow modeling reaction kinetics calculations. Input to the flow modeling program consists of the flue gas flow field at an appropriate point upstream of the injector locations described in terms of temperature and velocity profiles and the combustor geometry. Similarly, the physical data for the wall jets are defined. At the point of injection, and any plane beyond, the program calculates mixing of the wall jets with flue gas in terms of temperature profiles, NH<sub>3</sub> and NO<sub>x</sub> concentration profiles, velocity profiles, etc. The variations of these conditions with time serve as input to the kinetic model which then calculates deNO<sub>x</sub> performance and residual NH<sub>3</sub>.

### FIELD TEST DATA

A limited amount of test data is available for this system as summarized in Table 4. Major differences occur between the predicted deNO<sub>x</sub> and the test data. First, the initial NO<sub>x</sub> level is 125 vppm which is substantially lower than the design basis value of 200 vppm. Secondly, the relative amount of NH<sub>3</sub> required to achieve high performance is NH<sub>3</sub>/NO<sub>x</sub> = 4, whereas the design condition is NH<sub>3</sub>/NO<sub>x</sub> = 2. Also, the excess O<sub>2</sub> at the time of the testing was 10% versus the design values of 5% or 7%. All of these values enter into the process kinetics to provide different performance results.

In order to analyze the impact of the actual operating conditions versus the design basis conditions, we have performed kinetic model calculations for comparison purposes. The results of the calculations are shown in Fig. 3 where Case 1 is for actual operating conditions and Case 2 for design conditions. Even though these calculations exclude mass transfer effects (mixing) and the effects of temperature maldistribution, they are sufficient to study the qualitative impact on deNO<sub>x</sub> performance of different flue gas conditions.

Referring to Fig. 3 and Table 4, there are several conclusions which can be drawn from these calculations/data:

(a) The actual operating conditions (Case 1), having both higher excess O<sub>2</sub> and lower untreated NO<sub>x</sub> than Case 2, serve to reduce the deNO<sub>x</sub> process effectiveness in terms of % deNO<sub>x</sub> and NH<sub>3</sub> breakthrough.

(b) In order to achieve similar levels of deNO<sub>x</sub> for Case 1 as Case 2, it is necessary to increase the relative amount of NH<sub>3</sub> injection to NH<sub>3</sub>/NO<sub>x</sub>=4. This is consistent with the data shown in Table 4.

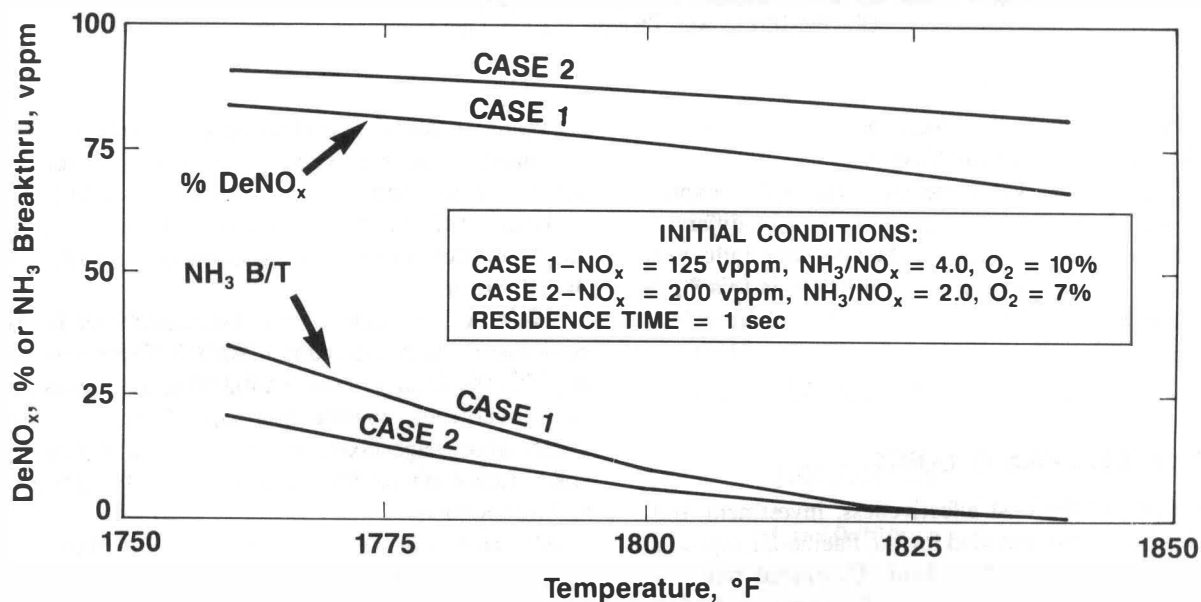
(c) In the range of temperatures tested and for which calculations were performed, % deNO<sub>x</sub> decreases with increasing temperature at a given NH<sub>3</sub> injection rate. For instance, compare tests 5, 6 and 8 in Table 4.

TABLE 4 FIELD TEST DATA  
(Pacific-Ultrapower 210,000 lb/hr Boiler)

Test	Outlet NO <sub>x</sub> , vppm	deNO <sub>x</sub> <sup>(1)</sup> , %	NH <sub>3</sub> /NO <sub>x</sub> (mole ratio)	NH <sub>3</sub> Breakthrough, vppm	Flue Gas Rate, SCFM (dry)	Excess O <sub>2</sub> , vol% (dry)	Measured Avg. Flue Gas Temp.(2), °F
1	70	44.0	2.1	0	96,400	10.6	1738
2	69	44.8	2.1	0	96,400	10.2	1740
3	113	-	-	0	96,400	9.9	1739
4	129	-	-	0	96,400	10.4	1727
5	25	80.0	4	0	96,400	9.9	1746
6	42	66.4	4	0	96,400	10.0	1771
7	125	-	0	0	96,400	10.0	1764
8	45	64.0	4	0	96,400	10.0	(1760) est.

- (1) Based on 125 vppm NO<sub>x</sub> in untreated flue gas.  
(2) Temperature data are uncorrected thermocouple readings.

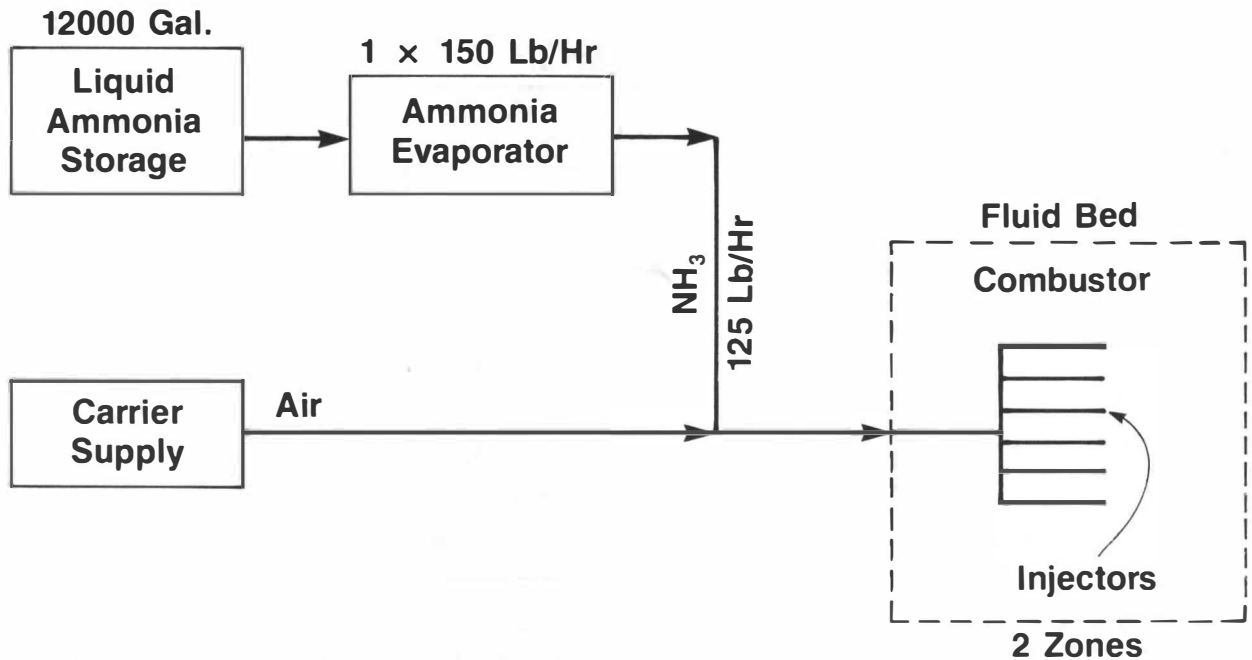
1 kg = 2.2046 US lb  
1 SCFM = 1.503 Nm<sup>3</sup>/hr  
°F = 1.8°C + 32



Note: Excludes mass transfer effects and actual reaction times, hence cannot be compared directly to performance data.

$$^{\circ}\text{F} = 1.8^{\circ}\text{C} + 32$$

FIG. 3 DeNO<sub>x</sub> KINETIC CALCULATIONS  
(Pacific-Ultrapower, Chinese Station, California)



1 m<sup>3</sup> = 264 US Gallons  
 1 Kg/Hr = 2.2046 US Lb/Hr

FIG. 4 SIMPLIFIED THERMAL DeNO<sub>x</sub> SUPPLY SYSTEM FLOW DIAGRAM  
 (Pacific-Ultrapower, Chinese Station, California)

According to Fig. 3, this decrease is more rapid for Case 1 conditions than for Case 2.

(d) High deNO<sub>x</sub> was achieved in this unit, in spite of the actual conditions being significantly different than design conditions, due to the favorable influence of flue gas temperature and residence time in this fluid bed geometry.

#### HOW MUCH DOES IT COST?

To illustrate the cost effectiveness, investment and operating costs are provided for the Pacific-Ultrapower facility operating at 100% load. Untreated flue gas contains 125 vppm NO<sub>x</sub> at 12% CO<sub>2</sub> (dry), and 80% NO<sub>x</sub> removal is achieved.

The deNO<sub>x</sub> facilities include one 150 lb/hr (68 kg/h) NH<sub>3</sub> vaporizer, one 12,000 gal (45.4m<sup>3</sup>) liquid NH<sub>3</sub> storage tank, two zones of injectors, piping and analog instrumentation. A schematic of the deNO<sub>x</sub> system is shown in Fig. 4. The vaporizer is designed to provide NH<sub>3</sub> for both units at the maximum rate required, and is electrically heated. The storage tank holds sufficient

ammonia to allow operation of both boilers for approximately two weeks at design load. Two zones of independently controlled injectors are provided one for each side of the boiler, because of the variations in flue gas flow rates that can be expected on opposite sides of this boiler.

As shown in Table 5, the investment cost for the equipment totally erected is \$190,000. Equipment cost is \$150,000. Indirect cost is \$40,000 and includes field labor overheads, construction supervision and equipment, labor wage taxes, erection fee and engineering costs. Costs are on the third quarter 1985 Southern California basis.

Also shown in Table 5 is the cost effectiveness for this installation in \$/lb (\$/kg) of NO<sub>x</sub> removed. Annualized costs are obtained by assuming a 5-year pay-out on investment and adding annual operating costs. For this system, the cost effectiveness is \$0.30/lb (\$.066/kg) NO<sub>x</sub> removed.

Annual operating costs are shown in Table 6. These costs are based on a 100% load factor, and include values for NH<sub>3</sub>, and electric power for NH<sub>3</sub> vaporization. The operating cost is \$0.24/lb (\$.53/kg) NO<sub>x</sub> removed.

TABLE 5 INVESTMENT COST AND COST EFFECTIVENESS FOR THERMAL DeNO<sub>x</sub> APPLIED TO 210,000 Lb/Hr WOOD-FIRED BOILER

Capital Investment <sup>(1)</sup> , k\$	190
Equipment <sup>(2)</sup>	150
Indirect <sup>(3)</sup>	40
Total	190
Cost Effectiveness <sup>(4)</sup>	
\$/lb (\$/kg) NO <sub>x</sub> removed	0.30 (0.66)

Notes:

1. Investment costs are on a third quarter 1985 Southern California basis.
2. Includes equipment items identified in text.
3. Includes field labor overheads, construction supervision and equipment, labor wage taxes, erection fee, engineering costs and contingency.
4. Cost effectiveness is based on an annualized cost consisting of capital based on a 5-year payout and annual operating cost. This is divided by annual NO<sub>x</sub> reduction based on 80% NO<sub>x</sub> removal.

1 kg = 2.2046 US lb

TABLE 6 ANNUAL OPERATING COSTS FOR THERMAL DeNO<sub>x</sub> APPLIED TO 210,000 Lb/Hr WOOD-FIRED BOILER

Item	Annual Consumption <sup>(1)</sup>	Unit Cost	Annual Cost
Ammonia	548 US Tons	\$250/US ton	\$137,000
Electricity <sup>(2)</sup>	177 MWh	\$ 60/MWh	<u>\$10,620</u>
			\$147,620

Notes:

1. Assumes 100% load factor.
2. Power requirement for NH<sub>3</sub> vaporizer.

1 US ton = 907.2 kg

1 MWh = 3.6 GJ

## SUMMARY

This paper illustrates the deNO<sub>x</sub> effectiveness of a THERMAL DeNO<sub>x</sub> ammonia injection system for a fluidized bed wood-fired boiler. Significant NO<sub>x</sub> reductions have been achieved in a very cost effective

manner with no impact on the operation of the boiler or other flue gas cleanup equipment. Even though certain key operating conditions differed from design conditions by a substantial amount, the process demonstrated sufficient flexibility to perform well at the off-design conditions.