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Project Summary

Evaluation of Natural- and Forced-Draft Staging Air Systems for Nitric Oxide Reduction in Refinery Process Heaters

R. C. Benson

Results of pilot-scale tests to evaluate combustion modifications for emission reduction and efficiency enhancement on petroleum process heaters are reported. Objectives were to determine nitric oxide (NO) emission reductions, thermal efficiency changes, long-term performance, and cost of both natural- and forced-draft staged-combustion-air modifications. Forced-draft staged-combustion-air modifications had been shown to be the most promising combustion modification in previous pilot-scale tests. The test unit was a vertical, cylindrical, natural-draft crude heater, and the test fuels were natural gas, refinery gas, and a combination of No. 6 oil and refinery gas. The unit had a 16 MW heat input capacity and was capable of a maximum throughput of 108 m^3/h of crude oil (rated input 96 m^3/h).

A natural-draft staging air system, capable of providing 50 percent of the staging air for 100 percent refinery gas firing and crude charge rates of 55 - 90 percent rated capacity, reduced NO emissions by about 50 percent. The stack O_2 was lowered from 4 percent baseline to 2 percent low NO condition. The efficiency gain with the natural-draft staging air system was about 1.5 percent. Natural-draft staged combustion air (4 percent stack O_2) with 80 percent oil/20 percent gas firing provided NO reduction of 30 percent and an average efficiency gain of 0.6 percent. Lowered excess air with staging (4 to 2 percent O_2) for the 80/20 mix provided an NO reduction of about 60 percent and an average efficiency gain of 3.6 percent, but unacceptable CO emissions and smoking problems. While firing 80 percent oil/20 percent gas, the forced-draft staging air system provided about 40 percent of the total combustion air and an NO reduction of 40 percent (6 percent baseline stack O_2 to 3 percent low NO stack O_2). The efficiency gain with the forced-draft staging air system was 5 percent. A 15-day evaluation of the natural-draft staged air system revealed no special operating difficulties or process constraints. Costs of the natural- and forced-draft staged air systems are compared. The natural-draft system (staging with lowered excess air) has a cost of $0.03/lb NO on 29.3 MW natural-draft process heater, compared to $0.32/lb NO for a forced-draft system.

This Project Summary was developed by EPA's Industrial Environmental Research Laboratory, Research Triangle Park, NC, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

The test work reported here includes results of combustion modifications for NO control on a refinery process heater. The crude heater tested is the same one described in EPA Contract 68-02-2645. The heater is a natural-draft, vertical, cylindrical crude heater containing six burners, capable of gas and/or oil fuel firing. Of the advanced combustion modification concepts considered for NO control, staged air lances were considered a feasible approach. The test program has two objectives with respect to staged air lances: (1) to evaluate the potential of natural-draft staged air lances for reducing NO emissions and increasing thermal efficiency; and (2) to evaluate the performance of a staged air system on a heater firing 100 percent residual oil. The heater could not be run on 100 percent oil as originally hoped. The original plan was to have a temperature controlled valve in the oil line to automatically adjust oil and gas flow rates to satisfy thermal input requirements. Since the valve was never installed, the crude oil outlet temperature was automatically controlled by gas flow and manually controlled by oil flow. For safety and control, the plant could not run the heater solely on manual control. The staged air system has 24 ports (4 per burner) through which either natural- or forced-draft staged air may pass.

Table 1 summarizes the significant results obtained during the pilot-scale test program. Natural-draft staged combustion air lowered NO emissions by about 45 percent, while low excess air decreased NO emissions by 20 percent with 100 percent gas firing. The stack O_2 was maintained at about 4 percent for the staged air test and lowered from 4 to 2 percent for the low excess air test. In a short term test, the combination of natural-draft staged combustion air and lowered excess air reduced NO emissions by about 50 percent (4.1 to 2.6 percent stack O_2) while decreasing gas consumption about 1-2 percent.

Forced-draft staged combustion air with 80 percent oil/20 percent gas firing (6 percent stack O_2) lowered NO emissions by about the same amount (20-25 percent) as low excess air with no staging (6 to 4 percent O_2). Lowered excess air together with staged combustion air reduced NO emissions by 40 percent (6 to 3 percent O_2) on natural-draft vertical cylindrical heater firing 80 percent oil/20 percent gas.

In addition to the testing described, a 15-day evaluation of the natural-draft staged air system was made. Cost analyses of the natural- and forced-draft staged air systems were performed to compare the two systems.

Test Heater Description

The test unit is a natural-draft, vertical, cylindrical crude oil process heater, used to supply a heated charge to a crude oil distillation column. A maximum load of 108 m^3/h (16,250 bbl/d) could be sent through the heater in two passes. The rated capacity of the heater is 91.8 m^3/h (14,000 bbl/day).

The maximum firing rate of the heater is 16.1 MW thermal input (55 x 10^6 Btu/hr). It is fired by six John Zink DBA-22 natural-draft burners. The burners are combination gas/oil burners rated at a maximum of 2.68 MW (9.14 x 10^6 Btu/hr) each with a turndown ratio of 3:1. Although combination gas/oil burners are used, some gas is always fired because the unit is base loaded on oil fuel and an automatic temperature controller adjusts the gas fuel flow to maintain crude oil outlet temperature.

Staged Air Systems

The forced draft system consisted of 24 vertical 316L stainless steel pipes of 3.18 cm (1-1/4 in.) diameter arranged four-per-burner, 90 deg. apart. A 45-deg. elbow on each pipe provided better mixing across the flame. A fan supplied air to the lances through a manifold and flexible tubing. The lances could be varied in height up to 1.2 m (4 ft) from the floor of the heater. Extensions for the lances allowed staging heights up to 2.4 m (8 ft) for oil firing tests.

For the natural-draft system, holes were drilled through the heater floor so that one end of the 4-in. pipe would be flush against the heater floor and the other end (threaded for pipe caps) would protrude a few inches below the heater floor. For the natural-draft staged air tests, the pipe caps were removed and 1-1/4 in. lances, 3-in. lances, or the 4-in. ports were used.

Emissions Test Instrumentation

All emission measurement instruments (see Table 2) were carried in a 12.8 x 2.4 m (42 x 8 ft) mobile laboratory trailer. The

Table 2. *Emission Measurement Instrumentation*

Species	Manufacturer	Measurement Method	Model No.
Carbon Monoxide	Beckman Instuments	IR Spectrometer	865
Oxygen	Teledyne	Polarographic	326A
Carbon Dioxide	Beckman Instruments	IR Spectrometer	864
Nitrogen Oxides	Thermo Electron Co.	Chemiluminescent	10A
Particulates	Andersen Samplers, Inc.	EPA Method 5 Train	EPA
Sulfur Dioxide	DuPont Instruments	UV Spectrometer	400
Particle Sizing	Andersen Samplers, Inc.	Cascade Impactor	Mark III
Smoke Spot	Bacharach	ASTM 2156-65	RCC
Opacity		EPA Method 9	
Sulfur Oxides		Goksoyr-Ross	

Table 1. *Summary of Combustion Modification Tests on a Pilot-Scale Process Heater*

Heat Input MW_T	Fuel	Baseline O_2, %	Combus. Mod. O_2, %	Baseline NO ng/J	Baseline NO ppm dry at 3% O_2	Percent Staging Air	NO Reduction from Baseline %	Change in Fuel Consumption, %	Combustion Modification[a]
14.2	Ref. Gas	4	3.9	67	131	40	43	-1.1	ND (SCA) 4" ports
12.8	Ref. Gas	4.2	3.8	73	142	33	21	0	ND (SCA) 3" lances
12.9	Ref. Gas	3.6	3.4	70	138	8	12	+1.8	ND (SCA) 1-1/4" lances
15.6	Ref. Gas	4	2.0	78	152	--[b]	21	-1.3	LEA
14.4	Ref. Gas	4.1	2.6	78	152	45	46	-1.4	ND (SCA + LEA) 4" ports
10.7	80% Oil/20% Gas	3.8	3.8	135	265	41	25	-4.5	FD (SCA)
9.4	80% Oil/20% Gas	4.1	2.0	167	328	--[b]	28	-2.4	LEA (4% + 2% O_2)
13.6	80% Oil/20% Gas	5.7	4.1	140	344	--[b]	13	-2.5	LEA (5.7% + 4.1% O_2)
15.2	80% Oil/20% Gas	6.1	3	176	345	39	37	-6.0	FD (SCA + LEA) 6% + 3% O_2

[a]FD = forced draft, LEA = lowered excess air, ND = natural draft, and SCA = staged combustion air.
[b]No staging.

gaseous species measurements were made with analyzers located in the trailer.

Baseline Conditions

Baseline conditions were 4 percent stack O_2 for 100 percent gas firing and 4 - 6 percent stack O_2 for 80 percent oil/20 percent gas firing. The 4 percent stack O_2 for 100 percent gas firing is considered to be a normal operating level by plant personnel. The 4 percent stack O_2 baseline for 80 percent oil/20 percent gas firing was also considered to be a viable starting point by plant pesonnel and also would permit direct comparison of NO emission data previously collected at the 50 percent oil/50 percent gas firing condition (Ref. EPA-600/7-83-022). Baseline stack O_2 of 4 percent was initially achieved for several test days under various thermal input rates and crude charge rates. However, some test series at the low and medium loads from February 22, 1983, onward could not be run at 4 percent baseline O_2 without making extreme stack damper and register adjustments. It is not clear why the 4 percent baseline O_2 was more difficult to achieve on some test days. Reasons may include the crude inlet temperature change (which alters the fuel input to maintain constant crude outlet temperature) or the fuel composition ratio (80 percent oil/20 percent gas) which was not burning effectively at lower stack O_2 levels. These baseline conditions could be achieved solely with stack damper and secondary air register adjustments (i.e., no combustion modifications). The 4 percent stack O_2 for 100 percent gas firing and 6 percent stack O_2 for the 80/20 oil/gas mixture was achievable under all process rates studied (55-96 percent full load). The baseline conditions were established to determine the extent of NO reduction to 2 percent stack O_2 on 100 percent gas firing and typically 3 percent O_2 on an 80/20 oil/gas mixture.

Results

Natural-Draft Staged Air

Three staged air injection configurations were tested using 4-in. ports, 3-in. pipe, and 1-1/4 in. pipe, respectively. Load was maintained nominally at 80 percent rated capacity and stack O_2 of 4 percent for testing with the three configurations. The 4-in. ports provided the most staging air: about 40 percent of the total combustion air.

The 4-in. ports achieved the greatest NO reduction. A reduction of about 45-50 percent was achieved from baseline conditions (SCA only).

The burner equivalence ratio,

$$\Phi_B = \frac{(air/fuel)_{burner}}{(air/fuel)_{stoichiometric}}$$

was about 0.72 with the secondary air registers 10 percent open. At this minimum Φ_B, NO emissions decreased 47 percent below the baseline of 131 ppm dry at 3 percent O_2 (67 ng/J). The 4-in. ports are flush with the heater floor; whereas, the pipes could be inserted through the ports to introduce the staging air higher above the heater floor.

Since the 4-in. ports had provided the most staging and NO reduction of the diameters tried, further testing with load variations and O_2 variations were conducted with the 4-in. ports. The three loads tested were 55, 80, and 90 percent rated capacity with O_2 variation from about 2 - 6 percent stack O_2. Under these conditions, the CO concentration levels measured were minimal, and flame impingement was not a problem.

Figure 1 shows the effect of staging (decreased burner equivalence ratio) on NO emissions. The crude charge rate for this test series was 52.7 m^3/hr (8000 bbl/day), 55 percent of rated capacity. For each O_2 level (2,4 percent), the burner equivalence ratio was lowered in increments by closing the stack damper and closing down the burner air registers to 50, 33, or 10 percent open. The minimum Φ_B for any O_2 level was that associated with the registers 10 percent open. At 4 percent O_2 (SCA only), the minimum Φ_B obtained was 0.63 (48 percent of total air is staged air) which reduced NO emissions 48 percent below the baseline of 152

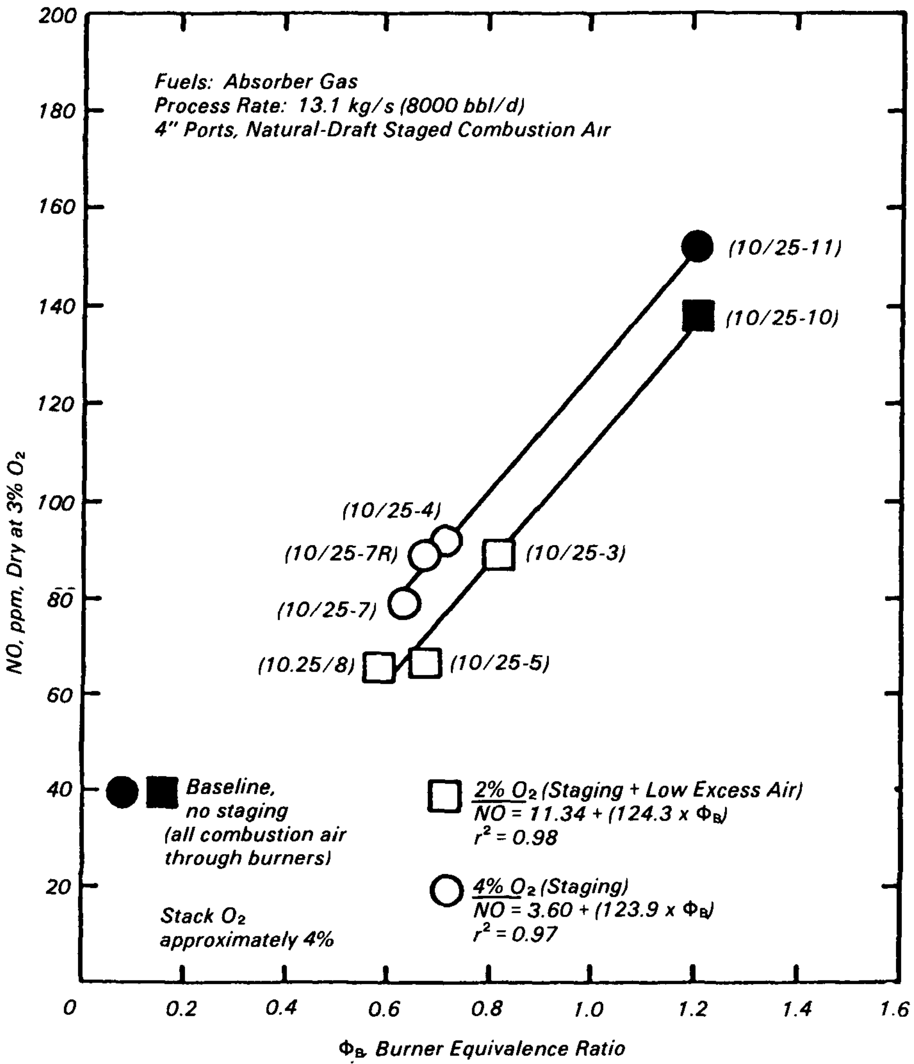

Figure 1. NO emissions at two different stack O_2 concentrations as a function of burner equivalence ratio.

ppm, dry at 3 percent O_2. At 2.3 percent O_2 (SCA + LEA from a stack O_2 percent of 3.7), the minimum Φ_B obtained was 0.58 (51 percent of total air is staged air) which reduced NO emissions 51 percent below the baseline.

Percent changes in fuel consumption with NO reduction were calculated to show the extent of fuel savings with staged air combustion modification, lowered excess air, and staged air combined with lowered excess air. Staged combustion air at 4 percent and 2 percent O_2 (no lowered excess air) showed consistent NO reduction rates 45 - 50 percent. Average fuel savings are on the order of 0.5 - 1 percent. The fuel savings become more significant (on the order of 1 - 2 percent) with staged air combined with lowered excess air.

Forced-Draft Staged Air System

Tests were initially conducted with the forced-draft staged-combustion-air system to assess the levels of NO reduction attainable at various staging heights and burner equivalence ratios. Only 1-1/4 in. lances were tested with the forced-draft system. The optimum stage height for NO reduction and minimal CO and smoke was determined to be 4 ft with the lance tips oriented toward the burner centerline.

Figure 2 shows NO emissions as a function of burner equivalence ratio for two O_2 levels. The staging height for these tests was 1.2 m (4 ft) and the crude charge rate was 76 m^3/h (11,500 bbl/day). The Φ_B was decreased in increments to its minimum value determined by limitations of the staged air combustion fan. At 4 percent O_2, the minimum Φ_B (maximum staging) obtained was 0.71 which decreased NO emissions 24 percent below the baseline of 265 ppm NO, dry at 3 percent stack O_2. About 40 percent of the total combustion air was injected through the 24 1-1/4 in. lances for the 4 percent stack O_2 tests, while 29 percent of the total combustion air was injected through the lances for the 6 percent stack O_2 tests. The lower percent staged air for the 6 percent stack O_2 tests is due in part to the higher fuel heat input rate that day.

The efficiency gains were significant with 80 percent oil/20 percent gas firing and forced-draft staged combustion air. The change in fuel consumption relative to baseline when SCA was applied was 3.5 percent for 6 percent stack O_2. Lowered excess air and forced-draft staged combustion air reduces fuel consumption by 6 percent.

Natural- Versus Forced-Draft Staging

Figure 3 compares the effectiveness of natural- with forced-draft staged air for NO reduction only. In this instance, the process rate was maintained at about 14,000 bbl/day and stack O_2 maintained at 4 percent for baseline and staging conditions. The results show that, for maximum staging (minimum Φ_B), the 4-in. ports (NDSCA) and 1-1/4 in. lances (FDSCA) provide very comparable NO reduction for about the same staging. Note that the 1-1/4 in. lances of the forced-draft system mixed the air and fuel better, resulting in lower amounts of smoke and CO compared with the 4-in. ports of the natural-draft system.

Long Term Test (Natural-Draft Staging with 3-in. Lances)

Figure 4 shows the baseline and staging data of NO versus stack O_2. Linear regression analyses were run for both the baseline and staged-air data points. The linear regression analysis shows a very good correlation for the staged air data (coefficient of determination, r^2 = 0.9), while the coefficient of determination is fairly good for the baseline data (r^2 = 0.78). Calculations with the linear curve fit equations were performed to determine the extent of NO reduction with staging only (SCA) and a combination of staging and low excess air (SCE + LEA). The NO reduction from baseline is about 15 percent with staging

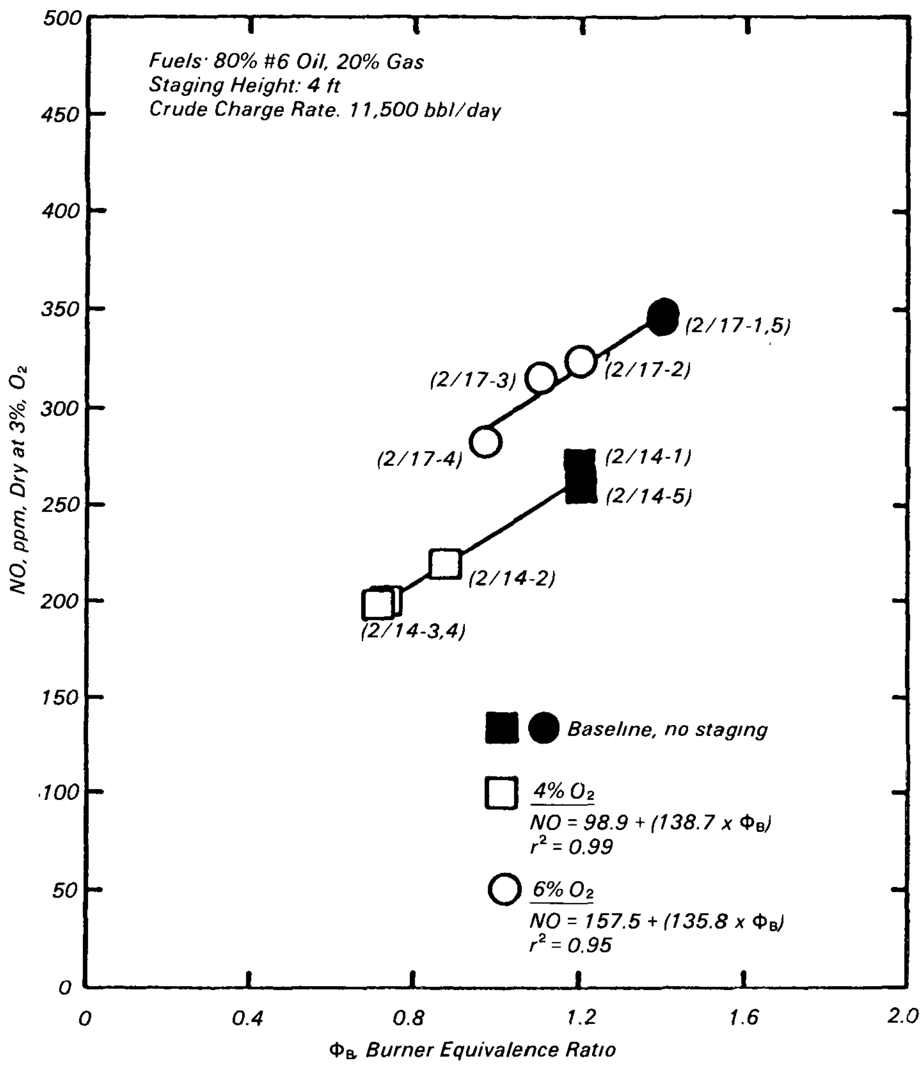

Figure 2. *NO emissions as a function of burner equivalence ratio for two stack O_2 concentrations.*

only, and about 28 percent with staging and low excess air.

Cost Analysis of Staged Combustion Air Applied to a Natural-Draft Process Heater

Total annualized costs for 16.1, 29.3, and 147 MW thermal input process heaters were calculated for SCA, LEA, and SCA + LEA. These total annualized costs were then divided by the annual NO_x reduction potential (Table 3) to give a dollar amount per metric ton of NO_x removed by the modification (Table 4). The savings of natural-draft staged combustion air on a natural-draft process heater applied at normal stack O_2 are calculated as $714/Mg NO_x reduction for a 16.1 MW heater, increasing to $964/Mg at 147 MW heat input. The cost of natural-draft staged air combined with lowered excess air on a natural-draft crude heater is calculated as $336/Mg NO_x reduction for 16.1 MW unit and a savings of $435/Mg NO_x reduction for a 147 MW unit. The net cost at lower unit heat rates with the combined modification is due to an automatic stack draft controller that permits operating the heater at lowered O_2.

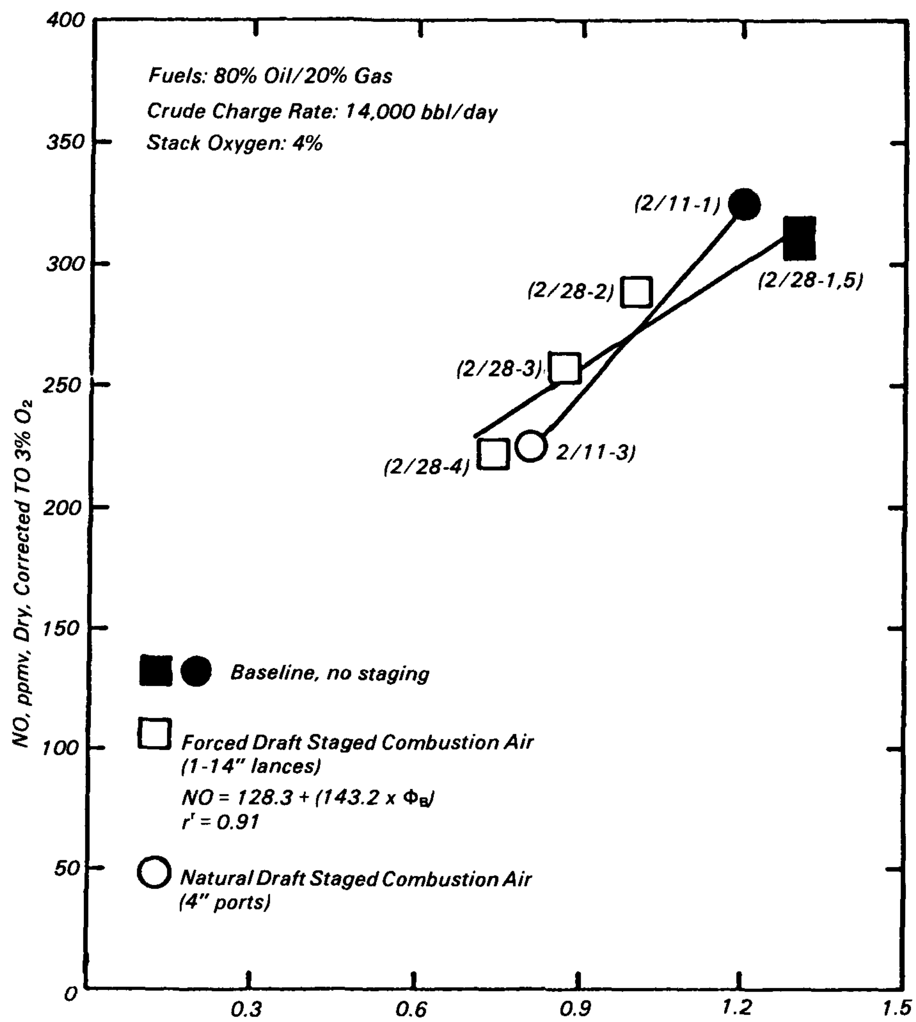

Figure 3. *NO emissions as a function of burner equivalence ratio for natural- and forced-draft staged air.*

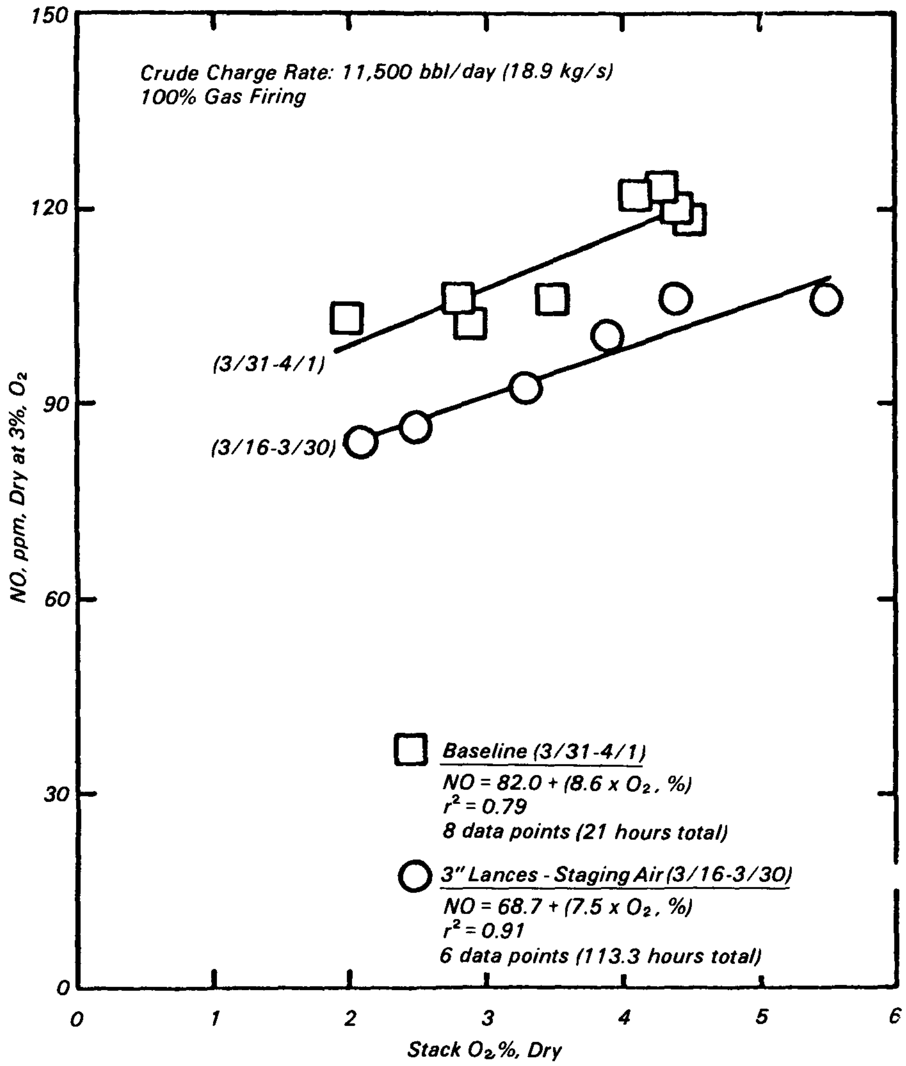

Figure 4. NO versus O_2 under baseline and staging conditions.

Table 3. *Annual NO Reduction Potential of Combustion Modifications for Three Heater Sizes*

Modification/Test Series	Baseline NO (ng/J)	ng/J Reduction	% Reduction from Baseline	NO Reduction, Mg/yr[a] 16.1 MW	29.3 MW	147 MW
Natural-Draft Staged Combustion Air, 100% Gas Firing (4% O_2) / 10/8/82	67	30	45	10.7	19.4	97.7
Natural-Draft Staged Combustion Air + Lowered Excess Air, 100% Gas Firing (4% + 2% O_2) / 10/27/82	73	40	55	14.2	25.9	129.7
Lowered Excess Air, 100% Gas Firing (4% + 2% O_2) / 10/27/82	67	10	15	3.7	6.8	34.1
Lowered Excess Air, 50% #6 Oil/50% Gas Firing (4.1% + 1.8% O_2)[b]	114	32	28	11.4	20.7	103.8
Lowered Excess Air, 80% #6 Oil/20% Gas Firing (4.5% + 1.8% O_2) / 2/11/83	176	60	34	18.1	33.0	165.4

[a]Mg/yr = megagrams per year.
[b]Tidona, R.J. et al., "Refinery Process Heater NO_x Reductions Using Staged Combustion Air Lances," EPA-600/7-83-022 (NTIS No. PB83-193946), March 1983.

Table 4. *Cost Effectiveness Ratio of Combustion Modifications Applied to Three Natural-Draft Process Heater Sizes*

	16 1 MW			29.3 MW			147 MW		
Modification	Total Annualized Costs $ (Savings)	Annual Reduc. Poten. Mg/yr[a]	Cost Effec. Ratio $/Mg	Total Annualized Costs $ (Savings)	Annual Reduc. Poten. Mg/yr[a]	Cost Effec. Ratio $/Mg	Total Annualized Costs $ (Savings)	Annual Reduc. Poten. Mg/yr[a]	Cost Effect. Ratio $/Mg
Natural-Draft Staged Combustion Air 100% Gas Firing (4% O_2)	(7,642)	10.7	(714)	(15,593)	19.4	(804)	(94,146)	97.7	(964)
Natural-Draft Staged Combustion Air + Lowered Excess Air, 100% Gas Firing (4% + 2% O_2)	4,775	14.2	336	1,770	25.9	68	(56,475)	129.7	(435)
Lowered Excess Air, 100% Gas Firing Firing (4% + 2% O_2)	812	3.7	218	(3,755)	6.8	(543)	(68,263)	34.1	(1,997)
Lowered Excess Air, 80% #6 Oil/20% Gas Firing (4.5% + 1.8% O_2)	(30,516)	18.1	(1,686)	(60,798)	33.0	(1,842)	(354,201)	165.4	(2,141)
Lowered Excess Air, 50% #6 Oil/50% Gas Firing (4.1% + 1.8 % O_2	(18,914)	11.4	(1,659)	(39,652)	20.7	(1,911)	(248,270)	103.8	(2,392)

[a]Mg/yr = megagrams per year.

R. C. Benson is with KVB, Inc., Irvine, CA 92714.
***Robert E. Hall** is the EPA Project Officer (see below).*
The complete report, entitled "Evaluation of Natural- and Forced-Draft Staging Air Systems for Nitric Oxide Reduction in Refinery Process Heaters," consists of two volumes:
"Volume I. Technical Report," (Order No. PB 84-229 640; Cost $20.50, subject to change).
"Volume II. Data Supplement," (Order No. PB 84-229 657; Cost 17.50, subject to change).
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