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Research and Development

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Project Summary

Application of Advanced Combustion Modifications to Industrial Process Equipment—Subscale Test Results

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Results of subscale tests to evaluate combustion modifications for emission control on petroleum process heaters, cement kilns, and steel furnaces are reported. The objective was to assess applicability, NO_x emissions reductions, and cost effectiveness of several modifications and to select the most promising for pilot scale tests. Subscale process heater baseline NO_x emissions were about 55 ng/J firing natural gas at 2.9 MW heat input. NO_x was reduced by 67% with staged combustion (SC) and by 63% with flue gas recirculation (FGR). Firing No. 6 oil, baseline NO_x of 160 ng/J was reduced by 51% with SC and by 39% with FGR. SC was selected for pilot scale tests. Subscale cement kiln baseline NO_x emissions were 30-60 ng/J firing natural gas at about 80 kW heat input. Fly ash, kiln dust, water, and sulfur were injected separately to evaluate the NO_x reduction potential. Fly ash injection reduced NO_x emissions by 28%, while the other injectants reduced NO_x by 12-20%. Further work on a larger scale is planned prior to selecting modifications for pilot scale tests. For the subscale steel furnace, baseline NO_x emissions of 115 ng/J firing natural gas at 0.6 MW heat input were reduced by 88% with FGR and by 47% with water injection. Firing No. 2 oil, baseline NO_x emissions of 160 ng/J were reduced by 77% with FGR and by 89% with steam injection.

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

This report documents the subscale activities of a program whose objective was to develop advanced combustion modification concepts requiring relatively minor hardware modifications that could be used by operators and/or manufacturers of selected industrial process equipment to control emissions. The development was to be performed for equipment in which the modifications would be most widely applicable and of the most significance in mitigating the impact of stationary source emissions on the environment. Modifications were sought which could be readily adopted by fuel-burning-equipment manufacturers. The path to this goal included concept definitions, economic and technical assessment, subscale performance evaluation tests, cost/benefit analysis, full scale equipment modification or retrofit, full scale performance evaluation tests, and preparation of final reports and instructional guidelines.

Subscale testing is a necessity for such process categories as petroleum process heaters where equipment operators are naturally reluctant to cooperate in a modification test program until the principle has been demonstrated on a smaller scale. Subscale tests of three industrial combustion devices were conducted following a nationwide survey of industrial combustion equipment. The survey ranked these devices according to NO_x emissions and heat input capacity. The equipment tested in this program was chosen based on these rankings and the modifications tested were determined by process constraints and cost considerations as well as the potential for NO_x reduction.

The final report covers the test site survey, combustion modification concept definition, subscale test results, and cost analyses. The subscale test sites included a process heater, rotary kiln, and a steel furnace. Cost analyses were performed for the process heater and the steel furnace. Because the test results at the kiln were not deemed representative of a full scale unit, a cost analysis was not performed for the device.

Past Work

The present program is a follow-on study intended to build upon the results of the program reported in EPA-600/7-79-015a (Ref. 1). The objective of that earlier effort was to investigate the effectiveness and applicability of combustion modifications involving only operating variable changes as means of improvement in thermal efficiency and for emissions control in industrial combustion equipment.

The program scope provided for tests on 22 industrial combustion devices representative of kilns, process furnaces, boilers, stationary engines, and gas turbines in industrial use. Emissions measured included NO, NO_x, SO_2, SO_3, CO, CO_2, O_2, gaseous hydrocarbons, and where possible, particulates, particle size distribution, smoke number, and opacity. Combustion modifications evaluated, where possible, included lowered excess air, staged combustion, reduced air preheat, and burner register adjustments. No hardware modifications were attempted, however. All experiments involved only operating changes.

Summary of Results of Present Program

The initial task of the present program was to review existing source inventories and update them where possible to more clearly define those processes where controls would be of maximum benefit. The review of source emission data provided a relative ranking of each candidate process.

The equipment recommended for testing included: (1) natural draft process heaters, (2) forced draft process heaters, (3) cement kilns, (4) steel soaking pits and reheat furnaces, (5) glass container furnaces, and (6) woodbark boilers. The NO_x emissions and other characteristics of these industrial processes are presented in the final report.

Subscale Process Heater

Tests were conducted to evaluate the effect of combustion modifications on emissions from a natural draft process heater. The reduction in NO_x emissions and the change in efficiency were evaluated for these modifications: (1) lowered excess air, (2) staged combustion air, (3) low-NO_x burners (tertiary air injection and recirculating tile designs), (4) flue gas recirculation, (5) steam injection, and (6) altered fuel injection geometry. The tests were conducted with natural gas and No. 6 oil. Only burner baseline measurements were made with No. 2 oil. Fuel samples were taken for all tests and the analyses were obtained from an independent laboratory.

Baseline measurements were made prior to the implementation of combustion modifications with the burner firing natural gas, No. 6 oil, and No. 2 oil.

Table 1 shows that the largest percentage reductions in NO_x occurred with staged combustion air (SCA) or flue gas recirculation (FGR) techniques when compared to conventional burner designs MA-16 and DBA-16 (a conventional burner differing only in tile design from the MA-16 burner). With SCA, these reductions seem to be a relatively

Table 1. *Summary of NO_x Reduction and Efficiency Change as a Function of Combustion Modification Technique for Natural Gas and No. 6 Oil for Natural Draft Burners*

Fuel	Natural Gas		No. 6 Oil	
Average Baseline NO_x	ppm, dry @ 3% O_2	ng/J	ppm, dry @ 3% O_2	ng/J
MA-16	107	54.6	285	160
DBA-16	131	66.8	—	—
Combustion Modification Technique	NO_x Reduction %	Efficiency Change %	NO_x Reduction %	Efficiency Change %
Lowered Excess Air	27	+4.7	10	+0.1
Staged Combustion Air				
Floor Lances, Normal O_2	46	+0.7	35	-0.7
Floor Lances, Low O_2	67	+2.6	51	-0.4
Central Cylinder, Normal O_2[a]	31	0.0	—	—
Central Cylinder, Low O_2[a]	59	+3.4	—	—
Tertiary Air Burner, Lowest NO_x Configuration (relative to average baseline NO_x for the MA-16)	30	-2.0	42	0.0
Flue Gas Recirculation				
Normal O_2	59	+4.7	31	-2.6
Low O_2	63	+4.9	39	+2.0
Steam Injection, Normal O_2	33	—	—	—
Altered Fuel Injection Geometry				
Normal O_2[a]	31	0.0	—	—
Low O_2[a]	44	+3.4	—	—

[a] NO_x reduction is relative to average baseline NO_x for the DBA-16.

strong function of excess air; whereas, with FGR they are a rather weak function of excess air. With natural gas fuel, all modifications (except the tertiary air burner) appeared to increase furnace efficiency. With No. 6 oil, efficiency decreased slightly with SCA and decreased with FGR, but increased when FGR was coupled with low excess air.

The cost effectiveness (CE) of the most effective NO_x reduction techniques is graphed versus heater size in Figures 1 and 2. As with other modifications, the CE ratio decreases as the unit size increases. Costs are based on 1978 dollars.

Subscale Rotary Cement Kiln

KVB completed a series of tests on a subscale cement kiln. The cement kiln, at a major cement industry association facility, had a 13 cm (5 in.) ID, 30 cm (12 in.) OD, and was 4.6 m (15 ft) long. The maximum kiln feed rate was only 0.0015 kg/s (12 lb/hr), and the unit had no air preheat capability.

All tests were conducted with natural gas fuel. The combustion modifications tested were: (1) sulfur addition either with the fuel or with the feed, (2) water injection at the burner, (3) kiln dust injection at the burner, and (4) fly ash injection at the burner. The effects of these modifications on gaseous emissions, kiln operating conditions (temperature), and clinker quality were studied.

Table 2 summarizes the NO_x reductions obtained with each of these techniques. Essentially, the injection of these materials had little effect on clinker quality. Excess air changes had more significant effects on the clinker with the clinker noticeably degraded at oxygen contents of 0.5% or less.

It is important to note that the baseline NO_x levels observed for the subscale kiln (< 100 ppm, dry at 3% O_2) were far lower than any observed by KVB on full-scale kilns. The most likely explanation is that ambient air was used in all of the subscale tests. In an actual kiln, air preheater temperatures of 144 K (1600°F) are not uncommon. In addition, the high surface-to-volume ratio in the small kiln may have resulted in greater heat losses from the flame zone, thus lowering NO_x production. Also, the high gas-to-solids ratio limited the effect of kiln feed nitrogen on the NO_x emissions.

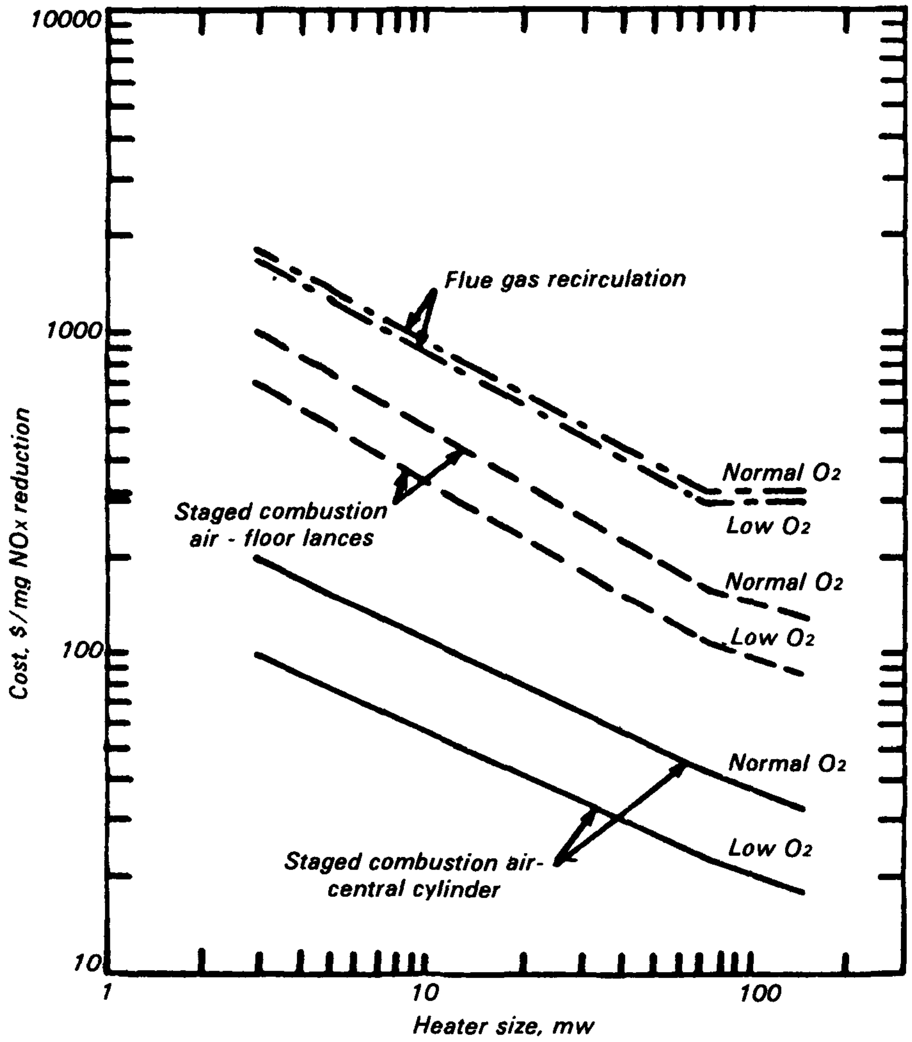

Figure 1. *Estimated cost as a function of heater size for three combustion modifications to natural draft process heaters firing natural gas only.*

Combustion Modifications to a Steel Furnace

The average baseline NO_x emission for a steel furnace burner firing natural gas and No. 2 oil is given in Table 3. The maximum NO reductions obtained for each modification are summarized in Table 4.

The cost effectiveness of these modifications is plotted in Figures 3 and 4 against heater size for No. 2 oil fuel and natural gas, respectively. Flue gas recirculation (FGR) with heat recovery capability has the lowest cost per Mg NO_x reduction for heaters larger than 13.5 MW (46 x 10^6 Btu/hr). For natural gas fuel, FGR with heat recovery becomes less expensive than water injection for heater sizes greater than 8.5 MW (29 x 10^6 Btu/hr), and it is less expensive than steam injection at heater sizes in excess of 60 MW (205 x 10^6 Btu/hr) as shown in Figure 4. Costs for the steel furnace modifications are in 1980 dollars.

Conclusions and Recommendations

From the data obtained and the analyses made during this program, the following conclusions and recommendations may be made.

1. For a subscale natural draft process heater, baseline NO_x levels for two standard burners were 54.6-67.0 ng/J firing natural gas. One standard burner was found to emit 150 ng/J firing No. 6 oil and 63 ng/J firing No. 2 oil.

2. Two low-NO_x burner designs had baseline NO_x emissions of 47.1-53.0 ng/J firing natural gas. Thus, the mean NO_x emission level from these burners was about 18% lower than the mean

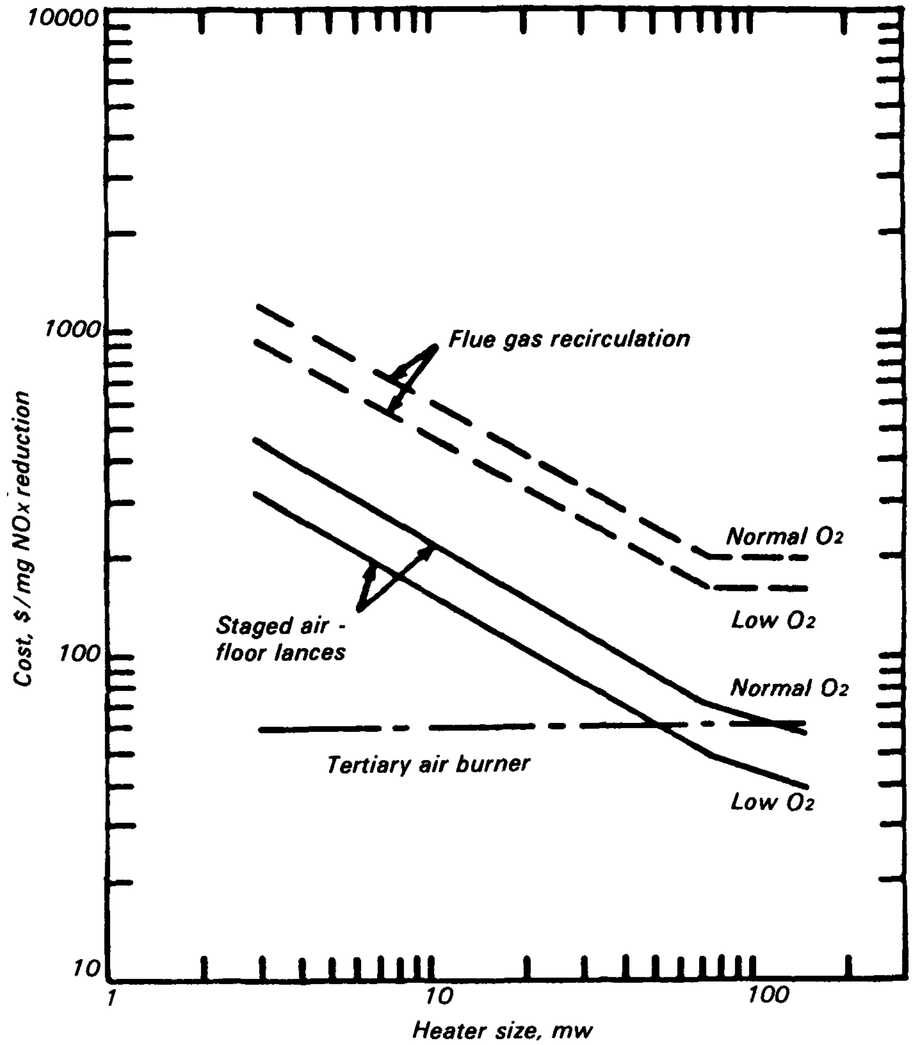

Figure 2. *Estimated cost as a function of heater size for two combustion modifications and for changeover to tertiary air burner in natural draft process heaters firing No. 6 fuel oil only.*

Table 2. *Maximum NO_x Reductions for Four Combustion Modifications to a Research Cement Kiln*

Combustion Modification	*Maximum NO_x Reduction, %*
Sulfur Injection	*12-20*
Water Injection	*14*
Kiln Dust Injection	*14*
Fly Ash Injection	*28*

value for the two standard burners. Firing No. 6 oil, one low-NO_x burner design produced 149 ng/J, a reduction of 7% below the standard burner. The reduction of NO_x due to the low-NO_x burner when firing No. 2 oil was only 2% below the standard burner baseline.

3. Combustion modification techniques were effective in reducing NO_x emissions on a subscale process heater firing either natural gas or No. 6 oil. Staged combustion air (accomplished by lances through the heater floor and coupled with lowered excess air) was the most effective technique, followed by flue gas recirculation at either normal or reduced excess air. When properly adjusted and under reduced excess air conditions, a low-NO_x (tertiary air design) burner was also shown to be effective in lowering NO_x emissions firing both natural gas and No. 6 oil fuel. Lowered excess air alone was not very effective in reducing the NO_x concentration when firing No. 6 oil.

4. Modifications which worked well firing gas fuel but which were not tried firing oil because of time or test equipment limitations included staged combustion air using a central cylinder above the primary air zone, steam injection, and altered fuel injection geometry. Each of these modifications reduced NO_x emissions by more than 30% below baseline and some may be applicable to oil firing as well as gas firing.

5. Staged combustion air by means of floor lances reduced the NO_x at a normal operating excess air level by 46% below baseline (54.6 ng/J) firing natural gas fuel. At lowered O_2 levels the reduction was as much as 67% (natural gas fuel). At normal O_2 conditions the NO_x reduction firing No. 6 oil was 35% below baseline (160 ng/J), and at reduced O_2, the reduction reached 51%. This staged air technique was also the most cost-effective technique based on the data available. Costs are predicted to be roughly $700/Mg of NO_x reduction for small heaters (2.9 MW and below) firing gas, dropping to only $39/Mg of NO_x reduction for large heaters (147 MW and above) firing oil.

6. Cost calculations did not include annual fuel costs or savings due to the combustion modifications because of the unrealistic efficiency changes that were observed on the small-scale heater. With staged combustion air, however, no large effect on efficiency is foreseen except in cases where excess air can be reduced. Then, efficiency can be expected to increase with the application of staged air.

7. In all tests, the NO_x levels observed at the pilot kiln were well below those previously reported for full-scale kilns indicating that the subscale unit was not truly representative of a production kiln. It is thought that the use of ambient temperature combustion air as well as high gas-to-solids ratio in the small kiln were the primary factors contributing to low-NO_x emissions.

8. Although the absolute NO_x levels may not have accurately reflected those present in a full-scale kiln, the trends in emission levels which resulted from the injection of sulfur, water, kiln dust, and fly ash should still provide a basis for determining the relative effectiveness of each injected material in reducing NO_x. With that in mind, it was discovered that fly ash injection was the most effective of the above in reducing NO_x emissions. At normal operating O_2, NO_x emissions were reduced by 28% of the baseline value when fly ash was injected into the flame zone. Clinker

Table 3. *Average Baseline NO_x Emission, Subscale Steel Furnace Burner (Including All Baseline Tests at Location 4)*

Fuel	NO_x ppm[a]	NO_x ng/J	Number of Tests	Coefficient[b] of Variation
NG	222	114.6	11	0.19
No. 2	277	153.4	8	0.23

[a] ppm corrected to 3% O_2, dry.

[b] $\text{Coefficient of variation} = \frac{\text{Std. deviation}}{\text{Mean}}$.

Table 4. *Summary of Significant Test Results, Subscale Steel Furnace Burner*

Test Number	Fuel	Combustion Modification	Firing Rate % Cap.	O_2 %	NO ppm[a]	% Reduction in NO From Nearest Baseline
4/3-11	NG	Water Injection	100	2.2	98	47
4/4-13	NG	FGR	100	2.0	38	88
4/3-12	NG	FGR + Water Inj.	100	1.8	24	87
4/7-2	No. 2	Steam Injection	100	2.1	24	89
4/8-10	No. 2	FGR	100	2.0	57	77

[a] NO corrected to 3% O_2, dry.

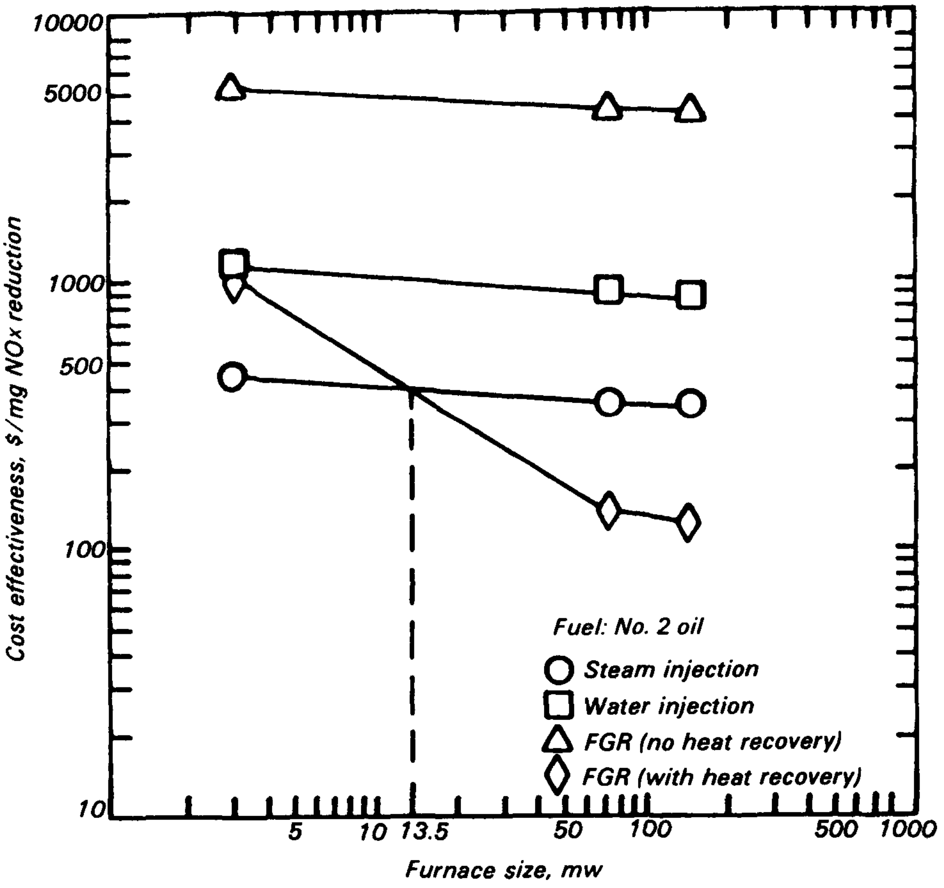

Figure 3. *Cost effectiveness as a function of furnace size for No. 2 fuel oil.*

quality was actually slightly improved during those tests. Injection of the other materials reduced the NO_x levels by 12-20% with essentially no effect on product quality.

9. Lowered excess air (< 1.5% O_2) was not a practical NO_x reduction technique for the subscale kiln. Accompanying CO levels were high and clinker quality was degraded. In general, it was found, the industry already maintains the lowest practical oxygen levels in most kilns (1.5-2.0% O_2).

10. For the two fuels tested at the subscale steel furnace, natural gas and No. 2 oil, FGR proved to be the most effective combustion modification. Steam injection was effective firing No. 2 oil but was not tried firing natural gas because of constraints in the test apparatus. Water injection was less effective firing natural gas than steam injection was when firing oil.

11. FGR of 20% applied to the subscale steel furnace at normal O_2 levels reduced NO_x emissions firing gas fuel by 88% and firing No. 2 oil by 77%. Cost analyses showed that FGR is the most attractive combustion modification for larger furnaces (73.3 MW and up) if the waste heat of the recirculated flue gas is recovered. However, FGR is not as cost effective as steam injection firing No. 2 oil for heaters smaller than about 13.5 MW nor is it as cost effective as water injection firing natural gas for heaters under 8.5 MW in size.

Based on the test results on the subscale process heater, KVB recommends testing the staged air lances on a pilot scale process heater. The test variables should include injection height and pattern, the burner stoichiometric ratio, the excess air level, and system performance as a function of load. Natural gas, refinery gas, and residual fuel oil should be tested as these are the fuels most commonly used at refineries.

Because of the very low NO_x concentrations measured in the subscale cement kiln, KVB recommends further subscale studies in its own laboratory. A nonproducing nonrotating model should be constructed and tests made in which the level of air preheat is varied. Other operating variables which should be investigated include inside wall temperature, primary and secondary air velocities, and primary air vitiation (variation of O_2 in the primary air stream). Tests should be done for coal firing and for natural gas firing.

Post-combustion-zone mechanisms of NO_x formation as well as near-burner mechanisms should be considered to ensure that NO_x destroyed at the burner end of the kiln will not be recreated at the opposite end of the kiln. A full-scale kiln should be tested with the most promising combustion modification techniques.

Both steam injection and FGR should be applied to a pilot-scale steel furnace based on the results of the subscale tests reported here. Appropriate methods to recover the waste heat of the recirculated flue gas stream or the steam (such as heat exchangers or condensation heat recovery devices) could be used to minimize efficiency losses due to these modifications. The possibility of doing this should be investigated. Application of steam injection firing gas fuel should be investigated to verify that the technique is effective for that fuel as well as for No. 2 oil.

Reference

1. Hunter, S. C. et al., "Application of Combustion Modifications to Industrial Combustion Equipment," EPA-600/7-79-015a, NTIS PB 294 214, January 1979.

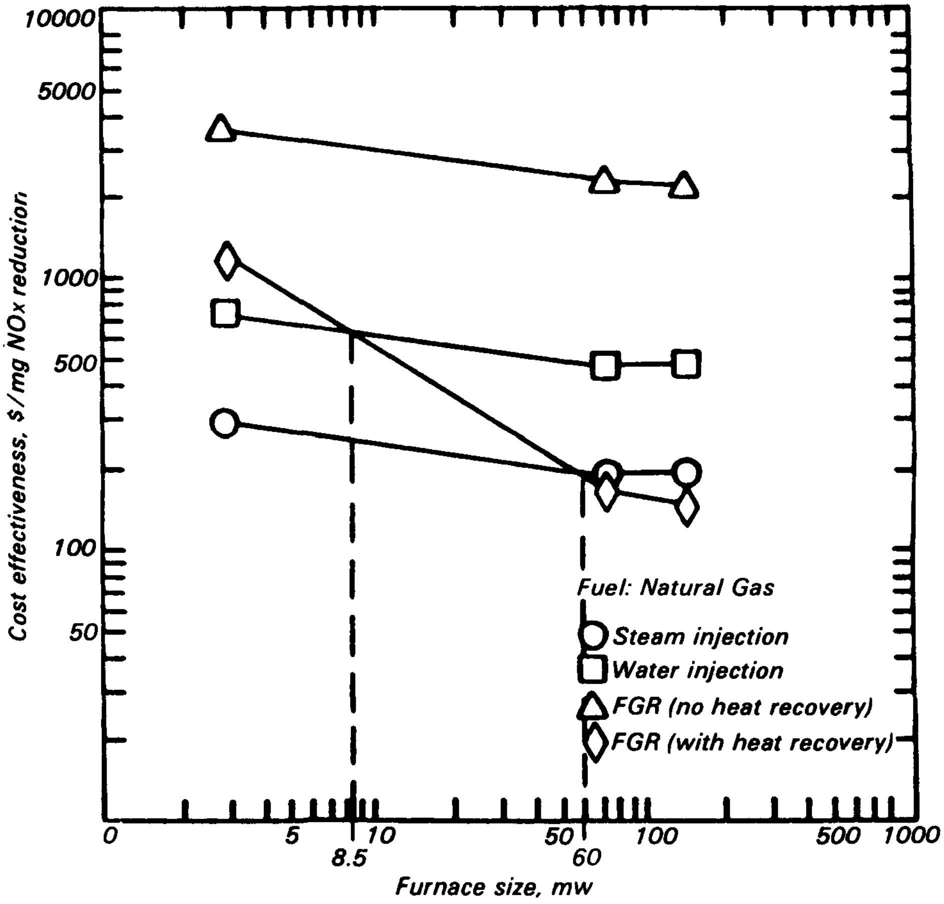

Figure 4. Cost effectiveness as a function of furnace size for natural gas fuel.

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***Robert E. Hall** is the EPA Project Officer (see below).*

The complete report, entitled "Application of Advanced Combustion Modifications to Industrial Process Equipment: Subscale Test Results," (Order No. PB 82-239 310; Cost: $21.00, subject to change) will be available only from:

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