United States
Environmental Protection
Agency

Industrial Environmental Research
Laboratory
Research Triangle Park NC 27711

Research and Development

EPA-600/S9-81-028 Sept. 1981

EPA

Project Summary

Proceedings of the Joint Symposium on Stationary Combustion NO_x Control

J. Edward Cichanowicz

The Joint Symposium on Stationary Combustion NO_x Control was held October 6-9, 1980, in Denver, CO. The symposium was sponsored by the Environmental Protection Agency (EPA) and the Electric Power Research Institute (EPRI). More than 50 speakers presented papers on recent developments in NO_x control technology. Cochairmen of the symposium were Robert E. Hall, EPA, and J. Edward Cichanowicz, EPRI. Introductory remarks were made by Dan V. Giovanni, Program Manager for Air Quality Control, Coal Combustion Systems Division, EPRI. The welcoming address was given by Roger L. Williams, Regional Administrator, EPA Region VIII. Stephen J. Gage, Assistant Administrator for Research and Development, EPA, was the keynote speaker. This project summary includes abstracts of the papers presented at the symposium. They have been published in five volumes:

I. NO_x Emission Issues and Invited Papers
II. Utility Boiler NO_x Control by Combustion Modification
III. Utility Boiler NO_x Control by Flue Gas Treatment
IV. NO_x Control and Environmental Assessment of Industrial Process Equipment, Engines, and Small Stationary Sources
V. Fundamental Combustion Research and Advanced Processes

For ordering purposes, the papers are keyed to their respective volumes according to session.

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

Session I (Volume I) NO_x Emissions Issues

(Michael J. Miller, EPRI, Session Chairman)

"Regulatory Pressures for Increased NO_x Control," Ronald E. Wyzga, EPRI

With a few notable exceptions, powerplants can satisfy present regulations with existing NO_x controls. However, proposed and likely NO_x regulations are likely to require more extensive NO_x controls of new, and in some cases, existing powerplants.

The Clean Air Act Amendments of 1977 establish a legislative basis in three areas which could impact NO_x control. A short-term NO_2 ambient standard could be more restrictive for powerplants than existing SO_2 standards, although the short-term standard will probably not affect relatively isolated small powerplants. A PSD

(Prevention of Significant Deterioration) program could produce significant constraints on powerplant size, siting, and control technologies. For example, a PSD increment program, similar to the SO_2 increment program, would probably be much more restrictive than the current SO_2 short-term increments. Finally, imminent regulations could be more constraining than current PSD increments for powerplants in the vicinity of Class I visibility areas.

Two additional sets of regulations could also impact NO_x emissions limits. Many believe that NO_x contributes significantly to an acid rain problem, and there are efforts to limit emissions to address this problem. Such efforts are likely to require stricter control of powerplant NO_x emissions. Additonally, increased limitations on NO_x emissions may be required in some areas to achieve ozone compliance.

An added regulatory dimension is the requirement that control technologies not introduce new environmental risks. An interpretation and the significance of this requirement for NO_x control technologies are discussed.

"Development and Revision of Air Quality Standards with Special Attention to the NO_2 Standard Review," Michael H. Jones, EPA

This paper describes the process for review of National Ambient Air Quality Standards. Special attention is given to the issues facing the EPA in assessing the need for and nature of possible modifications to the NO_2 ambient air quality standards. The legal requirements for the Clean Air Act Amendments of 1977 are discussed as they apply to this review and to the decision process in making a standard choice. The paper describes not only the importance of the scientific basis for selecting a standard, but also the role of the policymaker and the judicial process. Criteria document development, the scientific review process, the preliminary staff decision paper, and the public review process are all described. Finally, the critical elements in the upcoming NO_2 standard decision are identified and discussed.

"Acid Rain Issues," Ralph A. Luken, EPA

EPA is concerned about the effects of acid rain because the acidity of precipitation falling in the U.S., Canada, and Scandinavia has been increasing for the past 20 years. An annual average precipitation of pH of 4.0 to 4.5 is not uncommon in the eastern U.S., southeastern Canada, and western Europe.

Acid rain has also become more widespread in the past 20 years. Once confined to urban and industrial areas, the effects of acid rain are now being experienced in places as remote from industry as northern Minnesota and Florida.

Although all the consequences of acid deposition are not well understood, a growing body of evidence suggests that acid rain is responsible for substantial adverse environmental effects. These include the acidification and demineralization of soils; reduction of forest productivity; damage to crops; and deterioration of buildings and manmade materials. In addition, the effects of acid rain on metallic elements in soil, aquatic ecosystems, and drinking water systems may affect human health adversely.

Current EPA authority generally focuses on control of the groundlevel concentrations of the precursor pollutants of acid rain. Control of these concentrations will not necessarily impact the level of acid rain which is more a function of the total precursors emitted into the air in a region over an extended period of time.

To reduce SO_2 and NO_x emissions, EPA (in cooperation with the Department of Energy) is evaluating alternative emissions reductions strategies. These strategies focus primarily on utility and industrial boilers.

"State of California Perspective on Stationary Source NO_x Controls," Alan Goodley, California Air Resources Board

The California NO_x control program is directed toward the achievement and maintenance of air quality standards not only for NO_2, but also for ozone, total suspended particulate, and visibility. In addition to stringent controls on mobile sources, controls on existing stationary sources and best available control technology (BACT) on new sources are needed in nonattainment areas. In these nonattainment areas, the state is encouraging local districts to adopt controls on refinery boilers and heaters, industrial boilers, gas turbines, stationary internal combustion engines, glass plants, and cement plants, in addition to existing controls on powerplants. The state considers selective catalytic reduction (SCR) to be BACT for most natural-gas- and oil-fired combustion sources, and that SCR will be BACT. for coal-fired powerplants. It is also believed that combustion modification techniques can be improved so that SCR may be unnecessary on some sources.

Session II (Volume II) Manufacturers Update of Commercially Available Combustion Technology

(Joshua S. Bowen, EPA, Session Chairman)

"Fossil Steam Generator NO_x Control Update," Joseph A. Barsin, Babcock & Wilcox Company

Since the Second NO_x Control Seminar of 1978, much additional information has been collected concerning actual NO_x emissions from fossil fuel powerplants equipped with Babcock & Wilcox Dual Register Burners/compartmented windboxes/furnace systems on a wide range of both bituminous and subbituminous coals. These field results from actual units firing coal, oil, and /or gas have demonstrated NO_x reductions of up to 60 percent compared to no NO_x control. This presentation shares Babcock & Wilcox's present controlled NO_x emissions level experience and the present status of their advanced NO_x control system to meet the more restrictive NO_x emission levels expected in the future.

"Current Developments in Low NO_x Firing Systems," Donald J. Frey, Combustion Engineering, Inc., and Tomozuchi Kawamura, Mitsubishi Heavy Industries

The development of low NO_x firing systems for utility and industrial steam generators is reported. Low NO_x firing systems for natural gas and oil were developed for horizontal and tangential firing. The oil and natural gas "PM" firing system uses fuel-rich and fuel-lean regions in combination with flue gas recirculation to achieve low NO_x emissions; the former region is produced by a diffusion of flame, the latter, by a premixed flame. The pulverized coal "SGR" and "LNCFS" tangential firing systems achieve low NO_x emissions by delaying mixing of the main combustion air with the fuel.

"Development and Field Operation of the Controlled Flow/Split-Flame Burner," Joel Vatsky, Foster Wheeler Energy Corporation

An advanced low NO_x coal burner has been installed in a 375-MW front-wall-

fired steam generator. Unstaged NO_x levels below 0.4 lb/million Btu are being consistently obtained with burners having a maximum liberation rate of 285 million Btu/hr. Prototype tests of this burner, in a 50 million Btu/hr test furnace, have resulted in unstaged NO_x emissions of 0.25 lb/million Btu; when staged using overfire air ports, emissions were reduced below 0.20 lb/million Btu.

This high capacity low NO_x burner permits new steam generators to be equipped with the same number of burners and the same type of burner management system as were used prior to the advent of emission regulations.

The Foster Wheeler low NO_x system is also available for retrofit to older steam generators.

This availability is timely in that it provides an option for utilities, which must convert from oil to coal, to use a modern combustion system. This can be of particular importance to those units designed to fire "future coal," based on the boiler, firing system, and performance coal availability of the 1950's and 1960's, but have instead been firing oil. A further advantage may be provided by the large NO_x reductions attainable since these may permit trade-offs within EPA's "bubble concept." However, the actual NO_x levels attainable for older units would be site-dependent.

"An Evaluation of NO_x Emissions from Coal-fired Steam Generators," John J. Marshall and R.A. Lisauskas and Riley Stoker Corporation

The design evolution of the Riley coal-fired Turbo Furnace and Directional Flame Burner is reviewed. Burner aerodynamics are characterized and the effectiveness of burner adjustments and staged combustion in reducing NO_x emissions in this unique firing system are discussed. Field test emissions data are presented and analyzed with respect to burner operating variables. A decrease in NO_x emissions is observed as mixing of fuel and air in the near-burner zone is delayed. Further development of directional flame and controlled mixing burners for coal-firing applications is also discussed.

Session III (Volume II) NO_x Emissions Characterization of Full Scale Utility Powerplants

(David G. Lachapelle, EPA, Session Chairman)

"Fireside Corrosion and NO_x Emission Tests on Coal-Fired Utility Boilers," Erwin H. Manny and P. S. Natanson, Exxon Research and Engineering Company

This paper describes the status of an EPA-sponsored field study of NO_x emissions from coal-fired utility boilers. Previous reports discussed the effectiveness of combustion modification techniques to significantly reduce NO_x emissions. The simultaneous investigation of side effects (e.g., particulate emissions, boiler slagging, boiler performance) did not identify any significant problems. However, one potential side effect—fireside corrosion on the boiler waterwalls—was only partially studied. Fireside corrosion rates obtained via probes (short-term exposure) could not be correlated conclusively with actual furnace tube wastage experience. Therefore, a long-term corrosion test was undertaken to obtain representative furnace tube corrosion rate data. Results of this test, conducted on the 500-MW No. 7 pulverized-coal-fired boiler at the Crist Station of the Gulf Power Company, are presented and discussed. Details and a progress update are also given for ongoing corrosion investigations sponsored by EPA on four large coal-fired utility boilers designed to meet NSPS NO_x emission standards. Information is also included on a field test using additives to suppress slag formation in a 330-MW pulverized-coal-fired utility boiler.

"NO_x Emissions Characteristics of Arch-Fired Furnaces," Tim W. Sonnichsen, KVB, Inc., and J. E. Cidianowicz, EPRI

Field tests have been conducted on three subbituminous pulverized-coal arch-fired utility boilers. The objective of these tests was to determine "as-found" NO_x emission levels and the influence of combustion modifications on these emissions. These configurations are unique in that the coal is introduced downward from the arch into the furnace with the bulk of the combustion air added through the front wall perpendicular to the flame jet. Staged combustion conditions are thereby generated which have been shown to be conducive to low NO_x emissions.

Corrected NO_x levels ranged from 200 to 350 ppm. The lowest emissions were emitted from the largest (275 MW) boiler. Variations in excess air, air flow injection distribution between burner and front wall, burner stoichiometry, and coal properties were shown to impact NO emissions by 5 to 35 percent. These results are discussed. Comparisons are made between these emissions and the NO_x levels from low NO_x burner/furnace designs to meet NSPS regulations.

"Combined-Cycle Powerplant Emissions," P.L. Langsjoen, R.E. Thompson, and Lawrence J. Muzio, KVB, Inc., and M.W. McElroy, EPRI

The retrofit of existing utility steam boilers with a combustion gas turbine to supply hot vitiated combustion air to the windbox of a fired boiler, in place of the normal forced-draft fans and air preheaters (i.e., repowering), can lead to increased power output at improved heat rates. A major consideration in converting to combined-cycle operation is the impact on the NO_x emissions from the system.

A field test program was conducted to determine the NO_x characteristics of a 220-MW supplementary-fired unit. A primary objective was to determine the fraction of the gas-turbine generated NO_x that can potentially be reduced upon passage through the combustion zone of the boiler. As part of this test program, the boiler was operated in a low-NO_x staged-combustion configuration by removing selected burners from service.

Baseline NO_x emissions from the combined-cycle system were found to be substantially lower than NO_x emissions from the boiler alone when operated with ambient air supplied by forced-draft fans: 1.4 lb NO_2/MW-hr compared to 2.3 lb NO_2/MW-hr at boiler loads of 190 and 200 MW, respectively. In a staged combustion configuration with 4 of 20 burners removed from service, the combined-cycle NO_x emissions were reduced to 0.9 lb NO_2/MW-hr.

The fraction of gas-turbine-generated NO_x reduced upon passage through the combustion zone of the boiler was determined by doping the gas turbine fuel with nitrogen (ammonia) to artificially vary the boiler inlet NO_x levels during combined-cycle operation. The results showed that during normal operation of the combined-cycle system with all burners in service, 10 to 28 percent of the NO_x produced by the gas turbine was reduced (destroyed) in the supplementary-fired boiler. During operation of the boiler in a combustion configuration, staged by removing four

burners from service, a greater portion of the gas-turbine-generated NO_x was reduced in the boiler.

"Relationship Between NO_x and Fine Particle Emissions," Michael W. McElroy and R.C. Carr, EPRI

Data from EPRI -sponsored field test programs at pulverized-coal-fired utility plants indicate that boiler combustion conditions producing low NO_x emissions also tend to suppress the generation of fine, submicron particulate matter. Specifically, the mass of fine particles measured at the outlet of the boiler in the 0.1 μm diameter region are reduced by up to one or more orders of magnitude when low NO_x emissions are observed. These observations are consistent with the present theories of volatilization/condensation processes believed to be responsible for particle generation in the particle size region.

The significance of this discovery is that particulate collectors (electrostatic precipitators and fabric filter baghouses) generally exhibit a minima in collection efficiency at this size region. Furthermore, these particles: (1) can contribute to visibility problems due to particle growth within the plume, and (2) have been implicated as bad actors from a health effects standpoint due to their possible enrichment in trace elements and unfavorable transport properties. It now appears that these deficiencies inherent to particulate control devices may, in part, be overcome by the application of NO_x combustion controls.

Session IV (Volume II) Low NO_x Combustion Development

(Michael W. McElroy, EPRI, Session Chairman)

"Commercial Evaluation of a Low NO_x Combustion System as Applied to Coal-Fired Utility Boilers," Stephen A. Johnson and Todd M. Sommer, Babcock & Wilcox Company

Development testing of an advanced, two-stage combustion system, capable of limiting NO_x emissions from pulverized-coal-fired boilers to less than 0.2 lb_m $NO_2/10^6$ Btu has been completed. Test programs have been conducted on both 1.2 MW_T and 10.2-MW_T systems. These tests have confirmed that NO_x emissions can be correlated to a dimensionless parameter proportional to the second stage flame temperature. In addition, scaleup criteria were formulated allowing the design of commercial-scale low-NO_x combustion systems.

Subsequently, a detailed engineering evaluation was performed on two candidate applications of this technology. The objectives of that study were: (1) to refine scaleup correlations and design procedures; (2) to conceptually design a steam generator incorporating the two-stage combustion concept; (3) to economically evaluate that design as compared to a conventional, post-NSPS steam generator design; and (4) to identify areas of commercial concern with the new designs and to recommend further research to address these concerns.

This paper summarizes the significant results and conclusions from the test programs and the engineering study. The favored venturi furnace system is expected to limit NO_x emissions from coal-fired boilers to less than 0.2 lb_m $NO_2/10^6$ Btu, while increasing the capital cost of the boilers by significantly less than the projected cost of tailend NO_x removal systems to meet future strict NO_x emission standards.

"Pilot Scale Evaluation of a Low NO_x Tangential Firing Method," John T. Kelly, R.A. Brown, J.B. Wightman, R.L. Pam, and E.K. Chu, Acurex Corporation

The EPA/Acurex 293-kW pilot-scale facility was used to develop a low-NO_x pulverized-coal-fired tangential system. Low NO_x is achieved by directing the fuel and less than 20 percent of the secondary combustion air into the center of the furnace with the remaining secondary combustion air directed parallel to the furnace walls. The separation of secondary combustion air in this manner creates a fuel-rich zone in the center of the furnace where NO_x production is minimized. This combustion modification technique has lowered NO_x 65 percent relative to conventional tangential firing. In addition, CO, UHC, and unburned carbon emissions are substantially unaffected by the modification. Also, the modification places a blanket of air on the furnace walls which is beneficial from wall corrosion and slagging points of view. Finally, the modification shows a decrease in NO_x emissions as firebox gas temperature is increased. This characteristic might be beneficially applied in a large-scale system to reduce furnace volume, and thereby capital cost, for a given combustion heat release.

Tests are now underway to further optimize and characterize this low NO_x combustion modification technique.

"The Development of Distribution Mixing Pulverized Coal Burners," Dee P. Rees, J. Lee, A.R. Brienza, and M.P. Heap, Energy and Environmental Research Corporation

This paper summarizes work sponsored by EPA to develop a low-emission, distributed-mixing burner for pulverized coal. Data for single and multiple configurations in research furnaces at 10, 50, and 100 x 10^6 Btu/hr are presented. NO_x emissions down to 100 ppm (0 percent O_2, dry) have been obtained for bituminous coals under acceptable burnout conditions by substoichiometric burner staging. These data show that the optimum burner zone stoichiometry is approximately 70 percent of theoretical air for all burners tested to date.

"The Development of a Low NO_x Distributed Mixing Burners for Pulverized Coal Boilers," Blair A. Folsom, L.P. Nelson, Energy and Environmental Research Corporation, and J. Vatsky, Foster Wheeler Energy Corporation

This paper describes the development of a low NO_x pulverized coal burner for demonstration in two small pulverized-coal-fired boilers by 1982. The Distributed Mixing Burner concept provides for controlled mixing of the coal with the combustion air to minimize NO_x emissions while maintaining an overall oxidizing environment in the furnace to minimize slagging and corrosion. The design of a prototype field-operable burner is discussed, and test data are presented in a research facility, suggesting that NO_x emissions less than 84 ng/J (0.2 $lb/10^6$ Btu) might be attainable in the field.

"Field Evaluation of Low Emission Coal Burner Technology on a Utility Boiler," Edward J. Campobenedetto, Babcock & Wilcox Company

A program is currently in progress to demonstrate the NO_x reduction potential of EPA's distributed-mixing burner applied to a utility boiler. The demonstration program will evaluate both emissions attributed to this burner as well as the effects of the burner retrofit on overall boiler performance and efficiency.

The boiler selection process is near completion: a single-wall-fired unit is

being reviewed by EPA prior to final negotiations. Several opposed-fired units are still under consideration, pending final decisions by the utilities as to their interest in participating in the retrofit demonstration program.

"Operating Experience and Field Data of a 700-MW Coal-Fired Utility Boiler with Retrofit Low NO_x Staged Mixing Burners," K. Leikert and Sigfrid Michelfelder, Steinmueller GmbH

Forthcoming new federal regulations on emission control for stationary combustion systems will clearly define tolerable NO_x emission levels in Germany and thus replace the present "best technical means" approach.

This fact initiated an R&D program for the development of cost-effective low-NO_x combustion equipment for use in pulverized-coal-fired boilers.

The program, financially assisted by the Federal Ministry for Research and Development (Bundesministerium fur Forschung und Technologie, BMFT), was divided into two parts.

First, a distributed-mixing burner design concept adopted for an envisaged 50 percent NO_x reduction was tested and optimized in a pilot plant test program with a 2.5-MW burner. The burner design concept was based on a conventional circular burner with additional tertiary air nozzles distributed concentrically about the burner mouth. Within this program, a 65 percent NO_x reduction was achieved with an optimized configuration of the distributed mixing—respectively staged mixing burner (SM-burner)—without disadvantageous changes in combustion and emission characteristics.

Following the successful pilot plant tests, the combustion equipment of a 700-MW coal-fired powerplant was changed to SM-burners. Both to ease the retrofit and to safely allow the execution of a measuring program, a retrofit burner (a modified version of the optimized pilot burner design) was used for the boiler. The modification resulted in a limitation of the safely operable teritary air mass flows and, thus to a certain extent, reduced the staging capability of the large burner.

In spite of the narrow operational limits, the envisaged goal of a 50 percent NO_x reduction was met in the boiler demonstration tests. Furthermore, a burner-load-dependent automatic secondary/tertiary air flow control system (developed to guarantee safe burner operation at low NO_x levels over a wide turndown ratio) was operated successfully.

"Japanese Technical Development for Combustion NO_x Control," Kunihiko Mouri and Y. Nakabayashi, Electric Power Development Company, Ltd.

The Electric power Development Company, Ltd., has been conducting a research and development program on combustion NO_x control for coal-fired boilers in cooperation with Japanese boiler manufacturers. The target emission levels are 100 ppm (at 6 percent O_2 and 1.8 percent fuel nitrogen) and have not yet been achieved.

However, the results obtained through this R&D program have been applied step by step to existing or new coal-fired powerplants, with NO_x emissions of existing plants reduced to 160-300 ppm (O_2 = 6 percent, N = 1.2 percent), from uncontrolled levels of 400-500 ppm. As for the new coal-fired units, EPDC is constructing boilers of 250 ppm (target) level (O_2 = 6 percent, N = 1.7 percent) at Matsushima Thermal Power Station (2,500 MW units) and is to construct a 200 ppm (target) boiler at Takehara Thermal Power Station, unit NO. 3 (700 MW).

At this moment, EPDC believes that NO_x emission levels will be 150 ppm (O_2 = 6 percent, N = 1.8 percent design base) for new boilers in the near future.

This paper describes an outline of EPDC R&D programs, results of combustion modification such as low-NO_x burners, two-stage combustion gas mixing, a report of actual operation after combustion modification, and an outline of NO_x control countermeasures for new boilers.

Session V (a) (Volume III) Postcombustion NO_x Control

(George P. Green, Public Service Company of Colorado, Session Chairman)

"Empirical Evaluation of Selective Catalytic Reduction as a NO_x Control Technique," J. Edward Cichanowicz and D.V. Giovanni, EPRI

Selective Catalytic Reduction (SCR) has been proposed as a technique for control of NO_x emissions to levels significantly below those mandated by NSPS for coal-fired utility steam generators. EPRI is conducting an empirical assessment of the feasibilty and cost-effectiveness of SCR, using a pilot scale system at the EPRI Arapahoe Emission Test Facility to simulate authentic coal-fired utility operating conditions. The program is a logical extension of earlier EPRI work defining economic feasibility of postcombustion control, and complementary to other pilot scale studies in the U.S. and Japan.

The test program was initiated in September 1980 on a facility capable of treating 5,000 scfm of coal-fired flue gas, an equivalent of 2.5 MW of electrical generating capacity. The facility employs a regenerative air heater in series with a catalytic reactor to assess potential impacts on air heater performance. The tests will focus on four major issues important to the evaluation of SCR technology: (1) *process performance* as defined by the NO_x removal capabilities at conditions representative of authentic utility application; (2) *process operating demands* including the need for monitoring and control systems, consumables such as ammonia, energy (pressure drop and auxiliary power), operating and maintenance requirements to maintain process performance, and catalyst lifetime; (3) *environmental impacts* due to emissions of residual ammonia, SO_3 and sulfates and biosulfates of ammonia; and the potential effects on SO_2 and particulate control; and (4) *systemwide operating effects* such as increased operating and maintenance of downstream surfaces (particularly the air heater), heat rate penalty, and limitations in load-following.

Results are presented for the initial tasks dealing with the evaluation of measurement techniques, and preliminary data describing reactor and air heater performance.

"Assessment of NO_x Flue Gas Treatment Technology," J. David Mobley, EPA

EPA has maintained a program to further the advancement of NO_x control by flue gas treatment technology since the early 1970's. The program consists of technology assessment studies in conjunction with small scale experimental projects. These activities have shown that an 80 to 90 percent reduction of NO_x emissions by selective catalytic reduction with ammonia has been commercially demonstrated on gas- and oil-fired sources in Japan, and that such processes are ready for test application on coal-fired sources. The Japanese experience, combined with

experimental projects in the U.S., should establish the technology as a viable control technique for use in tackling NO_x environmental problems in the U.S. However, some significant technical concerns need to be addressed in demonstration projects before widespread application of the technology can be recommended.

"Development of Flue Gas Treatment in Japan," Y. Nakabayashi, H. Yugami, and Kunihiko Mouri, Electric Power Development Company, Ltd.

The Electric Power Development Company, Ltd. (EPDC) has been conducting a research and development program on selective catalytic reduction (SCR) systems through joint research with manufacturers since 1975.

From the results of this R&D program, EPDC has identified a strong commercialization prospective for the Low Dust SCR System (LDSS) for coal-fired powerplants. At this moment, EPDC is constructing the demonstration test equipment at Takehara Thermal Power Station, Unit No. 1 (250 MW coal-fired), and plans to construct the first full scale commercial SCR equipment at Takehara Thermal Power Station, Unit No. 3 (700 MW coal-fired).

Additionally, the High Dust SCR System (HDSS) also offers significant commercialization prospective, with the exception of establishing removal technology for NH_3 contained in the ash collected by cold-side electrostatic precipitators.

This paper is mainly directed to the results of R&D programs executed by EPDC concerning SCR and air preheater problems, overall flue gas treatment technology for coal-fired boilers, and an outline of Takehara's SCR systems.

"Status of SCR Retrofit at Southern California Edison Huntington Beach Generating Station Unit 2," L.W. Johnson, Cornelis L. Overduin, and D.A.Fellows, Southern California Edison Company

Utilities in the Southern California South Coast Air Basin are subject to a regulation (Rule 1135.1) requiring 90 percent NO_x reduction. Rule 1135.1 consists of four basic compliance options: the first two options require two stages with an intermediate milestone reduction and a demonstration unit of a 90 percent NO_x reduction system.

This paper describes the Selective Catalytic Reduction (SCR) 107.5-MW demonstration facility that SCE plans to install on half of the Huntington Beach Unit 2, 215-MW boiler. The physical size, operation and maintenance, and controls for achieving 90 percent NO_x reduction through normal load variations, as well as the status of the project, are discussed.

The system retrofit requirements are discussed with specific reference to the differences between the demonstration unit and other larger units and the site constraints for retrofit on the larger units. The operational and maintenance requirements for a systemwide retrofit and potential problem areas are also reviewed.

The paper presents cost estimates for the Huntington Beach demonstration facility as well as SCE's projection of cost for adding SCR on the majority of its oil-fired units in the South Coast Air Basin. These costs include capital as well as O&M. All costs are in 1981 dollars.

Session V (b) (Volume V) Fundamental Combustion Research

(Tom W. Lester, EPA, Session Chairman)

"The Fundamental Combustion Research Program," T.J.Tyson, C.J. Kau, T.L. Corley, WM. Randall Seeker, W.Clark, J. Kramlich, M.P. Heap, and W.S.Lanier, Energy and Environmental Research Corporation, and W.S.Lanier, EPA

EPA's Fundamental Combustion Research (FCR) Program's goals, management structure, and output are discussed. The basic research in this coordinated effort is conducted in support of EPA's low NO_x burner development program. The most immediate objectives are: (1) a determination of the chemical limits of NO_x production in order to determine the lower bounds of fuel and thermal NO_x; and (2) a description of fuel NO_x formation in turbulent diffusion flames with gaseous, liquid, or solid fuels. To achieve these goals, FCR's subcontracts are divided among studies in transport processes in reacting flows, gas-phase chemistry, and the physics and chemistry of two-phase reacting flows. Work performed in these areas is split almost evenly between the prime contractor and subcontractors. Among the most important results to date are the characterization of pyrolysis products from a number of coals, the determination of the influence of particle size on the physical mode of devolatilization, and the initial development of gas-phase kinetic schemes to model higher hydrocarbon pyrolysis and oxidation.

"Two-Phase Processes Involved in the Control of Nitrogen Oxide Formation in Fossil Fuel Flames," Adel F. Sarofim, J.M. Beer, L.D. Timothy, S.P. Hanson, A.Gupta, and J.M. Levy, Massachusetts Institute of Technology

The conversion of fuel-nitrogen to nitric oxide in flames depends on a number of physical and chemical factors, three of which are discussed in this paper: the rate of evolution of fuel nitrogen by heavy fuel oils, the temperature-time history of burning coal particles, and the kinetics of the reduction of NO by char.

The nitrogen evolution of a stream of a 150 μm fuel droplet injected into a heated helium stream was measured for a Raw Paraho Shale oil and an Indo-Malaysian residual fuel oil. The nitrogen evolution during vaporization of the dispersed oil droplets is found to depart significantly from that obtained under equilibrium distillation. For a Paraho shale oil, the rate of nitrogen evolution under the rapid heating experienced by the droplets is retarded relative to that observed under equilibrium conditions. By contrast, preferential vaporization of the nitrogen was observed for an Indo-Malaysian residual fuel oil. The temperature-time history and burning times of coal particles burning singly were determined by two-color optical pyrometry to provide insights on the role of volatile combustion on nitric oxide formation. The burning times and intensity traces showed that 100-μm particles of a bituminous coal produced a detached volatile flame that was not evident during the combustion of smaller 40-μm particles. The last part of the paper summarizes data on the kinetics of NO reduction by char, the enhancement of the rate of reduction in the presence of CO, and the inhibition of the reduction reaction by H_2O.

"Gas-Phase Processes Involved in the Control of Nitrogen Oxide Formation in Fossil Fuel Flames," J.M. Levy, MIT Energy Laboratory

Optimization of a control strategy for NO_x emissions from fossil fuel combustion requires an understanding of the mechanistic chemistry of fuel-

nitrogen conversion. Computational capabilitites are demonstrated to be quite accurate in the presence of simple fuels, but break down somewhat in the presence of hydrocarbons. A quasi-global method for computing fuel-nitrogen conversion in a higher hydrocarbon environment is described, and the current status of modeling bound nitrogen profiles in a C_1/C_2 environment is presented.

Session VI (Volume III) Status of Flue Gas Treatment for Coal-Fired Boilers

(Dan V. Giovanni, EPRI, Session Chairman)

"Countermeasures for Problems in NO_x Removal Process for Coal-Fired Boilers," H. Itoh and Yoshihiro Kajibata, Kawasaki Heavy Industries, Ltd.

The construction of many coal-fired powerplants is being planned as a result of the recent petroleum shortage, and so the need for a $DeNO_x$ process for coal-firing is increasing. However, there are many problems to be solved in the practical application of the $DeNO_x$ process for coal-fired boilers, because high concentrations of dust particles and SO_x are contained in the flue gas. The major problems are: (1) catalyst bed pluggage and catalyst erosion by dust particles; (2) the influence of unreacted NH_3 and SO_3 from the $DeNO_x$ reactor to the downstream equipment; and (3) deactivation of the catalyst by dust particles and SO_x.

KHI has been working to solve these problems and to put the $DeNO_x$ process into practical use for coal-fired boilers with the cooperation of EPDC for many years. They have developed superior catalysts having several characteristics, including long life, SO_x-resisting properties, dust-resisting properties, and low conversion of SO_2 to SO_3. Further, they have solved these problems and have developed the most economical and stable $DeNO_x$ process.

This paper describes the problems involved in the practical application of the $DeNO_x$ process for coal-fired boilers and the countermeasures undertaken in KHI's $DeNO_x$ process.

"Treating Flue Gas from Coal-Fired Boilers for NO_x Reduction with the Shell Flue Gas Treating Process," Jack B. Pohlenz, and A.O. Braun, UOP Inc.

Copper as copper sulfate ($CuSO_4$) is one of the groups of metals which, at tempertures of 350° to 450°C, effectively catalyze the selective reduction of NO_x in flue gas to nitrogen and water with ammonia (NH_3). Conversions and efficiency (ammonia utilization) are high, resulting in low concentrations of NH_3 in the treated gas.

If flue gas containing both sulfur and NO_x and the reductanct ammonia is processed over copper at 400 °C, the copper is converted first to the oxide, then to the sulfate, and NO_x reduction begins. As the conversion to copper sulfate continues, the NO_x content of the treated gas decreases to a minimum value and the SO_x increases approaching that at the reactor inlet.

Copper sulfate can be reduced with a variety of fuels: H_2, CO, CH_4, etc., at 400°C, yielding a concentrated stream of SO_2, along with water and elemental copper.

Thus, the copper system provides the technical base for flue gas treating capable of SO_x reduction, NO_x reduction, and the simultaneous reduction of both. It offers the potential of a dry process, without byproducts, and with modest energy requirements.

Such a process, the Shell Flue Gas Treating (SFGT) process, is the subject of this presentation. Commercial applications have been in operation since 1973, processing flue gas from various fuels (not including coal).

UOP has operated an SFGT pilot plant for several years at Tampa Electric Company's Big Bend Station near Ruskin, FL. The pilot unit treats a slipstream of flue gas from one of the utility's coal-fired boilers. $DeSO_x$-only, simultaneous $DeSO_x/DeNO_x$, and (most recently) $DeNO_x$-only operations have been conducted. The current program is sponsored by EPA. Results of this effort are described.

"The Hitachi Zosen NO_x Removal Process Applied to Coal-Fired Boilers," Richard S. Wiener, P. Winkler, Chemico Air Pollution Control Corporation, and S. Tanaka, Hitachi Zosen

Hitachi Zosen is a leading supplier of flue gas treatment systems for the removal of NO_x. They have nine commercial plants in operation. Early in 1978 Chemico Air Pollution Control Corporation acquired the North American license for the Hitachi Zosen technology, a dry process with selective catalytic reduction, using ammonia. Because many sources of flue gas that require NO_x removal also contain a high level of dust, Hitachi Zosen has expended considerable effort in developing a catalyst bed that can operate without plugging even though the gas contains particulates. Pilot plant tests using a specially designed metallic catalyst have been successfully operated on very dirty gases from steel sinter operations and coal-fired boilers. An extensive pilot plant program has been in operation for over 1 year at Georgia Power Company's Plant Mitchell in Albany, GA. This is an 0.5-MW equivalent demonstration plant for coal-fired denitrification sponsored by EPA. Hitachi Zosen believes that this testing has shown the effectiveness of the process over extended operating periods and the soundness of the control system and basic design.

"Babcock-Hitachi NO_x Removal Process for Flue Gases from Coal-Fired Boilers," T. Narita, Hiroshi Kuroda, Y. Arikawa, Babcock-Hitachi, and F. Nakajama, Hitachi Ltd.

At the symposium in 1978 a paper was presented entitled, "Some Experiences of NO_x Removal in Pilot Plants and Utility Boilers." That paper gave the history of developments of Babcock-Hitiachi NO_x removal processes, catalyst characteristics, and several operating experiences. This paper introduces some of the improvements and developments achieved since then.

As far as coal-fired applications are concerned, two systems are required. The first one is $DeNO_x$ with low dust loading, where the $DeNO_x$ reactor is downstream of the hot electrostatic precipitator (ESP); the second is $DeNO_x$ with high dust loading, where the $DeNO_x$ reactor is upstream of the cold ESP. Although the selection of an ESP system should be determined mainly from the standpoint of performance of collecting fly ash through the boiler, the $DeNO_x$ process is applicable in either case.

As for the two commercial $DeNO_x$ plants with low dust loading from coal-fired boilers, the design and manufacture are already complete; they will go into commercial operation in November 1980 and July 1981, respectively. Concerning the $DeNO_x$ with high dust loading, this paper introduces the results of abrasion and performance tests, under dust concentration of 15 to 20 g/Nm^3, which confirm the reliabilty of the catalyst.

Another important aspect of the Selective Catalytic Reduction (SCR) process is reducing the conversion of SO_2 to SO_3 to minimize the influence on the downstream equipment. A catalyst has been developed with the lowest conversion rate less than 0.5 percent without decreasing the NO_x conversion activity at the rated load.

"Test Summary of an Integrated Flue Gas Treatment System Utilizing the Selective Catalytic Reduction Process for a Coal-Fired Boiler," N. Aoki, Ishikawajima-Harima Heavy Industries Company, Ltd., and John S. Cvicker, Foster Wheeler Energy Corporation

This research program was initiated to determine if flue gases from a coal-fired boiler can be effectively denitrified by using the selective catalytic reduction process in combination with desulfurization and dust control as an integrated system.

An experimental system was designed to handle between 1,000 and 2,000 Nm^3/hr of flue gas and measure such parameters as catalyst life, catalyst plugging, catalyst abrasion rate due to ash, air heater plugging, hot ESP, wet ESP, and bag filter efficiencies, along with the efficiency of a limestone desulfurization system.

Test results show that this integrated approach to flue gas cleanup is feasible and may be incorporated into a full-scale, coal-fired boiler flue gas design. This testing will be continued to develop a more reliable integrated flue gas treatment system prior to commercialization.

"The Development of a Catalytic NO_x Reduction System for Coal-Fired Steam Generators," Tadamasa Sengoku, Y. Todo, N. Yokoyama, Mitsubishi Heavy Industries, and Brooks M. Howell, Combustion Engineering, Inc.

Work done recently by Mitsubishi Heavy Industries in Japan has resulted in the design and successful operation of a full-scale catalytic NO_x reduction system for utility steam generators firing coal.

This paper describes the design, operation, and results of pilot-plant and full-scale demonstration testing to evaluate the commercial feasibility of catalytic NO_x removal from coal-fired powerplant flue gases. In addition, the design of a large, modern coal-fired central station catalytic removal system is presented.

Pilot testing of catalytic systems on coal-firing was initiated at the Takasago Station of EPDC in early 1977 using plate type catalysts. In the third stage of testing at Takasago (Fall 1979) the program switched to testing grid type catalysts. Since the conversion to grid type support, more than 5,000 hours of operation have been logged while maintaining 90 percent NO_x removal in both a low and high dust load environment.

At the Nakoso Station of the Joban Joint Power Company, a grid type catalytic system has been operating for over 6,000 hours with a removal efficiency of 85 percent. Operating under both high and low dust load conditions, there as at Takasago, draft losses have been maintained at low levels with only limited soot blowing in the low dust load case and no soot blowing in the high dust load case.

At the Shimonoseki Station of the Chugoku Electric Power Company (156 MW), in operation since April 1980, the first full-scale coal-fired system in the world has run smoothly since startup at 51 percent removal efficiency. The design removal target value for this system was 50 percent.

The paper also discusses ammonia slip, gas flow requirements, catalyst life, and catalyst blinding from fly ash. The design of a 500-MW commercial unit based on the results of the test program is explained and the various factors affecting large commercial designs are discussed.

Session VII (Volume IV) Small Industrial, Commercial, and Residential Systems

(J. David Mobley, EPA, Session Chairman)

"Evaluation of Emissions and Control Technology for Industrial Stoker Boilers," Robert D. Giammar, R.H. Barnes, D.R. Hopper, P.R. Webb, and A.E. Weller, Battelle-Columbus Laboratories

This paper gives results of a three-phase program to evaluate emissions and control technology for industrial stoker boilers. The paper focuses on the third phase, Limestone/Coal Pellet Development, but summarizes the first two phases, Alternate Fuels Evaluation, and Control Technology Evaluation. Because SO_2 appears to be the most troublesome emission to control for stokers, a limestone/high-sulfur coal pellet was developed and evaluated as an SO_2 control technique. Initially, this pellet with a Ca/S molar ratio of 7 was successfully fired in an 8-MW_{th} industrial spreader-stoker boiler with SO_2 emissions reduced by 75 percent, However, from economical and operational standpoints, the amount of limestone required had to be reduced to correspond to a Ca/S molar ratio of 3 to 4. Furthermore, the mechanical properties of this pellet were inadequate to withstand the severe stresses of an industrial fuel-handling system. Accordingly, an R&D effort was undertaken to refine the pellet. A refined pellet, with a Ca/S molar ratio of 3.5 with appropriate binders was produced that had similar or improved physical characteristics of raw coals. Additionally, economic analysis indicates that this pellet can be produced for approximately $15/ton above the cost of the high-sulfur coal. This refined pellet was fired in a 200-kW_{th} laboratory spreader-stoker boiler achieving sulfur captures as high as 70 percent. However, when fired in the 8-MW_{th} (25,000 lb steam/hr) stoker boiler, sulfur captures on the order of 50 percent were achieved.

"Control of Emissions from Residential Wood Combustion by Combustion Modification," John M. Allen, Battelle-Columbus Laboratories

This program was conducted to identify promising methods of reducing emissions of air pollutants from residential wood-burning stoves. The overall study included a review of the few ongoing and recently reported studies related to emissions measurements, causes, and characterization.

The most significant emissions are the hydrocarbons and CO released by wood pyrolysis and the CO formed by combustion under locally starved air conditions. The hydrocarbons are especially important: they have been shown to contain polycyclic species suspected as being carcinogenic.

An experimental phase of the Battelle program included stove operations in the laboratory, designed to correlate emissions with design and operating characteristics of the stoves. The burning properties of different types of fuel wood have also been investigated. The combustion tests in radiant stoves have been designed to identify those phenomena that contribute directly and indirectly to the emissions. The following emissions have been monitored con-

tinuously: O_2, CO_2, CO, NO, SO_2, and total hydrocarbons. In a few tests, stack gases have been batch-sampled to determine particulate emissions, and the concentration of polycyclic organic species in both particulate and gaseous emissions. Continuous weighing of the stoves during operation has provided a measurement of burning rate.

The average emission factors for CO and total hydrocarbons varied by more than a factor of 10 between different burning modes and rates. Both emission factors vary inversely with burning rate. At the higher burning rates, CO constitutes a larger fraction of the emissions of combustibles. The emission factors also vary inversely with excess air ratio as measured at the stove outlet, although a large fraction of the total air may bypass the active burning zone in most stoves. True down-draft combustion produces low emission factors compared to other modes of burning, especially with a preheated air supply. NO_x emissions increase with overall excess air in all the naturally drafted stoves, ranging between 1 and 10 lb/ton fuel.

Combustion modification techniques were found to affect emissions and therefore are of interest for emission controls. These include fuel modifications, thermal and flow modifications in the stove design, and operator techniques.

"Field Tests of Eleven Stoker Coal-Fired Boilers for Emissions Control and Improved Efficiency," P.L. Langsjoen, KVB, Inc.

This stoker test program was awarded to the American Boiler Manufacturers Association (ABMA) in late 1977 as a result of the national interest in coal utilization. The objective of the program is to improve specification data relating to emissions and efficiency of coal-fired stoker boilers. Such data are required by both industry and government to increase coal usage.

Eleven stoker boilers were tested including six spreader stokers, one vibragrate stoker, and four overfeed traveling and chain grate units. The emissions and efficiency of each unit were measured under a variety of operating conditions. This paper deals with particulate loading, NO_x concentration, and combustibles in the bottom ash and fly ash. The effects of stoker design, boiler loading, excess air, overfire air, and coal properties on these three types of emissions are also discussed.

Test results show that overfeed stokers have lower particulate and NO_x emissions, and lower combustible heat losses than do spreader stokers. Fly ash reinjection is shown to substantially increase particulate loading in some cases. Overfire air is shown to have little or no effect on NO_x emissions, and fly ash combustible content is a function of particle size. These and other relationships are discussed. More importantly, an attempt is made to quantify these relationships and provide a broad data base from which government and industry may draw to implement sound decisions for the future of coal.

Field testing was completed in late 1979. Individual site reports are available. A final project report is scheduled for completion in late 1980.

Session VIII (Volume IV) Large Industrial Boilers

(J. David Mobley, EPA, Session Chairman)

"Combustion Modification for Coal-Fired Stoker Boilers," Kenneth L. Maloney, K.F. Maloney, and M.J. Pfefferle, KVB, Inc.

Preliminary results are presented from a program to develop and assess advanced combustion modification concepts for coal-fired stoker boilers. Tests on a 100,000-lb/hr steam-spreader stoker boiler showed that overfire air reduces smoke emissions only when injected in a zone extending a few feet above the fuel bed. Improved overfire air design can permit lower excess O_2 firing for NO_x control, while maintaining acceptable smoke and CO emissions. Staged combustion was applied to a laboratory underfeed stoker (approximately 240,000 Btu/hr heat input) to reduce NO_x emissions.

"Thirty-Day Field Tests of Industrial Combustion Modifications," Wallace A. Carter, KVB, Inc.

This paper is based on field tests sponsored by EPA to evaluate the long-term effectiveness of combustion modifications for reducing NO_x emissions from industrial boilers. Five 30-day field tests have been conducted so far. The combustion modifications evaluated include low excess air on a coal-fired spreader stoker, staged combustion air on a residual-oil-fired boiler and staged combustion on a pulverized-coal-fired boiler, low excess air and staged combustion air on a spreader stoker, and a gas-fired low-NO_x burner. Reductions in NO_x varied from 15 percent with the pulverized-coal-fired boiler to approximately 70 percent with the gas-fired low-NO_x burners. No serious operational or reliability problems were encountered, and most units demonstrated an increase in boiler efficiency.

"Applicability of Thermal DeNO$_x$ to Large Industrial Boilers," Boyd E. Hurst and C.E. Schleckser, Jr., Exxon Research and Engineering Company

Exxon Research and Engineering Company has developed and successfully applied a process called Thermal DeNO$_x$ for removing NO_x from flue gas in stationary combustion sources. This noncatalytic process is based on a gas-phase homogeneous reaction. The technology involves injection of ammonia (NH_3) and hydrogen (H_2) into hot flue gas within a prescribed temperature range.

Thermal DeNO$_x$ has been commercially demonstrated in gas- and oil-fired steam boilers, utility boilers, and process furnaces. Successful tests have also been conducted on a municipal incinerator and an oil-field steam generator. Tests on flue gas generated by coal combustion have demonstrated the applicability of the process to coal-fired boilers.

Cost effectiveness of the process is superior to other competing flue gas treatment processes in most applications. Also, Thermal DeNO$_x$ is not as capital intensive as competing processes and can be applied with similar cost and performance effectiveness for either grass roots or retrofit applications.

Session IX (Volume IV) Environmental Assessment

(Robert P. Hangebrauck, EPA, Session Chairman)

"Conventional Combustion Environmental Assessment Program," Wade H. Ponder, EPA

EPA's Industrial Environmental Research Laboratory at Research Triangle Park, NC, has developed and implemented a major program for assessing the environmental, economic, and energy impacts of multimedia pollutant emissions from stationary residential, commercial, institutional, industrial, and utility combustion processes. The

Conventional Combustion Environmental Assessment (CCEA) Program has become a major source of data and information for Agency use in developing and modifying standards and control technologies.

This paper presents the. theme, objectives, pollutants of concern, current activities, and some representative data from CCEA Program projects. Included are data from: (1) a comparative assessment of coal- and oil-firing in an industrial boiler, (2) environmental assessments of an 820-MW, FGD-controlled, coal-fired utility boiler and a 342-MW oil-fired utility boiler, (3) a 170-site field study of combustion sources, (4) dry bottom industrial boilers firing pulverized coal, (5) residential coal combustion, and (6) wood combustion studies.

"Combustion Modification Environmental Assessment," E. Brent Higginbotham, C. Castaldini, R.M. Evans, K.J. Lim, Howard B. Mason, and L.R. Waterland, Acurex Corporation

The Combustion Modification Environmental Assessment (CMEA) was started in 1976 as part of the EPA's Conventional Combustion Environmental Assessment Program. The primary CMEA objectives are to:

- Identify potential multimedia environmental hazards from stationary combustion sources before and after the use of combustion modifications to control NO_x and other combustion-related pollutants.
- Develop combustion modification application guidelines documenting the economic, energy, operational, and environmental impacts of meeting prescribed emission levels.
- Identify the most cost-effective and environmentally acceptable combustion modification techniques to achieve and maintain environmental goals for NO_2.

To support these objectives, the emphasis in the CMEA is on field tests to quantify changes in emissions, energy efficiency, and operation due to the use of combustion modifications. The field testing uses the EPA environmental assessment Level 1 protocol which includes sampling and analysis for NO_x, SO_2, SO_3, CO, CO_2, O_2, trace metals, organics, and trace inorganic species. During the first 3 years of the CMEA, field tests were done on three utility boilers, two industrial boilers, a gas turbine, and a residential warm air furnace. Each source was either modified in the field for low NO_x operation or was equipped with low NO_x designs. Test results showed no major increase in emissions due to combustion modifications. Changes in emissions other than NO_x were typically within the accuracy of the experimental methods, or within the range of changes due to day-to-day variations in fuel composition or unit operation.

Changes in the severity to the environment of total source effluents were secondary to the improvement due to NO_x reduction. Energy efficiency was generally unimpaired or improved through the use of combustion modifications. One exception was a water-injection-equipped gas turbine for which a 2 percent efficiency decrease was observed.

The CMEA program was recently renewed to extend the field tests to additional sources, advanced combustion modification controls, alternate fuels, and nonsteady operation. The site selection and field test status for the extended tests are described.

"Utility Boiler Environmental Assessment—the EPRI Approach," Monta W. Zengerle, EPRI

EPRI's environmental assessment program for air emissions includes physical and chemical characterization, ecological and human health research, and an integrated analysis of costs, benefits, and risks associated with various generating technology and emission control approaches. Physical and chemical characterizations are approached from regional and localized aspects and include primary and secondary pollutants. Regional transport research began with the Sulfate Regional Experiment (SURE) in the northeastern U.S. and continues with visibility and acid deposition research in the East and West.

Localized plume distribution is being studied on a site-specific basis beginning with simple, and continuing with more complex, terrain. Both efforts include extensive field measurements designed to evaluate or develop modeling techniques for predicting utility contributions to ground-level concentrations or deposition.

Ecological research currently emphasizes the potential effects of acid deposition and includes watershed, aquatic, forest, crop, and grassland research. Currently studies focus on biogeochemical processes which influence resultant soil and water acidity and nutrient balance.

Health effects research concentrates on determining human health effects of airborne utility emissions using animal studies, human clinical studies, and epidemiology.

The ultimate objective of these research efforts is the evaluation of relative risk of generation mixes and emission control strategies.

Session X (Volume IV) Stationary Engines and Industrial Process Combustion Systems

(Robert E. Hall, EPA, Session Chairman)

"Characterization and Oxidation of Diesel Particulate," David A. Trayser, L.J. Hillenbrand, M.J. Murphy, J.R. Longanbach, and A. Levy, Battelle-Columbus Laboratories

This study is being conducted for EPA to evaluate emissions control on light-duty diesel vehicles by postcylinder oxidation. The primary objective is to determine the feasibility of thermal or catalytic oxidation as a means of diesel particulate emissions control.

The program plan includes a review of the state of technology, detailed chemical and physical characterization of the particulate from a light-duty diesel engine, bench experiments to define the ignition and oxidation properties of the particulate, experiments with catalytic ignition of particulates, and experimental evaluation of concepts and devices for particulate emission control by oxidation in the exhaust of an engine.

The particulate characterization is being carried out using an Oldsmobile 4.3-liter diesel engine coupled to a dynamometer with direct and diluted exhaust particulate sampling and measurement. Bench experiments are being conducted with various types of hot-tube reactors and instrumentation.

The particulate characteristics being measured include: mass concentration soluble organic content; carbon, hydrogen, and ash; trace mineral content surface area; size distribution; and volume concentration. Results to date show that, as engine load is increased mass concentration increases substantially and soluble organic content decreases, both hydrogen content and

ash content vary between 0.5 and 2 percent, the surface area is approximately 100 m^2/g, and the mass median particle diameter increases with load increase and is in the range of 0.1 to 0.3 μm.

Preliminary catalytic ignition results indicate that the ignition temperature of the particulate can be substantially reduced (at least 150°C) by application of small concentrations of metal salt solutions. In addition, it has been found that the catalytic action of the metal salt is enhanced by admixing salts such as sodium or ammonium chloride and nitrate. Copper salts have been found to work best of the materials studied to date.

"Single-Cylinder Tests of Emission Control Methods for Large-Bore Stationary Engines," Robert P. Wilson, Jr., Arthur D. Little, Inc.

The research work presented was undertaken to develop combustion modifications that substantially reduce NO_x emissions of large-bore engines, without significantly increasing fuel consumption of carbonaceous emissions. The scope of the project covers NO_x control technology for diesel and spark ignition engines, bore sizes ranging from 8 to 20 in, and both two- and four-cycle charging methods. The current status of the project permits reporting the results of 40 percent of the Phase III experimental tests. In Phases I and II, a compendium of 40 emission control methods was prepared, and an evaluation procedure was used to narrow the list to the 12 methods now being tested in Phase III.

Cooper Energy Services used a 20 in bore, 330-rpm, single-cylinder engine to test the effect of unmixedness (modified fuel gas injection) and conventional "tuning" methods (timing, equivalence ratio, spark location, gas valve location, and piston shape). The principal finding was that NO_x emissions are more sensitive to air/fuel ratio than any other variable, giving a factor of five reduction as the equivalence ratio was leaned out from $\phi \simeq 0.76$ to $\phi \simeq 0.62$. The practical implication is that spark gas engine emissions are limited primarily by turbocharger efficiency and the combustion lean limit. Rate of heat release analysis confirmed that a reduction in fuel/air ratio produces longer ignition delay and lower flame speed. Gas valve modifications degraded NO_x; piston shape had more effect on NO_x than either gas valve or spark plug location.

Fairbanks Morse tested pilot injection and increased rate of injection on an 11-in bore model PA-6 engine at 1,000 rpm. At 9 g/bhp-hr, the baseline NO_x is characteristic of this class of engines. Retarded timing increases BSFC 1.1 percent and decreases NO_x 4 percent per degree crank angle. Exhaust temperature was found to limit the NO_x reduction achievable with either pilot injection or injection rate at full load; however, at part load, NO_x reductions of 20 percent were found for both methods with some BSFC improvement. Analysis of derived heat release profiles shows that the "spike" observed for high-speed diesels does not appear for the PA-6 engine.

"Emission Reduction by Combustion Modification for Petroleum Process Heaters," R.J. Tidona, Wallace A. Carter, J.R. Hart, and S.C. Hunter, KVB, Inc.

This paper is based on work sponsored by EPA to evaluate combustion modification technology applied to industrial process equipment. The tests described were aimed at developing combustion modifications for reducing NO_x emissions from process heaters. In particular, staged combustion air and lowered excess air were applied separately and in combination to a natural-draft vertical-cylindrical crude heater and the effects on heater efficiency and NO_x emissions were studied.

At a crude throughput of approximately 59 percent of the heater capacity, reductions in NO_x emissions of over 50 percent from baseline emission levels were observed when firing refinery gas fuel and using the combined modifications of staged combustion air and lowered excess air. Burner and heater performance actually improved slightly with the application of these modifications. An increase in heater efficiency of over 2 percent was observed for low NO_x firing as compared to baseline conditions.

The same modifications were tried firing residual oil simultaneously with the gas fuel. Some reduction in NO_x emission was achieved; however, the magnitude of the reduction was smaller than that obtained for gas fuel only.

The cost effectiveness in dollars per unit mass of NO_x removed was calculated and the feasibility of the staged air/low excess air modification for retrofit application to natural-draft process heaters is discussed.

"Kinetics and Mixing in Industrial Afterburners," Arthur Levy, A.A. Putnam, H.A. Arbib, and R.H. Barnes, Battelle-Columbus Laboratories

Industrial afterburners can be effective control devices for limiting the emissions of organic species to the atmosphere. For practical and effective operation, the demands of fuel and engineering economics must be balanced with afterburner size and complexity, operating and maintenance costs, and meeting other specific requirements, such as turndown capabilities. This paper considers combustion phenomena in afterburners from the points of view of the turbulent mixing necessary for a compact system, and the kinetics involved in the reaction process. The mixing aspects are considered: first on the basis of the implications of the constructional details of industrially available afterburners, and second from the potential for applying mathematical modeling techniques in the design of more effective afterburners. Examination of the constructional details (in terms of the components of generic burner type, approach section, and fume incineration section) shows that the mixing phenomenon can be considered from a relatively simple point of view that can be quite amenable to mathematical modeling. The chemical aspects of afterburner systems are analyzed with respect to hydrocarbon oxidation processes. Special attention is devoted to the quasi-global and global kinetics of these oxidation processes. Appropriate equations are examined for calculating chemical performance based on theoretical and laboratory data. Some generalized kinetic predictive procedures are also discussed.

"Subscale Tests of Combustion Modification for Steel Furnaces," Robert J. Tidona, W.A. Carter, and S.C. Hunter, KVB, Inc.

This is a report of a research program to develop combustion modification technology as means of emissions reduction and thermal efficiency improvement on industrial process equipment. The work is an extension of EPA Contract 68-02-2645, which concentrated on operational adjustments. Presented are results of subscale tests for steel furnaces.

Subscale tests with a standard steel furnace burner firing natural gas and

NO. 2 oil were conducted to determine the effects on NO_x emission and furnace efficiency of water injection into the flame zone, steam injection into the flame zone, flue gas recirculation, and lowered excess air. With natural gas fuel, the largest NO_x emission reduction was obtained using flue gas recirculation (88-percent reduction). With No. 2 fuel oil, the largest reduction occurred using steam injection (89 percent).

The costs of water injection, steam injection, and flue gas recirculation were evaluated. Steam injection was found to be the most cost-effective combustion modification technique for three heater sizes firing either natural gas or No. 2 oil.

Session XI (Volume V) Advanced Processes

(G. Blair Martin, EPA, Session Chairman)

"Low NO_x Combustors for High Nitrogen Liquid Fuels," Glenn C. England, M.P. Heap, D.W. Pershing, J.H. Tomlinson, and T.L. Corley, Energy and Environmental Research Corporation

The results of bench scale experiments in a 21-kW tunnel furnace show that, under unstaged combustion conditions, total and fuel NO_x emissions from 26 petroleum and alternative liquid fuels correlate well with fuel nitrogen content. The optimization of staged combustion parameters in the fuel-rich primary zone was studied to provide direct guidance for advanced low NO_x burner designs for evalulation in a 900-kW pilot-scale combustor. Detailed in-flame measurements were made in addition to exhaust measurements to quantify the influence of first-stage stoichiometry and temperature on the fate of fuel nitrogen species. Exhaust NO_x emissions were found to be directly related to the amount of total fixed-nitrogen species (TFN = NO + HCN + NH_3) leaving the first stage. Increasing the temperature of the primary zone decreased TFN concentration, resulting in lower exhaust NO_x emission.

"Fate of Coal Nitrogen During Combustion," S.L. Chen, M.P. Heap, David W. Pershing, R.K. Nihart, and D.P. Rees, Energy and Environmental Research Corporation

Twenty-six coals covering all ranks have been burned under a wide variety of conditions to ascertain the impact of coal properties on the fate of fuel nitrogen. Three burner systems were used to vary the rate of fuel/air mixing and fuel NO was identified by using a nitrogen-free oxidant. It was found that fuel nitrogen content is not the only property controlling fuel NO formation. It appears that nitrogen volatility as well as total nitrogen content is important, particularly under well-mixed conditions.

Detailed specie concentrations were measured under fuel rich conditions and it was found that:

- The partition of nitrogen between NO, NH_3, and HCN depended on coal type.
- Total gas-phase nitrogen specie (fuel-rich) correlated with exhaust NO (fuel-lean).
- Reducing the temperature of the first stage increased gas-phase nitrogen specie concentrations, but reduced fuel emissions.
- This work will help in the generalization of low NO_x burner technology to a wide range of fuels.

"System Applications of Catalytic Combustion," John P. Kesselring, W.V. Krill, S.J. Anderson, and M.J. Friedman, Acurex Corporation

The development of catalytic combustion systems is continuing toward the prototype demonstration phase. Improved catalyst materials have shown higher maximum throughput capability and uniform axial temperature profiles. Special auxiliary components required for fuel injection, ignition, and catalyst temperature measurement have been developed and incorporated into system concept designs. The three combustor concepts developed to the system integration phase include a small gas turbine combustor, a watertube boiler concept, and a firetube boiler burner.

The model gas-turbine combustor shows continued promise for low NO_x emissions with gaseous and distillate fuels. Greatest development difficulties are associated with introduction of the premixed fuel/air mixture and its interaction with catalyst lightoff systems. An integrated system has been developed, including a multiple nozzle, atomizing injector, and an opposed-jet lightoff burner. Testing of the concept is nearing completion to show its transient and steady-state capabilities.

The watertube boiler concept uses direct radiative transfer to watertubes in the combustion region. Structural problems of the radiative zone are currently being addressed, and final integration of the concept will follow. Thermal NO_x emissions are typically less than 2 ppm.

The firetube boiler burner also uses radiative heat transfer from a fiber matrix burner to the wall of the firetube. The matrix burner operates at a surface temperature below 1644 K at low excess air levels to control the formation of thermal NO_x. Pad material screening tests have been conducted, and a mockup burner test is in preparation. Continuing program work will focus on prototype development of the watertube and firetube boiler concepts.

"Fixed-Bed and Suspension Firing of Coal," S.P. Purcell, D.M. Slaughter, J.M. Munro, G.P. Starley, S.L. Manis, and David W. Pershing, University of Utah

This paper summarizes the progress made during the second year of a grant to study the formation of pollutant species, particularly NO_x and SO_x in fixed-bed and suspension combustion of coal. During this period, the suspension furnace was completed and preliminary experiments conducted. The results suggest that the large particles are essentially unreacted when they reach the stoker bed. The burning rate of the small particles increased with increased local oxygen concentration and increased heating rate.

The fixed-bed furnace was also completed and initial results were obtained. These data suggest that the nitrogen volatiles evolve from the bed early in the combustion process and form significant amounts of NO_x. Staged combustion appears to be a potentially effective means of controlling NO emissions from a fixed-bed system. Increased clinkering was not observed under staged combustion conditions; however, this is a potential problem in the application of this technology to larger scale units. Both overall excess air level and overfire-air height were studied: neither appeared to be of first order importance at the conditions investigated.

The model spreader stoker was designed and the fabrication drawings prepared. Construction should be completed in late 1980.

"Pressurized Bench Scale Testing of Low NO_x LBG Combustors," Wyman D. Clark, B.A. Folsom, W.R. Seeker, C.W. Courtney, and M.P. Heap, Energy and Environmental Research Corporation

The high efficiencies obtained in a combined gas-turbine/steam-turbine power cycle burning low-Btu gas (LBG) make it a potentially attractive alternative to the high sulfur emitting direct-coal-fired steam cycle. In the gasification process, much of the bound nitrogen in coal is converted to ammonia in the LBG. This ammonia is largely converted to NO_x in conventional combustors. This paper examines the bench scale performance of reactors previously demonstrated to produce low NO_x emissions in laboratory scale experiments. Low Btu gas was synthesized in a catalytic reformer and fired in two primary combustors: a diffusion flame and a platinum/nickel oxide catalytic combustor. Effects of scale, primary stoichiometry, pressure, throughput, and primary residence time were examined. Lowest NO_x emissions were produced in rich/lean combustion, utilizing either the diffusion flame or the catalyst in the fuel-rich primary stage.

"Control of NO_x and Particulates Emission from SRC-II Spray Flames," Janos M. Beer, M.T. Jacques, S. Hanson, A.K. Gupta, Massachusetts Institute of Technology, and W. Rovesti, EPRI

Experiments were carried out with SRC-II fuels in a laboratory-scale laminar-flow reactor and in the 4- by 4-ft MIT Combustion Research Facility. In the laminar-flow reactor, monosize droplet arrays were pyrolyzed in an inert atmosphere at variable temperatures and the time-resolved evolution of the fuel nitrogen was determined. This information was needed for the development of a NO_x control strategy by staged combustion. Parallel with the laboratory studies, experiments were carried out with SRC-II liquid fuel sprays in unstaged and staged turbulent diffusion flames in a thermal environment similar to that in a utility boiler. The NO_x and particulates emission was determined in unstaged flames for the effects of the rate of fuel/air mixing, air preheat, and the quality of atomization. The results show that low overall excess air (in a long slowly mixing turbulent flame with a low degree of swirl in the air for flame stabilization) can reduce the NO_x emission level to about 250 ppm from the 550 ppm obtained for high-intensity fast-mixing flames. A significant further reduction of NO_x can be achieved with staged combustion by physically separated stages. In these latter experiments, a computer analysis of the fuel nitrogen conversion was used to guide the experiments carried out using the MIT Combustion Research Facility. The distributions of NO_x and particulates in the flames were determined for the effects of the primary stage fuel/air ratio, temperature, and atomization quality. The mixing in both the fuel-rich and -lean stages and the heat extraction along the flame were closely controlled in these experiments. Results show that NO_x (3 percent O_2) levels below 100 ppm can be achieved without excessive emission of particulates. The experimental data show the same general trends for NO_x emission as a function of fuel equivalence ratio as that predicted by the computer model. While the NO_x and particulate levels achieved in these studies are most encouraging, it is the development of a strategy of NO_x and particulate emission control that is the main objective of the present study. The emission levels achieved in this study can be considered as lower bounds for conditions in which the mixing in the flame is controlled more closely than can be achieved in practical utility boiler combustion chambers.

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The complete report, entitled "Proceedings of the Joint Symposium on Stationary Combustion NO_x Control," is in five volumes:
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