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Project Summary

Proceedings: First Joint Symposium on Dry SO_2 and Simultaneous SO_2/NO_x Control Technologies

P. Jeff Chappell, Compiler

The First Joint Symposium on Dry SO_2 and Simultaneous SO_2/NO_x Control Technologies was held November 13 through 16, 1984, in San Diego, California. Forty-six papers were presented, beginning with a keynote address on acid rain strategies and control technology implications, followed by overviews of EPRI, EPA, and Canadian programs and the utility perspective for dry control technologies. Other papers focused on the latest advances in fundamental research and process design, power plant integration and economics, field applications, and full-scale testing.

Participants from West Germany, France, The Netherlands, Austria, Canada, and Japan provided a worldwide update on technological developments and an international perspective on SO_2 and SO_2/NO_x control issues.

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

Preface

The First Joint Symposium on Dry SO_2 and Simultaneous SO_2/NO_x Control Technologies was held November 13 through 16, 1984, in San Diego, California, and jointly sponsored by EPRI and EPA, was the first meeting of its kind devoted solely to the discussion of emissions control processes based on dry injection of calcium or sodium sorbents to meet SO_2 and NO_x regulations for coal-fired power plants. Processes that were discussed included: direct furnace injection of calcium-based sorbents, sorbent injection combined with low-NO_x burners for simultaneous SO_2/NO_x control, and post-furnace injection of calcium and sodium sorbents. The symposium provided a timely forum for the exchange of data for information on the current status and plans for these emerging technologies.

Forty-six papers were presented, beginning with a keynote address on acid rain strategies and control technology implications, and followed by overviews of the EPRI, EPA, and Canadian programs, and the utility perspective for dry control technologies. Other papers focused on the latest advance in fundamental research and process design, power plant integration and economics, field applications, and full-scale testing. A panel of representatives from architect-engineering firms, boiler manufacturers, and utility companies discussed the impact of dry SO_2 control processes on new and existing power plants.

Speakers included EPRI and EPA staff members as well as representatives of utility companies, manufacturers of utility boilers and process equipment, sorbent suppliers, and research and development groups conducting investigations sponsored by EPRI, EPA, and others. Participants from West Germany, France, The Netherlands, Austria, Canada, and Japan provided a worldwide update on technological developments and an international

perspective on SO_2 and SO_2/NO_x control issues.

Symposium Cochairmen were Michael W. McElroy, Subprogram Manager of EPRI's Air Quality Control Program in the Coal Combustion Systems Division, and Richard D. Stern, Chief of EPA's LIMB Applications Branch of the Air and Energy Engineering Research Laboratory. The welcoming address was given by John Hamrick, Vice President of Customer Service for San Diego Gas & Electric, and the keynote address was given by Donald J. Ehreth, Deputy Assistant Administrator, Office of Research and Development, EPA.

The symposium proceedings have been published in two volumes:

- Volume 1: Fundamental Research and Process Development
  - —Session I: Introduction
  - —Session II: Fundamental Research
  - —Session III: Pilot-Scale Development of Furnace Injection
  - —Session IV: Burners for Simultaneous SO_2/NO_x Control
  - —Session V: Post-Furnace SO_2 Removal
- Volume 2: Power Plant Integration, Economics, and Full-Scale Experience
  - —Session VI: Process Integration and Economics
  - —Session VII: Sorbent Availability and Costs
  - —Session VIII: Field Applications and Full-Scale Testing

1. *"Acid Deposition Strategies and Implications for Control Technology Requirements,"* Donald J. Ehreth, EPA/Office of Research and Development.

This paper represents the keynote address for the First Joint Symposium on Dry SO_2 and Simultaneous SO_2/NO_x Control Technologies. The paper presents the factors that have guided EPA's interest in the Limestone Injection Multistage Burner (LIMB) technology. The approach and funding for the demonstration of this technology are also discussed.

2. *"The EPRI Program—Background and Motivation,"* John S. Maulbetsch, EPRI/Coal Combustion Systems Division

This paper presents the Electric Power Research Institute's (EPRI's) perspective on dry SO_2 control and simultaneous SO_2/NO_x control. The paper includes an historical overview of the scope of the EPRI research effort and present plans for future programs.

Session I—Introduction

Richard Stern, EPA/AEERL, and Michael McElroy, EPRI, Session Chairmen

3. *"EPA's LIMB R&D Program—Evolution, Status, and Plans,"* G. Blair Martin* and James H. Abbott, EPA/AEERL

The LIMB R&D program has provided a detailed understanding of the key processes governing sulfur capture with sorbents. While it appears that limestone alone will not achieve program goals, several other promising sorbents have been identified. Based on the R&D results and cost estimates of using these sorbents, LIMB shows substantial promise as a SO_x and NO_x control technology for retrofit applications. The ongoing R&D program should resolve the remaining technical questions and provide a basis for widespread private sector commercialization.

This paper provides a brief history of sorbent injection technology, synopsizes the status of LIMB R&D, and discusses future program plans.

4. *"Overview of Canadian Research, Development and Demonstration Program for Low NO_x/SO_2 Control Technologies,"* William A. Warfe and G. K. Lee, Energy, Mines & Resources Canada

One of the major concerns, associated with the expanded use of coal for heat and electricity, is the emission to atmosphere of the acid rain precursors, NO_x and SO_2.

This paper outlines the technologies, the status of research, development and demonstration activities, and future plans for low NO_x/SO_2 control technologies in Canada. It includes federal government activities as well as those of the Canadian Electrical Association.

5. *"The Utility Perspective on Dry SO_2 Control Technologies,"* George P. Green, Public Service Co. of Colorado

This paper summarizes current understanding and provides comparative descriptions of two promising techniques for dry SO_2 control in utility applications: flue gas sodium sorbent injection, and in-furnace calcium sorbent injection. In both cases, dry sorbents are injected in powdered form and react chemically with SO_2 to form a dry particulate waste which potentially can be collected in either a baghouse or electrostatic precipitator (ESP). Two electric utilities, Public Service Co. of Colorado and the Colorado Springs Dept. of Public Utilities, have announced firm plans to employ flue gas sodium sorbent technology. In-furnace calcium sorbent injection is still under active development, and no long-term utility commitment to this technology has yet been made in the U.S. Both control techniques show potential as reliable, efficient, and economic SO_2 control options, giving utilities greater flexibility in meeting their environmental control responsibilities.

6. *"EPA Experimental Studies of the Mechanisms of Sulfur Capture by Limestone,"* Robert H. Borgwardt, EPA/AEERL, and K. R. Bruce and J. Blake, Northrop Services, Inc.

Reaction kinetics of limestone particles were measured under conditions that eliminate pore-diffusion and interparticle-diffusion effects. Included in these laboratory studies were: the reaction of H_2S and sulfur with $CaCO_3$, the calcination of $CaCO_3$ to CaO, the reaction of CaO with H_2S and COS, and the reaction of CaO with SO_2. The results show that nascent lime formed immediately after $CaCO_3$ decomposition has a specific surface area of about 80 m^2/g. In all cases, the reactivity of the CaO increased with the square of the B.E.T. surface area. The reactivity is markedly affected by the presence of foreign metal oxides or salts on the CaO surface; carbonates and sulfates of the alkali metals are effective additives for promoting CaO reactivity under laboratory conditions.

7. *"Flow Reactor Study of Calcination and Sulfation,"* Lawrence Muzio and V. P. Roman, KVB, Inc., Michael W. McElroy, EPRI, Kerry W. Bowers and David T. Gallaspy, Southern Company Services

The renewed interest in direct furnace injection of dry sorbents for SO_2 control from coal-fired boilers has prompted bench-scale studies of the calcination and sulfation of calcium compounds. The bench-scale study was conducted in a one-dimensional flow reactor. The objective of the study was to determine the inter-relationships of the calcination and sulfation processes and how these processes are influenced by the type of sorbent material, temperature, and residence time. Four materials were studied: two limestones, a calcium/hydroxide, and

*Speakers are listed first.

a pressure-hydrated dolomitic lime. Calcination and sulfation of these sorbents were investigated over the temperature range of 760-1,093°C and residence times of 0.20-0.75 seconds. The reaction environment consisted of combustion products from a natural-gas or hydrogen-fired burner doped with SO_2 and CO_2.

Session II—(Part 1) Fundamental Research

Kerry Bowers, Southern Company Services, Session Chairman

8. *"Calcium-Based Sorbents for Dry Injection,"* Jeffrey L. Thompson, Dravo Lime Company

Dry injection technologies for SO_2 capture required that the mass mean diameter of the sorbent particle be relatively small, less than 20 μm, to obtain removal rates high enough to make the process economically competitive with wet scrubbers. The least expensive method of producing fine sorbent particles is by hydrating lime. Typical commercial hydrates have a mass mean diameter less than 5 μm. New studies of hydrate particles used in SO_2 capture show that the reactant layer is less than 1000 Å thick, the subject of this paper. These studies define the limiting mechanism for sorbent utilization; i.e., the conversion ratio of CaO $CaSO_4$. Moreover, this understanding of the SO_2 adsorption process points to how hydration production methods might be modified to enhance SO_2 capture.

9. *"Laboratory-Scale Production and Characterization of High Surface Area Sorbents,"* David A. Kirchgessner, EPA/AEERL

The objectives of the research described are to produce high surface area sorbents in an apparatus amenable to scale-up, and to determine those characteristics in the raw carbonates which correlate to the development of high surface areas in the calcined product. Thus far, limestones crushed to minus 600 μm have been calcined to produce maximum surface areas of 40-58 m^2/g in a laboratory-scale fluidized-bed reactor with a pulsed air flow. A dolomite similarly treated has produced a surface area of 74 m^2/g.

Particle size and elemental analyses of the raw stones have been performed, and a significant negative correlation between maximum surface area development and iron content has been noted. No correlation between surface area development and petrographic properties has yet been demonstrated.

10. *"Reactivity of Calcium-Based Sorbents for SO_2 Control,"* Randy Seeker, J. A. Cole, J. C. Kramlich, G. S. Samuelsen, and G. D. Silcox, Energy and Environmental Research Corporation

Laboratory-scale controlled-temperature experiments were used to study aspects of SO_2 capture by limestone sorbents in a flame-gas environment. Experimental parameters were sorbent type, temperature, residence time, and the effects of mineral additives, or promoters, on sorbent reactivity. The data revealed that isothermal capture is greatest at 1,000°C, and that above 1,000°C sintering of the limestone can occur which reduces the sorbent utilization. High surface area precalcined sorbents achieved moderately higher ultimate utilization than their parent carbonates, but their real advantage was more rapid sulfation at lower temperatures where raw stones were limited by calcination. At 900 and 1,000°C the time for calcination of carbonate sorbents was significant. Pressure hydrated (type S) dolomite limes consistently achieved the highest utilizations. The results suggest that—at ideal sulfation conditions (1,000°C, isothermal residence times greater than 1 second, no deactivation of the sorbent by coal ash minerals)—the best calcium utilizations achievable would be about 25-30% with the raw limestone tested (Vicron 45-3), about 30-35% with the raw dolomite tested, and about 40% with precalcined dolomite (precalcined to a surface area of 60 m^2/g) and with pressure-slaked dolomitic lime. The addition of Cr_2O_3, alkali metal salts, and certain other promoters increased the utilization of limestone. Cr_2O_3 effected a factor of 3.5 increase in utilization after calcination at 1,600-1,700°C.

Session II—(Part 2) Fundamental Research

Dennis Drehmel, EPA/AEERL, Session Chairman

11. *"Bench-Scale Evaluation of Sulfur-Sorbent Reactions,"* David W. Pershing, D. M. Slaughter, G. D. Silcox, P. M. Lemieux, and Gerry H. Newton, University of Utah

High temperature, isothermal data on calcination and SO_2 capture were obtained as a function of temperature, residence time, and Ca/S molar ratio for a wide variety of sorbents including limestones, dolomite, and slaked limes. The calcination results include the extent of both calcination and surface area and definition of the relationship between the thermal environment and sorbent characteristics. The experimental sulfation data indicate that sulfur capture is strongly dependent on the general class of sorbent. Reaction zone temperature was also found to critically influence the overall effectiveness of sulfur capture by sorbent injection; as the local temperature increases, the rate of heterogeneous chemical and diffusion increase but they are ultimately compensated for by a decrease in initial sorbent surface area due to desurfacing during flash calcination. The results from the experimental studies are compared with theoretical predictions using a combined diffusion/heterogeneous chemical reaction model which was developed based on a grain formulation.

12. *"Evaluation of SO_2 Removal by Furnace Limestone Injection with Tangentially Fired Low-NO_x Burner,"* K. Tokuda, M. Sakai, T. Sengoku, and Nobuaki Murakami, Mitsubishi Heavy Industries, Ltd., Michael W. McElroy, Electric Power Research Institute, and K.Mouri, Electric Power Development Co.

Mitsubishi Heavy Industries (MHI) contracted with the Electric Power Research Institute (EPRI) and Electric Power Development Company (EPDC, Japan) to evaluate the SO_2-removal effectiveness of furnace limestone injection when applied in combination with a low-NO_x burner.

The evaluation included a series of furnace limestone injection tests conducted at MHI's 4 ton/hour pulverized coal-fired test furnace equipped with the Low-NO_x PM burner developed by MHI. The results showed 30-40% reduction of SO_2 at a Ca/S molar ratio of 2:1 while maintaining low-NO_x combustion conditions compatible with full-scale utility boilers and operating practices.

Basic (bench-scale) tests were carried out prior to the combustion tests, using an electrically heated flow reactor. The results from the basic tests were applied in interpreting the results from the combustion tests.

13. *"Performance of Sorbents With and Without Additives, Injected into a Small Innovative Furnace,"* Sam L. Rakes, EPA/AEERL, and G. T. Joseph and J. M. Lorrain, Northrop Services, Inc.

The Environmental Protection Agency (EPA) Innovative Furnace was used to develop information on the performance of sulfur sorbents with and without additives. The sorbents were injected at

two points in the furnace using the low-NO_x-type burner fired at a 14-kW thermal input rate on coal or liquefied petroleum gas (LPG), propane. The sorbents, a calcitic limestone (Vicron), a pressure-hydrated dolomite, and pure calcium hydroxide [$Ca(OH)_2$], were tested at Ca/S ratios of 1 and 2. The additives $NaHCO_3$ and Na_2CO_3, mixed with the sorbent, were tested at 5 weight % of the sorbent. Sodium carbonate (Na_2CO_3) appears to be an effective additive, giving increases in sulfur reduction of 6 to 12 percentage points, depending on the amount of additive, the sorbent, and injection location.

14. *"Pilot-Scale Characterization of a Dry Calcium-Based Sorbent SO_2 Control Technique Combined with a Low-NO_x Tangentially Fired System,"* John Kelly, Shigeto Ohmine, and Richard Martin, Acurex Corporation, and Dennis C. Drehmel, EPA/AEERL

A 380-kW_t (1.3 million Btu/hr) two-burner-level tangentially fired pilot-scale facility was used to characterize a dry calcium-based sorbent SO_2 capture technique combined with an offset auxiliary air low-NO_x burner with and without overfire air. Baseline tests using a conventional burner design, with and without overfire air, showed that the facility properly simulates full-scale uncontrolled and controlled NO emissions and furnace temperature histories. SO_2 test results with dry sorbent injection and the conventional burner were consistent in level and trend with limited field data. Efficiency, as determined by carbon monoxide, unburned hydrocarbon and carbon in flyash levels, was good for all test conditions and consistent with field practice.

Dry sorbent SO_2 test results showed that SO_2 capture is increased by: (1) utilizing conventional rapid fuel/air mixing burners; (2) injecting sorbent away from the flame (i.e., not mixing sorbent with the fuel); (3) avoiding contact between ash and sorbent; and (4) holding sorbent in the sulfation temperature zone (i.e., 1,505 to 1,255K) as long as possible. In addition, fuel and sorbent type had a significant impact on SO_2 capture.

15. *"Boiler Simulator Studies on Sorbent Utilization for SO_2 Control,"* D. W. Pershing, B. J. Overmoe, S. L. Chen, L. Ho, W. R. Seeker, and M. P. Heap, Energy and Environmental Systems Corporation

A 300-kW Boiler Simulator Furnace was used to investigate the influence of combustion and sorbent parameters on the effectiveness of dry sorbent injection for SO_2 control under conditions typical of current utility practice. Extensive characterization studies were conducted to investigate the role of boiler thermal history on capture effectiveness for limestone, dolomites, and slaked limes. Data were also obtained for high surface area sorbents (produced by pressure slaking) and for promoted sorbents (produced by the addition of appropriate metallic additives) as a function of thermal environment, sorbent injection location, calcium-to-sulfur molar ratio, and SO_2 partial pressure. In general, the results show that captures in excess of 50% at a Ca/S ratio of 2.0 can be achieved by several alternative methods. The experimental studies were supported by theoretical calculations using grain and pore models which combined consideration of the heterogeneous chemical reaction and diffusion processes.

Session III—Pilot-Scale Development of Furnace Injection

Michael McElroy, EPRI, Session Chairman

16. *"Studies of Sorbent Calcination and SO_2-Sorbent Reactions in a Pilot-Scale Furnace,"* Roderick Beittel, Southern Research Institute, Lawrence J. Muzio, Fossil Energy Research Corporation, and John P. Gooch and Edward B. Dismukes, Southern Research Institute

Furnace injection of calcium-based sorbents for SO_2 reduction was examined using a 1 x 10^6 Btu/hr pulverized-coal-fired combustor. The effects of sorbent type and rate, residence time, injection site, staged combustion, and CO_2-enriched transport air on overall SO_2 removal are reported. Properties of calcine were determined for gas firing at selected conditions.

Variations in calcine surface area of 2-30 m^2/g were found, corresponding to a range of calcium utilization of 12-38%. Sorbent type and temperature at the point of injection were primarily determinants of calcium utilization.

17. *"Recent IFRF Fundamental and Pilot-Scale Studies on the Direct Sorbent Injection Process,"* S. Bortz and P. Flament, International Flame Research Foundation

Pilot-scale experiments (2-4 MW_t) using a staged combustion air burner have shown that under optimised conditions, substantial reduction of SO_2 emissions by direct injection of calcium-based sorbents is possible. Various fuels including coals, ranging from subbituminous to low volatile bituminous, petroleum residues, and SO_2-doped gas flames, have been tested with this technique and SO_2 capture levels, with a Ca/S molar ratio of 2 and a calcium hydroxide sorbent, of between 70 to 80% have been achieved in cases when the peak flame temperatures were reduced to about 1,250°C or lower. Both the temperature field in the furnace and the sorbent type used have been shown to strongly influence the SO_2 capture efficiency, with other parameters (such as the SO_2 and O_2 concentration) playing a somewhat lesser role.

Some more fundamental work has also been conducted in plug flow reactors, both isothermal and non-isothermal, to better define calcination and sulphation rates at temperature levels of 700-1,300°C. The work which is only partially complete, will also examine the effect of sorbent characteristics, gas environment, and initial particle size distribution on the calcination and sulphation process. The results obtained thus far have shown that, at temperatures above 1,000°C, calcination is more than 80% complete in less than 200 ms with $CaCO_3$ and less than 40 ms with $Ca(OH)_2$. Sulphation also appears to be reasonably fast, reaching an asymptotic value in less than 600 ms for $CaCO_3$ when the gas temperature is between 1,000 and 1,100°C. The mean particle size, in the range 3-50 μm, has a large influence on calcium utilization for short particle residence times.

18. *"Demonstration of Boiler Limestone Injection in an Industrial Boiler,"* R. M. Statnick, C. E. Fink, N. S. Harding, B. J. Koch, and D. C. McCoy, Conoco Coal Research Division, and T. J. Hassell, E. I. DuPont de Nemours and Company

Consolidation Coal Company (Consol), through its Research & Development arm, Conoco Coal Research Division, made a commitment to expedite the development of Boiler Limestone Injection (BLI) technology via demonstration in a DuPont boiler (110,000 lb/hr of steam) during the summer and fall of 1984. The goal of the program was to demonstrate the technical and economic viability of both LIMB and LI (injection above the burner zone) as low-cost retrofit SO_2 control technologies while burning a Consol Northern West Virginia high-sulfur coal. Technical objectives included SO_2 removal capability with 50% as a minimum target, boiler

operability issues, and ESP impacts. Commercial low-NO_x burners purchased from Foster Wheeler Energy Corporation were used in the LIMB testing. Research-Cottrell supplied an ESP and humidification system. The demonstration program, test equipment, preliminary results, and BLI economics are described.

19. *"Pilot-Scale Studies of In-Furnace Hydrated Lime Injection for Flue Gas SO_2 Emission Control,"* G. F. Weber, M. H. Bobman, and G. L. Schelkoph, University of North Dakota Energy Research Center

Simultaneous control of SO_x/NO_x emissions, derived from the combustion of low-rank coal, is under investigation at the University of North Dakota's Energy Research Center (UNDERC). Process development work has been performed on both bench-and pilot-scale systems. Direct furnace injection of calcium-based SO_2 sorbent materials is the SO_2 control technique under evaluation.

Furnace injection tests have focused on the direct injection of pressure-hydrated lime at flue gas temperatures ranging from 815 to 1,650°C, followed by collection in a baghouse operated at temperatures up to 540°C. Sorbent utilization values up to 55% at a Ca/S mole ratio of 1.0 have been observed. SO_2 reduction of 80% has been observed at Ca/S mole ratios of $\leq$2.0. Sorbent utilization in the baghouse has never exceeded 10% for baghouse temperatures ranging from 425 to 540°C. Residence time and the temperature regime of the sorbent injection location appear to be the critical parameters controlling SO_2 reduction and sorbent utilization.

20. *"Bench-Scale Process Evaluation of In-Furnace NO_x and SO_x Reduction by Reburning and Sorbent Injection,"* W. R. Seeker, S. B. Greene, S. L. Chen, D. W. Pershing, and M. P. Heap, Energy and Environmental Research Corporation

Reburning involves the injection of a secondary fuel above the main firing zone of a combustor to produce a reducing zone which acts to reduce NO_x to molecular nitrogen. Overfire air is added above the reburn reducing zone to complete the combustion. The reburning process has been combined with the injection of calcium-based sorbents (e.g., limestone) to investigate the potential for combined NO_x and SO_x reduction. Bench-scale evaluations of the process carried out in a plug flow furnace at 23 kW_t have indicated that NO_x reductions of up to 70% and sulfur captures of up to 50% (at Ca/S = 2) can be achieved depending on a number of process variables. The dominant variables include the initial NO_x level that is to be reduced, the reburning fuel type (pulverized coal or natural gas), and the residence time and temperature in the reducing zone. For sulfur control, the dominant parameters are the amount of sorbent added, the sorbent type, and the injection temperature.

21. *"Evaluation of Low-NO_x Burners for SO_2 Control,"* R. Payne and A. R. Abele, Energy and Environmental Research Corporation

Limestone injection with multistage burners, termed "LIMB," was conceived as a process in which sulfur capture by sorbent material injected through burner passages may be combined with conditions which produce low-NO_x emissions in staged pulverized-coal flames. The potential for simultaneous NO_x/SO_x control by low-NO_x distributed mixing burners was evaluated in pilot-scale research furnaces. Experimental and commercial burner designs, ranging in capacity from 10 x 10^6 to 100 x 10^6 Btu/hr, were considered. Sulfur capture by injected sorbents was relatively insensitive to burner design. Sulfur capture with limestone was generally in the range of 35-40% at Ca/S = 2, and up to 40-55% for hydrated lime. The key factors in SO_2 removal were reactivity of the sorbent and the temperature history to which the sorbent particles were exposed.

Session IV—Burners for Simultaneous SO_2/NO_x Control

G. Blair Martin, EPA/AEERL, Session Chairman

22. *"Limestone Injection with an Internally Staged Low-NO_x Burner,"* Joel Vatsky and Edmund S. Schindler, Foster Wheeler Energy Corporation

Foster Wheeler's internally staged, Controlled Flow/Split-Flame low-NO_x burner has been in utility field service since 1979. The ease of retrofit to existing steam generators would make the burner a cost-effective means of implementing the LIMB concept if satisfactory sulfur capture can be achieved. Two methods of limestone injection internal to the burner are available: premixed with the coal and separate from the coal. The former technique was evaluated in a joint program with USEPA, while the latter was evaluated independently by Foster Wheeler Energy Corporation using a novel injection method. Over 60% greater sulfur capture was obtained using the FWEC technique on a 50 x 10^6 Btu/hr single-burner test furnace.

23. *"Development of Internally Staged Burners for LIMB,"* G. C. England, R. Payne, and J. Clough, Energy and Environmental Research Corporation

This paper discusses an experimental investigation directed toward the development of retrofit technology to achieve simultaneous in-furnace control of NO_x and SO_x emissions from coal-fired boilers. Results obtained in a 2.9 MW_t (10 x 10^6 Btu/hr) test furnace show that NO_x reductions of 50% can be obtained from high-velocity pre-NSPS burners by modification of both the coal nozzle and the air distribution without the use of external air ports. The effectiveness of calcium-based sorbent injection for SO_2 control is limited by sorbent reactivity and time/temperature characteristics of the boilers. Experimental results suggest that sorbent injection can be optimized using coaxial air/sorbent jets to achieve maximum sorbent reactivity and dispersion, and thereby optimize SO_2 removal.

24. *"Characterization of Alternate Sodium Sorbents for Fabric Filter SO_2 Capture,"* R. Hooper, Electric Power Research Institute, Arapahoe Test Facility

Injection of dry-sodium powders into the inlet plenum of fabric filters (baghouses) has been demonstrated to be an effective flue gas desulfurization (FGD) technique. On a full-scale utility boiler, injected sodium products have been shown to meet New Source Performance Standards (NSPS) of 70% removal for low-sulfur coal applications. Higher levels of SO_2 removal have also been demonstrated with the injection of greater quantities of sodium reagent. The amount of reagent required is shown to be sensitive to the reagent particle diameter. Results are given for commercially available sodium bicarbonate, trona, and light soda ash (sodium carbonate). Supply of sodium reagents is becoming increasingly more abundant as several chemical commodity suppliers expend both research and venture capital dollars to enter the potential utility market. To date, sodium bicarbonate reagents have been shown to provide better sodium utilization than sodium carbonate and trona.

25. *"Dry Injection Scrubbing of Flue Gases with the SHU Processes,"* Manfred Schutz, Saarberg-Holter Umweittechnik GmbH

The SHU dry sorbent injection process has been installed at the Ruhr recycling center refuse incinerator to remove stack gas SO_x, HCl, and HF. The incinerator produces 60,000-142,000 m^3/hr of flue gas with typical or design concentrations of 70-275 ppm SO_x, 300-1,080 ppm HCl, and 20 ppm HF. Prior to gaseous pollutant cleanup, particulates are removed in an ESP, and the combustion gases are cooled to 200-220°C by heat exchangers. Dry scrubbing occurs in a contact section fed by calcium hydroxide and steam at a feed ratio of 0.5 kg steam/kg $Ca(OH)_2$. The feedrate is metered based on the pollutant level in the treated gas. The flue gas, $Ca(OH)_2$, and steam are swirled to enhance contact and absorption. Following absorption, spent sorbent is removed by a fabric filter. The unit entered service in 1982. Test results show SO_2 removal efficiencies of 55-85%, depending on inlet concentration, and HCl removal efficiency usually over 90%. Selected solids analyses showed about 37% calcium hydroxide consumption corresponding to a utilization ratio of 1:2.7.

Session V—Post-Furnace SO_2 Removal

Dan Giovanni, Electric Power Technologies, Session Chairman

26. *"Flue Gas Desulfurization by Combined Furnace Limestone Injection and Dry Scrubbing,"* L. E. Sawyers and P. V. Smith, Babcock & Wilcox Company, Research & Development Division, and T. B. Hurst, Babcock & Wilcox, Fossil Power Division

Furnace limestone injection with dry scrubbing offers a viable economic alternative to wet scrubber systems for flue gas desulfurization. The combined technology is most promising from a technical and economic standpoint in application to eastern high-sulfur coals, where SO_2 reduction requirements are most stringent. Combining the two systems can offer required SO_2 reduction in excess of the sole use of either system. Also, combined use of the two systems can represent significant savings in reagent costs over more expensive lime reagent. This is because low-cost limestone is injected into a furnace for calcination to lime, and collected lime and ash materials are recycled and employed at the principal reagent in the dry scrubber system.

In pilot plant tests sponsored by the Department of Energy, which investigated the combined process as applied to eastern high-sulfur coals, various furnace injection methods, calcium-to-sulfur stoichiometric ratios (Ca/S), furnace load, and rear-furnace temperatures were studied. Results indicated potentially high SO_2 removal and a cost-effective process with a combined optimized system. These test results, in addition to Babcock & Wilcox research and development experience with the two technologies (separately and in combination), are reviewed in this paper.

27. *"Pilot Evaluation of Combined SO_2 and Particulate Removal on a Fabric Filter,"* Franz G. Pohl, Southern Research Institute, and Michael McElroy and Richard Rhudy, Electric Power Research Institute

The injection of calcium compounds into the flue gas upstream of a fabric filter is under evaluation as a means of simultaneous SO_2 and particulate emission control. Pilot tests are being conducted on a 200 acfm slipstream from a pulverized-coal-fired boiler burning 3% sulfur coal. Water injection, steam injection, and heat extraction are used to condition the flue gas to desired temperatures and humidities. SO_2 removal occurs in the flue gas ductwork, in the expansion plenum upstream of the fabric filter, and across the fabric dustcake. Tests with pressure-hydrated dolomitic lime indicated higher SO_2 removal as the flue gas temperature approached the saturation temperature. SO_2 removal of 50% was observed at an approach temperature of -4°C when the sorbent was injected at a calcium-to-sulfur ratio of 1:1 and up to 80% SO_2 removal at a calcium-to-sulfur ratio of 2.9:1.

28. *"Fireside Consequences of Furnace Limestone Injection for SO_2 Capture,"* G. J. Goetz and M. D. Mirolli, Combustion Engineering, Inc., and D. Eskinazi, Electric Power Research Institute

The influence of limestone injection on the furnace performance characteristics of two coals was investigated experimentally in Combustion Engineering's pilot-scale Fireside Performance Test Facility (FPTF), under an EPRI-sponsored study. The slagging, fouling, and emission characteristics of a high-sulfur, high-iron Illinois No. 6 bituminous coal and a low-sulfur, high-sodium Montana subbituminous coal were investigated under low-NO_x conditions. Calcium-to-sulfur ratios of 2-4 were investigated in detail.

Results indicate that limestone can be injected without adversely affecting the slagging and fouling performance of units firing these fuels. For high-sodium coals it has significant potential for reducing fouling by weakening the deposit-to-tube bond, thereby enhancing sootblower cleaning effectiveness. With each coal upper limits for limestone dosage were established based either on deposit accumulation and/or heat transfer rates.

29. *"Effects of Furnace Sorbent Injection on Fly Ash Characteristics and Electrostatic Precipitator Performance,"* Robert S. Dahlin and John P. Gooch, Southern Research Institute, and James D. Kilgroe, EPA/AEERL

The effects of furnace sorbent injection on the electrical resistivity and the size distribution of particles suspended in flue gas have been studied at temperatures near 149°C. *In-situ* resistivity and impactor data have been obtained using various sorbents and sorbent injection modes while firing coal in a 1.06 GJ/hr (1×10^6 Btu/hr) combustion system. Laboratory resistivity measurements have also been made with fly ash/sorbent mixtures using various simulated flue gas conditions.

When using a 2.3% sulfur Indiana coal the fly ash resistivity was in the range of 8×10^8 to 1×10^9 ohm cm at a flue gas temperature of 147-153°C and in the presence of 26-31 ppm of SO_3 produced from the coal. With burner injection of Vicron 45-3 limestone at a calcium-to-sulfur ratio of 1.8, the resistivity was increased to 1 to 2×10^{12} ohm cm with virtually no measurable SO_3 left in the gas phase at 150-158°C. Experiments with flue gas conditioning showed that the resistivity of ash/sorbent mixtures produced from limestone injection could be reduced to less than 5×10^{10} ohm cm with the injection of 30-40 ppm of SO_3, if residence time for uptake of SO_3 was adequate. Preliminary data suggest that the effectiveness of SO_3 conditioning may be influenced by sorbent injection temperature when hydrated lime is injected downstream from the burner.

The implications of these and other results on ESP performance are discussed, together with potential corrective measures for improving the collection efficiency of ash/sorbent mixtures.

Session VI—Process Integration and Economics

David Lachapelle, EPA/AEERL, Session Chairman

30. *"Evaluation of Temperature Histories in the Radiant and Convective Zones of a Pulverized-Coal-Fired Steam Generator,"* D. G. Lachapelle, EPA/AEERL, and B. M. Cetegen, J. L. Reese, K. Kurucz, and W. Richter, Energy and Environmental Research Corporation

The effectiveness of *in-situ* desulfurization by direct injection of calcium-based dry sorbents is sensitive to the thermal environment in boilers. More specifically, the temperature histories of gas and sorbent particles in the radiant zone and the high-temperature convective pass sections play an important role in the sulfur capture process. Estimation of temperature histories requires a detailed description of the furnace heat transfer and flow field. This paper discusses the detailed field measurements of temperature and velocities in a wall-fired utility boiler. The temperature measurements at full boiler load indicate that an assumed sulfation temperature window (800 $<T<$ 1,200°C) starts near the beginning of the high-temperature radiant superheater and extends to the back pass cavity. The residence times for the bulk flow in this temperature zone are about 1 second at full boiler load. At 60% load, the residence times are longer.

31. *"Impact of Sorbent Injection on Power Plant Heat Rates,"* Dan V. Giovanni, Electric Power Technologies, Inc., and Michael W. McElroy, EPRI

In-furnace SO_2 control via sorbent injection impacts boiler performance as a result of heats of reaction of chemical processes and increased auxiliary power demands. In addition, dry injection may effectively reduce flue gas acid dew points and thereby permit low-level heat recovery. This paper summarizes the effects of the chemical reactions and quantitatively evaluates the potential for heat rate improvement through supplemental heat recovery.

32. *"Boiler Design Criteria for Dry Sorbent SO_x Control with Low-NO_x Burners,"* R. W. Koucky, A. Kokkinos, D. C. Borio, J. P. Clark, and C. Y. Sun, Combustion Engineering, Inc., and D. G. Lachapelle, EPA/AEERL

A program to develop boiler design criteria for application of dry sorbent SO_x control technology with low-NO_x burners is being conducted with EPA sponsorship. A comprehensive review of past and current research in the area of sorbent SO_x control was performed to provide a basis for evaluating the implications of this technology on boiler design, cost effectiveness, and operability. Historical and projected design trends were analyzed for all tangentially fired pulverized-coal utility boilers built from 1960 to the present, including the effect of coal rank. The design changes necessary to incorporate dry sorbent SO_x control for utility pulverized-coal-fired boilers were evaluated. Among the design and operating factors considered were coal and sorbent type, sorbent-to-sulfur molar ratio, time/temperature history, and back-end effects. Limestone preparation requirements were defined.

33. *"Wall-Fired Boiler Design Criteria for Dry Sorbent SO_2 Control with Low-NO_x Burners,"* R. K. Mongeon, Riley Stoker Corporation, J. P. Mustonen, Stone & Webster Engineering Corporation and D. G. Lachapelle, EPA/AEERL

Limestone injection multistage burner (LIMB) technology is being actively investigated as a potentially economical and attractive means of reducing SO_2 and NO_x emissions in coal-fired boilers. Although primary emphasis is on the retrofit potential for existing boilers that are not currently equipped with scrubbers, application to new boilers is being investigated as well.

This paper concentrates on LIMB technology for new and existing coal-fired power stations and also discusses historical and projected design trends which have an effect on it. Advantages and disadvantages of various LIMB methods are discussed, including the effect on steam generator design criteria. A suggested approach is developed, and its ramifications on the boiler and the balance of plant design are discussed.

34. *"Dry Sorbent Emission Control Prototype Conceptual Design and Cost Study,"* D. T. Gallaspy, Southern Company Services, Inc.

The Dry Sorbent Emission Control (DSEC) program conducted by the Electric Power Research Institute (EPRI) is aimed at developing the DSEC technology in three successive steps: a fundamental pilot- and bench-scale test program, a prototype or intermediate-scale test program at a small production boiler, and a full-scale demonstration at a 400-MW or larger utility boiler. The first step of this process has been in progress since mid-1983 under the joint sponsorship of EPRI and Southern Company Services (SCS), Inc. One product of the current program is a conceptual design and cost study for a 1- to 2-year prototype evaluation of DSEC technology at a 40-MW utility boiler. This paper reports the results of the prototype study, which is based on Gulf Power Company's Plant Scholz Unit 2. A prototype design based on an evaluation of major process performance and engineering issues is described. Estimated capital and O&M costs for the prototype are presented. A feature of the study is its organization by process subsystems, which allows a variety of test scenarios to be constructed. The projected capital cost of an alternate test scenario is reported.

35. *"EPA's LIMB Cost Model: Development and Comparative Case Studies,"* Norman Kaplan, David G. Lachapelle, and Jeff Chappell, EPA/AEERL

The LIMB cost model is used to project the capital and annualized costs and the cost per unit of pollutant controlled for LIMB systems installed on generic coal-fired utility boilers. The type of sorbent, unit size, unit life, level of control, and coal sulfur content are among several items specified by the user. In addition, flexibility in user input or default values enables various parametric and sensitivity analyses. Basic economic premises for the model are taken from the EPRI Technical Assessment Guide (TAG™).

Case studies compare various LIMB process options with each other and with wet limestone slurry scrubbing, the current standard SO_x control technology, under a variety of conditions. For a new 500-MW unit burning 1.92% S coal and achieving control to meet NSPS, costs per ton of sulfur removed are estimated to be $1,377 and $1,078 for limestone FGD and LIMB using dolomitic hydrate, respectively. At 0.48% S in the coal, these costs are estimated at $3,715 and $1,366 for limestone FGD and LIMB, respectively. Case studies involving comparisons between LIMB and FGD are accomplished through the use of the LIMB cost model and the TVA Shawnee Flue Gas Desulfurization Computer Model.

36. *"An Update on the Application of Lime Products for SO_2 Removal,"* David C. Hoffman, Chemical Lime, Inc., and Donald H. Stowe, Jr., Dravo Lime Company (in conjunction with the National Lime Association)

In the early years of utility SO_2 removal in the U.S. scrubbing equipment manufacturers offered several "wet" processes utilizing different reagents. As in most industries where technology is continuously evolving, these processes have become more and more efficient, along with the commercialization of a major new process—dry scrubbing. Because of the need for further SO_2 reductions from existing sources, new technologies are starting to be visualized and are receiving more laboratory and developmental attention. One of the more promising technologies involves the direct injection of lime-based absorbents into the hot flue gas stream.

The major objective of this discussion is to highlight current economics on today's most popular wet scrubbing systems with major emphasis on reagent aspects. Additionally, state-of-the-art technical and economic considerations on direct lime injection will be reviewed, with the commercial reagent emphasis centering on today's existing lime industry (location, tonnage, manufacturing processes, etc.). The question of lime manufacturing flexibility to meet current and projected lime demand will be discussed with respect to assumed commercialization of direct lime injection technology.

With these variables in better perspective, it can be seen that today's lime industry is attuned to SO_2 removal reagent needs, and will readily respond to the anticipated needs for lime-based alternative absorbents.

37. *"Dry Injection FGD Sodium-Based Sorbents: Availability and Economic Evaluation,"* R. M. Wright, FMC Corporation, Alkali Chemicals Division

Dry injection using sodium-based sorbents offers a simpler and less costly method of SO_2 removal than can be realized with either wet scrubbing or spray drying for boilers firing low-sulfur coal. Sorbents for dry injection FGD include the minerals trona and nahcolite along with compounds derived from them. Huge deposits of these minerals are found in Wyoming, California, and Colorado.

The general properties and availability of the various candidate materials are discussed. In addition, the effects of inert content, molecular weight, and reactivity on the ultimate cost of using each of the materials are addressed. Finally, advanced products which are being developed are touched upon.

Session VII—Sorbent Availability and Costs

Richard Hooper, EPRI, Session Chairman

38. *"Sodium Bicarbonate for Sulfur Dioxide Emission Control,"* Ray Shaffery, Church & Dwight Co., Inc.

It is anticipated that more and more stringent controls on SO_2 emissions from public utility and industrial coal-fired boilers will be imposed. It is further recognized that wet scrubbers, spray dryers, and variant systems require heavy capital investment and are troublesome to operate. The dry sodium-based sorbent injection technique using a bag house for collection of fly ash and reactants is attractively simple in operation and effective. Important considerations in the selection of this technique over alternative systems are the reliable availability of sorbents and the impact of freight to allow dry injection to be competitive with alternative systems.

The focus of the paper will be on a concept to economically provide sodium bicarbonate as a sorbent to control SO_2 emissions using the dry injection technique.

39. *"Reduction of SO_2-Emission in Brown Coal Combustion, Results from Research and Large-Scale Demonstration,"* K. R. G. Hein and G. Kirchen, Rheinisch-Westfälisches Elektrizitätswerk

For more than 10 years the Rheinisch-Westfälisches Elektrizitätswerk (RWE), Germany's largest utility company, was involved in the development of the Dry Additive Process (DAP) for SO_2 removal by utilizing dry calcium-based materials. Based upon results from trials at a combustion rig and a 60-MW utility boiler, a full-scale demonstration plant was installed at a 300-MWe brown coal boiler.

During this program that lasted over a year at this installation, the reduction of SO_2 emissions and the maximum possible amount of additives with regard to operational behavior of various power station components and different injection modes have been investigated. The large-scale operation was accompanied by rig tests concerned with the application of CaO-rich ashes from different preparation procedures.

The paper deals, apart from the major results for SO_2 reduction of the three different test scales, with various operational problems associated with the additive injection and discusses the experience with practical solutions.

40. *"Reduction of SO_2 Emissions from a Coal-Fired Power Station by Direct Injection of Calcium Sorbents in Furnace,"* G. Flament and G. Chelu, Charbonnages de France, CERCHAR, H. Brice, Charbonnages de France, Houilléres de Lorraine, R. Manhaval, Charbonnages de France, Houilléres de Provence, and M. Vandycke, Stein Industrie

Houilléres de Provence, a company of the Nationalized Group "Charbonnages de France," has conducted a trial series in a 50-MWe power station in Gardanne (south of France) in order to evaluate the feasibility of applying direct SO_2 capture in flames by dry calcium sorbents injection to a newly built 600-MWe unit.

This campaign of measurements on the 50-MWe boiler followed a preliminary study—subcontracted to the International Flame Research Foundation (Ijmuiden) in 1982—where effects of sorbent quality, sorbent injection location, flame temperature, and flue gas recirculation upon efficiency of SO_2 capture had been determined.

The experiments have indicated similar trends on the 50-MWe boiler as on pilot scale except for flue gas recycling which was effective in improving SO_2 capture in the pilot-scale experiments but had no effect on the boiler.

On the boiler, it was found that natural retention of sulphur in the calcium-rich ash followed similar trends as retention by injected calcium carbonate; more than 50% SO_2 removal could be obtained with $Ca/S = 3$. $Ca(OH)_2$ was a much more efficient sorbent, and 60% SO_2 removal could be obtained with some $Ca(OH)_2$ injection and a high ash coal at a total $Ca/S = 3$ (2.4 for the ash and 0.6 for $Ca(OH)_2$).

Injection of sorbents above the upper burners elevation gave the best results. The results of the 50-MWe tangentially fired boiler have been used to design the modifications required for applying the technique to the 600-MWe boiler which has just started operating.

Session VIII—Field Applications and Full-Scale Testing

Richard Stern, EPA/AEERL, Session Chairman

41. *"Direct Desulfurization at the 700-MW Weiher III Unit,"* M. Yaqub Chugtai, L&C Steinmuller GmbH

Abstract not available.

42. *"Laboratory Tests, Field Trials, and Application of Furnace Limestone Injection in Austria,"* G. Staudinger, Technical University Graz, H. Schrofelbauer, Osterreichische Draukraftwerke AG

In Austria six boilers ranging from 20 to 330 MWe, having tangential firing or wall-firing, are equipped with furnace injection. In all cases, the limestone powder is introduced with the secondary air. Addition of the additive through the coal mills was less effective. Ca/S molar ratios of 3 to 4 gave average sulfur removal rates of 50-60%, depending on the type and size of the furnace and on fuel. Fouling is a serious problem with hard coal at full load, not at all at reduced load, and only under certain circumstances with lignite.

Furnace conditions were simulated in laboratory experiments by putting single limestone particles with diameters from 3 to 100 μm for 3 to 20 seconds into a hot flue gas stream. The question on reaction rates as a function of particle size, SO_2 concentration, temperature (900-1,150°C) and residence time could be answered.

Experiments in a pilot bag filter with 1 m^2 filter area and jet cleaning showed that the poor utilization of dry limestone in furnace injection of only 10% can be improved to up to 26% if the ash is separated from the flue gas. Sulfur removal of up to 80% and SO_2 outlet concentrations as low as 100 ppm were achieved.

43. *"Experience with Furnace Injection of Pressure-Hydrated Lime at the 50-MW Hoot Lake Station,"* H. Ness and T. P. Dorchak, USDOE, James R. Reese, Energy and Environmental Research Corporation, and Verlin Menz, Otter Tail Power Company

Tests were recently completed at a 50-MW power plant to evaluate direct furnace injection of pressure-hydrated lime to reduce SO_2 emissions. Both high calcium and dolomitic limes were evaluated over a range of injection rates. The sorbents were injected at selected points above the burners in the radiant sections of the boiler. Temperatures in these sections ranged from about 1,090 to over 1,370°C. The low-sulfur lignite fired was from the Beulah mine in North Dakota. The boiler, Hoot Lake Station, Unit 2, was a tangentially fired, balanced draft unit equipped with an ESP for particulate emission control. The burners were operated within normal ranges except in one test with a low-NO_x configuration. Some 30 short-term tests were conducted, typically 2 to 4 hours long. The tests also included injecting hydrated lime for a continuous 30-hour period to evaluate longer-term effects on boiler performance.

This paper gives preliminary results of sulfur reduction and calcium utilization. Sulfur reduction values are based on SO_2 measurements in the gas stream. The simple pneumatic system, used to inject the dry sorbents, is also described. The results are compared to those from earlier tests at the station evaluating limestone as the sorbent. Impacts on the performance of the boiler and ESP are briefly described.

44. *"EPA Wall-Fired LIMB Demonstration,"* Robert V. Hendriks, EPA/AEERL

The USEPA is engaged in a research program to develop improved control technologies for emissions of sulfur and nitrogen oxides (SO_x and NO_x) from the combustion of fossil fuels. Previously developed low-NO_x systems for coal combustion are being demonstrated, and methods for removal of SO_x in the combustion process in conjunction with these systems are under development.

A low-cost method for SO_x control is the use of Limestone Injection with a Multistage Burner (i.e., low-NO_x burner). This technology, abbreviated LIMB, promises to be retrofittable to large and small coal-fired boilers at lower capital and operating costs than currently available pollution control alternatives such as flue gas desulfurization.

EPA has recently awarded a contract to Babcock & Wilcox for a full-scale utility size demonstration of LIMB. This paper describes the recently initiated EPA LIMB Demonstration Project with emphasis on outlining the project objectives and scope and describing the demonstration host site.

45. *"The Homer City Experience in Developing a LIMB Process for Use with Coal Preparation,"* D.I. Cessna, J. H. Tice, and D. W. Carey, Pennsylvania Electric Company, and the New York State Electric and Gas Corporation

Pennsylvania Electric and the New York State Electric and Gas Corporation have been experimenting with and further developing a system of Limestone Injection Multistage Burner (LIMB) that can supplement an existing coal cleaning application to bring their Homer City No. 3 unit into compliance with EPA's 1971 New Source Performance Standard. Two series of limestone injection tests have been carried out during short runs on the full-scale unit with encouraging results. Small-scale combustion tests are now being performed by contractors to lead to the design of a flexible boiler LIMB retrofit. This flexible system will be operated while varying the parameters of injection location, furnace load, firing mode, and limestone type during a 4-month test series planned for late-1985. The objectives for the Homer City retrofit are 25% SO_2 removal from flue gas containing 1.6 lb $SO_2/10^6$ Btu using a calcium/sulfur ratio of 1.0 or less. This paper gives results of the owner's tests to date and their plans for further LIMB development specific to Unit No. 3.

46. *"NO_x/SO_2 Control Experience at Saskatchewan Corporation's Boundary Dam G.S.—Unit #6,"* R. D. Winship, Combustion Engineering-Superheater Ltd., and J. A. Haynes, Saskatchewan Power Corporation

This paper describes the SO_2 emission reductions achieved with Combustion Engineering's Modified Combustion Techniques, with and without limestone injection on a lignite-fired utility boiler at Saskatchewan Power. The paper discusses the operational considerations and effects of the modified operation on boiler fouling and efficiency.

An outline of the system design and the modifications to the No. 6 unit are described. The results of the SO_2 and NO_x testing under different operating conditions are summarized. The paper provides a preliminary indication of the economics of the C-E Modified Combustion Technique and outlines future research and development plans.

47. *"Suction Pyrometry Tests and Innovative Furnace,"* Samuel L. Rakes, EPA/AEERL

Suction pyrometry tests were conducted on the EPA's innovative furnace at Research Triangle Park, NC, to establish the actual gas temperatures at several points in the furnace at specified operating conditions. Gas residence times were calculated using the temperatures established by the suction pyrometry tests and

gas compositions measured by the monitors. At the selected firing rate of 47,300 Btu/hr (14 kW) thermal input, gas residence times of about 1.5 sec between the temperatures of 2,250 and 1,600°F (1,232 and 871°C) were calculated.

48. *"Surface Characterization and Microanalysis of Sorbents and Ash/Sorbent Mixtures,"* R. S. Dahlin, Southern Research Institute, and David A. Kirchgessner, EPA/AEERL

This paper presents a survey of techniques for the surface characterization and microanalysis of particulate samples related to EPA's Limestone Injection Multistage Burner (LIMB) program. The following techniques are discussed: scanning electron microscopy (SEM), carbon replica transmission electron microscopy (TEM), thin section TEM, energy dispersive X-ray (EDX) analysis, electron microprobe analysis (EMS), electron spectroscopy for chemical analysis (ESCA), and Auger electron spectroscopy (AES). Example applications of these techniques to various LIMB samples are presented, and the limitations of the techniques are discussed.

*The EPA compiler, **P. J. Chappell** (also the EPA Project Officer, see below), is with Air and Energy Engineering Research Laboratory, Research Triangle Park, NC 27711.*

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"Volume II. Power Plant Integration, Economics, and Full-Scale Experience," (Order No. PB 85-232 361/AS; Cost: $29.50, subject to change).

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