**ENGINEERING DEVELOPMENT OF ADVANCED
COAL-FIRED LOW-EMISSIONS BOILER SYSTEMS**

Project Technical Status Report

QUARTERLY REPORT

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I. Project Management

I.1 Summary of Activities

I.1.1 Period of October 1994 to December 1994

On October 12, 1994 a Phase II & III pre-kick-off meeting was held to discuss planning and the budget for the LEBS project. A preliminary schedule was developed by each subsystem along with a coinciding budget. The initial budget was set up to support the preliminary planning activities of the project. A detailed project schedule was then drafted for review by the Subsystem team leaders and a preliminary budget through the end of the B&W fiscal year was prepared. A complete budget through the end of the project was initiated.

DOE project manager, Tony Mayne, visited the Alliance Research Center, including a tour of B&W's Clean Environment Development Facility (CEDF), to discuss activities of Phase II & III along with the DOE workshop scheduled for February. He was also able to observe the initial test period for the burner development program which was occurring at the Small Boiler Simulator. PSI (Physical Sciences, Inc.) was present during this testing, and described the work that they are doing on the sensor development.

I.1.2 Period of January 1995 to March 1995

A status meeting was held in January to review the work completed in Phase II to date and to discuss the future work planned. All members of the project team were present in order for the new technical manager, Denny McDonald, to meet all participants and to discuss each individual activity.

Representatives from B&W participated in the U.S. DOE sponsored LEBS Workshop held in Atlanta, Georgia, on February 22, 1995.

A technical paper "Development of LIDS™ as a Part of B&W's Low Emission Boiler System" was presented March 20-23 at the 20th International Conference on Coal Utilization and Fuel Systems in Clearwater, Florida. A draft manuscript was submitted and accepted for "Component Development in Support of B&W's Advanced Coal-Fired Low-Emission Boiler System" for the 1995 International Joint Power Generation Conference in October 1995.

I.1.3 Period of April 1995 to June 1995

A status meeting was held with DOE project manager Tony Mayne on April 28, 1995. An update of the work completed to date was given and the work in progress and work planned were discussed.

A technical review meeting was held on June 27, 1995, to discuss the release of the Task 8 -

Preliminary POC Test Facility Design Report.

The project team assisted in the preparation of LEBS material to be presented in May by Stan Vecchi to Ralph Regula, United States House Representative for Ohio, in support of the LEBS program. A presentation of B&W's LEBS effort was made on April 12 to Mr. Howard Feibus and Dr. Jer-Yu Shang from DOE Washington.

Two abstracts for papers were submitted; 1) "Development of an Advanced Low-NO_x Burner in Support of B&W's Advanced Coal-Fired Low-Emission Boiler System," for the 1995 AFRC Fall International Symposium on "Combustion Research and Industrial Practice: From Equations to Equipment" and 2) "On-Line Measurement of Pulverized Coal", for the upcoming Power-Gen Conference. Papers for the July PETC Contractor's Conference and the International Joint Power Conference were submitted for final review.

1.1.4 Period of July 1995 to September 1995

B&W hosted Tony Mayne, B&W's LEBS DOE project manager, and Dr. Sun Chun, Director of PETC, in separate visits to the Alliance Research Center (ARC). An update on the activities occurring under the LEBS program were discussed and a tour of the Research Facility was given.

Phase IV planning continued. The SO₂ subsystem is leading a proposal effort to the Ohio Coal Development Office (OCDO) requesting cost sharing for the B&W LEBS proof-of-concept demonstration. A proposal outline was developed. A discussion with Jackie Bird of OCDO will be arranged to receive guidelines on how to approach the request and proposal. In parallel, other sources of funding are also being explored.

A meeting was held with the Electric Power Research Institute to discuss B&W air toxics investigations. Included in the discussion was a presentation of the LIDS mercury measurements made to date and plans for future LEBS air toxics studies.

A technical paper entitled "Update of Progress for Phase II of B&W's Advanced Coal-Fired Low-Emission Boiler System" was presented at the DOE Pittsburgh Energy Technology Center (PETC) Contractors' Review Conference in July. Preparations were completed for presentation of a paper titled "Component Development in Support of B&W's Advanced Coal-Fired Low Emissions Boiler System" at the upcoming International Joint Power Generation Conference held October 9-11 in Minneapolis, Minnesota.

1.1.6 Period of October 1995 to December 1995

A status review meeting was held October 26, with Tony Mayne and Neal Coates of the DOE at the Alliance Research Center. An update of the subsystem activities was given along with a tour of the B&W test facilities noting the modifications being made as a part of the Combustion 2000 program.

A meeting was held with subsystem team leaders to determine the effect of postponing the end date of the project from September 1996 to March 1997. The effect of another government shutdown, and possible work stoppage as a result, was also discussed.

Three papers were presented; 1) "Development of an Advanced Low-NO_x Burner in Support of B&W's Advanced Coal-Fired Low-Emission Boiler System," at the AFRC 1995 Fall International Symposium October 15-18, 1995, 2) "Component Development in Support of B&W's Advanced Coal-Fired Low-Emission Boiler System," at the International Joint Power Generation Conference, October 9-11, 1995 and 3) "On-Line Measurement of Pulverized Coal" at the PowerGen '95 conference.

Abstracts for two papers for presentation at the CSTA/ASME-FACT/PETC Conference on Coal Utilization to be held in Clearwater Florida March 18-21, 1996 were accepted: 1) "B&W's Advanced Coal-Fired Low-Emission Boiler System; Preparation for and Preliminary Results of Subsystem Testing" and 2) "10 MW_e Prototype Testing of LIDS™ As Part of the Babcock & Wilcox Low Emission Boiler System". An abstract for a paper entitled "Evaluation of Two Commercially Available Sensors for Use in Pulverized-Coal Burner lines" about the Endress + Hauser microwave meter was prepared for an Engineering Foundation meeting in April 1996.

II. NO_x Subsystem

The goal of the NO_x Subsystem is to achieve continuous operation of the Low-Emissions Boiler System (LEBS) at NO_x emissions at or below 0.20 lb/MBtu through combustion techniques only, with a further target of 0.1 lb NO_x/MBtu using supplementary advanced flue gas cleanup technologies if necessary. These goals place practical constraints that must be considered on the NO_x Subsystem design. Not only must the boiler be designed to achieve time-temperature mixing histories that minimize NO_x, but it must also be designed to operate that way throughout its working lifetime. Therefore, NO_x minimization strategies must be integrated into the control systems for every boiler component from the pulverizers to the stack. Furthermore, these goals must be met without increases in carbon loss and CO emissions from the levels achieved with current low-NO_x combustion systems. Therefore, the NO_x Subsystem requires not only sound mechanical designs of burners, furnace surface, and staging air/fuel injectors, but also sensors and software to allow control of their operation. Through engineering analysis, experimental testing, and numerical modeling in Phase II, an advanced low-NO_x control system is being developed. The progress of these activities is presented in this report.

II.1 Summary of Activities

II.1.1 Period of October 1994 to December 1994

The initial pilot-scale burner development test program began in November. The first round of testing was used to determine the effect of the OFA ports in the Small Boiler Simulator (SBS) test facility. The B&W pilot-scale DRB-XCL[®] was used to characterize the SBS furnace with the Illinois #6 design coal. Chemical analyses were performed on samples taken during testing.

Work began on the development of two baseline combustion models of the B&W pilot-scale advanced low-NO_x burner (ALNB). Two configurations were chosen based on best overall performance observed during previously completed in-house test campaigns in the SBS. Geometry models were completed for two configurations in December. Flow predictions for these two cases were started.

Characterization testing of the B&W 100 MBtu/hr Clean Environment Development Facility (CEDF) began in December. Initial temperature probing showed good correlation to the design specifications.

Design of the corrosion probes for testing on the SBS during the burner development and LIDS testing was completed in December. Construction of the probes began, with scheduled completion in January to be used during the LIDS testing.

II.1.2 Period of January 1995 to March 1995

Meetings were held with the NO_x subsystem members to discuss further development work on

the ALNB. A series of burner modifications were agreed upon and a test matrix developed. The ground work was laid for further development based on the results of the experimental testing and modeling studies. Modifications to the ALNB were designed and approved by subsystem members. The second round of SBS testing was scheduled for the end of February.

The B&W DRB-XCL[®] pilot-scale burner was fired first as a baseline for testing the ALNB#1 and ALNB#2. Testing was completed in March with promising results.

NO_x subsystem team members met several times to refine the burner development plan. As part of the revised plan, it was decided to use modeling to aid in screening some minor variations of the pilot-scale ALNB, and to investigate more significant burner geometry variations before fabrication of a new burner for SBS testing in the mid-summer of 1995.

The baseline ALNB combustion modeling runs were completed in January. Burner modeling studies included variations of the ALNB#1 and modified concepts. Two variations on the ALNB with swirling primary air and fuel have been completed, and additional runs evaluating core air swirl were in progress. Flow models for four alternate concepts have been completed to provide boundary conditions for axisymmetric combustion predictions.

Characterization testing of the CEDF continued in January. Initial results showed good comparison to modeling predictions for furnace temperature distributions. Testing was completed in February and data analysis begun. The DRB-XCL[®] burner characterization and in-furnace probing results will be used as a benchmark for comparison with the ALNB subsystem testing and as a comparison to commercial units.

The NO_x subsystem design effort in support of Subsystem Testing began in March. Modifications to B&W's CEDF will include an overfire air (OFA) port arrangement for staging tests and the installation of a 100 MBtu/hr ALNB.

Preliminary design of the Proof-of-Concept (POC) test facility began. A preliminary process flow diagram, major equipment list, and material balance were completed.

A corrosion probe was exposed to the combustion gas in the convection pass of the SBS downstream from the limestone injection during the SO₂ subsystem pilot-scale testing.

II.1.3 Period of April 1995 to June 1995

A NO_x subsystem team meeting was held to discuss the results of the burner development pilot-scale tests completed in February/March on the SBS. The experimental results were reviewed and compared to the modeling runs. Results of both the modeling predictions and the testing indicated that the same burner configuration provided the best design platform for further development. A few extra modeling cases were determined to be necessary in preparation of the next pilot-scale test series. The modeling focused on changes to the burner configuration that are easier to model than to fabricate and test.

Preparation for the final pilot-scale test series began. Work on modifying the OFA ports on the SBS also began. Design work was started for building a staged and unstaged version of the ALNB#3 for the final testing series.

Modeling runs were initiated to evaluate possible improvements to the existing SBS overfire air injection ports. Two completed analyses indicated a significant improvement in performance by use of larger port diameters. Additional analyses will be completed with the selected port diameter, both with and without a 45°F swirler.

The Subsystem Test Design & Plan Report was completed and sent for NO_x team review in April. Revisions were incorporated and the final report was sent to the DOE for approval. Comments were received from DOE project manager Tony Mayne. Permission to begin Task 10 - Subsystem Test Unit Construction was granted.

The design of the OFA system for the Subsystem Testing continued. Initial modeling results were reviewed and some additional runs were recommended. The piping and arrangement drawings were completed in June. Detailed drawings of the OFA registers began. Design of the 100 MBtu/hr ALNB continued, keeping on schedule of a delivery date by the first of September.

A initial draft of the NO_x subsystem write-up for the Preliminary Design of the POC Test Facility Report was completed and sent for team review.

The first bench-scale corrosion test began. Different commercial alloys and coatings were exposed to a simulated low-NO_x combustion environment containing 5000 ppm H₂S at 1000°F in a still retort. This environment is expected to be one of the worst corrosion conditions in the lower furnace. The samples will be exposed in the retort for 1000 hours.

II.1.4 Period of July 1995 to September 1995

Fabrication of the pilot-scale (5 MBtu/hr) ALNB#3 (staged and unstaged versions) was completed in July along with the OFA port modifications to the SBS facility. Testing began in July with B&W's pilot-scale DRB-XCL[®] burner for baseline comparison. Testing continued into August with the unstaged ALNB#3. Variations on the hardware configurations were tested. Staged tests of the optimal hardware configuration were performed. In-furnace probing of gas species were performed to use with the modeling cases and the corrosion study. Pilot-scale testing was completed in September. The most promising hardware configuration design was scaled-up for the subsystem testing scheduled for mid-September. Fineness testing was performed during the last two days of testing. Coal fineness levels of 80% and 92% less than 200 mesh were tested.

Fabrication of the 100 MBtu/hr ALNB was completed in August. Additional hardware configurations for testing were fabricated. Fabrication of the OFA system continued. Modifications to the facility were performed in-between test programs.

Baseline testing was performed in the CEDF with the 100 MBtu/hr DRB-XCL[®] firing the Illinois #6 design coal. The results will be used as a comparison with the ALNB. The initial round of subsystem testing with the ALNB was performed in September firing two coals, the Illinois #6 and a Mahoning 7A coal. Although minor modifications are in order for the ALNB, the general hardware configuration was found to be promising and therefore, the burner was given the name DRB-4Z[™]. This name provides a continuity with the low-NO_x DRB product line from which it originates, while still accommodating its uniqueness.

A burner flow model of the 100 MBtu/hr DRB-XCL[®] burner was completed for CEDF modeling studies. A baseline combustion model for the DRB-XCL[®] and the DRB-4Z[™] firing in the CEDF were near completion, and will be used in conjunction with CEDF burner tests to evaluate the DRB-4Z[™] at near full-scale and to aid in planning the next test series.

II.1.5 Period of October 1995 to December 1995

A paper entitled "Development of An Advanced Low-NO_x Burner in Support of B&W's Advanced Coal-Fired Low-Emission Boiler System," was presented at the AFRC 1995 Fall International Symposium, October 15-18, 1995. The paper reviewed the progress of the NO_x Subsystem.

Data analysis continued for pilot and subsystem scale testing. Chemical analysis results were received for both test series and are being evaluated. Approximately ten fly ash samples from both pilot and subsystem scale test series that were previously analyzed for loss on ignition (LOI) were analyzed for unburned carbon (UBC). This information will be used as a correlation between the LOI measurement and UBC for the other samples.

Site restoration activities were completed on the pilot-scale test facility. Restoration activities had been on hold due to higher priority work.

Models of the staged and unstaged ALNB#3 in the SBS were underway to provide additional model validation information for application to the burner prototype. These runs will also aid in evaluation of burner scale-up for staged operation. A 2-D axisymmetric and full 3-D prediction has been completed for one unstaged configuration. Prediction cases for another unstaged and a staged configuration will be started in January.

The OFA registers for subsystem testing were completed in November. The registers will not be installed until just before the scheduled test period so as not to interfere with test operation of the facility. Installation of the ducting and windboxes was completed in December. Final connection to the main secondary air line will wait until just before testing so as not to cause interference with other testing. Design modifications of the DRB-4Z[™] burner continued for the next series of tests scheduled for the end of January.

Initial 3-D predictions completed for the DRB-4Z[™] configuration in the CEDF indicated atypical flame behavior that had not been observed in either the pilot-scale testing or modeling.

Comparison of the 5 MBtu/hr and 100 MBtu/hr near-burner predictions conditions with and without combustion indicated that scale differences may introduce additional sensitivity to the specified burner boundary conditions in the 100MBtu/hr scale for this burner design. As a result, axisymmetric combustion predictions for the burner were initiated to provide detailed burner exit conditions for the full 3-D CEDF models. Preliminary results indicate that this approach has significantly improved the 3-D CEDF flame predictions.

A second bench-scale laboratory corrosion test was completed in November. The test involved exposure of candidate superheater/reheater alloys to coal ash deposit under a mixed gas at 1250°F for 1000 hours. The test conditions simulated the environment anticipated on the superheater/reheater surfaces. Corrosion rates of these alloys are being determined.

II.2 Key Accomplishments

II.2.1 Component Development

Phase II began with further development of an advanced low-NO_x burner. As a separate effort to the LEBS program, B&W was developing an advanced low-NO_x burner through an internally funded program. Initial results of this internally funded program looked promising, therefore, the burner concept developed in this program was determined to be a starting basis for the LEBS advanced low-NO_x burner development. Through engineering analysis, a list of configuration variations were developed. From this list, the configurations with the greatest potential for improvement were chosen.

Numerical modeling and pilot-scale testing were used concurrently through the burner development activities in Phase II. Starting with the existing advanced low-NO_x burner concept, modeling was used to evaluate concept variations which would be expensive and time consuming to build and test. These variations included changes in the number of burner air zones, zone areas and velocities, and flow splits. Parallel with this modeling effort, pilot-scale testing was used to investigate parameters that could be more efficiently evaluated with experimental tests on the 5 MBtu/hr scale. These included burner air swirl, air/coal ratio, and burner stoichiometry. In addition, pilot-scale testing was used to further evaluate key burner concepts identified with numerical modeling. Results from these tests were then fed back to additional model studies. This provided an efficient means to evaluate and revise likely burner concepts.

Initial concept evaluations at pilot-scale were completed using three-dimensional (3-D) flow models and two-dimensional (2-D) axisymmetric combustion models. Axisymmetric modeling was used to parametrically evaluate a range of burner configurations with faster turn-around time than would be possible with full 3-D models. This approach was proven during Phase I validation efforts using data collected at the Massachusetts Institute of Technology (MIT) for two burner concepts. An example of a typical 2-D axisymmetric combustion prediction is shown in Figure II-1. Complete 3-D burner internal flow models are employed to obtain the correct flow splits, velocity distributions and swirl profiles within the burner before application of the 2-D

FIGURE II-1 2-D Axisymmetric Combustion Prediction for a Typical Phase II Pilot-scale Burner Concept

models. These models proved useful to qualitatively evaluate the effect of burner design variations on fuel penetration and mixing, internal and external recirculation zones, flame shape, and near-burner temperatures.

As final pilot-scale burner design concepts evolved, both 2-D and full 3-D predictions were used together with experimental testing to evaluate burner performance and provide input to burner scale-up. In addition, modeling was also used to examine and improve facility configurations. As part of the pilot-scale test program, combustion modeling of the SBS was completed to evaluate and revise the existing overfire air port design prior to staged testing of the concept burner. Figure II-2 shows a comparison of an existing OFA port design and the revised port design. The figure depicts a constant oxygen concentration surface within the furnace from the OFA ports. The revised configuration prevents recirculation of the port air into the lower furnace. This provided an improved evaluation of the burner in staged operation.

Pilot-scale burner development testing was performed in B&W's 5 MBtu/hr Small Boiler Simulator (SBS) Test Facility at the Alliance Research Center. Using the SBS was necessary in order to have a realistic furnace for burner development and one in which the DRB-XCL[®] and the advanced low-NO_x burners had been extensively tested^{1,2}. Figure II-3 shows a schematic of the SBS.

The SBS was equipped with an indirect pulverized coal feed system which allowed flexibility in adjusting the primary air-to-coal ratio. Primary (coal conveying) air temperature was controlled to 120°F at the burner inlet, while the secondary (combustion) air was preheated to 620°F. Stack gases were sampled continuously from a location above the convection pass section outlet through a heated sample line. After filtering and drying, CO, CO₂, O₂, and NO_x concentrations were measured and plotted on a Chessell strip chart recorder. Furnace exit gas temperatures were

FIGURE II-2 Comparison of Predicted Burner and Port O₂ Distributions for the SBS Overfire Air Port Evaluation

FIGURE II-3 Small Boiler Simulator

measured by a K-type, high-velocity-thermocouple (HVT) probe. Non-intrusive flame temperature mapping was done with an optical pyrometry system from Diamond Power Specialty Company called FLAMEVIEW™. The unit was comprised of a Charge Coupled Device (CCD) array camera mounted on the roof of the SBS and directly above the flame with a 50° field of view. Two dimensional temperature maps were generated from the live flame image via a patented process utilizing two-color pyrometry. Stack fly ash was sampled isokinetically according to an EPA recommended method, using an Anderson Stack Sampler. Cumulative batch samples were obtained by radial traverses and analyzed for carbon utilization.

Initial testing utilized a pilot-scale B&W DRB-XCL® burner for a benchmark comparison. Benchmark testing was performed in the SBS with the Illinois #6 design coal. Operating conditions at various loads and excess air levels were documented. Furnace exit gas temperatures, FLAMEVIEW™ temperature mappings, and fly ash samples were taken for various furnace conditions.

The original overfire air ports on the SBS were tested while firing with the pilot-scale DRB-XCL® burner. Two sets of ports were tested and the results were compared to typical field performance. Initial results showed that the lower front wall ports, located at typical residence times, gave good results, however, modifications were needed to improve the air flow direction and velocity. These modifications were incorporated with the third series of testing on the SBS with the advanced low-NO_x burner.

The NO_x emissions and UBC measurements during benchmark testing were found to be similar to results obtained in the Phase I testing at MIT³ and previously obtained results firing other coals with the pilot-scale DRB-XCL® burner¹. Flame characteristics, burner pressure drop, and CO emission were also noted for each condition. Overall, the burner fired in a typical fashion to what has been seen in commercial operation and previously on the pilot-scale facility. During the overfire air tests, the burner was operated at stoichiometries of 1.20 to 0.7 with no effect on the stability of the flame. The unburned carbon remained below 5% in all cases.

After completion of the benchmark testing with the DRB-XCL® burner, testing with the first configuration of the advanced low-NO_x burner (ALNB#1) was initiated. Testing began with the burner in a previously tested configuration to test the repeatability and to benchmark the burner with the Illinois #6 coal. Emission values were found to be similar to those previously obtained². Minor variations to the air distribution, excess air, and coal delivery were tested while in the original configuration. All variations showed similar trends as those obtained during previous testing. NO_x emissions were approximately 5-10% lower than the baseline DRB-XCL® values. A number of hardware changes, including various flame stabilizer rings (FSR) and air distribution cones (ADC), were tested. Again, similar variations to the air distribution, excess air, and coal delivery were tested for each hardware configuration. Operating conditions, including air and coal flows, FLAMEVIEW™ temperature mappings, and stack emissions, were recorded for each test series. Fly ash samples and furnace exit gas temperatures were obtained for a number of cases. All variations were compared to one another and the optimum hardware and settings were determined.

After the optimum hardware (ADC, FSR) and operating settings for the advanced low- NO_x burner were determined, further hardware modifications to the air flow distribution and coal delivery system were made (ALNB#2). These changes were found to be very promising. NO_x emissions of the advanced low- NO_x burner (ALNB#2) were found to be at an approximately 10-15% reduced value compared to the DRB-XCL[®] burner benchmark values. The unburned carbon and CO emissions were found to be similar with both burners, while the burner pressure drop increased only slightly with the ALNB#2.

Based on the first two series of pilot-scale testing and the results obtained from numerical modeling of various hardware and operating configurations, further improvements were made to the advanced low- NO_x burner. Staged (STAGED ALNB#3) and unstaged (UNSTAGED ALNB#3) versions of the modified advanced low- NO_x burner were fabricated. Again, a series of minor hardware changes (FSR, ADC) were tested. Another series of tests was performed with the pilot-scale DRB-XCL[®] and the ALNB#2 developed during the second series of testing, for baseline comparisons. A 10-15% reduction in NO_x emissions was again noted for the ALNB#2 over the DRB-XCL[®].

Preliminary results indicate that the UNSTAGED ALNB#3 has a 20-25% reduction in NO_x emissions in comparison to the DRB-XCL[®]. Again, the CO emissions and unburned carbon levels were similar, while the burner pressure drop increased only slightly. Figure II-4 shows the comparison between NO_x emissions and burner configurations tested at the pilot-scale level.

After an optimum burner configuration was determined for the UNSTAGED ALNB#3, staging tests were performed. The STAGED ALNB#3 was set-up in the optimum hardware configuration for the UNSTAGED ALNB#3. The STAGED ALNB#3 was first tested in an unstaged mode to obtain a baseline. This baseline was found to be somewhat higher than when testing the UNSTAGED ALNB#3. The STAGED ALNB#3 was then tested at stoichiometries between 1.15 to 0.85. Due to fan limitations on the SBS facility, stoichiometries lower than 0.85 could not be achieved. The flame was found to be stable throughout all stoichiometries tested. In-furnace probing was performed during these tests to measure the gas species concentrations in the near-burner region of the furnace for comparison to the numerical modeling tests being

FIGURE II-4 Comparison Between NO_x Emissions and Burner Configuration

performed. NO_x emissions were found to be reduced by 35% when staged to a stoichiometry of 0.85 from the baseline stoichiometry of 1.15. This reduction is comparable to what is seen in field application.

The information gained from the pilot-scale experimental testing and the numerical modeling was used to scale-up the burner design to 100 MBtu/hr for subsystem testing.

II.2.2 Subsystem Test Unit

A 100 MBtu/hr version of the advanced low- NO_x burner was fabricated for subsystem testing in B&W's new Clean Environment Development Facility (CEDF), located at the Alliance Research Center. The advantage of using the CEDF for subsystem scale testing is in the ability to test a full-size burner in an environment which closely simulates a utility boiler.

The CEDF is designed for a heat input of 100 MBtu/hr, and integrates combustion and post-combustion testing capabilities to facilitate the development for the next generation of power generation equipment. A wide range of fuels including pulverized coal, fuel oil, and natural gas can be fired. The furnace (Figure II-5) is designed for testing a single 100 MBtu/hr burner, or multiple wall-fired burner configurations. It has been carefully designed to yield combustion zone temperatures, flow patterns, and residence times representative of commercial boilers. In order to provide maximum flexibility and control, separate fans and air heaters are used for supplying the pulverizer, primary (coal conveying) air, and secondary (windbox) air. The use of

FIGURE II-5 B&W Clean Environment Development Facility

an indirect pulverized coal feed system in conjunction with the separate air supplies decouples pulverizer and burner operation, and permits operation over a wide range of coal types, air-to-fuel ratios, fuel moisture contents, and coal particle size distributions.

Boiler convection pass and air heater simulators maintain representative conditions through the entire boiler system to facilitate studies of air toxics capture in back-end flue gas clean-up devices. Representative gas phase time-temperature profiles and surface metal temperatures are maintained throughout the convection pass. Convection pass metal temperatures are maintained in the 600-1100°F range by way of a novel double-walled tube design.

Following the air heater, the flue gas enters a vertical dry scrubber unit to control sulfur dioxide emissions. The resulting dry by-products are then filtered from the gas by a multi-chamber pulse-jet baghouse.

Preliminary characterization of the CEDF was performed in the winter of 1994-1995 under the LEBS program using the state-of-the-art DRB-XCL® low-NO_x burner. The characterization was done using representative eastern bituminous coals with fixed carbon/volatile matter in the range of field experience with this burner. Furnace temperatures were within 50°F of design (2250°F at furnace exit). Unburned carbon combustibles, flame shape and stability were evaluated for numerous burner settings, excess air and furnace load conditions.

Baseline testing was performed with the 100 MBtu/hr DRB-XCL® firing the Illinois #6 coal. These results were used as a comparison for the advanced low-NO_x burner. A 100 MBtu/hr advanced low-NO_x burner was fabricated for subsystem testing based on results from pilot-scale testing and numerical modeling. Initial testing was performed to confirm the scaling-up process from pilot-scale and numerical modeling, and to obtain some initial observations of the advanced low-NO_x burner at the near full-scale. Minor hardware changes and various mixing devices were tested during this initial round of subsystem testing. Operating conditions including load and excess air were varied for each hardware configuration and data was collected in terms of operating conditions, stack gaseous emissions, and fly ash samples.

Testing was also performed with the advanced low-NO_x burner firing a Mahoning 7A Seam coal. This coal was also utilized during some of the early CEDF testing with the DRB-XCL® burner. Again, operating conditions were varied and similar data was collected. The proximate analysis for the Illinois #6 and the Mahoning 7A coals is given in Table II-1.

Although conclusions on the advanced low-NO_x burner are being reserved until further optimization tests can be performed, preliminary results show that the advanced low-NO_x burner provides lower NO_x emissions in comparison to the DRB-XCL®. However, these NO_x emissions reductions were at the expense of CO and unburned carbon. Further optimization is required through testing and numerical modeling. Although minor modifications are in order for the advanced low-NO_x burner, the general hardware configuration is promising and therefore, the burner was given the name of DRB-4Z™. This name provides a continuity with the low NO_x DRB product line from which it originated, while still accommodating its uniqueness.

TABLE II-1 Proximate Analysis of Test Coals

<i>Proximate Analysis, %</i>	Raw Coal Composite Illinois #6 Coal		Raw Coal Composite Mahoning 7A Seam Coal	
	As Received Basis	Dry Basis	As Received Basis	Dry Basis
Moisture	14.25	----	5.70	----
Volatile Matter	36.14	42.15	37.85	40.14
Fixed Carbon	41.81	48.75	49.98	53.00
Ash	7.80	9.10	6.47	6.86
<i>Gross Heating Value (Btu/lb)</i>	10980	12805	13120	13913
<i>Btu/hr (M&A Free)</i>	----	14087	----	14938

The preliminary results from the initial round of subsystem testing are shown in Table II-2. As previously mentioned, the results show promise, but further modifications are required. Initial cases have been set up for numerical modeling investigation. The results of these cases will be used for alterations on the DRB-4ZTM burner for testing in Spring of 1996. Fabrication of some modifications are currently underway and will be completed for the first scheduled test series.

TABLE II-2 Initial NO_x Subsystem Testing - Preliminary Results

<i>DRB-4ZTM in Comparison to DRB-XCL[®] Baseline</i>		
	Illinois #6 Coal	Mahoning #7A Coal
NO _x emissions	15 - 20% reduction	45 - 50% reduction
CO emissions	Slight increase	Significant increase
Flyash LOI	No difference	Significant increase

As with the pilot-scale component design, numerical modeling is being used to investigate burner performance, through both near-flame characteristics and full system evaluation. Detailed 3-D flow models have been used to predict burner flow splits and velocity distributions.

Axisymmetric burner combustion models are currently being used to study near-burner behavior for a series of burner variations at the 100 MBtu/hr scale. The idealized furnace geometry for these models has been generated to mimic the flow area and heat transfer characteristics of the CEDF burner tunnel. The 2-D models are also being used to provide detailed boundary conditions for full 3-D combustion predictions of the burner in the CEDF facility. These complete facility predictions, as shown by a representative result in Figure II-6, are important to evaluate qualitative trends for carbon monoxide levels, carbon burnout, flame length, and NO_x.

Modifications are being made to the CEDF to incorporate an overfire air system. Designs were

**FIGURE II-6 Predicted Temperature Distribution in the CEDF with the
DRB-4Z™ Burner**

initiated in late spring of 1995. Construction of the ducting and windboxes was completed in December of 1995. Final installation and connection will occur right before the staging tests that are scheduled for the Spring of 1996. By delaying the final connection, there will be no operational interference with other test programs.

II.2.3 Preliminary POC Demonstration Facility Design

In order to satisfy the intent of Proof-of-Concept (POC) testing in a cost-effective manner, B&W has elected to further modify the 100 MBtu/hr CEDF to create the POC Demonstration Facility for Phase IV. A preliminary POC design has been reported to the DOE as part of Phase II. The results of development and testing efforts in Phase II will be incorporated into the POC final design in Phase III. The POC facility builds on the modifications made to B&W's CEDF in Phase II for subsystem testing.

The majority of the modifications to the CEDF will be associated with the NO_x and Controls & Sensors subsystems. The major modifications will include "hardening" of the systems to permit extended periods of operation, incorporation of advanced controls and sensors, installation of multiple opposed wall-fired DRB-4Z™ burners and an overfire air system, and the incorporation of two feeders to simulate multiple pulverizers. The POC Demonstration will employ eight burners of 12.5 MBtu/hr capacity. Since the burner scale-up issues will be addressed in Phase II,

the integration of the burners, the ability to control their individual operation, and optimization of a complete overfire air system must be demonstrated in Phase IV. Previous work in Phase II employing the 5 MBtu/hr and 100 MBtu/hr burners as well as modeling of the POC facility will provide the performance characteristic link between the POC and the CGU.

Modeling completed to date for the POC has included preliminary furnace exit gas temperature and wall heat flux predictions using the UBC code. UBC is a one-dimensional design code used to predict furnace heat loss and carbon burnout. This model is based on the same flow, heat transfer, chemistry and char oxidation submodels as are used more detailed 2-D and 3-D combustion models while allowing rapid turn-around for design studies. UBC was used to evaluate possible refractory designs required to modify the heat transfer characteristics of the single-burner CEDF for POC multiple-burner operation. These studies indicated that suitable refractory materials are available to retrofit the multiple-burner POC to attain a design FEGT of 2250°F. This information was incorporated into the POC Test Facility Design Report.

Wall conductance distributions obtained from the UBC runs were then used during 3-D combustion modeling studies to investigate the placement of the multiple burner arrangement and to optimize sizing and mixing of the POC overfire air ports. An unstaged baseline case and five staged cases with ports of varying mass-velocity ratio (MVR) were completed. Figure II-7 provides a comparison between the predicted furnace stoichiometric ratio contours on the furnace

FIGURE II-7 Comparison of POC Overfire Air Port Design Optimization Results

mid-plane. Based on these cases, a port size was recommended which would permit satisfactory mixing performance over a range of burner staging conditions. These results were presented to NO_x team members and the optimum sizing was incorporated in to the POC facility design.

II.2.4 Corrosion

The first pilot-scale corrosion probe was exposed to combustion gas in the convective pass of B&W's Small Boiler Simulator downstream from the limestone injection during the SO₂/Particulate Subsystem testing in January 1995. The total exposure time was 55 hours with the probe metal temperature varying from 1200 to 1300°F. After the exposure, the corrosion probe was recovered and visually examined. Ash deposit from the leading and trailing edges of the probe was collected for X-ray analyses. Preliminary results indicated that the ash deposit consisted primarily of CaSO₄, and no alkali sulfates were identified. The surfaces of T2, T22, and T9 at the 2 and 10 o'clock locations appeared to have suffered some corrosion attack compared to the other areas. However, because of the short exposure time, the corrosion wastage was too negligible to be accurately measured. The surfaces of 304SS and 310SS did not show any corrosion attack.

The corrosion resistance of several commercial alloys has been evaluated in a benchscale test facility. To date, two 1000-hour corrosion tests have been completed. The tests involved exposing the alloy samples to reducing and oxidizing mixed gases, which simulated the combustion environments likely to exist in the burner zone and convective pass of LEBS, respectively. The alloys selected for the corrosion study included carbon steel, low-alloy steels, and stainless steels.

The bench-scale test system consists of three major sections in sequence: (1) the gas-supply section, (2) the retort section which is located in a high temperature furnace, and (3) the effluent disposal section. The mixed gases were introduced from the gas-supply section. After exiting the gas blender, water was pumped into the mixed gases from a reservoir. The mixed gases then entered the steel retort in which the alloy samples were accommodated. The flow rate of the mixed gases was kept sufficiently high so that depletion of the corrosive gaseous species due to chemical reactions with the samples was minimized. The effluent disposal section consisted primarily of a gas scrubber, in which a 10% NaOH solution was used to absorb the sulfur-bearing vapors leaving the test retort. After the scrubber, the mixed gases were diluted with air and vented to the atmosphere.

Two sample arrangements were implemented for the corrosion test involving the reducing condition simulating the burner zone: (1) samples were exposed to the mixed gas without a coal-ash deposit and (2) samples were exposed with the coverage of ash deposit. The ash deposit was prepared from reagent-grade chemicals at a composition determined theoretically from thermodynamic calculations. On the other hand, all samples were covered with a coal ash deposit in the test under the oxidizing condition simulating the superheater/reheater environment. Three different sulfate-base compositions were prepared for the oxidizing test, which varied primarily in the amounts of CaSO₄ and CaO.

Prior to the corrosion exposures, the initial weights and dimensions of the alloy samples were carefully measured. After the tests, the samples were chemically descaled, followed by measurements of the remaining sample weights. Based on the weight-change data, along with the original surface areas, the corrosion rates of alloys were calculated.

Cross-sectional metallography was also performed on selected samples. The standard metallographic procedures for the cross-sectional preparation were employed. However, for those covered with the simulated coal ash deposit, methanol was used as the polishing fluid to preserve any water-soluble constituents that might exist on the surfaces. The scale morphologies and their chemical compositions were investigated using SEM/EDS. The results of the analysis are being reviewed.

A description of desired changes to the RD&T Plan to address corrosion, including estimated costs, was completed and transmitted to DOE for review approval. The revised projects address additional laboratory testing and field testing but will only be performed to the extent possible within the existing budget. Based on the prioritization of the projects, it appears furnace wall corrosion will be the focus and coal-ash corrosion concerns must be addressed by another means.

III. SO₂/Particulate/Air Toxics/Solid By-Product Subsystem

The scope of the SO_x subsystem comprises the control of SO_x, particulate matter, hazardous air pollutants (commonly called "air toxics"), and solid byproduct from the B&W LEBS plant. The specific goals for the SO₂ subsystem are:

So _x	minimum requirement	less than 0.20 lb SO ₂ /MBtu
	LEBS target	less than 0.10 lb SO ₂ /MBtu
Particulates	minimum requirement	less than 0.015 lb particulates/MBtu
	LEBS target	less than 0.010 lb particulates/MBtu
	B&W goal	less than 0.005 lb particulates/MBtu
- Any processes selected for application in the B&W LEBS plant have the potential to comply with possible emissions control regulations for targeted air toxics.
- At a minimum, the selected processes produce an environmentally benign solid byproduct. Recycle in the process (regeneration) or elsewhere (utilization) is desirable.
- The selected processes integrate with other plant subsystems to yield optimal overall performance of the LEBS plant.

On the basis of results compiled during a concept selection process completed in Phase I, the Limestone Injection with Dry Scrubbing (LIDS) process was selected for further development and evaluation in B&W's LEBS project. The LIDS process comprises the cost-effective integration of three commercially-proven flue gas cleanup technologies: furnace limestone injection, dry scrubbing, and pulse-jet fabric filtration. Through engineering analysis, experimental testing, and numerical modeling, a LIDS process capable of ultra-high SO₂ removal and superior particulate control while addressing the potential issues of air toxics emissions and solid byproduct utilization is being developed. The progress of the LIDS activities follows.

III.1 Summary of Activities

III.1.1 October 1994 to December 1994

The solid by-product cognizance effort began. B&W is aggressively pursuing ways to reduce or utilize the solid waste produced by its various clean coal and FGD processes through a variety of in-house and externally-funded development programs. The effort will continue throughout the project.

The air toxics cognizance effort began. B&W is conducting a wide variety of air toxics-related research projects, and is closely following the regulatory process. The effort will continue throughout the project.

The 5 MBtu/hr LIDS facility located on the Small Boiler Simulator (SBS) was modified and prepared for the LIDS Process Definition Test Series. The testing took place in January, 1995. The detailed test plan was also completed in preparation for testing.

The CEDF furnace limestone injection modeling was begun. The purpose of the effort was to determine an optimum location for placement of the in-furnace sorbent injection ports for the future Task 11 Subsystem LIDS testing.

III.1.2 January 1995 to March 1995

A technical paper entitled "*Development of LIDS™ as a Part of B&W's Low Emission Boiler System*" was written and presented at the 20th International Conference on Coal Utilization and Fuel Systems. The conference was held March 20-23, 1995, in Clearwater, Florida.

The LIDS 5 MBtu/hr process definition testing was completed January 9 - 27, 1995. The tests were carried out to further define LIDS in terms of its optimum configuration to cost-effectively achieve the LEBS SO₂ removal. Data reduction and analysis was carried-out during the remainder of the quarter resulting in the definition of the optimum LIDS configuration.

The LEBS commercial dry scrubber model preparation began. Comparison runs were completed using COMO and DIAN3D. The comparisons were evaluated to pinpoint modeling requirements and code modifications that will be needed for the full-scale dry scrubber modeling efforts.

The preliminary POC plant design was begun. The SO₂ subsystem began work on a conceptual design of the LIDS system for the POC plant to be operated in Phase IV of the LEBS project.

The LIDS subsystem test design and plan was started.

Furnace injection modeling, solid by-product and air toxics cognizance efforts continued during the quarter.

III.1.3 April 1995 to June 1995

The baghouse design engineering analysis was kicked-off. Currently, there is no utility experience in operating a pulse-jet fabric filter downstream of a dry scrubber. The high inlet grain loading, unique particle size distribution, low operating temperatures, and very low particulate emission requirements fall outside the known data base used to determine PJFF size requirements. The objective of the effort was to define the LIDS pulse-jet baghouse in terms of fabrics, cleaning mode, air-to-cloth ratio, componentry, and other design considerations.

The furnace injection port placement modeling was completed. Details of this effort are included in the SO₂ subsystem key accomplishments section of this report.

The SO₂ subsystem preliminary design of the LIDS system for the POC facility was completed

and provided for inclusion in the B&W LEBS report.

The *Subsystem Test Design and Plan Report* was completed and sent as a deliverable to DOE -- May 5, 1995. Permission to begin Task 10 - Subsystem Test Unit construction was granted late in the month of May. Detailed design of the LIDS Subsystem test facility continued through the quarter.

Procurement of long lead-time and critical path items for the LIDS subsystem test unit kicked-off the SO₂ subsystem test unit construction effort. The CEDF was modified to include a LIDS configuration for subsystem testing. The LIDS limestone storage silo and particulate collection device were ordered late in May. Procurement of other items continued through the quarter.

Construction of the LIDS modifications to the CEDF began with the installation of the necessary foundations. Construction efforts continued through the quarter.

III.1.4 July 1995 to September 1995

A meeting was held with the Electric Power Research Institute to discuss B&W air toxics investigations. Included in the meeting was a presentation of the LIDS mercury measurements made to date and plans for future LEBS air toxics studies.

Testing of the modifications required to add dry scrubbing capability to the COMO model occurred during the quarter. Minor discrepancies between COMO and DIAN3D were resolved.

All of the equipment procured for the LIDS subsystem test unit construction effort was received by September 1, 1995.

Construction of the LIDS subsystem test unit as part of the CEDF dominated the SO₂ subsystem efforts during this quarter. Details of the LIDS subsystem construction effort are highlighted in the SO₂ subsystem key accomplishments section of this report.

III.1.5 October 1995 to December 1995

Phase IV planning continued. The SO₂ subsystem is leading a proposal effort to the Ohio Coal Development Office (OCDO) requesting 5 million dollars for the B&W LEBS POC demonstration. A meeting was held with Jackie Bird, Director of the OCDO, to discuss the B&W LEBS project. Ms. Bird appeared interested in the LEBS project and encouraged B&W to submit a proposal for the OCDO's participation in LEBS - Phase IV. The OCDO RFP original due date is January 19, 1996. In order to coordinate the OCDO proposal with the DOE proposal, B&W will prepare a letter requesting an extension.

The LIDS baghouse performance engineering analysis was completed.

The LIDS subsystem test unit equipment checkout and site preparation was completed.

Three days of LIDS testing were carried out in October to define any modifications that were necessary to successfully carry-out the first LIDS subsystem test series. Several modifications were defined for the slurry system at the point of the solids/liquid interface. The modifications were completed in October.

LIDS Subsystem Testing was conducted for 7 days in November. Details of the LIDS subsystem testing are provided in the SO₂ subsystem key accomplishments section of this report.

III.2 Key Accomplishments

III.2.1 LIDS Process Definition Testing

SO₂ Removal. The feasibility of achieving the project SO₂ removal goal of 0.10 lb SO₂/MBtu with a fully-integrated LIDS process under cost-effective operating conditions was demonstrated in Phase I. Although the feasibility of utilizing the LIDS process to achieve ultra-high SO₂ removal was proven, potential limitations inherent to the basic LIDS system were identified. This led to the Phase II LIDS Process Definition testing. The main objective of the testing was to further define the LIDS process in terms of its optimum configuration to cost-effectively achieve the LEBS SO₂ removal goal. Areas considered to address the basic LIDS limitations and to optimize the process included alternate system configurations and/or additives.

The Phase II LIDS Process Definition testing was conducted for three weeks and achieved the goal of 98% SO₂ removal. SO₂ removal at the furnace outlet was 31%, dry scrubber outlet was 79%, and LIDS system outlet was 98%. The LIDS process was defined such that the potential limitations inherent to the base LIDS system were eliminated. Figure III-1 shows the Phase II Process Definition total SO₂ removal accomplished at the outlet of each LIDS process unit operation.

FIGURE III-1 Phase II LIDS Process Definition SO₂ Removal

Mercury Removal. Mercury emissions from coal-fired power plants are a matter of intense debate. It seems likely that mercury emissions will be regulated in some manner in the future due to its potential to bioaccumulate in the food chain. Since mercury is a likely target for regulation, screening test of mercury emissions were carried out in Phase I. An average of 97% Hg removal was seen in Phase I. In order to confirm the high mercury removals the mercury measurements were repeated during the Phase II Process Definition Testing. The measurements were made by Frontier Geosciences, Inc., to characterize the process in terms of its mercury capture potential. Measurements were made at the system inlet, dry scrubber outlet, and baghouse outlet. Phase II LIDS total mercury results are presented in Table III-1. Values recorded for total mercury clearly indicate a repeated pattern of greater than 90% mercury reduction across the LIDS system.

TABLE III-1 Phase II LIDS Mercury Removal

Stream	Total Hg, $\mu\text{g}/\text{Nm}^3$	Hg Removed Across System
System Inlet	19.85	86.25%
Inlet Baghouse	4.90	
Outlet Baghouse	2.73	
System Inlet	16.49	92.97%
Inlet Baghouse	3.49	
Outlet Baghouse	1.16	
System inlet	17.85	95.52%
Inlet Baghouse	3.58	
Outlet Baghouse	0.80	

III.2.2 Furnace Injection Port Placement Modeling

The objective of this modeling activity was to numerically evaluate potential full-load limestone injection locations for the Phase II LIDS Subsystem Test Series.

A single burner CEDF furnace and convection pass was modeled with COMO. The model was based on as-built furnace dimensions and refractory insulation specifications. Limestone injection was modeled with an Eulerian inert particle model since a reactive sorbent model was not available. The sorbent velocity and the local gas velocity were assumed to be equal. The COMO model assumed equal rates for mixing the sorbent and injection air with the flue gas. Mixing was qualitatively evaluated for each port arrangement by comparing the standard deviation of local stoichiometry at the entrance to the first tube bank (furnace exit plane) and at

the exit of the second tube bank.

The predictions formulated were used to optimize port size and momentum for maximum sorbent mixing given limited options for port locations. Completed predictions allowed for proper locating and sizing of the sorbent injection port on opposing side walls during the LIDS subsystem test unit construction effort.

III.2.3 LIDS Subsystem Test Unit Construction

In order to accomplish the goals of the LIDS subsystem test series the CEDF was modified to include a LIDS configuration. The furnace, dry scrubber and pulse-jet fabric filter were all provided by the existing CEDF and therefore used as part of the LIDS configuration. To complete the LIDS system a furnace limestone injection system, recycle solids system, and ash slaking system were added to the CEDF. A description of each system is provided below.

Furnace limestone injection system. Pulverized limestone is received from self-loading bulk transport trucks. The trucks pneumatically fill a storage silo using a loading station located at grade level on the silo. The feed rate of limestone to the furnace is controlled using a loss-in-weight feeder. Limestone is removed from the hopper at a controlled rate using a screw feeder. The speed of the screw is adjusted to match the change in weight of the hopper with the desired feed rate set point. When the level in the hopper reaches a preset value, the knife-gate is opened to allow more solids to flow into the weigh feeder hopper. The screw discharges the limestone into a rotary feeder which drops the solids into a pick-up box in the transport line.

A rotary blower supplies low pressure air for pneumatic transport of the limestone from the storage silo to the furnace injection ports. A single line is used to transport solids to a splitter located near the injection ports. The limestone is injected through the furnace wall into a temperature zone of 2100-2300°F. Two port holes were constructed on opposing side walls in the upper portion of the furnace.

Recycle solids system. A portion of the solids collected in the baghouse is recycled to the ball mill slaker to make slurry. A vacuum transport system is used to deliver the fly ash. The solids are pneumatically transported to the LIDS system and discharged into a recycle solids surge bin. Solids from the bin are metered into a ball mill slaker by a weight belt feeder with a variable speed drive.

Ash slaking system. The slaker is a conical ball mill. A grit screen on the ball mill discharge removes any oversized material from the product. The product is pumped to the reagent storage tank. From there, it is pumped to the dry scrubber atomization system. The existing CEDF lime storage and slaking system is used as an emergency back-up. If the LIDS system should fail, lime slurry from the CEDF can be pumped to the dry scrubber to keep in compliance with B&W CEDF permits.

Instrumentation and Data Acquisition. Instrumentation was added to the CEDF to monitor the

following key variable: 1) limestone feed rate, and 2) SO₂ concentrations in four locations, dry scrubber and baghouse inlet and outlet temperature, slurry flow rate, and solids flow rates. The personal computer based, STARS/LabVIEW Data Acquisition System is used for acquiring on-line data during the CEDF test series.

III.2.4 LIDS Subsystem Testing

The first subsystem LIDS test series was conducted in November. During the series several LIDS equipment problems were experienced. Once the fully-integrated LIDS process was able to run, several equipment problems were experienced causing a switch back to the back-up CEDF lime slurry to remain in SO₂ permit compliance for the facility. During the times LIDS was successfully running continuously, the SO₂ removal was lower than expected. It appears that this was due to unreactive LIDS slurry.

Evaluation of the information gathered during the first LIDS test series included: inspecting the CEDF for operational clues, analyzing samples taken during the testing for solids and slurry stream compositions, compiling electronic data, and summarizing start-up and equipment problems. From the evaluation it was concluded that the unreactive LIDS slurry was due to the lack of calcium in the ash from the furnace. A likely cause is an inaccurate indication of the limestone flow rate to the furnace injection ports -- ie., not as much limestone was being injected as thought. Evidence to support this includes: 1) chemical analyses indicating that the fraction of silica in the solids to the slurry system was much higher than expected and calcium was much lower than expected based on previous successful SBS test (task 7.2) results; 2) calcination of the limestone used over the entire test period based on the feed rate was over twice as much as was actually used based on levels in the limestone silo; 3) a bearing on the limestone screw feeder failed during testing causing the screw to stop turning, however the feed system continued to send a false reading to the DAS indicating flow; 4) after the bearing was changed, the SO₂ removals and amount of calcium found in the solids from the furnace remained low, leaving the feed rate signal from the limestone feed system suspect.

Evaluation of the chemical analysis and operational information will continue. A plan of action will then be prepared based on the evaluation. The next round of LIDS testing in the CEDF is scheduled to occur late in the spring of 1996.

IV. Controls & Sensors Subsystem

In order to maintain low stack emissions and optimum boiler performance throughout the operating range and lifetime of the LEBS, a state-of-the-art integrated control system must be developed. This control system must include new sensors as well as old sensors used in new ways. It must make sense out of the data provided while initiating or directing the operator to take appropriate action. The control system that will help assure that the LEBS will meet its stack emission, efficiency, availability, and cost of electricity goals.

The overall philosophy of the LEBS control system is to use conventional, state-of-the-art solutions to satisfy new control requirements. Existing sensors, hardware, and software are specified whenever possible and new measurements or advanced equipment are recommended for development only where necessary to assure the success of the project. The progress of the Controls & Sensors Subsystem is contained in this report.

IV.1 Summary of Activities

IV.1.1 Period of October 1994 to December 1994

An analysis of available information for pulverized coal flow measurement/control was performed. In addition, an air/particle flow loop was set-up and calibrated for testing of meters and control devices.

PSI collected flame scanner data during burner development testing on the SBS in November. The data was collected over a wide range of burner configurations and operating conditions. PSI began processing the flame data in December.

Preliminary planning activities for the dynamic system modeling effort began.

IV.1.2 Period of January 1995 to March 1995

Preliminary sensors and controls for the POC facility were given in February. Draft P&IDs were provided to the NO_x Subsystem team for review.

A higher volume particle feeder was added to the Air/Particle Flow Facility. The new feeder was necessary to increase the particle flow rates to that expected for typical pulverized coal burner lines. Check-out and particle calibration were performed in February.

Discussions were initiated with two vendors regarding their possible participation in the test evaluation work on the coal flow sensor. One vendor (Auburn International) has a particle flow measurement sensor and the other (Candy Co.) a vision system for particle sizing.

Members of the coal sensor development team visited EPRI's Instrumentation and Control

Center at TVA in March. In addition, a request for patent rights for three B&W test evaluations of pulverized coal flow monitors were sent to the Contracts Research Division in January. Also, a request was sent for information on pulverized coal flow metering work being done in Finland and Australia.

PSI continued reduction and analysis of the flame scanner data collected in November 1994.

Development of the Combustion and Emissions Module (CEM) began. The CEM will model the actual furnace and will interface to another modeling package which will model the remainder of the proof-of-concept facility. Development work on the CEM included model formulation, implementation, coding and testing of sub-modules. Selection of a dynamic modeling package for the balance of the proof-of-concept simulator began.

IV.1.3 Period of April 1995 to June 1995

A 12-inch ID Plexiglass elbow and piping were designed and installed on the Air/Particle Flow Facility. An Endress + Hauser microwave meter was tested on the new 12-inch line in June. Based on two calibration points, the output was nonlinear (approximately second order) and repeatable. In addition, a Kurz mass flow insertion probe was also tested in the Air/Particle Facility during June. Output of the Kurz probe was proportional to air flow velocity and insensitive to changes in particle flow. This probe would provide the air velocity needed to calculate primary air flow and, when combined with the output from the Endress + Hauser meter, provide the coal mass flow. A confidentiality agreement was executed with Kurz Instruments Inc. prior to testing.

B&W installed acoustic emission sensors on the burner line in the Clean Environment Development Facility (CEDF) during May. Data was collected from these sensors during CEDF testing in June. Preliminary analysis shows the output to change as coal flow changes.

In April, a confidentiality agreement was executed with Spectrum Diagnostix (formerly Physical Sciences Inc.) in preparation for a technical exchange meeting that occurred on May 1. Spectrum Diagnostix has been attempting to show application of their SpectraTune™ technology to accurately discern the air-to-fuel ratio of individual burners in a multiple burner configuration over a broad load range. Though the technique is promising for evaluating combustion quality and burner tuning, Phase I efforts to apply the technology to determine air-to-fuel ratio were less promising than hoped.

Members of the Control & Sensors Subsystem team traveled to Boston on May 1 to meet with Spectrum Diagnostix. The purpose of the meeting was to thoroughly review the SpectraTune™ technology to decide its viability for further development for the LEBS application. Spectrum Diagnostix provided B&W with previously unknown detailed theories and methods regarding the SpectraTune™ technology as well as some recent data analysis results. Control & Sensors Subsystem team members thoroughly evaluated this new information and reached the conclusion that the probability of SpectraTune™ producing a useful control signal required for LEBS to

maintain individual burner air-to-fuel ration was very low. The review team recommended not to continue with Spectrum Diagnostix on the LEBS program. Instead, the review team recommended pursuing chaotic time series analysis techniques as an alternative.

The evaluation of available dynamic simulation software was completed. The simulation package selected was SPEEDUP. A preliminary version of the CEM module was completed and tested as a stand alone model. Steady-state testing of the module showed good agreement to data. Dynamic runs showed the correct trends, no dynamic data was available for testing.

IV.1.4 Period of July 1995 to September 1995

A review meeting was held to discuss the activities of the sensor development program.

Tests were performed with the Kurz insertion mass flow sensor and the Endress + Hauser microwave meter in the Air/Particle Flow Facility. The signal output changed with air velocity, was repeatable, and somewhat insensitive to changes in particle flow with the Kurz sensor. The significance of this results is an output signal that would provide a reading of air flow independent of particle (coal) flow. The Endress + Hauser sensor signal output changed with air velocity and particle flow. Repeatability was not as good as the Kurz sensor. Plans and preparations are being made for testing of the Kurz sensor and the Endress + Hauser microwave meter in the CEDF 12-inch burner line.

A short-term evaluation of the acoustic emission sensor was completed on the CEDF. The results were found to be positive. Additional testing has been proposed.

Optical, acoustic, and pressure sensors were installed on the B&W Small Boiler Simulator (SBS) to collect time series measurements for chaos analysis. A high speed data acquisition system was set up to collect data from the sensors. Data sets for a range of burner stoichiometries and other operating conditions were collected during July. Analysis of the data began to determine if burner stoichiometry can be correlated to the time series signatures when analyzed with chaotic time series analysis techniques. A decision will be made relative to the feasibility of applying this technique to burner control.

Work on the balance of the proof-of-concept preliminary simulator began with the integration and testing of the CEM module into SPEEDUP. The CEM models the combustion and heat transfer processes occurring in the furnace and convection pass of the CEDF. SPEEDUP is the dynamic simulation package which was used to model the balance of the CEDF equipment and the controls. The purpose of the preliminary simulator is to provide the control system designer with a working model that has included the major equipment of the proof-of-concept facility. The control system designer will use the preliminary simulator to become familiar with running SPEEDUP and to guide the further development of the proof-of-concept simulator. The preliminary simulator was released in September as scheduled.

IV.1.5 Period of October 1995 to December 1995

A technical paper on the Endress + Hauser microwave meter entitled "On-Line Measurement of Pulverized Coal" was presented at the PowerGen '95 conference.

An abstract for a second paper on the Endress + Hauser microwave meter and the Kurz insertion mass flow sensor entitled "Evaluation of Two Commercially Available Sensors for Use in Pulverized-Coal Burner Lines" was prepared for an Engineering Foundation meeting in April 1996.

Preparations continue for testing of the Kurz insertion mass flow sensor and the Endress + Hauser microwave meter in the CEDF 12-inch burner line. The fitting for installation of the instrumentation was completed in December with installation scheduled in early January.

Scope was added to collect burner pressure, optical, and acoustic data from the CEDF during burner testing. High-speed data was collected over a range of burner stoichiometries and operating conditions. Reduction and analysis of this data was initiated. The only scope remaining is to finalize data analysis and submit a summary report of the chaos analysis effort.

ARC began training SI&DT in the use of SPEEDUP and the preliminary simulator. Work continued on the secondary simulator, the dry scrubber module, and details of the air heaters.

IV.2 Key Accomplishments

IV.2.1 Coal & Air Flow Sensors Development

The objective of this task is to evaluate sensors to monitor pulverized coal flow and air flow to individual burners to maintain optimum fuel-air ratios. The approach consisted of using commercially available sensors and to locate these sensors in the burner line to take advantage of the flow characteristics unique to dilute-phase transport. Initial evaluations of the sensors were performed in the Air/Particle Flow Facility.

Sensors. Two commercially available sensors were evaluated: a microwave flow indicator by Endress + Hauser and an insertion mass flow sensor by Kurz Instruments, Inc.

The Endress + Hauser flow indicator is the Granuflow GMR 130 used for noncontact solids flow indication on volumetric feeders or constant-velocity, pneumatic conveying systems. The GMR 130 is a new, low-energy microwave device that senses material flow via a microwave transceiver that transmits and receives microwave energy to and from passing material.

The microwave emission is less than the international standard for disturbances operating in K band 24.125 GHz. Field strengths are typically less than 1400 mV/m at 3 meters for both the horizontal and vertical antenna polarization. The operating principle used by the GMR 130 to measure the solids flow is to eliminate all reflected energy from stationary objects by using the

Doppler frequency shift. The Gunn diode transducer transmits microwaves at a constant frequency and energy level. Reflected energy from stationary objects will be at the same transmission frequency. Reflected energy from moving objects will be at a different frequency due to the Doppler shift. It is this reflected energy intensity at the different frequency that is measured to determine the resulting output signal. The reflected Doppler frequency shifted energy is proportional to the solids concentration, which is related to the material's reflectivity, dielectric, and cross-sectional area. The output signal is then converted to an analog signal that can be spanned for a 0% to 100% indication of the solids concentration with a 4 mA to 20 mA output range.

The Kurz insertion mass flow sensor is the Series 450, 1/2-inch diameter. The sensor uses a thermal probe that responds to changes in velocity over a heated element. The operating principle is based on constant temperature anemometer with RTDs (resistance temperature detector) used for reference and process temperatures.

Test Set-up. The Air/Particle Flow Facility was used to evaluate the performance of both the GMR 130 microwave flow indicator and the Series 450 insertion mass flow sensor. This facility, with its flexible piping configuration, is used for application to two-phase (gas/solids) transport.

Ambient temperature air is used as the transport medium as provided by an induced-draft 15,000 CFM fan. A wide variety of solids can be handled by the feeder with flow rate measured up to 20,000 lb/hr, sizes from micron to 1/4 inch, and bulk densities varying from 10 lb/ft³ to 190 lb/ft³. To provide a safe simulation of pulverized coal, an inert material was used to simulate its flow characteristics. This material has the same size distribution and density as pulverized coal. The operating conditions of the facility were established to simulate the expected range of velocity (50 to 75 ft/sec) and solids loading (0.2 to 0.5 lb solids/lb air) for a typical pulverized-coal burner line in a utility power plant.

Figure IV-1 shows the installation of the sensors on a 12-inch ID pipe in the facility. Both sensors were located at the outlet of a 90-degree elbow to take advantage of the fairly stable "rope" effect that occurs at the elbow exit, with the velocities and solids loading used for pulverized-coal transport. The GMR-130 flow indicator was mounted on a sight glass (Model No. 012-178-0000 by Endress + Hauser), which was welded on a 6-inch schedule 40 carbon steel pipe section. The pipe section was contoured to fit an opening in the 12-inch pipe. The Kurz sensor was inserted through a 1/2-inch compression fitting welded on the 6-inch contoured pipe section.

A 250-ohm resistor was connected to the 4 mA to 20 mA output terminals of both sensors to provide a voltage output of 1 to 5 volts. A Fluke digital multimeter (Model 8505A) was used to measure the voltage signal. The air velocity was calculated at the 12-inch pipe test location with the air flow rate measured at the air inlet (prior to the solids feed point). The solids flow rate was based on a calibration of the feeder.

Results. For the evaluation of the sensors in the Air/Particle Flow Facility, tests were conducted

FIGURE IV-1 GMR 130 with Sight Glass and Kurz Flow Meter on 12" I.D. Pipe

at three air velocities of 50, 60, and 75 ft/sec. At each air velocity, the solids flow rate was set for the range expected in pulverized-coal burner lines. The range is from a solids loading of 0.2 lb solids/lb air at 50 ft/sec to 0.5 lb solids/lb air at 75 ft/sec.

The voltage output of the Endress + Hauser GMR 130 increased as the concentration of solids (lb solids/ft³ of air) increased. This trend is encouraging, since it shows that the GMR 130 does respond to changes in the flow conditions in the pipe, particularly at the elbow exit where the roping of the solids is established. Also, data taken at an air velocity of 75 ft/sec exhibit good repeatability for the conditions evaluated at this velocity level.

The voltage output of the Kurz Series 450 insertion sensor increased with an increase in the air velocity, and it was linear and repeatable over the velocity range tested of 50 ft/sec to 75 ft/sec. The output was found to be insensitive to the solids loading. This is also encouraging, as this sensor should provide the signal for the primary air in the burner line.

IV.2.2 Acoustic Emission Sensor Development

The objective of this task is to develop a method to continuously monitor and control pulverized coal streams to individual burners to maintain optimum fuel-air ratios. It was hypothesized that the intensity and/or character of structure-borne acoustic waves generated through the interaction of pulverized coal particles with the burner line would be a function of coal flow, and possibly that of coal fineness. This phenomenon, often referred to as acoustic emission (AE), is the result

of coal particles impacting the burner splashplate or sliding along the outer radius of 90-degree bends. To investigate this in more detail, AE-data were concurrently collected with DRB-XCL[®] burner data during tests run on the CEDF from July 24 through August 2, 1995.

Test Procedures. Figure IV-2 shows how and where the sensors were installed for this study. The splashplate was the initial monitoring site where 150, 300, and 750 KHz sensors were mounted. A fourth sensor (300 KHz) was attached to a burner line elbow. To insure a low loss signal path between the waveguides and sensors, a pea-size quantity of vacuum grease which serves as a couplant was applied to each sensor's base before it was installed on the waveguide and clamped in place.

All sensors, except the 750 KHz model, contained integral signal preamplifiers which allowed direct connection to a four-channel B&W ALL[®] (Acoustic Leak Locator) system. This component provided additional signal conditioning functions such as gain, frequency filtering,

FIGURE IV-2 Installation of Acoustic Emission Sensors

and conversion to a dc-voltage output. While some applications rely on additional signal filtering for optimum system performance, none were used for this investigation. A dc-output voltage proportional to the signal strength generated by each sensor was fed to the CEDF data acquisition system and logged with other operating parameters for each burner test run. This was supplemented with data taken during CEDF start-ups and shutdowns when burner testing was not required.

Burnerline AE-data was collected with burner performance data during the day. Data collection normally required 10 minutes per test run at full load with lower firing rates requiring 15 to 20 minutes to allow enough time to collect flyash samples for LOI analyses. Coal firing was usually discontinued 15 to 20 minutes after the last test run. Start-up data collection typically covered a two to two and a half hour period.

Start-up Data Analysis. Figure IV-3 shows how typical acoustic emission sensor output voltages, coal flows (indicated and calculated), primary air flow, primary air-to-coal ratio, and carbon monoxide concentration varied with time. The beginning and ending time for the data set are shown in the lower left and right hand corners with the alphanumeric term between them being the test identity.

FIGURE IV-3 Startup Burner Line Acoustic Emission Data

Splashplate-mounted sensors showed the most sensitivity to coal flow. During the first couple of days, the 750 KHz sensor signal was found unreliable because of an intermittent electrical connection leaving available only those outputs from the 150 and 300 KHz sensors. Of these two, the 300 KHz sensor showed less jitter making plot interpretation easier, however, very little lead-in data was collected prior to coal firing making it difficult to show how steady the background signal was.

Once the 750 KHz sensor was deemed reliable, it was used for all graphical comparisons because its output was much less jittery than the 300 KHz sensor. A review of all start-ups and shutdowns showed that regardless of which sensor type was used, all responded in step changes with the start and stop of coal flows.

Shutdown Data Analysis. Typical shutdown data is represented by Figure IV-4. Shutdown data are, in effect, "mirror images" of start-up data, but over a generally shorter time period. Note that when the feeder was stopped, the AE signal suddenly dropped off as well. This was most noticeable for plots (not given) that showed several minutes worth of data following a coal feeder shutdown. For completeness, a calculated coal flow is also shown, however, it is not relevant because gas firing is normally established prior to stopping the feeder.

FIGURE IV-4 Shutdown Burner Line Acoustic Emission Data

Constant Load Data Analysis. All burner performance tests were conducted at fixed operating conditions; typically 100, 60, 40, and 35 x 10⁶ Btu/hr. A representative time history plot is shown as Figures IV-5.

FIGURE IV-5 Representative Time History Plot for Burner Line Acoustic Emission Data

To summarize and compare results among the four sensors, AE-sensor output signals and coal flows were averaged for each firing rate, fitted with straight lines, and plotted as shown in Figure IV-6. Note the rather good fit for the splashplate-mounted sensors versus the elbow-mounted sensor as indicated by the regression coefficient values in the legend box. It is interesting to note that all three splashplate sensors showed a slight upward trend at the lowest coal flow rate. It is not clear why this occurs. Elbow sensor data shows a rather poor trend; remaining almost flat throughout the coal flow range then dropping significantly between a firing rate of 40 and 35 x 10⁶ Btu/hr.

AE SENSOR OUTPUT vs CALCULATED COAL FLOW
CEDF XCL BURNER TEST PROGRAM
 July 24, 1995 - August 2, 1995

FIGURE IV-6 Comparison of Burner Line Acoustic Emission Results

IV.2.3 Flame Signature Analysis

Early in Phase II, Spectrum Diagnostix (SDx) had the responsibility of developing a system to determine the air-to-fuel ratio of a burner by analyzing optical flame data from that burner. SDx decided to use their SpectraTune™ technology for this task. The SpectraTune™ system calculates several "quality factors" (Q factors) from a linear analysis of an optical signal's power spectrum. In November 1994, SDx collected optical flame data during pilot-scale DRB-XCL® burner tests being conducted in the SBS. The SBS data was collected using three silicon-based sensors mounted to "look" at three different parts of the flame. The data was also collected over a range of stoichiometries and operating conditions. SDx analyzed the data with the SpectraTune™ system to arrive at several Q factors for each sensor for each test. SDx then attempted to correlate these Q factors with burner stoichiometry as well as other operating conditions (i.e. NO_x level). SDx's analyses showed promising correlations between Q factors and NO_x emissions. The correlations between Q factors and burner air-to-fuel ratio were not as promising. After an extensive review of the SpectraTune™ technology and the results of the SBS tests, the Controls & Sensors Subsystem team decided to abandon SDx's techniques in favor of an approach based on nonlinear evaluation of optical flame signals using techniques from chaotic time series analysis.

In July 1995, B&W collected pressure, optical, and acoustic data from the SBS in support of the newly adopted nonlinear analysis approach. This data collection effort was conducted simultaneously with LEBS advanced low-NO_x burner testing (see Section II.2.1). Several sets of data were collected over a wide range of operating conditions. Some of the operating parameters that were varied included: load, burner stoichiometry, primary air-to-coal ratio, and vane angles. In addition, the tests included both staged and unstaged operation with the DRB-XCL[®] burner and the ALNB#3 burner. Pressure, optical, and acoustic data was also collected from similar tests conducted during September 1995 in the CEDF (see Section II.2.2). The CEDF tests employed only unstaged operation of the DRB-4Z[™] burner during the data collection periods. However, data was still collected over a wide range of operating conditions.

A total of seven sensors were used to collect data during the SBS tests. Two high-speed MKS Baratron pressure transducers were installed to measure the fluctuations in static pressure. One transducer was connected to the primary air/coal line just upstream of the 90° elbow leading into the burner. The second transducer was connected to a tap on the burner secondary air line. Four identical optical sensors were used to measure the fluctuations in the visible light being emitted by the flame. Each sensor consisted of a lead-silicon photodiode with a frequency response in excess of 5 kHz connected to an eight-foot long fiber optic cable. The open end of each fiber optic cable was held in a mounting assembly and connected to a sight port on the unit. The first optical sensor was installed to provide a side view of the flame approximately ½ burner diameters downstream of the burner throat. The second optical sensor provided a view of the flame back into the burner throat from a location approximately 2 burner diameters downstream. The third optical sensor afforded a side view of the flame approximately 5 burner diameters downstream. The fourth optical sensor was mounted to look at the flame through the windbox (typical commercial scanner location). One acoustic transducer was installed in a sight port opposite the first optical location approximately ½ burner diameter downstream. The acoustic transducer was used to measure the airborne acoustic emissions from the combustion process. A TEAC Digital Audio Tape (DAT) recorder was used to collect and store the data from all sensors simultaneously. The TEAC DAT recorder was connected through an interface card to a personal computer. The computer was used to monitor and control the TEAC as well as to provide real-time graphing of the data.

The data acquisition arrangement for the September CEDF tests was similar to the July SBS tests except that only six sensors were utilized. The same two pressure transducers used on the SBS were connected to the CEDF. One pressure transducer was connected to a tap on the primary air/coal line upstream of the burner. The second pressure transducer was connected to a pressure tap on the windbox. Only three of the four optical sensors were used on the CEDF. The first optical sensor provided a side view of the flame at approximately ⅔ burner diameters downstream. The second optical sensor was oriented to "look" back into the burner throat from approximately 2 burner diameters downstream. The third optical sensor gave a side view of the flame roughly 5 burner diameters downstream. One acoustic transducer was mounted in a sight port about 3 burner diameters downstream on the same wall as the optical sensors. The same TEAC DAT recorder and computer system used on the SBS was used on the CEDF.

B&W analyzed the data from the SBS and CEDF using both linear and nonlinear analysis techniques. The linear techniques included general time series statistics (e.g., mean and variance), probability distributions, and Fourier frequency analysis. The nonlinear techniques used included: mutual information⁴, phase-space trajectory analysis⁵, correlation integral⁶, correlation dimension⁷, entropy⁸, and the method of surrogates⁹. In general, B&W found that the nonlinear techniques provided better resolution of differences between operating conditions than the linear techniques. B&W also found, however, that the combination of both linear and nonlinear techniques provided the most information about the state of the burner.

For burner air-to-fuel determination, B&W found that entropy analysis of data from the second optical location (looking back into the burner throat) provided the best correlation. Entropy is an indicator of the predictability of a system. Higher entropy indicates higher unpredictability and a closer approach to stochasticity. Entropy reflects the possibility of predicting the value of a future measurement based on the outcomes of recent previous measurements. Typical results of entropy analysis for the SBS and CEDF data are shown in Figures IV-7 and IV-8 respectively. These figures show entropy plotted against burner stoichiometry for the SBS data and against primary air-to-coal (PA/Coal) ratio for the CEDF data. The entropies shown are expressed as relative entropies. These relative entropies were determined by dividing the measured entropy of the data by the entropy of an equivalent set of random data. Relative entropies, therefore, have values between 0 (completely predictable behavior) and 1 (unpredictable or stochastic). The error bars on the data points represent an estimate of the calculation error found from repetitive calculations of the entropy. The straight lines in each figure represent linear fits of the data. As

FIGURE IV-7 Nonlinear Analysis Results for SBS Testing

FIGURE IV-8 Nonlinear Analysis Results for CEDF Testing

can be seen, both the SBS and CEDF data show good correlations with entropy. B&W, therefore, is optimistic that optical flame signals can be used to monitor and control burner air-to-fuel ratio. Future work will be aimed at verifying and extending these correlations to multi-burner environments.

IV.2.4 Dynamic System Simulation

The objective of this task is to develop a simulator that can be used to evaluate alternative operating procedures and control philosophies for the proof-of-concept facility. Dynamic system simulation is used for developing and testing state-of-the-art integrated control system techniques for LEBS. System simulation will be used to predict LEBS dynamic response to operations such as load maneuvering, changes in subsystem operation, and/or system reaction to external stimuli. This includes full simulation of the control system subsystem components including control logic, and the associated control hardware.

A dynamic system simulation used to model the LEBS systems dynamic response was developed by assembling models of the various subsystems and components that make up the LEBS. Such components include the boiler, flue gas clean up equipment, controls and other auxiliary equipment that effect the overall system performance. The complex physical processes of combustion, heat transfer, and emissions formation and reduction within a boiler are examples of the types of detailed physical phenomenon which must be accurately modeled in order to determine the ultimate performance of a boiler system.

The actual proof-of-concept furnace is modeled by a separate stand-alone FORTRAN program, referred to as the Combustion and Emissions Module (CEM). The CEM module is interfaced to

SPEEDUP to make a complete dynamic simulator. The CEM module was developed to represent the detailed fluid dynamics, combustion, and heat transfer phenomena occurring in a commercial boiler. Its development was based on extensions of existing models developed at B&W. These models are formulated from the fundamental principals of mass, material, and energy conservation. The models account for multi-dimensional radiative heat transfer and chemical kinetics for coal.

SPEEDUP was the software package selected to model the balance of the proof-of-concept facility. SPEEDUP is a dynamic simulation tool which uses physical property models from the state of the art steady-state process simulator ASPEN-PLUS. SPEEDUP has some unit operations and many controls in its model library. Some of the unit models will need to be developed during the contract. Software support is extensive with experienced on site help available. The selection was made based on the strengths of SPEEDUP (training, support, physical properties), and the fact that B&W has previous experience using the software.

The purpose of the preliminary simulator is to provide the controls developer with a working model that has included the major equipment of the proof of concept facility. The preliminary simulator is used to become familiar with running SPEEDUP and to guide the further development of the proof-of-concept simulator. The individual models used, and the general arrangement of the models in the simulator are briefly described below.

The block diagram of the preliminary simulator is shown in Figure IV-9. The unit names are shown on each block. A list of the SPEEDUP models is given below along with a brief description of each model. The unit names of the components which use each model are listed as bulleted items under each model.

CEM - Combustion and Emissions Module Interface

This is a dummy model to provide an interface to the CEM module. This model calls the CEM subroutines, passes the inputs, and receives the outputs from the CEM subroutines. At the present time the only controllable parameters are flow rate and temperatures of the fuel, air and flue gas recirculation (fgr).

- CEM

CEMII - CEM Inlet Interface

This model provides the interface between the upstream SPEEDUP models and the CEM. The interface has three main functions: convert speedup streams to arrays to be passed to the CEM, convert the input from US Engineering units to SI units, and provide control interface (sensors) to the upstream controllers. At the present time the interface is configured for 2 levels of burners and 2 levels of overfire air (OFA) ports. The burners can use any combination of air, coal, natural gas or fgr. The ofa ports can use any combination of air and fgr.

- CEMII

FIGURE IV-9 Preliminary Simulator Block Diagram

CEMOI - CEM Outlet Interface

This model provides the interface between the CEM and the downstream SPEEDUP models. The main function of this model is to convert CEM arrays into SPEEDUP streams for the downstream models and to convert from SI to US Engineering units.

- CEMOI

COMPRESSOR_SS - Steady-State Compressor

This is a model of a steady-state compressor. The model raises the pressure of a stream and calculates the work needed to raise the pressure based on a specified efficiency.

- ID_FAN

HEAT_COOL - One Stream Heat Exchanger

This heat exchanger model is a one stream model. The model heats or cools a stream to a specified outlet temperature.

- FG_COOLER

HEAT_EXCH - Two Stream Heat Exchanger

This heat exchanger model is a two stream model. The model is configured for counter flow applications. The model was "tuned" by setting the overall heat transfer coefficient to 10 Btu/hr/ft²/°F, and then determining the heat transfer surface area needed to give the design outlet temperature.

- SA_HEATER1
- SA_HEATER2
- SA_TRIM_HEATER

MOL_FEED - Mole Specified Feed

The model provides stream starting points. The user must specify stream composition, temperature, pressure and molar flowrate. Flowrate cannot be specified if a flow controller is used downstream of the feed.

- SAIRFEED1
- SATHCAIR

PID_CONT - PID Controller

Simple Proportional Integral controller with Derivative action term.

- OFAFLOWC1
- OFAFLOWC2
- SAFLOWC1
- SAFLOWC2

SPLIT - Stream Splitter

This model will split one stream into two streams with identical temperature pressure and composition. The flowrate of one outlet stream can be fixed and the remainder of the flow will go to the second outlet stream. In the simulator the secondary air is divided into four

streams (Secondary Air 1, Secondary Air 2, Overfire Air 1, Overfire Air 2) by the use of 3 cascaded splits.

- SASPLIT1
- SASPLIT2
- SASPLIT3

TEAR - Stream Tear

This model is used in the convergence of the steady-state or initial run. The run is converged and the tear closed when the slack variables are set to 0.0. Therefore, the slack variables should not be changed on dynamic runs.

- SATR

VALVE - Gas Valve

This model represents the steady state relationship between stem position and vapor flow through an adiabatic valve. The model is presently configured for a linear response but other response characteristics can be used.

- OAIRD1
- OAIRD2
- SAIRD1
- SAIRD2
- SATC_VALVE

VALVE_DYN - Actuator Dynamics

Valve_dyn models the dynamic relationship between the input signal to a control valve and the output valve stem position. The model can be configured for negligible dynamics, second order dynamics and second order rate limited dynamics.

- OFAVD1
- OFAVD2
- SAVD1
- SAVD2

WT_FEED - Weight Specified Feed

Model provides stream starting points. User must specify stream composition, temperature, pressure and flowrate. The model will convert mass flow units to molar flow units compatible with downstream models.

- COALFEED1
- COALFEED2
- PAIRFEED1
- PAIRFEED2

V. Boiler Subsystem

At the heart of the LEBS is the boiler. Within this advanced B&W boiler, all of the low emission technologies are integrated. To meet the net plant efficiency goal of 42%, the boiler must be designed not only to achieve the proper conditions for low NO_x combustion with air staging and accommodate the in-furnace injection of the limestone for the LIDS process, but it must also efficiently capture the heat to produce high temperature steam at well above critical pressure. The steam conditions selected for the boiler are 4500 psi, 1100°F/1100°F/1100°F.

Since the steam-side pressure and main and reheat steam temperatures are higher than conventional cycles and operation of low NO_x burners creates sub-stoichiometric conditions in portions the furnace, additional challenges are presented. Higher alloy materials must be used in the outlet portions of the superheater and reheater banks to obtain acceptable surface metal temperatures. In addition, materials must be selected that will resist corrosion since the surface of these outlet tubes will operate at temperatures which will allow the coal ash to remain molten on their surfaces. Consideration must also be given to furnace wall corrosion in the combustion zone. Thus, boiler design work has been identified to address the integration of the NO_x and SO₂ subsystems while applying B&W's advanced supercritical boiler technology. Work addressing furnace corrosion based on gas-side sampling during burner testing is reported separately under the NO_x subsystem.

V.1 Summary of Activities

V.1.2 Period of October 1994 to December 1994

Nothing to Report

V.1.2 Period of January 1995 to March 1995

Nothing to Report

V.1.3 Period of April 1995 to June 1995

Work began to consider a heat pipe air heater in addition to the regenerative air heater selected in Phase I for the Commercial Generating Unit. A specification for the CGU based on the same criteria as used in Phase I for the regenerative air heater was developed and forwarded to the vendor for performance and quote. Performance and cost are expected to be favorable since the design appears to be simpler and there is no leakage to consider

The Phase I Commercial Generating Unit boiler design was reviewed in preparation for discussions about the steam cycle and Balance of Plant (BOP) with Raytheon planned for July or August and to begin evaluation of modifications to the boiler and LIDS system to improve efficiency.

V.1.4 Period of July 1995 to September 1995

Design and cost of a heat pipe air heater was completed. The performance and cost will be compared with a regenerative and other design alternatives to identify the approach that results in the lowest cost of electricity for the Commercial Generating Unit.

Due to schedule conflicts the meeting with Raytheon was rescheduled until early December 1995.

V.1.5 Period of October 1995 to December 1995

Work completed during Phase I for the Commercial Generating Unit (CGU) was reviewed and general modeling requirements were defined for use in Phase II work originally planned to begin in November. Boiler subsystem team members met on November 1 to discuss planned modeling activities for the CGU and the possible revision of the CGU size from 350 MWE to 400 MWE. Based on the results of this meeting, modeling of the CGU furnace has been delayed until after the meeting with Raytheon when an evaluation of economic and efficiency issues can be completed and the CGU size is finalized. To assess the impact of changing the unit size, a revised estimate and schedule for this activity have been completed, since additional modeling scope may be necessary due to the change in furnace size.

A description of desired changes to the RD&T Plan to address corrosion was completed and transmitted to DOE for approval. The revised projects address additional laboratory testing and field testing but will only be performed to the extent possible within the existing budget.

Cost and performance for the heat pipe air heater was received from the vendor. Though the performance is better due to lack of leakage, the cost is significantly higher. The trade-offs will have to be assessed with the rest of the plant.

Due to the federal budget impasse and funding concerns, initiation of the BOP work with Raytheon has been postponed until sufficient funding is released. This also delays the decision on boiler size.

V.2 Key Accomplishments

V.2.1 Heat Pipe Air heater Evaluation

Costs and performance for a heat pipe air heater based on the same criteria as used in Phase I for the regenerative air heater for the Commercial Generating Unit were obtained. Performance is better since there is no leakage to consider but the overall impact on cost must be evaluated with the whole plant.

V.2.2 Boiler Design Improvements

In the review of the Phase I boiler design, several ideas have emerged which better integrate the SO₂ subsystem with the boiler gas-side while reducing it's impact on boiler efficiency and auxiliary power requirements. These will be pursued and evaluated during upcoming boiler design work.

VI. Balance of Plant Subsystem

In order to develop an overall plant design and to evaluate plant efficiency and cost, B&W subcontracted with Raytheon Engineers and Constructors of Denver, Colorado. Together a Phase I concept was developed that achieved the initial LEBS goal of 38% net plant efficiency. That design resulted in identification of a number of potential improvements to the turbine cycle and auxiliary equipment needed to meet the Phase II goal of 42% net plant efficiency. Although several concepts have been identified, the DOE budget delays have postponed work on the balance-of-plant systems until early spring 1996.

VI.1 Summary of Activities

VI.1.1 Period of October 1994 to December 1994

Nothing to Report

VI.1.2 Period of January 1995 to March 1995

Nothing to Report

VI.1.3 Period of April 1995 to June 1995

Nothing to Report

VI.1.4 Period of July 1995 to September 1995

Nothing to Report

VI.1.5 Period of October 1995 to December 1995

A meeting with Raytheon was arranged for December 8 but had to be postponed until additional funding is released. A meeting in the 1st quarter of CY96 is anticipated to get this effort underway. The three key issues to be addressed are 1) the size of the CGU (400 MWE instead of 350 MWe), 2) improvements to the steam cycle needed to achieve the net plant efficiency goals and 3) anticipated changes in the boiler and air-gas side to better integrate the LIDS system improve boiler and cycle efficiency.

VI.2 Key Accomplishments

Nothing to Report

References

1. Sarv, H., "Advanced Low-NO_x PC Burner Development Program: Pilot-Scale DRB-XCL[®] PC Burner Characterization Report," Babcock & Wilcox Report, RDD:93:23090-005-405:01, March 1993.
2. Sarv, H., "Advanced Low-NO_x PC Burner Development Program: PC Burner Characterization Report," Babcock & Wilcox Report, RDD:94:25090-005-540:01, April 1994.
3. Sivy, J.L., Rodgers, L.W., Kaufman, K.C., and Koslosky, J.V., "Development of an Advanced Low-NO_x Burner in Support of B&W's Advanced Coal-Fired Low-Emission Boiler System," presented at the 1995 Fall International AFRC Conference, Monterey, CA, October 15-18, 1995.
4. Fraser, A.M., and Swinney, H.L., 1986, *Phys. Rev.*, Vol. 33A, pp. 1134-1140.
5. Takens, F., 1981, *Dynamical Systems and Turbulence, Warwick 1980*, Lecture Notes in Mathematics, No. 898., Springer, Berlin.
6. Abarbanel, H.D.I., Brown, R., Sidorowich (Sid), J.J., Tsimring, L. Sh., 1993, *Rev. Mod. Phys.*, Vol. 65, pp. 1331-1392.
7. Broomhead, D.S., and King, G.P., 1986, *Physica D*, Vol. 20, pp. 217-236.
8. Grassberger, P. And Procaccia, I., 1983, *Phys. Rev. A*, Vol. 28, pg. 2591.
9. Theiler, J., Eubank, S., Longtin, A., Galdrikian, B., and Farmer, J.D., 1992, *Physica D*, Vol. 58, pp. 77-94.