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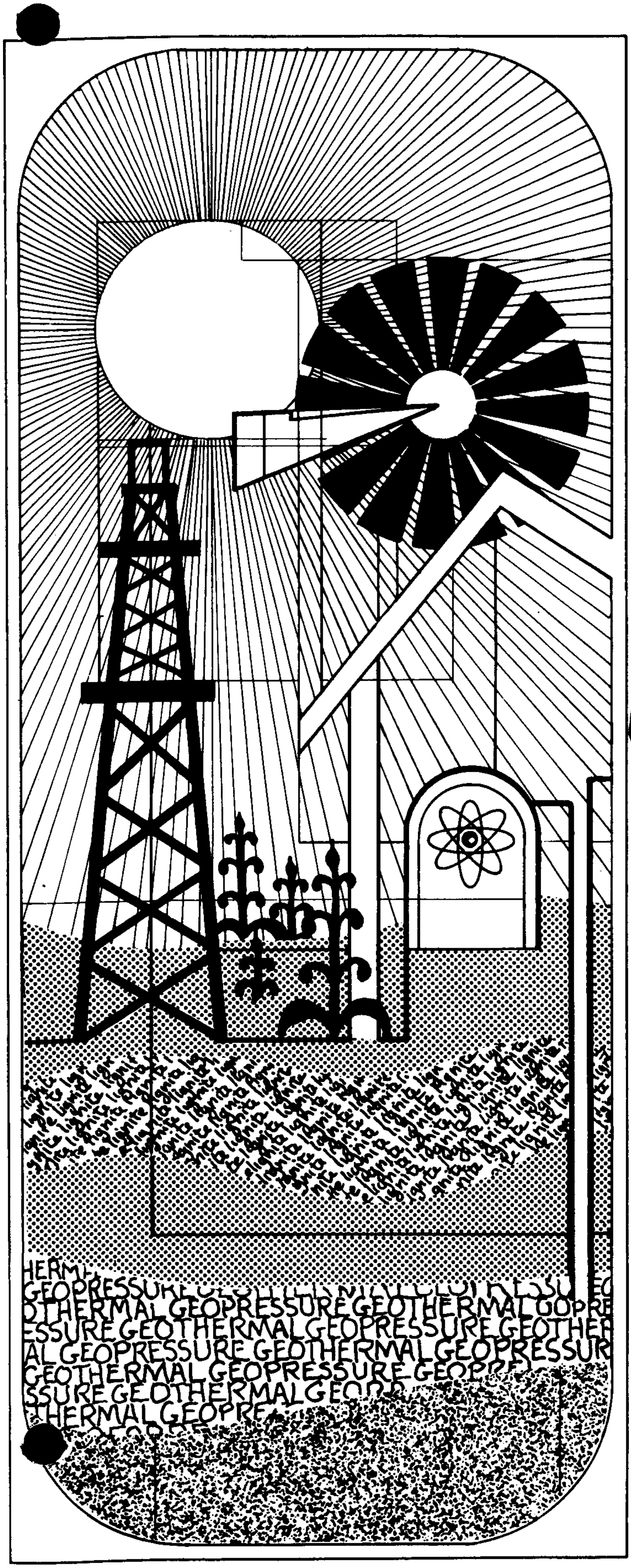

Texas Energy Development Fund

TESTING AND EVALUATION OF FLUIDIZED BED COMBUSTION OF TEXAS LIGNITE

TENRAC/
EDF-068

MASTER

TEXAS ENERGY AND
NATURAL RESOURCES
ADVISORY COUNCIL

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TESTING AND EVALUATION OF FLUIDIZED-BED COMBUSTION OF TEXAS LIGNITE

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EXECUTIVE SUMMARY

In 1980, approximately 18 percent of the electricity generated in Texas was produced by large pulverized coal boilers firing Texas lignite. However, use of lignite in smaller scale industrial-sized applications has not been widely practiced. Recently, atmospheric fluidized bed combustion (AFBC) technology for industrial boilers has become commercially available but, as of yet, has received very limited application.

The Texas Energy and Natural Resources Advisory Council (TENRAC) supports utilization of the state's lignite resources through lignite research, development, and demonstration. This report presents the results of a testing and evaluation program to assess the technological, environmental, economic, and institutional issues affecting the utilization of Texas lignite for industrial-sized AFBC applications.

BACKGROUND

In 1974, Texas accounted for 25 percent of all oil and natural gas used nationally in large industrial-sized boilers (1). Provisions of the Power plant and Industrial Fuel Use Act of 1978 combined with decontrol of natural gas prices have provided added stimulus for the use of other fuel sources. As a result, fuels such as coal will be used in Texas in the future for industrial applications. Several studies have identified that significant potential exists for industry in Texas to use coal in fluidized boilers. Estimates of the potential for using AFBC technology in Texas range from 540 to 800 trillion Btu in the year 2000. This represents from 18 to 28 percent of the projected total for industrial AFBC boilers in the U.S. (1, 2, 3). Texas lignite, because of its proximity to demand centers in the state, appears to be a likely fuel to satisfy a significant portion of the projected demand.

In a report to the TENRAC prepared by the Advisory Committee on Lignite Research, Development, and Demonstration, the following statement was presented in the Executive Summary:

> Essentially all future use of Texas lignite will be accomplished through the use of four technologies: pulverized coal combustion, atmospheric fluidized bed combustion, medium Btu gasification and in-situ gasification...[with the exception of pulverized coal combustion], atmospheric fluidized bed combustion has the greatest potential energy impact. (4)

In spite of the potential for use of Texas lignite in FBC boilers, published test results on the performance of Texas lignite in a fluidized bed combustor are limited. Prior to the initiation of this study, available data were limited to a series of tests conducted at the Department of Energy's (DOE's) Morgantown Energy Technology Center (METC) on a single Texas lignite and an evaluation of sulfur retention capacity of Texas lignite ashes conducted at The University of Texas (5, 6).

More extensive testing of Beulah North Dakota lignite sponsored by DOE's Grand Forks Energy Technology Center (GFETC) has indicated that the characteristics of that lignite significantly affect the performance and design requirements of fluidized bed combustors. The North Dakota lignite contains a high percentage of sodium in the ash which has the advantage of reducing limestone requirements by participating in sulfur capture reactions. However, severe agglomeration of bed material and corresponding loss in fluidization have also been observed.

In general, Texas lignite contains more ash and volatiles but is lower in sulfur and sodium content than North Dakota lignite. Furthermore, the composition of the lignite can vary significantly by lignite group and location within the state. Therefore, the effects of the unique characteristics of Texas lignite on performance and design requirements of fluidized bed combustors have not been adequately investigated. Additional test data are necessary to determine the potential for using Texas lignite in AFBC systems in the state.

PROGRAM OBJECTIVES

The major objectives of this project are to 1) provide baseline test data on the performance of AFBC boilers firing Texas lignite and 2) investigate the potential for future demonstration and deployment of AFBC technology in Texas. In order to achieve the above objectives in the most cost-effective manner, testing conducted on this project was coordinated with concurrent testing of Texas lignite at DOE's Grand Forks Energy Technology Center.

SUMMARY OF RESULTS

Tests were conducted by Combustion Power Company (CPC) on Texas lignites from the Wilcox Group (Monticello mine) and from the Jackson Group (San Miguel mine). In general, these lignites are poor quality fuels with low heating values and high moisture and ash contents. Jackson lignite contains high sulfur and moderate sodium levels. Wilcox lignite is low in sulfur and sodium content. Short-term tests were conducted with these lignites that primarily investigated the effect of bed temperature and limestone addition rate.

The test unit was an atmospheric pressure fluid bed combustor with a seven square foot bed area capable of firing up to 800 pounds per hour of Texas lignite at the conditions tested. The size of this test unit should be large enough to yield data useable for designing larger industrial-sized facilities. However, the bed area may be too small to provide scalable data regarding lignite feed points and air distribution in the boiler. The test unit was also equipped with components that are being considered for use in industrial systems such as a limestone feed system and baghouse for SO_2 and particulate emissions control, respectively, and a recycle cyclone to improve combustion efficiency and limestone utilization. Major results of the project are summarized below.

Combustion Characteristics

The operation of the fluidized bed combustion test unit was stable using each Texas lignite and satisfactory performance was achieved. Combustion efficiencies for operation at 20 percent excess air increased from 96 to 99.6 percent as bed temperature increased and generally exceeded 99 percent. No indications of bed particulate agglomeration or accumulated deposits in the combustor were observed for either lignite at the conditions tested. However, the solid components in the system may not have reached steady-state conditions due to the relatively short test durations (120 hours per series with 4 test points per series).

Air Emissions

Some sulfur capture was provided by the alkaline components of the ash, but SO_2 removal without limestone addition was generally less than 50 percent. Addition of limestone could provide sulfur captures well above 90% and limestone rates could be controlled to achieve desired SO_2 emission levels. Some basic differences in sulfur capture characteristics were observed for each of the lignites tested (e.g., inherent sulfur capture, optimum bed temperature, calcium-to-sulfur ratio, etc.). While test results indicate that the Jackson lignite requires a lower calcium-to-sulfur ratio than the Wilcox lignite to achieve comparable sulfur retentions, the overall limestone requirements for the Jackson lignite are nearly three times greater due to it's higher sulfur content.

Nitrogen oxide (NO_x) emissions were very low for both lignites and tended to increase with bed temperature. The NO_x emissions (as NO_2) were below 0.20 lb/10^6 Btu and as low as 0.10 to 0.12 lb/10^6 Btu at the lower temperatures. This compares to New Source Performance Standards for utility boilers of 0.6 lb NO /10^6 Btu for lignite. The levels produced by Texas lignite were equivalent to less than 10 percent of the fuel-bound nitrogen.

Solid Waste Characteristics

Solid wastes produced during testing of the Wilcox and Jackson lignites were characterized to evaluate disposal requirements. Samples of bed material, baghouse catch, and composites of bed and baghouse catch materials were subjected to 1) chemical analysis to quantify major and trace components, 2) leachability characterization to determine disposal requirements with respect to federal and state regulations, and 3) physical characterization to define properties relating to handling, disposal, and treatability.

The leachability characteristics of the solid wastes were determined based on procedures outlined by the Resource Conservation and Recovery Act (RCRA) and the Texas Department of Water Resources (TDWR) to assess disposal requirements. None of the AFBC solid wastes produced leachable concentrations of regulated elements great enough to be classified as hazardous under RCRA procedures. In fact, levels for the eight criteria elements were one to two orders of magnitude less than RCRA limits.

Based on TDWR classifications, none of the Texas lignite solid waste sampled would be Class I wastes (most hazardous). Leachates produced by TDWR procedures resulted in solid wastes classified as either Class II (intermediate hazard) or Class III (inert, insoluble) wastes depending on the particular samples tested.

Limestone addition during combustion significantly reduced selenium levels in leachate but barium and chromium appeared more susceptible to leaching. Limestone addition also appears to be a major factor in producing both stronger and less permeable solid waste for landfill disposal.

Cost Analysis

Cost comparison studies conducted by other investigators indicate a small economic advantage for fluidized bed boilers (FBB) over conventional systems. A cost analysis was conducted in this program to compare the costs of AFBC systems firing Wilcox and Jackson lignites.

Capital and operating costs for a base case industrial-sized FBB design were estimated using test data. The sensitivity of costs compared to the base case was assessed by evaluating the effects of variations in important design and economic parameters on steam cost. The sensitivity analysis indicates that capital cost and the cost of money are the most significant parameters impacting the cost of steam.

Assuming that fuel costs ($\$/10^6$ Btu) for the Jackson and Wilcox lignite were the same, steam costs would be over eight percent greater for an FBB firing Jackson lignite due to greater limestone and solid waste disposal requirements. If the lower quality Jackson lignite could be purchased for over 14 percent less than the Wilcox lignite, then the cost of steam would become less for the Jackson-fired FBB.

Market Potential

The major constraint to commercialization of AFBC systems appears to be the lack of demonstrated long-term reliability of the technology. Because of this, the major steam using industries in the state (petroleum refining, petrochemicals, and primary metals) appear likely to wait for industries with lower steam reliability requirements to initially install the technology. Because of location and process-specific considerations, these initial users will probably be located along the lignite belt in the food processing; pulp, paper, and wood products; and enhanced oil recovery industries. Data being gathered from AFBC demonstration units at Georgetown University in Washington, D.C. and at Great Lakes Naval Training Center will help answer some of the questions relating to long-term reliability. However, due to less severe reliability requirements in these two installations (i.e., space conditioning), the value of direct transfer of the data to Texas industries may be limited.

CONCLUSIONS

Texas lignites seem particularly well suited for combustion in fluidized bed boilers due primarily to 1) the ability of FBB's to accommodate a wide range and fluctuation in lignite quality and 2) the favorable combustion characteristics of Texas lignites in fluid bed combustors.

While Texas lignite has been fired in utility boilers in the state for a number of years, use of the low quality fuel has resulted in design and operating problems. A contributing factor has been the fluctuation in fuel quality resulting from the inherent variability in mining conditions and lignite characteristics at many operating mines. For industrial boilers which could potentially rely on lignite from different mines, variations in fuel quality could be even greater. The ability of fluidized bed boilers to accommodate a wide range of lignite qualities permits increased fuel supply flexibility for industrial users.

The combustion characteristics of the Texas lignites in the fluidized bed combustor were favorable resulting in high combustion efficiencies and stable, non-agglomerating fluidized bed operation. In addition, the inherent sulfur capture capability of the ash and the low sulfur content of some of the lignites (especially from the Wilcox group) can result in operation with high sulfur captures (e.g., 90 percent) with relatively low limestone rates and correspondingly reduced costs. Sensitivity studies indicate the cost of lignite as delivered will tend to have a more significant impact on the cost of steam than sulfur content. Therefore, potential users are expected to identify applications which minimize lignite costs such as installing an FBB at a facility in close proximity to the mine rather than paying a premium for higher quality lignite.

The major factors limiting the application of AFBC in the state of Texas are 1) reluctance of users to switch from oil or gas to coal or lignite and 2) concern that the advantages projected for the cost of steam produced by FBB compared to conventional coal-fired boilers are not sufficient to justify employing a largely unproven technology. However, once AFBC technology has been adequately demonstrated to be a reliable, operable system, users are expected to consider using AFBC technology to take advantage of the projected savings in steam costs compared to conventional lignite-fired boilers.

RECOMMENDATIONS

The recommendations from this program are aimed at further addressing the feasibility of firing Texas lignite in AFBC systems. Use of Texas lignite in fluidized bed boilers for industrial applications is primarily limited by two constraints: 1) the lack of an extensive data base to allow the design of a unit optimized for utilizing Texas lignite and 2) a general lack of demonstration of AFBC technology in commercial, industrial-scale operation. The following recommendations address these two constraints.

Texas lignite is a unique fuel in many respects. For example, the high volatile and high ash content typical of Texas lignite is not found in most bituminous coals or even North Dakota lignites. Other differences exist such as the composition of the ash and the forms of sulfur present in Texas lignite. These fuel characteristics may affect the performance of AFBC systems using Texas lignite. For example, the data obtained in this program indicate that Texas lignite combusted in an FBB is characterized by excellent combustion efficiencies, very low NO_x emissions, and very high recycle rates. These fuel characteristics may also affect major considerations in the design of an AFBC unit, such as feed points (e.g., overbed, underbed), lignite feed particle size, recycle rate, bed temperature, and superficial velocity. In fact, alternatives to the basic bubbling bed design tested in this program, such as recirculating bed and staged bed designs, might well be better suited to Texas lignite fuels. The test results from this program are certainly encouraging, but are not extensive enough to provide an adequate data base for the design of an AFBC unit optimized for Texas lignite. Thus, a major recommendation is the implementation of a feasibility study to identify the most promising AFBC design option(s) based on the unique properties of Texas lignite and the special requirements for users in the state of Texas such as petroleum and petrochemical industries.

The other major recommendation is to address the primary concern of most industrial steam users in the state regarding the lack of commercial demonstration of AFBC technology. The results of the above recommended study to identify the most promising AFBC design could be used as the basis for a funded demonstration unit using Texas lignite. Several industrial-sized AFBC units are slated for startup in the state during the next two to three years. However, none of these units will fire Texas lignite. Undoubtedly, these industrial-sized units will demonstrate some aspects of the technology. However, the fact that none of the proposed systems will use Texas lignite underscores the need to adequately demonstrate the design and reliable operation of AFBC units firing Texas lignite in order to stimulate the use of this resource in the state.

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Section 1

INTRODUCTION

The State of Texas through the Texas Energy and Natural Resources Advisory Council (TENRAC) is supporting utilization of Texas lignite through research, development, and demonstration programs. This report presents the results of a test program to evaluate Texas lignite in industrial-sized atmospheric fluidized bed combustion (AFBC) applications.

A significant potential exists for using Texas lignite in atmospheric fluidized bed combustion technology in the state. The major objectives of this program are to (1) provide baseline test data on the performance of AFBC boilers firing Texas lignite to define design requirements and (2) investigate the potential for future demonstration and deployment of AFBC technology in Texas.

To accomplish these objectives, a parametric test program using lignites from the Wilcox and Jackson groups was conducted on a pilot-scale fluid bed combustor. The test program defined important process performance and design variables for AFBC units firing Texas lignite. Solid waste from the pilot tests was characterized to determine disposal requirements under federal and state regulations.

A conceptual design and cost estimates were prepared for an industrial-sized fluidized bed boiler using test data from the program. Results of the test program and interviews with Texas companies with an interest in AFBC systems were used as input to assess the market potential for AFBC technology in Texas over the next ten years.

The program approach is discussed in more detail in Section 2. Results of pilot testing and solid waste characterization are presented in Sections 3 and 4, respectively. Operating and economic tradeoffs for a fluidized bed boiler firing Texas lignite are discussed in Section 5 and the associated market potential is presented in Section 6. Appended information includes detailed test results (Appendix A) and analytical procedures for the solid waste characterization (Appendix B).

Section 2

APPROACH

The general approach to achieving the objectives of this study as discussed in Section 1 is briefly presented here. More detailed discussions of the approach to accomplish each phase of the project are included in subsequent sections of this report. Several groups have participated in the project. The general approach employed and the roles of the two major participants are summarized as follows:

- Conduct AFBC pilot plant testing and correlate data on process performance and environmental characteristics for two Texas lignites - Combustion Power Company (CPC).
- Compare test results with available data from other testing of Texas and North Dakota lignites to identify significant relationships in order to expand the useable Texas lignite data base - CPC.
- Characterize AFBC solid waste produced during the lignite tests to estimate disposal requirements - Radian Corporation.
- Prepare a conceptual design of an industrial-sized Texas lignite-fired AFBC boiler, estimate costs, and conduct a sensitivity analysis of projected cost estimates - CPC.
- Investigate technical, environmental, economic, and institutional issues affecting the market potential for fluidized bed combustion of Texas lignite - Radian.

This project approach is illustrated in Figure 2-1. Radian Corporation was responsible for overall program planning and coordination. In addition to the efforts of Radian and CPC listed above, Grand Forks Energy Technology Center (GFETC) of the U.S. Department of Energy conducted tests of Texas lignite in parallel to this project and provided significant informational, financial, and consultative assistance. Input to the project was also received from Texas firms interested in utilizing FBC technology.

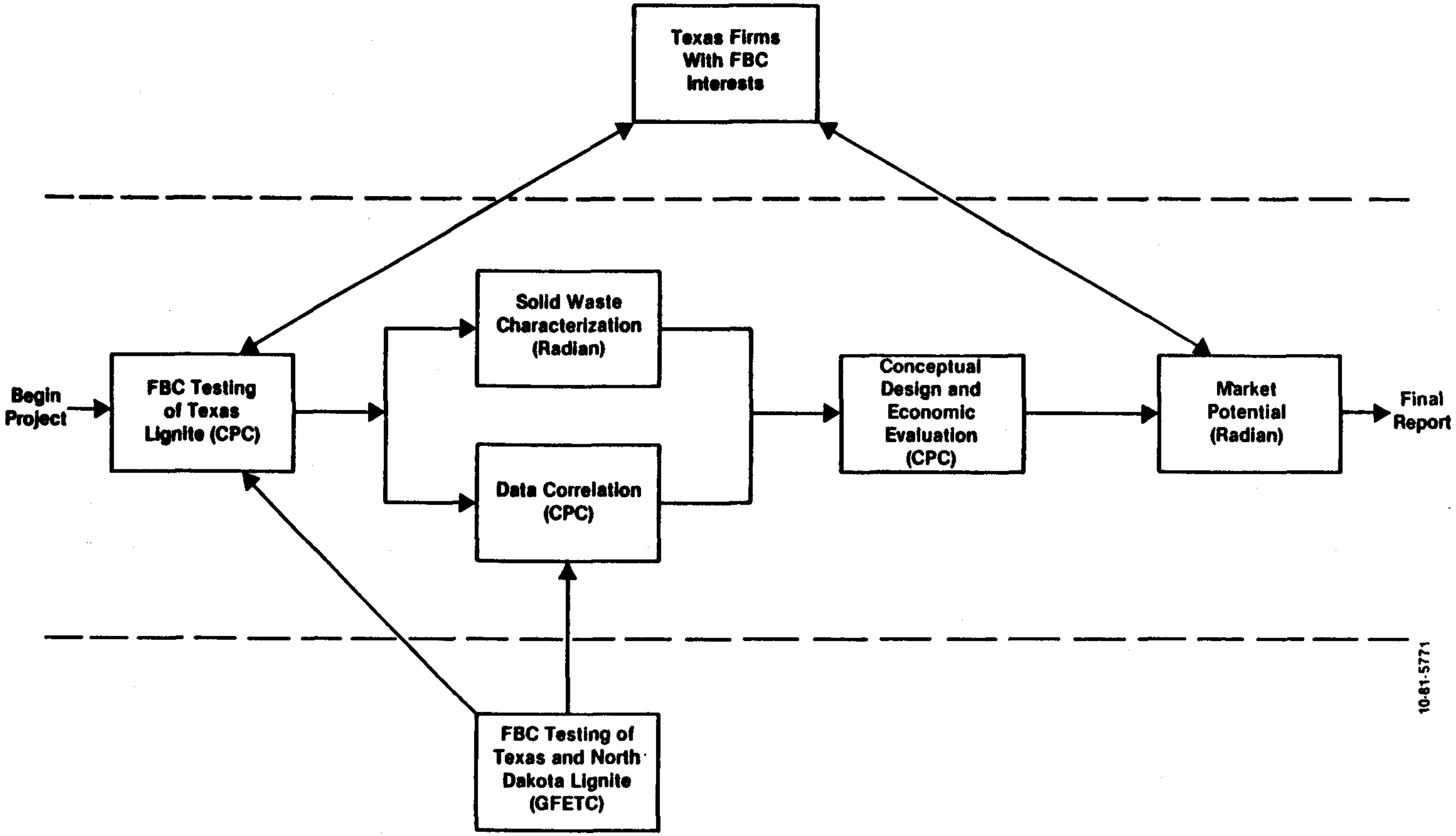

Figure 2-1. Illustration of project approach.

2.1 TEXAS LIGNITE TESTING

Significant testing of North Dakota lignites for AFBC applications has been conducted over the past several years. Initial testing was conducted at GFETC on a 0.2 square foot AFBC unit and at Morgantown Energy Technology Center (METC) in a 1.7 square foot AFBC unit (2-1). Because of the small size of these systems and to expand the available data base on using Texas lignite in AFBC units, a series of experiments was conducted in the 7 square foot atmospheric AFBC Test Facility at CPC. This unit is capable of operating over a wide range of operating conditions including bed temperature (up to 1800°F), superficial velocity, excess air rate, bed depth, and material feed rates and characteristics.

Lignite deposits in Texas are primarily found in three narrow bands identified as the Wilcox, Claiborne, and Jackson Groups that extend from east Texas to southwest Texas. The majority of lignite deposits are found in the Wilcox Group. Lignites in the Claiborne and Jackson Groups are less abundant, but may be locally significant. One characteristic of Texas lignite (and other low-rank fuels) is the large variability in chemical and physical properties between different lignite deposits as well as within a given lignite seam. In general, lignite from the Wilcox Group tends to be higher quality than the lignites from the Claiborne and Jackson Groups.

In order to develop test data needed to better understand the performance of Texas lignite in AFBC applications relative to the lignites of North Dakota, three series of parametric tests were conducted by CPC on two Texas lignites. The first two series of tests were conducted on Wilcox lignite from Texas Utilities Generating Company's Monticello Plant. This Wilcox lignite is from northeast Texas and is typically a medium quality lignite with relatively high ash, but low sulfur and sodium levels. The third series of tests used a Jackson Group lignite from the San Miguel Electric Cooperative's San Miquel mine in southwest Texas which typically contains relatively high ash, sulfur, and sodium levels. These two lignites were selected for testing because 1) they cover the general range of lignite qualities available in the state and 2) they were considered representative of lignites available to industrial facilities located in different areas of the state. The characteristics of the lignites tested are discussed in more detail in Section 3.

In order to simplify data correlation for the proposed test program and to permit comparisons with earlier experiments on North Dakota lignite, the parametric studies conducted by CPC concentrated on two variables which have been determined in earlier work to show major influences on AFBC performance: 1) bed temperature and 2) total alkaline-to-sulfur ratio[1]. Superficial velocity was also included as a test parameter although it received only secondary emphasis.

In addition to testing of the two lignites by CPC, GFETC concurrently conducted a more extensive independent test program using Jackson lignite from the San Miguel mine. The test plan prepared by GFETC included investigation of bed temperature, alkaline-to-sulfur ratio, superficial velocity, excess air, and recycle rate. GFETC also shared in the costs of FBC testing at CPC and furnished consulting services for this project.

A test program was prepared by the project team with input from GFETC and based upon consultation with Texas firms known to have an interest in FBC. The duration of testing for each of the three series was 120 hours. Four tests were conducted per series resulting in a total of twelve test points. Operational experience with North Dakota lignite indicates that operating at four distinct test points per 120 hour run is sufficient to determine steady-state gaseous emission characteristics. Longer duration tests (approximately 250 hours each) would likely be required to reach steady-state bed composition. Longer duration tests were not conducted on this program due to the greater

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[1] Defined as the ratio of alkaline calcium and soidum species contained in the lignite ash (and limestone, if added) to the sulfur content of the lignite fed to the test unit.

costs involved. However, bed samples from this program can be compared to the longer duration GFETC tests on Jackson lignite to determine if discrepancies were observed.

The starter bed material for the first and third series of tests was 20 mesh silica sand, the same initial bed material used by GFETC. The Linwood limestone used was the same limestone which was used by GFETC for both their Texas lignite tests and their earlier North Dakota lignite tests. CPC's second series started with the used bed material from the first series. Since the fuel for both these series was Wilcox lignite, it was felt that this bed starter material would allow the pilot plant to approach steady-state operation sooner.

Selected fuel, particulate, and other solid samples were collected on a routine basis and analyzed for physical and chemical properties. These analytical results were used to determine combustion efficiencies, sulfur retention, and particulate and gaseous emissions. In addition, the flue gas composition was monitored on a continuous basis via an extractive, conditioned gas sampling system with individual analyzers for O_2, CO_2, CO, SO_2, NO, and hydrocarbon content.

2.2 DATA CORRELATION

The process and emissions data from both the CPC and GFETC tests were evaluated to accomplish the following objectives:

- identify similarities and dissimilarities in the two Texas lignite data sets and determine the factors affecting AFBC design and performance;
- determine if relationships for Texas lignite performance, especially for sulfur capture and combustion efficiency, are such that the North Dakota data base can be used to effectively expand the Texas lignite data base;

- identify any unique or especially favorable characteristics of Texas lignite; and
- identify areas warranting further research efforts.

2.3 SOLID WASTE CHARACTERIZATION

The attractiveness of AFBC as compared to conventional lignite firing with flue gas desulfurization is in large measure attributable to the ability to control sulfur oxide emissions without the use of flue gas cleaning technology and to the production of a dry, granular solid waste rather than a waste sludge. Solid wastes produced during the tests conducted at CPC were characterized to evaluate disposal requirements for future units combusting lignites from the Wilcox and Jackson Groups. The solid waste production rate is directly related to the lignite composition and feed rate and to the limestone feed rate required to meet sulfur capture requirements. Solid waste from an AFBC unit may be produced from the following sources:

- the main bed,
- the primary particulate collection devices (e.g., cyclones), and
- secondary particulate collection devices (e.g., baghouse).

The quantity and characteristics of the solid waste produced are dependent on several design and operating variables, such as:

- lignite and limestone feed material composition and particle size,
- feed material attrition rates,
- lignite combustion efficiency, and
- limestone utilization.

The solid waste characteristics, in turn, affect solid waste disposal requirements. Since the characteristics of solid residue collected at various points in the system may be different, the various solid waste streams were characterized individually. These streams were later combined to assess the advantages and disadvantages of various disposal options. In general, the least expensive disposal option would be to combine the waste streams in a common landfill. However, the waste streams were also characterized individually to determine if their characteristics are consistent with this approach. For example, if one of the waste streams is classified to require more stringent disposal measures, then separate disposal may be preferred.

The following solid waste characteristics were determined for Texas lignites tested at CPC:

- chemical composition,
- physical properties, and
- leachability.

Chemical characterization parameters included elemental analyses to quantify major component (e.g., calcium, sulfur, silicon) and important trace component (e.g., arsenic, mercury, lead) concentrations.

Physical testing was directed toward defining properties relating to handling, disposal, and treatability. One disposal option that may be attractive for AFBC solid waste is to moisten the waste in order to initiate cementation reactions and produce a strong, less permeable waste material. Physical characterization included testing to assess the feasibility of this disposal option and to quantify other physical properties such as dry bulk density and particle size.

Leachability testing was conducted in order to determine disposal requirements for the solid waste. Both Resource Conservation and Recovery Act (RCRA) and Texas Department of Water Resources (TDWR) procedures were used to assess the leachability of the material.

Because of the relatively short durations of the AFBC tests for each test run, collection of solid waste samples at steady-state conditions was not possible. The time constants for the solids in an AFBC unit are much longer than for the gas streams. In previous tests sponsored by GFETC on a North Dakota lignite with higher sodium levels, solids compositions have been observed to change over long periods (over 200 hours) so that steady-state conditions with respect to solids were never achieved. Therefore, these tests were used to both characterize solid waste from combusting Texas lignite, and identify areas where potential concerns exist that may require further testing. An additional consideration in evaluating these test results was that sand initially was added to the AFBC test units at CPC. Consequently, the impacts of sand addition must be appropriately accounted for in evaluating the solid waste characterizations.

2.4 CONCEPTUAL DESIGN AND OPERATING AND ECONOMIC TRADEOFFS

The test data and analytical results were used to develop a conceptual design of an industrial-sized FBC boiler and to project estimates of capital and operating costs.

A cost sensitivity analysis was conducted to assess the impact of important design parameters on the cost of steam for the FBC design. Parameters considered include:

- sulfur capture requirements,
- lignite sulfur content,
- limestone utilization,
- lignite and limestone cost,
- solid waste disposal cost, and
- economic factors
  --discount rate
  --investment tax credit.

This analysis provides a review to identify parameters which could significantly affect cost.

2.5 MARKET POTENTIAL

The ultimate goal of TENRAC's support of energy technology research, development, and demonstration (RD&D) is to encourage the widespread application of more economically and environmentally efficient energy technology in Texas. In order to allocate its resources most effectively and to facilitate private sector efforts, it is important for TENRAC to identify the constraints on and market potential of new technology. By so doing, future support for RD&D efforts by both TENRAC and the private sector can be better targeted and, ideally, lead to more rapid deployment of new technology. The following activities were initiated in direct response to this need: 1) identify technical, economic, environmental, and institutional constraints on the development of AFBC using Texas lignite; and 2) estimate the market potential for AFBC in Texas over the next ten years.

The first objective, identifying constraints, was investigated using the results of the project plus other information on AFBC to conduct a series of interviews with various parties of interest (experts) to identify their perceptions of the limiting constraints on FBC deployment in Texas. Twelve interviews were conducted with respresentatives of the petroleum, petrochemical, food processing, paper, and other major industries. Prior to each interview, the identified representative was sent a background paper reviewing the project's findings and other pertinent information on AFBC. Based on the interviews, key constraints were identified which need further investigation and/ or action.

The second objective, the estimation of potential markets for AFBC of Texas lignite during the next decade, utilized the results from the first objective plus information on the characteristics of various end-user energy demands and operational requirements, relative fuel prices, federal and state energy and environmental policies, and other pertinent information. This input was used to identify key industries likely to employ AFBC and to estimate the magnitude of the AFBC market under various assumptions.

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Section 3

FBC TESTING OF LIGNITES

Texas lignites from the Wilcox and Jackson groups were tested in CPC's pilot fluidized bed combustor. These tests were aimed at fulfilling the following technical objectives:

- Obtain parametric data on process performance by varying bed temperature, superficial velocity, and limestone addition rate.
- Obtain samples of spent bed material and baghouse catch material to assess solid waste characteristics and disposal requirements.
- Obtain data on air emissions to assess environmental performance at the selected test conditions.
- Obtain data sets for correlation or comparison to other data sets on Texas and North Dakota lignites to expand the data base available to potential users.
- Obtain operational and process data for use in the conceptual design and economic evaluation of industrial-scale fluid bed boilers firing Texas lignites.

The CPC test facility used in these tests is described in Section 3.1, and general test procedures used at the facility are discussed in Section 3.2. In Section 3.3, results of the FBC testing of the Wilcox and Jackson lignites are presented and evaluated. These results are compared to previous data on FBC testing of Texas lignites by GFETC in Section 3.4. In Section 3.5, results of the Texas lignite AFBC tests are compared to those of previous North Dakota lignite tests. Overall results are summarized in Section 3.6. Detailed test procedures and results are included as Appendix A.

3.1 TEST FACILITY DESCRIPTION

Combustion testing of the Texas lignites was conducted in CPC's atmospheric pressure FBC pilot combustor system, referred to as the Customer Test Unit (CTU) and depicted schematically in Figure 3-1. The CTU consists of the following major components: a low-pressure fluidizing air blower, an oil-fired preheat burner, a coal and limestone feed system, a cylindrical combustor with a cross-sectional area of 7 ft^2, in-bed horizontal and vertical water-cooled tubes, a water circulation system, a bed material drain, a recycle cyclone for return of elutriated solids to the combustor, a spray tower for cooling the exhaust gases (heat transfer surface is not included in the convection pass), a baghouse, instrumentation and control panels, and a gas sampling and analysis system. The CTU has been described in further detail in Appendix A and elsewhere (3-1).

3.2 GENERAL TEST PROCEDURES AND METHODS

To fulfill the technical objectives, test schedules were established with input from TENRAC, CPC, and Radian Corporation. The FBC testing of the Wilcox lignite by CPC was scheduled to require a total of eight tests. Test conditions were chosen on the basis of intermediate test results, according to the appropriate flowpath as indicated by the "decision tree" logic flow diagram presented in Figure 3-2. The decision for CPC to test the Jackson lignite was made after testing of the Wilcox lignite was completed. The Jackson lignite test series consisted of four tests, conducted according to the schedule shown in Figure 3-3. The total of 12 Wilcox and Jackson lignite FBC tests were grouped into the following test series:

- Test Series L116: Comprised of four nominally 24-hour tests (Nos. 1 through 4) to determine the FBC performance of Wilcox lignite under low SO_2-removal conditions, with no limestone addition;

- Test Series L117: Comprised of four nominally 24-hour tests (Nos. 6 through 9) to determine the FBC performance of Wilcox lignite under more stringent SO_2-removal conditions, with limestone addition; and

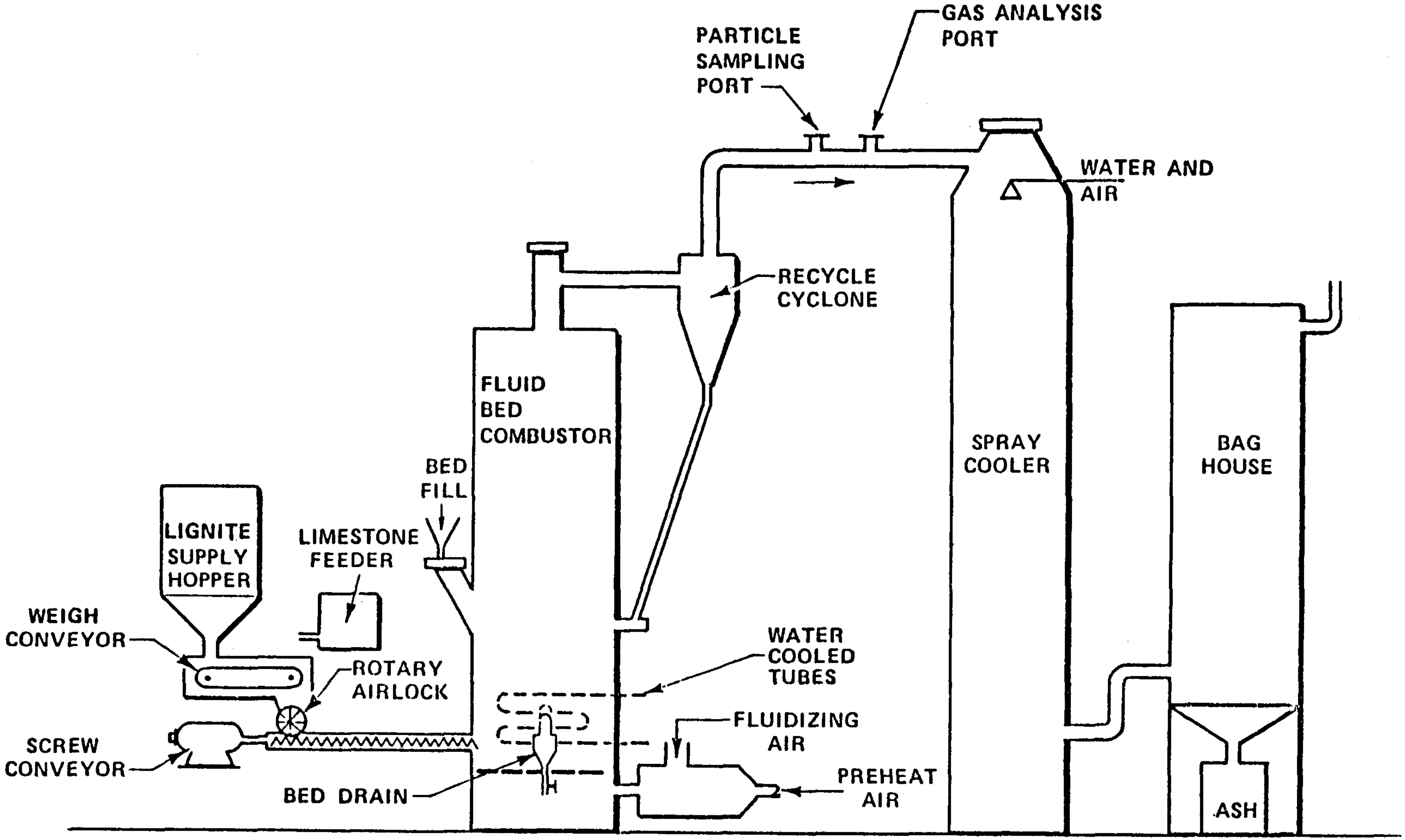
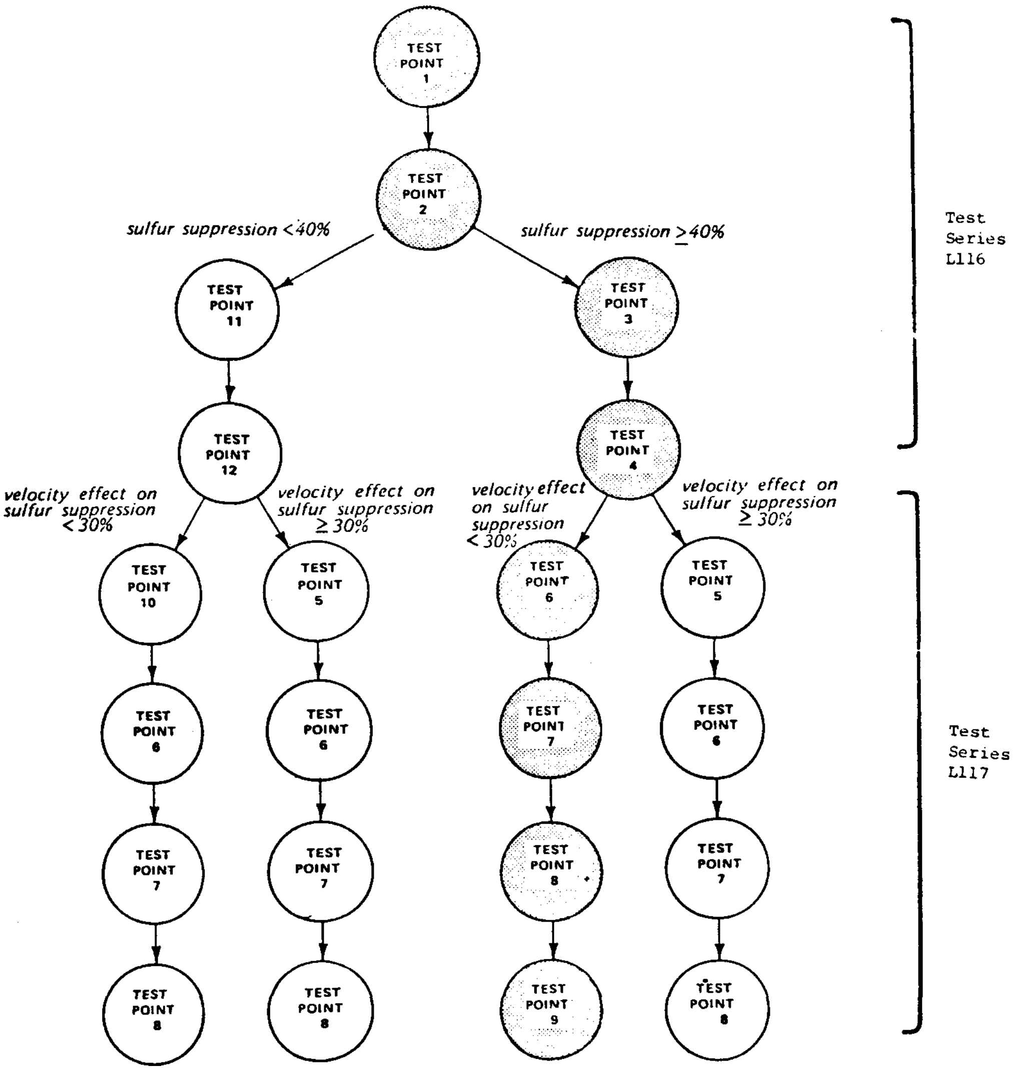


Figure 3-1. Schematic diagram of CTU used for FBC testing of Texas lignites.



NOTE: Shaded tests indicate selected test conditions.

LEGEND:

Test*	Nominal Bed Temperature, °F	Nominal Superficial Velocity, ft/sec	Limestone Addition Rate
1	1500	8	None
2	1400	6	None
3	1500	6	None
4	1600	6	None
5	1500	8	As required for 70 percent SO_2 removal
6	1400	6	As required for 70 percent SO_2 removal
7	1500	6	As required for 70 percent SO_2 removal
8	1500	6	As required for 90 percent SO_2 removal
9	1600	6	As required for 90 percent SO_2 removal
10	1400	6	As required for 50 percent SO_2 removal
11	1500	6	As required for 50 percent SO_2 removal
12	1600	6	As required for 50 percent SO_2 removal

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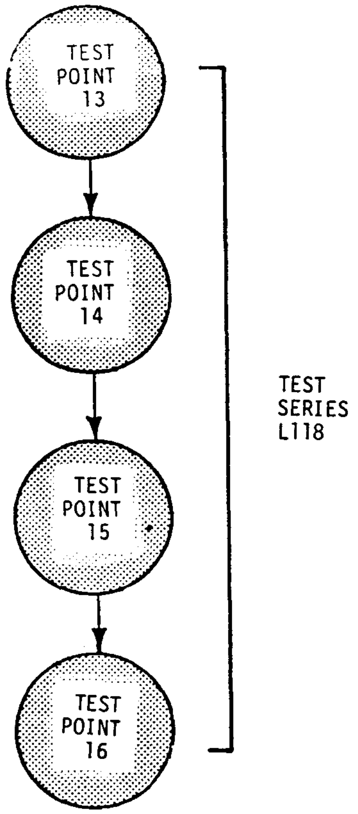
*All tests conducted at nominal excess air conditions of 20 percent.

Figure 3-2. Wilcox lignite decision tree test matrix.



LEGEND:

Test*	Nominal Bed Temperature, °F	Nominal Superficial Velocity, ft/sec	Limestone Addition Rate
13	1400	6	None
14	1400	6	As required for 70 percent SO_2 removal
15	1500	6	As required for 90 percent SO_2 removal
16	1600	6	As required for 90 percent SO_2 removal

*All tests conducted at nominal excess air conditions of 20 percent.

Figure 3-3. Jackson lignite test matrix.

- Test Series L118: Comprised of four nominally 24-hour tests (Nos. 13 through 16) to determine the FBC performance of Jackson lignite under a variety of SO_2-removal conditions, with and without limestone addition.

Each of the tests within the test series was designed to show the effect of a certain parameter on system performance. The parameters that were varied from test to test included bed temperature, superficial velocity, and amount of limestone addition, as shown in Figures 3-2 and 3-3 and discussed in later sections.

The test procedures were designed so that the following functions could be performed:

- determine FBC operating conditions,
- determine performance parameters, and
- quantify and evaluate solid waste streams.

Operating conditions that were determined from measurements made during the FBC testing of the Texas lignites included feed and recycle rates, mean bed temperatures, superficial velocity[1], and alkaline-to-sulfur ratio (defined in this study as the mole ratio of calcium and sodium in the feed lignite plus calcium in the feed limestone to sulfur in the feed lignite). The instrumentation and methods used to measure the data required to determine the operating conditions of the CTU included Dwyer Magnehelic® gauges for pressures and pressure differentials, orifice plates and flowmeters for fluidizing air velocity, chromel-alumel thermocouples for critical system temperatures, and manually controlled feeders for lignite and limestone flows. Approximate recycle rates were determined from EPA Method 5 measurements of particulate loadings to and from the recycle cyclone.

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[1] For convenience, superficial velocity is based on the fraction of the gases which can be measured outside of the combustor; i.e., the feed stream air fraction only, and is defined at temperature and pressure conditions within the bed. The velocity is defined for the total combustor cross-sectional area.

Continuous exhaust gas sampling and analyses were performed using the monitoring system depicted in Figure 3-4. Specific gas analyzers used to determine exhaust gas composition and gaseous air emissions are described in Table 3-1. Gas samples were obtained downstream of the recycle cyclone.

In addition to the gaseous air emissions, other performance parameters that were determined include combustion efficiency and heat transfer characteristics. Combustion efficiency was based on carbon conversion as determined by loss on ignition (LOI) analysis of the solid waste products. Inefficiencies due to conversion of coal carbon to CO and other combustibles in the flue gas were minor and were therefore not included in the determination of combustion efficiency.

Overall heat transfer coefficients were calculated for the horizontal and vertical water-cooled tubes in the bed. These performance parameters, which indicate the heat transfer capability of the system, were calculated as described in Appendix A.

Solid samples were collected to determine overall mass balances, for analysis to determine combustion efficiency and disposal requirements, to determine particulate emission rates from the combustor, and to estimate solid recycle rates. Samples were collected of the bed material, baghouse ash, spray tower deposits, flue gas particulates in the duct between the cyclone and the spray tower, and recycled solids. Particulate collection and measurement were performed using EPA Methods 5 and 17. Solid sample analyses are detailed in Section 4.

3.3 CPC TESTING OF WILCOX AND JACKSON LIGNITES (TEST SERIES L116, L117, AND L118)

FBC testing of the Wilcox lignite was conducted according to the sequence (Test Series L116 and L117) shown in Figure 3-2. In order to cover the water-cooled tubes in the bed, Test #1 was initiated with a starter bed of Grade No. 10-20 Unisil high purity quartz sand. The quartz sand was selected as the initial bed material due to its high purity, thermal stability, proper

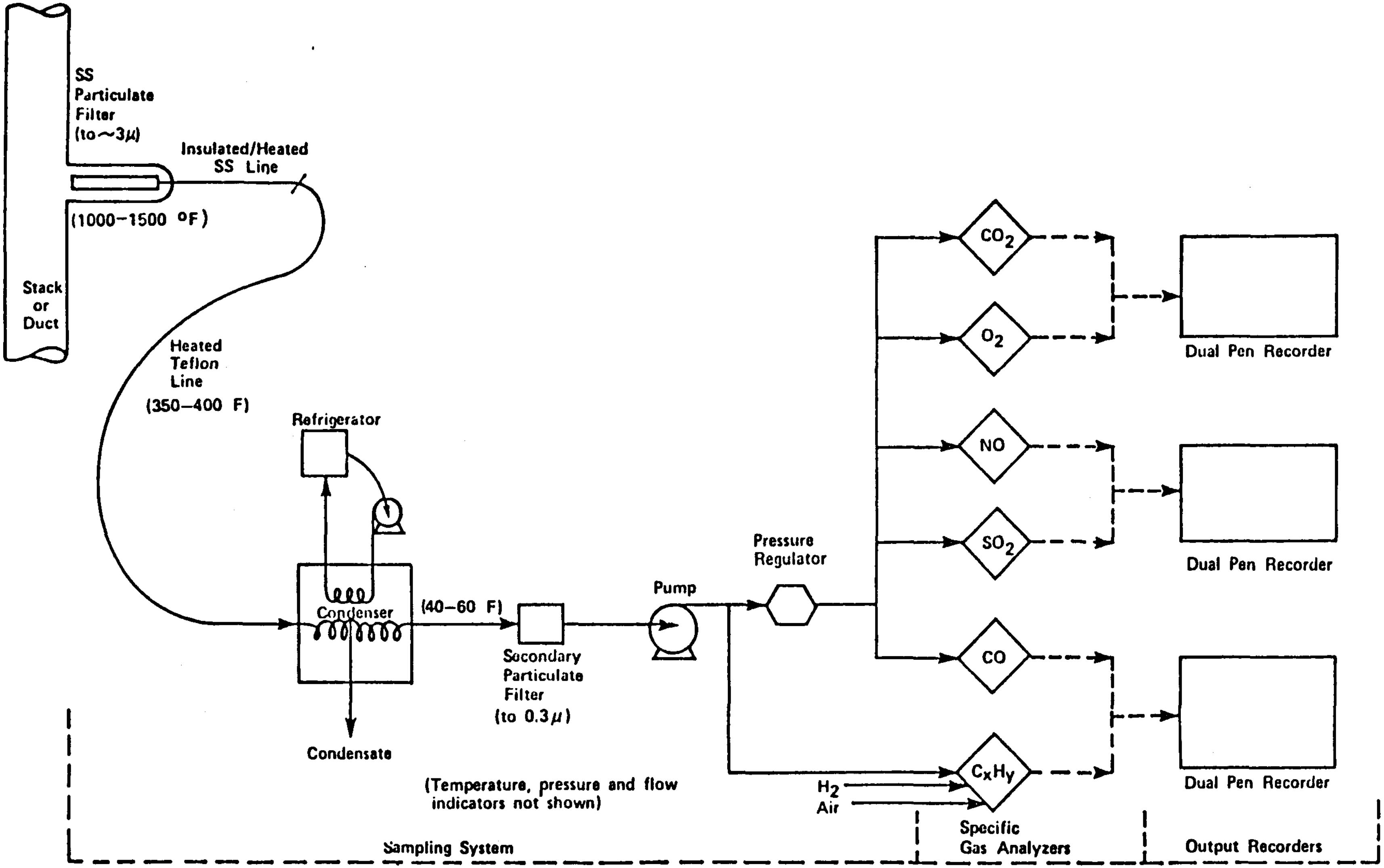

Figure 3-4. CTU gas monitoring system schematic.

Table 3-1

SPECIFIC GAS ANALYZERS UTILIZED IN THE CPC GAS MONITORING SYSTEM

Gas Component	Analyzer Manufacturer & Model	Type of Analyzer	Available Detection Ranges (Vol. Concentration, Dry Basis)[a]	Comments
CO_2	Beckman 864	Non-dispersive infrared	0 to 25%[a]	Non-linear lower concentration range (0.5%-5%) is available.
O_2	Teledyne 346A	Electrochemical	0 to 25% 0 to 10%[a] 0 to 5%	Beckman 715 analyzer available as backup unit (0.5%-5% & 1%-25%).
CO	Anarad 500	Non-dispersive infrared	0 to 500 ppm[a] 0 to 5000 ppm	Beckman 864 analyzer available as backup unit (10-1000 ppm).
SO_2	DuPont 400	UV absorption	0 to 500 ppm 0 to 5000 ppm	SO_3 removed via condenser system.
NO	Thermo Electron 10A	Chemiluminescence	0 to 250 ppm[a] 0 to 1000 ppm	NO_2 typically removed by condenser system. By altering sampling system, analyzer can also detect and measure NO_2 and/or total NO_x.
C_xH_y as CH_4 (Hydrocarbons)	Beckman 400	Flame ionization detector, hydrogen fuel	0 to 100 ppm[a] 0 to 1000 ppm 0 to 10,000 ppm as methane, i.e., CH_4	Detects combustibles up to approximately C_5. Heavier hydrocarbons are removed in the condenser system.

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[a] Indicated ranges are the standard ranges utilized. Other ranges can be utilized with proper calibrations if sufficient planning time is allowed for ordering calibration gases.

Response Times: The response times for the IR, UV, FID, and chemiluminescence type analyzers are less than one second for 90% of full scale, while the electrochemical type (i.e., O_2) is ten seconds for 90% of full scale. With the recorder response times of 0.25 second for 100% of full scale, the total response times are determined by the analyzers. The sampling system has a total internal volume of approximately 0.2 cu ft, resulting in a delay of 30-35 seconds from duct to analyzer. Thus, the total gas monitoring system records the composition in less than 45 seconds after the gas sample is extracted from the duct.

size, low cost, and availability. It has been used in many previous test programs conducted at CPC. All subsequent tests in Test Series L116 and L117 were initiated using the spent bed material from the previous test; i.e., the mixture of ash, sand, and sulfated sorbent (if any) remaining in the bed. At the end of Test #2, Test #3 was selected from the "decision tree" rather than Test #11 because the inherent alkalinity of the lignite ash achieved a sulfur retention level greater than 40 percent. This choice called for testing at sulfur removal levels of 70 to 90 percent, rather than starting at 50 percent removal before increasing removal to 90 percent. Because the effect of superficial velocity on sulfur retention in Test #1 (8 ft/sec) and Test #2 (6 ft/sec) was shown to be minor (e.g., less than 30 percent), Tests #6 through #9 were conducted rather than #5 through #8. That is, Test #5 which called for testing at 8 ft/sec was omitted, and all subsequent tests were conducted at 6 ft/sec to focus on the effects of bed temperature and limestone addition rate on unit performance.

The Jackson lignite was tested according to the test matrix (Test Series L118) shown in Figure 3-3. The four-test schedule, authorized after completion of the Wilcox lignite testing, maximized the amount of useful data obtained by applying the results of the previous Wilcox lignite testing. For example, all Jackson lignite testing was conducted at one superficial velocity (6 ft/sec), and emphasis was placed upon testing the combustor with, rather than without, limestone addition. Test Series L118 was initiated with a starter bed of fresh sand, and subsequent tests in the series were started with the spent bed material from the previous test to parallel the operating conditions of the earlier Wilcox lignite test series.

3.3.1 Raw Materials

The analyses of the Wilcox lignite test batch from the Monticello mine in northeast Texas which was combusted in Test Series L116 and L117 are summarized in Table 3-2. It should be noted that the samples tested were not representative of analyses of typical lignites from the Wilcox group as reported in the literature (3-2, 3-3, 3-4). Compared to reported analyses of Wilcox lignite,

Table 3-2

COMPOSITION OF WILCOX LIGNITE USED IN TEST SERIES L116 AND L117

Sample Identification (CPC#)	Test #1 Composite 81x052	Test #2 Composite 81x053	Test #3 Composite 81x054	Test #4 Composite 81x055	Test #6 Composite 81x116-119	Test #7 Composite 81x120-123	Test #8 Composite 81x124-127	Test #9 Composite 81x108	Mean of All Test Analyses
A. Proximate Analysis, weight % of as-received coal:									
Moisture	29.17	28.98	28.59	29.61	28.64	28.91	28.42	26.86	28.6
Ash	25.88	27.07	27.14	26.80	27.26	26.84	27.08	25.71	26.7
Volatiles	25.96	27.26	24.87	24.56	24.25	24.43	24.76	28.61	25.6
Fixed Carbon[a]	18.99	16.69	19.40	19.03	19.85	19.82	19.74	18.82	19.1
B. Ultimate Analysis, weight % of as-received coal:									
Moisture	29.17	28.98	28.59	29.61	28.64	28.91	28.42	26.86	28.6
C	32.31	31.72	31.91	31.22	31.09	31.46	31.73	33.74	31.9
H	2.50	2.47	2.46	2.46	2.58	2.55	2.54	2.71	2.53
N	0.54	0.57	0.55	0.51	0.39	0.37	0.53	0.50	0.50
Cl	0.03	0.03	0.03	0.02	0.03	0.02	0.02	0.02	0.02
S	0.53	0.53	0.54	0.53	0.57	0.58	0.50	0.53	0.54
Ash	25.88	27.07	27.14	26.80	27.26	26.84	27.08	25.71	26.7
O[a]	9.04	8.63	8.78	8.85	9.44	9.27	9.18	9.83	9.21
C. Heating Value (HHV), Btu/lb of as-received coal:									
	5490	5491	5476	5297	5286	5305	5327	5729	5400
D. Elemental ("Mineral") Analysis of Ash, weight % of dry ash:									
SiO_2	62.89	64.34	64.34	62.88	61.41	60.58	62.50	61.98	62.6
Al_2O_3	19.28	18.93	18.93	19.64	19.34	18.76	19.51	18.40	19.1
TiO_2	1.24	1.50	1.34	1.46	1.18	1.15	1.21	1.22	1.29
Fe_2O_3	2.88	2.88	2.77	3.03	3.01	2.74	3.00	2.55	2.86
CaO	5.52	5.19	5.34	5.46	5.24	4.77	5.05	5.63	5.28
MgO	1.61	1.60	1.56	1.56	1.73	1.68	1.69	1.70	1.64
K_2O	1.06	0.91	0.96	1.01	1.05	1.01	1.03	0.93	1.00
Na_2O	0.42	0.39	0.39	0.34	0.51	0.47	0.43	0.47	0.43
SO_3	4.04	3.79	3.68	4.03	5.10	5.21	4.21	5.05	4.39
Other oxides	0.04	0.04	0.05	0.04	0.27	0.29	0.23	0.35	0.16
Undetermined[a]	1.03	0.43	0.64	0.55	1.16	3.34	1.14	1.72	1.23
E. Forms of Sulfur, weight % of as-received coal:									
Pyritic	-	-	-	-	0.05	-	-	0.03	-
Sulfate	-	-	-	-	0.00	-	-	0.00	-
Organic	-	-	-	-	0.52	-	-	0.50	-

All data from analyses by Commercial Testing and Engineering Company, South Holland, Ill.

[a] By difference; i.e., not determined directly.

the lignite tested here had a lower heating value, a lower sulfur content, and a higher ash content. The higher ash content resulted in more solids within the system, especially within the recycle loop. Because solids cooled in the recycle loop, the reintroduction of large quantities of cooled solids to the bed inventory resulted in greater heat removal rates from the system than planned. Therefore, heat exchange areas used during testing were less than predicted so as to maintain bed temperature, excess air level, and superficial velocity near planned conditions.

Table 3-3 shows analyses and heating values to the Jackson lignite samples from the San Miguel Mine in South Texas, which were combusted in Test Series L118. Similarly to the Wilcox samples, the test batch from San Miguel was not representative of "typical" lignites in the Jackson group reported in the literature (3-2, 3-3, 3-4, 3-5). In contrast to the Wilcox lignite samples, however, the Jackson lignite tested had lower ash and higher sulfur contents than usually reported for Jackson lignites. The lower ash content of the Jackson lignite tested may be due, in part, to the mining techniques used at the San Miguel mine where the lignite was obtained.

An Easi-Miner has recently been used for lignite recovery at San Miguel which tends to reduce ash content by selectively mining lignite seams which are only a few inches thick. The blade on the Easi-Miner is adjustable to a ±1/2 inch accuracy, so with careful staking of the lignite seams, mining of ash material not inherent to the lignite can be avoided.

While more typical lignite compositions would have been preferred for the testing, the data are still useful in predicting atmospheric FBC boiler performance and design requirements. Sensitivity studies are presented in Section 5 to assess the impact of lignite sulfur variability (and SO_2 removal requirements) on design requirements. Additionally, the Jackson lignite tested may be more representative than "typical" analyses previously reported in literature if mining techniques such as the Easi-Miner are widely used.

Table 3-3

COMPOSITION OF JACKSON LIGNITE USED IN TEST SERIES L118

	Sample Identification							
	Test #13 81-222		Test #14 81-223		Test #15 81-224		Test #16 81-225	
Compositions	As Rcv'd	Dry Basis	As Rcv'd	Dry Basis	As Rcv'd	Dry Basis	As Rcv'd	Dry Basis
A. Proximate Analysis, weight % of coal:								
Moisture	30.11	-	30.01	-	29.49	-	29.19	-
Ash	23.24	33.25	22.61	32.30	22.77	32.29	23.62	33.36
Volatiles	28.08	40.18	28.79	41.14	28.42	40.30	28.10	39.69
Fixed Carbon[a]	18.57	26.57	18.59	26.56	19.32	27.41	19.09	26.95
B. Ultimate Analysis, weight % of coal:								
Moisture	30.11	-	30.01	-	29.49	-	29.19	-
C	32.86	47.02	33.36	47.66	33.79	47.92	33.66	47.54
H	2.65	3.76	2.74	3.92	2.74	3.88	2.58	3.65
N	0.40	0.57	0.40	0.57	0.57	0.81	0.55	0.77
Cl	0.06	0.09	0.06	0.09	0.05	0.07	0.05	0.07
S	2.25	3.22	2.27	3.24	2.31	3.27	2.34	3.31
Ash	23.24	33.25	22.61	32.30	22.77	32.29	23.62	33.36
O[a]	8.43	12.06	8.55	12.23	8.28	11.76	8.01	11.30
C. Heating Values (HHV), Btu/lb	5687	8137	5790	8272	5850	8296	5813	8209
D. Elemental (Mineral) Analysis of Ash, weight % dry ash basis								
Major Components		Dry Ash		Dry Ash		Dry Ash		Dry Ash
SiO_2	-	53.82	-	54.10	-	54.33	-	53.19
Al_2O_3	-	18.20	-	18.33	-	18.51	-	18.14
CaO	-	5.52	-	5.89	-	5.95	-	5.85
Fe_2O_3	-	5.13	-	4.76	-	4.40	-	4.72
Minor Components								
MgO	-	0.79	-	0.71	-	1.44	-	0.74
K_2O	-	1.90	-	1.95	-	1.96	-	1.92
Na_2O	-	3.81	-	3.89	-	3.55	-	3.92
TiO_2	-	0.75	-	0.73	-	0.75	-	0.75
Other Oxides	-	0.37	-	0.44	-	0.38	-	0.36
SO_3	-	7.00	-	7.09	-	7.35	-	7.60
Undetermined[a]	-	2.71	-	2.11	-	1.38	-	2.81
E. Forms of Sulfur, weight % of coal:								
Pyritic	-	-	0.53	0.75	-	-	0.44	0.63
Sulfate	-	-	0.17	0.24	-	-	0.18	0.25
Organic	-	-	1.57	2.25	-	-	1.72	2.43

All data from analyses by Commercial Testing & Engineering Company, South Holland, Ill., of composite samples from the feed stream of each of the 4 tests.

[a] By difference, i.e., not determined directly.

Based upon the lignite compositions in Tables 3-2 and 3-3, the as-fired lignites had potential sulfur emissions and inherent alkaline-to-sulfur ratios as shown below:

	Wilcox Lignite	Jackson Lignite
Potential sulfur emissions, lb $SO_2/10^6$ Btu:	1.84-2.16	7.84-8.05
Ca/S molar ratio:	1.26-1.58	0.33-0.34
$(Ca + Na_2)/S$ molar ratio:	1.37-1.68	0.52-0.54

Thus, the two lignites were considerably different in sulfur content and alkaline ash to sulfur ratios.

The limestone used in Test Series L117 and L118 was Linwood limestone from Davenport, Iowa. Its composition is shown in Table 3-4. Basically, the limestone contains 35 to 37 percent calcium (as-received) and less than 1 percent of other alkalis. There are other materials besides $CaCO_3$ in the limestone, probably shales or clays (i.e., the SiO_2, Al_2O_3, and Fe_2O_3 content), which constitute 5 to 8 percent of the as-received limestone, and less than 2 percent dolomite. Ultimate and proximate analyses on the limestone samples indicate that they contain up to 3 percent moisture. If this is indeed the case, then a portion of the loss on ignition (LOI) is attributable to volatilization of moisture rather than loss of CO_2. By material balance, it appears that some of the calcium must be present in a form other than as $CaCO_3$, and consequently may be unavailable for sulfur retention. These other calcium species appear to account for 3 to 8 percent of the total calcium content of the limestone.

The limestone contains a small amount of sulfur, apparently as a sulfate. Very likely the mineral is gypsum ($CaSO_4 \cdot 2H_2O$) which could constitute 1 to 2 percent of the as-received limestone. Thus, it is possible that the limestone contains only 32 to 34 percent available calcium (as-received) for sulfur suppression. However, in all evaluations with alkaline-to-sulfur ratios, it was assumed that:

Table 3-4

COMPOSITION OF LINWOOD LIMESTONE USED IN TEST SERIES L117 AND L118

Sample Identification	from Test #7 (CPC#81x140-144) (CTE#71-67951) As Received Basis	from Test #9 (CPC#81x152-156) (CTE#71-67952) As Received Basis	from Test #14 (CPC#81 x 202) (CTE#71-72778) As Received Basis	from Test #16 (CPC#81 x 204) (CTE#71-72779) As Received Basis
Loss on Ignition (1100°C), weight % of limestone:	40.02%	39.94%	41.40%	41.08%
Elemental ("mineral") Composition, weight % of limestone:				
CaO	52.31%	50.88%	49.5 %	50.0 %
SiO_2	4.26	4.64	4.16	4.55
Al_2O_3	1.17	1.29	1.20	1.22
Fe_2O_3	0.43	0.55	0.52	0.39
MgO	0.40	0.38	0.39	0.50
K_2O	0.18	0.21	0.19	0.21
Na_2O	0.08	0.05	0.09	0.09
Other oxides	0.21	0.25	0.21	0.28
Undetermined	0.48	1.24	1.75	1.10
SO_3	0.46	0.56	1.08	0.67
	100 %	100 %	100 %	100 %

- all of the Ca in the limestone is available for sulfur suppression;
- the limestone contains no reactive S or Na;
- all of the Ca, Na, and S in the lignite are available for reaction; and
- no K or Mg are involved in the sulfur suppression reactions; i.e., only Ca and Na are involved.

It is obvious that the assumptions are not completely correct, especially for sulfates in both the lignites and limestone (which do not emit sulfur at typical FBC conditions and usually exist as $CaSO_4$), but the above general relations were used to simplify calculations and should have a negligible impact on data evaluation conducted in this study.

Size fractions of the lignites, limestone, and sand (starter bed material) used in Test Series L116, L117, and L118 are shown in Table 3-5.

3.3.2 Testing

The tests were planned for 24 hours duration each. During each of the tests in a series, the feed rates of the lignite and limestone were controlled manually with typically a constant air flow rate. The lignite feed rates were adjusted to control bed temperatures while the limestone rate usually remained at a constant setting. (Adjustment of the bed temperature by controlling water flow rates within the tubes typically has a very minor effect and was not used.) Thus, the ratio of calcium added as sorbent to sulfur in the lignite was not always constant throughout a test period. And, with the large mass of solids within the bed and recycle loop, it is not likely that steady-state conditions with respect to the bed composition were achieved during the 24-hour test period. Previous tests at CPC have indicated that the time to achieve steady-state bed composition may be as long as 100 to 200 hours, depending on the ash level in the fuel, fraction of large material in the "ash" (e.g., rocks, foreign material, etc.), and the test conditions. However, gas compositions have been observed to respond relatively quickly to process and

Table 3-5

NOMINAL SIZE FRACTION OF TEST MATERIALS

		Weight % Retained			
		Crushed Lignite			
U.S. Mesh No.	Sieve Opening, mm or µm	Wilcox	Jackson	Limestone (As Received)	Unisil Sand (Nominal Size)
1/4"	6.3 mm	8%	2%	0%	-
7 M	2.8	22	20	7	-
12	1.70	-	-	-	0%
14	1.40	19	25	28	-
16	1.18	-	-	-	10
20	850µm	-	-	-	80
24	710	-	19	-	-
30	600	19	-	26	10
35	500	-	7	-	-
60	250	14	-	17	0
70	212	-	12	-	-
120	125	8	-	8	-
Pan		11	15	13	-
TOTAL*		101%	100%	99%	100%

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*Total may not be 100% due to rounding error.

feed changes and approach stable "steady-state" values within a few hours. It is unlikely that the solids within the bed and recycled fines had achieved constant composition; i.e., had reached steady-state conditions with the gases, in the 24-hour periods planned for each test condition. However, periods of relatively stable operation at the test conditions were designated as "steady-state" for each test. Mean values used in data evaluation are based upon the selected "steady-state" periods. These "steady-state" periods are based primarily on relatively stable bed temperature, O_2 and SO_2 content of the flue gases, and recycle temperatures, within the limits of measurement errors and variation of coal feed quality.

The selected "steady-state" periods were quite short (typically only 2 to 4 hours) except for the final test (#16), which was stable for more than 10 hours. Due to erratic velocity-related operations early in Test #1 and recycle malfunctions in Test #7, the operating-at-conditions periods were quite short (only 3 to 7 hours) for these two tests. Also, the test period was inadequate to reach stable operating conditions when limestone was first added to the bed in Test #6. Consequently, no selection of "steady-state" periods could be made for Tests #1, #6, and #7. Thus, mean data from Tests #1, #6, and #7 were not included in the final results.

Results of Test Series L116, L117, and L118, expressed as mean values, are presented in Table 3-6. Included in these results are those associated with:

- operating conditions (feed rates, temperatures, recycle rates, etc.);
- performance parameters (gaseous air emissions, combustion efficiency, heat transfer coefficients, etc.); and
- solid waste streams (bed drain rate, particulate emission rate, etc.)

Operating Conditions. The actual test conditions accomplished during each test were reasonably close to the conditions specified in the test matrix

Table 3-6

SUMMARY OF MEAN TEST DATA AND RESULTS FOR SELECTED STEADY-STATE PERIODS (CPC Testing of Wilcox and Jackson Lignites)

Series	L116 (Wilcox)[a]			L117 (Wilcox)[a]		L118 (Jackson)			
Test #	2	3	4	8	9	13	14	15	16
Total Test ET's, Min.	2100-3500	3550-4890	5020-6340	3870-4720 &4940-5280	5400-6600	0570-1420 &1500-2070	2380-3640	3830-4790 &4940-5300	5310-6720
(Total Test Duration, Hrs.)	(23.3)	(22.3)	(22.0)	(19.8)	(20.0)	(23.7)	(21.0)	(22.0)	(23.5)
Steady-State ET's, Min.	3300-3500	4200-4350	5750-6000	4300-4400 &5150-5250	6400-6600	1100-1200	3450-3600	5150-5300	6000-6700
(Steady-State Duration, Hrs.)	(3.3)	(2.5)	(4.2)	(3.3)	(3.3)	(1.7)	(2.5)	(2.5)	(11.7)
A. **Feed Streams:**									
Lignite rate, lb/min	12.8	12.2	12.0	10.6	10.7	10.3	10.2	10.0	9.8
Limestone rate, lb/min	-	-	-	0.91	0.90	-	2.1	1.8	1.10
($Ca+Na_2$)/S, molar									
Inherent	1.61	1.65	1.67	1.68	1.68	0.53	0.54	0.52	0.54
Added	-	-	-	5.06	4.61	-	2.57	2.23	1.37
Total	1.61	1.65	1.67	6.74	6.29	0.53	3.10	2.74	1.91
Air rate, scfm	760	690	700	700	660	720	700	660	650
B. **Fluid Bed Combustor:**									
Bed Temperature, °F	1395	1533	1640	1526	1610	1414	1458	1546	1533
Freeboard Temp., °F	1403	1538	1646	1533	1618	1432	1471	1555	1545
Excess Air,[b] %	20.6	20.6	19.9	19.9	19.3	∿22	19.9	18.7	19.3
Superficial Velocity (air fraction), ft/sec	6.3	6.2	6.6	6.1	6.0	6.0	6.1	6.0	5.9
Recycle rate, lb/lb feed ash	∿200	∿140	∿220	N.D.	∿140	∿90	∿60	∿50	∿60
Heat Transfer Coef., Btu/hr ft^2 °F									
HX#1 (horiz.)	52.7	50.1	52.8	48.5	48.2	∿48	52.9	∿47	54.6
HX#2	63.6	63.1	0	65.4	-	-	-	-	-
HX#4 (horiz.)	47.3	47.8	51.0	52.2	52.6	∿54	59.2	∿54	61.9
HX#5	-	-	-	-	-	∿50	-	-	-
HX#6	61.5	-	-	-	-	68.5	73.8	-	-
C. **Solids and Gas Emissions:**									
Bed Drain, lb/hr	∿28	∿5	∿18	∿32	∿24	27	129	106	84
Particulate Emissions, lb/hr (gr/sdcf)	176 (27)	150 (28)	165 (24)	∿160 (23)	∿170 (27)	118 (17)	137 (22)	163 (27)	109 (18)
Exhaust Gases, (dry)									
O_2, %	3.6	3.5	3.5	3.4	3.4	3.8	3.6	3.5	3.5
CO_2, %	15.3	15.0	15.5	15.0	15.5	14.7	15.4	15.9	15.5
CO, ppm(v)	360	85	50	65	50	570	190	80	75
C_xH_y, ppm(v)	11	2	1	1	1	13	2	1	2
NO, ppm(v)	120	120	140	110	140	65	80	100	100
SO_2, ppm(v)	520	700	820	15	100	2970	400	370	810
Moisture in Gases, %	19.4	16.4	16.1	∿14	∿14	12.2	14.0	14.4	15.6
NO_x Emission[b], lb/10^6 Btu	0.17	0.18	0.20	0.17	0.20	0.10	0.11	0.14	0.14
SO_2 Emission[b], lb/10^6 Btu	1.1	1.4	1.7	0.03	0.20	6.2	0.83	0.74	1.6
Sulfur Retention[b], %	45.8	26.4	16.8	98.3	89.0	21.5	89.8	90.9	80.0
Combustion Efficiency[b], %	98.3	99.3	99.6	97.3	97.6	96.1	96.6	97.7	97.8

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[a] Data for Tests #1, #6, and #7 not included due to a lack of stable conditions.

N.D. = Not Determined.

[b] Per Equations (1a), (3a), (4), (5), and (6), respectively. See Appendix A, Section A.3.

NOTE: The approximate sign (∿) indicates a value of lower precision for the selected steady-state periods due to the lower quality of the measurement (usually a mean value over a longer period of time), the measurement being conducted at a time near to but outside the selected period, or, in a few cases, to changing values of the particular parameter during the selected period; i.e., not completely stable.

except for Test #7 (which experienced a recycle malfunction) and Test #16. Test #16 conditions were modified after the series was in progress because of concern for possible bed agglomeration at higher temperatures (i.e., above 1650°F) which could have resulted from the combination of limited available heat exchange surface and the high ash recycle rate conditions of the test.

In general, the manually controlled combustor operated smoothly. The system downtimes during the test series were less than 5 percent of total operating time and were principally due to high exhaust particulate loadings and high recycle rates resulting, in part, from the high ash content of the Texas lignites. The high particulate emission rates resulted in significant deposition of ash within the spray cooler. These deposits collapsed periodically and restricted the exhaust gas flow. Also the high recycle rates caused erosion of the recycle cyclone, which required periodic repairs.

During the test runs, certain operating parameters were monitored and recorded continuously. These parameters included bed and freeboard temperatures, superficial velocity, excess air level, and lignite feed rate. An example of the results of this continuous monitoring system is illustrated in Figure 3-5, which is for Test #3.

The excess air levels and superficial velocities were maintained within the desired ranges of 20±5 percent and 6±0.5 ft/sec, respectively, for the individual tests (except for Test #1, in which the velocity was planned and maintained at 8±0.5 ft/sec). For convenience, the superficial velocities were defined as the velocities of the feed air fraction of the combustion gases only, since it can be measured externally from the combustor. The <u>total</u> gas velocities from all feedstream components, including lignite combustion, moisture evaporation, and limestone calcination, were typically in the 7 to 8 ft/sec range on a superficial basis; i.e., calculated as though the bed contained only gases and no solids.

Based upon the mean values for the selected steady-state test periods, the bed temperatures were consistently above the planned values except for Test #2.

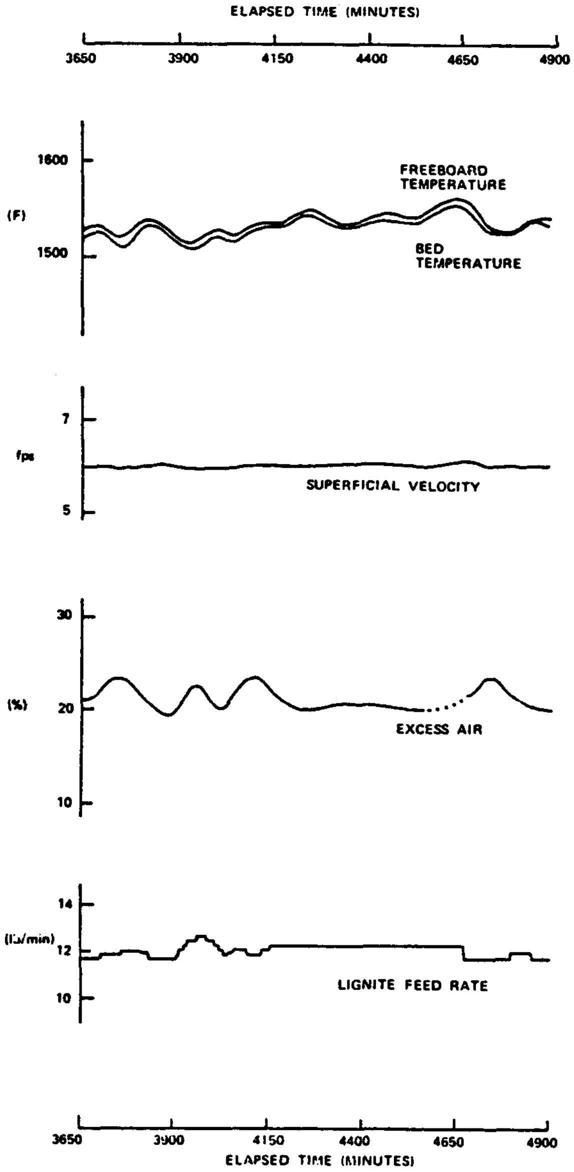

Figure 3-5. Elapsed time histories of Test #3 data--operating parameters.

Apparently, little afterburning occurred in the freeboard, as indicated by freeboard temperatures typically within 10°F of the bed temperatures for all tests.

At the operating velocities of the test series, the high ash contents and the apparently fine size of the ash/mineral matter in both lignites resulted in high recycle rates of solids within the combustor-cyclone loop. The recycle rates were much higher than rates experienced previously at CPC such as during tests with Beulah lignite from North Dakota. As shown in the summary of recycle rates in Table 3-7, the recycled solids were being circulated at rates 120 to 220 and 50 to 90 times the feed rate of ash in the lignite and limestone feed streams for the Wilcox and Jackson lignite tests, respectively. Expressed in an alternate manner, the recycle rates were 170 to 260 and 60 to 110 times the rates of particulates in the cyclone exhaust for the Wilcox and Jackson lignites, respectively. Apparently, the Wilcox lignite contained ash/mineral matter of a size range more readily elutriated and captured by the recycle cyclone at the selected test conditions.

Recycle generally improves combustion efficiency and sulfur capture by recirculating unburned char and unreacted sorbent particles back to the combustor for further reaction. High recycle rates are indicative of a "dust storm" in the freeboard which increases the contact of gases and solids and promotes good combustion efficiency and sorbent utilization in the freeboard. However, the extremely high recycle rates experienced in the Texas lignite tests are believed to have caused accelerated cyclone erosion. Erosion of heat exchange surface would also be of concern in a commercial facility. Recycle rates using lignites with these ash properties could be lowered by utilizing cyclones with lower collection efficiencies or could be controlled by purging small amounts of solids from the recycle loop.

Performance Parameters. In addition to certain operating parameters discussed previously, flue gas composition (O_2, CO_2, SO_2, NO, CO, and CH_x) was continuously monitored and recorded during the test runs, as shown by the example in Figure 3-6.

Table 3-7

APPARENT RECYCLE RATES

Test	Sampling Time (ET), Minutes Inlet/Outlet	Elutriated Fines Recycle Rate[a]			Ranking[b]	Comments
		lb/min	lb/lb Feed "Ash"[c]	Ratio of Inlet/Outlet Loading		
L116, Wilcox						
Lignite:						
1	1843/1883	520	120	170	High	System not at stable operating conditions
2	2848/3314[d]	680	200	220	High	
3	4336/4207	460	140	180	High	
4	5944/5880	700	220	260	High	
L117, Wilcox with						
Limestone:						
6	1579/1826	560	150	240	High	System not at stable operating conditions
7a	-	-	-	-		
7b	3182/3092	50	15	20	Moderate	System not at stable operating conditions
7c	3858/3818	300	100	90	Moderate	
8	-	-	-	-		Not determined
9	5892/5807[d]	470	140	170	High	
L118, Jackson						
Lignite:						
13	2035/1996[d]	210	90	110	High	
With Limestone:						
14	3503/3404[d]	210	60	90	Moderate	
15	5227/5189	160	50	60	Moderate	
16	6600/6560	190	60	110	High	

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[a] All data are based on EPA-5 particulate loading measurements at the "inlet" (i.e., within the recycle loop) and "outlet" (i.e., exhaust from recycle cyclone) positions. Due to the configuration, turbulent flow, short sampling times, and high loadings, the inlet data are questionable--in fact, may be invalid--and should be considered as an indication of the values only (rather than being numerically precise). Unreliable inlet gas flow rates were corrected to outlet gas stream mass flow conditions.

[b]

Ratio of inlet-to-outlet loadings:	Near 1	1-10	10-100	Above 100
Recycle Condition:	No recycle	"Low"	"Moderate"	"High"

[c] Feed ash includes ASTM ash of lignite feedstream, which includes some sulfate as SO_3, and LOI residual of limestone (typically 60% of raw limestone).

[d] Sampling period was outside "steady-state" period identified after completion of testing.

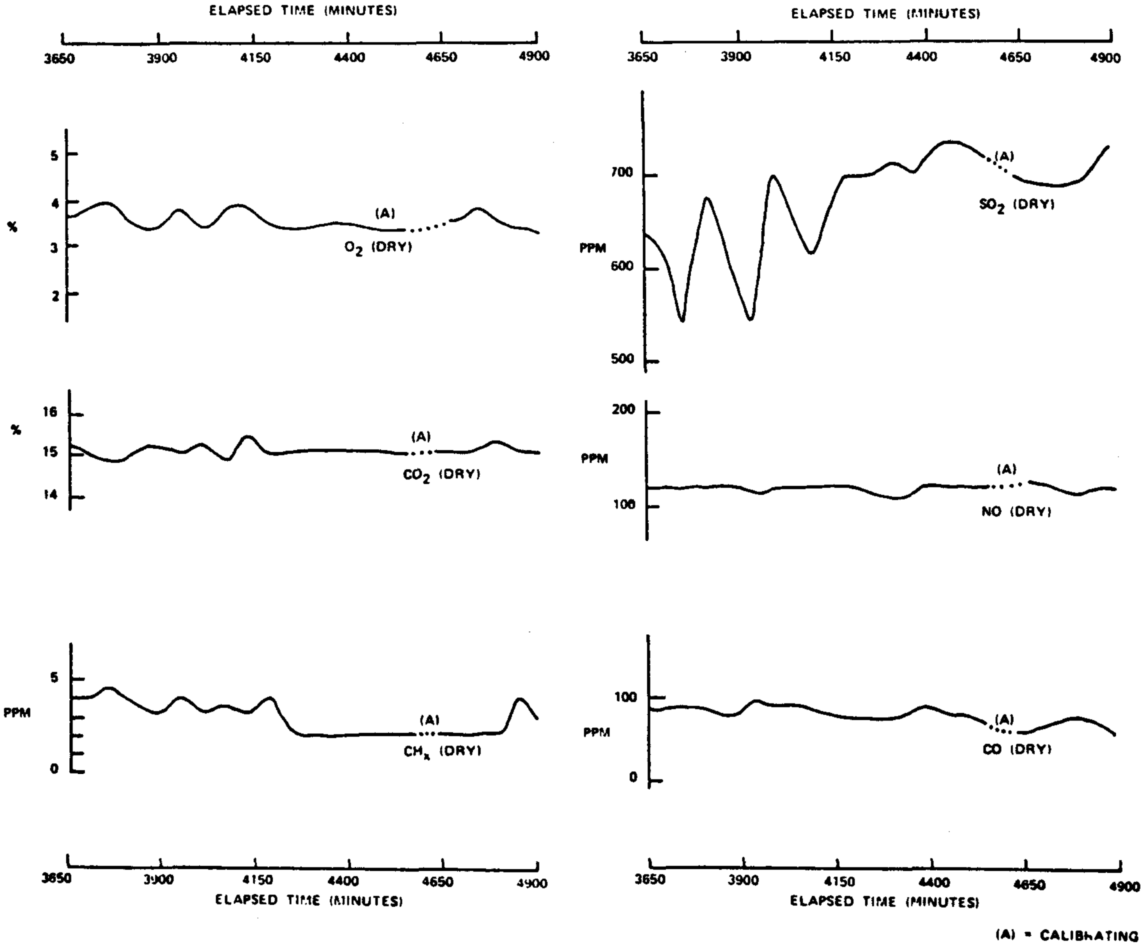
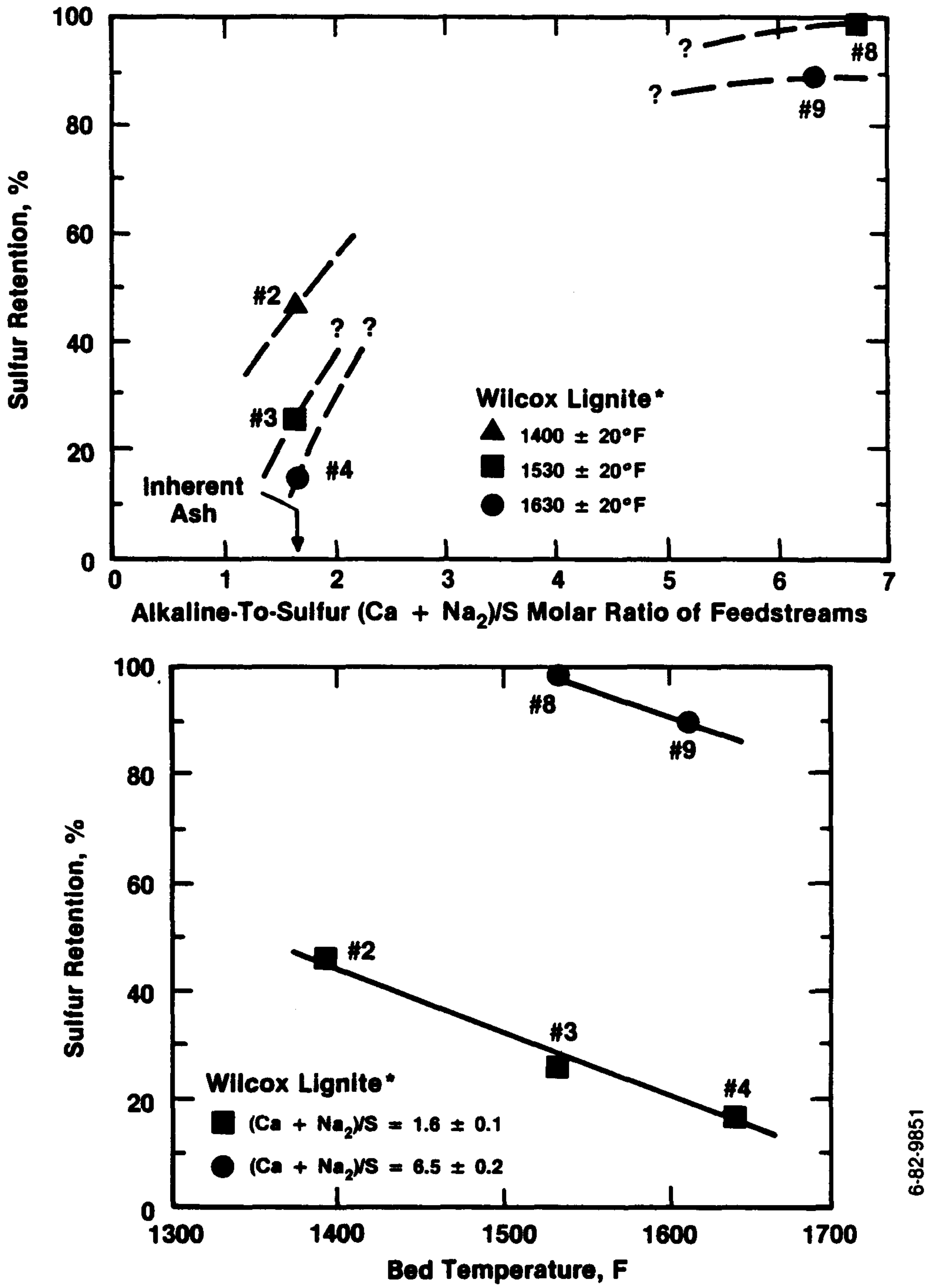


Figure 3-6. Elapsed time histories of Test #3 gas emission data.

Sulfur retention by the inherent alkalinity of the Wilcox lignite ash was generally below 50 percent, as determined by the tests comprising Test Series L116. In fact, sulfur retention was reduced from 46 to 17 percent, corresponding to SO_2 emissions of 1.1 and 1.7 lb $SO_2/10^6$ Btu, respectively, as bed temperature was increased from 1400 to 1640°F. These results are illustrated in Figure 3-7. Results of Test #1 are now shown in Figure 3-7 because of the short test duration and failure to reach stable operation.

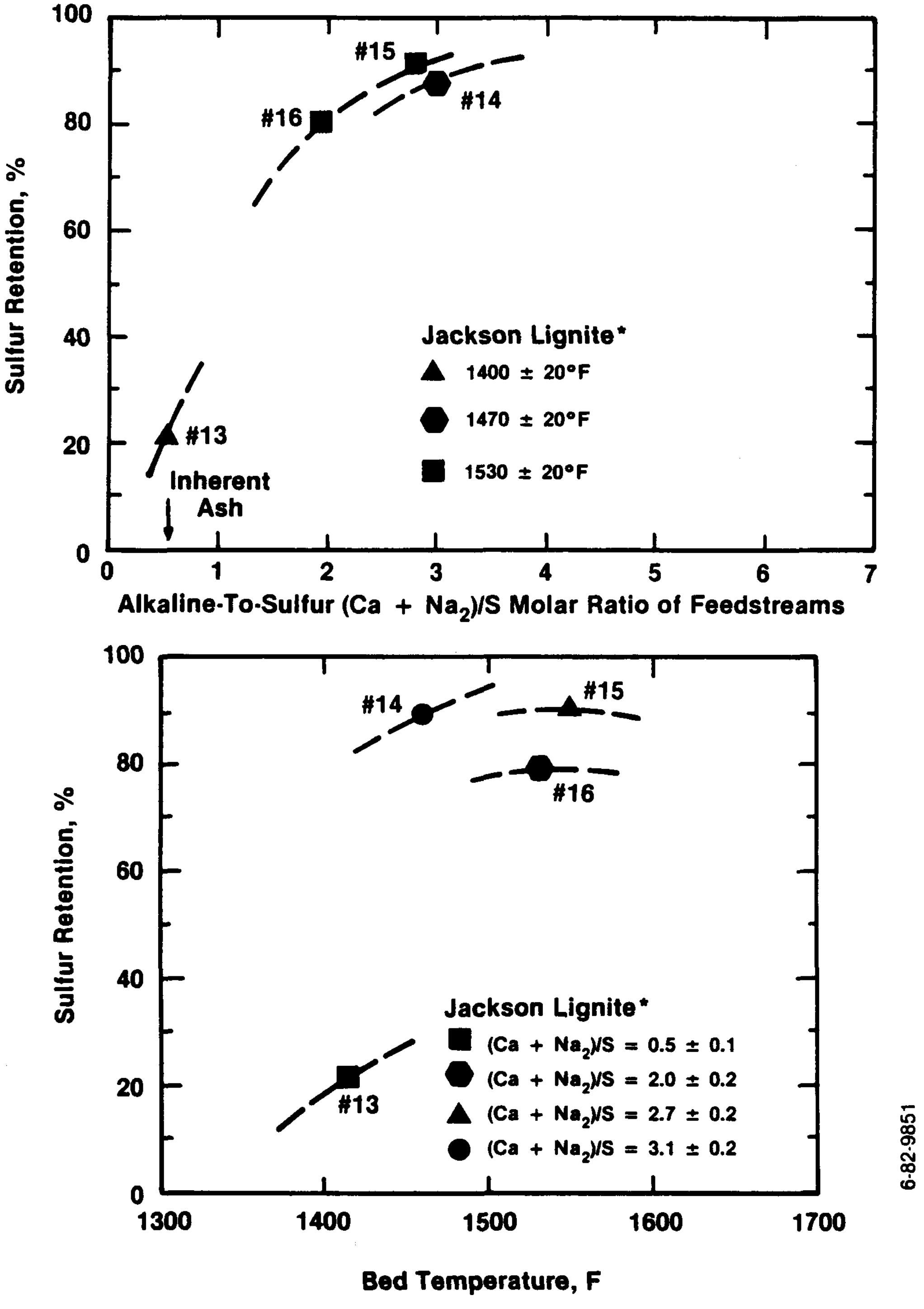
During Test Series L117; i.e., Wilcox lignite testing with limestone addition, emissions of SO_2 were reduced by more than 90 percent at total (inherent plus added) alkaline-to-sulfur ratios of six and greater, as shown in Figure 3-7. Test #7 results are not shown because of the severe operating upsets that invalidated much of the data. Test #6 results are also not shown since the stable operating periods could not be sustained and it appears from the inorganic solids balance that the system was still in transition. Since Test #6 was the first test in the series with limestone addition, it is likely that the bed compositions were still increasing in calcium and retained sulfur during the entire duration of the test. The SO_2 emissions (see page A-15 in Appendix A) were changing during the test.

Testing of Jackson lignite without limestone addition in Test Series L118 resulted in considerably higher SO_2 emissions (6.2 lb $SO_2/10^6$ Btu at 1400°F) than for the Wilcox lignite, due to the Jackson lignite's higher sulfur content (2.3 vs. 0.5 percent) and correspondingly lower inherent molar alkaline-to-sulfur ratio (0.5 vs. 1.7). However, addition of limestone to the Jackson lignite-fired combustor resulted in sulfur retentions exceeding 90 percent at total alkaline-to-sulfur ratios of only three as shown in Figure 3-8. The apparent better utilization of sorbent during the Jackson lignite tests could be due to several factors including: 1) the higher Na_2/S ratios (nominally 0.2 compared to approximately 0.1 for the Wilcox lignite), and 2) the forms of sulfur (25 to 30 percent as pyritic and sulfate sulfur compared to less than 10 percent for Wilcox lignite). In addition, sulfur retention appears to be maximized at higher bed temperatures (1550 vs. 1400°F) than in the



*(All Data at 20 ± 2% Excess Air, 6.1 ± 0.2 FPS Superficial Velocity (Air Fraction), and 180 ± 40 lb Recycled Fines Per lb of Feed "Ash"). Numbers Identify Data Points By Test.

Figure 3-7. Sulfur retention of Wilcox lignite as a function of bed temperature and alkaline-to-sulfur ratio for selected steady-state periods in Test Series L116 and L117.



*(All Data at 20 ± 2% Excess Air, 6.0 ± 0.2 FPS Superficial Velocity (Air Fraction) and 70 ± 20 lb Recycled Fines Per lb Feed "Ash"). Numbers Identify Data Points By Test.

Figure 3-8. Sulfur retention of Jackson lignite as a function of bed temperature and alkaline-to-sulfur ratio for selected steady-state periods in Test Series L118.

Wilcox lignite tests. This maximum is observed when the CPC data is compared with the GFETC data, as is shown in Section 3.4, and cannot be directly observed from the test results presented in Figure 3-8.

From the limited test data, therefore, combustion with the Jackson lignite appeared to require lower alkaline-to-sulfur ratios to achieve equivalent percent sulfur retention levels than with the Wilcox lignite. However, since the Jackson lignite contained more sulfur, SO_2 emission levels on a $lb/10^6$ Btu basis at equivalent alkaline-to-sulfur ratios were equivalent or slightly higher. Conclusions about alkaline-to-sulfur effects upon sulfur control should be tempered by the knowledge that 1) the bed and recycle compositions may not have reached steady-state conditions, especially for the initial tests of each series, 2) potential sulfur retention capabilities of potassium, also an alkaline component of the lignite ash, were not included in the evaluations, and 3) the availability of the alkaline species in the lignite ash for participation in sulfur capture reactions may be different for each lignite tested. An additional consideration in comparing the effects of alkaline-to-sulfur ratio on sulfur retention for the two lignites is the differences in the form of the sulfur contained in each lignite. That is, the Jackson lignites contained nearly one-fourth of their sulfur in a pyritic form (as an iron compound), while the Wilcox lignite had nearly all of its sulfur present in an organic form. The effects of lignite sulfur form on alkaline requirements for sulfur retention are not known. However, it is speculated that sulfur from the solid pyrite is released during the combustion process much more slowly than organic sulfur and, therefore, may experience better contact with the solid sorbent particles in the bed.

To complete the evaluations of sulfur emissions, selected measurements of SO_3/H_2SO_4 concentrations in the exhaust gas stream were made via the EPA Method 8 extract-and-titrate procedure. The SO_2 values determined by the same procedure agreed reasonably well with the continuous SO_2 monitor values (except in the sample for Test #16). The determinations are summarized below:

Test	Lignite Type	Elapsed Time, Minutes	SO_2 by Monitor ppm (dry)	SO_2 by EPA 8, ppm (dry)	SO_3 by EPA 8, ppm (dry)
4	Wilcox	6320-6340[a]	675±25	690	93
8	Wilcox	5018-5078[a]	40±35[b]	50	2
9	Wilcox	6465-6525	75±30[b]	87	2
14	Jackson	3318-3348[a]	360	290	43
16	Jackson	6429-6459	850[b]	550	37

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[a] Sampling was outside steady-state period identified after completion of testing.

[b] Monitored SO_2 emissions were not stable during the sampling period.

The sulfur distributions for the above tests are summarized below:

		Weight Fraction of Product Sulfur,			
Test	Lignite Type	In Bed Drain	Sulfate in Particulates Upstream of Bag Filter	SO_2 in Gases	SO_3 in Gases
4	Wilcox	0.9	7.6	81.4	10.9
8	Wilcox	5.4	87.7	6.7	0.3
9	Wilcox	2.8	86.1	10.7	0.3
14	Jackson	~65	~26	~8	~1
16	Jackson	~67	~17	~15	~1

From these results, the sulfur output from the system accounted for 95 to 97 percent of the sulfur fed into the system for the first three tests; the sulfur balance had to be estimated from the particulate and gas compositions for the last two tests since the actual sulfur content of the bed was not determined. SO_3 emissions were significant only in low alkaline-to-sulfur feed tests (i.e., those with inherent ash suppression only, such as Test #4). For tests with high calcium addition, the SO_3/H_2SO_4 emissions were low, typically below one percent of the total sulfur accounted for.

One important difference between the tests of the two lignites is evident in the sulfur distributions shown above. In Tests #8 and #9, with the Wilcox lignite and limestone added, most of the sulfur retained is found in the bag filter catch. In contrast for Tests #14 and #16, with the Jackson lignite and limestone added, the majority of the sulfur is retained in the bed. Since the L117 (Wilcox lignite) and L118 (Jackson lignite) series were conducted with essentially the same velocities, excess air levels, and type of limestone (although at different lignite-feed-to-limestone-feed ratios), the differences in the distribution of the sulfur retained may be due to the forms of sulfur present in the two lignites, the forms and sizes of the alkaline ash components, and/or to the amounts of alkalis in the lignites relative to the limestone calcium. Of these, the differences in forms of the sulfur present in the two lignites was significant. Pyritic sulfur is anticipated to be released much more slowly on combustion than is organic sulfur. The Jackson lignite, which contains up to one-fourth of its total sulfur concentration in a pyritic form, was observed to retain much more sulfur in the bed. Another major consideration is the high sodium content of the Jackson lignite ash. Sodium has been observed to accumulate in the bed during AFBC test series with North Dakota lignites. The retention of sulfur in the bed during the Jackson lignite runs may in part be caused by a buildup of sodium and subsequent sulfur retention during the nonsteady-state 24-hour tests.

As shown in Table 3-6, emissions of NO increased with bed temperature in testing of the Wilcox and Jackson lignites, ranging from approximately 70 ppm (dry) at 1400°F to 140 ppm at 1600°F. The nitrogen in the gaseous NO emissions typically represented only 4-5 percent of the nitrogen in the feed lignite.

Although NO_2 concentrations were not measured, it is common practice to report all NO_x emissions ($NO + NO_2$) as an equivalent amount of NO_2. It is assumed, based on previous coal combustion experience, that the actual NO_2 content of the flue gas is less than 10 percent of the total NO_x. However, if the NO concentrations measured for the test steady-state periods are assumed to be all of the NO_x present, when expressed as an equivalent amount of NO_2 (i.e., via equation [3a] in Appendix A), the NO_x emissions for all tests were below 0.20 lb $NO_2/10^6$ Btu. The NO_x emissions at the lower temperatures of 1400°F were as low as 0.17 $lb/10^6$ Btu for the Wilcox lignite test without limestone and 0.10 $lb/10^6$ Btu for the equivalent Jackson lignite test. These results are shown in the steady-state summaries of Table 3-6 which summarize both measured NO concentrations in ppm and NO_x emissions in $lb/10^6$ Btu (as NO_2). It is significant to note that the values reported are well below the current New Source Performance Standards for NO_x emissions from lignite-fired utility boilers of 0.6 $lb/10^6$ Btu.

Emissions of CO and other combustible gases decreased with increasing bed temperature in all three test series. CO emissions were reduced from 360 and 570 ppm (dry) at 1400°F to 50 ppm at 1600°F. The Jackson lignite tests generally resulted in moderately higher CO levels than the Wilcox lignite tests. Over the same bed temperature increase described above, emissions of other combustible gases (CxHy, expressed as CH_4 equivalent) were reduced from greater than 10 to nominally one ppm.

Combustion efficiencies, based on carbon conversion as determined from LOI analysis of the solid waste streams, ranged from 96.1 to 99.6 percent. These results are shown in Table 3-6. The Jackson lignite combustion tests were characterized by somewhat lower efficiencies than the Wilcox lignite tests.

Heat was removed from the bed by the water-cooled tubes to maintain the desired bed temperature at specified superficial velocity and excess air conditions for all tests. However, the higher than expected ash contents and the resulting high recycle rates resulted in greater heat losses than projected prior to testing. Consequently, less heat exchange area than anticipated was utilized to achieve each test condition. The water-cooled heat removal system operated reasonably well, except for one specific heat exchanger. This heat exchanger, #5, was utilized in Tests #6 and #13. Its erratic behavior was apparently due to fouling and problems with the water flow control valve and meter. Except for shutdown periods and during recycle malfunctions in Test #7, the overall heat transfer coefficients were relatively stable for the individual heat exchanger tubes. Heat transfer coefficients are shown for each test in Figures 3-9, 3-10, and 3-11.

The mean heat transfer coefficients for the water cooled tubes in the bed were in the range of 45 to 61 Btu/hr-ft^2-°F for the horizontal tubes and in the range of 58 to 74 Btu/hr-ft^2-°F for the vertical tubes, increasing with bed temperature for each test series. The tube orientation phenomena of higher heat transfer coefficients for vertical tubes have been observed in previous tests at the CPC facility, although the causes for the differences have not been explained. Since the defined overall heat transfer coefficient includes all measurement errors, assumptions, and secondary effects (e.g., scaling on the water side) the differences could be due to errors in measurements or fallacies in assumptions. Checks of the heat exchanger tubes for scaling and flow meters for error after the test series indicated no obvious problems. However, the differences resulting from tube orientation are reproducible and appear to be real. Possible explanations are that they could be due to gas bubbles in the bed, to the degree of local fluidization, or to differences in local particle size and location of the tubes in the bed.

Solid Waste Streams. Solid waste streams were sampled and measured during the FBC testing of the two lignites. Solid waste flow rates discharged from the bed drain, the spray cooler, and the baghouse drain are listed in Table 3-8.

The larger sized particles from the sorbent and ash/mineral matter in the lignites accumulated within the bed and were drained periodically from the combustor to maintain a relatively constant bed height of approximately 4 feet, which was indicated by the bed pressure drop. As shown in Table 3-8, the mean bed drain rates for the total test periods were 5 to 50 lb/hr (which ranged from 3 to 19 percent of the total solids produced) for the Wilcox lignite tests. The higher bed drain rates for the Jackson lignite tests (22 to 110 lb/hr) were consistent with the differences in recycle rate.

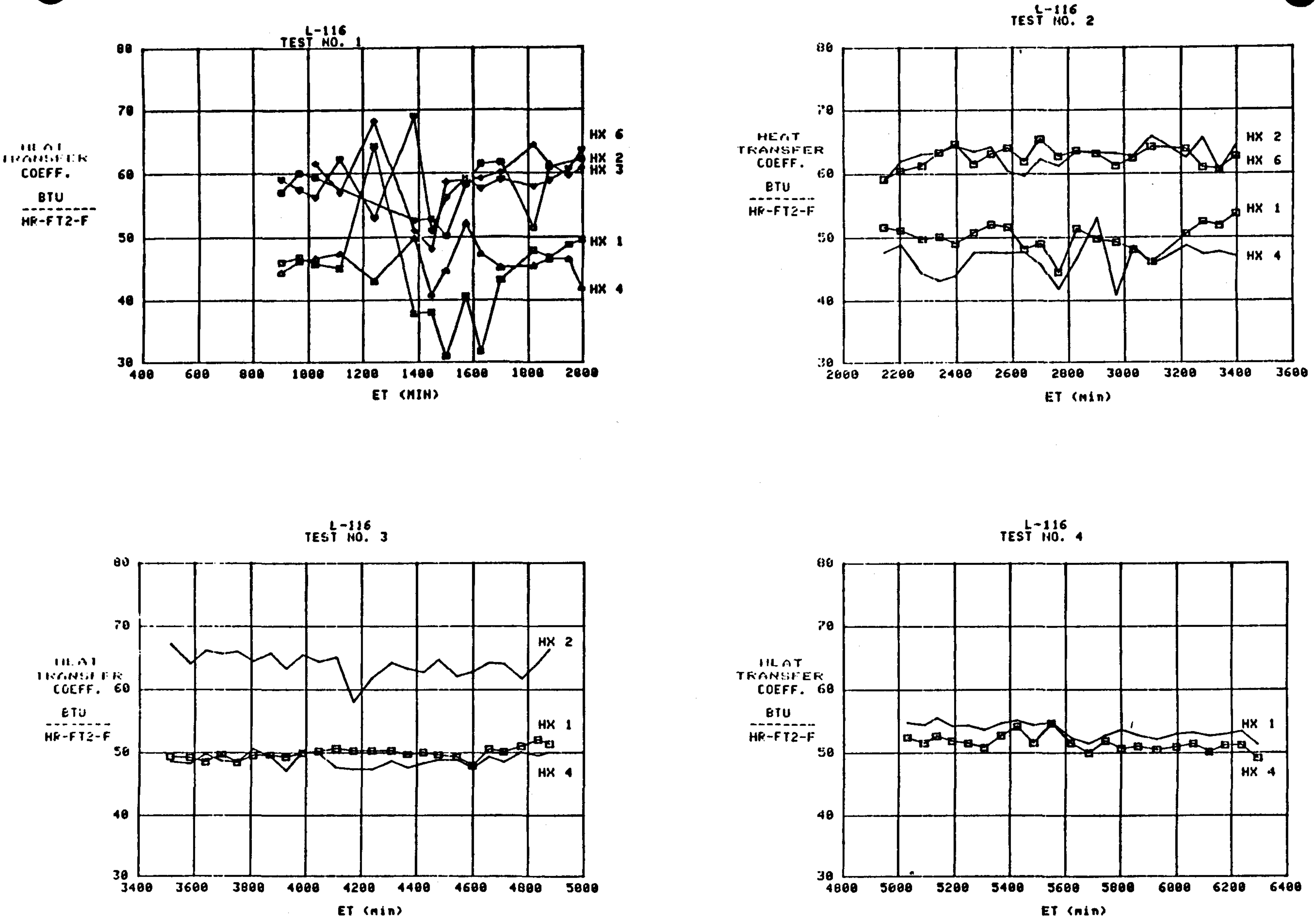

Figure 3-9. Heat transfer coefficient vs. elapsed time - Test Series L116.

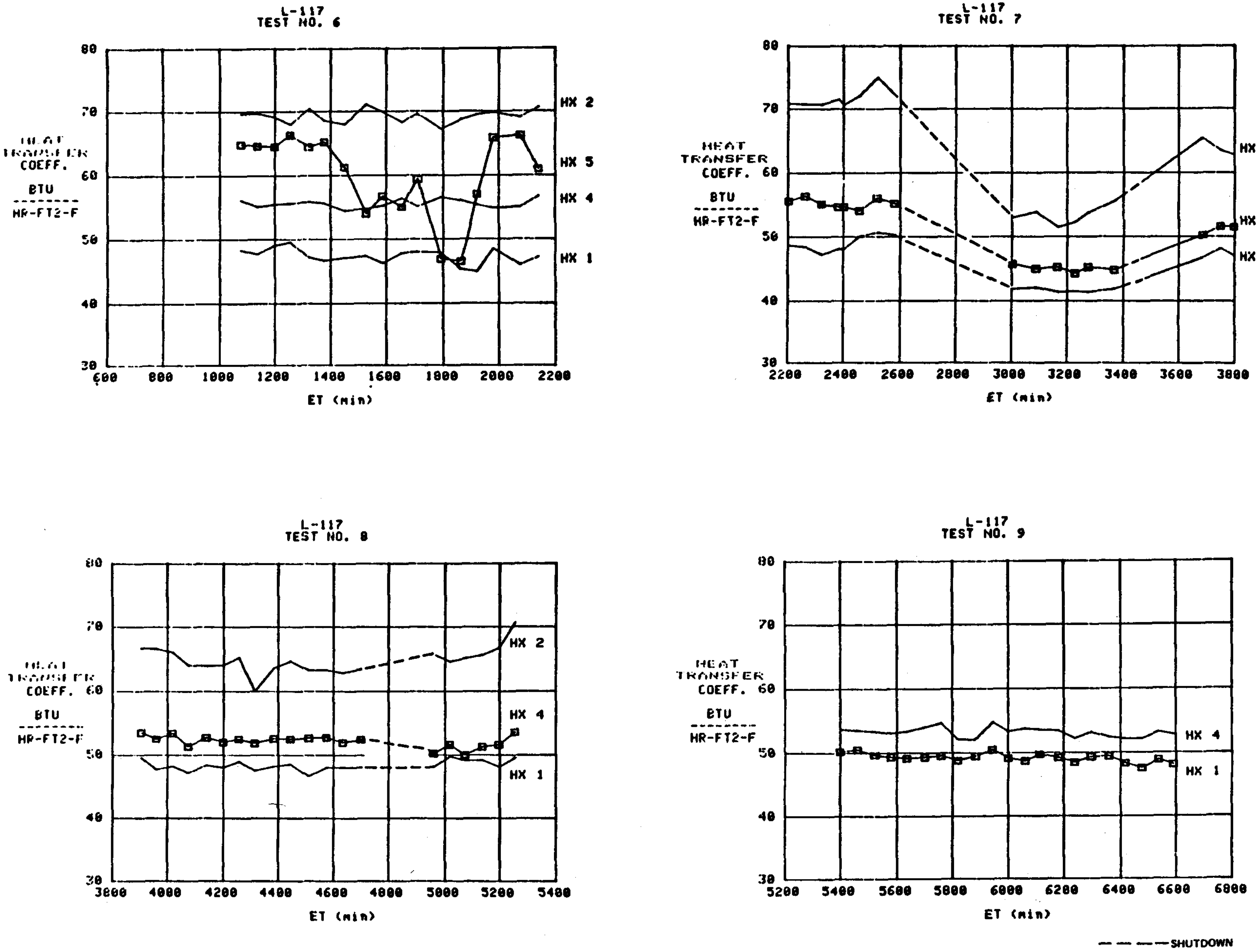

Figure 3-10. Heat transfer coefficient vs. elapsed time - Test Series L117.

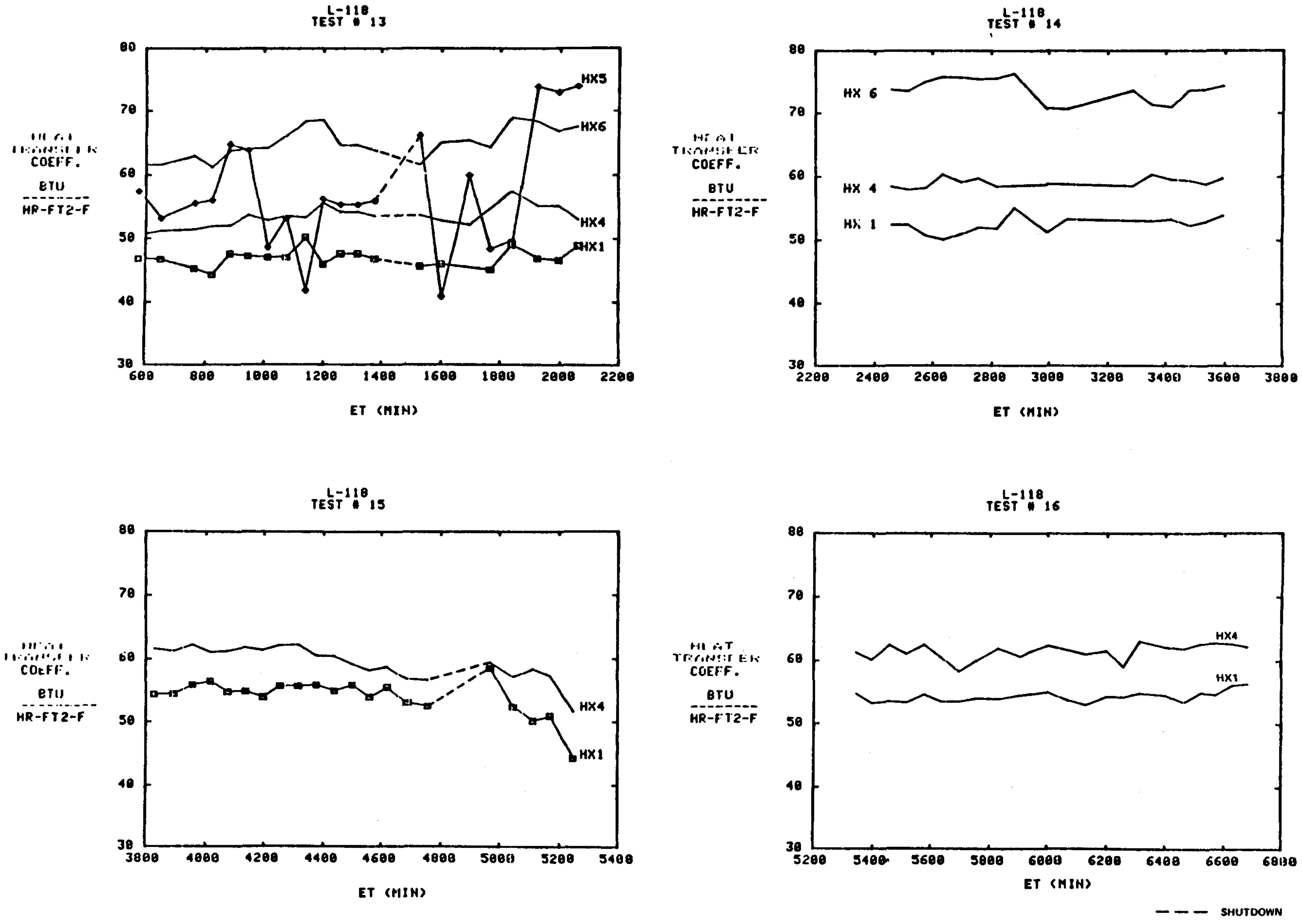

Figure 3-11. Heat transfer coefficient vs. elapsed time - Test Series L118.

Table 3-8

RATES OF INORGANIC SOLID PRODUCTS FROM TEST SERIES L116, L117, AND L118

			Total Test Period						"Steady-State" Period									
Test	Lignite Source	Limestone Addition	Elapsed Time,[a] Minutes	Bed Drain, lb/hr	Spray Cooler Deposits, lb/hr	Baghouse Drain, lb/hr	Baghouse and Spray Cooler lb/hr	Total Solids lb/hr	Elapsed Time,[a] Minutes	Bed Drain, lb/hr	Spray Cooler Deposits, lb/hr	Baghouse Drain, lb/hr	Baghouse and Spray Cooler lb/hr	(Emissions via EPA5, lb/hr)	Total Solids lb/hr	Steady-State Inorganic Solid Feed Rate[c], lb/hr	Difference of Feed and Product Solids lb/hr	Difference of Feed and Product Solids %
1	Wilcox	No	1830-2000	40 (18%)	-	28	~180[b] (82%)	~220	1883	-	-	-	-	(178)	-	~246	~26	~11
2	Wilcox	No	2100-3440	28 (13%)	-	69	~180[b] (87%)	~208	3314	-	-	-	-	(176)	-	195	-13	-6.7
3	Wilcox	No	3550-4890	5[d] (3%)	-	90	~150[b] (97%)	~155[d]	4207	-	-	-	-	(150)	-	194	39[d]	20[d]
4	Wilcox	No	5020-6340	18 (10%)	-	100	~160[b] (90%)	~178	5880	-	-	-	-	(165)	-	187	9	4.8
6	Wilcox	Yes	1100-2130	32 (19%)	-	83	~140[b] (81%)	~172	1826	-	-	-	-	(142)	-	218	46	21
7a	Wilcox	Yes	2200-2580	50	-	141	>140[b]	>190	-	-	-	-	-	-	-	-	-	-
7b	Wilcox	Yes	3000-3410	ND	-	80	~120[b]	>120	3092	-	-	-	-	(119)	-	-	-	-
7c	Wilcox	Yes	3680-3860	16[d] (8%)	-	91	~190[b] (92%)	~206[d]	3818	-	-	-	-	(194)	-	~184	~22[d]	~12[d]
8	Wilcox	Yes	3870-4720 &4940-5280	32 (17%)	-	95	~160[b] (83%)	~192	4470	-	-	-	-	(156)	-	206	14	6.8
9	Wilcox	Yes	5400-6600	24 (12%)	-	79	~170[b] (88%)	~194	5807	-	-	-	-	(171)	-	197	3	1.5
13	Jackson	No	570-2073	22 (19%)	~25[b]	71	96 (81%)	118	1700-2050	27 (19%)	~25[b]	93	118 (81%)	(118)	145	141	-4	-2.8
14	Jackson	Yes	2378-3643	110 (52%)	32	70	102 (48%)	212	3320-3640	129 (50%)	32	97	129 (50%)	(137)	258	234	-24	-10.3
15	Jackson	Yes	3830-5308	57 (32%)	34	86	120 (68%)	177	5000-5300	106 (53%)	39	55	94 (47%)	(163)	200	222	22	9.9
16	Jackson	Yes	5370-6720	63 (39%)	39	59	98 (61%)	161	6400-6706	84 (43%)	39	71	110 (57%)	(109)	194	195	1	0.5

All solids are dry but do include small amounts of char (from 0.5 to 6.6% per LOI analyses at 950°C).

[a] Elapsed times may not match other ET's of test and steady-state periods due to frequency and timing of solids drains during tests.

[b] Estimated by volume and density of deposits. Other deposits weighed in L118 series. Reliable weighings of spray cooler deposits were not available during test series L116 and L118. Total spray cooler deposits and baghouse drain rates in Tests #1 through #5 estimated from EPA 5 determinations, which were discrete point-in-time measurements.

[c] Includes SO_3-free ash of lignite, calcined residual solids of limestone (typically 59 to 60 percent of limestone feed), and sulfur from lignite (as SO_3) which was retained in the system as determined from SO_2 emission measurements.

[d] Inspection of data indicate an apparent inconsistency in measured flow rates. Bed drain rates are the most likely source of error.

As expected, the bed drain rates were greater with tests utilizing limestone to suppress sulfur emissions. As shown by the bed drain rates during the test periods of the Jackson lignite tests in Table 3-8, the change upon adding limestone was significant, increasing from 22 lb/hr to over 100 lb/hr for essentially the same test conditions of temperature, velocity, and excess air. (Note that due to the complications in accurately weighing hot solids, larger errors for drain rates can result than would be encountered with the other measurements.) As noted in Table 3-8, the solid product rates agreed reasonably well with the feed rates to the system except for Tests #3 and #14 (which may be the result of questionable data) and for Tests #1, #6, and #7 which had not achieved stable operating conditions.

Visual examination of the drained materials and the post-test beds indicated no signs of particulate agglomeration or deposits within the combustor for either lignite. The drained solids were free flowing in nature.

Samples of bed materials were analyzed for alkaline content. The analyses indicate that the bed compositions varied with test conditions, as shown in Figure 3-12. In general, the alkali (Na and K) concentrations in the bed materials followed the same relative pattern with both lignite fuels. Concentrations increased with time (even when diluted with the limestone) and exhibited approximately the same relative changes for both sodium and potassium. Sodium was higher in concentration than potassium for the Jackson lignite tests and lower in the Wilcox lignite tests, as would be expected from the ash compositions of the two lignites.

Of course, the calcium content of the bed materials increased significantly upon adding limestone, as shown by comparing Tests #1 through #4 to Tests #6 through #9 for Wilcox lignite and comparing Test #13 to Tests #14 through #16 for Jackson lignite. Of interest in the suppression of sulfur was the relative <u>decrease</u> in sulfur content of the bed material upon increasing temperature as shown by the relative changes in Figure 3-12 from Tests #2 to #3 to #4 (Wilcox lignite without limestone) and from Tests #6 to #8 and #9 (Wilcox lignite with limestone).

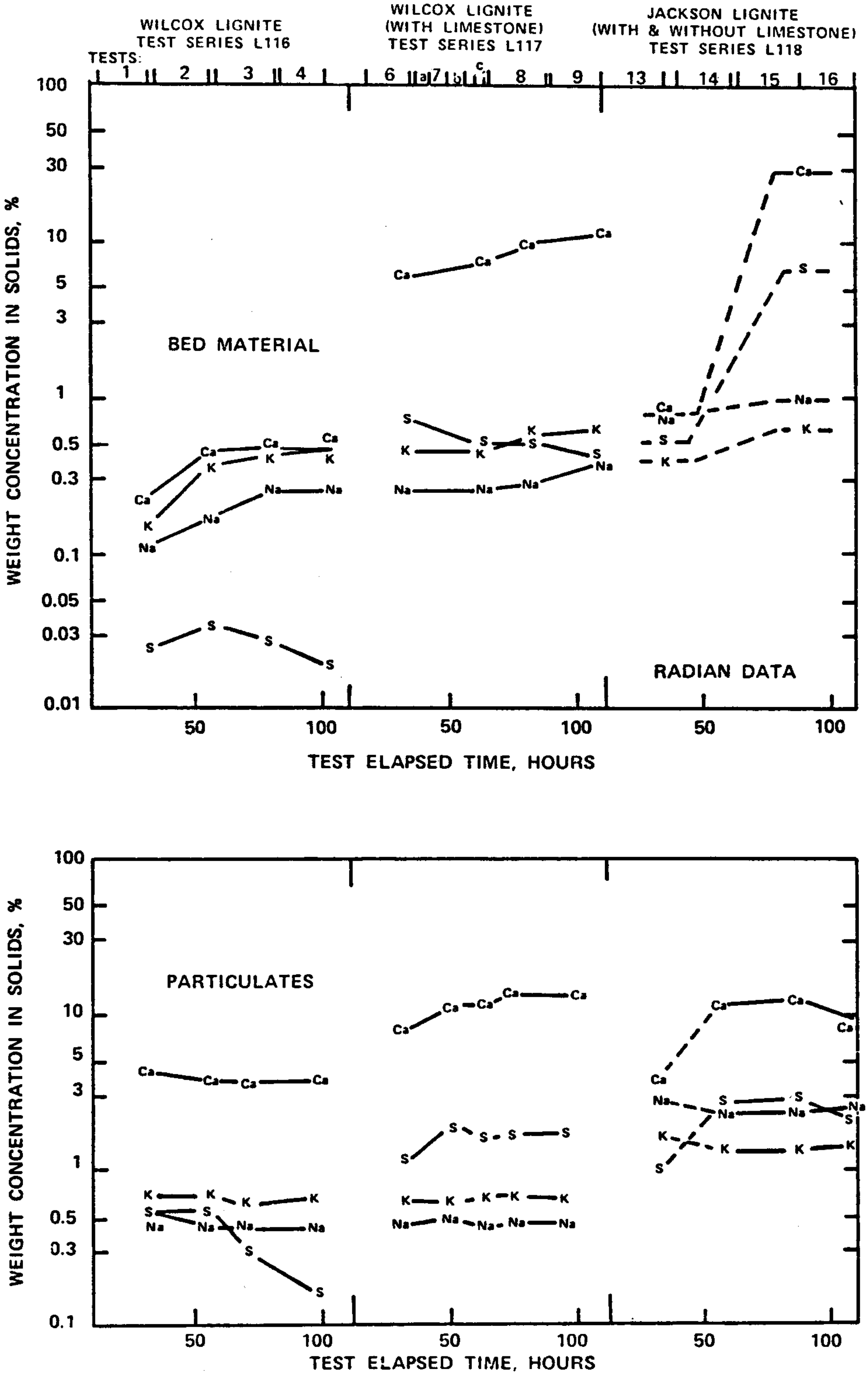

Figure 3-12. Concentration of Ca, Na, K and S in drained bed material and EPA 5 particulates.

Particulate loadings in the exhaust gas stream were determined via EPA Method 5/17 during each test. Typically, the particulate sampling periods concurred with the steady-state periods, as both were based upon stable periods for major operating parameters. The particulate emission loadings were determined in the outlet duct from the recycle cyclone and, thus, represent the total particulates emitted from the lignite-fired AFBC system without any control system. As shown in Table 3-9, the particulate loadings from the FBC-and-recycle-cyclone combination were high for all tests, being in the 5 to 8 gr/acf range (duct conditions) due to the high ash content of the lignites. Any combustion system firing the two lignites tested would require primary and, likely, secondary particulate emissions control systems (e.g., baghouses, electrostatic precipitators). As stated previously, the recycle rates were higher for the Wilcox lignite tests than for the Jackson lignite tests, i.e., in spite of the two having similar ash contents, more of the ash and sorbent materials were elutriated from the bed during the Wilcox lignite tests. This is apparently an effect of the relative ash/mineral matter particle sizes. The effect of ash/mineral matter sizes in the two lignites with similar ash contents was also illustrated in the particulate emissions. For the Wilcox lignite tests, the combined effects of high ash content and high recycle rates overshadowed any additional particulate loading resulting from limestone addition. Even in the very highest limestone addition test (#8), the increase in loading was less than 20 percent more than the lignite-only tests. For the Jackson lignite tests, which retained more of the lignite ash in the bed and recycled less, the limestone increased the particulate loading to the baghouse by up to 60 percent over the lignite-only tests. Of course, differences in sulfur content and overall alkaline-to-sulfur ratio requirements for the two lignites also affected the increase in baghouse loading on the addition of limestone. Obviously, though, consideration of the effects of high recycle rate and particulate loading upon equipment erosion (e.g., cyclones, boiler tubes) will have to be considered in any potential plant design.

The high particulate emissions were used to estimate the production rates of solid products in Table 3-8 (deposits within the spray tower made it impossible to obtain reliable total emission rates). As shown in the table, 81 to 97

Table 3-9

PARTICULATE ANALYSES FROM L116, L117, AND L118

Test Number	Lignite Source	Limestone Addition	Sampling Period (Elapsed Time), Minutes	Sampling Duration, Minutes	Particulate Loading Via EPA 5 Inlet Position[b] gr/acf	Inlet Position[b] gr/sdcf	Outlet Position[b] gr/acf	Outlet Position[b] gr/sdcf	Loss on Ignition (@800°C) Weight % Dry Solids[a]	Comments
1	Wilcox	No	1843-1845	2	∿ 890	∿4000				Loading questionable and may be invalid[c]
			1883-1893	10			6.1	23	0.95	1st and 2nd traverse points sampling
2	Wilcox	No	2848-2850	2	∿1600	∿6000				Loading questionable and may be invalid[c]
			3314-3322	8			7.1	27	0.52	
3	Wilcox	No	4207-4215	8			7.6	28	0.28	
			4336-4338	2	∿1300	∿5100			0.10	Loading questionable and may be invalid[c]
4	Wilcox	No	5880-5888	8			6.4	24	0.19	
			5944-5946	2	∿1700	∿6200				Loading questionable and may be invalid[c]
6	Wilcox	Yes	1579-1581	2	∿1200	∿5100			0.82	Loading questionable and may be invalid[c]
			1826-1834	8			5.9	21	0.92	
7b	Wilcox	Yes	3092-3100	8			4.8	19		No samples obtained during 7a. Wet filter pad due to moisture condensation.
			3182-3202	20	∿ 110	∿ 440				Loading questionable and may be invalid[c]
7c	Wilcox	Yes	3818-3825	7			8.4	31	1.37	
			3858-3860	2	∿ 720	∿2900				Loading questionable and may be invalid[c]
8	Wilcox	Yes	4470-4478	8			6.5	23	1.66	
			- -	-	-	-				Inlet sample aborted. Spray tower plugged.
9	Wilcox	Yes	5807-5815	8			7.4	27	1.80	
			5892-5897	5	∿1100	∿4500				Loading questionable and may be invalid[c]
13	Jackson	No	1996-2004	8			4.9	17	2.8	
			2035-2037	2	∿ 460	∿1900				Loading questionable and may be invalid[c]
14	Jackson	Yes	3404-3412	8			5.9	22	3.5	
			3503-3505	2	∿ 480	∿2000				Loading questionable and may be invalid[c]
15	Jackson	Yes	5189-5197	8			7.3	27	2.2	
			5227-5229	2	∿ 360	∿1600				Loading questionable and may be invalid[c]
16	Jackson	Yes	6560-6568	8			4.7	18	1.1	
			6600-6602	2	∿ 430	∿1900				Loading questionable and may be invalid[c]

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[a] Dried at 300°C inside a furnace and cooled over H_2SO_4 to prevent or minimize moisture pickup by $CaSO_4$ and other components in the solids.

[b] The "outlet" position is located in a straight run of the exhaust duct from the recycle cyclone and upstream of the spray tower. The "inlet" position is located between the FBC freeboard and the inlet duct to recycle cyclone.

[c] Due to the configuration, turbulent flow, short sampling times, and particulate loadings, the "inlet" position data are questionable and may be invalid. The pitot tube plugged easily causing unreliable gas velocity measurements. Thus, the sampling was not at isokinetic conditions and the sample is probably not representative. Inlet EPA 5 data should be used as a general indication of particulate loading only.

percent of the solid products (fuel ash, sulfated sorbent, and unreacted sorbent) were collected by the combined spray tower and baghouse in the Wilcox lignite tests and 48 to 81 percent were collected in the Jackson lignite tests. The balance of solids produced was drained from the bed periodically to maintain bed height.

Due to the complications of accurately weighing the hot solids drained from the FBC bed, difficulties in handling the fine-sized, fluffy warm baghouse product, and the accumulations of deposits in the spray tower, the solids production rates are perhaps the least accurate of all measurements within the system. Relative errors may be as large as ±25 percent. Additionally, the particulate measurements were discrete in nature (i.e., for specified time periods) rather than being averages for the total test periods, which affects specific conclusions on exact values of solids/particulate production rates. However, the general conclusions and reported approximate rates should be valid.

As shown in Figure 3-12, the alkali (Na and K) content of the particulates was essentially the same for all Wilcox lignite tests. Levels of 4000 to 7000 ppm were measured even for tests with limestone addition, indicating accumulation in the bed material. The potassium was higher than the sodium content, as in the raw lignite ash. The same general trend, with some variation, was found in the Jackson lignite tests. Alkali content was measured at 1.4 to 2.8 percent, with the sodium higher than the potassium content (as in the raw Jackson lignite ash). Of course, the calcium content of the particulates increased with limestone addition from 4 percent to 7 to 13 percent. Individual values at the increased levels depended on the limestone rate, operating temperature, and recycle rate.

While the sulfur content of the particulates in tests #2 through #4 (i.e., Wilcox lignite without limestone) decreased, apparently as a function of increasing bed temperature, the sulfur content of particulates from most of the other tests appeared to correlate with the calcium content. This would be expected in processes utilizing calcium-based alkali for suppressing sulfur emissions.

3.4 GFETC TESTING OF JACKSON LIGNITE

Results of CPC's Jackson lignite testing were compared to results of an earlier series of tests with Jackson lignite completed with GFETC's 2.25 ft^2 atmospheric fluidized bed combustor (3-6). The GFETC tests were conducted in a manner generally similar to that of the CPC tests except that smaller fractions of the elutriated solids were recycled to the combustor, typically 0.5-2.2 lb/lb of feed ash (compared to 50-90 lb/lb of feed ash in the CPC tests), and little or no solids were drained from the bed. Also, the GFETC tests were conducted for 40- to 80-hour periods and the stable operating periods (i.e., steady-state periods) were longer than those in the equivalent CPC tests.

The GFETC tests were conducted on a batch of Jackson lignite with an average ash content of 23.5 percent (dry basis) and an average sulfur content of 3.4 percent (dry basis). However, it was reported that the sulfur content varied widely from the mean values during the individual tests (e.g., from 3.1 to 3.9 percent, dry basis). The moisture content of the lignite varied over a wide range from 10 percent to above 30 percent, due to the variable quality of the lignite and as the lignite dried out upon storage. Although the ash content of the GFETC batch was lower than the nominal 33 percent (dry basis) ash content of the batch of Jackson lignite tested by CPC, the level of sulfur and the sulfur variation within the batches tested by CPC and GFETC were very similar.

Since the GFETC test program involved varying several test parameters, including bed temperature, limestone addition rate, recycle/nonrecycle tests, excess air levels, and superficial velocity, the test data were organized into several groups as shown in Table 3-10. The test data are the mean values from steady-state periods which had been selected from each test as periods of stable operation. The steady-state periods ranged from 9 to 47 hours in duration.

All of the GFETC test data with recycle are reduced to show sulfur retention as a function of temperature and feedstream alkaline-to-sulfur molar ratio ($(Ca + Na_2)/S$) in Figure 3-13. The data include tests with excess air levels

Table 3-10

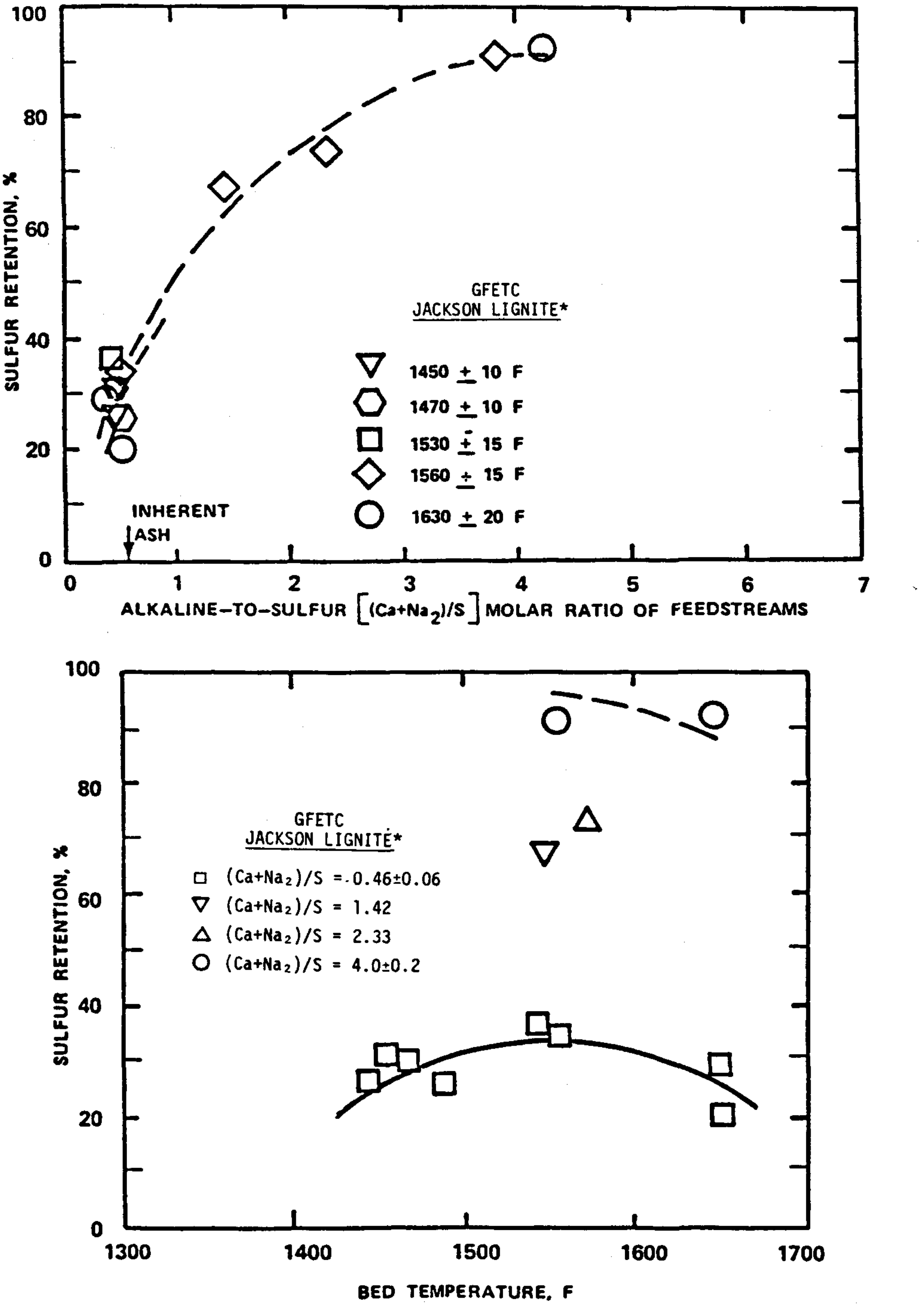
GFETC TEST DATA ON JACKSON LIGNITE[b]

Test # (Hours at Steady rate)	Temperature °F	Recycle Rate lb/lb Feed Ash	Limestone Addition lb/lb Dry Coal (Ca/S, molar)[a]	Superficial Velocity, ft/sec	Excess Air, %	Total Ca/S[a], Molar	Total $(Ca+Na_2)/S$[a] Molar	Sulfur Retention, %
A. **Tests with recycle, V_{SF} = 6±0.7 fps, and EA = 20±2%:**								
TL2-3280 (19.5)	1443	0.78	- (-0-)	5.9	20.6	0.32	0.46	26.9
TL3-3380 (21.0)	1542	1.25	- (-0-)	6.1	18.2	0.31	0.45	36.9
TL3-1581 (14.4)	1555	1.59	- (-0-)	6.6	20.6	0.33	0.52	34.9
TL4-1681 (18.5)	1650	1.94	- (-0-)	6.7	20.9	0.32	0.50	20.7
TL10-1881 (24.0)	1648	2.22	0.43 (3.10)	6.4	21.4	3.76	4.22	92.4
B. **Tests with recycle, V_{SF} = 6±0.5 fps, and higher and lower excess air:**								
TL5-0181 (30.4)	1453	1.39	- (-0-)	5.9	47.8	0.29	0.47	31.4
TL2-1481 (26.1)	1468	1.97	- (-0-)	6.0	24.9	0.29	0.46	30.6
TL8-0481 (16.4)	1547	1.05	0.14 (0.64)	6.2	23.4	1.12	1.42	67.6
TL9-1781 (10.7)	1555	2.15	0.39 (3.27)	6.3	16.5	3.62	3.82	91.4
TL4-3480 (14.1)	1650	0.56	- (-0-)	6.4	26.2	0.26	0.39	29.6
C. **Tests with recycle, other velocities, and other excess air:**								
TL11-1981 (24.8)	1465	2.16	- (-0-)	8.0	23.0	0.36	0.51	30.3
TL6-0281 (8.6)	1487	2.11	- (-0-)	3.5	32.7	0.32	0.50	25.6
TL12-2081 (16.9)	1571	2.10	0.17 (1.22)	9.2	25.3	1.88	2.33	73.4
D. **Tests without recycle:**								
TL1-1281 (9.3)	1472	-	- (-0-)	6.2	20.4	0.33	0.52	32.9
TL1-1381 (12.9)	1476	-	- (-0-)	5.8	26.9	0.32	0.50	36.9
TL7-0381 (47.4)	1512	-	- (-0-)	5.6	20.6	0.32	0.51	22.2

All data are means from steady-state periods during each test.

[a] Total for feedstreams, i.e., not including recycled ash. Limestone data based upon 46.2% CaO in the limestone.

[b] Source: 8/26/81 per G. Goblirsch, GFETC.



(*INCLUDES DATA WITH EXCESS AIR OF 16–48%, SUPERFICIAL VELOCITY (AIR FRACTION) OF 3.5–9.2 FPS, AND RECYCLED FINES RATES OF 0.5–2.2 LB/LB FEED "ASH". DOES NOT INCLUDE NON-RECYCLE TESTS).

Figure 3-13. Sulfur retention of Jackson lignite for steady-state periods of GFETC tests.*

Source: 8/26/81 per G. Goblirsch, GFETC.

of 16 to 48 percent and superficial velocities (air fraction) from 3.5 to 9.2 ft/sec. No attempt has been made to evaluate the relationships or effects of the latter parameters upon sulfur retention at this time. However, it appears that higher excess air improves sulfur retention from the data of paired tests #TL1, #TL2, and #TL4.

As shown in the figure, sulfur retention by inherent ash alkalinity alone reaches a maximum of 37 percent at 1530 to 1550°F. There are insufficient data to establish the temperature effects during limestone addition (i.e., at higher alkaline-to-sulfur ratios) or to estimate the relationship of alkaline-to-sulfur molar ratios on sulfur retention at intermediate values of sulfur retention.

As discussed earlier, the recycled solids rates were considerably different for the GFETC and CPC tests. The GFETC tests were conducted in the 0.5 to 2.2 lb/lb feed ash range while the CPC recycle rates were measured in the 50 to 90 lb/lb feed ash range. Even though the recycle rates were very different, *test data from the two programs are very similar* when compared at the same excess air and superficial velocity values. The combined test data from the GFETC and CPC programs on Jackson lignite are shown in Figure 3-14 for excess air values of 20±2 percent and supervicial velocities of 6±0.5 ft/sec. As can be seen in Figure 3-14, for the combined CPC and GFETC test data, the maximum sulfur retention at temperatures near 1550°F may also be valid at higher alkaline-to-sulfur ratios, i.e., with added limestone. There are inadequate data at a single (Ca + Na_2)/S molar ratio to confirm the relationship from these test series.

Since recycling of solids to the combustor enhances sulfur retention by increasing utilization of the available sorbent, then it appears from the good agreement between the CPC and GFETC test data that the much higher recycle rates during the CPC test were above the ratios which contribute to *additional* sulfur retention. Apparently, lower recycle rates in the CPC test would have been adequate to achieve the maximum sorbent utilization effects from recycle.

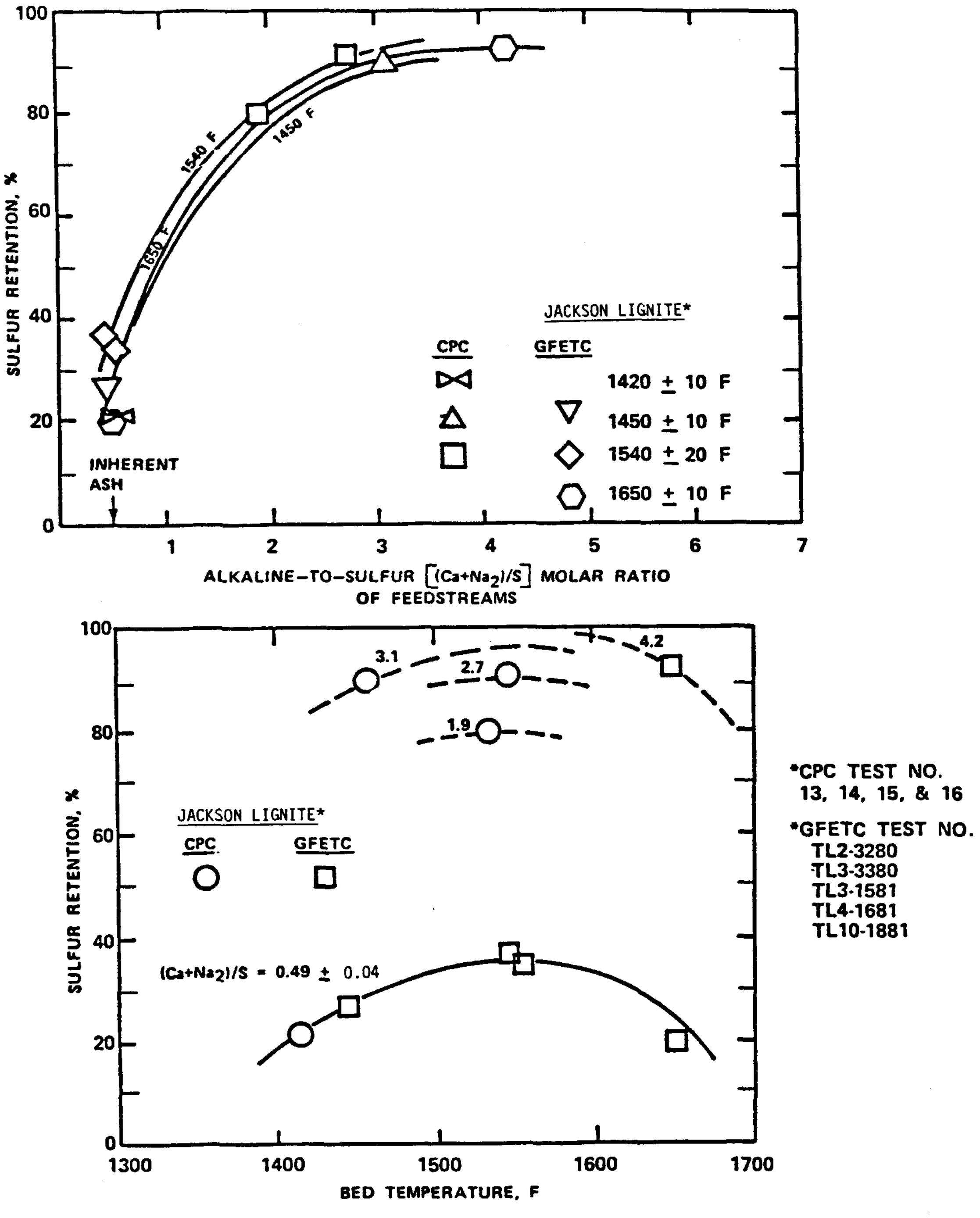


Figure 3-14. Combined CPC and GFETC test data for Jackson lignite at base conditions of 20±2% excess air, 6±0.7 fps superficial velocity, and recycled fines to the FBC (CPC at 70±20 and GFETC at 1.5±0.8 lb/lb feed ash).

And if recycle rates can be adjusted in a full scale process by the proper design of the recycle cyclone or by purging appropriate amounts of recycled material to lower the rate, then erosion of tubes, cyclones, and other components can be reduced to increase the service life of the system.

3.5 COMPARISON OF AFBC TESTS WITH NORTH DAKOTA LIGNITE AND TEXAS LIGNITES

A series of AFBC tests was conducted at CPC in 1978-1979 firing the Beulah lignite from North Dakota. The evaluations of the 15 tests in the series were only recently completed and have not yet been published (3-7). The objectives of the program were to determine sulfur suppression and emissions of other species during combustion of Beulah lignite in a parametric test matrix of bed temperatures, superficial velocity, limestone addition, and recycle rate. Individual tests were up to 200 hours in duration, but most tests were of nominally 80 hours duration. Some of the 15 parametric tests were conducted at the same conditions as in the L116, L117 and L118 series, which utilized Wilcox and Jackson lignites from Texas. However, due to the complexity of the North Dakota lignite test program and the effects of deposits and agglomerates formed within the system, it is recommended that the reader refer to those program results (3-7) for detailed comparisons of the test results for the various lignites.

Summary of North Dakota Lignite Test Results

The composition and properties of the Beulah lignite were different than the two Texas lignites, being lower in ash content, higher in heating value, and intermediate between the two Texas lignites in sulfur content. The Beulah ash also contained more sodium than either of the Texas lignites. The Beulah lignite compositions for the 15 tests were:

	Mean of All Tests	Range of Values
Moisture, as received	33.5%	29.8 - 35.4%
Ash, dry basis	11.8%	11.0 - 12.8%
Sulfur, dry basis	1.4%	1.3 - 1.7%
Nitrogen, dry basis	0.9%	0.8 - 0.93%
Heating value, dry basis	10,700 Btu/lb	10,400 - 10,800 Btu/lb
SiO_2, ash basis	21.1%	19.2 - 25.3%
CaO, ash basis	18.1%	14.4 - 19.4%
Fe_2O_3, ash basis	10.3%	9.4 - 11.8%
Al_2O_3, ash basis	10.2%	8.2 - 11.4%
Na_2O, ash basis	8.3%	7.3 - 10.1%
MgO, ash basis	5.4%	4.1 - 6.3%

Based on a few analyses, the sulfur was composed of 30 to 50 percent organic, 40 to 70 percent pyritic, and 3 to 6 percent sulfate forms. As shown above, the alkaline content of the ash was high. Potassium was typically a very minor component of the ash (typically less than 0.5% of the ash).

The potential emissions and inherent alkaline-to-sulfur ratios for the as-received Beulah lignite were:

Potential sulfur emissions:	2.4 - 3.2 lb $SO_2/10^6$ Btu
Inherent Ca/S molar ratio:	0.67 - 1.05
Inherent $(Ca + Na_2)/S$ molar ratio:	1.3 - 1.8

The Beulah lignite had the potential for high sulfur retention with the higher amounts of alkaline components in the inherent ash and a sulfur content between those of the Wilcox and Jackson lignites from Texas. It should also be noted that the fusion temperatures of the Beulah lignite ash were 1900 to 2200°F in reducing environments and 2000 to 2300°F in oxidizing environments. With the high sodium content of the ash and the low ash fusion temperatures, the Beulah lignite would be ranked as "severe" (which is the most detrimental ranking) in both slagging potential and fouling potential per the indices developed by Babcock and Wilcox and others (3-8) for coal-fired boilers.

The North Dakota lignite tests were also conducted at CPC and, therefore, the test system utilized was very similar to the one used in the Texas lignite tests. The 7 ft^2 FBC with water tubes in the bed was used to maintain low excess air levels at specified bed temperatures. A recycle cyclone was utilized in all but two tests with the Beulah lignite. The sulfur sorbent was also Linwood limestone.

The parametric tests were conducted over nominal ranges of bed temperatures of 1400 to 1800°F, excess air levels of 20 to 30 percent, superficial velocities of 4 to 9 fps, both with and without limestone addition, and with and without recycle. The mean values of the prime process data collected during selected periods of stable operation are summarized in Table 3-11. Variations in the

Table 3-11

SUMMARY OF MEAN PROCESS DATA FOR SELECTED "STEADY-STATE" PERIODS IN AFBC TESTS FIRING BEULAH LIGNITE FROM NORTH DAKOTA

	Low Temp. Test	Moderate Temperature Tests												High Temp. Tests	
Test#	L107	L101	L113	L106	L114	L110	L111	L109	L115	L112	L104	L103	L102	L108	L105
Duration at Conditions, hrs	80	80	60	54	80	66	80	132	242	80	80	80	69	22	80
Selected Steady State Periods (Elapsed Time, hrs)	65-80	40-75	17-31	8-20	30-75	26-56	24-80	65-120	170-187 200-205	45-80	52-79	59-80	43-62	0-12	30-51
Steady State Duration, hrs	15	35	14	12	45	30	56	55	22	35	27	21	19	12	21
Bed Temperature, °F	1399	1584	1603	1600	1617	1602	1604	1603	1567	1607	1606	1619	1617	1810	1816
Freeboard Temperature °F	1463	1712	1681	1727	1622	1617	1673	1678	1678	1664	1692	1655	1647	1823	1818
Superficial Velocity ft/sec	5.5	6.1	6.0	6.2	5.9	8.2	5.3	5.8	6.3	5.6	4.8	5.1	5.7	5.6	5.0
Excess Air %	30.4	18.7	20.8	19.4	26.1	21.2	21.6	20.6	21.7	21.5	21.6	23.1	23.0	22.9	22.3
Recycle Mode	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes
Limestone Added	No	No	No	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Feedstream Ca/S Molar	0.95	1.03	0.87	0.73	0.87	0.93	1.54	1.38	1.92	3.07	3.23	4.48	5.19	1.80	3.22
Feedstream (Ca+Na$_2$)/S, Molar	1.77	1.83	1.54	1.32	1.59	1.59	2.21	2.13	2.63	3.32	3.90	5.29	5.89	2.59	3.85
SO$_2$, ppm$_v$ (dry)	200	968	942*	733*	574	865	614	383	568	380	14	21	26	937*	729
Sulfur Retention, %	83.8	21.1	26.2*	54.6*	56.6	29.9	52.3	72.1	61.2	70.7	98.9	98.4	98.1	32.1*	47.1
Particulates in Exhaust, gr/sdcf	1.9	0.2	0.4*	1.4*	1.2	2.7	0.7	2.1	0.3	0.5	3.9	4.1	0.4	3.3*	2.1
CO, ppm$_v$ (dry)	94	50	50*	29*	40	60	46	83	48	40	37	UD	UD	60*	38
NO, ppm$_v$ (dry)	210	133	196*	232*	268	256	UD	240	184	266	225	138	115	224*	179
Initial Bed Material	Quartz	Quartz	Alundum	Quartz	Quartz	Quartz	Quartz	Limestone & Quartz	Limestone & Quartz	Quartz	Quartz	Quartz	Quartz	Quartz	Quartz
Comments	Higher Excess air	—	Terminated early & tube failure	Terminated early: & deteriorating heat removal		Higher Velocity. Ran out of Coal.			New Coal Batch				Terminated early: tube failure	Terminated early: bed agglomeration	

*Data from shorter period early in test, which may not be representative of conditions.
UD=Unreliable data

North Dakota lignite test results were due to differences in the lignite composition over the long duration of the program, erratic behavior of the recycle subsystem during several tests, the use of less sensitive instrumentation, and the tendency for agglomerates to form within the system.

From the test program, several results and conclusions on the firing of the AFBC test system with the Beulah lignite from North Dakota are summarized below:

- Sulfur retention decreased with increasing temperature and reached a maximum at temperatures near 1400°F.
- Sulfur retention levels of 98 percent and above could be achieved with the addition of limestone at Ca/S molar ratios of 2.5 to 4.5.
- Sulfur retention by the alkaline components of the inherent ash ranged from 20 to 50 percent at nominally 1600°F to more than 80 percent at nominally 1400°F with recycle, 20±2 percent excess air, and 5.5±0.8 fps superficial velocity.
- The effects of recycling solids to the combustor were significant in inherent ash sulfur retention but were less important at high limestone addition rates.
- Even with test durations above 80 hours, the process had not reached steady-state conditions with the incoming feed streams, as evidenced by changing composition of the bed material.
- The NO_x emissions were low, being in the 100 to 300 ppm NO (dry) range, which corresponded to less than 10 percent of the nitrogen content in the lignite feed.
- CO emissions were quite low, being below 100 ppm (dry). Carbon combustion efficiencies determined for three tests via LOI analyses were above 98 percent.
- Overall heat transfer coefficients for the water-cooled tubes in the bed were in the range of 55 to 62 Btu/ft^2-hr-°F. The vertical tubes were found to have higher coefficients. Some degradation of the coefficients with time was observed during several tests.
- Most (80 to 95 percent) of the inorganic solids were retained by or drained from the bed, and the particulate loadings from the recycle cyclone were low at 0.3 to 4.0 gr/sdcf. The solids recycle rates were low at rates typically below 10 lb/min (which was less than 4 percent of the rates with the Wilcox lignite and less than 7 percent of the rates with the Jackson lignite).

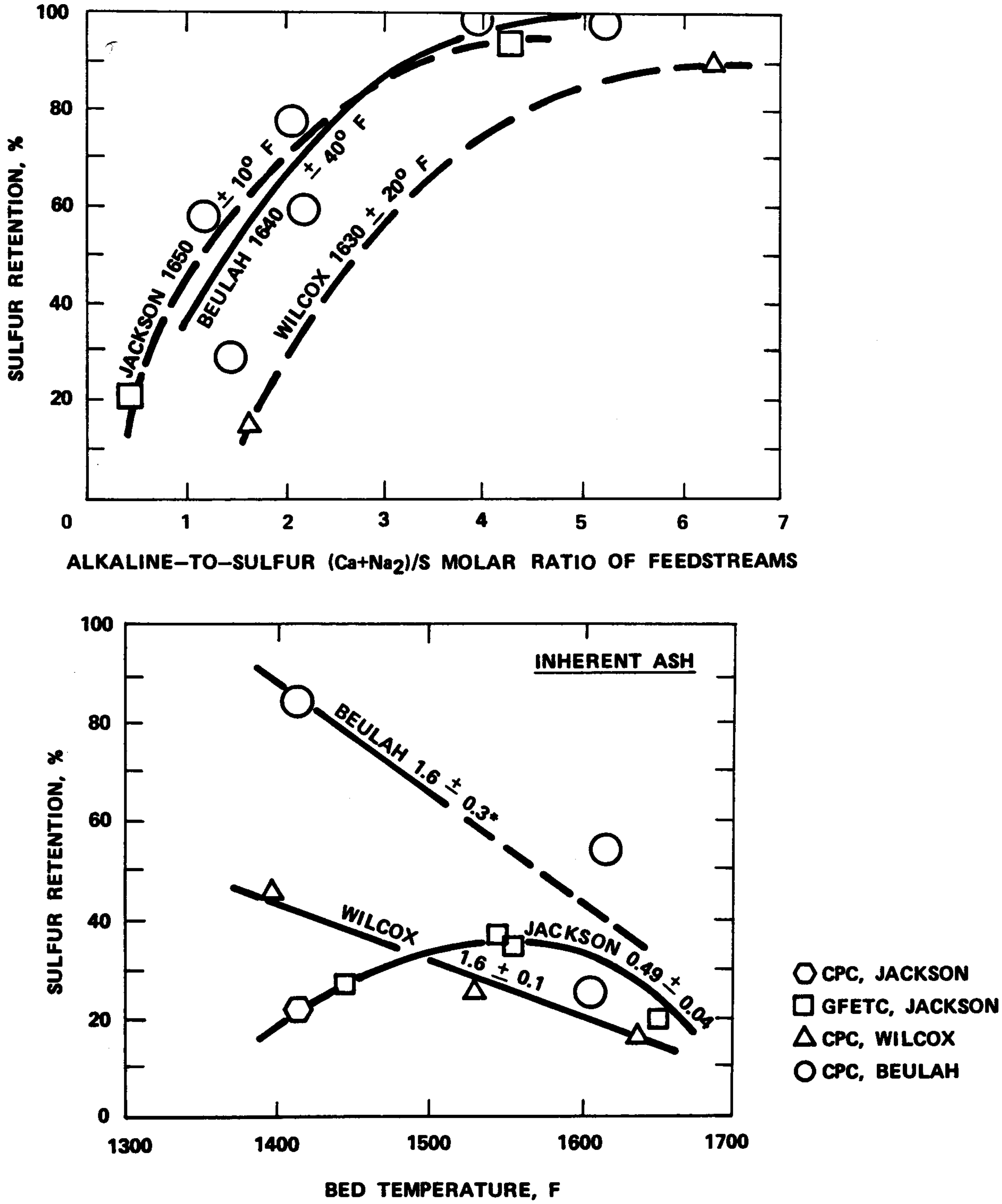
- There was evidence of bed particle agglomeration and associated phenomena. This evidence included erratic and sluggish operation in some tests, increasing bed particle size with time, and even bed solidification at high temperature and low or no limestone addition conditions. One high temperature test (L108) was terminated early due to major bed agglomeration.

Comparison of Texas and North Dakota Lignite Test Results

The emissions from AFBC systems are functions of the system configuration, operating conditions, and the lignite properties. The Beulah lignite from North Dakota had different properties than either of the Texas lignites tested, principally in the amount and composition of the ash.

NO_x and CO emissions were low for all three lignites. Less than 10% of the fuel-bound nitrogen was emitted as nitrogen oxides. A slight temperature effect was noted in that slightly higher NO_x levels and lower CO levels were generally observed at higher bed temperatures.

Sulfur emissions from any of the lignite fuels could be controlled by adding the proper amounts of limestone. At bed temperatures in the range of 1630 to 1650°F, the Beulah lignite required less limestone addition on a molar ratio basis than the Wilcox lignite and nearly the same as the Jackson lignite to achieve a desired percent level of <u>relative</u> sulfur retention. This effect is shown in Figure 3-15 (which includes only the Beulah test data from conditions similar to the Texas lignite test data). It should be noted that the performance data with various alkaline-to-sulfur ratios for the Beulah lignite in Figure 3-15 were measured at bed temperatures of greater than 1600°F. However, as shown in the lower plots of Figure 3-15, the Beulah lignite appeared to achieve maximum sulfur retention at lower bed temperatures, near 1400°F. (Tests at GFETC indicate that the maximum sulfur retention for Beulah lignite may be at a temperature below 1400°F (3-1).) In Figure 3-15, the relative sulfur retention data for Beulah lignite at higher temperatures appear to be similar to data for Jackson lignite. However, if these tests were repeated at temperatures closer to optimum bed temperatures for sulfur retention by the Beulah lignite ash, it is projected that the Beulah lignite would achieve higher retention levels than the Jackson lignite at equivalent alkaline-to-sulfur



*$(Ca + Na_2)/S$ MOLAR RATIO

Figure 3-15. Sulfur retention of Beulah, Wilcox and Jackson lignites at comparable conditions of nominally 20 percent excess air, 6 fps superficial velocity, and recycled solids to the FBC.

ratios. For proper comparisons of the sulfur retention capabilities of the various lignites, test data should be generated at temperatures selected for the maximum sulfur retention of the individual lignites, i.e., 1550°F for Jackson and near or below 1400°F for Wilcox and Beulah.

The lower relative limestone requirements for the Beulah lignite to achieve a high percent sulfur retention level were apparently due to the greater amounts and/or better utilization of the alkaline ash components. The higher content of sodium in the Beulah ash was the principal difference in the ash compositions of the three lignites. The greater sulfur retention with the Beulah lignite could have been due to the higher sodium levels causing lower calcination temperatures and/or higher limestone calcination rate (e.g., via surface films of liquid material) or to the formation of major sodium-containing sulfur species (e.g., glauberite, $CaNa_2(SO_4)_2$, which was identified in one of the Beulah tests at CPC).

Sulfur retention by the alkaline ash components was influenced by factors other than the alkaline-to-sulfur ratios and bed temperature, as shown by the lower sulfur retention of Wilcox lignite compared to Beulah lignite in Figure 3-15, even though both lignites had feedstream alkaline-to-sulfur molar ratios of nominally 1.6. The forms of the sulfur in each of the lignites was different, which affects the rate of sulfur release from the lignites upon combustion (3-9). The sulfur content and alkaline ash ratios for the three lignites were:

	Total Sulfur (wt.% of dry coal)	Forms of Sulfur (wt.% of Total S)			Alkaline Ash Molar Ratios		
Lignite		Organic	Pyritic	Sulfate	Ca/S	Na_2/S	$Ca+Na_2/S$
Jackson	3.2-3.3	69-74	18-23	7-8	0.33-0.34	0.19-0.21	0.52-0.54
Wilcox	0.70-0.81	91-94	6-9	0	1.3-1.6	0.08-0.13	1.6-1.7
Beulah	1.3-1.7	40-70	30-50	3-6	0.67-1.03	0.59-0.80	1.3-1.8

Thus, there were considerable differences among the three lignites in the forms of sulfur and the individaul alkaline component ratios to sulfur.

And, as would be expected of run-of-mine lignites, even the forms of sulfur can vary considerably within the same lignite as shown by the range of values above.

The sulfate sulfur was probably gypsum. At the combustion temperatures of the tests, it would have remained in the system as solid anhydrite ($CaSO_4$) and would not have required additional sorbent. Thus, the remaining sulfur fraction as pyrite (or related sulfide minerals) may have favored the sulfur retention by the alkaline ash components due to the intimate contact of the solid minerals in the bed. Additionally, the retention of lignite sulfur can be affected by a number of other variables and could involve catalysis by the iron ash components (3-9).

Previous experimental testing has shown that the sodium content of the ash also effects sulfur retention, but the relationship for the current FBC test program remains undefined. It is also likely that the forms of the alkalis and calcium influence the sulfur retention since neither the sodium-to-sulfur nor the sodium-to-calcium molar ratios seem to correlate with sulfur retention in these tests. The lack of sufficient data on alkaline forms for these lignites prevents the identification of the role of the forms of sulfur and alkaline components in sulfur retention.

The Beulah tests at CPC were conducted in the same system as utilized in the tests with the Wilcox and Jackson lignites (except for minor changes in the water tubes and in the feed system). In all of the test series, the cyclone was operated in either a 100% recycle mode or a separation mode. At no time were fractions or portions of the recycled solids drained from the loop. Thus, for the same flow and temperature conditions, the recycle system was the same for the Beulah and Texas lignite test series, except for any changes from deposits in the cyclone during the Beulah tests. However, solids recycle rates were considerably lower for the Beulah lignite, which had a lower ash content and lower limestone requirement than the Texas lignites. Thus, the recycle rate in these tests was a function of the ash amount and ash properties (e.g., particle size and density, stickiness), i.e., the lignite type.

The lower solids recycle rate not only results in lower particulate loading to be controlled but would also result in lower erosion rates for system components (e.g., cyclones) and a higher proportion of solid material leaving the system in the bed drain.

Another major difference between the lignites besides the degree of sulfur retention by the inherent ash was an observed particle agglomeration and related operating temperature limit with the Beulah lignite, which was not observed with the Texas lignites. The Beulah lignite showed particle agglomeration and accumulation of deposits at higher temperature (e.g., above 1600°F), which would limit acceptable operating conditions to lower temperatures. The agglomeration behavior has been observed by others (3-1, 3-11). However, the Texas lignite tests were conducted for shorter periods (normally 24 hours) and at lower temperatures than most of the Beulah tests. Also, the sodium content in the inherent ash, which has been observed to be a major contributor to agglomeration problems, was lower in the Texas lignites. The absence of any deposits or agglomerates during the Texas lignite tests therefore indicated, but did not prove, that particle agglomeration would not occur.

3.6 SUMMARY OF TEXAS LIGNITE TEST RESULTS

The following summarized results are based on the mean process data characterizing the stable operating periods (referred to as "steady-state" periods) in the Wilcox and Jackson lignite tests conducted in the CPC facility.

- In general, the manually controlled AFBC system operated smoothly except for recycle malfunctions in Test #7 and some process upsets due to variations in lignite compositions.
- The specified excess air and superficial velocity conditions of 20±5 percent and 6±0.5 ft/sec, respectively, were achieved and maintained during the tests with the water-cooled tubes in the bed. The test temperatures were often higher than planned due to the combination of limited available heat exchanger areas and the high ash content of the lignites, which resulted in high recycle rates and, thus, alteration of the heat balance of the system.

- Both the Wilcox and Jackson lignites contained high amounts of fine sized ash, which resulted in high recycle rates within the system, affecting both operations and loadings for particulate emissions control. Recycle rates for the Wilcox lignite were higher than the rates for the Jackson lignite (120 to 220 lb/lb feed ash vs. 50 to 90 lb/lb feed ash), even though the Jackson lignite-fired tests produced more solids when using limestone to suppress sulfur.

- With the high ash contents, both lignites had high particulate loadings from the FBC-recycle cyclone system. The particulate loadings in the exhaust gases were 17 to 28 gr/dscf (5 to 8 gr/acf at duct conditions).

- Larger sized solids accumulated in the bed and were drained periodically during the tests. Greater fractions of the total solids produced were drained from the bed during the Jackson lignite tests (∿20 percent with inherent ash only and 40 to 50 percent with limestone addition) than with the Wilcox lignite tests (3 to 18 percent with inherent ash only and 10 to 20 percent with limestone addition). The balance of the solids was contained in the flue gas from the recycle cyclone as particulate matter.

- Although the test durations were relatively short, there were no indications of bed particle agglomeration or accumulated deposits in the combustor for either lignite at the conditions tested.

- Based upon the LOI content of the solid products, the carbon combustion efficiencies for the low excess air test conditions were above 96 percent in all tests, ranging up to 99.6 percent with increasing temperatures.

- Carbon monoxide (CO) emissions were low, reaching a maximum of 570 ppm (dry) for the Jackson lignite tests and 360 ppm for the Wilcox lignite tests at the lower temperatures of ~1400°F, and decreasing with increasing temperature to 50 ppm at 1600 to 1650°F. Other combustible gas emissions were below 15 ppm, typically being 1 to 2 ppm at the higher temperatures.

- The nitric oxide (NO) emissions were very low. They increased with increasing temperature from 65 ppm (dry) for the Jackson lignite tests and 80 to 120 ppm for the Wilcox lignite tests at the lower temperatures to 140 ppm at 1600 to 1650°F. On an equivalent NO_2 concentration basis, emissions were below 0.20 lb/10^6 Btu, reaching 0.10 to 0.12 lb/10^6 Btu at the lower temperatures. This represented less than 10 percent of the nitrogen in the lignite feedstreams.

- Sulfur retention levels by the alkaline components of the inherent ash were below 50 percent, reaching a maximum of 46 percent for the Wilcox lignite, which contained an alkaline-to-sulfur molar ratio of constituents in the ash three times greater than the Jackson lignite. The maximum sulfur retention for the Wilcox lignite was at the lower temperatures of nominally 1400°F and decreased to ~16 percent (from the inherent ash only) at 1640°F. The maximum sulfur retention for the Jackson lignite appeared to be (and when comparing with the GFETC test data was later confirmed to be) at higher temperatures, near 1550°F. Sulfur retention of the Jackson lignite by the inherent ash alkalinity was only 21 percent at nominally 1400°F. From the GFETC test data, it appears that sulfur retention for the Jackson lignite by the inherent ash was increased to nominally 36 percent near the optimum bed temperature of 1550°F.

- Based upon the short duration of Test #1 (which had not reached stable operating conditions) at the bed depths tested, velocity had a minor effect upon sulfur retention. Subsequent tests were conducted at a single bed velocity, nominally 6 ft/sec (based on the superficial velocity of the combustion air alone).

- Sulfur emissions were reduced by adding limestone to the FBC. Sulfur retentions above 90 percent could be accomplished with high rates of limestone addition. With an added Ca/S molar ratio above 5 at 1530°F for the Wilcox lignite, sulfur retention of 99 percent was achieved, which resulted in very low SO_2 emissions of 0.03 lb/10^6 Btu. (Other levels of sulfur retention could be accomplished by selecting the proper limestone addition rate at the desired temperature as shown previously in Figures 3-7 and 3-8.)

- For a total 90 percent sulfur retention, the Wilcox lignite required added Ca/S of 4.6 (molar) at ~1600°F (which was <u>not</u> the best sulfur retention temperature for the Wilcox lignite) while the Jackson lignite required an added Ca/S of 2.2 (molar) at ~1550°F (which <u>was</u> the best sulfur retention temperature for the Jackson lignite). Although it appears that the Jackson lignite utilized the limestone more effectively, the higher sulfur content of the Jackson lignite and the temperature effects should be remembered in making comparisons. There were insufficient data (i.e., test points) to allow comparisons at properly equivalent conditions. Comparisons should ideally be made at the best sulfur retention temperature for each individual lignite. Also, comparisons should consider the incremental change with limestone addition above the retention with the inherent ash alkalinity alone, e.g., (ΔSO_2 emission)/(Δadded Ca/S), on a molar basis. Finally, the effects of different forms of sulfur present in each of the lignites could have affected the relationship of Ca/S on sulfur retention and should be considered.

- Comparing these results with results of a similar test series on a North Dakota (Beulah) lignite, the Beulah lignite achieved similarly low NO_x and CO emissions, but was found to more effectively retain sulfur than the Texas lignites. At optimum bed temperatures (nominally 1400°F), the Beulah lignite retained up to 80 percent of its sulfur content with inherent ash alkalinity. In contrast, the Wilcox lignite retained only 46 percent at optimum temperatures. Similarly, the Beulah lignite required a relatively low Ca/S ratio from added limestone to achieve high (above 90 percent) sufur retention levels. Another difference between the Beulah and Texas lignites was that agglomeration and associated phenomena were observed during the Beulah test series but not during the Texas lignite test series. However, the Beulah lignite contains higher ash sodium levels and the tests were generally conducted at higher bed temperatures and for longer periods of time. These factors appear to contribute to the occurrence of agglomeration during the Beulah tests. It has not been conclusively demonstrated that the Texas lignites would not exhibit agglomeration tendencies at higher bed temperatures and for longer operating durations.

3.7 REFERENCES

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Section 4

SOLID WASTE CHARACTERIZATION

The dry solid wastes produced during the fluidized bed combustion of two Texas lignites were characterized to evaluate the disposal requirements of these wastes. The objective of the solid waste characterization was to determine the effect of lignite properties, limestone addition, and other process variables on characteristics of solid wastes generated. Samples of bed material and baghouse ash were subjected to:

- chemical characterization to quantify major and trace constituents;
- leachability characterization to determine disposal requirements with respect to federal and state law; and
- physical characterization to define properties related to handling, disposal, and treatability.

In addition, supplementary chemical analyses were performed on selected samples of bed material, baghouse ash, particulates, and limestone. These supplementary data were used to establish material and energy balances for various lignite tests.

Through the remainder of this section, the details of the solid waste characterization and the results obtained are presented. First, an overview is presented in a brief description of the analytical test plan. Then, results of chemical, leachability, and physical characterization of the FBC solid wastes are presented. Finally, some observations and recommendations are presented concerning the disposal of solid wastes generated by the fluidized bed combustion of Texas lignite.

Because of the relatively short duration of the FBC tests (approximately 24 hours each), the samples collected and characterized may not be indicative of steady-state conditions. The data obtained also reflect certain operating conditions which would probably not be observed in a commercial FBC unit (e.g., sand content of the bed). Therefore, the purpose of the solid waste characterization task was not only to determine and evaluate analytical data, but also to identify areas of potential concern which may require further testing. The samples collected and characterized do, however, provide a useful comparison between solid wastes from the lignites tested and various operating conditions.

4.1 TEST PLAN FOR SOLID WASTE CHARACTERIZATION

Chemical, leachability, and physical characterization were performed on bed material and baghouse ash from four of the twelve FBC tests conducted on Texas lignite. The materials characterized were from:

- Test 3, Wilcox lignite without limestone addition;
- Test 8, Wilcox lignite with limestone addition;
- Test 13, Jackson lignite without limestone addition; and
- Test 15, Jackson lignite with limestone addition.

These test points were selected to best compare the lignites tested and the process variables, primarily limestone addition (and temperature to a limited degree), given the constraints of sample availability. A summary of major operating variables during the four tests is presented in Table 4-1.

Bed material and baghouse ash from each of the four tests were characterized according to the scheme presented in Table 4-2. Additionally, a composite sample consisting of 15 weight percent bed drain material and 85 weight percent baghouse catch material was prepared for each of the four tests and characterized to simulate the effects of codisposal. This ratio was selected and used for all four tests to approximate the proportional generation rate of the two solid waste streams based on preliminary flow rate data from CPC and the constraints of sample availability.

Table 4-1

MEAN TEST DATA FOR TESTS GENERATING SOLID WASTE FOR CHARACTERIZATION

Performance Variables	Test Point			
	3	8	13	15
Lignite	Wilcox	Wilcox	Jackson	Jackson
Bed Temperature (°F)	1533	1526	1414	1546
Superficial Velocity (ft/sec)	6.2	6.1	6.0	6.0
Excess Air (%)	20.6	19.9	∿22	18.7
Limestone Addition, Ca/S[a]	0	5.06	0	2.23
Sulfur Retention	26.4	98.3	21.5	90.9

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[a] Ca/S - molar ratio of calcium fed in limestone to sulfur in lignite

Table 4-2

CHARACTERIZATION OF SOLID WASTE SAMPLES FROM CPC TESTING OF WILCOX AND JACKSON LIGNITES

	Bed Material			Baghouse Ash			Bed-Baghouse Composite		
Parameter	Dry Waste	RCRA[a] Leachate	TDWR[b] Leachate	Dry Waste	RCRA Leachate	TDWR Leachate	Dry Waste	RCRA Leachate	TDWR Leachate
Elemental Analysis	4[c]	4	4	4	4	4		4	4
Anions									
Cl^-	4		4	4		4			4
$SO_4^=$	4		4	4		4			4
Radioactivity									
α		4			4			4	
β		4			4			4	
Total Dissolved Solids			4			4			4
pH			4			4			4
Physical Tests									
Specific Gravity	4			4			4		
Dry Bulk Density	4			4			4		
Particle Size Distribution	4			4			4		
Permeability							4		
Compressive Strength	4			4			4		
Compaction							4		

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[a] RCRA - Resource Conservation and Recovery Act

[b] TDWR - Texas Department of Water Resources

[c] Number of samples characterized

Selected samples of bed material, baghouse ash, particulates, and limestone were subjected to supplementary chemical analyses to establish energy and material balances. These data were then used to evaluate test unit performance to provide input for the preparation of the conceptual design of an industrial-sized AFBC boiler. These samples, listed in Table 4-3 were analyzed for calcium, potassium, sodium, sulfur, total organic carbon (TOC), and loss on ignition (LOI).

The details and results of the chemical, leachability, and physical tests performed are presented in the following subsections. The procedures used to characterize the wastes are described in Appendix B.

4.2 CHEMICAL CHARACTERIZATION OF TEXAS LIGNITE FBC SOLID WASTE

Chemical analyses were performed on bed material and baghouse ash samples from the four tests mentioned above. In addition, spray tower deposit from Test 13 (Jackson lignite) was analyzed to compare its composition with that of the baghouse catch from that test. The analytical techniques employed and the digests analyzed to determine each parameter are summarized in Table 4-4.

The analytical results obtained are listed in Tables 4-5 and 4-6 for the Wilcox and Jackson tests, respectively. These data reflect the prevailing operating conditions, especially the initial bed composition (higher silica content in Test 3 than Test 8 due to startup procedures utilizing sand in the bed), limestone addition (higher calcium concentration in Tests 8 and 15), and sulfur suppression (higher sulfur concentrations in Tests 8 and 15).

In Table 4-7, the chemical composition of fly ash from the combustion of a Northern Great Plains (North Dakota) lignite in a conventional pulverized lignite-fired boiler is listed. This fly ash was generated at the Hoot Lake Power Plant, Fergus Falls, Minnesota. Although differences in combustion technique and lignites make rigorous comparisons tenuous, comparisons of concentration levels can be made. Of the 12 EPA priority pollutant metals remaining on exclusion of mercury, the levels of antimony, arsenic, cadmium,

Table 4-3

SUPPLEMENTARY FBC WASTES CHARACTERIZED FOR MATERIAL AND ENERGY BALANCES

Limestone	Bed Drain Material	Particulate[a]	Spray Tower Deposit (Ash)	Baghouse Catch
Test 6, Wilcox	Test 1, Wilcox	Test 1, Wilcox	Test 13, Jackson	Test 3, Wilcox
Test 8, Wilcox	Test 2, Wilcox	Test 2, Wilcox		Test 8, Wilcox
	Test 3, Wilcox	Test 3, Wilcox		Test 13, Jackson
	Test 4, Wilcox	Test 4, Wilcox		Test 15, Jackson
	Test 6, Wilcox	Test 6, Wilcox		
	Test 7, Wilcox	Test 7b, Wilcox		
	Test 8, Wilcox	Test 7c, Wilcox		
	Test 9, Wilcox	Test 8, Wilcox		
	Test 13, Jackson	Test 9, Wilcox		
	Test 15, Jackson	Test 13, Jackson		
		Test 14, Jackson		
		Test 15, Jackson		
		Test 16, Jackson		

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[a] Particulate - in-line sampling was conducted to obtain a particulate sample from the combustion gas after the cyclone and before the spray tower.

Table 4-4

CHEMICAL CHARACTERIZATION OF TEXAS LIGNITE FBC SOLID WASTE

Parameter	Digest/Extract Analyzed	Analytical Technique
Ag	PAD[a]	ETAAS[b]
Al	$LiBO_2$[c]	ICPES[d]
As	PAD	ETAAS
B	Na_2CO_3[e]	ICPES
Ba	$LiBO_2$	ICPES
Be	PAD	ICPES
Ca	$LiBO_2$	ICPES
Cd	PAD	ETAAS
Cl	Na_2CO_3	Titrimetry[f]
Co	PAD	ICPES
Cr	PAD	ICPES
Cu	PAD	ICPES
Fe	$LiBO_2$	ICPES
Hg	Oxygen Bomb	CVAAS[g]
K	$LiBO_2$	ICPES
Mg	$LiBO_2$	ICPES
Mn	$LiBO_2$	ICPES
Mo	PAD	ICPES
Na	$LiBO_2$	ICPES
Ni	PAD	ICPES
Pb	PAD	ETAAS
S	PAD	ICPES
Sb	PAD	ETAAS
Se	PAD	ETAAS
Si	$LiBO_2$	ICPES
SO_4	HCl Extract	Turbidimetry[h]
Sr	$LiBO_2$	ICPES
Ti	$LiBO_2$	ICPES
Tl	PAD	ETAAS
V	PAD	ICPES
Zn	$LiBO_2$	ICPES

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[a] Perchloric acid digestion

[b] Electrothermal (graphite furnace) atomic absorption spectroscopy

[c] Lithium metaborate fusion

[d] Inductively coupled argon plasma emission spectroscopy

[e] Sodium carbonate fusion

[f] Titration with mercuric nitrate, diphenylcarbazone indicator

[g] Cold vapor atomic absorption spectroscopy

[h] Determination as barium sulfate

Table 4-5

CHEMICAL COMPOSITION OF FBC SOLID WASTES - WILCOX TESTS[a]

Source	Test #3			Test #8		
	Lignite[b]	Bed	Baghouse	Lignite[b]	Bed	Baghouse
Limestone Addition, Ca/S		0			5.06	
Bed Temperature, °F		1533			1526	
Ag		<0.25	0.47		<0.25	0.32
Al	10%	5.2%	10%	10%	6.2%	8.4%
As		14	33		17	28
B		230	440		260	390
Ba		520	1000		310	630
Be		1.9	5.5		2.2	4.2
Ca	3.8%	4800	4.3%	3.6%	9.7%	11%
Cd		0.25	0.45		0.20	0.35
Cl		4700	1700		1660	1950
Co		9.3	30		10	23
Cr		44	140		65	100
Cu		47	100		42	83
Fe	1.9%	7400	1.9%	2.1%	9400	1.6%
Hg		<0.1	0.9		0.2	<0.1
K	8000	4300	6600	8500	5600	6600
Mg	9400	3200	1.1%	1.0%	4400	9300
Mn		70	390		220	420
Mo		32	41		19	27
Na	2900	2500	4300	3200	2900	4000
Ni		24	110		32	62
Pb		24	55		25	73
S		280	4700		5100	1.6%
Sb		<1.3	3.7		2.0	2.9
Se		<0.75	16		<0.75	11
SO_4		160	610		650	2200
Si	30%	37%	30%	29%	32%	26%
Sr		89	680		140	490
Ti	8000	2900	8000	7300	3600	6500
Tl		<1	<1		1.5	<1
V		99	225		110	175
Zn		32	48		46	58

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[a] All results expressed as μg/g except as indicated.

[b] Mineral analysis of lignite ash for comparison with solid waste characteristics.

Table 4-6

CHEMICAL COMPOSITION OF FBC SOLID WASTES - JACKSON TESTS[a]

Source	Test #13				Test #15		
	Lignite	Bed	Baghouse	Spray Tower	Lignite	Bed	Baghouse
Limestone Addition, Ca/S		0				2.23	
Bed Temperature, °F		1414				1546	
Ag		<0.25	<0.25	<0.25		<0.25	<0.25
Al	8.5%	3.0%	8.2%	7.7%	8.6%	3.1%	6.6%
As		8.3	71	52		22	39
B		170	1080	ND[c]		450	930
Ba		220	1600	5000		240	1200
Be		1.3	15	13		1.5	12
Ca	3.9%	7200	4.3%	4.4%	4.3%	29%	15%
Cd		0.20	0.62	0.55		0.10	0.35
Cl		5400	1570	ND		3400	3250
Co		<1.5	21	18		<1.5	16
Cr		16	130	115		22	82
Cu		4.3	27	39		1.1	27
Fe	3.6%	5200	3.9%	3.9%	3.1%	6000	3.0%
Hg		<0.1	0.2	0.6		<0.1	<0.1
K	1.6%	4000	1.3%	1.6%	1.6%	6100	1.1%
Mg	4700	1500	5000	5100	8600	2900	5300
Mn		45	520	430		430	610
Mo		8.9	38	41		5.6	30
Na	2.8%	7300	2.6%	2.5%	2.6%	9200	2.2%
Ni		18	160	130		12	77
Pb		21	54	48		9.0	32
S		510	1.4%	1.0%		6.6%	3.2%
Sb		<1.25	2.4	2.1		4.5	2.6
Se		<0.75	14	8.0		<0.75	5.7
SO_4		220	1900	ND		5400	4750
Si	25%	38%	22%	ND	25%	14%	17%
Sr		160	920	950		230	760
Ti	4500	1100	4400	4200	4500	1400	3800
Tl		<1	<1	<1		2.2	<1
V		15	96	110		10	89
Zn		83	146	93		96	140

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[a] All results expressed as μg/g except as indicated.

[b] Mineral analysis of lignite ash for comparison with solid waste characteristics.

[c] Not determined; analysis performed on perchloric acid digest only.

Table 4-7

CHEMICAL COMPOSITION OF FLY ASH FROM NORTHERN GREAT PLAINS (NORTH DAKOTA) LIGNITE[a,b]

Parameter	Quantitative Analysis[c]	Semiquantitative Analysis[d]
Ag		0.5
Al	6.2%	
As		45
B	310	
Ba	1.2%	
Be		2
Ca	19.3%	
Cd		0.8
Cl		41
Co		10
Cr		41
Cu		49
Fe	7.8%	
Hg	ND[e]	ND
K	0.85%	
Mg	6.2%	
Mn		>1000
Mo		8
Na	2.2%	
Ni		22
Pb		30
S	2.7%	
Sb		3
Se		7
SO_4	ND	ND
Si	11.7%	
Sr	1.3%	
Ti	0.31%	
Tl		1
V		120
Zn		27

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[a] Radian Corporation, Chemical/Physical Stability of Flue Gas Cleaning Wastes, Final Report to Electric Power Research Institute by Radian Corporation, Austin, Texas (January 1979).

[b] All results expressed in μg/g except as indicated.

[c] Atomic absorption or spectrophotometric analysis; relative accuracy is ±5 percent.

[d] Spark source mass spectrometric analysis; relative accuracy is ±100 percent.

[e] Not determined.

copper, lead, selenium, silver, and thallium in the North Dakota fly ash and Texas lignite FBC baghouse ash are comparable. The levels of beryllium, chromium, nickel, and zinc are higher for the Texas lignite but these elements appear in low concentration and at levels only two to five times those found in the North Dakota fly ash.

Supplementary chemical analyses were performed on various Texas lignite samples to establish material and energy balances. The results of the supplementary analyses are presented in Table 4-8. The loss of ignition (LOI) and total organic carbon (TOC) tests were performed to determine the amount of total carbon and organic carbon present, respectively.

4.3 LEACHABILITY CHARACTERIZATION OF TEXAS LIGNITE FBC SOLID WASTE

The leachability of the solid waste determines its disposal requirements and is, therefore, a very important characteristic. To address this concern, samples of bed drain material, baghouse catch, and bed/baghouse composite were subjected to extraction procedures (EP) outlined by the Resource Conservation and Recovery Act (RCRA) and the Texas Department of Water Resources (TDWR). The leachates generated were analyzed and the results compared to appropriate regulatory criteria. The parameters determined for the RCRA and TDWR extractions are listed in Table 4-9 with the analytical methods used to characterize the leachates.

The RCRA EP (<u>Federal Register</u>, Vol. 45, 18 May 1980) was developed in an effort to define the toxicity, and therefore hazard, of a solid waste by the level of specified elements in the leachate generated. This EP calls for equilibrating wastes with water and acetic acid at a pH of 5±0.1. The slurry must be stirred or shaken for 24 hours after which the solids are filtered off and the filtrate diluted to a volume equal to 20 times the original weight of the solids. The diluted filtrate is analyzed for eight elements specified by the EPA. If any of the eight elements in the filtrate exceed 100 times the National Interim Primary Drinking Water Standards (NIPDWS) for these elements, the solid waste under study is classified as hazardous with regard to toxicity.

Table 4-8

SUPPLEMENTARY CHEMICAL ANALYSES OF TEXAS LIGNITE FBC SOLID WASTES

Sample Type	Lignite/Test	Ca[a]	K[a]	Na[a]	S[a]	LOI[b]	TOC[c]
Bed Material	Wilcox/1	2300	1600	1100	240	0.15	0.04
	Wilcox/2	4500	3800	1800	360	0.25	0.04
	Wilcox/3	4800	4300	2500	280	0.18	0.06
	Wilcox/4	4800	4800	2600	180	0.09	0.03
	Wilcox/6	5.9%	4500	2600	7400	1.30	0.07
	Wilcox/7	7.3%	4700	2700	4900	2.04	0.14
	Wilcox/8	9.7%	5600	2900	5100	2.55	0.15
	Wilcox/9	11.0%	6200	3800	4000	1.83	0.06
	Jackson/13	7200	4000	7300	510	0.49	-
	Jackson/15	29%	6100	9200	6.6%	0.53	-
Baghouse Ash	Wilcox/3	4.3%	6600	4300	4700	1.26	-
	Wilcox/8	11.0%	6600	4000	1.6%	2.27	-
	Jackson/13	4.3%	1.3%	2.6%	1.4%	5.27	-
	Jackson/15	15%	1.1%	2.2%	3.2%	1.67	-
Particulate	Wilcox/1	4.1%	6900	5600	5500	2.83	0.69
	Wilcox/2	3.9%	6800	4400	5900	2.30	0.79
	Wilcox/3	3.7%	5900	4100	3000	1.02	0.53
	Wilcox/4	3.8%	6400	4200	1700	0.56	0.54
	Wilcox/6	7.2%	6200	4200	1.0%	1.84	0.67
	Wilcox/7b	11.0%	6100	4900	2.0%	6.19	0.75
	Wilcox/7c	11.0%	6800	4300	1.6%	2.81	0.89
	Wilcox/8	13.0%	6800	4500	1.7%	3.41	0.45
	Wilcox/9	13.0%	6500	4500	1.7%	3.01	0.54
	Jackson/13	4.0%	1.7%	2.8%	1.0%	6.65	1.35
	Jackson/14	11%	1.4%	2.3%	2.6%	5.08	1.06
	Jackson/15	13%	1.4%	2.3%	2.8%	2.87	0.48
	Jackson/16	9.8%	1.5%	2.6%	2.1%	3.99	0.50
Limestone	Wilcox/6	39%	2800	3100	1.2%	41.01	4.46
	Wilcox/8	39%	2800	3200	1.1%	40.90	4.98
Spray Tower Deposit	Jackson/13	4.4%	1.6%	2.5%	1.0%	5.43	-

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[a] All element concentrations in μg/g unless otherwise indicated.

[b] Results of Loss on Ignition (LOI) testing reported in percent loss.

[c] Results of Total Organic Carbon (TOC) analyses in percent carbon, dry weight basis.

Table 4-9

CHEMICAL CHARACTERIZATION OF RCRA AND TDWR LEACHATES

Parameter	Analytical Technique	
	RCRA Leachate	TDWR Leachate
Ag	ETAAS[a]	ETAAS
Al	ICPES[b]	ICPES
As	HGAAS[c]	HGAAS
B	ICPES	ICPES
Ba	ICPES	ICPES
Be	ICPES	ICPES
Ca	ICPES	ICPES
Cd	ETAAS	ETAAS
Cl	-	Titrimetry[d]
Co	ICPES	ICPES
Cr	ICPES	ICPES
Cu	ICPES	ICPES
Fe	ICPES	ICPES
Hg	CVAAS[e]	CVAAS
K	ICPES	ICPES
Mg	ICPES	ICPES
Mn	ICPES	ICPES
Mo	ICPES	ICPES
Na	ICPES	ICPES
Ni	ICPES	ICPES
Pb	ETAAS	ETAAS
pH	-	Potentiometry[f]
S	ICPES	ICPES
Sb	ETAAS	ETAAS
Se	HGAAS	HGAAS
Si	ICPES	ICPES
SO_4	-	Turbidimetry[g]
Sr	ICPES	ICPES
TDS[h]	-	Gravimetry
Ti	ICPES	ICPES
Tl	ETAAS	ETAAS
V	ICPES	ICPES
Zn	ICPES	ICPES
α	α Counting	-
β	β Counting	-

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[a] Electrothermal (graphite furnace) atomic absorption spectroscopy

[b] Inductively coupled argon plasma emission spectroscopy

[c] Hydride generation atomic absorption spectroscopy

[d] Titration with mercuric nitrate, diphenylcarbazone indicator

[e] Cold vapor atomic absorption spectroscopy

[f] Glass electrode

[g] Determination as barium sulfate

[h] Total dissolved solid

The results of the RCRA extractions and accompanying chemical analyses are listed in Tables 4-10 and 4-11 for the Wilcox and Jackson wastes, respectively. The RCRA limits for the eight regulated elements are also included for the convenience of the reader. None of the Texas lignite FBC wastes showed leachate concentrations high enough in the regulated elements to be classified as hazardous. In fact, the levels encountered for the eight elements were one to two orders of magnitude less than the RCRA limits.

The RCRA leachates were also analyzed for gross alpha and gross beta activity. Although no RCRA limit currently exists for alpha and beta activity, the RCRA leachates were analyzed to define leachable alpha and beta activity under the fairly rigorous conditions of a RCRA extraction. The limits for alpha and beta activity established by NIPDWS (State Drinking Water Act, Code of Federal Regulations, Title 40, Part 141) are listed in Tables 4-10 and 4-11 for comparison only. For all samples tested, the leachates contained alpha and beta activities below the NIPDWS limits.

The rules of the Texas Department of Water Resources go further than RCRA in that TDWR classifies wastes according to degree of hazard. Currently, three classifications of wastes exist. Two EP's are used to classify wastes according to TDWR toxicity (leachability). The RCRA EP and the RCRA limits described above distinguish between the Class I (most hazardous) and Class II (intermediate hazard) wastes. The RCRA results presented above indicate that the Texas lignite FBC wastes are not Class I wastes. A deionized water EP developed by TDWR serves to distinguish between Class II (intermediate hazard) and Class III (inert, insoluble) wastes.

The TDWR EP calls for equilibrating wastes with a volume of water four times the weight of the waste studied. The slurry is stirred mechanically for five minutes at low speed. The extraction vessel is then stoppered and allowed to stand seven days. At the end of this period, the supernatant solution is filtered and the filtered leachate analyzed for the parameters regulated by NIPDWS. If any of the elements exceed the NIPDWS limits, the waste is classified as a Class II waste. Otherwise, the waste is a Class III waste.

Table 4-10

ANALYSIS OF RCRA LEACHATES - WILCOX LIGNITE FBC WASTES[a]

	Test #3			Test #8			
Source	Bed	Baghouse	Composite[b]	Bed	Baghouse	Composite[b]	RCRA Limits[c]
Limestone Addition, Ca/S	0			5.06			
Bed Temperature, °F	1533			1526			
Ag	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	5
Al	0.096	8.3	4.9	0.050	1.3	1.2	-
As	<0.003	<0.003	<0.003	<0.003	0.020	0.019	5
B	1.1	1.5	1.3	0.010	1.8	1.8	-
Ba	1.3	0.060	0.037	3.3	0.48	0.83	100
Be	<0.0005	<0.0005	0.004	<0.0005	<0.0005	<0.0005	-
Ca	26	650	560	3300	2600	2400	-
Cd	<0.0005	0.0006	<0.0005	<0.0005	<0.0005	<0.0005	1
Co	0.010	0.043	0.015	<0.006	<0.006	0.050	-
Cr	0.008	0.027	0.028	0.023	0.13	0.16	5
Cu	0.021	0.053	0.040	<0.001	0.13	0.19	-
Fe	<0.008	0.10	0.065	<0.008	0.022	0.027	-
Hg	<0.0002	<0.0002	<0.0002	<0.0002	0.0003	<0.0002	0.2
K	5.5	17	16	4.5	14	12	-
Mg	2.5	99	87	0.21	61	31	-
Mn	0.31	2.4	2.1	0.004	1.3	0.028	-
Mo	0.007	0.011	0.056	<0.002	0.029	0.30	-
Na	2.5	7.8	8.0	2.2	7.0	6.6	-
Ni	0.010	0.19	0.021	<0.003	0.014	0.067	-
Pb	0.010	<0.002	<0.002	0.003	<0.002	<0.002	5
S	2.9	120	98	63	230	220	-
Sb	0.006	<0.005	<0.005	<0.005	0.029	0.025	-
Se	<0.004	0.038	0.032	<0.004	0.067	0.035	1
Si	7.5	60	52	0.55	31	16	-
Sr	0.13	7.3	6.2	0.32	3.2	2.3	-
Ti	0.019	<0.005	0.010	<0.005	0.25	0.36	-
Tl	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004	-
V	0.047	<0.003	0.054	0.040	0.46	0.82	-
Zn	0.052	0.13	0.12	<0.003	0.050	0.048	-
α[d]	1.3	5.0	3.8	<1.9	4.6	<1.8	(15)[e]
β[d]	11	<0.8	8.8	1.8	<0.8	<1.0	(50)[e]

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[a] All data expressed as μg/ml except as indicated.

[b] 15% bed material: 85% baghouse ash composite.

[c] *Federal Register*, Vol. 45, 18 May 1980.

[d] Radioactivity data expressed as pCi/ℓ.

[e] No RCRA limit; limit established by Safe Drinking Water Act, *Code of Federal Regulations*, Title 40, Part 141.

Table 4-11

ANALYSIS OF RCRA LEACHATES - JACKSON LIGNITE FBC WASTES[a]

	Test #13			Test #15			
Source	Bed	Baghouse	Composite[b]	Bed	Baghouse	Composite[b]	RCRA Limits[c]
Limestone Addition, Ca/S	0			2.23			
Bed Temperature, °F	1414			1546			
Ag	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	5
Al	0.053	5.1	5.2	3.3	1.8	3.2	-
As	<0.003	0.010	0.010	<0.003	0.013	0.005	5
B	1.1	30	26	1.9	4.7	4.2	-
Ba	0.16	0.040	0.080	1.5	1.1	1.2	100
Be	<0.0005	0.004	0.003	0.005	0.012	0.003	-
Ca	42	970	870	2300	2500	2200	-
Cd	<0.0005	0.0018	0.0018	<0.0005	<0.0005	<0.0005	1
Co	<0.006	0.021	0.023	0.026	0.011	0.020	-
Cr	0.006	0.024	0.029	0.040	0.025	0.039	5
Cu	0.006	0.033	0.039	0.055	0.029	0.052	-
Fe	0.22	0.14	0.14	0.16	0.078	0.14	-
Hg	<0.0002	<0.0002	<0.0002	0.0011	<0.0002	<0.0002	0.2
K	1.3	14	15	13	7.9	14	-
Mg	1.4	40	35	4.3	3.5	4.0	-
Mn	0.13	5.8	4.9	0.066	0.038	0.062	-
Mo	0.005	0.030	0.035	0.43	0.038	0.050	-
Na	8.4	96	82	7.4	35	34	-
Ni	0.026	0.091	0.093	0.24	0.013	0.022	-
Pb	<0.002	0.003	<0.002	<0.002	<0.002	<0.002	5
S	9.5	280	250	1200	1100	1100	-
Sb	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	-
Se	<0.003	0.009	0.012	<0.003	<0.003	<0.003	1
Si	5.6	38	35	1.7	12	3.2	-
Sr	0.25	7.8	6.9	0.46	2.2	1.9	-
Ti	0.018	0.063	0.074	0.062	0.056	0.10	-
Tl	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004	-
V	0.045	0.046	0.056	0.084	0.053	0.083	-
Zn	0.012	0.62	0.054	0.13	0.068	0.12	-
α[d]	<1.2	5.7	1.9	<1.8	<1.3	<1.3	(15)[e]
β[d]	8.6	21	23	<1.0	<0.8	<0.8	(50)[e]

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[a] All data expressed as μg/ml except as indicated.

[b] 15% bed material: 85% baghouse ash composite.

[c] Federal Register, Vol. 45, 18 May 1980.

[d] Radioactivity data expressed as pCi/ℓ.

[e] No RCRA limit; limit established by Safe Drinking Water Act, Code of Federal Regulations, Title 40, Part 141.

The results of the TDWR extractions and the accompanying chemical analyses are listed in Tables 4-12 and 4-13. The NIPDWS limits are also presented.

While the majority of the NIPDWS parameters determined were present at levels less than the NIPDWS limits, certain TDWR leachates contained barium, chromium, and selenium at levels greater than the NIPDWS limits. Thus, according to TDWR rules, the solid wastes tested during this program must be classified as Class II and Class III wastes as shown in Table 4-14. These classifications must be regarded as preliminary in nature. It is interesting to note that the composites for all the tests presented in Table 4-14 are classified as Class II wastes even though the bed material in Test 3, the baghouse ash in Test 15, and both the bed and baghouse ash in Test 13 are classified as Class III. While TDWR rules require that quadruplicate samples of waste be leached and all results reported, only a single sample of each waste was leached during this program. However, one of the Texas lignite wastes was leached and analyzed in duplicate and the results obtained agreed well.

The extent to which the offending elements exceed the respective NIPDWS is best illustrated by calculation of a discharge severity (DS) for each element and TDWR leachate; see Table 4-15. The DS is the ratio of observed concentration to a standard concentration, here the respective NIPDWS limits. The DS for barium and chromium in the TDWR leachates was generally less than three. Apparently, limestone addition (Tests 8 and 15) rendered barium and chromium more susceptible to leaching. Of greater concern is the level of selenium in the baghouse ash and composite from Test 3. It should be noted that limestone addition produced solid wastes from which selenium was less easily leached.

4.4 PHYSICAL CHARACTERIZATION OF TEXAS LIGNITE FBC SOLID WASTE

Typically, there are three issues of concern in waste disposal: (1) assessment of the environmental impacts on air, water, and land; (2) the identification of disposal technology consistent with preventing adverse impacts; and (3) evaluation of economic implications of implementing the appropriate

Table 4-12

ANALYSIS OF TDWR LEACHATES - WILCOX LIGNITE FBC WASTES[a]

Source	Test #3			Test #8			Primary Drinking Water Standards[c]
	Bed	Baghouse	Composite[b]	Bed	Baghouse	Composite[b]	
Limestone Addition, Ca/S	0			5.06			
Bed Temperature, °F	1533			1526			
Ag	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.05
Al	0.20	1.7	1.1	<0.050	1.3	0.26	-
As	0.011	0.010	<0.008	<0.003	<0.003	<0.003	0.05
B	0.57	20	18	<0.010	0.10	0.033	-
Ba	0.35	1.4	1.6	2.3	1.7	3.0	1
Be	<0.0005	0.003	0.003	<0.0005	<0.0005	<0.0005	-
Ca	44	770	700	1040	580	560	-
Cd	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	0.01
Cl	1.2	24	15	8.0	11	21	-
Co	<0.006	0.043	0.025	<0.006	<0.006	<0.006	-
Cr	<0.001	0.011	0.077	0.033	0.061	0.017	0.05
Cu	<0.001	0.012	0.062	0.009	<0.001	<0.001	-
Fe	<0.008	0.051	0.027	0.025	<0.008	<0.008	-
Hg	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	0.002
K	7.3	19	17	49	48	54	-
Mg	1.4	4.5	4.4	0.23	0.13	0.060	-
Mn	<0.001	0.014	0.010	0.003	0.002	0.007	-
Mo	0.063	0.076	0.064	0.090	0.039	0.033	-
Na	8.9	26	22	9.7	28	32	-
Ni	<0.003	0.031	0.015	<0.003	<0.003	<0.003	-
Pb	<0.002	<0.002	<0.002	<0.002	0.003	0.004	0.05
pH[d]	9.8	10.3	10.3	12.3	12.1	12.1	-
S	21	360	290	120	70	51	-
Sb	0.025	0.013	0.014	<0.005	<0.005	<0.005	-
Se	<0.004	0.33	0.33	<0.004	<0.004	<0.004	0.01
Si	13	5.3	5.2	0.44	2.1	1.8	-
SO_4	54	2030	121	360	220	280	-
Sr	0.19	6.9	6.4	2.3	3.8	3.7	-
TDS[e]	218	2770	2550	2320	1520	1500	-
Ti	<0.005	0.022	0.12	0.020	<0.005	<0.005	-
Tl	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004	-
V	0.12	0.087	0.093	0.080	0.043	0.049	-
Zn	<0.003	0.028	0.015	<0.003	<0.003	<0.003	-

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[a] All data expressed as µg/ml except as indicated.

[b] 15% bed material: 85% baghouse ash composite.

[c] Safe Drinking Water Act, Code of Federal Regulations, Title 40, Part 141.

[d] Conventional pH units.

[e] Total dissolved solids.

Table 4-13

ANALYSIS OF TDWR LEACHATES - JACKSON LIGNITE FBC WASTES[a]

Source	Test #13 Bed	Test #13 Baghouse	Test #13 Composite[b]	Test #15 Bed	Test #15 Baghouse	Test #15 Composite[b]	Primary Drinking Water Standards[c]
Limestone Addition, Ca/S	0			2.23			
Bed Temperature, °F	1414			1546			
Ag	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.05
Al	0.25	11	14	0.41	0.39	0.31	-
As	0.023	0.077	0.079	<0.003	<0.003	<0.003	0.05
B	0.96	61	54	3.8	1.7	1.8	-
Ba	0.37	0.37	0.49	2.5	0.81	1.0	1
Be	<0.0005	0.001	0.001	0.001	<0.0005	0.001	-
Ca	74	790	760	2000	720	840	-
Cd	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	0.01
Cl	<1	99	84	99	203	120	-
Co	<0.006	0.059	0.058	0.023	<0.006	<0.006	-
Cr	<0.001	0.012	0.019	0.080	0.032	0.052	0.05
Cu	0.003	0.015	0.014	0.083	0.009	0.051	-
Fe	0.010	0.070	0.060	0.044	<0.008	0.033	-
Hg	<0.0002	0.0007	0.0004	<0.0002	0.0003	0.0010	0.002
K	2.2	13	12	14	49	45	-
Mg	2.1	1.7	1.6	0.88	0.35	0.55	-
Mn	0.11	0.020	0.019	0.013	0.006	0.008	-
Mo	0.066	1.1	0.096	0.058	0.019	0.052	-
Na	21	310	260	30	420	370	-
Ni	<0.003	0.047	0.053	0.005	<0.003	<0.003	-
Pb	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	0.05
pH[d]	6.6	9.8	10.1	12.0	12.0	12.0	-
S	45	760	650	4800	430	430	-
Sb	0.012	<0.005	<0.005	<0.005	<0.005	<0.005	-
Se	<0.004	0.009	0.012	<0.004	<0.004	<0.004	0.01
Si	5.2	2.3	2.1	0.67	4.8	2.6	-
SO_4	185	1990	1820	710	1410	1170	-
Sr	0.61	7.4	7.0	2.9	4.2	5.0	-
TDS[e]	344	4210	3890	4570	3750	3670	-
Ti	0.009	0.29	0.027	0.16	0.034	0.11	-
Tl	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004	-
V	0.067	0.062	0.065	0.030	0.074	0.078	-
Zn	<0.003	0.034	0.033	0.024	0.005	0.017	-

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[a] All data expressed as μg/ml except as indicated.

[b] 15% bed material: 85% baghouse ash composite.

[c] Safe Drinking Water Act, Code of Federal Regulations, Title 40, Part 141.

[d] Conventional pH units.

[e] Total dissolved solids.

Table 4-14

CLASSIFICATION OF TEXAS LIGNITE FBC WASTES ACCORDING TO TDWR RULES

Test	Bed Material	Baghouse Ash	Composite
3	Class III	Class II[a,c]	Class II[a,b,c]
8	Class II[a]	Class II[b,c]	Class II[a]
13	Class III	Class III	Class II[c]
15	Class II[a,b]	Class III	Class II[a,b]

---

[a] Barium exceeded NIPDWR limit.

[b] Chromium exceeded NIPDWR limit.

[c] Selenium exceeded NIPDWR limit.

Table 4-15

DISCHARGE SEVERITIES FOR Ba, Cr, AND Se: TDWR LEACHATES[a]

		Discharge Severity		
Element	Lignite/Test	Bed	Baghouse	Composite
Ba	Wilcox/Test 3	0.4	1.4	1.6
	Wilcox/Test 8	2.3	1.7	3.0
	Jackson/Text 13	0.4	0.4	0.5
	Jackson/Test 15	2.5	0.8	1.0
Cr	Wilcox/Test 3	<0.02	0.2	1.5
	Wilcox/Test 8	0.7	1.2	0.3
	Jackson/Test 13	<0.02	0.2	0.4
	Jackson/Test 15	1.6	0.6	1.0
Se	Wilcox/Test 3	<0.4	33	33
	Wilcox/Test 8	<0.4	<0.4	<0.4
	Jackson/Test 13	<0.4	0.9	1.2
	Jackson/Test 15	<0.4	<0.4	<0.4

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[a] $$\text{Discharge Severity} = \frac{\text{observed concentration}}{\text{NIPDWS limit}}$$

disposal technologies. The physical characteristics of the FBC wastes affecting these disposal issues are addressed in this section. To evaluate the solid residues from FBC of Texas lignite with respect to waste disposal, laboratory tests were performed to predict the physical characteristics using established procedures approved by the American Society of Testing and Materials (ASTM) whenever possible. Several different variables affecting disposal were considered in the physical laboratory tests. These included:

- effect of different lignites burned,
- effect of limestone addition to the AFBC boiler, and
- separate and combined disposal of bed drain materials and baghouse catch.

The following describes AFBC waste materials in general from a physical standpoint, the experimental approach used to define the physical characteristics of these AFBC wastes, results of the physical characterization, and conclusions drawn from the physical testing results.

4.4.1 Disposal Materials

The solid residues from AFBC processes have potential for use as concrete additives, agricultural additives, and as aggregate in asphalt and concrete. However, the bulk of future AFBC wastes may likely be disposed in landfills. The investigation of physical properties was therefore conducted with an emphasis on the potential problems associated with landfill disposal. The following three areas of concern were investigated:

- handleability - the bulk volume of wastes and expected void ratios in transport and disposal;
- strength development - the load-bearing capacity and compaction properties as a function of moisture; and
- permeability - the rate at which water will pass through the waste, defining the quantity of leachate.

These parameters were defined for baghouse materials and bed materials separately and for composited mixtures of the two wastes.

The relative amounts of baghouse ash and coarser bed drain used for the physical testing were defined by approximate production rates of these materials estimated from individual test runs. Varying ratios of bed and baghouse materials will characterize an operating facility depending on the combustor design, temporary storage facilities, and operating conditions. The mass ratio of baghouse to bed materials selected in this study to examine physical properties resulting from codisposal was 85:15 based on preliminary flow rate data from CPC and the constraints of sample availability.

4.4.2 Physical Testing Approach

Six types of tests were performed to determine the following physical properties of the AFBC wastes: (1) the specific gravity, (2) the apparent bulk density, (3) particle size distribution, (4) the compaction behavior, (5) the permeability, and (6) the unconfined compressive strength.

The specific gravity and the apparent bulk density are used to determine the difference between how much volume a mass of the solid waste alone will occupy compared to how much volume the same mass of solids will occupy with natural voids between the individual particles (assuming little or no compaction during disposal). Determining the void volume allows for proper planning of the space necessary in transport and final disposal.

The particle morphology and particle size distribution directly affect the volume of these void spaces. If a material contains only coarse irregular aggregates, the void volume may be much higher in the bulk material than for a blend of small and large particles in which the small particles can fill the voids created by the coarser aggregates. Achieving a proper particle size distribution allows maximum volume efficiency.

Compaction tests are performed to determine the moisture content of the wastes at which maximum compacted density is obtained. The wet and dry bulk densities of the waste at different moisture contents are also determined during compaction tests.

The permeability of the disposal material influences the quantity of leachate that will be produced. The permeability is extremely important, especially if the quantity of leachate is environmentally unacceptable. If the waste forms an impermeable layer during hydration, water contaminated with soluble waste species will not leave the disposal site or will leave at such a slow rate that groundwater dilution will counteract any negative impact.

The permeability of the solid waste is related to the unconfined compressive strength. As the waste forms a stronger barrier (a higher unconfined compressive strength), it becomes more impervious (lower permeability). Therefore, high strength development is desirable in terms of potential leachate quantity as well as structural stability. For normal operation of a landfill disposal site, a waste must provide structural stability suitable to support the weight of the heavy equipment used to move the wastes.

The overall evaluation of the physical characteristics of the wastes helps to define the necessary degree of processing alternatives, transportation options, and disposal requirements.

4.4.3 Physical Characterization Results

Specific Gravity and Apparent Bulk Density. The specific gravities for the bed, baghouse, and composited bed/baghouse wastes were determined by ASTM Method D854 using a volume displacement technique. These results are given in Table 4-16. The apparent bulk densities for these same materials were determined by measuring the volume of a given mass of the solids after controlled vibrational taps simulating minimal compaction and setting. These results are also given in Table 4-16. The specific gravity indicates the disposal volume under saturated conditions while the apparent bulk density

Table 4-16

RESULTS OF SPECIFIC GRAVITY AND APPARENT BULK DENSITY DETERMINATIONS FOR TEXAS LIGNITE FBC RESIDUES AS RECEIVED (UNCOMPACTED)

Sample Description	Specific Gravity	Apparent Bulk Density (g/cc)	Calculated Percent Void Volume[a] (%)
Wilcox Bed #3	2.61	1.54	41
Wilcox Bed #8	2.60	1.38	47
Jackson Bed #13	2.61	1.70	35
Jackson Bed #15	2.74	1.62	41
Wilcox Baghouse #3	2.46	0.78	68
Wilcox Baghouse #8	2.53	0.86	66
Jackson Baghouse #13	2.35	0.64	73
Jackson Baghouse #15	2.41	0.82	66
Wilcox Composite[b] #3	2.46	0.78	68
Wilcox Composite #8	2.53	0.86	66
Jackson Composite #13	2.38	0.70	71
Jackson Composite #15	2.51	0.90	64

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[a] $$\% \text{ Void Volume} = \left(1 - \frac{\text{apparent bulk density}}{\text{specific gravity}}\right) \times 100\%$$

[b] Composite samples were prepared by mixing the bed and baghouse materials in the ratio of 15:85 by weight.

measures the disposal volume under "no-saturation" conditions. A comparison of the two mass/volume ratios defines the void volume for the wastes. The higher the void volume is for a waste, the higher the disposal volume necessary. These values are indicative of disposal volumes prior to compaction.

The specific gravity for all materials tested ranged from 2.35 to 2.74. These data are consistent with specific gravity determinations for other FBC wastes in current Radian studies and are similar to the specific gravities generally observed for ash materials from conventional coal combustion.

The specific gravity of the bed materials ranged from 2.60 to 2.74. These values were the same (2.60 to 2.61) for three of the bed materials while the Jackson #15 bed drain was slightly more dense (2.74). The specific gravity of the baghouse materials ranged from 2.35 to 2.53, while the composites ranged from 2.38 to 2.53.

The apparent bulk density results are also given in Table 4-16. These values ranged from 1.38 to 1.70 g/cc for the bed materials, 0.64 to 0.86 g/cc for the baghouse materials, and from 0.70 to 0.90 g/cc for the composited samples. These results show that the bed materials containing more grades of particles resulted in higher mass to volume ratio (lower void volumes) before compaction. The percent void volumes ranged from 35 to 47 percent for the bed materials, from 66 to 73 percent for the baghouse materials, and from 64 to 71 percent for the composites. The void volumes are generally lower for the bed materials because there is a larger particle size distribution. Normally, the larger the particle size range, the better the voids are filled. The baghouse material has a small particle size range resulting in a larger void volume. Compositing the bed and baghouse materials should theoretically decrease the void volumes; however, adding only 15 percent bed material by weight did not appear to significantly enhance the apparent bulk density or void volume. The void volumes were slightly higher in the bed materials and lower in the baghouse materials when limestone was added during the combustion process for both the Jackson and Wilcox FBC wastes. No major differences per collection point are apparent, and these physical properties appear uniform and generally unaffected by the different lignites or different combustion conditions for these isolated samples.

Compaction. The compaction properties of the composited wastes (85 weight percent baghouse and 15 weight percent bed material) were determined using the procedure ASTM D698. Table 4-17 and Figure 4-1 show the moisture-density relationships of these wastes. Two parameters are important here: the optimum moisture content and the compacted maximum bulk density at that point. The optimum moisture content shows at what percentage moisture the greatest compacted density will be obtained. The optimum moisture was higher for the wastes that had no limestone addition (Wilcox #3 and Jackson #13).

In general, an increase in the maximum bulk density is important because it results in a decrease in the disposal area required if the materials undergo compaction. The highest maximum bulk density was achieved by the composite from the Wilcox #8 test. The Wilcox wastes appeared to have higher maximum bulk densities (1.29, 1.40 g/cc) at the optimum moisture than the Jackson materials (1.25, 1.29 g/cc). It should be noted that it may be possible to achieve higher bulk densities by decreasing the baghouse/bed ratios and thus increasing the particle size distribution.

The compaction is related to the specific gravity and particle size distribution of the waste materials. A higher specific gravity and a larger particle size distribution normally account for better compaction. The shape of the moisture/density curve indicates the compaction behavior. If the curve is steep (see Wilcox #8, Figure 4-1), the optimum moisture must be more carefully achieved for the desired level of compaction. The other composites demonstrate gentler curves.

Particle Size Distribution. The gross particle size distributions were determined for the AFBC materials using four sieves and a standard dry sieve particle size technique described in method ASTM D422. The results are presented in Table 4-18.

Table 4-17

RESULTS OF COMPACTION DATA

Sample I.D.	Moisture ($\%$ H_2O)	Wet Bulk Density		Dry Bulk Density	
		lb/ft^3	g/cc	lb/ft^3	g/cc
Wilcox #3 Composite	42.7	104.4	2.91	73.1	1.17
	41.4	104.4	2.91	73.8	1.18
	30.5	105.0	1.68	80.4	1.29
	27.7	96.0	1.54	75.5	1.21
	25.2	94.5	1.51	75.5	1.21
Wilcox #8 Composite	33.2	105.6	1.69	79.3	1.27
	27.0	110.7	1.77	87.2	1.40
	25.0	105.3	1.68	84.2	1.35
	22.1	100.2	1.60	82.1	1.31
Jackson #13 Composite	37.4	102.3	1.64	74.5	1.19
	34.0	104.1	1.67	77.7	1.25
	30.8	92.1	1.47	70.4	1.13
	29.8	90.0	1.44	75.1	1.20
	27.2	96.0	1.53	71.7	1.15
Jackson #15 Composite	37.2	105.9	1.69	77.2	1.24
	35.8	102.0	1.63	75.1	1.20
	31.4	105.3	1.68	80.1	1.28
	28.0	103.2	1.65	80.7	1.29
	25.2	100.2	1.60	80.0	1.28

Notes: 1. Composite: 15 wt% bed material + 85 wt% baghouse catch.

2. Underlined numbers represent conditions that correspond to the optimum moisture content at maximum bulk density.

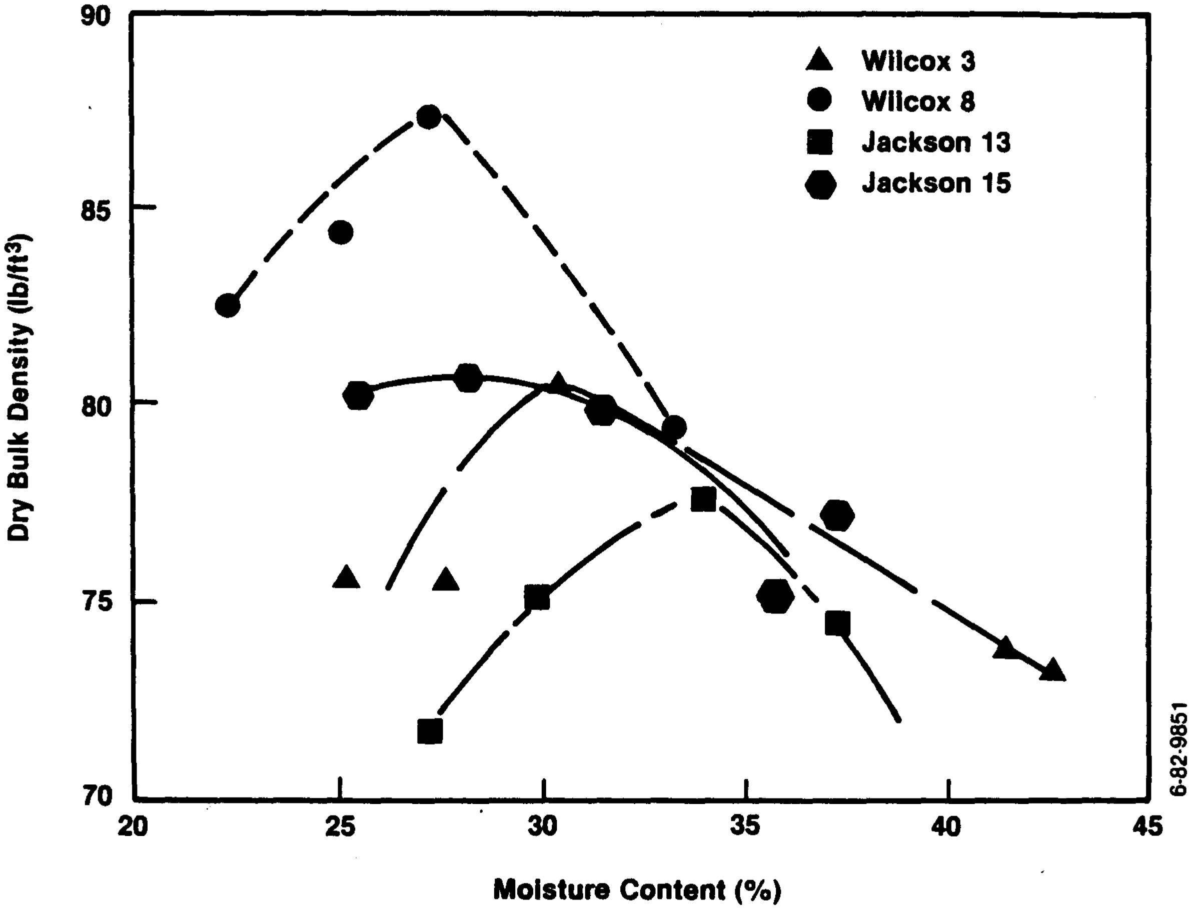

Figure 4-1. Results of compaction tests for optimum moisture.

Table 4-18a

PARTICLE SIZE DISTRIBUTIONS OF AFBC BAGHOUSE AND COMPOSITE SAMPLES

	Particle Size Weight % Finer Than				
Sample Number	75 μm	30 μm	20 μm	13 μm	7 μm
Baghouse #3	97	91	57	2	<1
Composite #3	81	74	37	4	<1
Baghouse #8	83	77	43	28	2
Composite #8	70	69	35	4	3
Baghouse #13	100	100	73	3	0
Composite #13	90	85	49	3	<1
Baghouse #15	99	94	40	6	5
Composite #15	86	79	23	8	5

Table 4-18b

PARTICLE SIZE DISTRIBUTIONS OF AFBC BED SAMPLES

	Particle Size Weight % Finer Than			
Sample Number	3350 μm	850 μm	250 μm	75 μm
Wilcox #3	95	55	11	1
Wilcox #8	95	59	9	1
Jackson #13	99	56	10	1
Jackson #15	96	58	7	1

The particle size distribution has been mentioned in previous sections since the range of distribution affects the void volume before compaction and the bulk density after compaction. The Texas lignite bed wastes have a much larger particle size distribution than the baghouse materials. This results in better overall disposal properties for the bed materials.

In comparison of the bed materials, the Jackson #13 contained slightly finer particles (from 250 μm to 3350 μm) than the other bed materials; however, these bed materials are extremely similar to each other with about 50 percent of the mass of these materials lying between 850 μm and 3350 μm.

For the distribution of particle size in the baghouse samples a much smaller range (7 μm to 75 μm) of sieves was used. Baghouse #13 showed the largest variation in particle size distribution behavior, having the highest concentration of particles fall into one single range (13-20 μm). The Baghouse #8 sample contained a larger percentage of fine material (28 percent of 7-13 μm). The particle size ranges are fairly uniform for the baghouse materials and composite samples. The majority of all of the baghouse wastes had the largest fraction of material in the 13-30 μm range.

Permeability. The permeability coefficients of the four composites were determined using a constant head permeameter. To obtain measurements, a head pressure of nitrogen was necessary. The cylinders were cured for 28 days in a constant humidity atmosphere prior to testing. The results are shown in Table 4-19. No actual measurements were obtained for Composite #15; however, the value is $\leq 10^{-9}$ cm/sec. The most permeable composite is #8. The permeability coefficients ranged from 10^{-4} cm/sec down to 10^{-9}cm/sec.

Table 4-19

RESULTS OF PERMEABILITY MEASUREMENTS FOR COMPOSITED BED/BAGHOUSE AFBC WASTES AFTER 28 DAYS OF CURING

	PERMEABILITY COEFFICIENTS in cm/sec			
Sample Description	1st Measurement	10th Measurement	Range	Average
Composite #3	1.8×10^{-6}	2.4×10^{-6}	$1.8\text{x}10^{-6}$–$3.2\text{x}10^{-6}$	$2.4\text{x}10^{-6}$
Composite #8	1.1×10^{-4}	7.2×10^{-5}	$5.9\text{x}10^{-5}$–$1.1\text{x}10^{-4}$	$8.1\text{x}10^{-5}$
Composite #13	8.3×10^{-6}	1.0×10^{-5}	$7.4\text{x}10^{-6}$–$1.0\text{x}10^{-5}$	$9.0\text{x}10^{-6}$
Composite #15[a]	$< 1 \times 10^{-9}$	a	a	a

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[a] No actual measurements could be made on composite #15; at 40 psi no leachate was collected after 3 weeks. Therefore, the permeability is probably less than 10^{-9} cm/sec.

The first measurement presented in Table 4-19 indicates the permeability that can be expected when a landfill is initially opened. The tenth measurement is more indicative of the permeability that a landfill will develop over a period of time. The average permeability is representative of overall behavior of the landfill, and the range of permeabilities indicates that minimum or maximum values can be observed with time.

Strength Development. The summary of results of the unconfined compressive strength measurements after 3, 7, 14, and 28 days of curing are given in Tables 4-20 through 4-23.

Strength data are not shown for the bed materials because there was not enough strength developed after three days of curing for the wastes to hold together. The cylinders crumbled into individual aggregates, and the unconfined compressive strengths were not measured (<10 psi).

The moisture contents of the cylinders for these tests are shown in Table 4-24. Materials were originally prepared at optimum moisture for maximum compaction density; however, these moisture contents had to be adjusted upward (about 10 percent) in order for cohesion and strength development to be initiated. Some of the moisture added may have evaporated as heat of hydration was expended. This is evidenced by the percent moistures added to the baghouse being greater than the total percent moisture after initial reaction.

After three days of curing, the Baghouse #8 sample had achieved an unconfined compressive strength of 1100 psi, almost twice as high as any of the other materials tested and approximately 30 times higher than the composite bed-baghouse sample from the same test (#8). The materials produced during tests with limestone addition appear to develop strength more rapidly than the samples produced without limestone addition. This behavior is consistent with prior Radian work in that cementitious hydration reactions require calcium-containing compounds in an alkaline environment.

Table 4-20

SUMMARY OF UNCONFINED COMPRESSIVE STRENGTH MEASUREMENTS ON FBC SAMPLES AFTER THREE DAYS OF CURING

Sample Identification	Curing Time (days)	Strength Range[a] (psi)	Average Strength (psi)	Strength Comparison After 3 Days of Curing
Baghouse #3	3	28-37	30	Baghouse 3 times greater
Composite #3	3	10-17	10	
Baghouse #8	3	660-1590	1100	Baghouse 30. times greater
Composite #8	3	25-35	35	
Baghouse #13	3	16-46	45	Composite is equal to baghouse
Composite #13	3	10-49	50	
Baghouse #15	3	360-410	390	Composite is 1.5 times greater
Composite #15	3	560-610	590	

Actual strength range of baghouse materials: 30-1100 psi.

Actual strength range of composited materials: 10-590 psi.

Order of strength: Baghouse #8>>Composite #15>Baghouse #15>>Composite #13 >Baghouse #13>Composite #8>Baghouse #3>Composite #3

[a] Range indicated from samples was analyzed in triplicate for strength development. If one value was greater than 25% different from the other duplicate values, it was not used in determining the average strength unless the strength values were less than 25 psi, where strength is so low that detection limits are susceptible to greater variability.

Table 4-21

SUMMARY OF UNCONFINED COMPRESSIVE STRENGTH MEASUREMENTS ON FBC SAMPLES AFTER SEVEN DAYS OF CURING

Sample Identification	Curing Time (days)	Strength Range (psi)	Average Strength (psi)	Strength Comparison After 7 Days of Curing
Baghouse #3	7	10-16	15	Baghouse is ∿1.2 times greater
Composite #3	7	7-19	10	
Baghouse #8	7	930-1030	970	Baghouse is ∿74 times greater
Composite #8	7	10-19	15	
Baghouse #13	7	43-45	45	Baghouse is ∿1.2 times greater
Composite #13	7	32-40	40	
Baghouse #15	7	1300-1610	1420	Baghouse is ∿1.1 times greater
Composite #15	7	1230-1260	1240	

Actual strength range of baghouse materials: 15-1420 psi.

Actual strength range of composited materials: 10-1240 psi.

Order of strength: Baghouse #15>Composite #15>Baghouse #8>>Baghouse #13>Composite #13 >Composite #8 = Baghouse #3>Composite #3.

Table 4-22

SUMMARY OF UNCONFINED COMPRESSIVE STRENGTH MEASUREMENTS ON FBC SAMPLES AFTER 14 DAYS OF CURING

Sample Identification	Curing Time (days)	Strength Range (psi)	Average Strength (psi)	Strength Comparison After 14 days of Curing
Baghouse #3	14	25-28	25	Baghouse is ∿2.6 times greater
Composite #3	14	7-13	10	
Baghouse #8	14	1850-1860	1860	Baghouse is ∿140 times greater
Composite #8	14	10-19	15	
Baghouse #13	14	7-16	10	Composite is ∿3.6 times greater
Composite #13	14	32-40	40	
Baghouse #15	14	1630-1940	1800	Composite and baghouse are essentially equal
Composite #15	14	1720-1890	1790	

Actual strength range of baghouse materials: 10-1860 psi.

Actual strength range of composited materials: 10-1790 psi.

Order of strength: Baghouse #8>Baghouse #15>Composite #15>>Composite #13>Baghouse #3
>Composite #8>Composite #3 = Baghouse #13.

Table 4-23

SUMMARY OF UNCONFINED COMPRESSIVE STRENGTH MEASUREMENTS ON FBC SAMPLES AFTER 28 DAYS OF CURING

Sample Identification	Curing Time (days)	Strength Range (psi)	Average Strength (psi)	Strength Comparison After 28 days of Curing
Baghouse #3	28	28-37	35	Baghouse is ∿2.5 times greater
		18*		
Composite #3	28	13	15	
Baghouse #8	28	2705-2722	2720	Baghouse is ∿85 times greater
		2560*		
Composite #8	28	28-40	30	
Baghouse #13	28	7-13	10	Composite is ∿3.7 times greater
		7*		
Composite #13	28	34-40	40	
Baghouse #15	28	2355-2546	2460	Baghouse is ∿1.1 times greater
		1443-1867*	1660	
Composite #15	28	2230-2360	2340	
		2750-2880*	2820	

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*3" x 6" cylinders

Actual strength range of baghouse materials: 10-2720 psi.

Actual strength range of composited materials: 30-2340 psi.

Order of Strength: Baghouse #8>Baghouse #15>Composite #15>>>Composite #13 = Baghouse #3 = Composite #8>Composite #3>Baghouse #13.

Table 4-24

PERCENT MOISTURE NECESSARY TO INITIATE STRENGTH DEVELOPMENT IN UNCONFINED COMPRESSIVE STRENGTH CYLINDERS

Sample Identification	Percent Moisture by Weight Added to Waste as Received	Total Percent Moisture
Composite 3[a]	8	32
" 8	40	44
" 13	45	45
" 15	35	35
Baghouse 3[b]	45	39
" 8	43	39
" 13	60	44
" 15	50	43

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[a] The small amount of moisture added compared to total percent moisture indicate that the sample may have been exposed to moisture prior to sample preparation or that an analytical error exists.

[b] Samples where the moisture added is greater than the total moisture measured probably result from the cementitious hydration reactions consuming water.

After seven days of curing, both the baghouse and composited materials from Jackson #15 had greater strengths than the Wilcox #8 baghouse. These three samples still showed strengths of at least 25 times greater than the other materials tested. Both the baghouse and composite bed/baghouse material from Wilcox #3 had begun to deteriorate in strength, as had the Composite #8 and Baghouse and Composite from Jackson #13.

Since steady-state operation with respect to solids composition was not achieved during these tests, the sand that was added to the bed as starter material before both the Wilcox and Jackson lignite tests probably affected the strengths of the samples. In particular, the tests near the beginning of test series L116 (Test #3) and L118 (Test #13) may have been more adversely affected than the other tests. The higher sand concentrations would have a tendency to produce lower strengths.

After fourteen days of curing, even a greater span of difference in unconfined compressive strength was observed. Baghouse #8, Baghouse #15, and Composite #15 had developed strengths at least 50 times greater than the other materials tested. After 28 days of curing very high unconfined compressive strengths were observed for Baghouse #8, Baghouse #15, and Composite #15. Samples produced without limestone addition did not develop any appreciable strength. Figure 4-2 illustrates the unconfined compressive strength development as a function of time for the baghouse and composite samples. Two strength ranges appear. Strength of samples produced during limestone addition generally appear an order of magnitude higher than the other combustion products. The only exception to high strength development in a sample in which limestone was used is Composite #8. Due to sample quantity limitations, Composites #8 and #3 had to be reused in a second cylinder preparation to develop enough strength to be removed from the molding cylinders. Composite #3 probably would not have achieved much more strength development; however, it is expected that Composite #8 would have developed greater strength if all of the moisture necessary to cause the initial (first three days) hydration was added at one time, rather than adding the moisture, finding that the FBC material had absorbed all of it, and requiring an extra addition of 10 percent more moisture. This difference

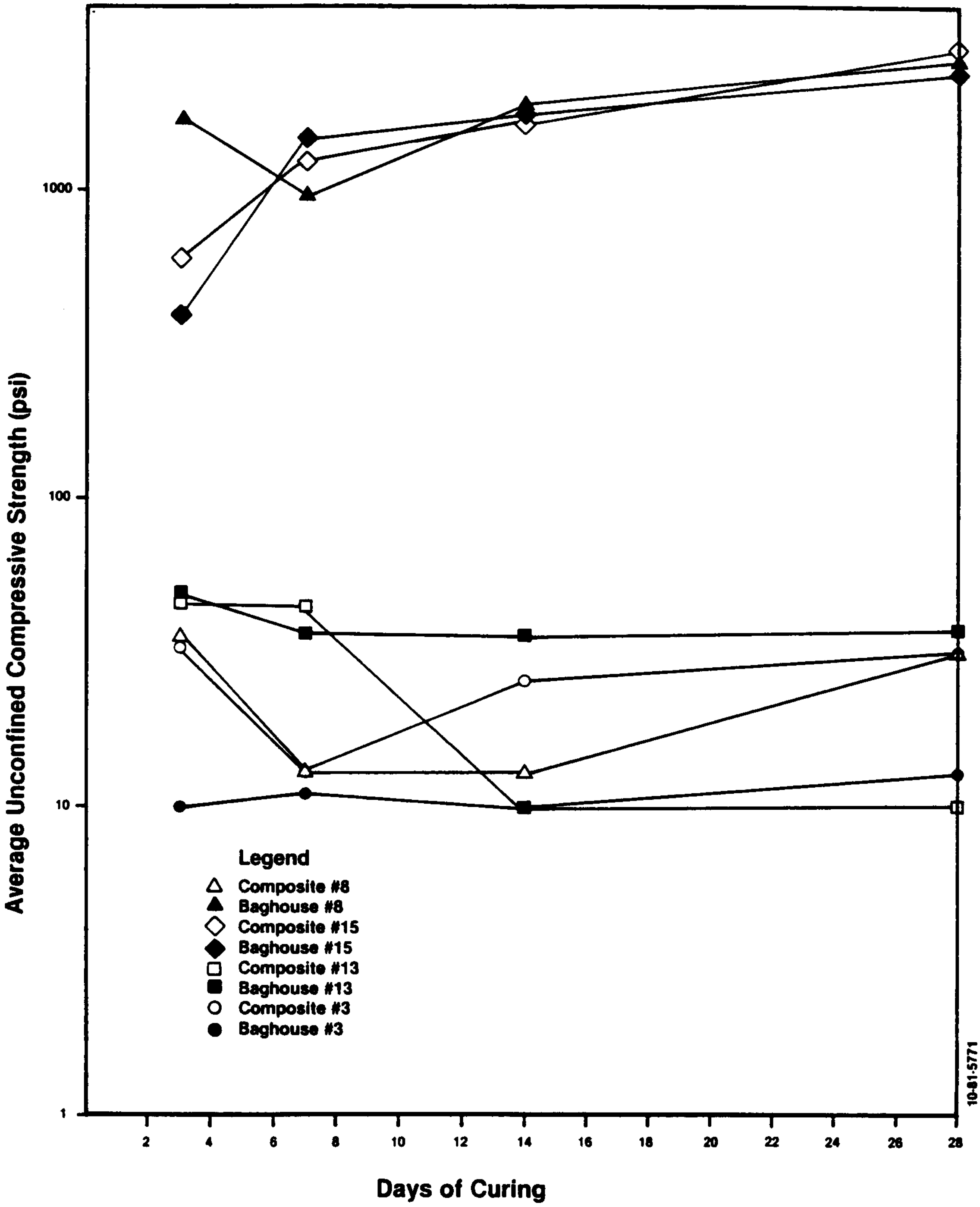


Figure 4-2. Summary of unconfined compressive strength.

in preparation may limit the validity of the strength development of Composite #8; however, it indicates the extreme importance of the necessary hydration and rapid rate of hydration reactions if cementitious reactions are desired.

4.4.4 Conclusions (Physical Testing)

All of the Texas lignite AFBC wastes will require approximately the same transport volume per mass and these volume/ton ratios are not dissimilar to those observed for other AFBC wastes and conventional coal combustion wastes. There appears to be no negative impact during transport of bed and baghouse materials for codisposal as compared to separate disposal. The volumes required for disposal as indicated by the compaction data are similar for all composite AFBC materials tested in this project. About 30 percent moisture at placement will be required to produce maximum dry bulk densities in the compacted materials. Water in excess of 30 percent must be added during the blending to allow for hydration and evaporation during transport.

For optimum strength development, about 10 percent more moisture or 40 percent total at placement will be required. Care must be exercised during shipment to allow for the rapid strength development (flash setting in some cases) accompanying the hydration reactions.

Each of the four bed materials studied was well-graded, coarse, and similar in particle size distribution to gravel or bottom ash from a conventional coal-fired boiler. Good gradation is responsible for higher bulk densities and lower void volume when compared with the baghouse material. The four baghouse materials were fine and similar to fly ash from conventional coal-fired boilers in particle size and gradation. Lower bulk densities and higher void volumes are the effect of their poor gradation. Blending of the coarse bed materials with the fine baghouse material will improve the gradation of the baghouse material but not to a significant degree.

Limestone added during combustion appears to be a major factor in both strength development and lower permeability. Unreacted calcined limestone provides the alkalinity required for the cementitious/hydration reaction responsible for strength development.

Section 5

TEXAS LIGNITE FLUIDIZED BED BOILER OPERATING AND ECONOMIC TRADEOFFS

This section describes a study conducted by Combustion Power Company (CPC) to assess the economics of employing fluidized bed boiler (FBB) technology to utilize Texas lignite to meet industrial steam requirements. Based on the results of subscale testing completed under this program, a conceptual design was developed for an industrial sized FBB. Capital and operating costs were estimated for the base case design and a corresponding steam generating cost was computed. Alternate cases were evaluated and compared with the base case to assess the sensitivity of steam costs to important economic and design parameter variations.

Process design assumptions were selected by Combustion Power Company based on previously described test results obtained for Wilcox lignite. The plant design basis, regulatory constraints, and financial basis assumptions were established by Radian Corporation. A computerized FBB process model developed by CPC was used to establish energy and mass balances and determine equipment sizes for the base case plant design and for subsequent sensitivity analyses. A detailed plant design for firing Jackson lignite was not prepared, although initial process modeling suggests that the design would be very similar to that developed for Wilcox lignite.

5.1 FLUIDIZED BED BOILER DESIGN

The design criteria used and the resulting FBB design based on Texas lignite test results are presented in Sections 5.1.1 and 5.1.2.

5.1.1 Process Design Criteria

The primary design objective was to develop a practical boiler configuration which would operate at process conditions comparable to those maintained on the subscale combustors during the test series conducted for this program. The base case design criteria were as follows:

Plant size	200 x 10^6 Btu/hr (gross)
Lignite type	Wilcox
Sulfur capture requirement	70% of fuel sulfur

The following operating criteria were selected based on Wilcox lignite test results, in order to achieve the specified sulfur capture:

Bed temperature	1450°F (1550°F for Jackson lignite)
Bed superficial velocity	6 ft/sec
Excess air	20%
Added Ca/S mole ratio	1.3
Fines recycle rate	2.5 x total fuel feed
Combustion efficiency	99%

Since compositions of both the Wilcox and Jackson lignites fired during test series L116 through L118 were somewhat different than what is considered typical for lignites from these groups, the design fuel compositions were adjusted from test values to reflect more typical compositions. The lignite analyses used are listed below:

Lignite Ultimate Analysis (percent by weight, as received)	Wilcox	Jackson
Moisture	29.0%	29.9%
Hydrogen	3.2%	2.7%
Carbon	39.6%	33.6%
Nitrogen	0.6%	0.5%
Oxygen	11.3%	8.4%
Sulfur	0.7%	1.7%
Ash	15.6%	23.2%
HHV	6700 Btu/lb	5800 Btu/lb

For design purposes, the fines recycle rate selected is significantly lower than that experienced in the tests conducted at CPC. This lowered recycle rate results in a more practical boiler design and is considered to be consistent with test conditions because:

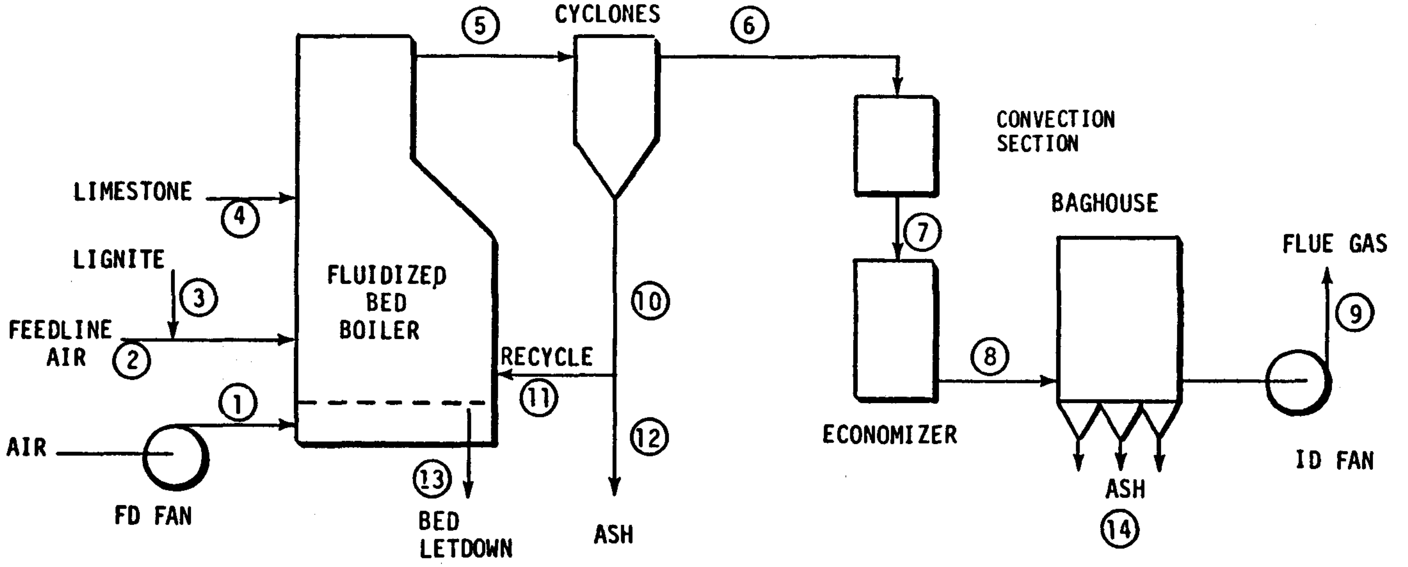
- Fines recycle can be strongly influenced by the quantity and size distribution of inert material contained in the fuel. A decrease in recycle rate is consistent with the adjustment in fuel composition from test values.
- Tests conducted at Grand Forks with the Jackson lignite had lower recycle rates without observable decrease in sulfur capture. Experience at Combustion Power Company indicates that while notable benefit results from some recycle of fines, the benefit to sulfur capture does not increase with recycle rate at rates above that chosen for the FBB design.

The process flowsheet identifying primary process conditions for the base case plant design is as shown in Figure 5-1.

5.1.2 Boiler Design

The fluidized bed boiler (FBB) unit is assumed to be an add-on system for which existing facility utilities are capable of meeting the additional system demands. For example, it is assumed that treated boiler feedwater is available. Also, coal and limestone receiving and storage facilities, and an ash transfer system are not included in the design. The equipment required for these facilities is very dependent upon site-specific factors. A cost sensitivity analysis was conducted which investigates the impact of variations of the cost of lignite, limestone, and solid waste disposal on the cost of steam.

The FBB was designed to utilize three water-walled fluidized bed modules, each having a 140 square foot bed area. The steam generator includes economizers for each module to facilitate system turndown. An air preheater is not used. The three shop-fabricated modules are top supported by suitable



STATION	GAS (LB/MIN)	SOLIDS (LB/MIN)	TEMPERATURE (F)	DESCRIPTION
1	3063	0	117	COMBUSTION AIR
2	105	0	165	FEEDLINE AIR
3	0	513	70	LIGNITE FEED
4	0	15.3	70	LIMESTONE FEED
5	3603	1344	890	CYCLONE INLET
6	3603	67.2	885	CYCLONE OUTLET
7	3603	67.2	769	ECONOMIZER INLET
8	3603	67.2	441	BAGHOUSE INLET
9	3603	0.07	458	I.D. FAN OUTLET
10	0	1275.3	885	CYCLONE DISCHARGE
11	0	1260	885	RECYCLED FINES
12	0	15.3	885	ASH DISCHARGE
13	0	15	1450	BED LETDOWN
14	0	67.1	435	FLYASH DISCHARGE

Figure 5-1. Lignite-fired fluidized bed boiler: process diagram with base case conditions.

framing and support structures. Mechanical collectors, manifolds, and economizer sections are shipped separately for site erection. The boiler is of balanced draft design with both ID and FD fans. Elutriated fines are captured for recycle by mechanical collectors; a baghouse provides final particulate control. The ID fan and baghouse are not shown on the boiler plan and elevation illustrations seen in Figures 5-2 and 5-3.

Lignite and limestone feed bins are included for each module. Weigh belt conveyors meter lignite, and screw conveyors meter limestone into Fuller-Kinyon pumps for pneumatic underbed feed. Fuel and limestone are distributed to six points in each module by pneumatic splitters. Ash and bed material are all discharged dry at atmospheric pressure and cooled below 200°F. Ash handling and storage equipment are not included.

Other boiler design parameters are as follows:

Steam Flow	154,000 lb/hr at 150 psig, saturated
Feedwater	220°F
Bed Dimensions	10 ft x 14 ft (3 each)
Bed Height (static)	4.5 ft
Freeboard Height	14 ft
Fuel Feed	Pneumatic underbed
Particulate Control	Baghouse
Fan Power: FD	820 hp
ID	500 hp
Lignite Feed Size	½" x 0
Limestone Feed Size	12 mesh

Nominal 150 psig saturated steam was selected for study purposes. Design pressure up to 600 psig (saturated) would have negligible impact on overall estimated boiler cost.

It should be noted that the boiler design has not been optimized, but represents the initial effort for design in accordance with subscale test results. Improvement in plant efficiency or decreases in capital costs can conceivably be achieved through more comprehensive design studies; consequently, the design and costs used are believed to be conservative.

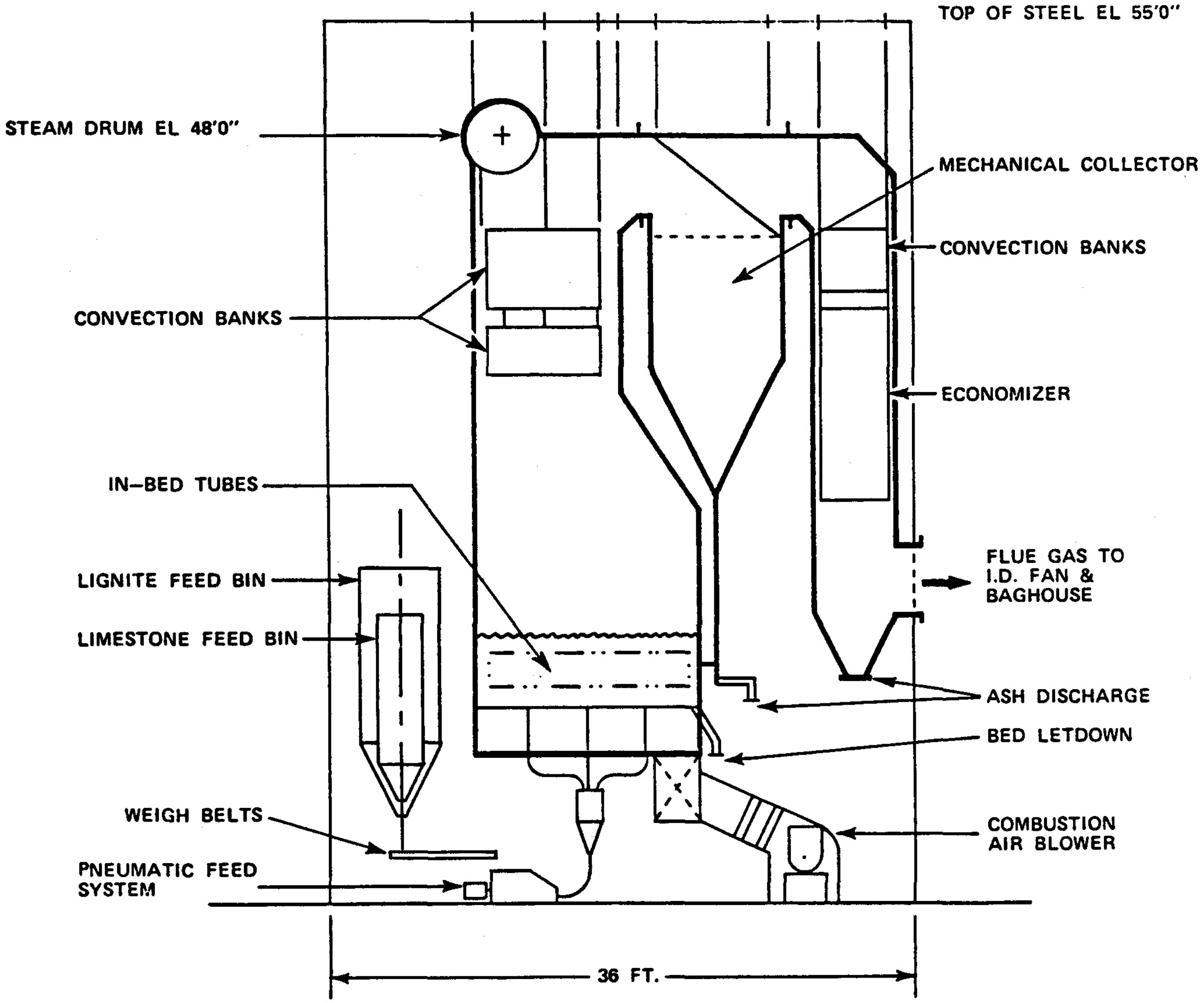


Figure 5-2. Lignite-fired fluidized bed boiler, elevation view.

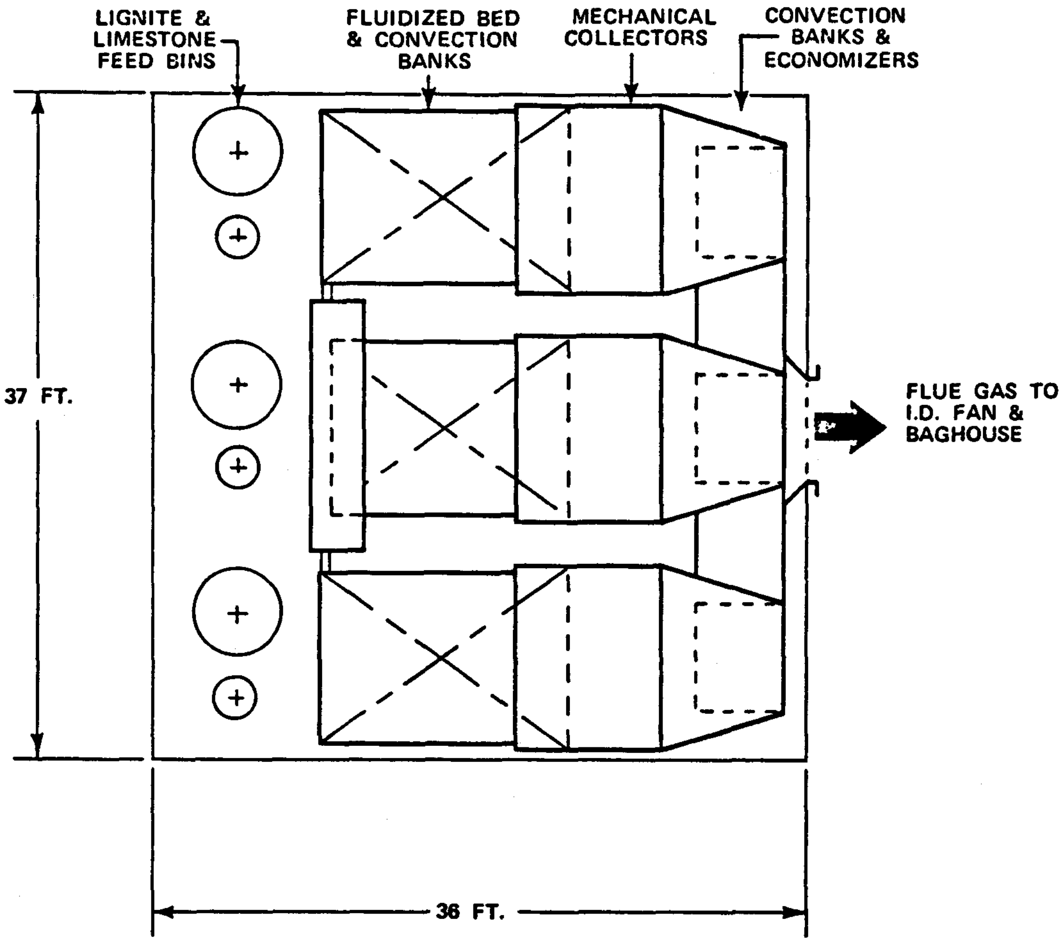


Figure 5-3. Lignite-fired fluidized bed boiler, plan view

5.2 ECONOMIC ANALYSIS

An economic analysis of the Texas lignite fired FBB described in Section 5.1 is presented below. Included are estimates of capital and operating costs, and of cost sensitivity to important design and economic parameters.

5.2.1 Costing Assumptions

The economic analysis of a Texas lignite-fired FBB is based on the revenue estimating, discounted cash flow methodology contained in the Electric Power Research Institute Technical Assessment Guide (EPRI PS-1201-SR). All costs are in January 1981 dollars and assume plant startup in the 1985-87 time period. Capital costs are levelized over the 30 year plant lifetime and charged to steam costs on the basis of an overall 70 percent capacity utilization factor.

5.2.2 Total Plant Investment

The Total Plant Investment (TPI) is the capital required to construct the steam generator. This investment is comprised of:

- Process Capital
- General Facilities
- Engineering and Home Office Fees
- Project Contingency
- Process Contingency
- Sales Tax

Process Capital. Process capital cost is the total constructed cost of on-site steam generation equipment listed in Table 5-1 including direct and indirect construction costs. All sales taxes are included. Capital cost estimates include all equipment and construction costs for the components listed in Table 5-1. Plant capital costs were based on vendor quotes, file data for recent projects, and on accepted industry estimating guidelines. Cost estimate accuracy is ±40 percent.

Table 5-1

EQUIPMENT LIST

Boiler

- Fluid Bed Modules (3 each) with:
  - Water tube walls
  - Bed and convective tubes
  - Distributor plate
  - Plenum
  - Steam drum and pressure parts
  - Sootblowers
  - Insulation and lagging
- Start-up Systems
  - Burners
  - Oil systems
  - Dampers and Valves
- Bed Solids
  - Water cooled letdown conveyors
  - Airlocks
  - Recycle injectors
  - Flyash discharge conveyors

Miscellaneous

- Instrumentation
- Structural supports and platforms
- Painting
- Compressed air system
- Undistributed equipment

Solids Feed

- Lignite Feed System
  - Lignite bins with dischargers
  - Weigh belt conveyors
  - Pneumatic feeders
  - Pneumatic splitters (six way)
  - Bin fill conveyor
- Limestone Feed System
  - Limestone bins with dischargers
  - Screw feeders
  - Bin fill conveyor

Draft Systems

- Combustion Air System
  - Forced draft fan
  - Ductwork
  - Control valves

- Flue Gas System
  - Induced draft fan
  - Insolation gates
  - Ductwork
  - Mechanical collectors
  - Convection heat exchanger
  - Economizer
  - Baghouse

Specifically not included in cost estimates for this study are the following:

- Foundations
- Buildings
- Stack
- Lignite, limestone, and oil receiving systems
- Lignite, limestone, oil, and ash storage bunkers
- Ash transfer system
- Motor control center
- Instrument and control panel
- Intermediate wiring and tubing
- Boiler feedwater treatment
- Boiler feedwater pumps

General Facilities. General facilities costs such as roads, office buildings, shops, or laboratories are not included in the scope of this study. No allowances are made for any offsite facilities.

Engineering and Home Office. Engineering design and construction management costs are taken to be 10 percent of process capital costs.

Project Contingency. A project contingency factor is added to cover additional equipment that might result from a more detailed design of a definitive project at an actual site. The project contingency is 25 percent for all plant systems and components and is applied to the above items.

Process Contingency. A process contingency factor is applied to unproven technology in an effort to quantify the uncertainty in the design and capital cost of the commercial-scale equipment. This contingency is used for comparing an unproven process with a commercially proven process, and is taken as 10 percent of boiler costs plus 5 percent of fuel feed equipment costs.

Sales Tax. Sales taxes are included in the Process Capital costs.

5.2.3 Total Capital requirement

The Total Capital Requirement (TCR) includes all the capital investment required to complete the project as specified in Table 5-1. This requirement is presented in Table 5-2 and is comprised of:

- Total Plant Investment
- Royalty Allowance
- Preproduction Costs
- Inventory Capital
- Initial Catalyst and Chemicals Charge
- Allowance for Funds During Construction
- Land

Table 5-2

TOTAL CAPITAL REQUIREMENTS

Description	Estimated Cost	
Boiler	$1,564,000	
Solids Feed	350,000	
Draft Systems	1,937,000	
Instrumentation, Structural, Misc.	519,000	
Total Process Capital	$4,370,000	
General Facilities	0	
Engineering and Home Office Fees	437,000	
Project Contingency	1,201,800	
Process Contingency - Boiler	156,400	
Feed Systems	13,500	
Total Plant Investment (TPI)	$6,178,700	($40.02/lb/hr)
Royalty Allowance	0	
Preproduction Costs	295,800	
Inventory Capital	278,600	
Initial Catalyst and Chemicals Charge	0	
Allowance for Funds During Construction	360,200	
Land	0	
Total Capital Requirements (TCR)	$7,113,300	($46.07/lb/hr)

Note: Site-specific facilities and equipment listed at the bottom of Table 5-1 are excluded.

Royalty Allowance. It is assumed that all royalties are paid by the equipment manufacturers and are included in the equipment cost.

Preproduction Costs. Preproduction costs are the costs of operator training, equipment checkout, major changes in plant equipment, extra maintenance, and inefficient use of fuel and other materials during plant startup. Preproduction costs are estimated as follows:

- One month's variable operation costs at full capacity excluding fuel. Variable costs are primarily for limestone, solid waste disposal and utilities.
- One month's fixed costs excluding income taxes. Fixed costs are operating and maintenance labor, administrative and support labor, and maintenance materials.
- Two percent of total plant investment (TPI). This charge covers expected changes and modifications to equipment needed to bring the plant up to full capacity.
- Twenty-five percent of full capacity fuel costs for one month. This charge covers inefficient operation that occurs during the startup period.

Inventory Capital. The value of inventories of fuel, other consumables, and by-products is capitalized and included in the inventory capital account. The inventory capital is estimated as follows:

- One month's supply of fuel based on full capacity operation.
- One month's supply of other consumables (excluding water) based on full capacity operation.

Initial Catalyst and Chemical Charge. All chemical costs are included in inventory capital.

Allowance for Funds During Construction (AFDC). AFDC is calculated from the center of gravity of expenditures, based on interest at the discount rate over the plant construction expenditure schedule. For a center of gravity of six months, corresponding approximately to an 18 month overall construction period, the AFDC is 5.83 percent of the Total Plant Investment (TPI).

5.2.4 Cost of Capital

The levelized cost of capital is found by applying the Fixed Charge Rate to the Total Capital Requirement (TCR) with working capital treated the same as depreciable capital. The fixed charges (income taxes, interest on debt, return on equity, depreciation, and property taxes and insurance) are computed on a levelized basis with the specified discount rate. The financial factors that form the basis for the capital charge computations are as follows:

Discount factor	12% (base case)
Investment tax credit	10% (base case)
Depreciation life (years)	22
Income tax rate	48%
Boiler operating life (years)	30
Property tax and insurance	2% of TCR
Retirement dispersion	Iowa Type S_1
Accelerated depreciation	Sum-of-the-years Digits Method

Using this basis the fixed charge rate is 18.65 percent per year of the TCR as presented in Table 5-3.

5.2.5 Operating Cost

Operating costs are divided into fixed and variable costs. Fixed costs are essentially independent of capacity factor and are expressed in $/yr. Variable costs are directly proportional to the amount of steam produced and are expressed in $\$/10^3$ lb steam. Fixed operating costs include the following:

- Operating Labor
- Maintenance Labor
- Maintenance Materials

Variable operating costs include the cost of consumables (lignite and limestone), solid waste disposal, utilities, etc. Radian specified the cost of lignite, limestone, and solid waste disposal for this study. The values estimated for base case fixed and variable operating costs are shown in Table 5-4.

Table 5-3

BASE CASE LEVELIZED FIXED CHARGE RATE

Cost of Capital (Discount rate)	12.00%
Depreciation (Sinking fund)	0.41
Allowance for Retirement Dispersion	0.66
Annual Income Tax	6.93
Property Tax, Insurance, etc.	2.00
Subtotal	22.00%
Accelerated Depreciation Allowance	(1.22)
Investment Tax Credit	(2.13)
Total Levelized Fixed Charge Rate	18.65%

Table 5-4

BASE CASE OPERATING COSTS

Variable Operating Costs

Lignite at $\$2.50/10^6$ Btu	$\$ 3.24/10^3$ lb steam
Limestone at $12/ton	.03
Solid waste disposal at $20/ton	.37
Other variable costs	.10
Total variable operating costs	$\$ 3.74/10^3$ lb steam

Fixed Operating and Maintenance Costs

Labor	$267,740/yr
Material	157,320
Total fixed operating and maintenance costs (1st year)	$425,060/yr

5.2.6 Cost of Steam

The total revenue requirement for steam generation represents the total of operating and capital related charges. The total steam cost is estimated for the first year of operation and is considered valid for the plant lifetime if operating costs are adjusted for inflation. The total steam cost and its components are presented in Table 5-5. Steam costs for a FBB fired with Jackson lignite were calculated based on the assumption that Total Plant Investment would be the same. However, the unit fired with Jackson lignite would have a lower net steam output. It should be noted also that the fuel cost for Jackson lignite was assumed the same as for Wilcox lignite.

The results presented in Table 5-5 indicate that for the base case, steam costs would be over eight percent greater for an FBB firing Jackson lignite than for an FBB firing Wilcox lignite. The increased cost for Jackson lignite results primarily from greater variable costs due to the higher limestone and solid waste disposal requirements. Note that the base case costs presented are for an add-on or replacement boiler. Estimated steam costs for combusting either lignite would be greater if equipment excluded in Table 5-1 were to be included.

5.2.7 Sensitivity Analyses

Alternate cases were evaluated and compared with the base case to assess the cost sensitivity of important parameters. In all cases the Total Plant Investment was held constant. Total Capital Requirement was adjusted only in the study of sensitivity to discount rate. Although plant steam output was nearly the same for all cases, the exact computed steam output and fuel feed rate were used in calculating fuel cost per 10^3 lb steam process variation.

The results of sensitivity analyses for a Wilcox lignite-fired FBB are summarized in Tables 5-6, 5-7, and 5-8 and are shown graphically in Figure 5-4. This study does not compare the steam costs estimated for the lignite-fired

Table 5-5

BASE CASE STEAM COST SUMMARY

	Wilcox	Jackson
Total Plant Investment	$\$40.02$/lb/hr	$\$41.08$/lb/hr
Preproduction Costs	1.92	2.14
Inventory Capital	1.80	2.07
AFDC	2.33	2.39
Total Capital Requirement	$\$46.07$/lb/hr	$\$47.68$/lb/hr
Levelized Fixed Charge Rate	18.65%	18.65%
Levelized Fixed Charge	$\$ 1.40/10^3$ lb	$\$ 1.45/10^3$ lb
Fixed O&M Cost	.45	.45
Total Fixed Cost	$\$ 1.85/10^3$ lb	$\$ 1.90/10^3$ lb
Limestone Cost	$\$ 0.03/10^3$ lb	$\$ 0.07/10^3$ lb
Solid Waste Disposal Cost	0.37	0.67
Other Variable O&M Cost	0.10	0.10
Total Variable O&M Cost (w/o Fuel)	$\$ 0.50/10^3$ lb	$\$ 0.84/10^3$ lb
Fuel Cost	$\$ 3.24/10^3$ lb	$\$ 3.32/10^3$ lb
Total Variable Cost	$\$ 3.74/10^3$ lb	$\$ 4.16/10^3$ lb
Fixed Cost	$\$ 1.85/10^3$ lb	$\$ 1.90/10^3$ lb
Total Steam Cost	$\$ 5.59/10^3$ lb	$\$ 6.06/10^3$ lb

Table 5-6

RESULTS OF SENSITIVITY ANALYSES OF PROCESS VARIABLES

Effect of Lignite Sulfur Content

Sulfur Content (As Rec'd)	Ca/S Mole Ratio	Limestone Plus S.W.[1] Disposal ($/10^3 lb Steam)	Steam Cost $/10^3 lb
0.4%	1.3	0.36	5.54
0.7% BASE	1.3	0.40	5.59
1.0%	1.3	0.44	5.65
2.7%	1.3	0.64	5.87

Effect of Sulfur Capture

Sulfur Captured In Bed	Ca/S Mole Ratio	Limestone Plus S.W. Disposal ($/10^3 lb Steam)	Steam Cost $/10^3 lb
36%	0	0.33	5.50
70% BASE	1.3	0.40	5.59
90%	3.0	0.49	5.71

Effect of Relative Limestone Utilization

Relative Limestone Utilization	Ca/S Mole Ratio	Limestone Plus S.W. Disposal ($/10^3 lb Steam)	Steam Cost $/10^3 lb
Poor Utilization[2]	2.0	0.44	5.64
Utilization as Tested[3]	1.3	0.40	5.59
Improved Utilization[4]	0.6	0.36	5.54

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[1] S.W. - Solid Waste

[2] Utilization assumed to be 46% of test results.

[3] Utilization assumed to be same as test results.

[4] Utilization is assumed to be 154% of test results.

Table 5-7

RESULTS OF SENSITIVITY ANALYSES OF FUEL AND OPERATING COSTS

Lignite Cost

Lignite Cost ($\$/10^6$ Btu)	Lignite Cost ($\$/10^3$ lb Steam)	Steam Cost ($\$/10^3$ lb)
1.50	1.94	4.25
2.50 BASE	3.24	5.59
3.50	4.53	6.92

Limestone Cost

Limestone Cost ($/Ton)	Limestone Cost ($\$/10^3$ lb Steam)	Steam Cost ($\$/10^3$ lb)
6	0.017	5.57
12 BASE	0.034	5.59
18	0.051	5.61

Solid Waste Disposal Cost

Disposal Cost ($/Ton)	Disposal Cost ($\$/10^3$ lb Steam)	Steam Cost ($\$/10^3$ lb)
10	0.18	5.41
20 BASE	0.37	5.59
30	0.55	5.77

Table 5-8

RESULTS OF SENSITIVITY ANALYSIS OF COST OF CAPITAL

Discount Rate

Discount Rate (%)	Fixed Charge Rate (%)	Fixed Cost ($\$/10^3$ lb Steam)	Steam Cost ($\$/10^3$ lb)
8	13.2	1.43	5.17
12 BASE	18.7	1.85	5.59
16	24.2	2.30	6.04

Investment Tax Credit

Tax Credit (%)	Fixed Charge Rate (%)	Fixed Cost ($\$/10^3$ lb Steam)	Steam Cost ($\$/10^3$ lb)
0	20.8	2.01	5.75
10 BASE	18.7	1.85	5.59
20	16.5	1.69	5.43

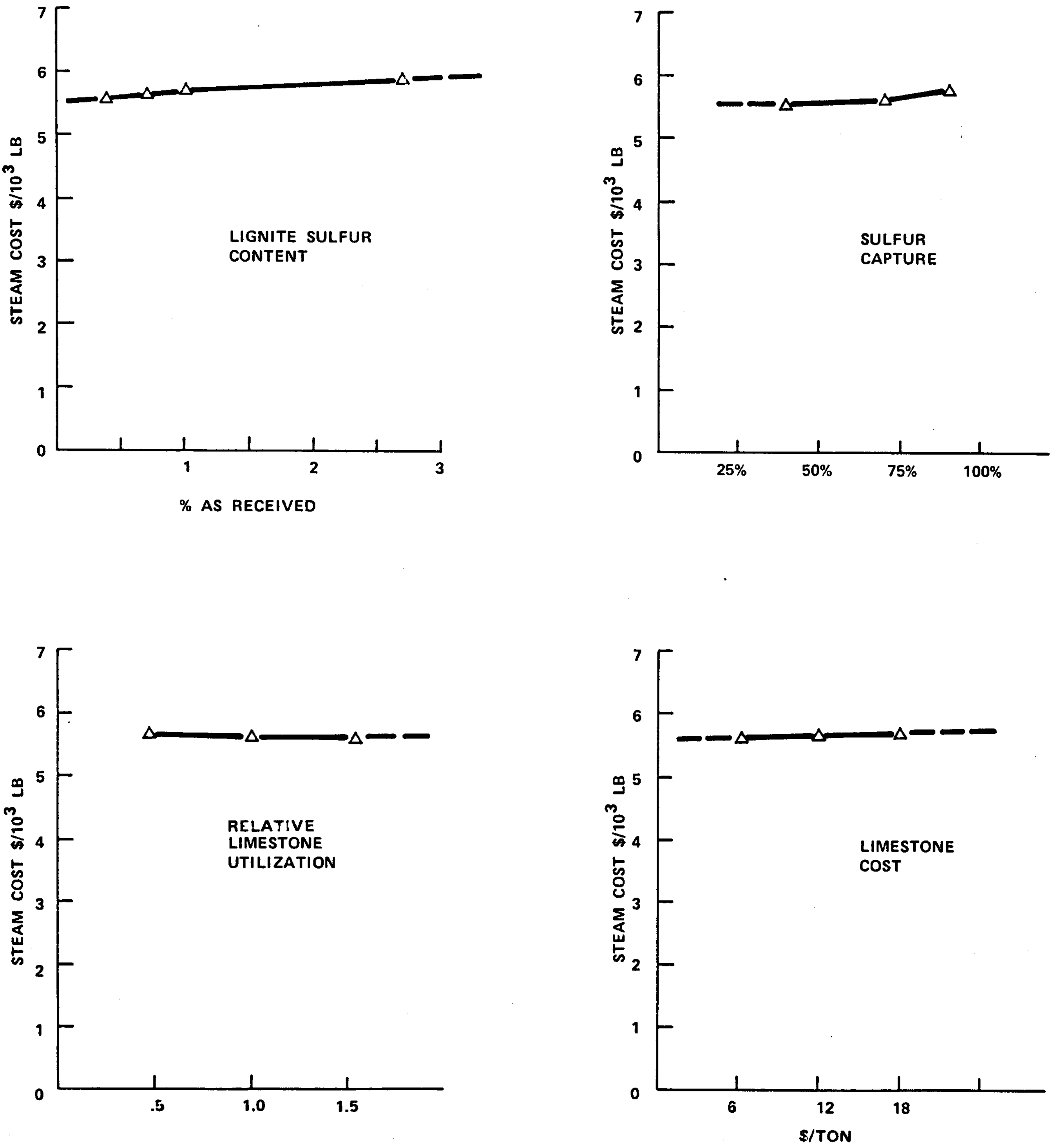

Figure 5-4. Sensitivity analyses.

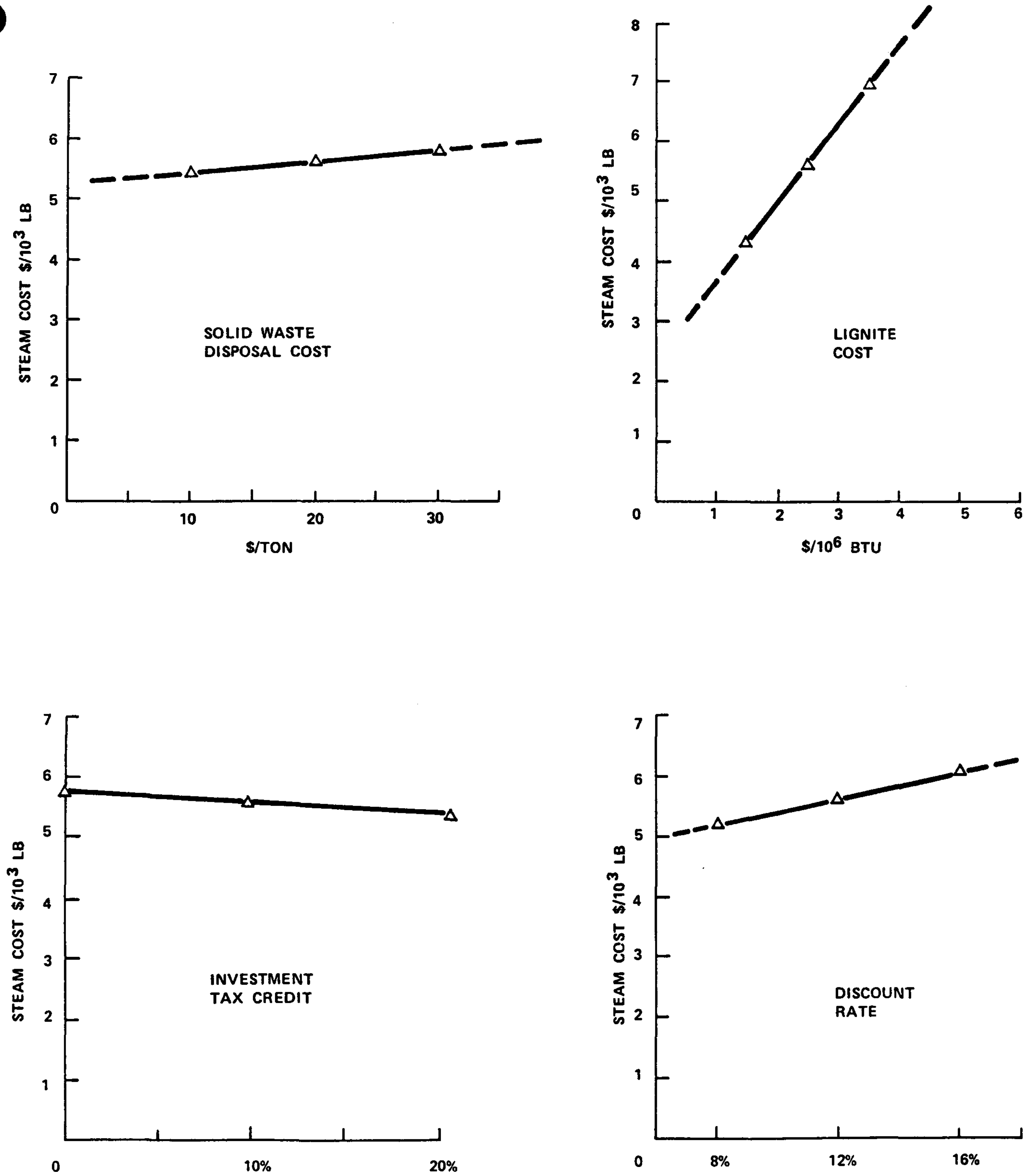

Figure 5-4. Sensitivity analyses (continued).

FBB with the cost of steam produced by other fuels or boiler design. In making such comparisons, the costs must be adjusted to include equivalent plant battery limits. Inclusion of omitted capital items would increase the cost of steam from the FBB and correspondingly increase sensitivity of steam cost to financing assumptions, e.g., discount rate.

The results of the study show that the effects of the cost of sulfur capture on the overall cost of steam are minimal. In general, the limestone requirements for the Wilcox lignite are so small that even large individual changes in lignite sulfur content, sulfur capture requirements, limestone utilization (Ca/S ratio requirements), and limestone costs have little affect on the cost of steam. However, combinations of several of these effects could have a greater impact on the cost of steam. For example, if a higher sulfur lignite such as the Jackson lignite is used, sulfur capture requirements may increase from 70 to 90 percent as well. The combined effects of increased sulfur content and increased sulfur capture requirement on the cost of steam may be significant.

The sensitivity analyses show that factors impacting lignite cost, waste disposal costs, and the cost of money have the greatest impact on the cost of steam. Therefore, a potential user must give special attention to considerations which can impact these parameters, such as the proximity of the facility to the mine or to a disposal area.

Once again, this study was limited to an add-on or replacement boiler. The difference between a grass-roots plant and the add-on plant design considered here would largely be increased capital, rather than operating expenses. Consequently, steam cost associated with operating costs should be applicable to a grass-roots plant as well as to an add-on or replacement boiler.

Section 6

MARKET POTENTIAL FOR FLUIDIZED BED COMBUSTION OF TEXAS LIGNITE

The ultimate goal of TENRAC's support for energy technology research, development, and demonstration is to encourage the widespread application of economically and environmentally efficient energy technology in Texas by the private and public sectors. In order to accomplish this objective, it is important for TENRAC to identify the constraints on and market potential of new technology. This project investigated the following in direct response to this need:

1. identification of technical, economic, environmental, and institutional constraints on the development of AFBC technology using Texas lignite, and
2. estimation of the market potential for AFBC in Texas over the next ten years.

Section 6.1 reviews the approach used in the analysis. Section 6.2 identifies the major technical, economic, environmental, and institutional issues influencing AFBC development in Texas and the use of lignite in the technology. Section 6.3 postulates the potential market for AFBC of lignite in Texas.

6.1 APPROACH

The analytical approach used in this task centered around conducting personal interviews with representatives of twelve individual companies having a known or potential interest in AFBC to determine 1) their perceptions of the current status of AFBC technology and 2) how AFBC is likely to fit into each company's energy needs over the next decade. The general categories of these twelve companies are presented in Table 6-1. The general discussion outline used in the interviews is presented in Table 6-2. In several of the interviews, the results from previous activities completed on this project were reviewed and used to gain further insight into industry's perception of AFBC technology and its potential use in conjunction with Texas lignite.

In parallel with and following the interview activities, an effort was also made to identify the major industrial categories in which early commercialization appeared most likely to occur and the potential magnitude of commercialization over the next decade. In addition to information gained through the interviews, major input for this analysis was taken from earlier studies conducted by the federal government and contractors regarding the market potential for AFBC applications nationally (6-1, 6-2, 6-3, 6-4).

6.2 MAJOR ISSUES INFLUENCING AFBC DEVELOPMENT IN TEXAS AND THE USE OF LIGNITE

Issues influencing industry's perceptions of AFBC technology are presented and discussed in summary form in Table 6-3. Each of the issues identified is rated as to whether it applies independent to the characteristics of coal used (Rating: C), favors the use of Texas lignite versus other coals (Rating: L+), favors the use of other coals versus Texas lignite (Rating: L-), or is an area where insufficient information exists to assess its implications regarding Texas lignite (Rating: ?). The ordering of issues presented reflects a declining level in the importance of each issue as measured by the frequency it was mentioned in the interviews. As discussed in Section 6.3, issues which affect the attractiveness of coal and/or lignite relative to other fuels directly influence the importance of the issues reviewed here.

Issues 1 and 2 are of major significance in the findings presented in Table 6-3. Two companies currently installing AFBC systems in Texas (Conoco and Iowa Beef Processors) have chosen AFBC because of application-specific reasons, but recognize that they are assuming significant technological risk with their decision to use AFBC. Interestingly, neither of the units being installed is of the conventional design being developed by most vendors.

Table 6-1

INDUSTRIES INTERVIEWED

Industrial Sector	Number of Interviews
Petroleum Production and Refining	2
Chemicals Manufacturing	3
Food Processing	2
Pulp, Paper, and Wood Products	3
Other Manufacturing	2
	12

Table 6-2

OUTLINE OF INTERVIEW DISCUSSION

- Location and description of existing boiler facilities in Texas
- Projected demand for new boilers over the next decade
- Consideration given to the use of lignite or other coals as a future energy source
- Technologies being considered in conjunction with lignite and/or other coals
- Level of existing interest in FBC technology
- Perceived technical, economic, environmental, and/or institutional problems influencing FBC utilization

Table 6-3

ISSUES IMPACTING THE USE OF TEXAS LIGNITE IN AFBC APPLICATIONS

Issue	Rating*	Comments
1. Lack of demonstrated, long-term (>1 year) reliability and operability at commercial scale.	C	Units at Georgetown University and Great Lakes Naval Training Center (GLNTC) are being watched, but neither is located in an industrial setting or uses lignite.
2. Lack of decisive economic advantage sufficient to overcome technical risk.	C	Primary economic advantage appears to be in the 100-250 million Btu/hr range, but is not sufficient in most cases to overcome technical uncertainties for first units or regulatory uncertainties for later units.
3. Need for design information regarding technical factors:		
--Sulfur retention	L+	Partially addressed by this project.
--Combustion efficiency	L+	Partially addressed by this project.
--Fines handling and recycle system design	?	Design of AFBC system handling high volume of fines needs to be further assessed.
--Limestone consumption	L+	Most Texas lignites are relatively low in sulfur content and will need little added limestone.
--Agglomeration	?	Limited data available for Texas lignites, but not expected to be significant due to low sodium content.
--Lignite feeding system	?	Design of feeding system should recognize high volatiles, moisture, and fines content in lignite feed.
--Erosion/corrosion of water tubes, feed points, etc.	?	No data available for Texas lignites. Units at Georgetown and GLNTC being watched.
--Particulate control	L-	May be a problem due to high fines volume with lignite.
4. Uncertainty of air pollution emission standards for industrial boilers.	C	Standards under development by EPA.
5. Uncertainty regarding technical and economic factors associated with system scale-up to commercial size.	C	Fluidization of large, dense beds is of some concern. Economies of scale may be small.
6. Ability to cofire lignite with wood and other agricultural wastes.	?	Of special interest to forestry and food processing companies.
7. Uncertainty regarding solid waste characteristics and disposal requirements.	C	Partially addressed by this project.

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*Ratings: C - applies equally to both coal and lignite
L+ - favors lignite versus other coals
L- - favors other coals versus lignite
? - insufficient data to assess

Conoco is employing "fast" or "circulating" bed technology (superficial velocities of 20 to 30 feet per second (fps) versus 4 to 8 fps in conventional designs) in an enhanced oil recovery (EOR) operation in Maverick County. Reasons for going to fast bed technology include concerns regarding tube erosion and system scale-up to commercial sizes with conventional technology. AFBC reliability in EOR applications is important, but is not as critical as in most process industries where steam supply interruptions are critical to avoid. Although the unit will initially fire bituminous coal and petroleum coke, lignite is being considered for use in the future.

Iowa Beef Processors (IBP) is employing an innovative FBC approach which separates the combustion materials and limestone by a horizontal grate. The system is designed to combust multiple fuels (coal and agricultural wastes) in a lower bed with combustion gases passing upward to the limestone bed where sulfur removal is accomplished. This "zoned" combustion/gas cleanup approach was selected because of the variability in the anticipated fuel. Located in Amarillo, IBP is not considering lignite for use in this unit.

Dow Chemical in Freeport, Texas conducted pilot plant studies and economic evaluations in early 1981 using Texas lignite and conventional AFBC technology. The pilot plant studies were reported as technically very encouraging, but economic studies failed to show sufficient economic advantage to merit taking the economic risk associated with further AFBC technology development work in the immediate future. However, Dow indicates that AFBC is still under consideration for use in later projects.

Although not interviewed, ENPEX Corporation of La Jolla, California is also evaluating the potential of using lignite in fluid bed technology for EOR in Texas. These studies have focused on use of conventional FBC technology. No financial commitments for construction of a facility had been made as of late 1981.

Of the other companies interviewed, several companies indicated that they were interested in being "second or third in line," but were unwilling to assume the financial risk associated with being the initial user of the technology in a process industry setting. Several interviewees also expressed the opinion that although available "paper studies" suggest a 10 to 15 percent advantage in steam costs for FBC over other coal-fired technologies, this advantage was insufficient to offset the risk associated with building and operating a "first-of-a-kind" technology which was not directly associated with profit margin and product output (e.g., production of ethylene by a chemical company).

Issues specifically related to the use of lignite were generally viewed as being either 1) favorable (e.g., good combustion efficiency and low limestone consumption) or 2) unknown but probably controllable with good system design (e.g., system design for handling high fines/recycle rates and agglomeration tendencies).

6.3 POTENTIAL MARKET OF LIGNITE AFBC IN TEXAS

The driving force behind interest in AFBC of Texas lignite is the number of large (≥100 million Btu/hr) industrial boilers and the amount of industrial boiler fuel use located in Texas. Using available census information on large boilers (6-5), approximately 20 percent (1,270 trillion Btu) of total fuel used nationally in industrial boilers occurs in Texas.

Based on this large share of the nation's boiler fuel demand and assumptions regarding economic growth, energy conservation, boiler sizes, industrial mix, and other factors, a 1977 study (6-1) estimated that by 1985, the Gulf Coast region (Texas, Oklahoma, Louisiana, and Arkansas) would account for 82 trillion Btu of coal use in AFBC systems out of a national total coal use in AFBC systems of 290 trillion Btu. Of the 82 trillion Btu in the region, an estimated 52 trillion would be in Texas. The same study estimated that by 1990, AFBC applications in the Gulf Coast region would total 280 trillion Btu and by 2000, 840 trillion Btu. Texas' market would equate to 180 trillion Btu and 540 trillion Btu in 1990 and 2000, respectively. These projections assumed that during the 1980's, AFBC would account for just under 50 percent of new sales of large, fossil fuel-fired boilers.

A 1979 study (6-2) estimated that between 1981 and 1985 AFBC would account for five percent of new and replacement boiler sales and would increase to 25 percent in the last half of the decade. Using these numbers and other assumptions made in the study, national AFBC fuel use in 1990 would be approximately 260 trillion Btu. Assuming regional distribution of this market similar to the earlier study, Texas' share would be roughly 50 trillion Btu (versus the earlier projection of 180 trillion Btu).

This slippage in estimated market size was explained by the U.S. Department of Energy (6-3) as resulting from "continued delays in proving out satisfactory AFBC performance at industrial scale." Due to cancellations of several DOE initiatives to stimulate AFBC development, slowed national economic growth, high financial interest rates, strong industrial energy conservation actions, and continuing uncertainty in future energy supplies (particularly regarding natural gas price and availability), industrial demonstration of AFBC technology continues to be delayed.

Despite these delays, available evidence suggests that the potential for a significant AFBC market in Texas still exists. In order to identify how this potential might be developed requires a recognition of the operational characteristics of the individual industries located in Texas. Major characteristics of importance are:

- boiler size,
- steam supply system reliability requirements,
- projected growth in steam requirements,
- willingness to take technological risk, and
- location and process-specific economics and environmental considerations.

Given these considerations, several observations can be made with regard to the potential for near-term use of AFBC in specific industries.

Petroleum refining and chemical manufacturing are the largest users of process steam in Texas, have boilers which are generally larger than average, require high reliability in steam supply systems, and have significant experience regarding introduction of new technology. Although individual plants are located throughout the state, a major concentration of these two industries is located along the Texas Gulf Coast. In terms of potential for the use of AFBC, requirements for high reliability of steam supply systems are a major impediment.

Petroleum production using steam for thermally enhanced oil recovery (TEOR) is generally of limited significance in Texas due to reservoir and petroleum characteristics found in most of Texas. However, important exceptions such as the tar sands found in the San Miguel Formation (API Gravity: -2) near Eagle Pass and the Sour Lake heavy oil reservoir (API Gravity: 14) in Hardin County exist (6-6).

The San Miguel tar sands deposits are located near deposits of Wilcox Group lignite. Boiler sizes required for these applications are generally smaller and reliability of steam supply less critical than in most large process industries. Technological innovation is also common in this industry. As pointed out in Section 6.2, at least two separate applications of AFBC technology for EOR are currently under consideration in Texas.

Food processing applications such as vegetable and fruit canning and freezing, milk pasteurization, livestock processing, and grain drying may have good potential for application of AFBC. Boiler sizes in this industry vary significantly from relatively small to above-average. Due to perishability of food materials, extended outages of steam supply due to boiler problems are not acceptable; however, short interruptions can be tolerated. Experience with technological innovation in the energy area is limited. Existence of agricultural wastes and residues which could be used as a fuel source by AFBC technology either separately or co-fired with coal may improve overall economics. Existence of numerous food processing activities along the Texas lignite belt is significant.

Pulp, paper, and wood products manufacturers located in the piney woods region of east Texas may have good potential for AFBC due to the ability to use wood wastes as a fuel and the relative proximity of the industry to lignite deposits. In the case of several companies, lands owned for forestry development are also underlain by lignite. While the industry is generally conservative with regard to introduction of new technology, several existing applications exist where wood wastes are being combusted using AFBC. Steam reliability requirements vary depending on specific applications.

Other industries investigated appear less likely to use AFBC in the next decade for a variety of reasons. For example, electronics and light manufacturing generally have relatively small boiler sizes which are uneconomical with regard to the use of coal. Primary metals applications, principally aluminum, generally exceed the size suitable for AFBC applications in the next decade, however. The application of AFBC to space conditioning use by large commercial or institutional buildings is also a possibility. In many cases, institutional buildings (i.e., schools and hospitals) are owned by state, local, or federal governments. High variability in boiler loads due to seasonal and diurnal changes in steam demand hamper the economics of capital intensive boiler installations such as with AFBC.

In summary, the major constraint to commercialization of AFBC appears to be the lack of demonstrated, long-term reliability of the technology. Because of this, the major steam using industries in the state (petroleum refining, petrochemicals, and primary metals) appear likely to wait for industries with lower steam reliability requirements to initially install the technology. Because of location and process-specific considerations, these initial users will probably be located along the lignite belt in the food processing; pulp, paper, and wood products; and enhanced oil recovery industries. Data being gathered from AFBC units at Georgetown University in Washington, D.C. and at Great Lakes Naval Training Center will help answer some of the questions relating to long-term reliability. However, due to less severe reliability requirements in these two installations (i.e., space conditioning), direct transfer of the technology to Texas industries may be limited. The Tennessee Valley Authority 20 MW AFBC pilot plant which will start up in 1982 will primarily focus on utility applications but will provide some useful data on reliability. Furthermore, due to design factors (such as high ash recycle rates and the impact of high volatile content in lignites on lignite feeding system selection) which may be distinct for Texas lignites, system design considerations may need to be resolved prior to widespread application of AFBC technology using Texas lignite.

6.4 REFERENCES

6-1 Farmer, M. H., et al. Application of Fluidized-Bed Technology to Industrial Boilers. Exxon Research and Engineering Company. U.S. Environmental Protection Agency. January 1977. EPA-600/7-77-011.

6-2 Energy Resources Co., Inc. Case Study Applications of Venture Analysis--Fluidized Bed. U.S. Department of Energy. April 1977. Contract No. EX-77-C-01-2687.

6-3 Freedman, S., et al. Commercialization Task Force on Industrial Atmospheric Fluidized Bed Combustion. U.S. Department of Energy. Undated. TID-28854.

6-4 Davy McKee Corporation. Cost Comparison Study, Industrial Size Boiler, 10,000 to 400,000 Pounds Per Hour. U.S. Department of Energy, October 1979. Contract No. Ex-77-C-01-2418.

6-5 "Tabulated Data Derived from FEA's Natural Gas Task Force and MFBI Surveys." Appendix 4 in Farmer, M. H., et al. Application of Fluidized-Bed Technology to Industrial Boilers. Exxon Research and Engineering Company. U.S. Environmental Protection Agency, January 1977. EPA-600/7-77-011.

6-6 Oil and Gas Journal. "EOR methods help ultimate recovery." March 31, 1980. p. 92.

Appendix A

DETAILED RESULTS OF CPC TESTS

The following supplementary information is included in Appendix A:

- detailed test procedures, including operational logs of each test and elapsed time plots of operating parameters and flue gas composition;
- a presentation and evaluation of results of loss on ignition (LOI) and total organic carbon (TOC) analyses of solid waste streams; and
- equations, terminology, and definitions used for the results of CPC's FBC testing of the Texas lignites.

A.1 TEST PROCEDURES

Under subcontract to Radian Corporation, three series of atmospheric FBC tests with Wilcox and Jackson lignites were conducted by CPC at their test facility located in Menlo Park, California. The two Wilcox lignite test series, consisting of four tests of nominally 24 hours' duration each, were conducted during the weeks of February 9-13 and March 2-6, 1981, and were referred to as L116 and L117, respectively. The third test series (referred to as L118) of four 24-hour tests was conducted with Jackson lignite during the week of May 11-15, 1981.

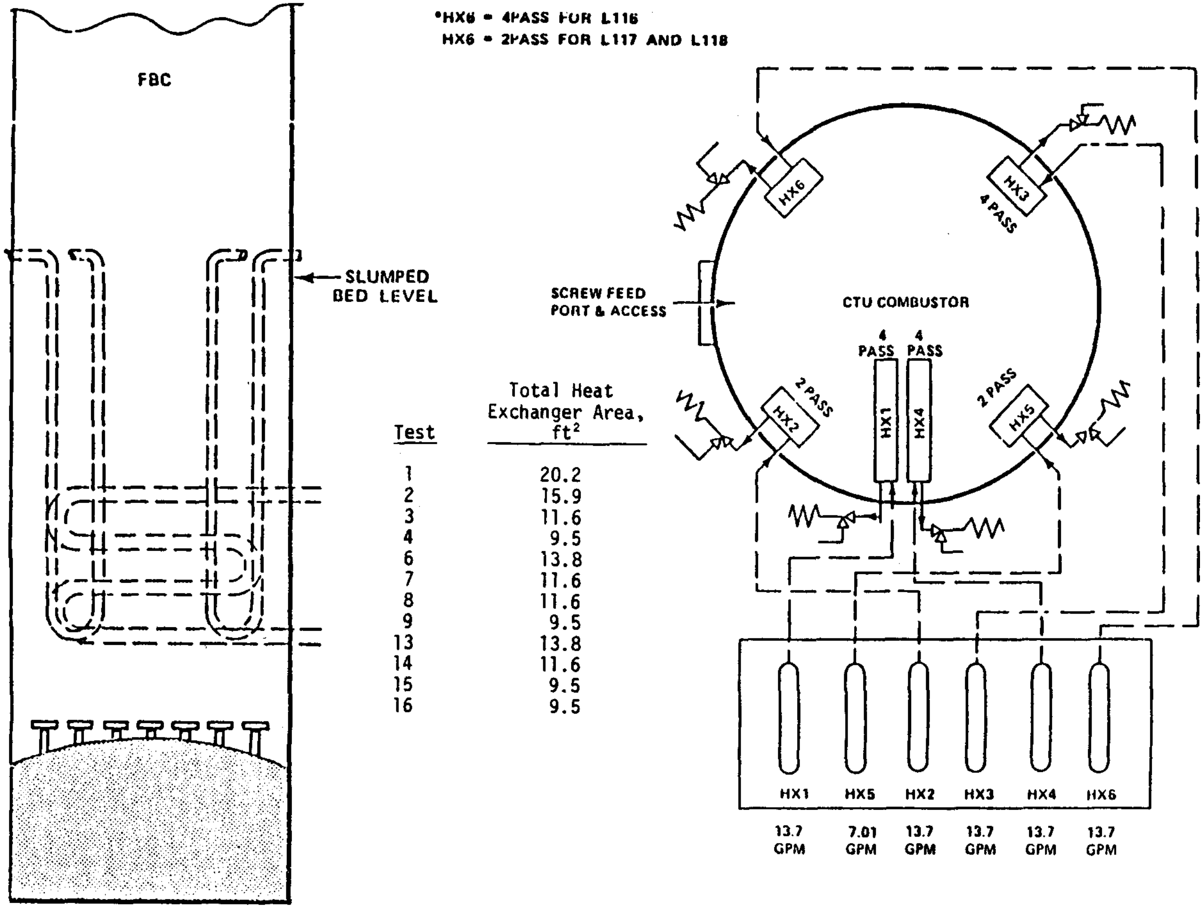
The Wilcox (Monticello mine) lignite consumed in Test Series L116 and L117 was procured from Texas Utilities Generating Company, Mt. Pleasant, Texas. The Jackson (San Miguel mine) lignite consumed in Test Series L118 was procured from San Miguel Electric Cooperative, Inc., Jourdanton, Texas. The lignites were crushed and delivered to the CPC test combustor in 50-ft^3 Flo-Bins. The lignite was fed to the combustor from a live bottom hopper via a K-TRON weigh belt feeder, 8-in. diameter rotary airlock valve, and a 6-in. diameter screw conveyor. Lignite feed was controlled by a manually adjusted rate setpoint on the K-TRON weigh belt.

The limestone used was obtained from the Linwood Stone Company, Davenport, Iowa. It was procured as crushed limestone and required no further processing by CPC. The limestone feedrate was controlled by a manually adjusted speed-of-rotation setpoint on the BIF feeder. It was fed from the BIF feeder into the rotary airlock feeder at the same point as the lignite. Approximately 12 scfm of blower air was introduced into the screw conveyor to minimize pyrolysis of the lignite within the screw. (For a short period early in Test Series L116 an attempt was made to inject the lignite pneumatically into the combustor through an existing pneumatic feed system. However, the very wet lignite was difficult to feed out of the pneumatic system hopper so the screw feed system was utilized for the balance of the tests.)

The starter bed material for L116 and L118 was Grade No. 10-20 Unisil high purity silica sand. Sand was added to the FBC during startup and the initial part of the L116 test series to establish the proper operating height of the bed material, viz., to cover the water-cooled tubes in the bed. (The L117 test bed material was the product of the final bed from the L116 test series.)

To maintain bed height to 4 feet or less (settled height), material was periodically removed through a manually operated bed drain.

The in-bed tubes cooling water system operated at 160 psig with typical tube inlet and outlet temperatures of 190°F and 300°F, respectively. The in-bed heat exchanger configuration, with locations as shown in Figure A-1, included two- and four-pass vertical tubes and four-pass horizontal tubes. All vertical tubes are fabricated from 3/4-in. schedule 40-type 316 stainless steel pipe and the horizontal tubes are fabricated from 1¼-in. schedule 40-type 316 stainless steel pipe.



Test	Total Heat Exchanger Area, ft^2
1	20.2
2	15.9
3	11.6
4	9.5
6	13.8
7	11.6
8	11.6
9	9.5
13	13.8
14	11.6
15	9.5
16	9.5

Figure A-1. Arrangement and location of bed tubes and associated plumbing in the CTU.

All critical system pressures and pressure differentials were measured using Dwyer Magnehelic® gauges. Fluidizing air flows were measured by use of orifice plates and flowmeters. Critical system temperatures from chromel-alumel thermocouples were continuously recorded on a 24-channel Leeds & Northrup multipoint recorder. The exhaust gas composition from an extractive system utilizing specific gas analyzers (viz., CO_2, O_2, CO, SO_2, NO, and C_xH_y) was recorded continuously except during equipment calibration periods.

Total inlet and outlet particulate loading samples were determined using EPA Method 5/17. The inlet sampling port was located 6 feet above the combustor outlet nozzle (i.e., freeboard) and the outlet sampling port was located 8 feet downstream of the recycle cyclone. For compositional analyses of the particulates, larger than normal samples were taken during the EPA-5 procedure due to the high exhaust loading (i.e., 5 grams or more particulate were captured on the EPA-5 filter pad). SO_3 in the exhaust gas was determined by EPA Method 8 with the sample extracted from the collection train impingers. Outlet particulate size distributions were attempted by Andersen cascade impactors. However, the impactors became overloaded even with short sampling times. The sizing data obtained are, therefore, invalid and not reported.

The heat exchanger surface areas shown in Table A-1 for L116 and L117 were calculated from CPC's fluid bed combustion model and they became the basis for the heat exchanger arrangement for the start of each test series. Actual areas required were at least one heat exchanger tube less than predicted for each test point, due principally to the extremely high recycle rate. The recycle rate was more than ten times the rates experienced in previous lignite testing and this was not accounted for in the combustion model. The areas listed for L118 were based on experience from the previous tests.

Table A-1

TEXAS LIGNITE: PLANNED TEST MATRIX FOR L116, L117 & L118 SERIES

Test Point		Temp. (F)	Vsf (ft/sec)	Excess Air (%)	Predicted HX Area (ft^2)	Limestone Rate
1	L116, L117	1500	8±.5	20 ± 5	22.4	----
2		1400	6±.5	↓	20.2	----
3		1500	6±.5	↓	18.1	----
4		1600	6±.5	↓	13.3	----
5		1500	8±.5	↓	22.4	As required for 70% sup.
6		1400	6±.5	↓	20.2	" " " " "
7		1500	↓	↓	18.1	" " " " "
8		1500	↓	↓	18.1	As required for 90% sup.
9		1600	↓	↓	13.3	" " " " "
10		1400	↓	↓	20.2	As required for 50% sup.
11		1500	↓	↓	18.1	" " " " "
12		1600	↓	↓	13.3	" " " " "
13	L118	1400	↓	↓	15.9	----
14		1400	↓	↓	15.9	As required for 70% sup.
15		1500	↓	↓	13.8	As required for 90% sup.
16		1600	6±.5	20 ± 5	11.7	" " " " "

For identification, the total test periods and durations and the selected "steady-state" periods and durations for the 12 tests are shown in Table A-2. Periods are indicated by the elapsed time (ET) from the start of the test series. Test #7 was divided into three separate entities (a,b,c) due to the totally different operating conditions during each period with the changes in operating mode of the recycle loop.

Table A-2

TOTAL TEST AND "STEADY-STATE" PERIODS AND DURATIONS

Test #	Total Test ET's (min)	Duration (hr)	Steady-State ET's (min)	Duration (hr)
1	1830-2000	2.8	(None)	
2	2100-3500	23.3	3300-3500	3.3
3	3550-4890	22.3	4200-4350	2.5
4	5020-6340	22.0	5750-6000	4.2
6	1100-2130	17.2	(None)	
7a	2200-2580	6.3	(None)	
7b	3000-3410	6.8		
7c	3680-3860	3.0		
8	3870-4720 &4940-5280	19.8	4300-4400 &5150-5250	3.3
9	5400-6600	20.0	6400-6600	3.3
13	0570-1420 &1500-2070	23.7	1100-1200	1.7
14	2380-3640	21.0	3450-3600	2.5
15	3830-4790 &4940-5300	22.0	5150-5300	2.5
16	5310-6720	23.5	6000-6700	11.7

Test Series L116

This test series, consisting of Tests #1 through #4, commenced with initiation of preheat at 0230 (24-hour clock time) on February 9, 1981, at which time the elapsed time clock was started (ET = 0000 minutes) and concluded with the initiation of cooldown at 1210 (ET 6340) on February 13, 1981.

Preheat commenced with a 1.7⁻ft starter bed of 16 x 30 mesh silica sand and 22.4 ft^2 of heat exchanger surface. Preheat of the bed to 880°F (T_B) was accomplished by use of the oil-fired preheat burner at which time (ET 0077) Wilcox lignite feed was started at 2 lb/min using the screw feed system. This lignite rate was increased gradually so at ET 0140 when the preheat burner was secured the lignite rate was 13 lb/min. During this time also the bed inventory was being built up by sand addition. At ET 0395 the lignite feed was shifted from the screw feed system to the pneumatic feed system since earlier lignite tests were conducted using the pneumatic system with minimal feed system upsets. The bed was at operating bed height (ΔP = 62 IW) at ET 0410 at which time the attempt to start the recycle failed. (This is a common occurrence since recycle is purposely made inactive on startup and condensation in the recycle dipleg usually forms a plug.) The CTU was then shut down at ET 0530 for 54 minutes to remove an ash plug in the recycle dipleg. Upon restart the recycle started functioning and except for six temporary stoppages which were corrected without shutdown, the recycle worked very well for the remainder of L116.

In proceeding to the test conditions for Test #1 (1500°F, 20 percent excess air, 8 ft/sec) the high superficial velocity caused high elutriation and decrease of bed inventory. Periodically throughout this test, sand was added totaling 1280 lb. Additionally, it became obvious that the heat transfer surface was too great to achieve a T_B of >1350°F. Therefore, water flow through one of the two-pass vertical tubes (HX-5) was stopped, i.e., HX-5 was "cut out" of service. This increased bed temperature to 1416°F. Although this was lower than the planned bed temperature of 1500°F, the baghouse temperature was reaching its design limit due to spray cooler limitations, so an increase in bed temperature (and the resulting exhaust gas temperatures) by "cutting out" another heat exchanger was no longer practicable for the high velocity conditions of this test. Subsequent tests were conducted at lower bed velocities, thus allowing higher bed temperatures.

The lignite as received was very wet which caused bridging in the pneumatic feed system supply hopper. At ET 1340 the feed was shifted to the screw feed system, which has a more active hopper vibrator and a larger discharge to the K-TRON weigh belt. The result was a much steadier feed and fewer bridging incidents. The screw feed system was used for the remainder of L116 and all of L117 and L118.

The elapsed time plots of important operational parameters and exhaust gas compositions for Test #1 are shown in Figure A-2. It should be noted that the superficial velocity averaged about 7 ft/sec for most of the test period because of concern for baghouse temperature and only during the last three hours was the superficial velocity close to the planned test condition of 8 ft/sec.

Test #2 (6 ft/sec, 20 percent excess air, 1400°F) was attained by eliminating water flow through, or "cutting out," one of the four-pass vertical tubes (HX-3). Starting with this test the lower superficial velocity resulted in less elutriation and a gradual increase in bed height. For the remainder of L116 about 100 lb of bed was drained every five to six hours.

No significant upsets occured during this test condition. Recycle was temporarily lost at ET 2390, 2572, and 2694, each time being corrected by rodding out the L-valve. The elapsed time plots of important operational parameters and exhaust gas composition for Test #2 are shown in Figure A-3.

At this point it was calculated that the sulfur retention was about 40 percent based on typical composition of Wilcox lignite (the analysis for the actual lignite used was not available) so the test conditions were altered to Test #3 on the decision tree in lieu of Test #11.

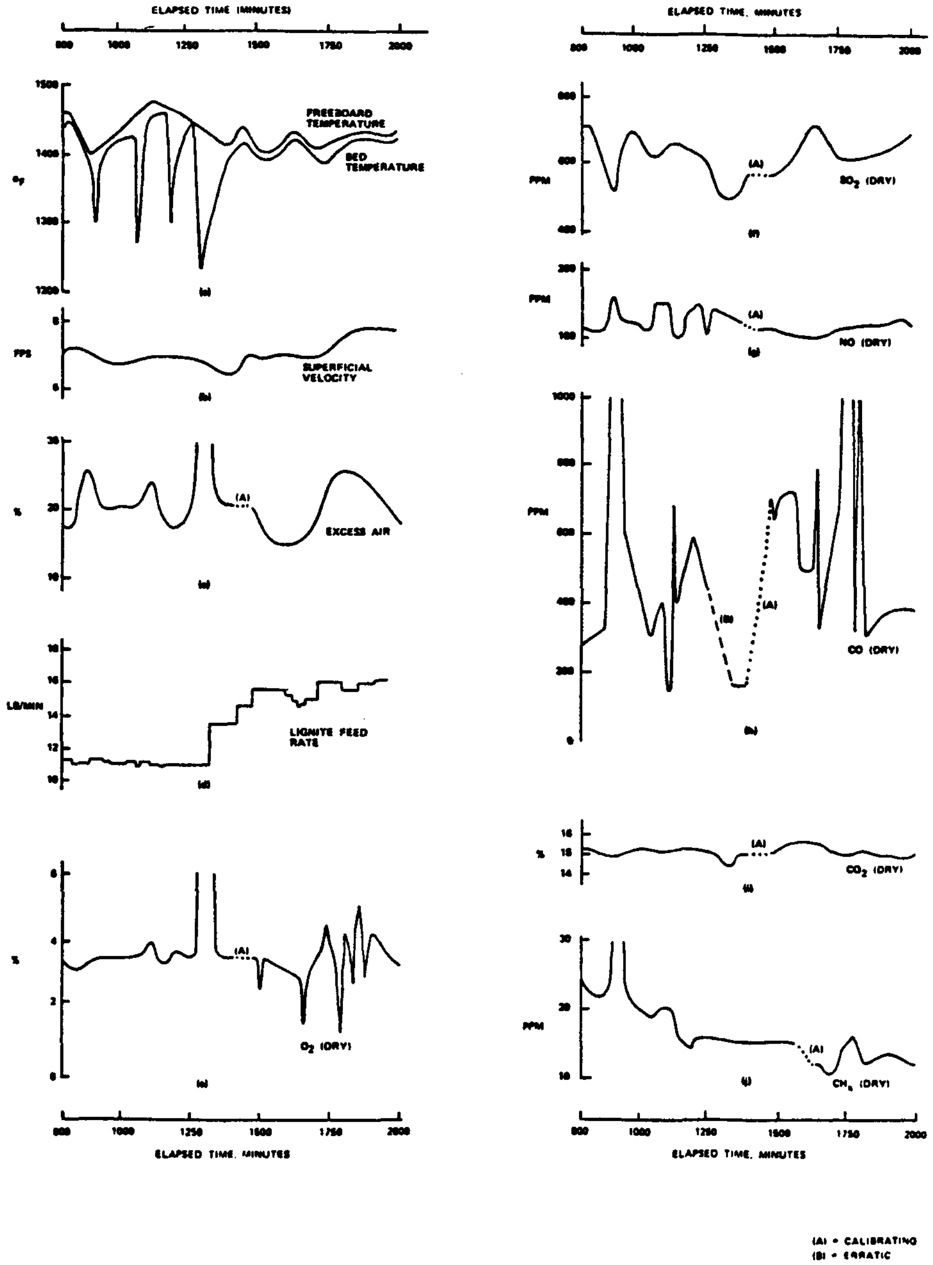


Figure A-2. Elapsed time histories of test #1 data.

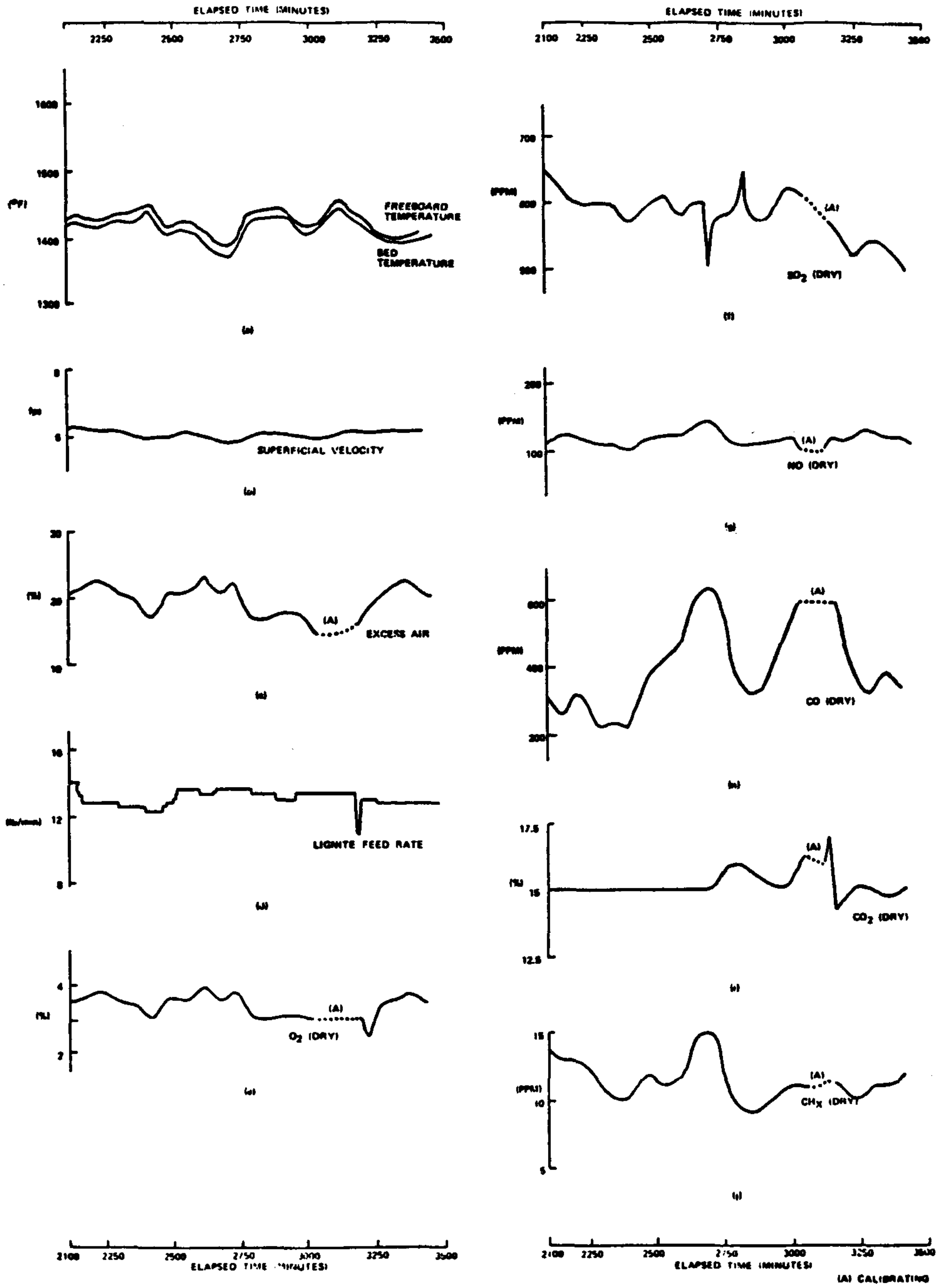


Figure A-3. Elapsed time histories of test #2.

Test #3 (6 ft/sec, 1500°F, 20 percent excess air) was attained by cutting out a four-pass vertical tube (HX-6). The planned test condition was reached at ET 3480. At ET 3530, the recycle stopped and bed temperature increased suddenly from 1525°F to 1575°F and bed ΔP started to decrease as could be expected from loss of several hundred pounds per minute of slightly cooler recycle material (i.e., more than 10 percent of total bed inventory). The recycle commenced working upon rodding out the L-valve and the bed temperatures and ΔP returned to their normal values. The elapsed time plots of important operational parameters and exhaust gas composition for Test #3 are shown in Figure A-4.

Test #4 (6 ft/sec, 1600°F, 20 percent excess air) was attained by cutting out a two-pass vertical tube (HX-2). Operation was very stable with no upsets. The elapsed time plots of important parameters and exhaust gas composition are shown in Figure A-5.

It should be noted here that the variations that occurred in some of the parameters were due to one or more of the following factors:

- Variations of the lignite properties (moisture, heating value, sulfur content, etc.) occurred from hopper to hopper.
- Some size classification of the lignite occurred as the hopper emptied. Usually the feed rate had to be adjusted for this reason alone.
- About every two hours a 10-second catch was made of the lignite feed as a check on the K-TRON accuracy. This interruption in feed appears in most of the process data.

Test Series L117

This test series, consisting of Tests #6 through #9, commenced with initiation of preheat at midnight (ET = 0000) on March 2, 1981. The preheat procedures were identical to those for test series L116 except that the starter bed was used bed material from Test #4 and heat exchanger HX-6 was changed from a four-pass to a two-pass vertical tube.

Lignite feed started at ET 0147, the preheat burner was secured, and recycle started (shutdown not required) at ET 0185. The bed reached operating height

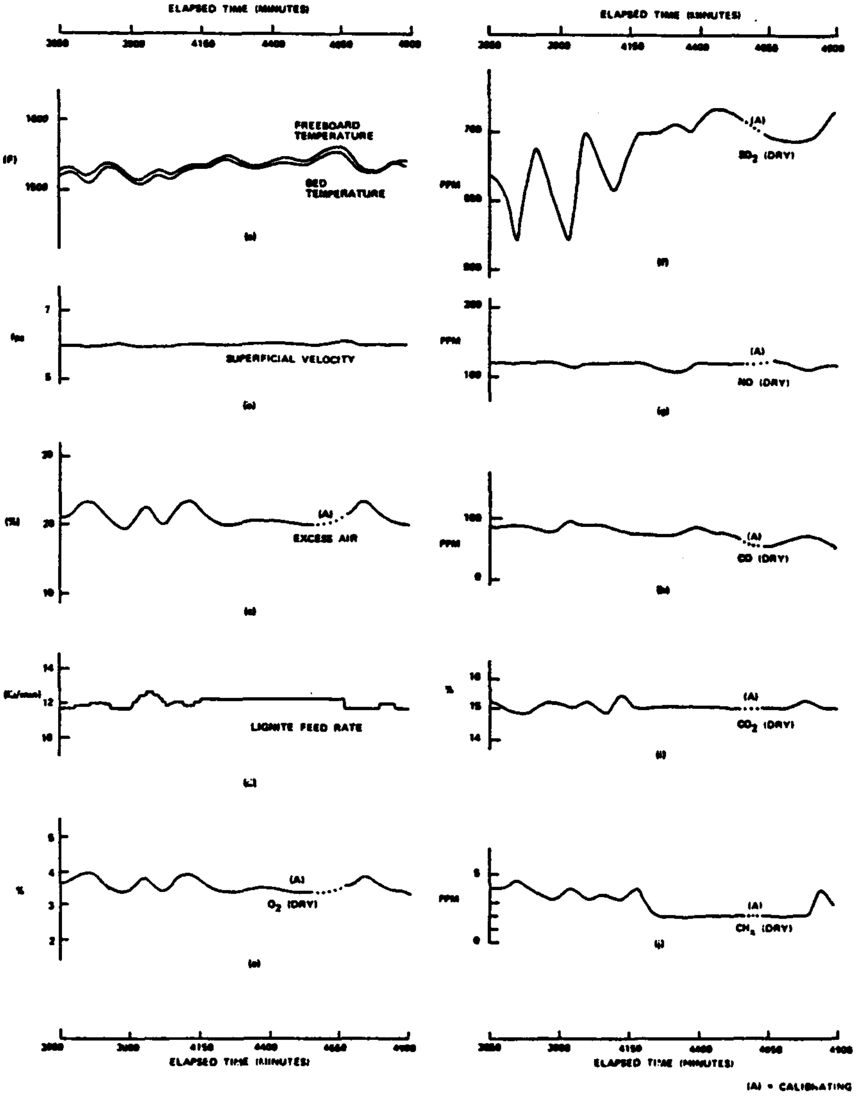


Figure A-4. Elapsed time histories of test #3 data.

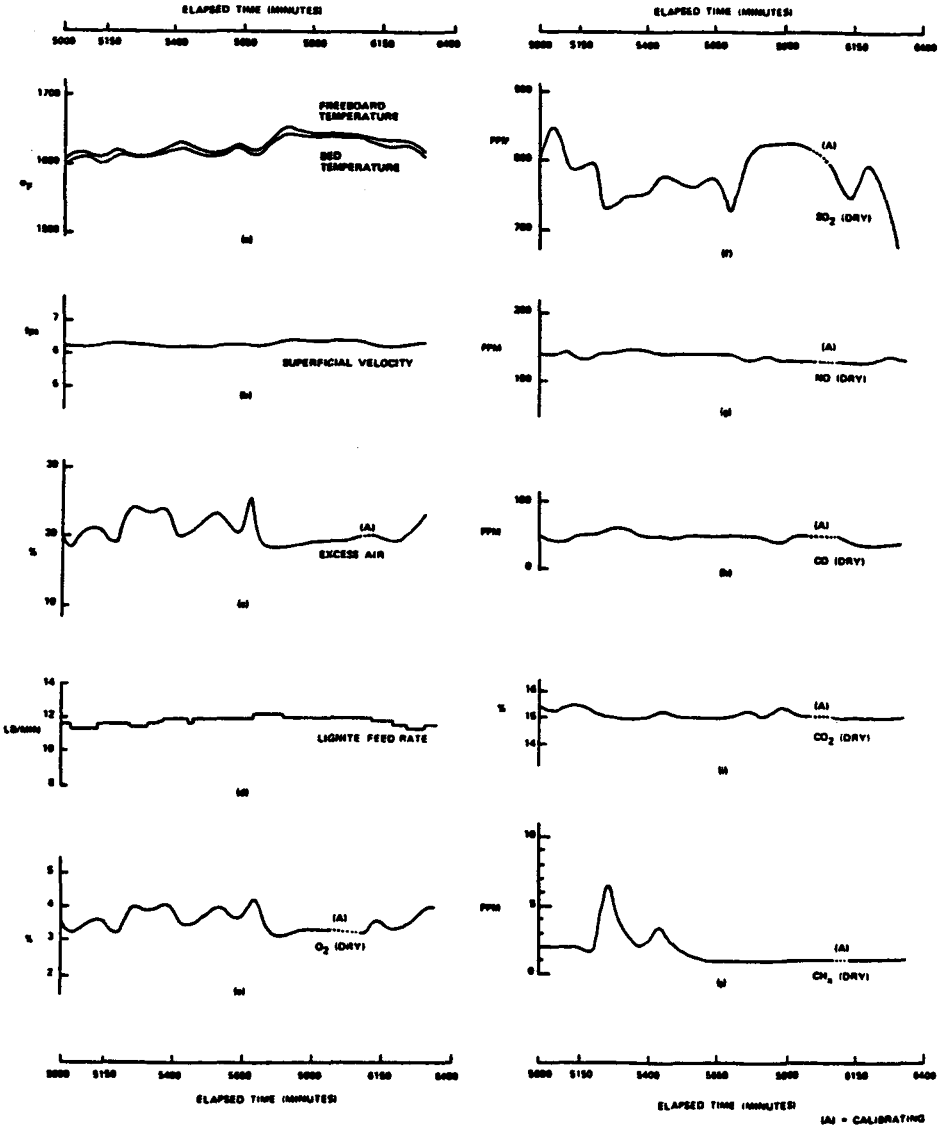


Figure A-5. Elapsed time histories of test #4 data.

at ET 0630. Limestone feed started at ET 0640 at a rate of 0.88 lb/min to meet the test conditions of Test #6 (6 ft/sec, 1400°F, 20 percent excess air, 70 percent sulfur retention). Test #6 was selected in lieu of Test #5 on the decision tree since the effect of superficial velocity on sulfur retention was minor (~5 percent).

When it became obvious that a reduction in heat extraction from the bed would be required to meet $T_B = 1400°F$, the four-pass vertical heat exchanger (HX-3) was cut out at ET 0715. At ET 0750 the planned test conditions were attained. At ET 0875 a rock entered the feeder valve with the fuel which caused a pin to shear and forced a 15-minute system shutdown.

Stable test conditions were achieved at ET 1100 and the remainder of Test #6 was conducted without upsets. The bed temperature was about 50°F higher than planned and, in retrospect, it appears that cutting out a two-pass rather than a four-pass vertical tube would have been a wiser choice. It should be noted that during the period ET 1161 to ET 2070 the operator made several changes to the limestone feed rate in order to maintain SO_2 within the desired 250 $\pm$25 ppm. The average limestone rate during this period was 0.80 lb/min. At ET 2070 the limestone rate was set at 0.6 lb/min and remainded at this value for the rest of Test #6. At ET 1279 130 lb of bed material was drained. With an exception during the middle portion of Test #7 when recycle was malfunctioning, approximately 100 lb of bed material was drained every three to four hours throughout Test Series L117.

The elapsed time plots of important operational parameters and exhaust gas composition for Test #6 are shown in Figure A-6.

Test #7 (6 ft/sec, 20 percent excess air, 1500°F, 70 percent sulfur retention) was attained by cutting out a two-pass vertical heat exchanger (HX-5) at ET 2156. Limestone feed rate remained at 0.5 lb/min. Stable test conditions were reached at ET 2200. The first major disturbance occurred at ET 2595 when bed temperature control became very erratic; recycle dipleg temperatures

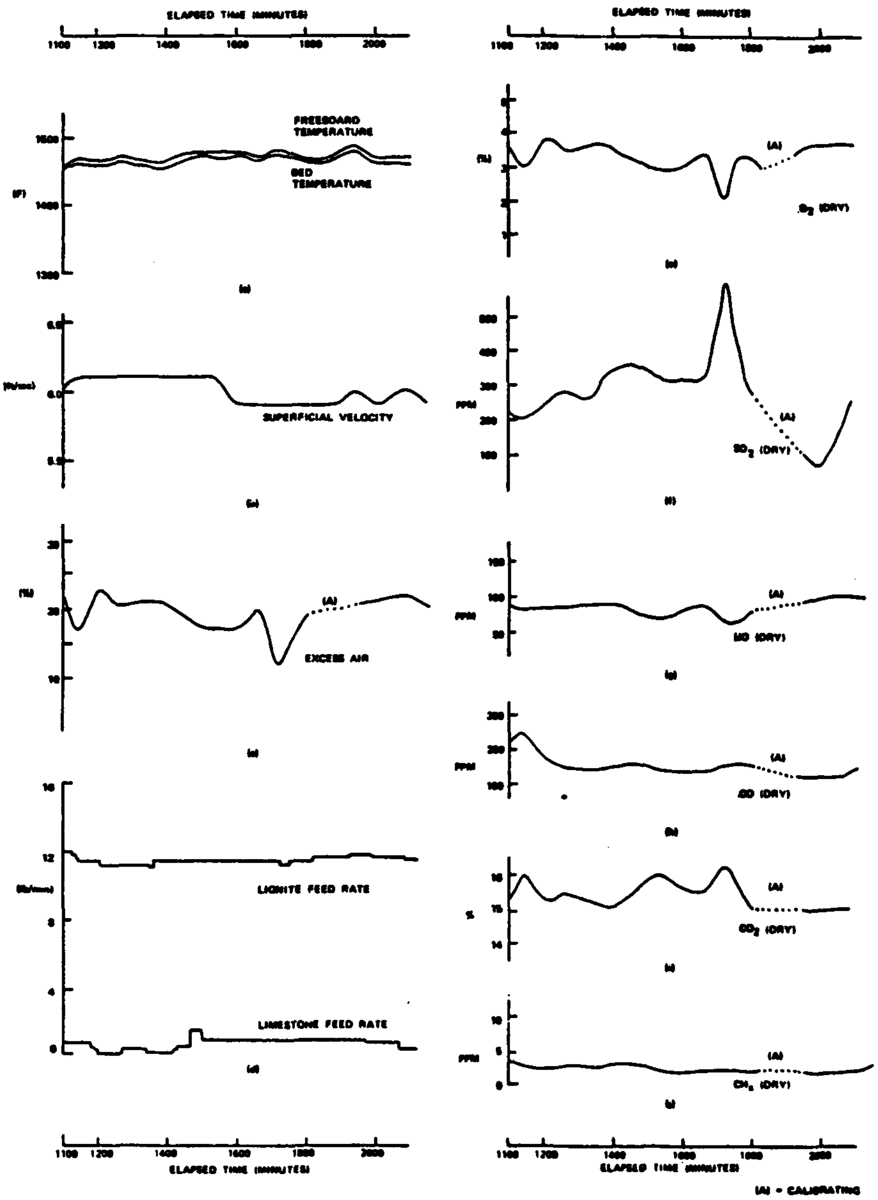


Figure A-6. Elapsed time histories of test #6 data.

dropped suddenly and stayed at lower values with very rough traces. Bed level also decreased to approximately 50 IW (ΔP). Indications are that the recycle had become partially plugged and attempts by the operator to clear the restriction added to the erratic behavior. The CTU was shut down at ET 2830 and the recycle leg cleared of ash. Immediately upon startup, the baghouse ΔP and freeboard pressure were abnormally high indicating very high ash accumulation in the spray cooler and baghouse. A second shutdown was necessary to clear out the accumulated ash. Upon startup, the system came quickly to stable conditions but at 100°F lower recycle dipleg temperature than normal, 20 percent lower lignite feed rate (to maintain the same T_B), higher excess air, and a reduction of bed ΔP. Another shutdown was initiated at ET 3410 to investigate the cause for this change of operational conditions. No reason was found and on restart at ET 3438 the system returned to its last operating state. Then suddenly at ET 3680, the recycle temperatures increased, the bed temperature dropped (until the lignite was increased), bed ΔP increased, and excess air came back to normal. Apparently a restriction in the recycle loop which permitted a continuous recycle (but at a reduced rate) had finally broken loose. Unfortunately, the process was probably not at steady state at the end (ET 3867) because SO_2 was very low due to the sudden recycle of large quantities of unreacted sorbent.

The elapsed time plots of important operational parameters and exhaust gas composition for Test #7 are shown in Figure A-7.

Test #8 (6 ft/sec, 20 percent excess air, 1500°F, 90 percent sulfur retention) was attained by increasing the limestone to 0.9 lb/min for 90 percent sulfur retention, all other parameters remaining the same as for Test #7. This test ran smoothly except for a shutdown at ET 4720 for 126 minutes to clean out the spray cooler.

The elapsed time plots of important operational parameters and exhaust gas composition for Test #8 are shown in Figure A-8.

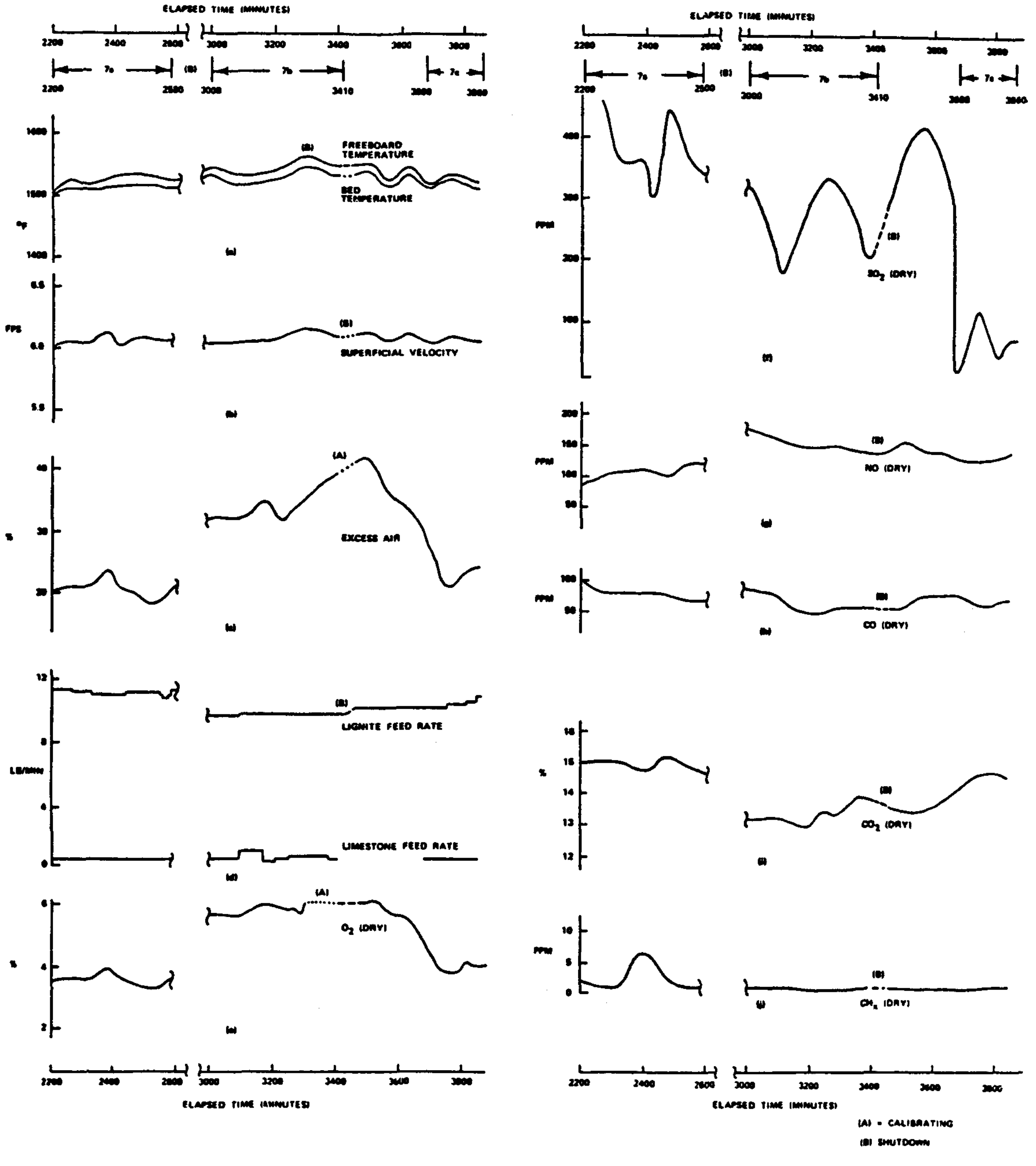


Figure A-7. Elapsed time histories of test #7 data.

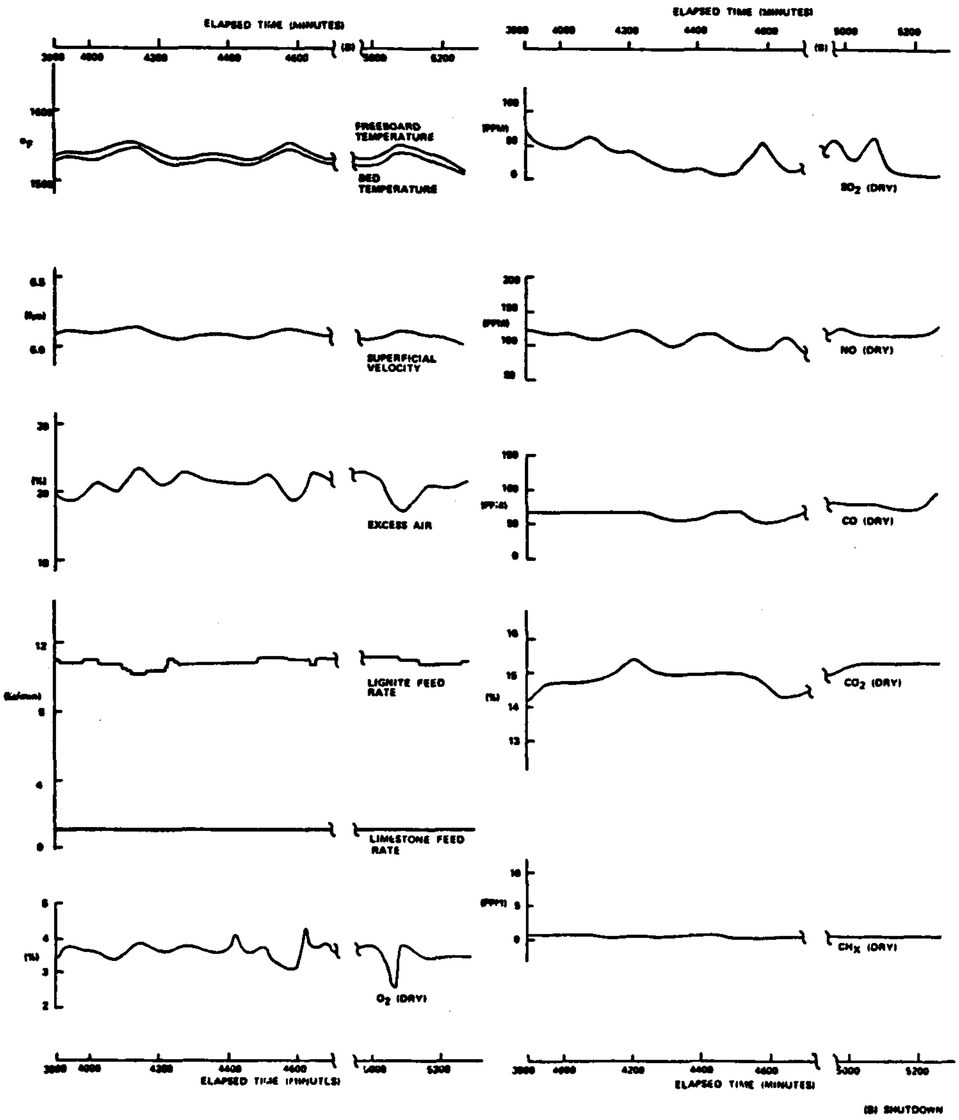


Figure A-8. Elapsed time histories of test #8 data.

Test #9 (6 ft/sec, 20 percent excess air, 1600°F, limestone injection same as Test #8) was attained by cutting out a two-pass vertical heat exchanger (HX-2) at ET 5283. The test ran very smoothly with the exception of one minor lignite feed upset at ET 5582 when a bridge occurred in the hopper. This test was concluded at ET 6600 and plant cooldown commenced. The elapsed time plots of important operational parameters and exhaust gas compositions for Test #9 are shown in Figure A-9.

Test Series L118

This test series (Tests #13 through #16) commenced with initiation of preheat at clock time 2325 (ET minus 0035) on May 10, 1981 using a starter bed of 16 x 30 mesh silica sand and the same heat exchanger configuration as in Test Series L117 for a total surface area of 20.2 ft^2.

Lignite feed started at ET 0000, the preheat burner was secured at 0133, and the bed reached operating height at ET 0393. Earlier, the four-pass vertical heat exchanger (HX-3) was cut out when it became apparent that it was not needed to meet test conditions. The recycle was started after a system shutdown to remove wet sand from the L-valve. After cutting out a two-pass vertical heat exchanger (HX-2), Test #13 (6 ft/sec, 20 percent excess air, 1400°F, without limestone) was reached at ET 0570. A hole in the recycle cyclone forced a 55-minute shutdown to make temporary repairs at ET 1428. Upon test point completion at ET 2073, the plant was shut down to effect further repairs to the cyclone. The elapsed time plots of important parameters and exhaust gas composition are shown in Figure A-10.

Test #14 (6 ft/sec, 20 percent excess air, 1400°F, 70 percent sulfur retention) was reached after cutting out a two-pass vertical heat exchanger tube (HX-5) at ET 2378. During the first half of this test, several changes were made to the limestone feed rate in an attempt to maintain 70 percent sulfur retention. The results were unpredictable; so from ET 2943 until completion of the test point at ET 3647, the limestone feed was not varied. The elapsed time plots of important parameters and exhaust gas composition are shown in Figure A-11.

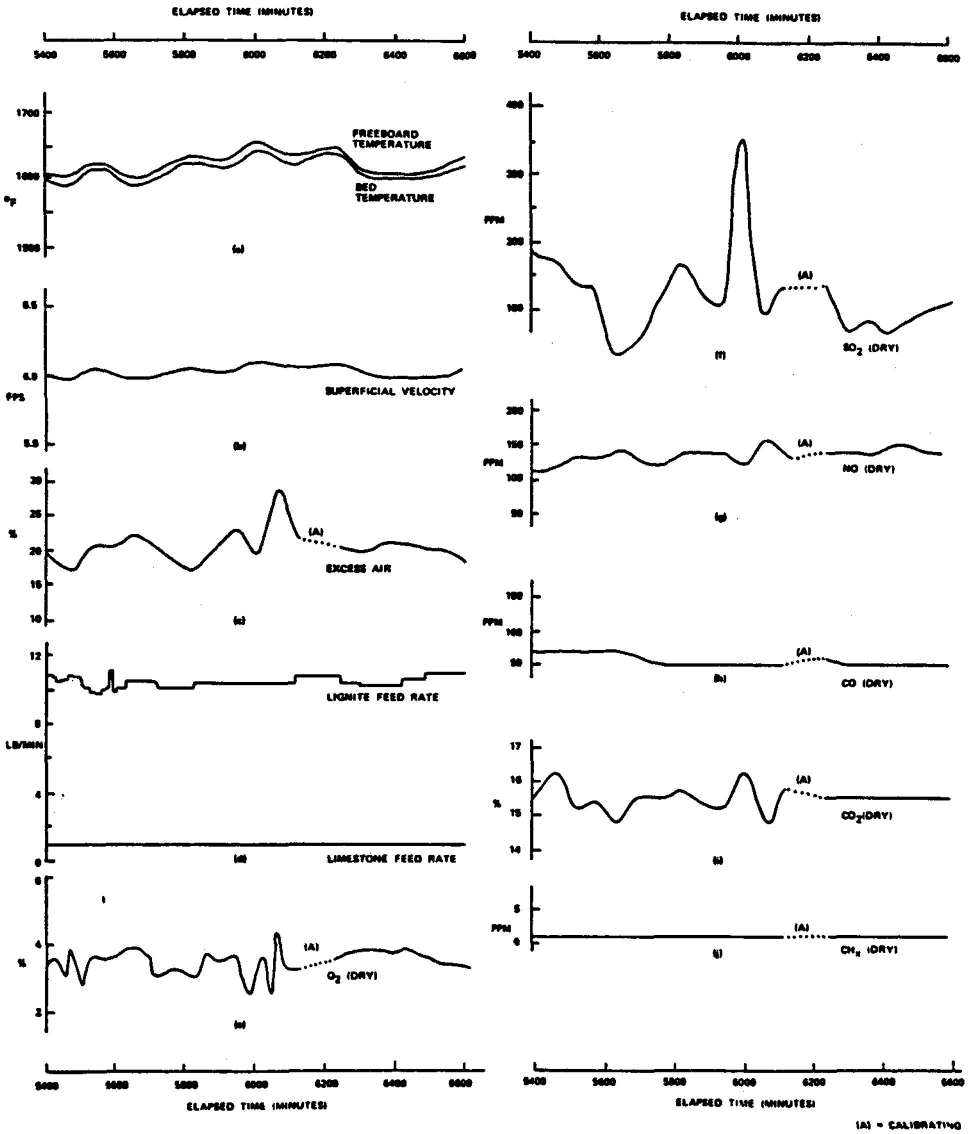


Figure A-9. Elapsed time histories of test #9 data.

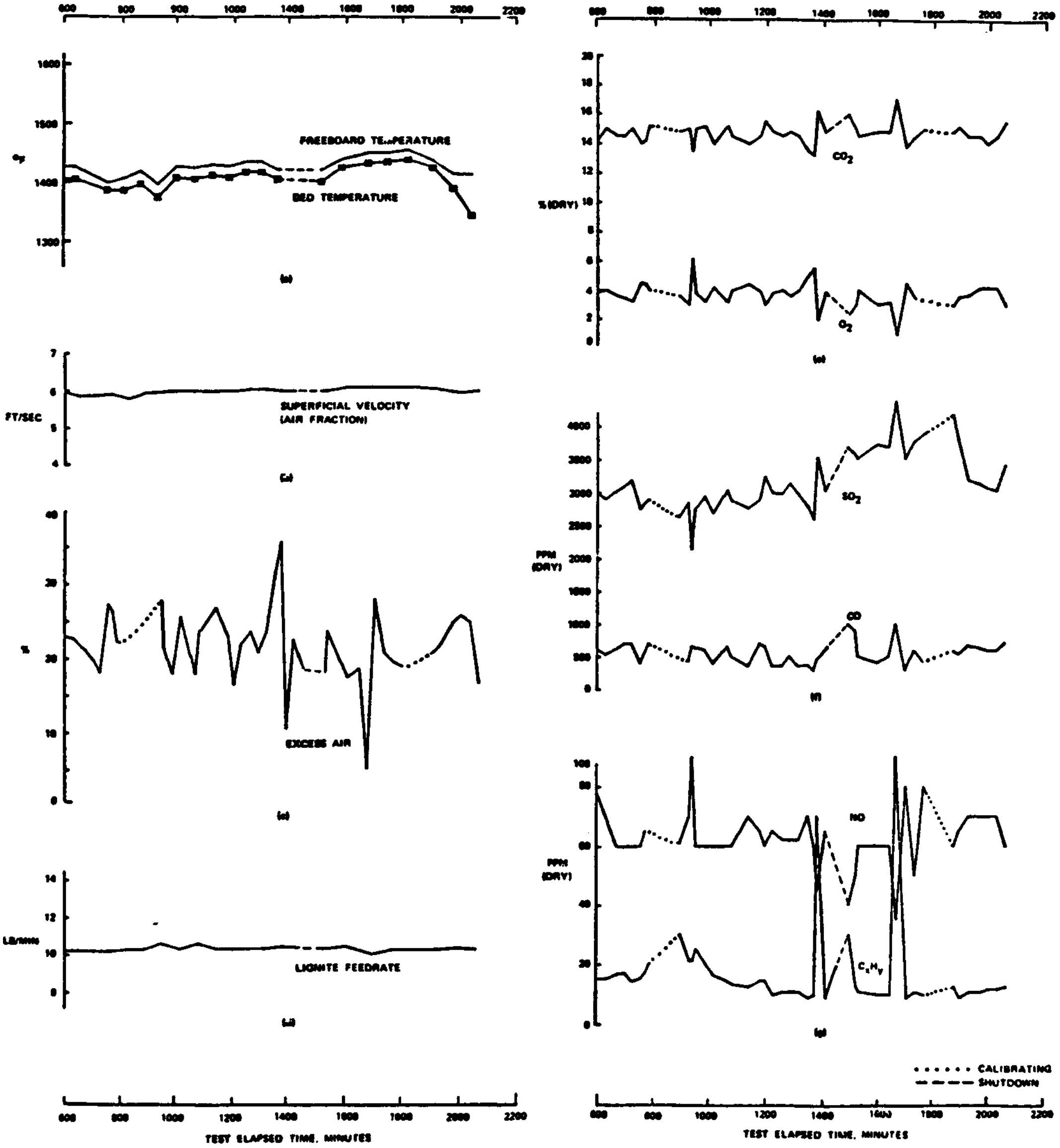


Figure A-10. Elapsed time histories of test #13 data.

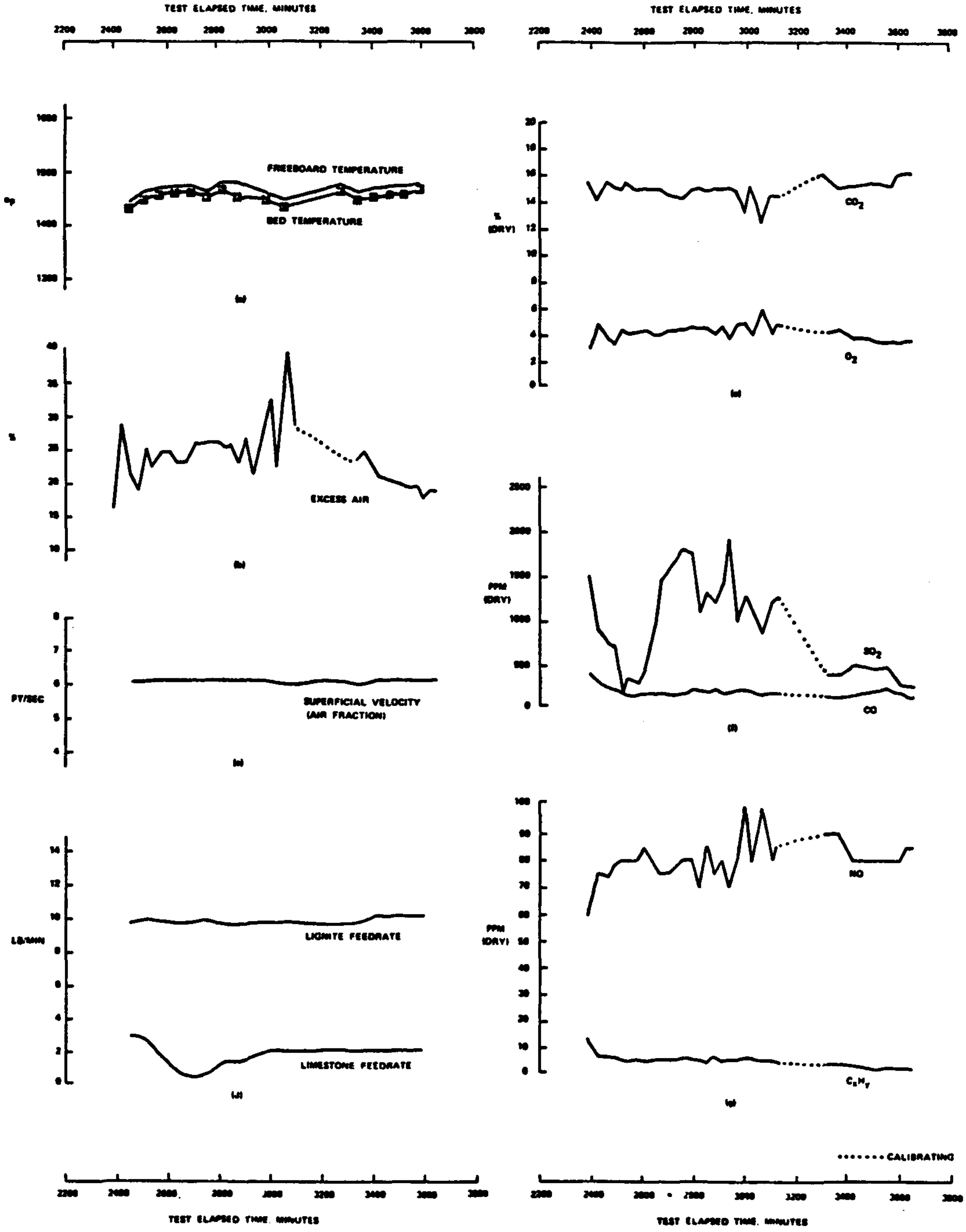


Figure A-11. Elapsed time histories of test #14 data.

Test #15 (6 ft/sec, 20 percent excess air, 1500°F, 90 percent sulfur retention) was reached at ET 3824 after cutting out a two-pass vertical heat exchanger (HX-6). Sixteen hours into the test the system was shut down for two hours to repair several holes in the cyclone and to remove ash deposits from the spray cooler. (The extremely high recycle rate experienced in all Texas lignite tests is believed to have caused accelerated cyclone erosion.) Test #15 was completed at ET 5308. The elapsed time plots of important parameters and exhaust gas composition are shown in Figure A-12.

Test #16 (6 ft/sec, 20 percent excess air, 1500°F, 70 percent sulfur retention) was run without problems and Test Series L118 was terminated on schedule. The elapsed time plots of important parameters and exhaust gas composition are shown in Figure A-13.

Operationally, it was much more difficult to control the process using Jackson lignite than in Tests L116 and L117 using Wilcox lignite. The operators had difficulty maintaining stable bed temperature or SO_2 emissions and this appeared to be related to changes of the lignite supply hopper, as shown in Figures A-10 through A-13.

Solids Consumption and Production

Table A-3 summarizes hours of testing, consumption of lignite, limestone, and sand, and production of bed drain material, baghouse ash, and spray tower deposits for Test Series L116, L117, and L118.

A.2 LOSS OF IGNITION (LOI) AND TOTAL ORGANIC CARBON (TOC) ANALYSES

LOI and TOC analyses of solid waste products from selected tests were performed. The results of the analyses are presented in Table A-4.

The LOI analyses are only indicative of the char content and are not numerically equivalent to the elemental carbon content since other elements (e.g.,

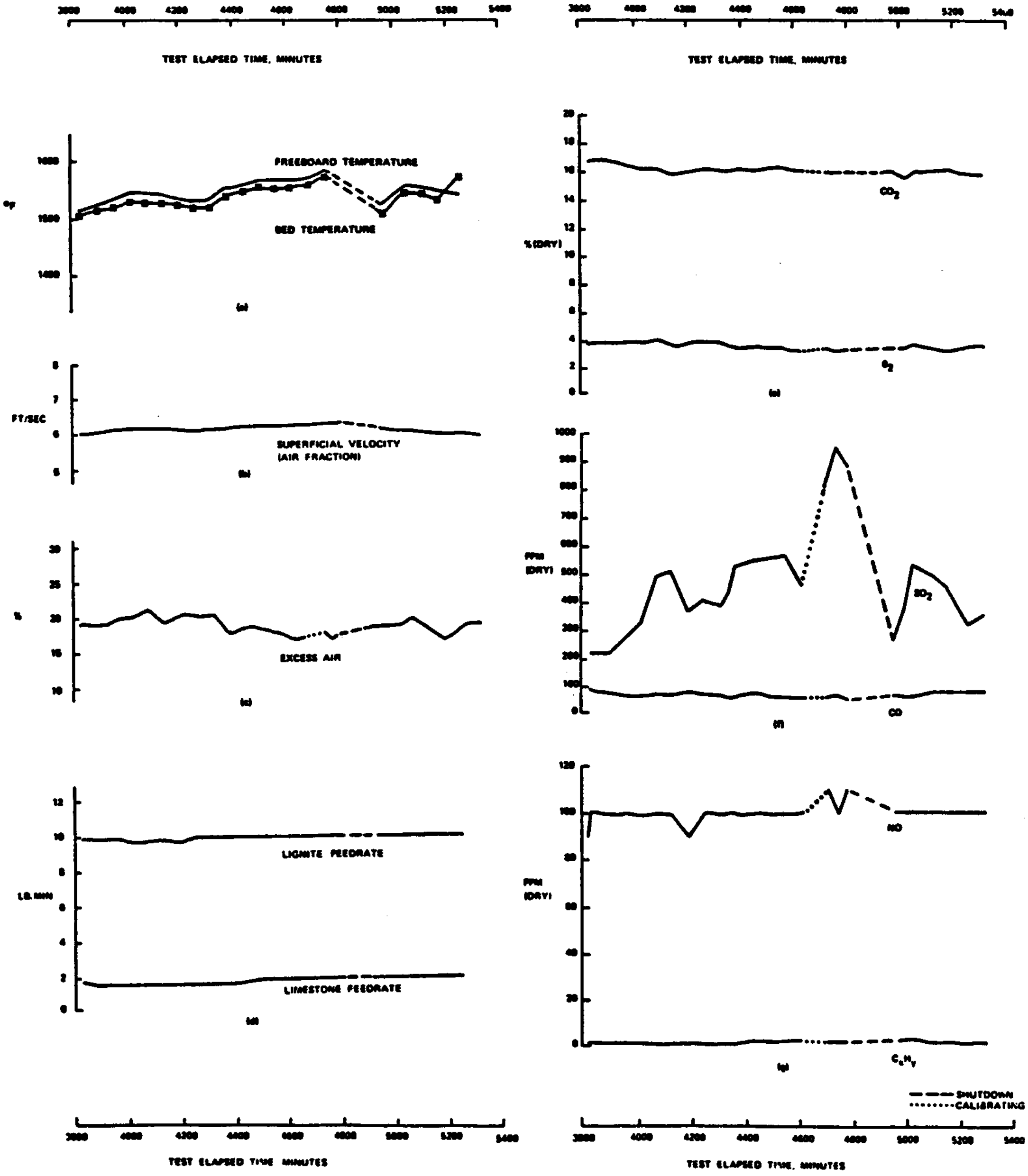


Figure A-12. Elapsed time histories of test #15 data.

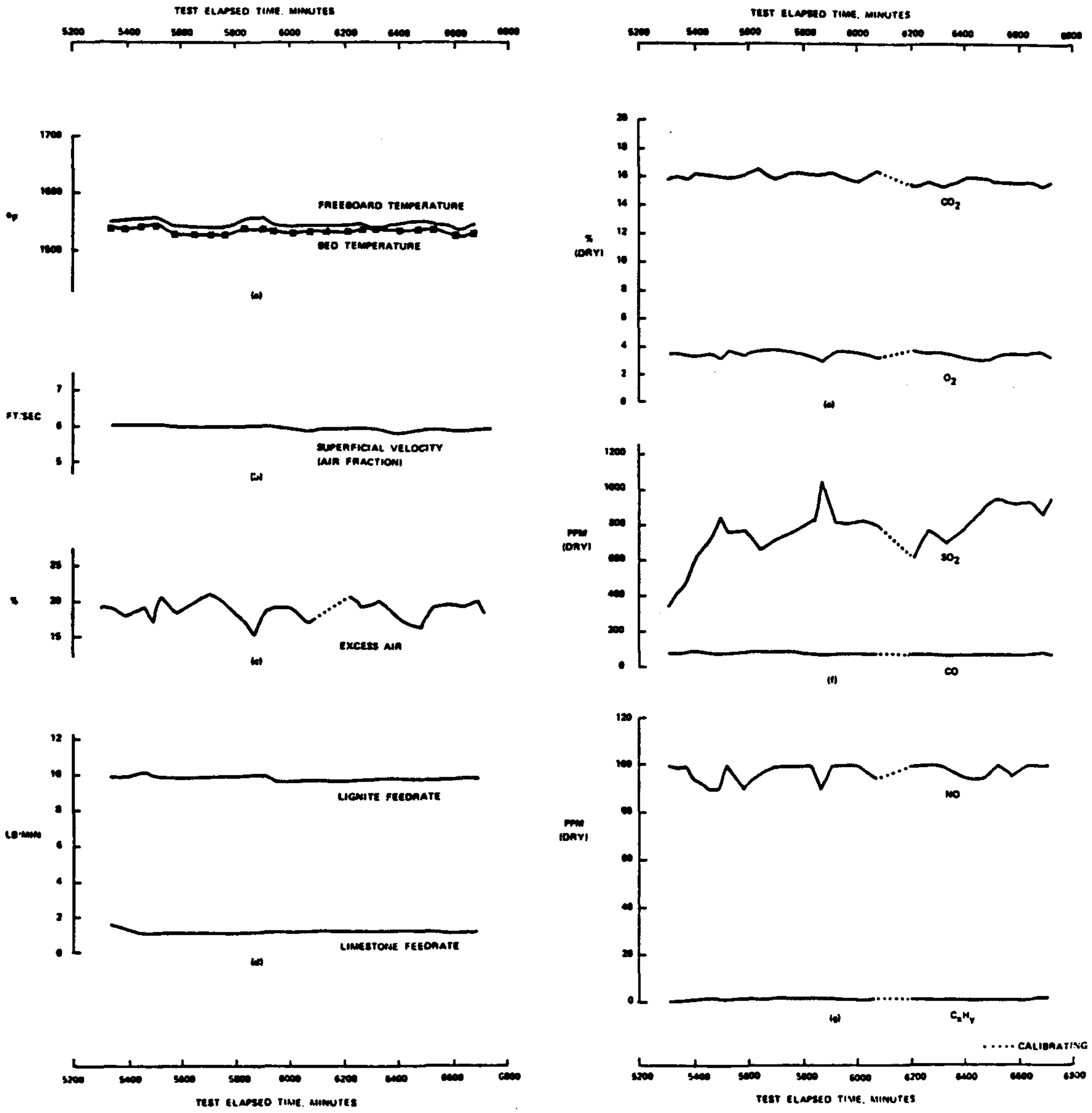


Figure A-13. Elapsed time histories of test #16 data.

Table A-3

SUMMARY OF OPERATING TIME AND MATERIALS CONSUMED AND PRODUCED IN TEST SERIES L116, L117, and L118

Operating Time	L116	L117	Total of L116 & L117	L118
Preheat Hours	2.3 (2.2%)	3.1 (2.8%)	5.4 (2.5%)	2.8(2.5%)
Hours on Lignite	102.5 (97.0%)	102.3 (93%)	204.8 (95.0%)	104.7(93.1%)
Hours on Limestone	0	95.1 (86.5%)		72.7 (64.6%)
Downtime	0.9 (0.8%)	4.6 (4.2%)	5.5 (2.5%)	5.0 (4.4%)
TOTAL HOURS	105.7	110.0	215.7	112.5
Materials Consumed				
Lignite Consumed	76,000 lbs.	67,800 lbs.	143,800 lbs.	59,700 lbs.
Limestone Consumed	0	4,160 lbs.	4,160 lbs.	6,980 lbs.
Sand Consumed	4,080 lbs.	2,800 lbs. of L116 Bed Material		2,800 lbs.
Materials Produced				
Bed Material Removed	1,450 lbs.	1,650 lbs.**	3,000 lbs.	6,600 lbs.
Baghouse Ash*	17,400 lbs.	15,800 lbs.	33,200 lbs.	7,400 lbs.
Spray Tower Deposits				5,400 lbs.***

* Baghouse Ash weight is an estimated weight based on outlet particulate loadings obtained during steady state periods and, therefore, includes spray tower deposits.

** 2,250 lbs. of bed removed. 600 lbs. of the removed material was added to the bed again at ET 3540-3354, resulting in a net bed removal of 1,650 lbs.

*** Wet solids (35-38% moisture) determined from two actual weighings of removed deposits totaling 4,000 lbs. and estimated 1,400 lbs. from volume of other deposits.

Table A-4

LOSS ON IGNITION AND TOTAL ORGANIC CARBON ANALYSES OF SOLID PRODUCTS

	Bed Material			Exhaust EPA-5 Particulates			Baghouse Material		
Test	Sample ET,* Minutes	LOI (950°C), %	TOC %	Sample ET, Minutes	LOI (950°C), %	TOC, %	Sample ET, Minutes	LOI (950°C), %	TOC %
L116, Wilcox lignite:									
1	1880[a]	0.15	0.04	1883[a]	2.83	0.69			
2	3340	0.25	0.04	3314	2.30	0.79			
3	4780[a]	0.18	0.06	4207	1.02	0.53	4782[a]	1.26	
4	6223[a]	0.09	0.03	5880	0.56	0.54			
L117, Wilcox lignite with limestone:									
6	1960[a]	1.30	0.07	1826[a]	1.84	0.67			
7a									
7b				3092[a]	6.19	0.75			
7c	3825[a]	2.04	0.14	3818[a]	2.81	0.89			
8	4935[a]	2.55	0.15	4470[a]	3.41	0.45	4935[a]	2.27	
9	6600	1.83	0.06	5807[a]	3.01	0.54			
L118, Jackson lignite:									
13	2075[a]	0.49		1996[a]	6.65	1.35	2075[a]	5.27	
with limestone:									
14				3404[a]	5.08	1.06			
15	5270	0.53		5189	2.87	0.48	5270	1.67	
16				6560	3.99	0.50			

* Elapsed time of sampling.

[a] Sampling occurred outside of period later identified to represent "steady-state" operation after tests were completed.

H and O) and other components (e.g., CO_2 from carbonates and H_2O) are included in the LOI determinations. The temperature of the LOI procedure is also critical, as evidenced by the differences in the values determined at 800°C for the particulates as shown in Table 3-9 in Section 3 and those determined at 950°C as shown in Table A-4. The LOI values are higher at higher procedural temperatures, which is likely due to the additional calcining of $CaCO_3$ at the higher temperatures.

Thus, the TOC contents of the solid waste streams were also determined to differentiate between carbonate and char carbon. The TOC contents of the solid streams during the steady-state periods of the tests were lower than the LOI (950°C) contents, as expected, and as shown in Table A-4. The TOC contents decreased with increasing bed temperatures in each series. In the lignite-only tests, the TOC of the particulate was 20 percent to 34 percent of the LOI at lower bed temperatures, and increased to 96 percent of the LOI at higher bed temperatures, indicating good agreement with the use of LOI for combustion efficiencies of lignite-only tests at higher temperatures (i.e., above 1600°F). Kinetics for calcination decrease at the lower temperatures.

In the tests with limestone addition, the TOC contents of the particulates were 12 percent to 36 percent of the LOI contents, indicating that <u>most</u> (typically 70 percent to 87 percent) <u>of the LOI values were due to carbonates and not char carbon</u> and that the combustion efficiencies were <u>higher</u> than those calculated by equation (6) in Section A.3. Thus, the combustion efficiencies for the ten tests with stable operating periods were above 99 percent for the steady-state periods as indicated by the TOC content of the particulate emissions. For this report, however, the combustion efficiencies based upon LOI determinations (i.e., the lower values) were used.

Although the samples of material drained from the bed were not protected from subsequent burning by inert gas purging during collection and the small amount of char would have probably burned upon standing (i.e., while cooling), the <u>trends</u> of LOI analyses for the bed materials are also of interest. As shown in Table A-4, the TOC content of the bed materials was low as expected, being below 0.2 percent. However, the LOI content was 0.1 percent to 2.5 percent and increased significantly in tests with limestone addition. Also, there is an indication that the LOI decreased with increasing temperature, although the trend must be tempered with the rate of limestone addition. Thus, it appears that if TOC is a valid indication of char content, then the difference between LOI and TOC (i.e., LOI - TOC) is an indication of carbonate content (i.e., the calcining of limestone and related materials). (However, the validity of this indication can be suspect when analytical procedures do not provide adequate protection to prevent hydration of hygroscopic sulfate from atmospheric moisture. The absorbed moisture would also be included in LOI determinations if the samples were "dried" first at standard temperatures of 105°C to 110°C instead of 170°C temperatures required to dehydrate gypsum to anhydrate. The calcium sulfate exists as anhydrate ($CaSO_4$) at the high temperatures within the FBC system and the moisture from hydration in improper analytical procedures would indicate additional char or carbonate than actually existed.)

A.3 EQUATIONS, TERMINOLOGY, AND DEFINITIONS

Equations for calculating:

(1) Excess Air in the combustion process, percent:

(a) $$EA = \frac{267\ (O_2)\ (C)}{(CO_2 + CO)(2.67C + 8H + S - O)}$$

(b) $$EA = \frac{100(O_2 - 0.5\ CO)}{0.264(100 - CO_2 - CO - O_2) - (O_2 - 0.5\ CO)}$$

(2) Overall Heat Transfer Coefficient for the water-cooled tubes in the bed, Btu/hr ft ^{2}°F:

$$U = \frac{Q}{(\Delta T_{LM})(A)}$$

(3) Nitric Oxide Emission in the exhaust gas stream, lb/10^6 Btu:

(a) Measured as NO, converted to NO_2, and reported as NO_x:

$$NE = \frac{3.83\ (C)(NO)}{(CO_2 + CO)(HHV)}$$

(b) Measured and reported as NO:

$$NE = \frac{2.50\ (C)(NO)}{(CO_2+CO)(HHV)}$$

(4) Sulfur Dioxide Emission in the exhaust gas stream, lb/10^6 Btu:

$$SE = \frac{5.33\ (C)(SO_2)}{(CO_2+CO)(HHV)}$$

(5) Sulfur Retention of the process based on emitted SO_2, weight %:

$$SR = \left[100\%\right] - \left[\frac{0.0267\ (C)(SO_2)}{(CO_2+CO)(S)}\right]$$

(6) Combustion Efficiency of the process based on carbon conversion, weight %:

For a selected time period, assuming LOI to be equivalent to the carbon in char and that the system is at steady-state with respect to ash inputs and outputs, and ignoring CO and and other combustible gas emissions (which are typically very small):

$$\eta_{LOI} = \left\{\left[\,1\,\right] - \left[\frac{\sum_i (LOI)_i\ (\text{Product Solids Rate})_i}{(C)\ (\text{Dry Coal Feed Rate})}\right]\right\} \times 100\%$$

where i's are all solid products from the system including particulates emitted and ash captured or drained.

(7) Combustion Efficiency can also be calculated by:

$$\eta_c = \left\{1 - \left[192.6(CO)V_v(1- \frac{M2}{100}) + \left(\left(\frac{\dot{W}xC}{100}\right)\left(1 - \frac{M1}{100}\right) - 0.019\ (CO_2+CO)\ldots\right.\right.\right.$$

$$\left.\left.\left.\ldots\left(1 - \frac{M2}{100}\right) V_v\right)\ 14{,}096\right] /\ HHV\left(1 - \frac{M1}{100}\right)\ \dot{W}\right\} \times 100\%$$

which is very sensitive to errors in the feedstream moisture content and feedstream and exhaust gas rates.

Nomenclature

SR = Sulfur retention, pct.
C = Carbon content of the coal on a moisture-free basis, pct.
SO_2 = PPM SO_2 = Parts per million sulfur dioxide in the flue gas on a dry basis, ppm.
CO_2 = Carbon dioxide concentration in the flue gas on a dry basis, pct.
S = Sulfur content of the coal on a moisture-free basis, pct.
O_2 = Oxygen concentration in the flue gas on a dry basis, pct.
H = Hydrogen content of the coal on a moisture-free basis, pct.
O = Oxygen content of the coal on a moisture-free basis, pct.
EA = Excess air in the flue gas, pct.
ηc = Carbon combustion efficiency, pct.

V_v = Flue gas volume flow, scfm.
M2 = Moisture concentration of the flue gas on a volume basis, pct.
$\dot{W}$ = Coal feed rate in lbs/hr as feed.
M1 = Moisture in the coal, pct.
HHV = Coal heating value on a moisture-free basis, Btu/lb.
Wh = Humidity ratio of combustion air, lbs/lb.
Wmc = Mass flow of moisture in the flue gas from the coal, lbs/lb coal.
RH = Relative humidity of the combustion air, pct.
VP = Vapor pressure of the water vapor in the combustion air at the conditions the RH is measured, psia.
P_p = Pressure at which the RH is measured, psia.
U = Overall heat transfer coefficient, Btu/hr - ft^2 °-F
Q = Heat removed from the bed by the tubes, Btu/hr.
ΔT_{LM}= Log mean of temperature difference between the bed and the tube water, °F
A = Total area of the tubes in the bed, ft^2.
SE = Sulfur emission level, lbs SO_2/million Btu.
NE = Nitric oxide emission level, lbs NO_2/million Btu.
PPM NO_x= Parts per million NO_x in the flue gas on a dry basis, pct.
Wa = Mass flow rate of combustion air.
NO = PPM NO in the dry flue gas.
LOI = Loss on Ignition of dry solid (950°C or higher), pct.
CO = Carbon monoxide concentration in the flue gas on a dry basis, pct.

Appendix B

ANALYTICAL PROCEDURES

In this appendix, techniques and procedures are presented for the chemical and physical characterization of the Wilcox and Jackson FBC wastes. The topics discussed below, in order, are:

- digestive techniques for whole sample chemical analysis,
- RCRA and TDWR extraction techniques,
- analytical techniques for chemical characterization, and
- techniques for physical characterization.

B.1 DIGESTIVE TECHNIQUES FOR WHOLE SAMPLE CHEMICAL ANALYSIS

Five digestive techniques were used to prepare the FBC solids for chemical analysis. A block diagram for the digestion and subsequent analysis of the Texas FBC wastes is presented in Figure B-1. The details of the digestive techniques are discussed in the following subsections.

Lithium Borate Fusion

A lithium borate fusion as outlined by Perkin-Elmer Corporation Methods Manual was used for determination of major species in the bed and baghouse samples. The procedure involves the mixing of sample with $LiBO_2$ in a disposable ultrapure graphite crucible. The mixture is then fused at 1050°C and the melt poured into dilute HCl for dissolution. ULTREX® $LiBO_2$ and HCl are used in these dissolutions to prevent sample contamination. Blanks, duplicates, and matrix standards (NBS SRM 1633-coal fly ash) were digested at the same time for quality control.

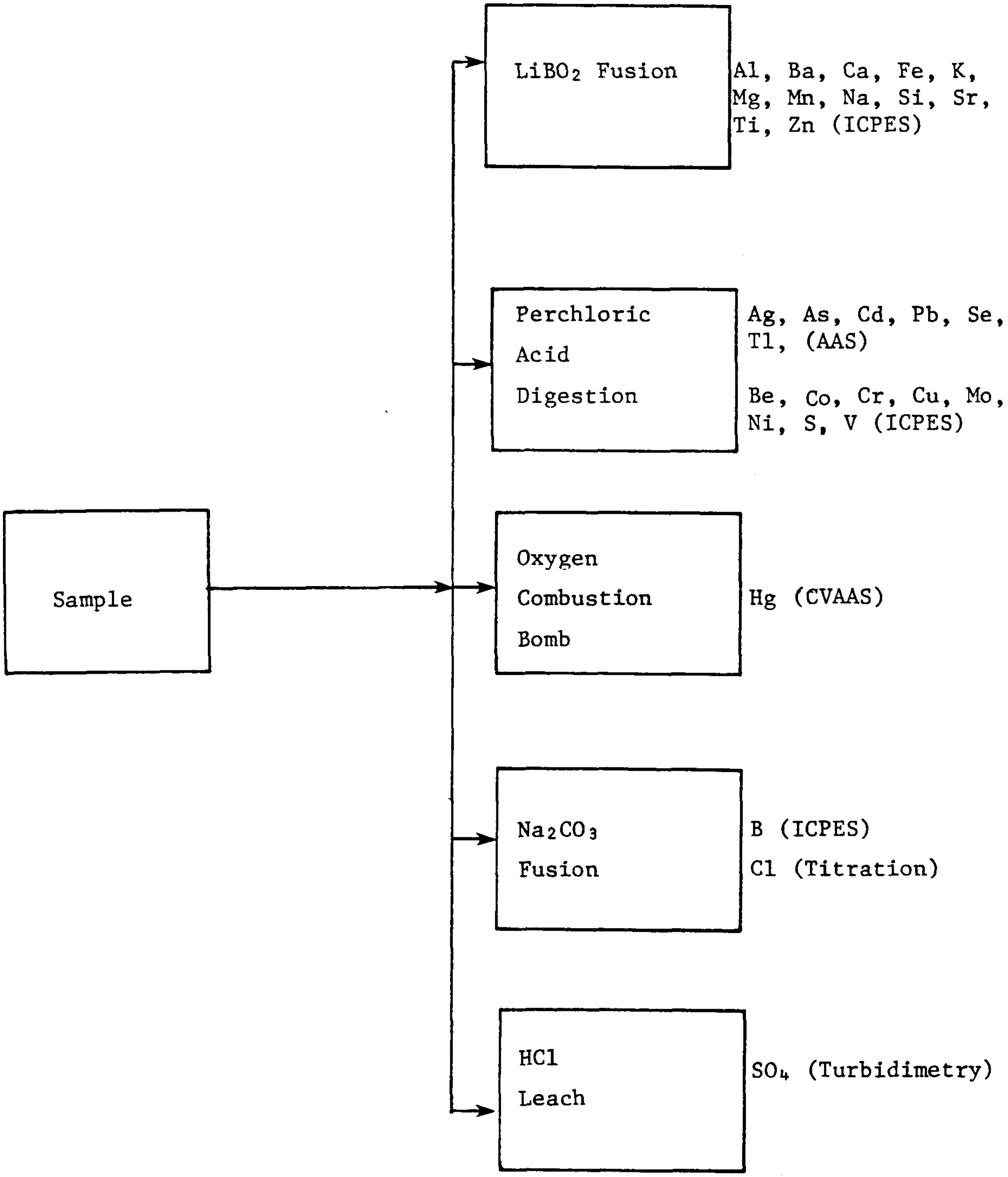


Figure B-1. Digestion and chemical analysis of Texas lignite FBC wastes.

Perchloric Acid Digestion

The perchloric acid digestion (PAD) has been found by Radian to have the widest application for coal and coal fly ash dissolution. The PAD technique employed was a modification of the method described by McQuacker, et al, ("Digestion of Environmental Materials for Analysis by ICPES," Analytical Chemistry, Vol. 51, No. 7, June 1979, p. 1082) differing primarily in the amount of acid used. The procedure is carried out in a perchloric acid fume hood for safety. The procedure entails the addition of HNO_3 and HF to dry sample. The sample is then covered, heated, and allowed to cool. Perchloric acid ($HClO_4$) is added and the sample is taken to dryness. This final step is repeated until the dried sample assumes a grey color. Fifty milliliters of deionized water and HCl are added and the sample is warmed to effect complete dissolutions. The sample is cooled and taken to volume. ULTREX® acids and TEFLON® digestive equipment are used to prevent contamination. Blanks, duplicates, and matrix standards (NBS SRM 1633) were digested alongside the samples for quality control.

Oxygen Combustion (Parr Bomb)

Mercury in the bed and baghouse samples was determined following combustion in an oxygen bomb with absorption in $KMnO_4$. The resultant solution was analyzed according to EPA Method 245.1 (Methods of Chemical Analysis of Water and Wastes, U.S. EPA, March 1979).

Sodium Carbonate Fusion

The sodium carbonate fusion for boron and chloride was performed by the addition of Na_2CO_3 to dry sample. The resultant mixture was then fused and dissolved in dilute HCl. Blanks, duplicates, and matrix standards (NBS SRM 1633) for quality control were digested alongside the samples.

Hydrochloric Acid Leach

The bed and baghouse samples were prepared for the determination of sulfate content by a hydrochloric acid leaching. One-tenth (0.1) gram of sample was extracted with 100 milliliters of 0.1 N HCl. The sample and acid were shaken together for one hour after which the remaining solids were filtered off. The resultant leachate was analyzed.

B.2 RCRA AND TDWR EXTRACTION PROCEDURES

Extraction procedures outlined by the Resource Conservation and Recovery Act (RCRA) and the Texas Department of Water Resources (TDWR) were employed to study the toxicity (leachability) of the bed, baghouse, and composite samples. The RCRA and TDWR leachates generated were analyzed and the results compared to appropriate regulatory criteria.

RCRA Extraction Procedure

The extraction procedure employed was that described in the May 19, 1980 (Vol. 45, No. 98) issue of the Federal Register. Fifty grams of sample were mechanically stirred for 24 hours with 800 milliliters of deionized water. Through the extraction period, 0.5 N acetic acid (ULTREX®) was added as specified to maintain a pH of 5 ± 0.2. Some of the samples extracted were sufficiently basic as to require the addition of the maximum acid allowed, 200 milliliters (4 ml acid/g). At the end of the 24-hour extraction period, the slurry was filtered (0.45-micron filter) and the filtrate diluted to one liter. This leachate was then split for elemental and radiochemical analysis.

TDWR Extraction Procedure

Samples of bed material, baghouse ash, and bed/baghouse composite were extracted according to the current TDWR procedure. Two-hundred-and-fifty (250) grams of sample were contacted with one liter of deionized water. This slurry was mechanically stirred at low speed for five minutes and then allowed to stand undisturbed for seven days. No pH adjustments were made. At the end of seven days, the supernatant solution was filtered (0.45-micron filter) and split for chemical analysis. The split for elemental analysis was preserved by the addition of ULTREX® nitric acid. No preservative was added to the other split slated for water quality analysis (pH, chloride, sulfate, TDS).

B.3 ANALYTICAL TECHNIQUES FOR CHEMICAL CHARACTERIZATION

Chemical analysis was performed on the various digests and leachates according to the analytical methods described below. These methods were chosen in order to obtain the best accuracy and precision at the concentration levels encountered for each sample type.

Inductively Coupled Argon Plasma Emission Spectroscopy (ICPES)

ICPES is a multielement technique which provides for simultaneous determination of over 40 elements with detection limits rivalling atomic absorption spectroscopy (AAS). ICPES was utilized to determine 21 elements in the digests and leachates described above. The elements determined were: Al, B, Ba, Be, Ca, Co, Cr, Cu, Fe, K, Mg, Mn, Mo, Na, Ni, S, Si, Sr, Ti, V, and Zn. The instrument employed was an Applied Research Laboratories Model 34000B vacuum spectrometer with off-peak background correction capabilities. Data handling for this instrument is performed by a dedicated mini-computer with data storage on floppy disk.

All analyses were performed in accordance with EPA Method 200.7 ("Inductively Coupled Plasma-Atomic Emission Spectrometric Method for Trace Element Analysis of Water and Wastes," November 1980) and McQuaker, et al (Analytical Chemistry, Vol. 51, No. 7, June 1979, p. 888). The spectrometer was calibrated daily for each element using freshly prepared multielement working standards (deionized water blank and three nonzero standards) covering the concentration ranges of interest. The working standards were prepared by mixing and diluting commercially available, certified standards (1000 ppm). Blanks and matrix standards (NBS SRM 1633, EPA Check Samples, and in-house QC samples) were analyzed alongside the samples to validate the ICPES results and check instrument stability.

If the recovery for a particular element exceeded established control limits, another determination of the element was made after any analytical problem was corrected.

Atomic Absorption Spectroscopy (AAS)

AAS was employed to determine eight elements (Ag, As, Cd, Hg, Pb, Sb, Se, Tl) requiring lower detection limits than those provided by ICPES. The FBC digests and leachates were analyzed for these eight elements by three AAS techniques:

- electrothermal (graphite furnace) AAS,
- hydride generation AAS, and
- cold vapor AAS.

Each technique is described in turn below.

The atomic absorption spectrometers employed for the AAS analyses were:

- Perkin Elmer Model 503,
- Instrumentation Laboratory Model 251, and
- Instrumentation Laboratory Model 351.

All instruments feature background correction capabilities (deuterium arc) and were equipped with strip chart recorders. All AAS analyses were recorded on strip charts and compared to calibration standards to determine elemental concentration. Calibration standards were prepared by diluting commercially available, certified standards (1000 ppm) to the working range of the instrument used and element determined. EPA Quality Control Check Samples and digests of NBS SRM 1633 were analyzed as QC samples at a frequency of one QC sample per ten samples. One sample in twenty was spiked and analyzed to define spike recovery and to ensure the absence of matrix interference.

Silver, arsenic (PAD digests only), cadmium, lead, antimony, selenium (PAD digests only) and thallium were determined by electrothermal AAS. The method used to determine each element was in accordance with EPA methods of analysis. The ashing and atomization times and the temperature programming used to set up the instruments for each element were those recommended by the instrument manufacturer. Prior to analysis for arsenic or selenium, small aliquots are treated with one percent nickel nitrate solution. The nickel arsenide and selenide formed, respectively, during the drying stage are more refractory than the element alone, oxyacid salts of both elements, and the sample matrices encountered. Thus, higher ashing and atomization temperatures can be employed while diminishing the loss of these elements and possible background effects.

Arsenic and selenium in the RCRA and TDWR leachates were determined by hydride generation AAS. The methods used were EPA 206.3 and 270.3, respectively. Both elements were converted to the respective hydride species by treatment with sodium borohydride. The gaseous hydrides were then swept into an argon-hydrogen flame for determination.

Mercury in the FBC solids (oxygen bomb digest) and leachates was determined by cold vapor AAS (EPA Method 245.1). Potassium permanganate was added to oxidize all mercury to its highest oxidation state. Excess $KMnO_4$ was removed by addition of hydroxylamine. Finally, mercury present was reduced to the metallic state with stannous chloride and purged through a quartz absorption cell for measurement.

Titrimetric Determination of Chloride

Chloride in the FBC solids (Na_2CO_3 fusion) and the TDWR leachates was determined by EPA Method 325.3. An acidified aliquot of each sample was titrated with mercuric nitrate in the presence of a diphenylcarbazone-bromophenol blue indicator. The end point of the titration was the formation of the blue-violet mercury diphenylcarbazone complex.

Turbidimetric Determination of Sulfate

Sulfate in the FBC solids (HCl leach) and TDWR leachates was determined turbidimetrically using EPA Method 375.4. Sulfate ion was converted to a suspension of barium sulfate under controlled conditions. The resulting turbidity was determined using a Bausch & Lomb Spectronic 20 and compared to a calibration curve prepared under identical conditions using standard sulfate solutions.

Potentiometric Determination of pH

The pH of the TDWR leachates was determined potentiometrically according to EPA Method 150.1. The measurements were performed with a Corning Model 130 pH meter equipped with conventional glass and reference electrodes. The pH meter was calibrated at pH 7 using a commercially available buffer solution. Two other commercial buffers (pH = 4 and pH = 10) were used as quality control samples.

Determination of Total Dissolved Solids

The determination of total dissolved solids (TDS) in the TDWR leachates was performed gravimetrically according to EPA Method 160.1. An aliquot of each sample was placed in a tared beaker. The leachate was then evaporated to dryness at 180°C. The beaker was reweighed to determine dissolved mass per volume of leachate.

Determination of Gross α and β Activity

The TDWR leachates were analyzed for α and β activity according to methods listed in the EPA Interim Radiochemical Methodology for Drinking Water (EPA-600/4-75-008, March 1976). A 250-ml aliquot of leachate was evaporated with 10 ml of concentrated nitric acid. The dried sample was transferred to a tared planchet with 3N nitric acid, evaporated, flamed, and weighed for self absorption correction. Gross α and β was counted utilizing a windowless gas flow proportional counter manufactured by Nuclear Measurements Corproation, model number PCC-11T/DS-3.

B.4 TECHNIQUES FOR PHYSICAL CHARACTERIZATION

Specific Gravity

Specific gravity was determined using a modified ASTM D-854 procedure, "Specific Gravity of Soils." A 100-ml class A volumetric flask was used with hexane as the displacement medium.

Apparent Bulk Density

The apparent bulk density was determined by loosely filling a 100-ml graduated cylinder with baghouse or bed material and lightly tapping it on a surface 100 times. The apparent bulk density is expressed as grams of tapped material per cubic centimeter of total volume.

Compaction

The four composite materials tested were subjected to the Method A procedure of ASTM D-558, "Moisture-Density Relations of Soil-Cement Mixtures" to determine the optimum moisture content and maximum unit dry density for compaction. In this procedure each of approximately five 2000-gram aliquots of the material is mixed with varying amounts of water and compacted with a standard amount of energy. Because of the cementitious nature of this FBC material, compaction was consistently initiated five minutes after the addition of the mixing water.

Permeability

The permeability of cured, hydrated compaction of the baghouse and bed materials from four different runs was determined by procedures outlined in ASTM Method D-2434 "Permeability of Granular Soils (Constant Head)" with appropriate modifications. Composited materials were first hydrated with the optimum moisture for strength development ($\sim$45 percent) and tamped into 3" x 6" cylinders and cured for 28 days at 100 percent relative humidity and a temperature of 73°F. Tamping into the cardboard cylinder molds was accomplished by the application of 14 blows of a 5.5-lb rammer falling 12 inches to each of four equal layers.

Cured samples were then cemented into 3.5-in diameter lucite columns with nonshrinking, nonexpanding, impermeable (<10^{-12} cm/sec) epoxy resin. A constant head of between 5 and 60 psi was applied depending on the permeability to allow for measurement of ten permeability coefficients for each material.

Unconfined Compressive Strength

The unconfined compressive strength was measured in accordance with ASTM D-1633 method, "Compressive Strength of Molded Soil-Cement Mixtures." Samples were prepared in general accordance with ASTM D-1632, "Making and Curing Soil-Cement Compression and Flexure Test Specimens in the Laboratory." Samples of the baghouse, bed, or composite material were blended at a moisture content approximating that of the plastic limit as defined by ASTM D-424, "Plastic Limit and Plasticity Index of Soils." Because of the limited amount of baghouse material available, the composite and baghouse were molded into 2" x 4" brass cylinder molds. Duplicate determinations were performed on several samples which were also molded in standard 3" x 6" molds. Good agreement of results was obtained for those samples molded in both 2" x 4" and 3" x 6" molds. All samples were vibrated to remove air voids. The bed material was compacted in accordance with Method A of ASTM D-558, "Moisture-Density Relations of Soil-Cement Mixtures."

Particle Size Distribution

The particle size distribution of the baghouse, bed, and composite materials was determined by procedures documented in ASTM D-422, "Particle Size Analysis of Solids." The distribution of the bed material was determined by dry sieving with the following sieves: #6 (3.35 mm), #20 (0.85 mm), #60 (0.25 mm), and #200 (0.075 mm). Since the baghouse and the composite are primarily fine material, a hydrometer analysis was used.