4.0 COMBUSTION RESEARCH

4.1 Fluidized-Bed Combustion

FLUIDIZED-BED COMBUSTION OF LOW-RANK COALS

Quarterly Technical Progress Report
for the Period January - March, 1990

by

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April 1990

Work Performed Under Cooperative Agreement No. DE-FC21-86MC10637T3

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1.0 BACKGROUND

The main driving forces behind the use of fluidized-bed combustion have primarily been environmental concerns, fuel flexibility, and compatibility with low-cost fuels. Both bubbling and circulating designs have been developed for operation at atmospheric pressure, and many industrial-scale units of both types are currently in operation. A limited number of larger utility boilers have recently been commissioned. In addition, pressurized fluidized-bed combustion (PFBC) is making its entrance on the utility scale with the PFBC being installed at the Tidd Station.

Even though fluidized-bed combustion technologies are being commercialized, a number of areas require further research. An integrated approach should be taken toward fluidized-bed combustion research interrelating those problems generic to bubbling, circulating, and pressurized fluidized-bed combustion systems. The program should also be designed to address specific problems related to each of these areas. Major issues facing fluidized-bed combustion are listed below:

- Methods are needed to minimize corrosion and erosion of in-bed and convective pass tubes, refractory and support surfaces, and expander turbines. Work should focus on:

  - Understanding mechanisms:
    Mineralogical properties of bed and coal,
    Fluid mechanics of bed,
    Corrosion versus erosion mechanisms, and
    Stress forces on tubes.
  - Assessing acceptable wastages.
  - Identifying cost-effective methods of combating tube wastage.
  - Developing systematic test devices.

- Retrofit applications should be addressed for all types of FBCs. According to information from the American Boiler Manufacturing Association (ABMA), approximately 200 existing units are candidates for retrofit technologies. The FBC retrofits at NSP's Black Dog Station, MDU's Heskett Station, and Colorado Ute's Nucla Station have demonstrated the feasibility of such applications.

- Fuel flexibility and characterization issues should be addressed to help users understand constraints of fuel switching, design considerations, and, most importantly, the economics involved in having fuel flexibility for the FBC.

- Agglomeration/sintering of bed material and deposition on tubes, support surfaces, and refractory has been identified as a problem by both manufacturers and users of FBC technology. The problem cases have been documented for both bubbling and circulating beds, using a variety of fuels, including coal. The EERC has extensive experience in this area to help understand and solve this operational problem.

- Scale-up effects need to be addressed so that vendors and users can take pilot-scale data and be assured that the large-scale system will perform as anticipated. This data base has been growing rapidly with all of the new units starting operation; however, much information is still required. The University of North Dakota will have an opportunity to observe scale-up effects for CFBC when the University includes a CFBC as a part of its steam system expansion. This will make a 5,000- and a 150,000-lb steam/hr unit available for scale-up studies.

- Advanced systems should be designed to resolve problems and improve overall FBC performance. These systems should:

  - Increase volumetric heat release rates,
  - Improve overall boiler efficiency,
  - Simplify fuel feed and ash removal systems,
  - Decrease capital and operating costs,
  - Improve turndown, and
  - Decrease the size of units to enable modular construction.

- Several problems related to emissions from FBC systems need to be addressed.

  - Better sorbent utilization would improve the economics of FBC.

  - NO_x control is currently not a major problem, but could become more difficult with bubbling beds if standards become more stringent.

  - Information indicates that particulate control problems may exist for certain types of ash. These ashes should be identified and the use of specific equipment, conditioning, or other methods should be applied to resolve the problem.

  - Hot-gas cleanup is required for PFBC to meet turbine specifications in addition to NSPS.

These problems and concerns could limit FBC from reaching its full potential. Special efforts should be taken to perform the necessary research to help FBC evolve to a mature technology meeting the technical, economic, and environmental needs of the future.

2.0 GOALS AND OBJECTIVES

A number of major issues have been identified that warrant further research. EERC has the capability to investigate several issues in atmospheric bubbling FBC. Some of these issues are proposed in this work plan. Other FBC research should be funded, at least partially, by the industrial sector, either through EPRI or private companies. Efforts should continue to transfer the expertise gained under previous Cooperative Agreements to the private sector.

The overall goal of the low-rank coal (LRC) fluidized-bed combustion (FBC) program at EERC is to develop a technology data base so that industry can introduce economically and environmentally acceptable coal technology options to the marketplace. Research will address those areas where data gaps exist in fuel flexibility and performance, potential operating problems, environmental compliance, advanced concepts, and system simplification.

2.1 Three-Year Objectives (7/89 - 6/92)

EERC has developed an extensive data base on corrosion and erosion of boiler tubes, agglomeration and sintering of bed material, fuels and sorbent characterization, and particulate emissions through testing funded under the Cooperative Agreement. To successfully transfer this information to the private sector, EERC will continue to publish results from this work at conferences and in refereed journals. The existing data base will be supplemented by low level experimentation, paper studies, economic evaluations, and surveys of operating plants and other researchers' data to fill gaps that may exist.

Pilot-scale work has been performed evaluating the corrosion and erosion of boiler tube surfaces in bubbling beds. EERC has done extensive analysis and characterization of samples generated from this testing. Over the next three years, available samples from industrial and utility-scale boilers will be analyzed and results correlated to bench- and pilot-scale work as well as to each other. EERC will also attempt to obtain funding from non-DOE sources to perform more work on large-scale systems.

Efforts in corrosion and erosion will switch focus to CFBC during this time period. A pilot-scale CFBC is being constructed as a part of another project. Initial work on this unit will involve system, coal, and sorbent characterization. During the characterization testing, an assessment will be made to determine if any meaningful corrosion and/or erosion data can be obtained. If meaningful data can be generated, EERC and METC personnel will discuss the possibility of incorporating CFBC corrosion and erosion work into this program.

Work will continue on the coal pretreatment cell currently being developed at EERC. After each phase of the project, an assessment will be made to determine if the concept is still technically and economically feasible. The end result of this effort is expected to be a design of the pretreatment cell in conjunction with a bubbling and circulating FBC and an economic evaluation of the concept. Testing will be done at the pilot-scale, with no demonstration planned as part of this program.

As part of the advanced concepts task and other noncooperative agreement work, EERC will work toward simplifying the control and operation of the FBC. As a part of this task, users of FBC technology will be polled to identify operational problems with fuel and sorbent feed and ash removal systems. Based on priorities identified from this poll and results of other work, EERC will work toward the simplification of control and operation of the FBC. Specific systems will be identified in either the second- or third-year work plans.

First generation PFBC technology has reached commercialization, as indicated by the two recent Clean Coal awards for utility-scale plants. Second generation concepts are now being developed. The success of these concepts will depend, in part, on an understanding of the effects of fuel properties on performance. The EERC will consult with developers of second generation technology on how fuel properties affect drying, pyrolysis, combustion, and topping cycles. The EERC is in the process of designing and constructing a pilot-scale CFBC as a part of a multiclient-funded program.

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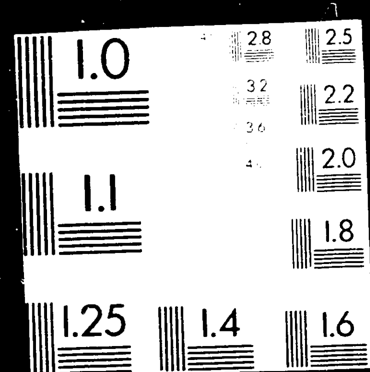

This unit will be used to investigate the impact of CFBC design and coal properties on performance. The test unit would not be available to this program for at least one year. Once the CFBC is available for testing, the current status of the technology will be assessed to determine if and how the unit should be incorporated into this test program.

Atmospheric fluidized-bed combustion has become an acceptable option for the generation of steam and electricity. A number of units are currently on-line in both the industrial and utility sector. Great market potential exists for the use of AFBC technology in both commercial and industrial sectors; however, to increase the acceptability of this technology, low cost, reliability, and ease of operation must be inherent to the system. The purpose of this task is to simplify the control and operation of the FBC for boilers in the range of 10,000 to 200,000 lbs/hr. The goal of this system simplification is to make the unit easier to operate, reduce capital and operating costs, and increase the overall reliability of the system.

2.2 Proposed First-Year Research (7/89 - 6/90)

Specific objectives of the Fluidized-Bed Combustion Project for Year One of this three-year period are as follows:

Task 1. Coal Characterization Reference Guide

To transfer information generated at EERC during the characterization studies, a reference guide will be prepared that discusses the performance, operational, and economic issues related to fuel quality. This guide will rely on information generated at EERC, with supplemental data from other researchers, vendors, and operating facilities. The guide will be directed toward users of FBC technology who need to know the impact of fuel switching on the operation of their unit.

Task 2. Corrosion/Erosion of Boiler Tubes

Samples of boiler tubes and deposits from full-scale units, both industrial and utility, will be obtained. Detailed metallographic analysis will be performed to enable a better understanding of the mechanisms of metal wastage and to extend the data base so that metal wastage between units and coal types can be better correlated. The impact of stress corrosion will also be examined. The success of this task will depend on the availability of samples and the cooperation from FBC users. EERC will also collaborate with Lawrence Livermore Laboratories on sample availability and analysis.

Task 3. Advanced Concepts - Coal Pretreatment Cell

Work will continue on the coal pretreatment cell currently under development at the EERC. Work during the year will focus on pilot testing the pretreatment cell. Information generated during pilot testing will be used to improve the design concept and to generate information for a more detailed economic evaluation of the concept.

Task 4. PFBC Consulting

The EERC will provide consulting services to Foster-Wheeler and MW Kellogg. The focus will be on the effects of fuel properties on the design and performance of their second generation concepts.

Task 5. System Simplification

The general approach to this work will be, first, to identify the most troublesome, complicated, and costly system components. A second step will evaluate the cost of improving each of the components identified, and the resulting benefits of the said improvement. Based on the cost/benefit analysis, a prioritized list of components for study will be developed. Before any work will begin on the component development phase, the EERC will make recommendations to the METC COTR to obtain approval of the test plan for developmental work. It is anticipated that the developmental work will focus on control systems.

3.0 RESULTS AND DISCUSSION

3.1 Corrosion/Erosion of Boiler Tubes - Deposit Analyses from MDU Heskett Station

The 80-MW FBC unit at the Montana Dakota Utilities Heskett Station has experienced deposition on both in-bed and convective pass heat transfer surfaces, causing significant reduction in overall heat transfer. The unit is fired with Beulah lignite with a bed material of river sand. Deposits from this unit were collected and analyzed using x-ray fluorescence, x-ray diffraction, scanning electron microscopy (SEM), microprobe analysis, and scanning electron microscopy point count (SEMPC). The last technique was developed at the EERC specifically to characterize ash-related phenomena. The river sand used as the bed material and a sample of spent bed material were also analyzed by SEMPC. Also a sample of ash coating from the spent bed material was analyzed. The focus of the analysis was to establish the mechanism of deposit formation and growth. The results of the analysis are as follows.

Table 1 compares the bulk chemical composition of the virgin bed material (river sand), the coal ash chemistry (ASTM ash prepared at 750°C), and the bulk chemical compositions of the in-bed tube and convective pass tubes. Table 2 shows the chemical composition of the samples on an SO_3 free basis. The coal ash was typical of Beulah lignite with high alkali and alkaline earth elements. On an SO_3 free basis, the Na_2O content of the ash was about 8.0 wt%. The virgin bed material was also high in alkaline earth and alkali elements. The spent bed material was surprisingly low in SO_3. This may be

TABLE 1

CHEMICAL ANALYSIS OF SAMPLES FROM THE 80-MW HESKETT STATION

wt% Oxides	Beulah Coal	Virgin Bed Material	Spent Bed Material	Bed Material Ash Coating	In-Bed Tube Deposit	Convective Pass Deposit
SiO_2	27.7	61.8	54.3	16.3	6.0	7.6
Al_2O_3	11.9	12.3	16.9	10.9	4.5	5.1
Fe_2O_3	8.3	0.6	2.5	9.9	8.2	28.4
TiO_2	0.7	0.0	0.3	1.0	0.6	0.7
P_2O_5	0.5	0.1	0.1	0.1	1.9	1.1
CaO	17.1	10.2	7.2	28.2	24.7	16.0
MgO	5.5	8.6	2.0	8.6	6.7	3.5
Na_2O	6.3	5.3	7.9	6.2	7.4	10.2
K_2O	0.6	1.0	4.6	0.8	0.4	0.3
SO_3	19.7	0.0	4.2	17.8	39.6	27.0
Total	98.3	99.9	100.0	99.8	100.0	99.9
% Ash	7.3	--	--	--	--	--
LOI	--	--	--	--	--	--

TABLE 2

CHEMICAL ANALYSIS OF SAMPLES FROM THE 80-MW HESKETT STATION ON AN SO_3 FREE BASIS

wt% Oxides	Beulah Coal	Virgin Bed Material	Spent Bed Material	Bed Material Ash Coating	In-Bed Tube Deposit	Convective Pass Deposit
SiO_2	26.5	61.8	56.7	19.8	9.9	10.4
Al_2O_3	15.6	12.3	17.6	13.3	7.5	7.0
Fe_2O_3	11.4	0.6	2.6	12.0	13.6	38.9
TiO_2	1.3	0.0	0.3	1.2	1.0	1.0
P_2O_5	1.6	0.1	0.1	0.1	3.1	1.5
CaO	27.3	10.2	7.5	34.3	40.9	21.9
MgO	6.5	8.6	2.1	10.5	11.1	4.8
Na_2O	9.6	5.3	8.2	7.5	12.3	14.0
K_2O	0.4	1.0	4.8	1.0	0.7	0.4
SO_3	--	--	--	--	--	--
Total	100.2	99.9	99.9	99.7	100.1	99.9

due to the high bed turnover rate used at the unit to prevent agglomeration and the high amount of finely dispersed ash which would tend to be elutriated. The Ca/S molar ratio for the spent bed material is 2.44, indicating free Ca available. The spent bed material was also rich in SiO_2 and Al_2O_3. However, the Si/Al molar ratio of the spent bed was much lower than that of the virgin bed (2.73 compared to 4.27). This would indicate a contribution of coal ash material (Si/Al molar ratio for the coal ash is 1.98). Just based on the Si/Al molar ratio, the bed inventory appears to be 35% river sand and 65% coal ash.

The ash coating was rich in SO_3, compared to the spent bed. The Ca/S molar ratio was 2.26, indicating an excess of Ca in the coating. Based on the SO_3 free chemical composition, the ash coating was slightly enriched in Ca and Mg, compared to the coal ash, and very enriched (compared to the spent bed chemistry) in Ca, Mg, and Fe. The Si/Al molar ratio was 1.27, indicating that the aluminosilicate component was formed from kaolinite-derived species (Si/Al molar ratio of about 1) with some quartz.

The two deposits had very high sulfate levels. Indeed, the Ca/S molar ratios for the deposits were less than 1.0, indicating that there was no free Ca in the deposits. The deposits had very similar levels of Si and Al. The Si/Al molar ratios were close to that of the ash coating, indicating that the aluminosilicate material originated from the kaolinite clay with some quartz. The in-bed tube deposit was richer in Ca and Mg compared to the convective pass tube deposit. Of interest is that the Na_2O levels for the two deposits were similar. Furthermore, the chemical composition of the ash coating on an SO_3 free basis was similar to the in-bed tube deposit. The notable exceptions were the SiO_2 and Al_2O_3 levels. The convective pass was very rich in Fe_2O_3. The ash coating and in-bed tube deposit had Fe_2O_3 levels similar to the coal ash. Of interest is that as the spent bed was depleted in Fe_2O_3, compared to the coal ash, indicating a large portion of the Fe_2O_3 was elutriated during combustion.

X-ray diffraction analysis was performed on the in-bed tube deposit and the convective pass deposit. The in-bed tube deposit was shown to contain $CaSO_4$ (anhydrite) and hematite (Fe_2O_3). The convective pass tube deposit, however, contained hematite, anhydrite, and glauberite ($Na_2Ca(SO_4)_2$).

The examination of the morphology and spatial distribution of the major elements in the deposit samples was determined using SEM and electron microprobe techniques. The samples in cross section appeared to be a dense matrix with low porosity. Individual fly ash particles were difficult to discern. The matrix material was predominantly calcium sulfate. Examination of the cross sections using backscattered imaging showed that the iron oxide was dispersed through the sulfate matrix as discreet grains. This showed that the iron oxide does not take part in the deposit growth mechanism or contribute to the overall strength. The composition of the matrix material was confirmed by selected point analyses performed using the electron microprobe. The analyses showed that the matrix was almost pure calcium sulfate or sodium calcium sulfate. Some points were almost pure sodium sulfate.

The results of the SEMPC analysis of the various samples are listed in Table 3. The results are listed in terms of volume percent of each of the phases. The virgin bed material contained albite ($NaAlSi_3O_8$), quartz, dolomite ((Ca, Mg) CO_3), illite, and trace amounts of kaolinite and unclassifieds. The unclassified phases are those which don't meet the chemical criteria of the technique. For our purposes, these were assumed to be amorphous. The analysis showed that while the virgin bed material had a high sodium composition, the sodium was bound chemically to Si and Al. Furthermore, there was some available sorbent in the form of dolomite in the bed material. The SEMPC analysis of the spent bed material showed that the bed material contained approximately the same amount of albite, but was significantly depleted in quartz. There was some anhydrite observed in the spent bed, along with traces of nepheline ($NaAlSiO_4$), akermanite ($Ca_2MgSi_2O_7$), and anorthite ($CaAl_2Si_2O_8$). The spent bed also contained kaolinite, illite, and montmorillonite, as well as a high level of unclassified (amorphous) material.

The ash coating was shown by SEMPC analysis to be rich in unclassified material, kaolinite, and anhydrite. Nepheline, akermanite, anorthite, and iron oxide were detected. Of significance was the absence of albite, illite, quartz, and dolomite (i.e., the phases in the virgin bed) within the ash coating. Based on this analysis, it appears that the ash coating was formed from the coal ash with no contribution from the bed material.

With respect to the in-bed tube deposit, only sodium calcium sulfate and unclassified phases were observed. The bulk of the unclassifieds were, on further analysis, sulfate phases mixed with other components. The iron oxide was shown by microprobe analysis to be finely dispersed discreet grains too small for spatial resolution by the SEMPC technique. The major phases observed in the convective pass tube deposit were iron oxide, sodium calcium sulfate, and unclassifieds. Some calcium sulfate and gehlenite ($Ca_2Al_2SiO_7$) were observed. Once again the unclassified material was shown to be predominantly rich in calcium and sulfur.

The results of the analysis showed that the Beulah coal ash has a definite propensity for deposition. The formation of ash coating on the surfaces of the bed material is a precursor to agglomeration. It has been shown that the ash coating is derived from the coal ash, in particular, the calcium and sulfur. The deposits, including the ash coating, had chemical compositions very different than the spent bed material. This indicated further that the deposition mechanism was a selective process. In all cases the predominant enrichment was observed with respect to the Ca and S. Significant Fe enrichment was observed in the convective pass tube deposit. However, the Fe did not appear to be responsible for the deposit growth.

The evidence suggested that the cause of the deposit growth was due to the formation and presence of sodium calcium sulfate in the bed. This material was formed from the organically bound sodium and calcium in the Beulah coal reacting with sulfur. There was no free calcium observed in the deposits. The fine-grained sulfate mixture appeared to have an affinity for the cooled surfaces, including the bed particles. Furthermore, there appeared to be a distinct tendency of sulfate species to sinter. The matrix was too fine-grained to establish the presence of a melt phase. It should be noted that sulfate species crystallize readily on cooling. It is suggested that the mode of growth may be a molten sulfate phase. Certainly the presence of sodium

TABLE 3

SEMPC ANALYSIS OF SAMPLES FROM THE 80-MW HESKETT STATION

	Coal	Virgin Bed Material	Spent Bed Material	Ash Coating	In-Bed Tube Deposit	Tube Deposit Morphology	Convective Pass Deposit
Silicates							
Nepheline	--	--	0.8	4.0	--	--	--
Aakermanite	--	--	0.4	2.0	--	--	--
Gehlenite	--	--	--	--	--	--	1.2
Pyroxene	--	--	--	--	--	--	0.8
Albite	--	32.6	39.9	--	--	--	--
Anorthite	--	--	0.4	2.0	--	--	--
Oxide or Carbonate							
Quartz	x	28.1	7.7	--	--	--	0.4
Iron Oxide	--	--	0.8	4.0	--	x	14.5
Ankerite	--	--	--	--	--	--	0.8
Dolomite	--	28.1	--	--	--	--	--
Sulfate and Sulfide							
Barite	x	--	--	--	--	--	1.2
Anhydrite	x	--	3.7	14.0	--	x	4.1
Sulfated Ankerite	--	--	--	--	--	--	1.2
Sodium Calcium Sulfate	--	--	--	--	35.4	x	12.8
Pyrrhotite	--	--	--	--	--	--	1.2
Pyrite	x	--	--	--	--	--	--
Unclassified or Amorphous							
Unclassified	x	1.1	38.7	64.0	64.6	x	71.5
Kaolinite	x	1.1	4.5	12.0	--	--	0.4
Kaolinite-Derived	--	--	--	--	--	--	0.4
Illite	--	9.0	2.5	--	--	--	0.4
Montmorillonite	--	--	0.8	--	--	--	0.8
Calcium-Derived	--	--	--	--	--	--	--
Amorphous	*						
SiO_2	27.7	NA	NA	NA	9.3	10.2	28.8
Al_2O_3	11.9	NA	NA	NA	7.2	10.5	16.9
Fe_2O_3	8.3	NA	NA	NA	11.6	12.4	25.8
TiO_2	0.7	NA	NA	NA	0.7	1.4	1
P_2O_5	0.5	NA	NA	NA	0	0	0.1
CaO	17.1	NA	NA	NA	36.7	30.9	10.9
MgO	5.5	NA	NA	NA	14.9	14.6	4.6
Na_2O	6.3	NA	NA	NA	17.4	14.8	8.7
K_2O	0.6	NA	NA	NA	1.1	1.3	2.3
SO_3	19.7	NA	NA	NA	0	0	0

* Sulk Ash Analysis for Coal
NA Data Not Available
-- Phase not detected
x Phase detected, but not quantified

with the calcium would be expected to lower the melting point. The presence of such phases as nepheline, anorthite, and gehlenite would suggest relatively high transient temperatures being reached within the bed. The silicate phases, while showing melting behavior, were not present in significant quantities to have a significant effect on the deposition phenomena.

The deposits formed are very similar to the dense fouling deposits observed with high alkaline earth and alkali fuels in large-scale conventional combustors. These deposits also tend to be predominantly calcium sulfate with the presence of fluxing components such as sodium or potassium. Here a significant amount of ash component partitioning within the combustor occurs to form an ash stream rich in calcium sulfate. These deposits grow relatively slowly, but are usually dense, hard-bonded, and in areas difficult to soot blow.

The analysis of the pilot-scale data and that from the 80-MW Heskett Station indicate that there is a tendency of certain coal ash to form deposits in a fluidized-bed combustor. The mechanism of adherence and growth, for the case with the Beulah coal, appears to be via a molten sulfate matrix, due to the fluxing action of sodium with the calcium sulfate matrix. The bed material plays no significant role in the deposition mechanism. This is in concurrence with the pilot-scale results and demonstrates the effect that ash chemistry can have on a fluid-bed system.

3.2 PFBC Consulting

A visit was made to Foster Wheeler Development Corporation to discuss ways in which the EERC DOE cooperative agreement program could meet the mutual goals of the two organizations. Foster Wheeler is currently working on a second generation PFBC which uses a pyrolysis step to produce a char burned in a circulating PFBC. The flue gas from the PFBC is combined with the low Btu gas from the pyrolysis step and burned in a topping cycle to raise the temperature of the gas going into the turbine. They propose a system efficiency of 45% and a reduction in the cost of electricity by 20%. The preliminary feasibility study was based on data generated at EERC on the entrained carbonizer. No tests have been done to date at the conditions proposed for the system.

Phase I of the Foster Wheeler program, which was all done on paper, has been completed. Phase II will involve testing each of the separate components to resolve problems and to develop the final design of a 5-MW demo plant. Phase III will involve the demo.

Some of the problem areas identified include hot-gas cleanup, performance of the carbonizer, alkali, and sorbent utilization. We discussed ways in which EERC could contribute technically to these areas. Since no data is available on operating the carbonizer at conditions proposed for the cycle, any data that EERC could generate on the mild gasification unit would be helpful. Some modifications will be required so that the system can operate up to 1700°F and 14 atmospheres. Pressure should be sacrificed if both conditions cannot be met. This will take some modification of the EERC mild gasification system. Testing should be done on one common coal to establish the scalability of the data between systems. After that, EERC could tack on additional run time to planned mild gasification runs. This would allow testing in a cost-effective manner and would expand the data base on the number and types of coals tested at the carbonizer conditions.

Discussions were held concerning using a bench scale reactor to look at kinetics and reactions of alkali release and gettering, sorbent utilization, and N_2O formation. FWDC felt these were all valid and important topics for the development of a second generation PFBC. One point discussed was whether there would be a problem sulfating the CaS from the carbonizer once it was introduced into the PFBC. Data from KRW indicated that a coating formed on the limestone particles, preventing sulfation when introduced into an oxidizing atmosphere. If there is sintering or deadburning occurring, this may limit the utilization of available Ca from the limestone and may make disposal a problem. Therefore, it was agreed that more work needed to be done on sorbent testing.

Information on several subjects generated at EERC under the Cooperative Agreement was requested and sent to FWDC. This included in-bed heat transfer; corrosion, erosion, and deposition in FBC; combustion efficiency vs. operating conditions; results from the 1-lb/hr mild gasification unit; SEM capabilities; and high-temperature ceramic bags. EERC will continue dialogue with FWDC as the next year's EERC Cooperative Agreement program plan is developed.

3.3 System Simplification

The technology assessment of control systems has been completed. The results of this assessment are currently being compiled and will be included in the next quarterly report. An experimental approach for the development of expert control systems is also being developed. This plan will be discussed with METC personnel upon completion.

4.2 Beneficiation of Low-Rank Coals

BENEFICIATION OF LOW-RANK COALS

Quarterly Technical Progress Report
for the period January - March 1990

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May 1990

Work Performed under Cooperative Agreement No. DE-FC21-86MC-10637

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1.0 GOALS AND OBJECTIVES

The overall objectives of the Low-Rank Coal Beneficiation project are to study methods of reducing the inorganic content and increasing the heating value of low-rank coal (LRC) to produce high quality dry coal products and/or coal/water fuels (CWF). The University of North Dakota Energy & Environmental Research Center (EERC) has demonstrated that high-energy content dry or slurry fuels can be produced from lignite and subbituminous coal using the hot-water drying process (HWD), and that low-ash, coal-based fuel can be produced using a combination of physical and chemical cleaning. The processes were integrated to achieve a greater than 400-lb/hr pilot-scale throughput for producing clean, energy-dense coal and/or CWF from low cost, highly reactive LRC feedstocks. These pilot-scale capabilities continue to supply fuels to DOE-sponsored combustion, gasification, and heat engine programs running concurrently with the Low-Rank Coal Beneficiation Program.

Current year LRC beneficiation project research will be conducted at the bench-scale level using the EERC's cold-charge autoclave and laboratory coal processing equipment. Analytical characterization of appropriate samples will be performed by UNDEERC's coal analysis and water analysis laboratories. Significant contributions in this year's work will be provided by the Fuels & Process Chemistry Group in support of the oil agglomeration process on lignites and subbituminous coals.

Current-year objectives for the EERC LRC Beneficiation project are to:

1. Evaluate oil agglomeration with acid leaching, as a combined process.

2. Investigate colloidal coal cleaning (CCC) based on previous efforts.

3. Explore pressurized hot-water drying (HWD) with direct air injection (partial oxidation) heating.

Initial emphasis has been placed on the oil agglomeration task. The CCC technique will be investigated later in the year at the conclusion of the oil agglomeration matrix testing and data reduction. The partial oxidation hot-water drying (PO-HWD) is being coordinated with similar testing for an outside client.

Near-term project objectives for the period January through March 1990 were to:

1. Evaluate the statistical results from the oil agglomeration matrix design to determine the optimal conditions for agglomeration of a North Dakota lignite.

2. Perform partial oxidation hot-water drying on a North Dakota lignite along with the same studies for another client.

2.0 INTRODUCTION

This report describes progress towards goals and objectives established previously (1), as well as those listed in section 1.0. Attention was devoted to evaluation of the statistical results from the central composite factorial design and PO-HWD of Beulah, ND, lignite.

3.0 BENEFICIATION OF LOW-RANK COALS

3.1 Oil Agglomeration Of Beulah Lignite

3.1.1 Statistical Results

The factors (independent variables) that were studied using the matrix design were feed coal particle size (X_1), acid mix time (X_2), acid mix speed (X_3), oil mix time (X_4), and oil mix speed (X_5). The responses (dependent variables) that were investigated were agglomerate ash content (Y_1), agglomerate yield (Y_2), recoverable oil--the oil retained in the agglomerates (Y_3), performance value--the general agglomerate quality (Y_4), ash efficiency index (Y_5), and ash reduction (Y_6). The numbers in parentheses are the identifier (variable name) for each respective independent or dependent parameter.

The data from the test matrix are given in Table 1. It should be noted that the X's were coded to be between -2 and +2 in order to facilitate the regression analysis that was performed. The actual values of the X's for each coded value (-2, -1, 0, +1, +2) are given in Table 2.

The matrix of runs performed was a central composite design for five independent variables, and it required 32 runs (2). The 33 runs actually performed included the matrix and one repeat run (Run 33). This matrix allowed the fitting of a full quadratic equation to describe the impact of the factors (X's) on each respective response. The quadratic equation for each response can be represented as:

$$F_i = b_o + b_1X_1 + b_2X_2 + b_3X_3 + b_4X_4 + b_5X_5$$

$$+ b_6X_{12} + b_7X_{22} + b_8X_{32} + b_9X_{42} + b_{10}X_{52}$$

$$+ b_{11}X_1X_2 + b_{12}X_1X_3 + b_{13}X_1X_4 + b_{14}X_1X_5 + b_{15}X_2X_3$$

$$+ b_{16}X_2X_4 + b_{17}X_2X_5 + b_{18}X_3X_4 + b_{19}X_3X_5 + b_{20}X_4X_5$$

TABLE 1. CODED INDEPENDENT VARIABLES AND RESPONSES

RUN	X_1	X_2	X_3	X_4	X_5	Y_1	Y_2	Y_2*	Y_3	Y_4	Y_5	Y_6
12	-1	-1	-1	-1	1	1.21	82.65	82.65	57.94	2	5821.58	82.39
19	1	-1	-1	-1	-1	2.12	22.94	22.94	42.34	1	1030.61	79.50
17	-1	1	-1	-1	-1	1.37	96.67	96.67	47.64	2	5703.78	80.06
8	1	1	-1	-1	1	2.20	48.92	48.92	46.78	3	1987.80	78.72
22	-1	-1	1	-1	-1	1.12	100.00	99.80	44.10	2	7443.59	83.70
5	1	-1	1	-1	1	1.89	4.24	4.24	37.56	0	222.47	81.72
32	-1	1	1	-1	1	0.92	100.00	99.80	39.52	4	9448.53	86.61
30	1	1	1	-1	-1	2.27	3.41	3.41	27.34	0	148.92	78.05
27	-1	-1	-1	1	-1	1.40	92.57	92.57	39.04	3	5367.64	79.62
31	1	-1	-1	1	1	2.62	69.37	69.37	38.82	3	2181.70	74.66
25	-1	1	-1	1	1	1.76	90.89	90.89	47.52	3	3976.92	74.38
3	1	1	-1	1	-1	2.64	15.71	15.71	58.90	1	570.69	74.47
6	-1	-1	1	1	1	2.35	100.00	99.80	39.74	5	2795.59	65.79
10	1	-1	1	1	-1	2.53	7.53	7.53	59.98	0	292.76	75.53
7	-1	1	1	1	-1	1.24	92.25	92.25	36.58	4	6191.44	81.95
24	1	1	1	1	1	3.37	0.70	0.70	17.53	0	20.81	67.41
16	-2	0	0	0	0	0.97	100.00	99.80	31.54	2	8812.83	85.69
1	2	0	0	0	0	3.88	2.10	2.10	43.86	0	53.73	70.63
18	0	-2	0	0	0	1.85	98.14	98.14	44.62	4	4211.52	78.88
23	0	2	0	0	0	1.45	91.30	91.30	40.90	3	5349.93	83.45
21	0	0	-2	0	0	1.85	94.41	94.41	42.86	5	4093.60	78.88
26	0	0	2	0	0	1.77	97.05	97.05	40.98	4	4396.96	79.79
13	0	0	0	-2	0	1.57	97.70	97.70	42.16	3	5132.06	82.08
2	0	0	0	2	0	1.66	98.38	98.38	44.12	5	4831.55	81.05
29	0	0	0	0	-2	3.02	29.95	29.95	34.14	1	888.27	65.53
20	0	0	0	0	2	1.23	88.22	88.22	43.26	4	6290.58	85.96
33	0	0	0	0	2	1.59	94.28	94.28	44.50	4	5077.89	81.85
4	0	0	0	0	0	1.79	91.60	91.60	51.24	4	4153.15	79.57
9	0	0	0	0	0	2.23	98.53	98.53	49.44	4	3303.78	74.54
11	0	0	0	0	0	1.33	99.48	99.48	49.56	4	6340.38	84.82
14	0	0	0	0	0	1.71	98.62	98.62	45.34	3	4648.71	80.48
15	0	0	0	0	0	2.80	98.49	98.49	45.64	3	2404.96	68.04
28	0	0	0	0	0	2.33	78.17	78.17	39.88	3	2661.87	73.40

X_1 Feed Coal Particle Size
X_2 Acid Mix Time
X_3 Acid Mix Speed
X_4 Oil Mix Time
X_5 Oil Mix Speed
* Normalized values of Y_2

Y_1 Agglomerate Ash
Y_2 Yield
Y_3 Free Oil
Y_4 Performance Value
Y_5 Efficiency Index
Y_6 Ash Reduction

TABLE 2. CODING USED FOR INDEPENDENT VARIABLES

X_i = Coded Factor i	Values of Coded Factors -2	-1	0	1	2	Units
i=1) Coal Mesh Size	-30x60	60x100	100x200	200x325	-325	mesh
i=2) Acid Mix Time	10	22.5	35	47.5	60	min
i=3) Acid Mix Speed	4	6	9	13.5	20.25	1000 rpm
i=4) Oil Mix Time	2	6.5	11	15.5	20	min
i=5) Oil Mix Speed	0.1	0.2	0.4	0.8	1.6	1000 rpm

In fitting this equation to the responses, any terms that were not statistically significant (at the 5% significance level) were deleted, so that, in all cases, a much smaller equation was finally obtained. The reduced equations are given in Table 3. Two summary statistics are also given in Table 3: a) the overall significance of the equation [which was always very high] and b) the amount of variation in the data explained by linear regression (called R^2). The R^2 varied from 0.26 for the percent ash reduction (Y_6), indicating a large amount of scatter around the equation, to a high of 0.87 for the yield (Y_2), indicating a good level of agreement between the data and the model.

TABLE 3. STATISTICAL REGRESSION SUMMARY

Response	Significant Terms	Overall Significance	R^2
Y_1 = Agglomerate Ash	$Y_1 = 1.94 + 0.59X_1 + 21X_4$	99.99%	0.60
Y_2 = Yield(*)	$Y_2^T = - 3.1 + 2.8X_1 + 0.8X_1^2 - 0.5X_5 + 0.7X_5^2 + 1.4X_1X_3 + 0.7X_2X_4$	99.99%	0.87
Y_3 = Free Oil	$Y_3 = 42.9 - 1.9X_2 - 3.3X_3 + 3.0X_1X_4 - 4.1X_1X_5 - 5.2X_2X_3 - 4.5X_4X_5$	99.99%	0.67
Y_4 = Performance Value(#)	$Y_4 = 3.53 - 0.88X_1 - 0.8X_1^2 + 0.38X_4 + 0.60X_5 - 0.34X_5^2 - 0.80X_1X_3 - 0.44X_2X_4$	99.99%	0.84
Y_5 = Efficiency Index	$Y_5 = 3810 - 2410X_1$	99.99%	0.67
Y_6 = Ash Reduction	$Y_6 = 78.15 - 2.27X_1 - 2.46X_4$	98.64%	0.26

* $Y_2 = \dfrac{100\%}{[1 + \exp(Y_2^T)]}$

Equation shows lack of fit at 4% significance level

The regression equations generated in Table 3 were used to draw conclusions about optimum operating conditions. To facilitate this data interpretation, the equation models were graphed for the predicted values, along with the actual data, shown in Figures 1-5. All the responses are depicted, except for Y_4, the performance value, which had lack of fit.

All responses were best at the lowest level of X_1 (-30 x 60 mesh). In addition, a low level of X_4 (oil mix time = 2 minutes) was best for Y_1 (agglomerate ash content) and Y_6 (ash reduction), while it did not adversely affect the other responses. With these two factors set, the best values for X_2, X_3, and X_5 are found via examination of responses Y_2, Y_3, and Y_4. The high level for X_3 (acid mix speed) was best based mainly on its affect on improved yields (Y_2), but it also accounted for higher free recoverable oil (Y_3) and performance values (Y_4). Mid to high values of X_5 (oil mix speed) were found to be best for all responses with too high or too low an oil mix speed, causing lower agglomerate yields, etc. The only factor giving mixed results was X_2 (acid mix time), which gave the best yields and performance values at high mix times, but the most recoverable free oil at low mix times. The impact on the recoverable oil was the greatest; therefore, low acid mix times were judged the best condition according to the statistical results.

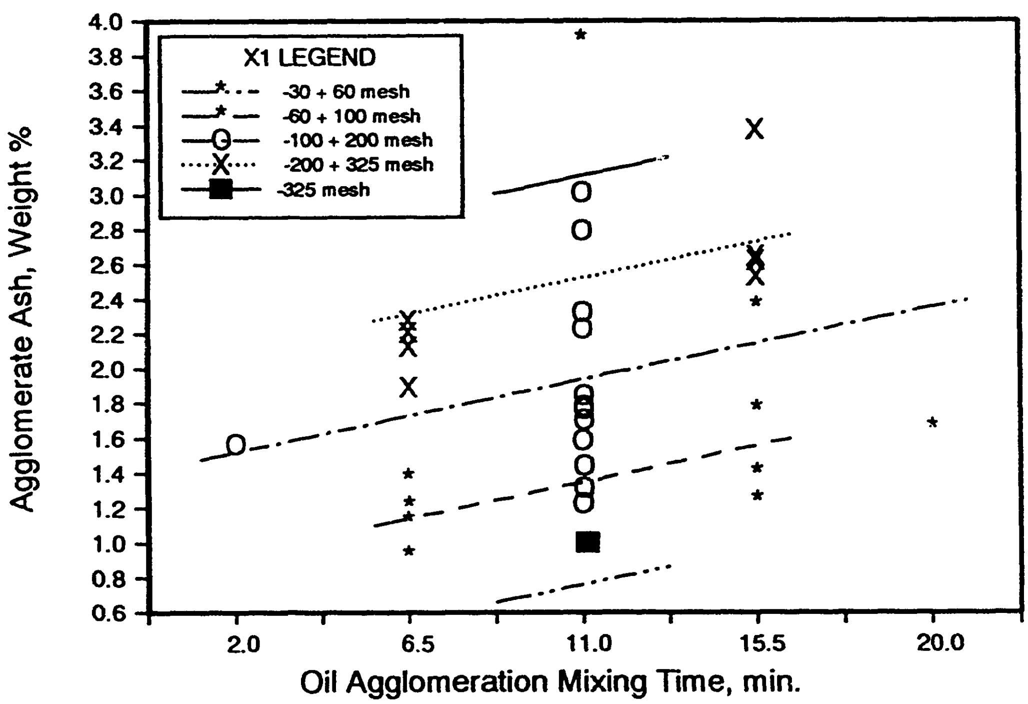

Figure 1. Ash content vs. oil mix time and particle-size fraction.

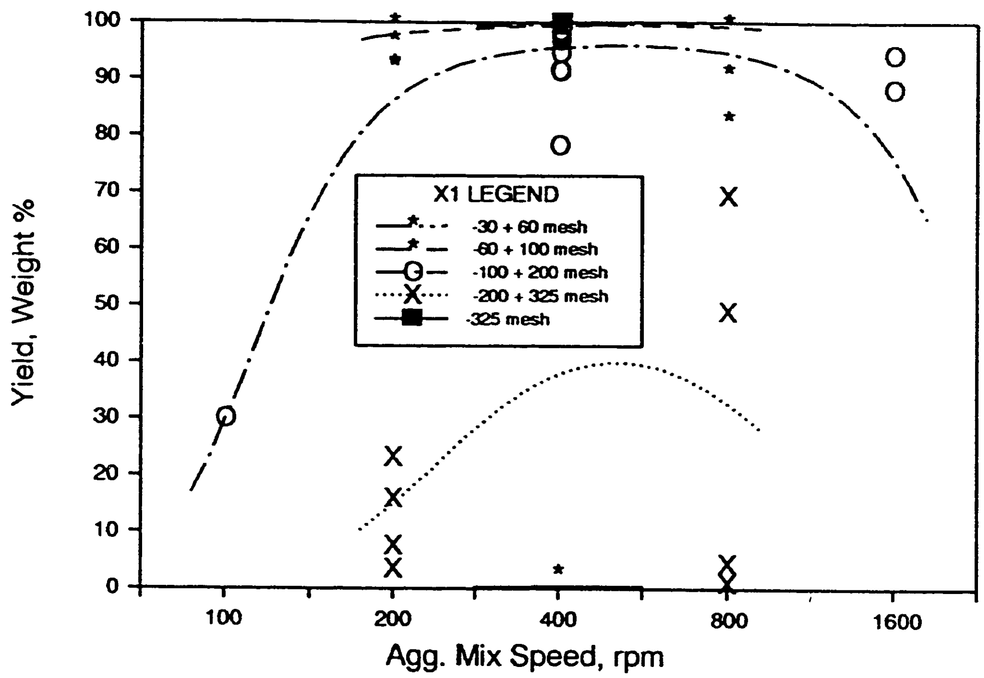

Figure 2. Agglomerate yield vs. agglomerate mix speed and particle-size fraction.

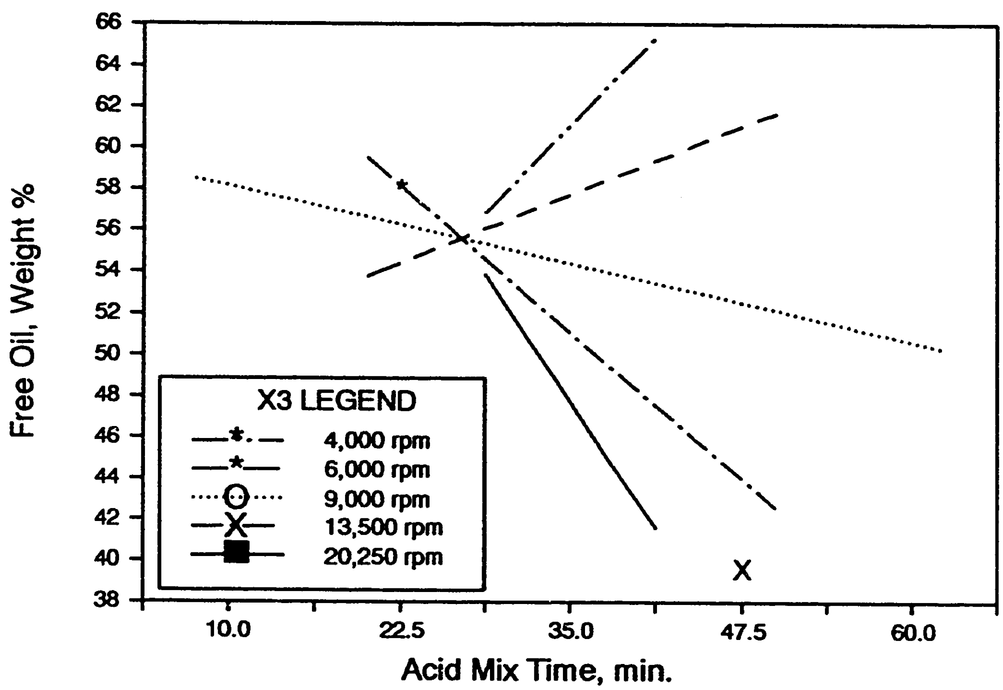

Figure 3. Free recoverable oil vs. acid mix time and acid mix speed.

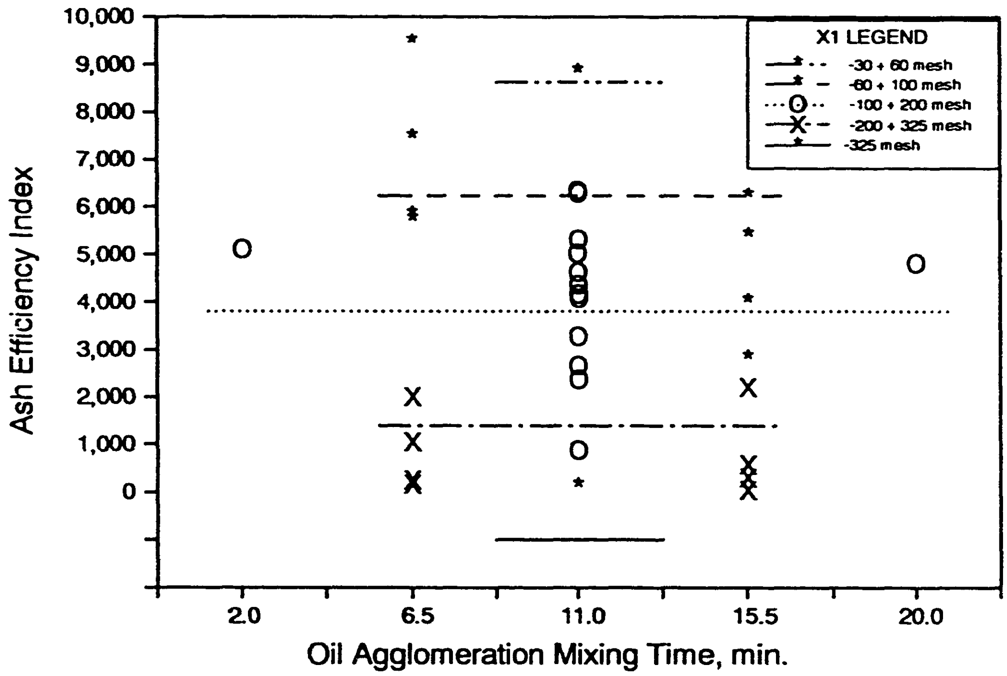

Figure 4. Ash efficiency index vs. oil mix time and particle-size fraction.

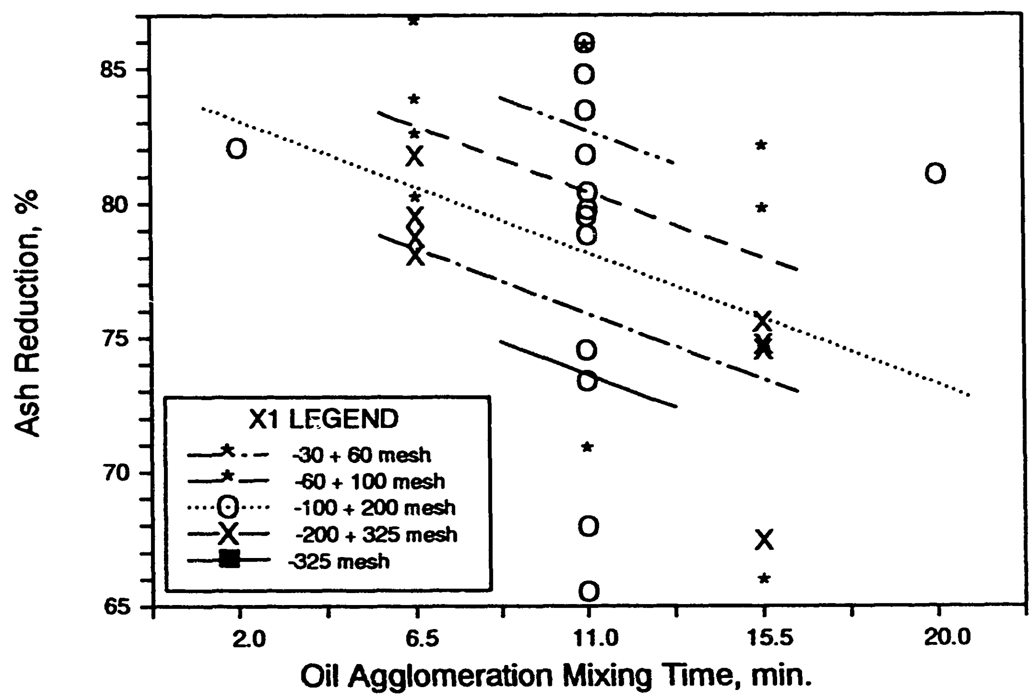

Figure 5. Ash reduction vs. oil mix time and particle-size fraction.

3.2 Partial Oxidation Hot-Water Drying

3.2.1 Objectives

The purpose of the testing was to determine if partial oxidation during hot-water drying would a) enhance the cleanability of the coal, b) improve the rheology of CWFs made from LRC, and c) improve the economics of hot-water drying by direct particle heating.

3.2.2 Experimental Procedure

Partial oxidation hot-water drying was performed in the EERC 7.6-liter externally heated, stirred autoclave. The autoclave was equipped with a dip tube in order to sparge oxygen through the agitated slurry. A metal frit was fastened to the bottom of the dip tube to facilitate oxygen dispersion within the slurry.

A 3.8-liter autoclave, filled from a cylinder tank, was used as an accumulator for oxygen charging. The volume of the accumulator was accurately determined by measuring the mass of water needed to fill the accumulator. The pound-moles of oxygen in the accumulator, as a function of pressure and temperature, were determined from Van der Waal's equation (3).

Approximately 2000 to 4000 grams of a 50% Beulah/50% water slurry was used in each test. After charging the slurry, the autoclave was evacuated of residual air, and the heaters were turned on. Heat-up to 200°C took approximately 1.5 hours, whereupon the contents of the autoclave were allowed to stabilize at 200°C.

Prior to charging oxygen to the 7.6-liter reactor, the pressure and temperature in the accumulator were recorded. The oxygen was then metered from the accumulator into the 7.6-liter autoclave until the desired slurry temperature was achieved. The final oxygen pressure and temperature in the accumulator were then recorded.

After completing the test, the autoclave and contents were allowed to cool overnight. The product gas was metered and vented, and the product slurry was recovered and weighed. Product gas sampling was performed for two tests. The process water was separated from the solids by filtering. The filter cake was washed with deionized water to help remove any cations loosely adhered to the coal surface.

The filter cake from each test was diluted with deionized water to produce slurry for rheological testing. Apparent viscosity was determined for the slurry at three different solid contents. Presently, Certigrav washability testing is being performed on the raw and hot-water dried coals for inclusion in the next Quarterly report.

3.2.3 Results

Combustion of the slurry was instantaneous upon addition of the oxygen, and temperature rise was rapid. Temperature control, however, in the batch autoclave system was limited by an unsuitable oxygen charge system. The maximum charge pressure for the accumulator was 2000 psig, as set by the pressure transducer. As a consequence, the tests usually required multiple charges of oxygen to approach the desired temperature. The temperature of the slurry in the 7.6-liter autoclave usually decreased before the accumulator could be recharged with oxygen. The temperature drop was rapid because the autoclave was absorbing heat from the slurry. Additionally, as the steam pressure in the 7.6-liter autoclave increased and as combustion gases were produced, subsequent charges delivered less oxygen, producing a progressively lower temperature increase. This shortcoming was somewhat alleviated by decreasing the mass of slurry in the last PO-HWD test.

The conditions for the three PO-HWD tests and one HWD test are presented in Table 4. The oxygen requirements, in pound-moles of oxygen charged per gram of slurry per Celsius degree temperature rise, are presented in Table 5. The oxygen utilization, as a percentage of the original oxygen charge, has not been determined because product gas analysis has not yet been performed. Selection of which test to perform gas analysis on is pending results of the Certigrav washability testing. The solids recovery per test is also presented in Table 5.

TABLE 4. CONDITIONS FOR HWD AND PO-HWD TESTS

Test #	Test Type	Temperature (°C)	Slurry Charge (grams)	Oxygen (lb-moles)
1	HWD	303	3984	NA
2	PO-HWD	239	3988	0.0195
3	PO-HWD	282	3989	0.0190
4	PO-HWD	303	1991	0.0227

HWD Hot-Water Dried
PO Partial Oxidation
NA Not Applicable

TABLE 5. OXYGEN REQUIREMENTS AND SOLIDS RECOVERY

Test #	Temperature Rise (dC°)	Oxygen (lb-mole/g-dC°)	Solids Recovery (wt%)
1	NA	NA	90.8
2	36	1.36×10^{-7}	93.4
3	75	6.35×10^{-8}	91.6
4	96	1.19×10^{-7}	80.5

NA Not Applicable

Preliminary calculations indicated that the lb-moles of O_2 necessary to raise one gram of slurry one degree Celsius via partial oxidation varies by only about 2% over the range of 300°C to 320°C. Similarly, over the range of 282°C to 303°C, the oxygen requirements should be nearly equal. However, the measured oxygen requirements varied by nearly 100% over the range of 282°C to 303°C. The large discrepancy may indicate overcharging of oxygen in order to achieve temperature.

The solids recovery for the HWD test at 303°C was approximately 91 wt%, while the solids recovery for the PO-HWD test at 303°C is approximately 81 wt%. The loss of solids in the HWD test is attributed to decarboxylation and mild pyrolysis reactions. The additional loss of solids in the PO-HWD test is presumably due to combustion reactions.

The large difference in solids recovery between the 282°C and 303°C PO-HWD tests also seems to substantiate the overcharging of oxygen in order to achieve 303°C.

The apparent viscosity at 100 sec^{-1} versus solids content is presented in Figure 6 for slurries produced from the raw, HWD and PO-HWD Beulah coal. The slurry with the highest solids content was achieved with the 303°C HWD coal. Partial oxidation hot-water drying at 303°C, however, did not produce a slurry with comparable solids content and viscosity. The variation may be due to insufficient residence time at temperature and consumption of combustible material during PO-HWD. The PO-HWD did, however, improve slurry solids content above that of a raw Beulah slurry.

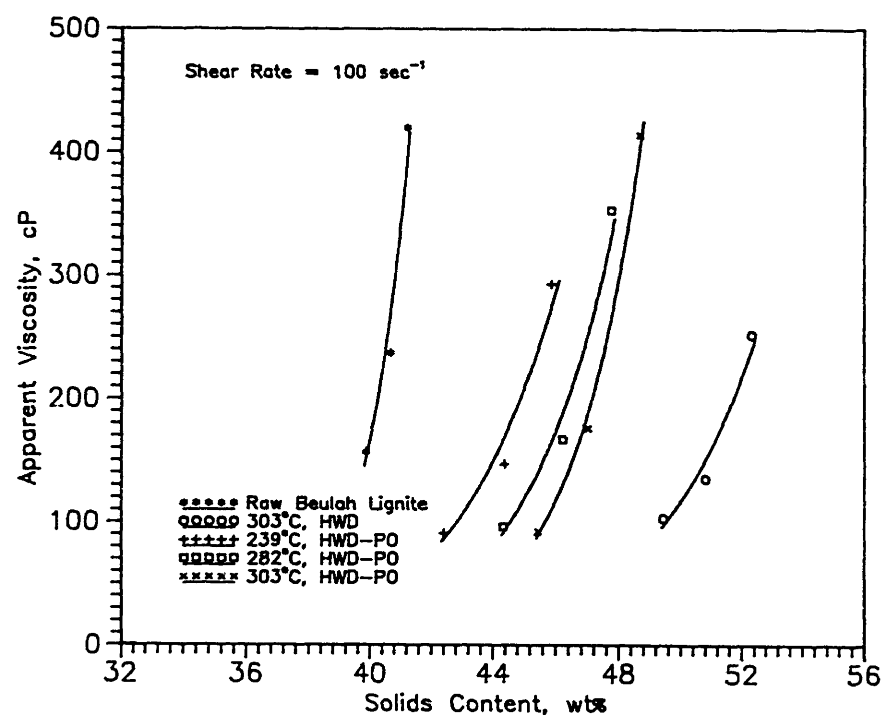

Figure 6. Apparent viscosity vs. solids content for raw, HWD and PO-HWD Beulah lignite.

3.2.4 Washability Testing

The Certigrav washability testing is currently being performed. Theoretically, the partial oxidation during hot-water drying will liberate ash material from the coal structure and, consequently, enhance ash removal via gravity separation. Results of the washability testing will determine if gas proximate, ultimate, and heating value analyses should be performed.

3.2.5 Economic Benefits

Presently the economic benefits of PO-HWD over HWD have not been determined. Most certainly an electrical cost savings will be realized by supplying a portion of the thermal requirements by direct (internal) heating. However, additional product gas and PO-HWD coal analysis (proximate, ultimate, and heating value) will have to be performed to determine the cost differential. The results of the cost savings calculations will be presented in the next quarterly.

4.0 CONCLUSIONS

1. The results indicate that finer particle sizes were not as successful in agglomeration or ash reduction as larger particle sizes were, which is probably due to the fact that the sizes were sieve fractions of the parent coal, instead of the parent coal being pulverized to smaller sizes.

2. Ash efficiency indexes of greater than 6,000 were attained for a few of the agglomerates and represent excellent agglomeration performance.

3. Autoclave testing has proven that heat for hot-water drying of Beulah coal slurry can be supplied internally by partial oxidation (combustion) of the coal.

4. Combustion of a 50/50 Beulah coal/water slurry is instantaneous at temperatures as low as 200°C.

5. The batch processing method is not reliable for temperature control and oxygen charging for partial oxidation testing.

5.0 RECOMMENDATIONS

1. Additional testing of acid strength needs to be performed on the oil agglomeration process in order to optimize the acid cleaning conditions.

2. Oil/coal ratios have to be investigated further for Beulah lignite because some agglomerate products were large clumps, instead of several smaller agglomerates.

3. Further statistical matrix testing of acid strength and oil strength will provide scale-up information for the developing oil agglomeration process data bank.

4. Future partial oxidation work, to accurately determine oxygen utilization and temperature control, should be performed in a continuous unit such as the EERC 10-lb/hr CPU or 600-lb/hr PDU.

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4.3 Combustion Characterization of Low-Rank Coal Fuels

COMBUSTION CHARACTERIZATION OF LOW-RANK COAL FUELS

Quarterly Technical Progress Report
for the Period January-March 1990

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May 25, 1990

Work Performed Under Cooperative Agreement No. DE-FC21-86MC10637

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COMBUSTION CHARACTERIZATION OF LOW-RANK COAL FUELS

1.0 INTRODUCTION

Coal research by the Pittsburgh Energy Technology Center (PETC) of the U.S. Department of Energy (DOE) is directed toward both increasing coal usage in existing markets and introducing new, premium quality coal-based fuels to markets currently dependent on oil or natural gas. Accordingly, the work concentrates on coal cleaning, fuel formulation and handling, combustion, and flue gas cleanups, all necessary technologies in the direct use of coal. Progress achieved over the past several years through PETC and related federal and private sector research activities has considerably strengthened these technologies, consequently enhancing the possibility of meeting DOE's coal research goals.

The industrial and utility sectors are major consumers of oil and gas. Many of these oil and gas systems could be converted to coal-fired systems, resulting in a significant reduction in the oil and gas needs of this country. As an example, oil- and gas-generating systems in the utility sector have a nameplate generating capacity of 156 gigawatts (GW). Of this, 91.6 GW have the potential for conversion to coal, based on remaining years of service. This represents 4.8 quads of energy per year. There are similar opportunities to reduce U.S. dependency on oil and gas in the industrial sector.

A number of critical factors need to be examined to determine the success of switching from oil or gas to coal. Significant differences exist in burner designs, furnace plan areas, heat release rates, tube spacing in convective passes, number and location of soot and wall blowers, and others. Combustion characterization of replacement fuels is needed to assess the impact of the new fuel's properties on the existing design. This characterization should help assess any equipment modifications or derating necessary as a result of switching fuels.

2.0 GOALS AND OBJECTIVES

The purpose of this project is to expand the scientific and engineering data base on the combustion characterization of advanced low-rank coal fuel types for combustion systems in the industrial and utility markets currently using oil or gas as the primary fuel. To accomplish this overall objective, specific objectives are to use existing and new laboratory-, bench-, and pilot-scale techniques to characterize various dry and slurried coals and coal blends. Results of these enhanced characterization tests will be used to assess the effect of switching fuels on the ignitability and stability of the flame, fouling and slagging, emissions, and carbon burnout as compared to the design fuel.

Work during the three-year period April 1986 through June 1989 focused on the development of a small-scale combustion device suitable for the residential and commercial marketplace, followed by characterization of coals and coal/water slurries as replacement fuels for oil and gas. The direction of the project has shifted, with the new emphasis on the industrial and utility marketplace. Low-rank coals and slurries, alone or in blends, with the potential to replace oil and gas will be characterized in the next three years (7/89 - 6/92).

The University of North Dakota Energy and Environmental Research Center (UNDEERC) has been involved in the characterization of coal for over 20 years. This work was initially developed to study fouling in the convective pass and has been expanded to also study boiler slagging and particulate emissions. A number of analytical techniques and bench- and pilot-scale tests have been developed. These techniques will be used as a part of the proposed work. EERC does not currently have the capabilities to study flame stability and ignitability; therefore, part of the three-year objectives will be to add this capability. The capability for flame stability testing will be combined with existing techniques for studying slagging, fouling, and emissions and new techniques being developed under other parallel DOE and EPRI programs to produce an "enhanced" combustion characterization program. This program will be used to characterize low-rank coals and slurries, alone or in blends, to determine their potential as replacements for oil and gas.

UNDEERC is also a subcontractor to Combustion Engineering, Inc. for work under DOE Contract No. DE-AC22-89PC88654, which was awarded in March 1989. This contract is for the combustion characterization of beneficiated coal-based fuels; the primary focus will be on fuels derived from eastern bituminous coals. In the subject three-year Cooperative Agreement, the intention is to expand the data base on selected, advanced, low-rank coal fuels in a manner generally parallel to the contract noted above. To achieve this objective, UNDEERC will develop a cooperative program with the Coal Combustion R&D Division at PETC. UNDEERC will perform laboratory analyses and bench-scale tests (similar to the work for CE) as far as practical and appropriate for the selected fuels. Atomization and combustion testing of these fuels will be performed at PETC.

It is not anticipated that the cooperative UNDEERC/PETC program will duplicate all aspects of the CE contract. The intention is to characterize the combustion properties of advanced LRC fuels (in both dry and slurry forms) by means broadly similar to those employed by CE and its subcontractors, within the constraints of the funding level of the Cooperative Agreement and the work priorities of the PETC staff and facilities.

Specific three-year objectives include:

1. Combustor Modifications and Development.

   Several modifications will be made to the EERC 550,000-Btu/hr test combustor to enhance its capabilities for characterizing fuels. These modifications include adding a data aquisition and control system, pressure transducers, thermocouples, control valves, and flow transmitters (this equipment is available from the residential-scale packed-bed combustion system). An adjustable swirl burner similar to that used by PETC will be purchased and installed. Modifications to the coal feed system are needed to allow accurate metering of the fuel and to eliminate problems with uneven feeding. Coal-sizing equipment will be upgraded to allow more control over the size of the feed of the coal. An existing tubular

ESP will be installed. Additional viewports will be added to the combustor.

2. Characterization of Combustion Performance.

   The performance of various fuels, including coal blends, coal (both dry and slurried), and oil (for comparative purposes) will be characterized. These characterization tests will be designed to determine combustion performance, mineral matter behavior, and emissions.

   Aspects of combustion performance to be measured will include flame stability, ignitability, and carbon burnout. Mineral matter observations will include slagging on furnace walls, deposition on convective pass tubes, fly ash formulation, and mineral matter transformations. Gaseous emissions, including NO_x, SO_2, CO, and particulates, will be measured. Fly ash particle size and resistivity will help evaluate ESP performance.

3. Comparison to Commercial-Scale Demonstrations.

   Results from the enhanced characterization tests performed under this project will be compared to results (where available) of existing DOE and EPRI large-scale demonstration projects.

3.0 PROPOSED WORK FOR THE FIRST YEAR (7/89 - 6/90)

To achieve the specific goals for the third year, a five-task program has been developed. The tasks include modifications to the 550,000-Btu/hr test furnace, system shakedown, and baseline testing of a western subbituminous coal and three characterization studies of various coals and coal blends.

3.1 Task A. Combustor Modifications

Several modifications will be made to the EERC 550,000-Btu/hr test combustor to enhance its capabilities for characterizing fuels. These modifications include adding a data aquisition and control system, pressure transducers, thermocouples, control valves, and flow transmitters (this equipment is available from the residential-scale packed-bed combustion system). An adjustable swirl burner similar to that used by PETC will be purchased and installed. Modifications to the coal feed system are needed to allow accurate metering of the fuel and to eliminate problems with uneven feeding. Coal-sizing equipment will be upgraded to allow more control over the size of the feed of the coal. An existing tubular ESP will be installed using non-DOE funds.

3.2 Task B. Shakedown and Baseline Testing

Procedures for measuring flame stability and ignitability will be refined. Equipment that has been modified will be tested to ensure it operates properly. The data acquisition and control system and new instrumentation will be tested.

A baseline test will be performed. The baseline coal will be a western subbituminous coal. Baseline testing will include flame stability testing and an extended ash fouling and slagging test. Funding for this task will be split 60%/40% Cooperative and non-Cooperative Agreement funding.

3.3 Task C. Characterization of a Lignite and Petroleum Coke Blend

This task is not part of the Cooperative Agreement, but will be performed in conjunction with this cooperative program.

A blend of a northern Great Plains lignite will be blended with petroleum coke in blends ranging from 60:40 lignite:petroleum coke to 100% lignite. The purpose of this blending is mainly to improve the energy density of the lignite so that it can be competitively marketed and used in the industrial sector. Results will be applicable to utility customers. It is expected that the blending will also improve the fouling characteristics of the lignite. The characterization will include a detailed analytical screening, carbon loss and deposition studies on the drop-tube furnace, and an extended fouling and slagging test on the ash fouling furnace, including flame stability. All work will be performed at EERC.

3.4 Task D. Characterization of a Subbituminous and Petroleum Coke Blend

This task is not part of the Cooperative Agreement, but will be performed in conjunction with this cooperative program.

A blend of a western subbituminous coal with high fouling tendencies will be blended with petroleum coke to a maximum blend ratio of 60:40 subbituminous:petroleum coke. The purpose of the blending in this case is primarily to reduce fouling and also to increase the energy density, while disposing of by-product from an associated industry. The target of this blending exercise is the utility industry; however, results will be applicable to users in the industrial sector. The test protocol will be the same as outlined in Task 4. All work will be performed at EERC.

3.5 Task E. Characterization of a Low-Sulfur Subbituminous Coal and a High-Sulfur Bituminous Coal Blend

This task assumes a carryover of $35,000 from the 1988-1989 Cooperative Agreement year.

A low-sulfur western subbituminous coal will be blended with a high-sulfur bituminous coal for this task. The target market would be utility customers in the Midwest. The main purpose of the blending is for sulfur control from the viewpoint of the bituminous coal. From the perspective of the subbituminous coal, the blending will increase the energy density and may improve the fouling tendencies.

EERC will perform a detailed analytical screening of the parent coals and various blends. The blend ratio will vary from 100:0 to 0:100 subbituminous:bituminous. Following the analytical characterization, drop-tube work to characterize carbon burnout and depositional characteristics will be performed by EERC. Combustion tests of this blend will be performed by the

Coal Combustion R&D Division of PETC. EERC and PETC personnel will work together to combine the results into a detailed package characterizing the blending of the two test coals.

4.0 PROJECT STATUS

Activities during the third quarter were scheduled to complete construction of new equipment (coal feed hoppers, sampling cyclones, and baseline heat flux probe), modifications to existing equipment, installation of purchased equipment (adjustable secondary air swirl burner, coal feeder, and coal-sizing equipment), installation of existing tubular ESP, and subsequent piping changes on the ash fouling furnace (AFU) at EERC. These changes were essential to completing the work load described in the annual project plan. Equipment shakedown was scheduled to be completed by March 1990; however, shakedown testing has been rescheduled to begin during the second or third week in May. Acquisition of equipment and supplies, questions regarding the compatibility of the swirl burner, and manpower availability were the factors that contributed most to the delays encountered.

4.1 Task A. Combustor Modifications

Modifications to the AFU and auxiliary systems were broad in scope and covered all aspects of the combustion system from the mill to the particulate control device. Many of the activities occurred simultaneously; however, most were dependent upon completion of one or more areas. This interdependence delayed the completion of combustor modifications, prompting the rescheduling of shakedown testing. System modifications completed during the third quarter included: the rearrangement of heat exchangers to accommodate the tubular ESP and sampling cyclones that were installed; the installation of the mechanical-aerodynamic coal sizer, the coal feeder, meters and control valves for the furnace wall slag probes and the data acquisition system; construction of the baseline heat-flux probe; and modifications to the probe bank and associated cooling air system. A schematic of the combustion test system prior to modification can be seen in Figure 1, and a schematic of the system showing some of the changes can be seen in Figure 2.

4.1.1 Coal Feed Characterization and Control

Changes in the particle size of the pulverized coal entering the combustion system can skew combustion results by decreasing the stability of the flame under a given set of conditions, lowering the rate of carbon burnout. This type of change cannot be tolerated for a series of tests on the same fuel. For the low-rank coal fuels test program, control of feed size will be accomplished using the mechanical-aerodynamic separator shown in Figure 3. The separator will allow a consistent particle size of approximately 75% less than 200 mesh for each combustion test. The separator was installed on a 400-lb/hr pulverizer in EERC's coal preparation facility and will be calibrated prior to shakedown testing.

Also purchased was a microprocessor-controlled weight-loss coal feeder. The new feeder, which can be seen in Figure 4, will allow on-line monitoring of the feed rate and will be used to maintain combustion conditions such as

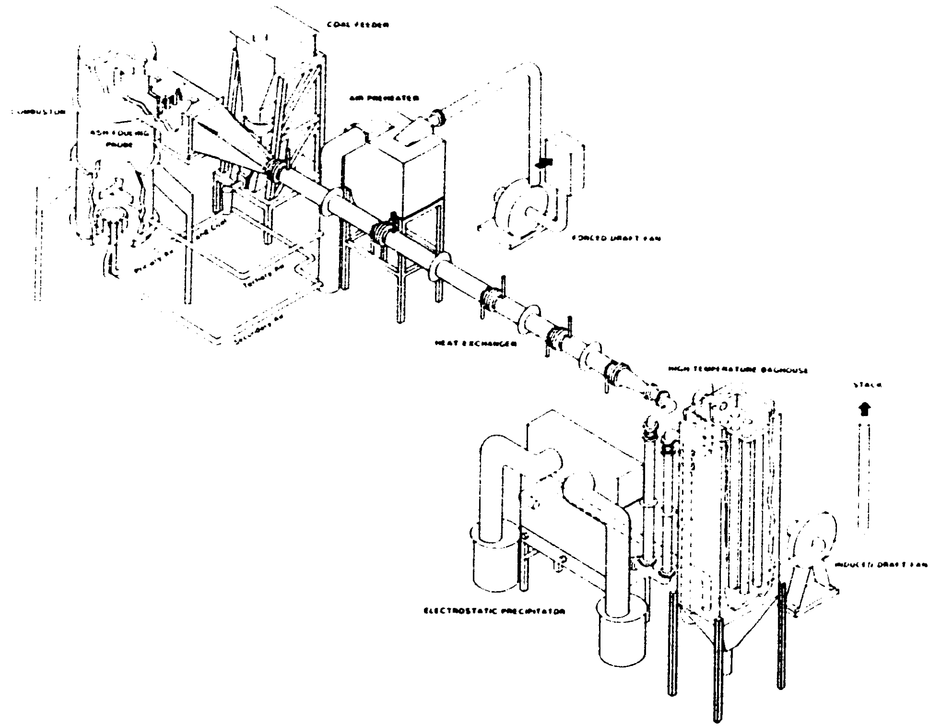

Figure 1. Schematic of EERC's combustion test system prior to modifications.

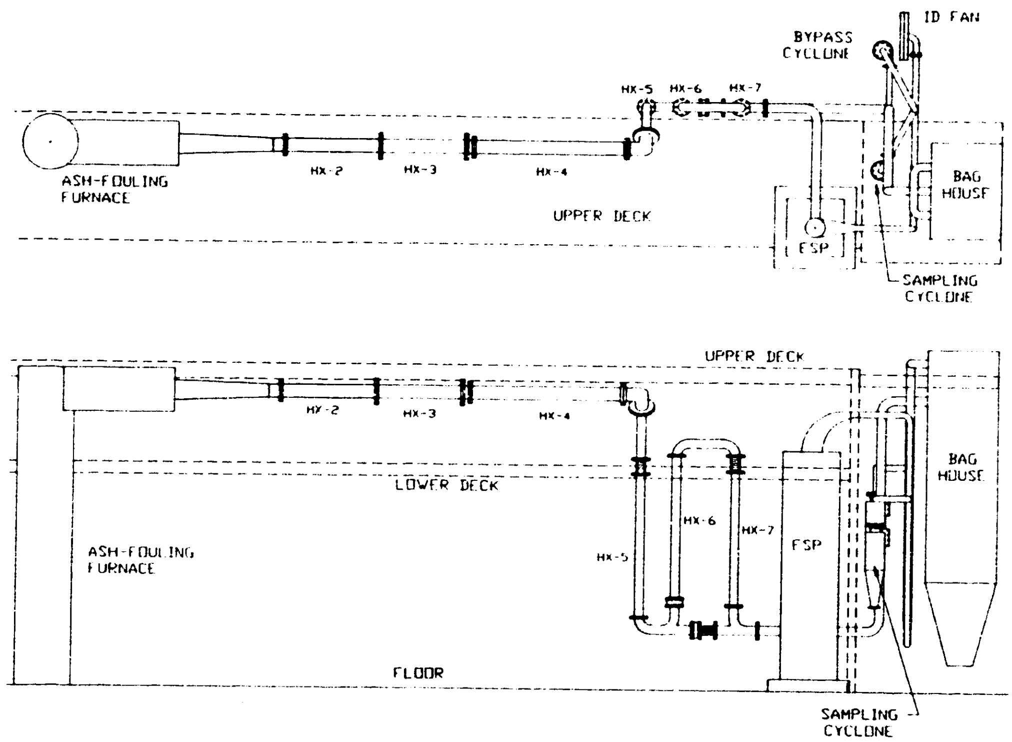

Figure 2. Schematic of EERC's combustion test system showing some of the completed modifications.

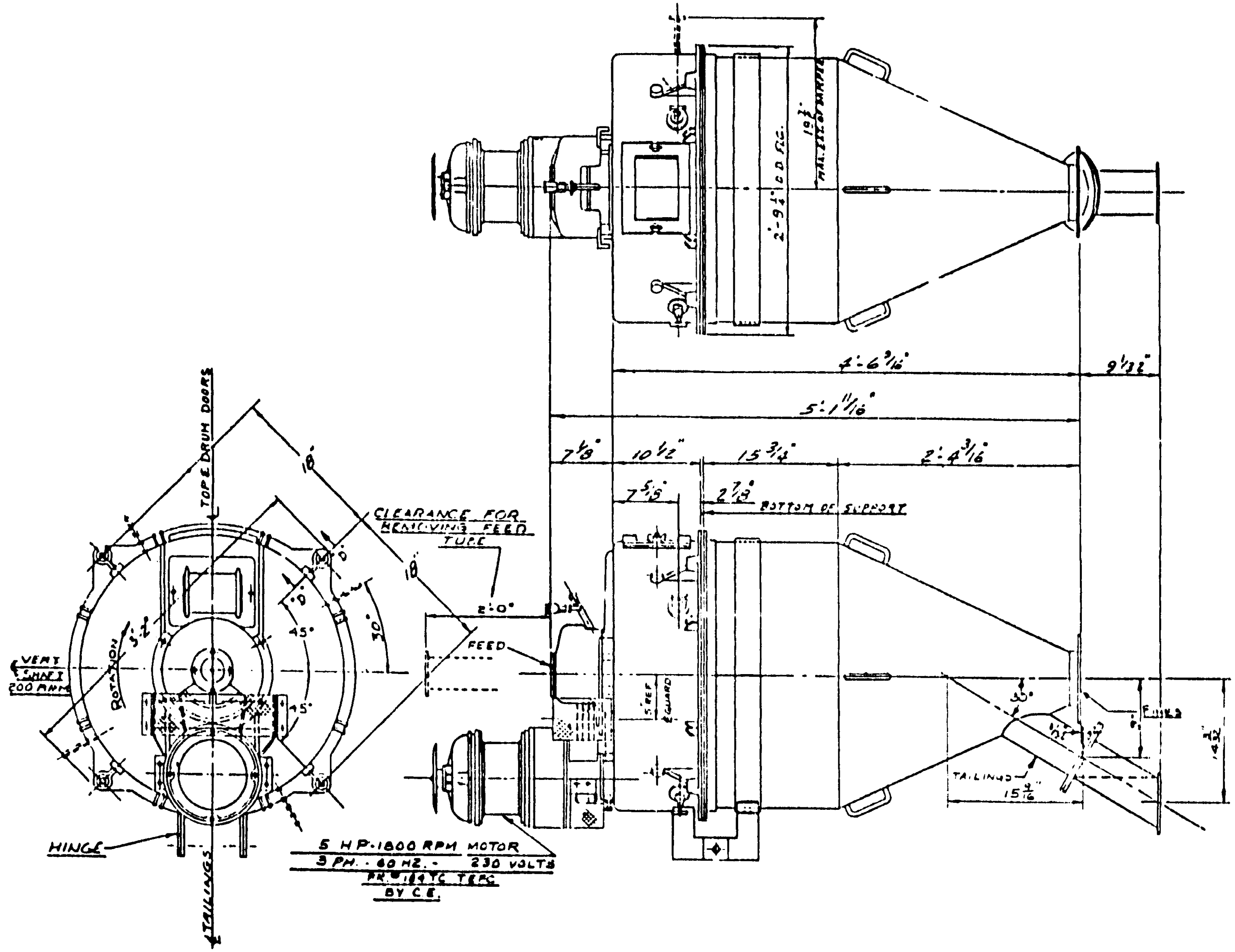

Figure 3. Schematic of 30" double whizzer mechanical separator.

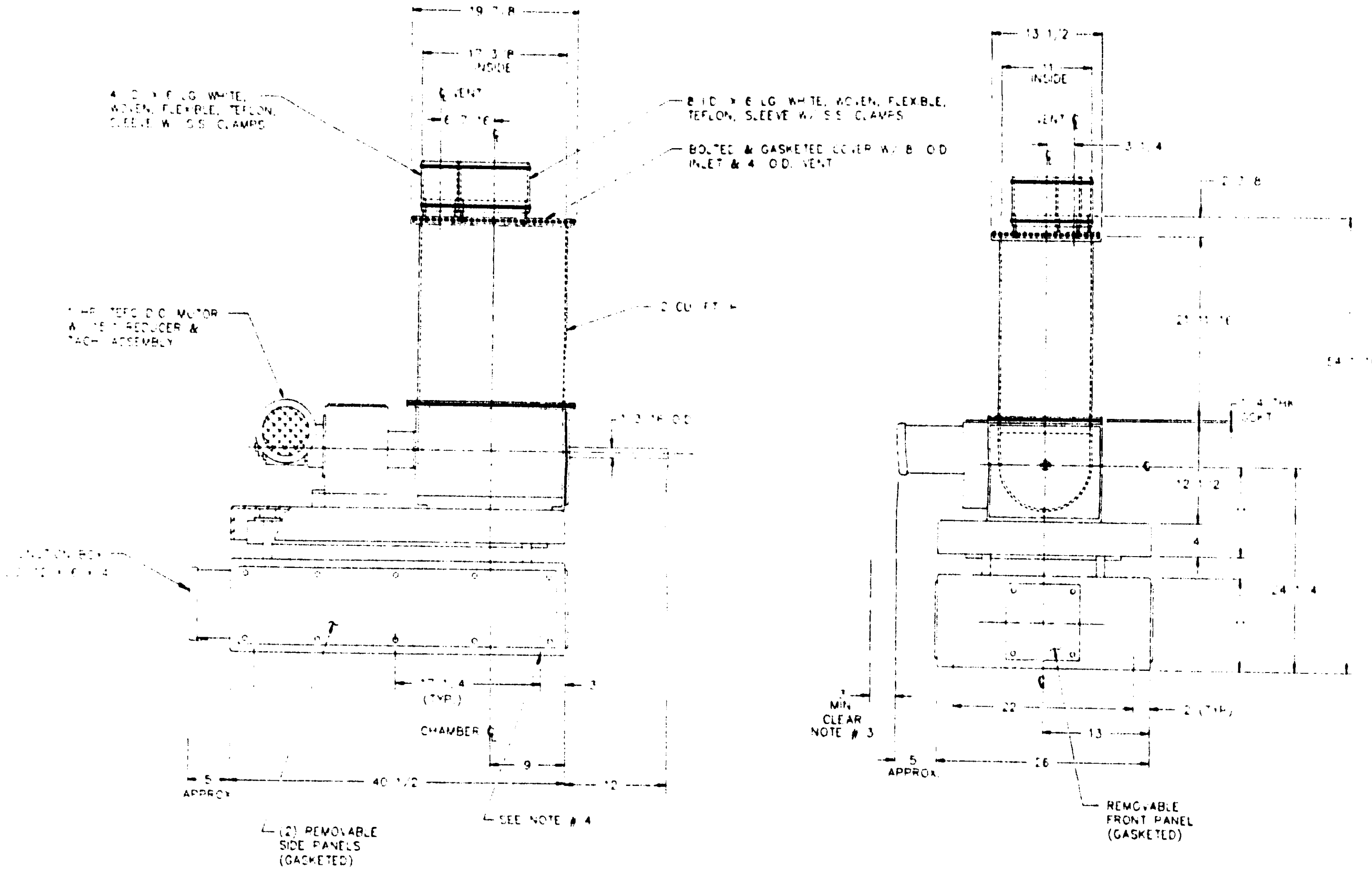

Figure 4. Schematic of microprocessor-controlled coal feeder.

air/fuel ratio and furnace exit gas temperature. Because of the sensitivity of the weight mechanism, the feeder has a small hopper (two cubic foot volume) and requires an additional hopper for coal storage. The microprocessor controls a pneumatic valve that will be opened to fill the feed hopper when the fuel level is below a given set point. The additional hopper will be constructed prior to shakedown next quarter.

4.1.2 Combustion Characterization

To aid in the characterization of the flame and the combustion environment, an adjustable secondary air swirl burner was installed, a high velocity thermocouple was constructed, and a baseline heat flux probe was also constructed. During flame stability testing, the swirl burner (shown in Figure 5) will be adjusted to determine the level of swirl required to achieve the proper backmixing of secondary air. Flame characterization will be performed during the first 3 to 5 hours of each combustion test. Visual observation of the flame will evaluate flame standoff as a function of swirl setting. Combustor sight ports were modified to give a better view of the burner cone and flame, and photographs (standard 35 mm and 35 mm infrared) will be used to record the results at each condition. In addition, a high-velocity thermocouple (HVT) and a baseline heat flux probe will be used to evaluate the furnace temperature profile and heat flux to the furnace wall, respectively.

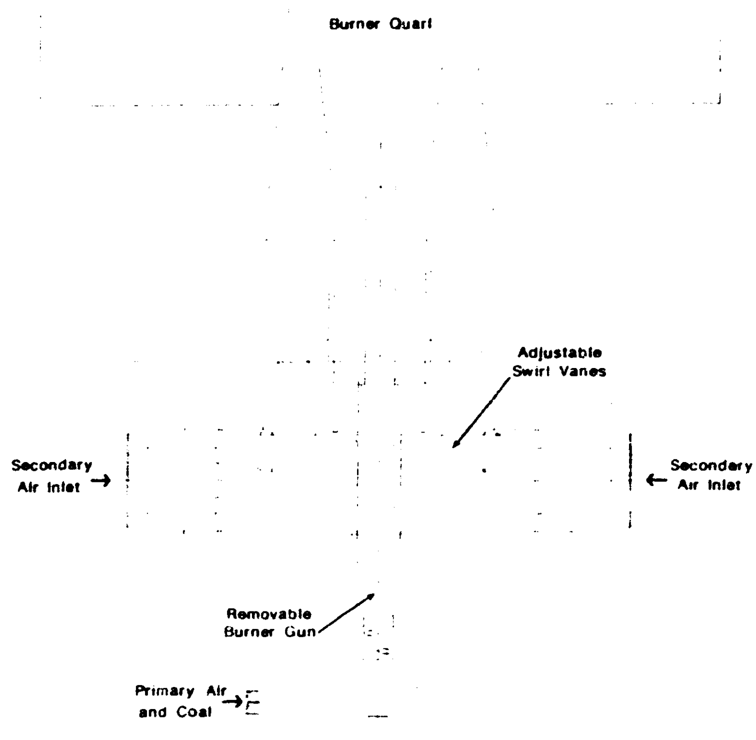

Figure 5. IFRF adjustable swirl burner.

A high-temperature extraction probe, designed by Northwest Research, Inc. in conjunction with EERC, is under construction and may be available for use during this test program. The extraction probe uses nitrogen to quench ash intermediates as they are collected and will be used to characterize carbon burnout as a function of residence time and swirl setting.

4.1.3 Fly Ash Characterization

Changes made to the combustion furnace's particulate collection and control systems were accomplished to increase fly ash characterization capabilities. The newly installed tubular ESP, which can be operated under cold-side (350°F) or hot-side (750°F) conditions, adds a degree of flexibility previously unavailable for particulate control testing. The rearrangement of heat exchange equipment allows the flue gas to bypass a pair of heat exchangers to achieve the higher gas temperature. The ESP has electric heaters to maintain gas temperature and will be operated at a flue gas velocity of 50 ft/sec. Excess flue gas (if any) will be bypassed through one of the cyclones. This arrangement should also give EERC the capability of testing ESP collection efficiency as a function of rapping frequency and/or flue gas conditioning at a constant SCA (standard collection area). The ESP is instrumented to monitor current through the collected ash layer to aid in determining the optimum rapping frequency.

Two cyclones were also added to the particulate control section of the furnace: a bypass cyclone and a sampling cyclone. The bypass cyclone will be used during heatup to prevent moisture from accumulating in the sampling cyclone or the ESP. The sampling cyclone will be used to collect a high-volume sample for resistivity testing and other analyses (SEMPC, XRF, XRD, ESCA, etc.). During sample collection, the sampling cyclone will be operated at a pressure drop of 4 inches of water column to achieve a cut size of 2.5 microns. Each cyclone will also be calibrated to measure flue gas flow rate as a function of pressure drop.

4.2 Task B. Shakedown and Baseline Testing

Shakedown testing of the ash fouling combustion system will begin immediately following the completion of all construction and modification activities. The initial shakedown schedule consists of four combustion tests to evaluate the effectiveness of the coal feeder, swirl burner, data aquisition system, sampling cyclone, and tubular ESP. Each test will include one standard 5.25-hour ash fouling test. Ash deposit samples will be collected for strength tests using EERC's drop impactor. A readily available coal will be used for the comparison of results between tests.

The first test will evaluate the operation of the coal feeder and the data aquisition and control system. The furnace slag probes will be maintained between 500° and 800°F by computer-controlled valves, and heat flux through the probes will be computed using the inlet and outlet water temperatures in conjunction with electronic flow meters. The temperature of the flue gas entering the ESP will also be monitored ' establish the need for additional heat exchange equipment to achieve desired operational parameters. The combustion system will also be checked for any piping leaks during the first test. The newly constructed HVT will also be tested. The natural gas heatup will be monitored to determine natural gas and air flows in an attempt to characterize combustor preheating during a standard 8-hour preheat cycle. The standard burner gun will be used to fire the pulverized coal at a rate sufficient to achieve a furnace exit gas temperature (FEGT) of 2,200°F. Combustion air will be maintained at about 21.5% excess air, and a deposit will be collected on the air-cooled convective pass deposition probes for strength evaluation.

Objectives for the second shakedown test are to evaluate the effectiveness of the sampling cyclone in obtaining a high-volume sample for fly ash characterization and to establish a baseline combustion test as a reference for future testing. The cyclone will be calibrated for air flow as a function of pressure drop and will be operated at 4 inches of water column during sampling. Three EPA method 5 (dust loading) tests will be run at the cyclone inlet and outlet to determine collection efficiency.

Based on results from the initial shakedown test, the combustor preheat cycle will be altered to achieve an appropriate air/fuel ratio (approximately 10%-15% excess air). Using this information, the firing rate may be increased to shorten the combustor preheat cycle. Prior to testing, a 2-inch refractory liner will be installed to reduce heat transfer through the combustor walls in preparation for future testing on the unit. The FEGT will be maintained at 2,000°F with 21.5% excess air. A standard 5.25-hour combustion test will be run to collect a deposit for strength evaluation, and results will be compared to those obtained in the first shakedown test to determine the effect of FEGT on deposit strength. Photographs of the combustion test furnace and the auxiliary systems will be taken to highlight modifications. Photographs of the flame will also be taken in preparation for the third shakedown test in which flame stability will be monitored as a function of swirl number.

The third shakedown test will use the adjustable swirl burner during the natural gas preheat cycle and combustion testing. The heating rate of the combustor will be compared to that obtained with the standard burner used in the second shakedown test. After the switch to coal, flame stability will be monitored as a function of swirl during the first 3 to 5 hours. Flame standoff will be monitored by visual observation and photography of the flame under varying swirl conditions, while combustion conditions will be monitored by the HVT, the slag probes, and the flue gas analyzers. Upon completion of flame stability testing, a standard 5.25-hour combustion test will be run at a FEGT of 2,000°F and an excess air level of 21.5%. A deposit will be collected on the air-cooled convective pass probes to determine the effect of using the swirl burner on deposition rate. Because the swirl burner uses only primary and secondary air, the potential exists for more ash to be carried out of the furnace proper into the probe bank duct, increasing the rate of deposition on the air-cooled probes. A multicyclone sample will also be obtained at the sampling cyclone inlet and compared to the sample obtained in the cyclone. Results will determine the effectiveness of the cyclone in obtaining a representative fly ash sample for characterization studies.

A fourth shakedown test will be run to determine the effectiveness of the tubular ESP for the collection of gas-borne particulate. Dust loading samples will be taken at the inlet and outlet of the ESP, and a standard procedure will be set for testing on the unit. ESP testing may require more than one shakedown to establish the optimum operational voltage and rapping frequency. The FEGT will be maintained at 2,000°F, and the excess air level will be maintained near 21.5%. Again, deposit samples will be obtained for strength evaluation, and the baseline heat flux probe will be used to monitor combustion conditions.

Baseline testing of a Great Plains lignite will begin when system shakedown is complete.

4.3 Task C. Characterization of a Lignite and Petroleum Coke Blend

A commitment has been made by Manalta Coal, Ltd. to participate in a blending study using a Great Plains lignite and a petroleum coke blend. The actual work on the project was expected to start in June 1990. This scope of work for the program includes detailed analytical characterizations of the coal and coke, drop-tube furnace tests of a range of blends and operating conditions, and a 32-hour combustion test on the optimal blend to determine combustion characteristics.

4.4 Task D. Characterization of a Subbituminous and Petroleum Coke Blend

Final fuel selections for the upcoming year for Detroit Edison did not include petroleum coke. Therefore, Detroit Edison decided not to fund this task.

4.5 Task E. Characterization of a Low-Sulfur Subbituminous Coal and a High-Sulfur Bituminous Coal

Due to funding limitations, no work has been performed on this task.

5.0 SUMMARY AND CONCLUSIONS

Modifications to the ash fouling combustor at EERC were nearly completed during the third quarter. Equipment shakedown was scheduled to be completed by March 1990; however, shakedown testing has been rescheduled to begin during the second or third week in May. Acquisition of equipment and supplies, questions regarding the compatibility of the swirl burner, and manpower availability were the factors that contributed most to the delays encountered. A schedule for shakedown testing has been completed and will include at least four combustion tests. Each test will contain a standard 5.25-hour combustion test using air-cooled probes to collect a convective pass deposit sample for strength evaluation. The operating conditions during combustor preheat will be varied to determine the optimum level of preheating required prior to the switch to coal. Furnace exit gas temperature (FEGT) will be varied between 2,000° and 2,200°F to compare the strength of deposits formed as a function of temperature. The first test will consist of system monitoring functions and will evaluate the operability of the newly installed equipment. The second test will evaluate the effectiveness of the sampling cyclone in obtaining a representative high-volume sample. The third test will evaluate the use of an adjustable swirl burner for flame stability testing, while the effect of using the swirl burner on the deposition rate observed for the same coal on the convective pass fouling probes will be monitored. Operation of the tubular ESP for fly ash collection testing will be evaluated in the final shakedown test(s).

Baseline testing will begin when shakedown is completed.

6.0 NEXT QUARTER ACTIVITIES

Combustor modifications and shakedown testing are scheduled to be completed next quarter.