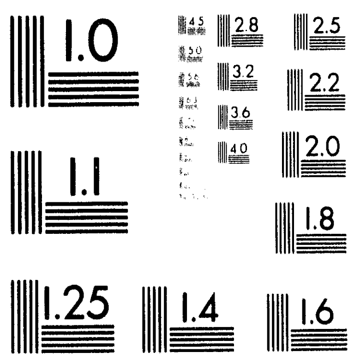
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COAL-WATER SLURRY FUEL COMBUSTION TESTING IN AN OIL-FIRED INDUSTRIAL BOILER

Semiannual Technical Progress Report
for the Period 02/15/1993 to 08/15/1993

By

Bruce G. Miller, Co-Principal Investigator
Joel L. Morrison, Research Assistant
Roger L. Poe, Research Assistant
Alan W. Scaroni, Project Manager

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For
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Pittsburgh Energy Technology Center
Pittsburgh, Pennsylvania

By
Energy and Fuels Research Center
The Pennsylvania State University
University Park, Pennsylvania

DISCLAIMER

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EXECUTIVE SUMMARY

The Pennsylvania State University is conducting a coal-water slurry fuel (CWSF) program for the United States Department of Energy (DOE) and the Commonwealth of Pennsylvania with the objective of determining the viability of firing CWSF in an industrial boiler designed for heavy fuel oil. Penn State and DOE have entered into a cooperative agreement with the purpose of determining if CWSF prepared from a cleaned coal (containing approximately 3.5 wt.% ash and 0.9 wt.% sulfur) can be effectively burned in a heavy fuel oil-designed industrial boiler without adverse impact on boiler rating, maintainability, reliability, and availability. The project will also generate information to help in the design of new systems specifically configured to fire these clean coal-based fuels.

The project consists of four phases: (1) design, permitting, and test planning, (2) construction and start up, (3) demonstration and evaluation (1,000-hour demonstration), and (4) expanded demonstration and evaluation (installing a CWSF preparation circuit, conducting an additional 1,000 hours of testing, and installing an advanced flue gas treatment system). The boiler testing and evaluation will determine if the CWSF combustion characteristics, heat release rate, fouling and slagging behavior, corrosion and erosion tendencies, and fuel transport, storage, and handling characteristics can be accommodated in a boiler system designed to fire heavy fuel oil. In addition, the proof-of-concept demonstration will generate data to determine how the properties of CWSF and its parent coal affect boiler performance. The economic factors associated with retrofitting boilers are also being evaluated. The CWSF demonstration program is being conducted on the 15,000 lb steam/h demonstration boiler located at Penn State.

The approach being used in the program is as follows:

1. Install a natural gas/fuel oil-designed package boiler and generate baseline data firing natural gas.
2. Shake down the system with CWSF and begin the first 1,000 hours of testing using the burner/atomizer system provided with the boiler. The first 1,000-hour demonstration was to consist of boiler optimization testing and combustion performance evaluation using CWSF preheat, a range of atomizing air pressures (up to 200 psig as compared to the 100 psig boiler manufacturer design pressure), and steam as the atomizing medium.
3. If the combustion performance was not acceptable based on the combustion efficiency obtained and the level of gas support necessary to maintain flame stabilization, then low-cost modifications were to be implemented, such as installing a quarl and testing alternative atomizers.
4. If acceptable combustion performance was not obtained with the low-cost modifications, then the first demonstration was to be terminated and the burner system replaced with one of proven CWSF design.

5. In addition to the advanced burner system, a superheater tube and advanced flue gas cleanup system were to be installed for the second 1,000-hour demonstration.

The first three steps (*i.e.*, the first demonstration) have been completed and the combustion performance of the burner that was provided with the boiler has been determined to be unacceptable. Consequently, the first demonstration has been concluded at 500 hours. The second demonstration (Phase IV) will be conducted after a proven CWSF-designed burner has been installed on the boiler.

As part of the second demonstration, a CWSF preparation circuit is being constructed. During this reporting period, the construction of the fuel preparation facility that will contain the CWSF preparation circuit (as well as a dry, micronized coal circuit) was completed. The CWSF preparation circuit will be operational by January 1,1994.

Proposals from potential suppliers of the flue gas treatment systems were received and have been reviewed by Penn State and DOE. Penn State is working with DOE in conjunction with another program (Cooperative Agreement No. DE-FC22-92PC92162) in selecting the flue gas treatment system.

1.0 INTRODUCTION

The Pennsylvania State University is conducting a coal-water slurry fuel (CWSF) program for the United States Department of Energy (DOE) and the Commonwealth of Pennsylvania with the objective of determining the viability of firing CWSF in an industrial boiler designed for heavy fuel oil. Penn State and DOE have entered into a cooperative agreement with the purpose of determining if CWSF prepared from a cleaned coal (containing approximately 3.5 wt.% ash and 0.9 wt.% sulfur) can be effectively burned in a heavy fuel oil-designed industrial boiler without adverse impact on boiler rating, maintainability, reliability, and availability. The project will also provide information to help in the design of new systems specifically configured to fire these clean coal-based fuels. The project consists of four phases: (1) design, permitting, and test planning, (2) construction and start up, (3) demonstration and evaluation (1,000-hour demonstration), and (4) expanded demonstration and evaluation (additional 1,000 hours of testing). The boiler testing and evaluation will determine if the CWSF combustion characteristics, heat release rate, fouling and slagging behavior, corrosion and erosion tendencies, and fuel transport, storage, and handling characteristics can be accommodated in a boiler system designed to fire heavy fuel oil. In addition, the proof-of-concept demonstration will generate data to determine how the properties of CWSF and its parent coal affect boiler performance. The economic factors associated with retrofitting boilers will also be evaluated.

The project consists of four phases as previously mentioned. Following is an outline of the project tasks that comprise the four phases:

Phase I: Design, Permitting, and Test Planning

- Task 1. Design
- Task 2. Permitting
- Task 3. Test Planning

Phase II: Construction and Start Up

- Task 1. Host Site Readiness/Boiler Retrofit
- Task 2. CWSF Preparation
- Task 3. Boiler Performance Prediction
- Task 4. Shakedown Testing

Phase III: Demonstration and Evaluation

- Task 1. Test Burn
  - Subtask 1.a. CWSF combustion performance
  - Subtask 1.b. Slagging/fouling propensity; corrosion characteristics
  - Subtask 1.c. Erosion characteristics
  - Subtask 1.d. Fuel transport, storage, and handling characteristics
- Task 2. Evaluation of Retrofit Economics

Task 3. Project Report

Phase IV: Advanced System Tests

Task 1. Procure and Install Burner and Superheater

Task 2. Construction of a CWSF Preparation Facility

Task 3. Installation of an Advanced Flue Gas Treatment System

Task 4. 1,000-Hour Test

Task 5. Final Report

Penn State began a coal-water slurry fuel (CWSF) research and development program in 1984 with the ultimate goal of facilitating the replacement of petroleum-based fuels with coal-based fuels in fuel oil-fired (designed) boilers. The Pennsylvania legislature appropriated funds in 1984 for the construction of a demonstration CWSF boiler with a capacity of approximately 15,000 lb steam/h on the main campus of Penn State at University Park. The project goal was to conduct a demonstration of the use of CWSF derived from Pennsylvania coal. The boiler performance was required to be environmentally acceptable and the testing was to evaluate the effects of long-term firing with CWSF on boiler performance. From a commercialization viewpoint, it was considered necessary to demonstrate at the industrial scale the technical feasibility of retrofitting existing fuel oil-fired units to burn CWSF, particularly in the commercial and light-industrial sectors. State funding was also provided for the installation of a 1,000 lb steam/h (nominally rated) Cleaver-Brooks A-frame watertube boiler (Kinneman et al, 1988) to investigate: the effect of boiler operating parameters on combustion performance (Miller et al, 1988); automation of the firing of CWSF, particularly with respect to start up and shutdown procedures but also for optimizing boiler performance (Wincek et al, 1989); testing candidate CWSFs (Miller et al, 1991); and providing the necessary research support and operator training prior to start up of the demonstration unit. The CWSF demonstration program is being conducted on the 15,000 lb steam/h demonstration boiler.

The approach used in the program was as follows:

1. Install a natural gas/fuel oil-designed package boiler and generate baseline data firing natural gas.
2. Shake down the system with CWSF and begin the first 1,000 hours of testing using the burner/atomizer system provided with the boiler. The first 1,000-hour demonstration was to consist of boiler optimization testing and combustion performance evaluation using CWSF preheat, a range of atomizing air pressures (up to 200 psig as compared to the 100 psig boiler manufacturer design pressure), and using steam as the atomizing medium.
3. If the combustion performance was not acceptable based on the combustion efficiency obtained and the level of gas support necessary to maintain flame stabilization, then

low-cost modifications were to be implemented, such as installing a quarl and testing alternative atomizers.

4. If acceptable combustion performance was not obtained with the low-cost modifications, then the first demonstration was to be terminated and the burner system replaced with one of proven CWSF design.
5. In addition to the advanced burner system, a superheater tube and advanced flue gas cleanup system were to be installed for the second 1,000-hour demonstration.

The first three steps (*i.e.*, the first demonstration) have been completed and the combustion performance of the burner that was provided with the boiler has been determined to be unacceptable. Consequently, the first demonstration (Phases I-III) has been concluded at 500 hours and the results have been presented elsewhere (Miller, et al 1993). The second demonstration (Phase IV) will be conducted after a proven CWSF-designed burner is installed on the boiler.

A summary of Phases I, II, and III is presented in Sections 2.0, 3.0, and 4.0, respectively. Detailed results from Phases I-III are contained in a project report previously submitted to DOE (Miller, et al, 1993). Section 5.0 summarizes the miscellaneous activities that were conducted. Activities planned for the next semiannual period are given in Section 6.0. References are contained in Section 7.0 and acknowledgments are given in Section 8.0. The milestone schedule is shown in Figures 1-6 and Table 1 contains the milestone description.

2.0 PHASE I RESULTS: DESIGN, PERMITTING, AND TEST PLANNING

The purpose of Phase I was to design the modifications for the boiler/system conversion, obtain the necessary permits, and prepare a test plan.

Design

The system is unique in that an existing fuel oil-fired boiler was not retrofitted to fire CWSF, rather, an oil-designed boiler was installed at Penn State's East Campus Steam Plant (ECSP). Excess capacity for auxiliary services existed at the plant, except that the building had to be extended to provide the space necessary to accommodate the boiler.

The majority of the facility design was performed by CDA International, Inc., the engineering firm assigned to monitor the construction of the state-funded facility. A portion of the design, such as the CWSF storage and handling facilities and specifying the manual/automatic control logic, was performed by Penn State.

Permitting

Permits for the project were required from the Commonwealth of Pennsylvania-Department of Environmental Resources-Bureau of Air Quality Control (DER). CDA International, Inc. applied for the initial permit, which granted approval for construction and served as a temporary

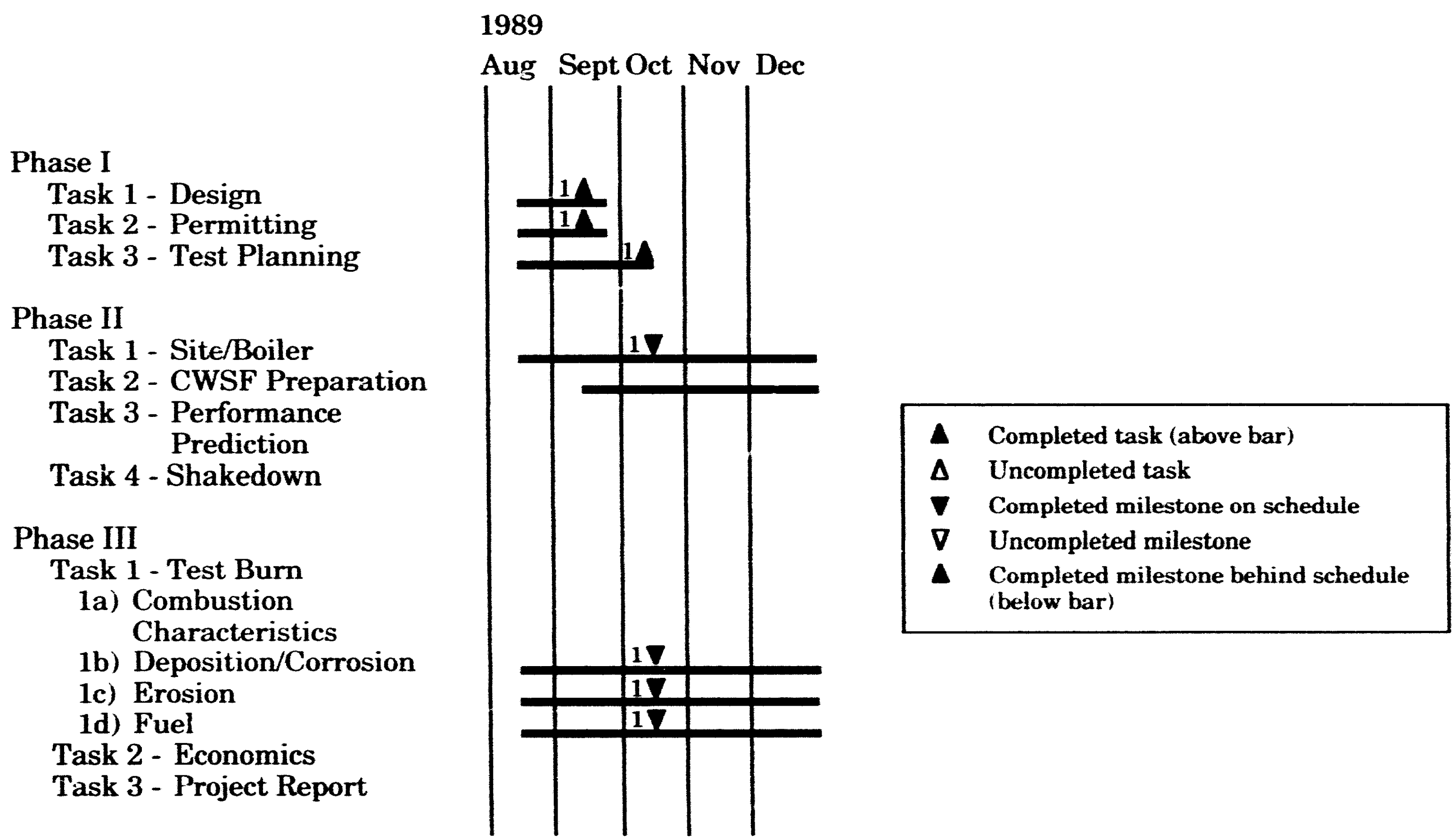

Figure 1. 1989 Milestone Schedule (First Demonstration)

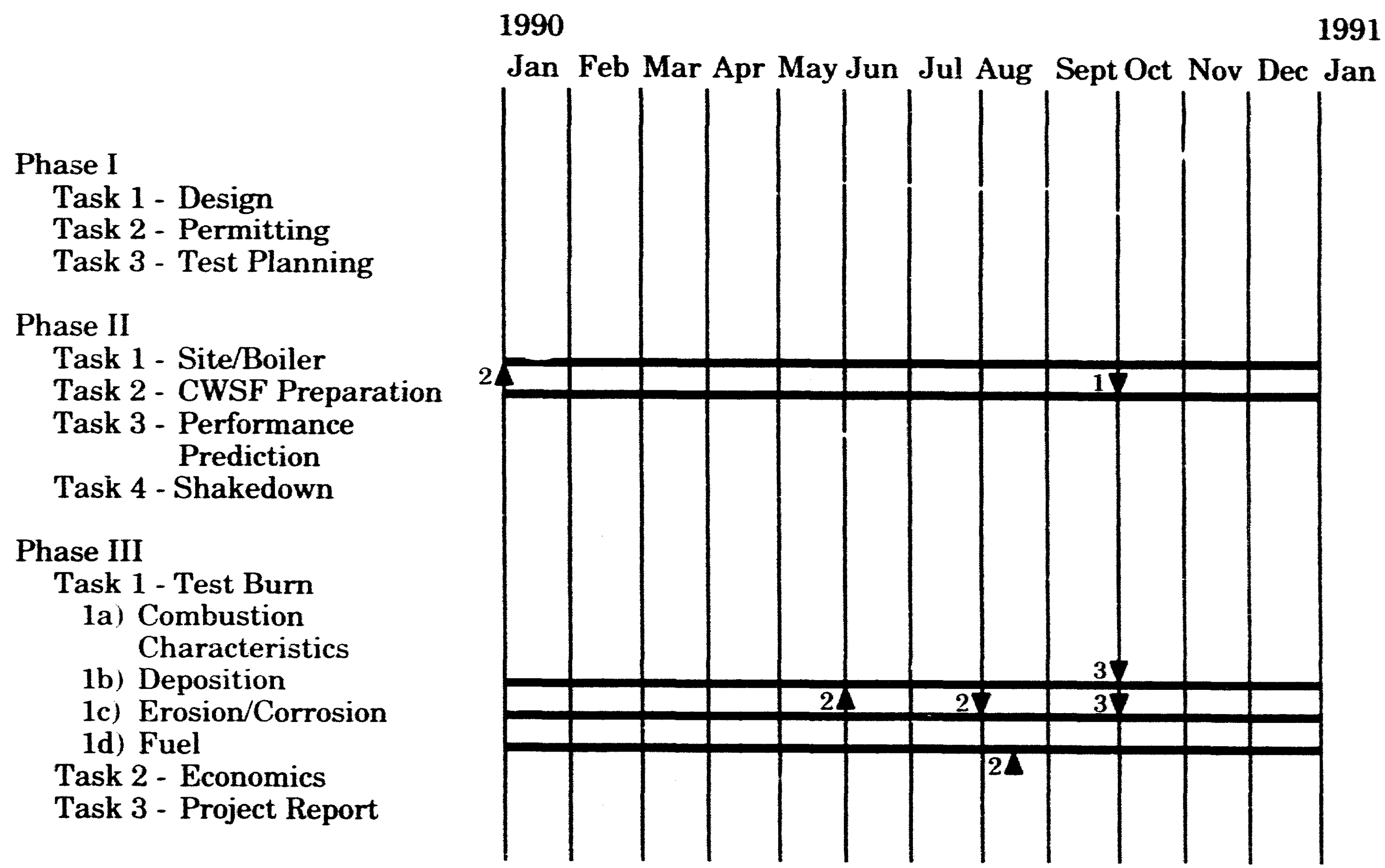

Figure 2. 1989 Milestone Schedule (First Demonstration)

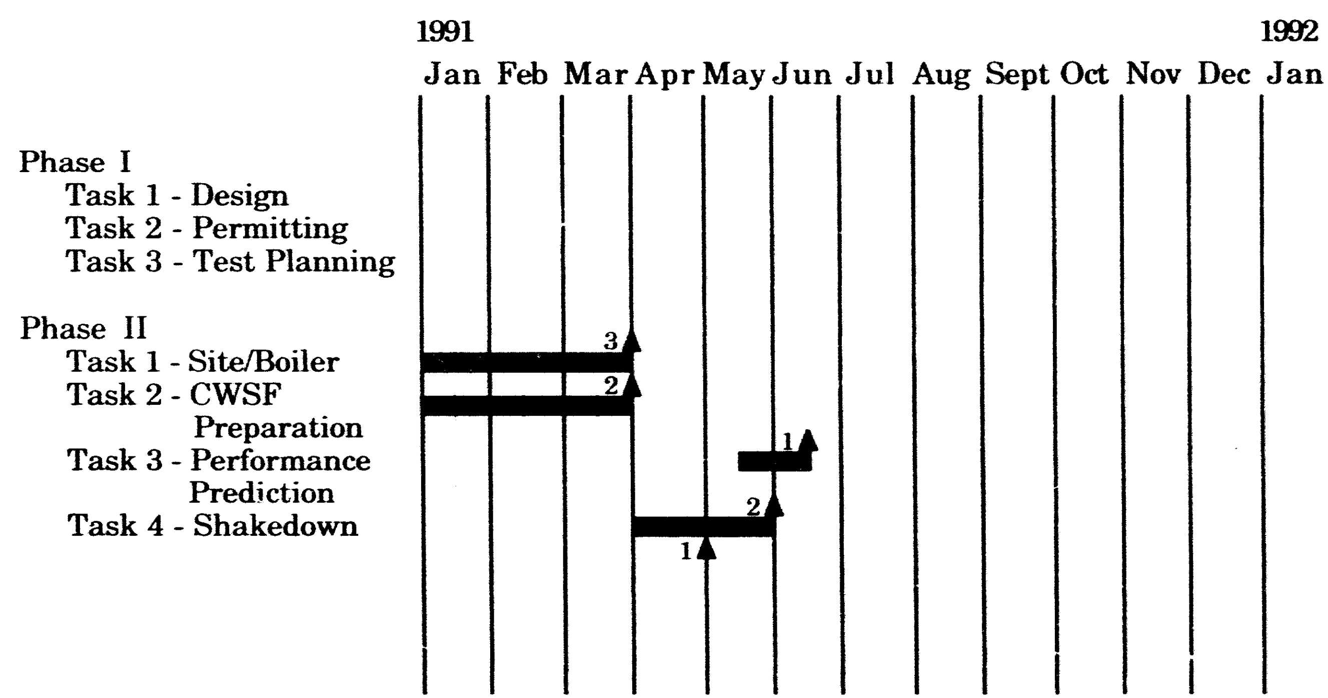

Figure 3. Phase I and II 1991 Milestone Schedule (First Demonstration)

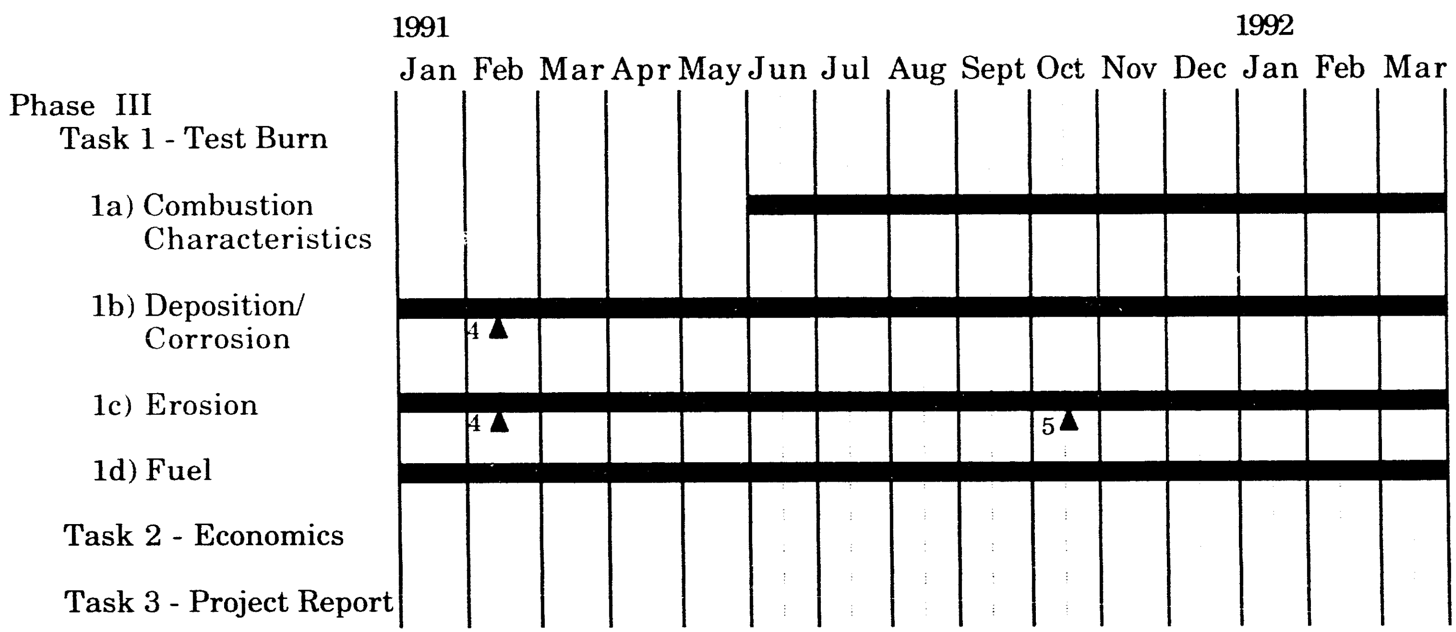

Figure 4. Phase III 1991 and 1992 Milestone Schedule (First Demonstration)

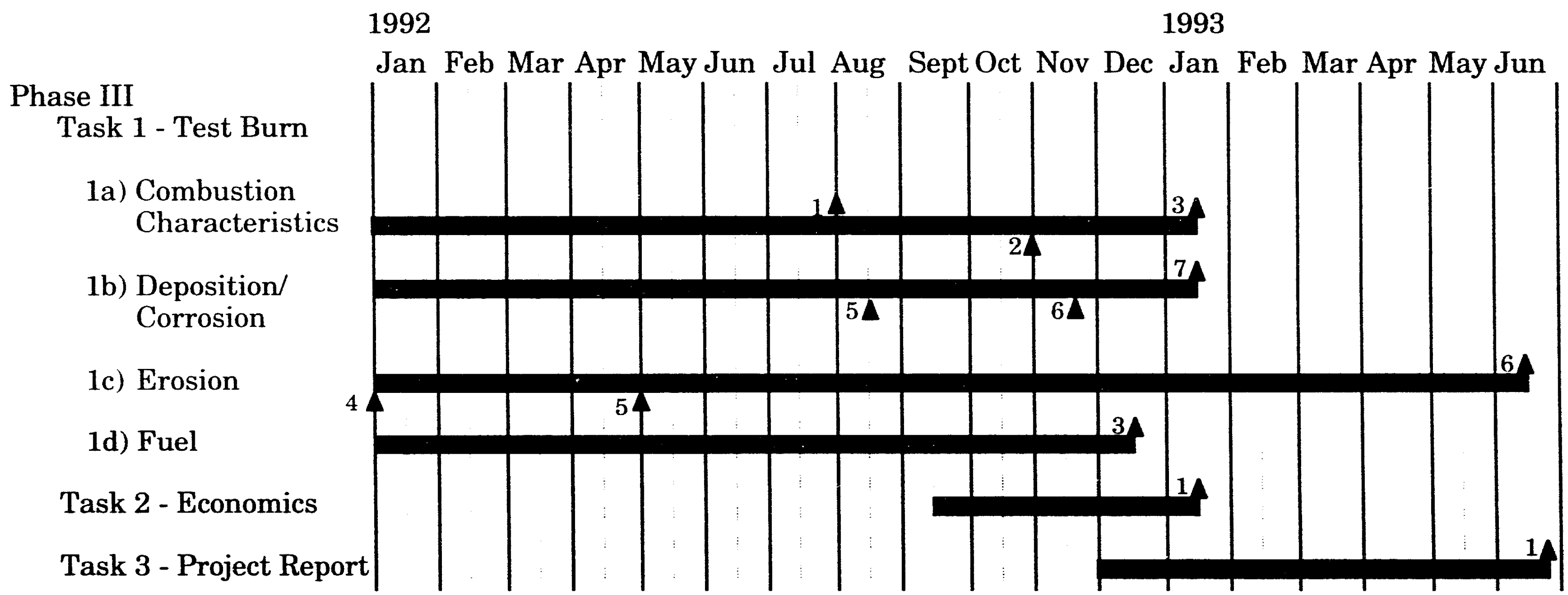

Figure 5. Phase III 1992 and 1993 Milestone Schedule (First Demonstration)

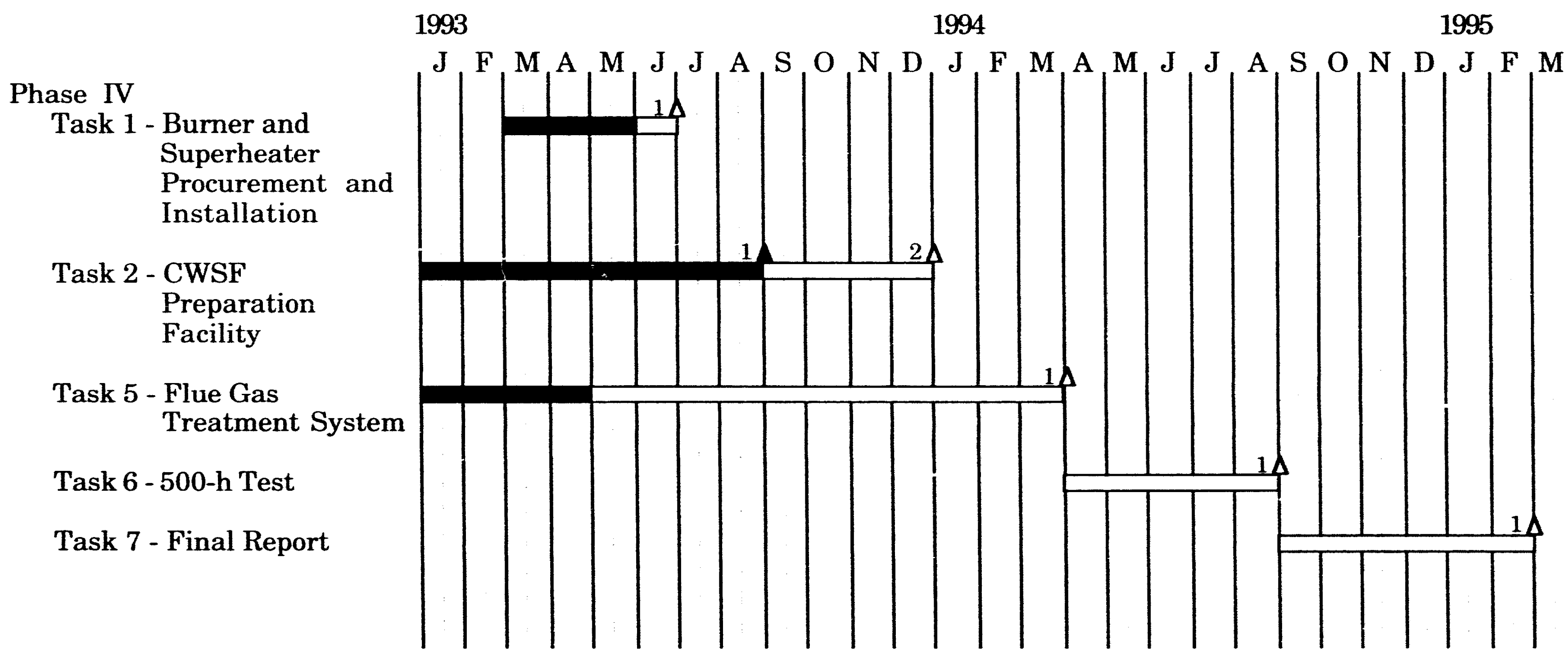

Figure 6. Phase IV Milestone Schedule (Second Demonstration)

Table 1. Milestone Description

Actual Milestone Completion Date	Description	Planned Completion Date	
Phase I			
Task 1, No. 1	Identify equipment and diagnostic instrumentation	09/15/89	09/15/89
Task 2, No. 1	Review present permit	09/15/89	09/15/89
Task 3, No. 1	Develop CWSF specifications, identify operating procedures, prepare detailed test plan	10/15/89	02/15/93
Phase II			
Task 1, No. 1	Building/boiler construction and installation let for bids	10/18/89	10/18/89
Task 1, No. 2	Building/boiler construction and installation awarded	12/31/89	03/23/90
Task 1, No. 3	Prepare site, install boiler and auxiliary equipment	04/01/91	01/31/92
Task 2, No. 1	Identify coal for CWSF preparation	09/30/90	09/30/90
Task 2, No. 2	Prepare CWSF for demonstration	04/01/91	10/13/92
Task 3, No. 1	Predict boiler performance	06/15/91	02/01/92
Task 4, No. 1	Shakedown boiler and auxiliary equipment	04/31/91	06/30/92
Task 4, No. 2	Generate baseline data on gas	05/31/91	09/30/91
Phase III			
Task 1, No. 1	Perform demonstration		
Subtask 1a, No. 1	300-hour demonstration milestone	07/31/92	07/31/92
Subtask 1a, No. 2	500-hour demonstration milestone	10/31/92	11/13/92
Subtask 1a, No. 3	Redefine CWSF specifications	01/15/93	01/15/93
Subtask 1b, No. 1	Develop deposition and corrosion test plan	10/15/89	10/15/89
Subtask 1b, No. 2	Design suction pyrometer	06/01/90	08/01/90
Subtask 1b, No. 3	Construct suction pyrometer	10/01/90	10/01/90
Subtask 1b, No. 4	Deposition characterization equipment design and specification	01/01/91	02/15/91
Subtask 1b, No. 5	Acquisition of baseline data for spectroscopic analysis of deposits; acquisition of baseline data for corrosion of tubes by ash components	08/31/91	08/15/92
Subtask 1b, No. 6	Coupon testing in boiler	10/31/92	11/13/92
Subtask 1b, No. 7	Complete deposition and corrosion testing	01/15/93	01/15/93
Subtask 1c, No. 1	Develop erosion test plan	10/15/89	10/15/89
Subtask 1c, No. 2	Complete research boiler erosion evaluation	08/01/90	08/01/90
Subtask 1c, No. 3	Full-scale erosion technique decision	10/01/90	10/01/90
Subtask 1c, No. 4	Design probe for full-scale erosion study	01/01/91	02/15/91
Subtask 1c, No. 5	Construct erosion probe	05/01/91	10/15/91
Subtask 1c, No. 6	Complete erosion modeling	01/15/93	06/15/93
Subtask 1d, No. 1	Identify viscometer	10/15/89	10/15/89
Subtask 1d, No. 2	Complete preliminary viscosity and stability tests	08/15/90	09/15/90
Subtask 1d, No. 3	Complete viscosity and stability tests	11/30/92	11/30/92
Task 2, No. 1	Complete economic evaluation	01/15/93	01/15/93
Task 3, No. 1	Complete project report	03/01/93	06/21/93
Phase IV			
Task 1, No. 1	Procure and install burner and superheater	07/01/93	
Task 2, No. 1	Complete construction of Fuel Preparation Facility	08/31/93	08/31/93
Task 2, No. 2	Install and shake down CWSF preparation circuit	12/31/93	
Task 3, No. 1	Install flue gas treatment system	03/31/94	
Task 4, No. 1	Complete 1,000-hr test	08/31/94	
Task 5, No. 1	Complete final report	03/01/95	

operating permit. Boiler performance and baghouse efficiency tests were performed, after which an operating permit was issued.

Test Planning

Test planning included developing CWSF specifications, identifying appropriate operating procedures, and preparing a detailed test plan.

Developing CWSF Specifications

Specifications for cleaned coals and CWSFs capable of being fired in boilers designed for fuel oil were developed. The specifications for the coals and the coal water slurry fuels formulated from them depend on an in-depth knowledge of how each critical property affects boiler performance and lifetime. The basic properties of interest were defined and certain values associated with them projected. The items considered of primary importance and their specifications are:

Ash content < 3.0 wt. % -- to minimize deposition and erosion in the convective pass
Sulfur content < 0.9 wt. % -- to meet SO_2 emissions of less than 1.2 lb/million Btu
Volatile matter content > 25-30 wt. % -- to facilitate ignition and achieve rapid combustion
Coal grind size -- 99.5% minus 74 μm -- to obtain high combustion intensity, facilitate complete burnout in the limited furnace residence time, and form small ash particles
Solids loading > 50 wt. % -- to minimize water injection
Heating value > 6,500 Btu/lb -- to maximize fuel heating value
Viscosity < 1,000 cp @ 77°F and 100/sec -- to facilitate handling (pumping)
Stability -- minimal settling and solids easily resuspended -- to minimize sedimentation

Identify Operating Procedures

Operating procedures were documented for: CWSF storage and handling; boiler operation including start-up, steady-state firing, and shutdown; water chemistry analysis; emissions monitoring; and sample collection and analysis. These summaries, along with the summary for operating the data acquisition system (under preparation), will be used to prepare a detailed operating manual. The manual will contain the operating procedures, drawings and specifications of the system components, and guidelines for troubleshooting and routine maintenance. The operating manual will be prepared prior to completion of the program (Phase IV).

Detailed Test Plan

A detailed test plan was prepared and submitted to DOE. Analytical techniques, test procedures, and sampling frequencies were identified.

3.0 PHASE II RESULTS: CONSTRUCTION AND START UP

Phase II included host site readiness/boiler retrofit, CWSF preparation, boiler predictions, boiler shakedown, and the generation of baseline data firing natural gas.

Host Site Readiness/Boiler Retrofit

Equipment that was installed includes: a 15,000 lb steam/h package D-type boiler; induced and forced draft fans; a flue gas-to-combustion air heat pipe heat exchanger; an auxiliary natural gas-fired in-duct combustion air preheater; a baghouse and an ash conditioning screw; a boiler feedwater pump; a CWSF unloading and pumping station, a 15,000-gallon CWSF storage tank, and a 2,000-gallon a CWSF day tank; a CWSF preheater; control panels, automatic and manual boiler control systems and instrumentation; and associated ductwork and piping. Details of the building construction, boiler modifications, and equipment descriptions and delivery schedule are discussed in Miller, et al (1993).

CWSF Preparation

The preparation of the CWSF for the demonstration program was achieved through a multi-level effort. First, coal sources were identified and the coal and CWSF preparation process were selected. This was followed by evaluating the atomization and combustion performance of the CWSF, which was prepared at Penn State (at the laboratory scale) using a formulation developed by Penn State. This lead to a full-scale CWSF production run and subsequent combustion test to evaluate the fuel. The preparation and combustion of the CWSF were successfully completed and, as a result, the process was used to prepare the CWSF for the demonstration.

The coal selected for the program was from the Brookville seam in Lawrence County, Pennsylvania and was mined by Perry Brothers Coal Company. The coal was cleaned at Reddinger Coal Company's coal cleaning plant located in Distant Pennsylvania. Approximately 518 tons of CWSF were prepared by Allis Mineral Systems, formerly the Kennedy Van Saun Corporation, located in Danville, Pennsylvania. The CWSF was transported to Penn State in transport tankers that were leased from Transport Technology of Berwick, Pennsylvania.

The original CWSF formulation was modified during the demonstration program in order to improve stability and minimize the formation of a hardpack (promote the formation of softpack which can be easily resuspended) of any material that did settle. Increased CWSF stability was accomplished by adjusting the coal particle size distribution through the production of more fines when grinding. Minimizing hardpack formation was done by increasing the pH of the slurry which allowed for less dispersant usage. Details of the CWSF preparation and reformulation are discussed in Miller, et al (1993).

Boiler Predictions

One aspect of the project was to predict the performance of the boiler firing CWSF. Burns & Roe Services Corporation has developed a computer model to predict the performance of utility boilers firing a range of fuels. Under direction from DOE, the model was modified to analyze the performance of Penn State's 15,000 lb steam/h industrial boiler. The model employs the basic laws of thermodynamics and simplified fluid dynamics, heat transfer, and combustion equations.

A description of the model and comparison between the model predictions and experimental data are presented in Miller, et al (1993).

Predicted and actual boiler exit gas temperatures and flue gas outlet temperatures from the heat pipe heat exchanger were compared when firing the boiler on natural gas and cofiring natural gas and CWSF. In general, the predicted values are lower than the measured data; however, the agreement is good given the uncertainties in some of the input variables (*i.e.*, flame and cold surface emissivities).

Boiler Shakedown

Construction of the facility was completed during the Spring of 1991, and this was followed by equipment shakedown and preliminary testing. The sequence of events was: the natural gas burner set-up and equipment shakedown firing natural gas were conducted during the Summer of 1991; baseline data firing natural gas were generated in September 1991; preliminary natural gas and CWSF cofiring data were generated in October 1991; further equipment shakedown and boiler performance testing were conducted in January 1992 firing CWSF; and boiler performance and stack (emissions) testing were conducted in January 1992 as partial requirement for the operating permit from DER. Several operational/mechanical problems were encountered during this period and a summary of these problems and their solutions is provided in Miller, et al (1993).

Generate Baseline Data Firing Natural Gas

Baseline data were obtained on two occasions firing natural gas. The first test was used to measure the performance of the combustion air/flue gas heat pipe heat exchanger while the second was used to verify the performance guarantee of the boiler.

On the first occasion, in September 1991, gas-fired performance data were collected for ABB Air Preheater Inc. (API) to evaluate the performance of their Q-Pipe® Air Preheater. API installed over 100 thermocouples on the heat pipes and collected continuous temperature readings using a computerized data acquisition system. The objective of the testing was twofold: to collect baseline gas-fired temperatures and gas velocities with clean heat pipes (prior to any CWSF, and hence ash, being introduced) to assist in future heat exchanger design and to determine heat pipe fouling factors when firing coal-based fuels in the boiler.

Testing was conducted in January 1992 by KirCon-Breco and Tampella Power Corporation as part of the boiler performance guarantee. The boiler met the performance guarantees firing natural gas. Performance items of primary concern that were met included: 10:1 turndown, 14,900 lb saturated steam/h at 250 psig, and steam quality >99.5%.

4.0 PHASE III RESULTS: DEMONSTRATION AND EVALUATION

The demonstration program is divided into five subtasks: CWSF combustion performance; deposition propensity; erosion characteristics; fuel transport, storage, and handling characteristics; and cost analysis.

CWSF Combustion Performance

The CWSF was burned in the fuel oil-designed boiler for about 500 hours to optimize combustion performance in the boiler, initially without any modifications and later following some minor, low cost modifications. The combustion performance was evaluated based on the percent thermal input of the natural gas support fuel, the total combustion efficiency, the coal combustion efficiency, and the boiler efficiency. Comprehensive discussions of the results have been presented elsewhere (Miller, et al, 1993) and a brief summary follows.

Coal combustion efficiency showed an increase over each month during the optimization testing from January to November 1992, increasing from 78 to 95%. Among the several variables evaluated, increasing the solids concentration in the CWSF and increasing the CWSF preheat temperature resulted in the greatest enhancement in the coal combustion efficiency. Air atomization was judged to be better than steam atomization in this study. Increasing the atomizing air pressure from 148 to 190 psig did not produce a significant increase in the coal combustion efficiency. Among the various nozzle spray angles studied (50, 65, 70, 75°), a spray angle of 65° produced the highest coal combustion efficiency when using the heavy oil atomizer provided with the boiler. An external mix atomizer was also tested but the internal mix nozzle's performance was superior. Minor modifications to the burner such as the addition of a refractory quarl and widening the burner throat to decrease the combustion air velocity also increased the coal combustion efficiency.

The study indicated that CWSF could not be burned in the fuel oil-designed package boiler, using the fuel oil burner provided with the boiler, without support from a natural gas flame. However, by optimizing the operating parameters, and making minor boiler modifications, the coal combustion efficiency was increased from 82 to 95%. The reason for not achieving coal combustion efficiencies higher than 95% is believed to be due to the inability of the existing burner to stage the combustion air to promote recirculation of the hot combustion products, thereby creating an optimum internal recirculation zone (IRZ). An IRZ enhances the convective heat transfer, which is the primary source of ignition energy, reduces the time required for evaporation of water in the droplets, and thereby reduces the ignition delay. The goal was to be able to achieve fuel firing rates of 100% CWSF, 100% natural gas, or any combination of the two. In order to achieve this goal with acceptable coal combustion efficiencies (>99%), the need for major modifications has been identified. Therefore, a new burner with air staging capabilities will be installed prior to the next 1,000-hour demonstration (Phase IV).

Deposition Propensity

A probe was constructed and inserted into the demonstration boiler in June 1992 to obtain long-term information on convective pass deposition. Details of the probe construction and the operating principle are presented in Miller, et al (1993).

The probe was inserted into the boiler for ~126 hours (June through August 1992) and there was no indication of the formation of any sintered ash deposits. The probe was removed prior to the testing in September because of a water leak in the cooling jacket and was not reinserted for the remainder of the program (testing ended in November 1992). A thin ash and carbon coating was collected on the probe as a result of the low combustion efficiency obtained during the testing, the low ash content of the CWSF, and the high ash fusion temperatures of the ash (initial deformation temperature >2,800°F).

Erosion Characteristics

Another aspect of the program was to determine the effect of the inorganic portion of the coal on convective pass erosion and, ultimately, determine the maximum flue gas velocity allowable in the convective section before erosion becomes a concern. Detailed results from the study are presented in Miller, et al (1993).

Erosion of carbon steel by fly ash and deposition of ash were studied in the convective section using a specially designed probe. Details of the probe and its operation are presented in Miller, et al (1993).

The effects of metal temperature, jet velocity (a jet of nitrogen, air, or oxygen is directed toward a test coupon and accelerates entrained fly ash toward the surface of a test specimen), and oxygen concentration on ash deposition and metal loss were investigated. The metal target temperature was varied from 350 to 710°F. The erosion rate increased with increasing metal temperature in the absence of oxygen, but in the presence of 21 and 100 vol% oxygen the erosion rate first increased then decreased as the metal temperature was increased from 350 to 530 to 710°F. These results suggest that the increase in ash deposition rate associated with the increase in oxygen concentration is the reason for the decline in importance of erosion at the highest temperature. A protective layer of particles better adheres to the surface as coverage of the surface by an oxide layer increases. This conclusion is supported by the observation that ash deposition also increased in importance as the oxygen concentration was increased at a fixed temperature, in all cases but one. Under the conditions investigated, changes in the target surface were smallest at the lowest temperature (350°F) and the intermediate oxygen concentration (air).

The competition between erosion by ash and deposition of ash was clear, as was the transition from one regime to the other as observed during variations in both jet velocity and metal temperature. Erosion of the tube material by the ash was the greatest for the high jet velocity, low metal temperature, and low oxygen concentration, while deposition of ash was greatest at low jet velocity, high metal temperature, and high oxygen concentration.

A model for the combined processes of metal oxidation, spalling, erosion, and deposition has been developed to establish the connection between the test results and heat exchange performance and is presented in Miller, et al (1993).

Fuel Transport, Storage, and Handling Characteristics

Fuel Transport

The CWSF was transported in unmodified, readily-available transport tankers. The tankers were leased 5,600 gallon, single cavity, insulated, rear discharge, stainless steel transport tankers. With each shipment, a small amount of sedimentation was observed in the tanker bottom after the CWSF was transferred to the storage tank. The sedimentation was rinsed into the storage tank.

Storage and Handling

The CWSF storage and handling system was originally designed such that a portable double-diaphragm pump and hoses were used to unload fuel from a tanker into the 15,000-gallon storage tank. The storage tank was hard piped to the 2,000-gallon day tank. After receiving several shipments of CWSF for shakedown testing during the Summer of 1991, it became apparent that the design was too manpower intensive and of limited versatility. Therefore, the CWSF unloading station was modified and now it contains the following attributes. The entire system is hard piped using 2.5" schedule 40 pipe, which is heat traced and insulated. A 3" double-diaphragm pump is mounted on a concrete pad with a header system that provides the following capabilities:

- unloading of CWSF from the transport tanker into the storage tank or directly into the day tank;
- pumping of CWSF from the storage tank into the day tank;
- pumping of CWSF from the storage tank into the transport tanker;
- purging of any line or the transport tanker with water;
- recirculation of the CWSF in the storage tank; and
- introduction of compressed air into the bottom of the storage tank to assist in breaking up any hardpack that might be formed.

A shelter was constructed over the pump and header system and electric heaters installed to protect them from the elements, primarily to guard against freezing.

Cost Analysis

A cost analysis was performed detailing costs for:

- retrofitting a natural-gas fired 15,000 lb steam/h boiler to fire CWSF at Penn State;
- two scenarios when retrofitting a fuel oil-fired 15,000 lb steam/h boiler to fire CWSF at Penn State.

- installing a facility at Penn State to produce 15,000 lb steam/h firing CWSF with research capabilities;
- installing a facility at Penn State to produce 15,000 lb steam/h firing CWSF (without research diagnostics);
- installing a facility at Penn State to produce 15,000 lb steam/h firing heavy fuel oil; and
- installing a facility at Penn State to produce 15,000 lb steam/h firing natural gas.

The costs that were considered include materials and labor, fees, and contingencies. They are actual expenditures and accurately reflect the costs necessary to either construct/install a new facility or retrofit an existing facility. A comprehensive discussion of the analysis is given in Miller, et al (1993).

Retrofit Cost Analysis

The existing demonstration facility was divided into ten sections for the retrofit analysis. These include: 1) CWSF storage tank, 2) unloading station, 3) day tank, 4) CWSF preheater, 5) burner pump, 6) combustion air preheater/ducting modifications, 7) baghouse, 8) fans, 9) ash hopper, and 10) burner. The first eight items exist at the site while the last two are in the process of being installed. Costs were determined for retrofitting a natural gas-fired boiler and a fuel oil-fired boiler with and without an oil preheater which could be used to preheat the CWSF. Using several cost sources (actual costs incurred by Penn State, estimates from CDA International, Inc., and established engineering estimates) the costs for the ten retrofit areas were determined (in 1992 dollars). The results are:

- \$763,330 to retrofit a natural-gas fired 15,000 lb steam/h boiler to fire CWSF at Penn State;
- \$679,760 to retrofit a fuel oil-fired 15,000 lb steam/h boiler to fire CWSF at Penn State in which a CWSF preheater is installed; and
- \$669,650 to retrofit a fuel oil-fired 15,000 lb steam/h boiler to fire CWSF at Penn State which uses an existing fuel oil preheater.

Facility Installation Cost Analysis

Actual costs incurred by Penn State to install a boiler system to provide 15,000 lb steam/h firing CWSF with research diagnostics were determined. These costs were then compared to those for installing similar sized boilers for steam production when firing CWSF (no research capabilities), natural gas or fuel oil. The results are:

- \$1,905,260 to install a facility at Penn State to produce 15,000 lb steam/h firing CWSF with research capabilities;
- \$1,667,190 to install a facility at Penn State to produce 15,000 lb steam/h firing CWSF (without research diagnostics);

- $987,420 to install a facility at Penn State to produce 15,000 lb steam/h firing heavy fuel oil; and
- $903,860 to install a facility at Penn State to produce 15,000 lb steam/h firing natural gas.

5.0 ADVANCED SYSTEM TESTS

5.1 Task 1. Procurement and Installation of Burner and Superheater

No work was conducted in Task 1 this reporting period. The burner will be installed prior to the Phase IV test (Fall of 1994). The superheater will be installed in December 1993.

5.2 Task 2. Construction of CWSF Preparation Facility

The construction of the fuel preparation facility that will contain the CWSF preparation circuit and a dry, micronized coal (DMC) circuit was completed this reporting period. Figure 7 shows the overall site view with the location of the facility in relation to the demonstration boiler.

Figure 8 is a schematic diagram of the equipment in the fuel preparation facility. During this reporting period, the installation of the DMC circuit was completed and work continued on the installation of the CWSF circuit. The DMC circuit was installed first because of testing commitments under two other DOE programs (Subcontract No. DOE-ABB-TPSU-91160-0001 from ABB Combustion Engineering under prime contract No. DE-AC22-91PC91160 and Cooperative Agreement No. DE-FC22-92PC92162). The 25-ton coal hopper, magnet for removing tramp metal, cage mill, reddler elevator, 5-ton surge bin, and screw feeder, which are common to both circuits, have been installed and are undergoing shake down.

The installation of the CWSF circuit is being conducted in conjunction with another program (Cooperative Agreement No. DE-FC22-92PC92162). A plan view of the facility showing the CWSF equipment layout is given in Figure 9. In addition to the coal handling and crushing facilities, work that was completed this reporting period includes painting the ball mill and setting the Morehouse mill (commonly referred to as a sand mill) into place.

5.3 Task 3. Installation of an Advanced Flue Gas Treatment System

Work conducted on this task included reviewing proposals from potential suppliers of flue gas treatment systems with DOE. Penn State is working with DOE in conjunction with another program (Cooperative Agreement No. DE-FC22-92PC92162) in selecting the flue gas treatment system.

6.0 MISCELLANEOUS ACTIVITIES

Two papers were prepared and presented at the 18th International Conference on Coal Utilization and Fuel Systems that was held April 23-26, 1993 in Clearwater, Florida. They are:

- "Preparing and Handling Coal-Water Slurry Fuels: Potential Problems and Solutions" authored by Joel L. Morrison, Bruce G. Miller, Roger L. Poe, and Alan W. Scaroni; and

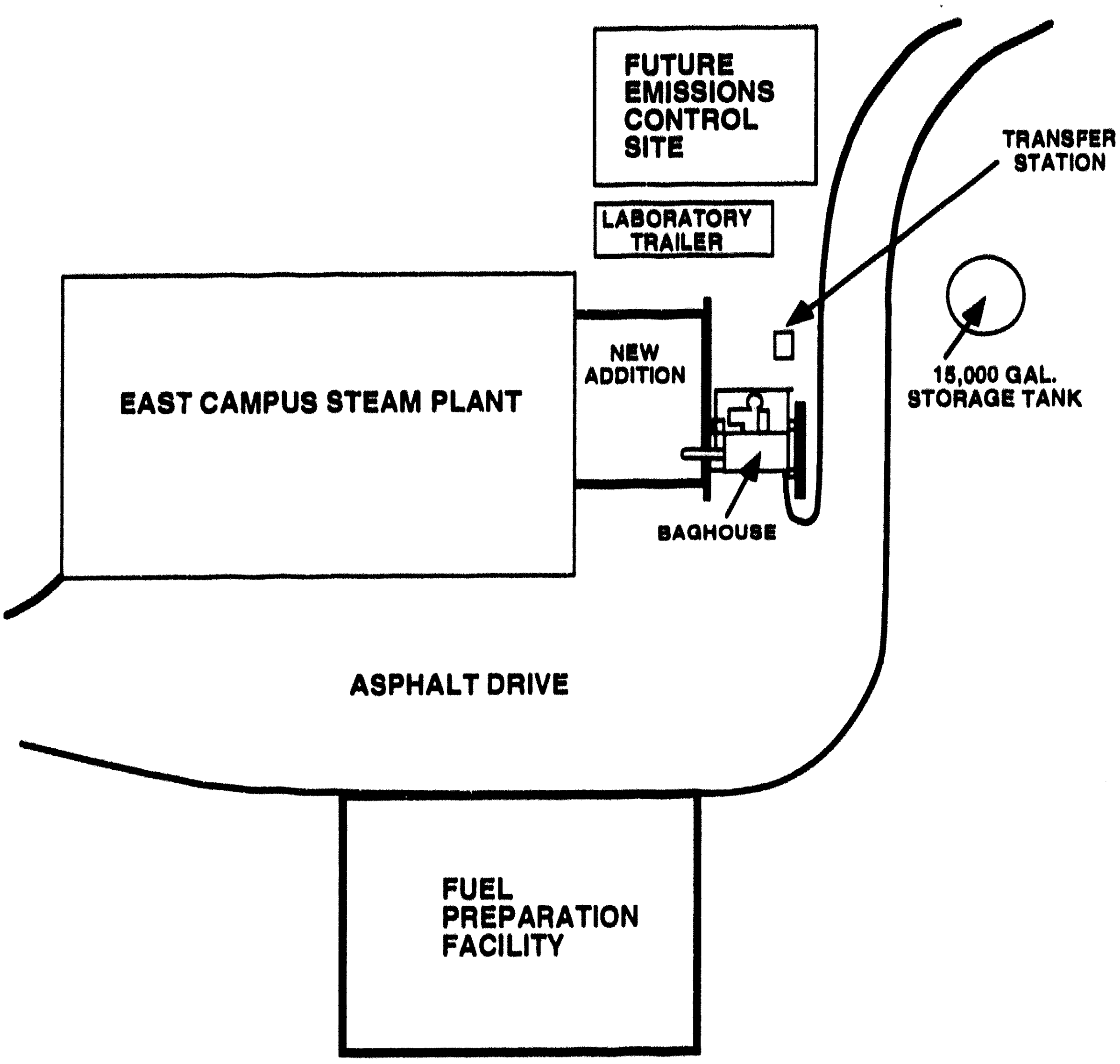

Figure 7. Overall Site View Showing the Location of the Fuel Preparation Facility and Future Emissions Control Site

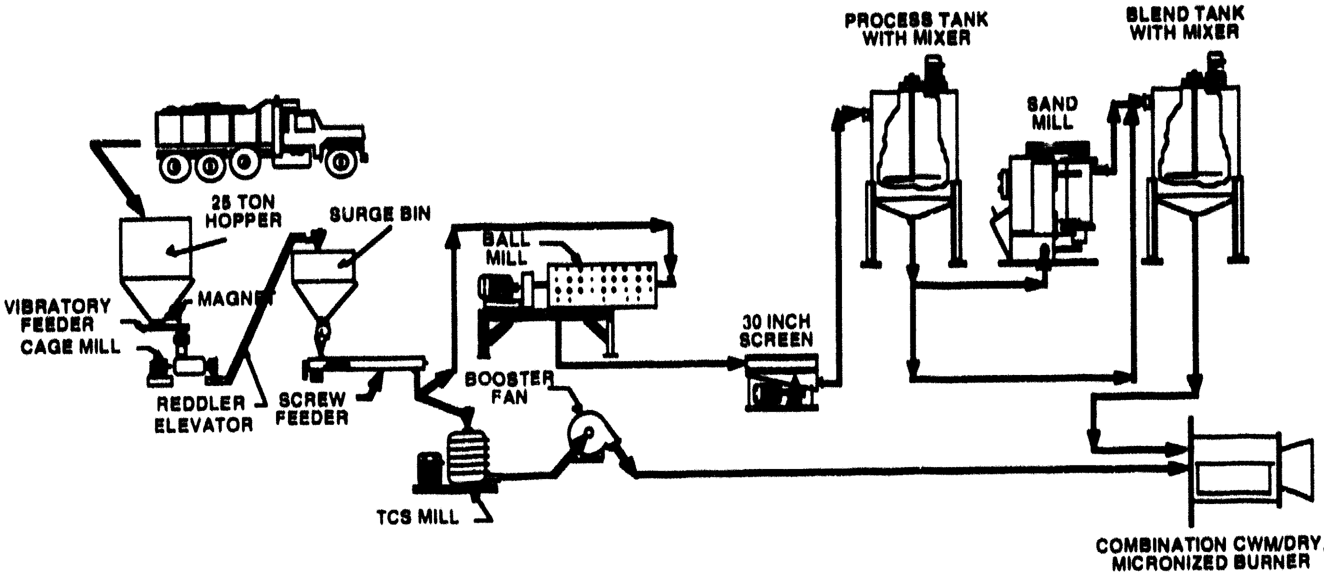

Figure 8. Schematic Diagram of the Equipment Train in the Fuel Preparation Facility

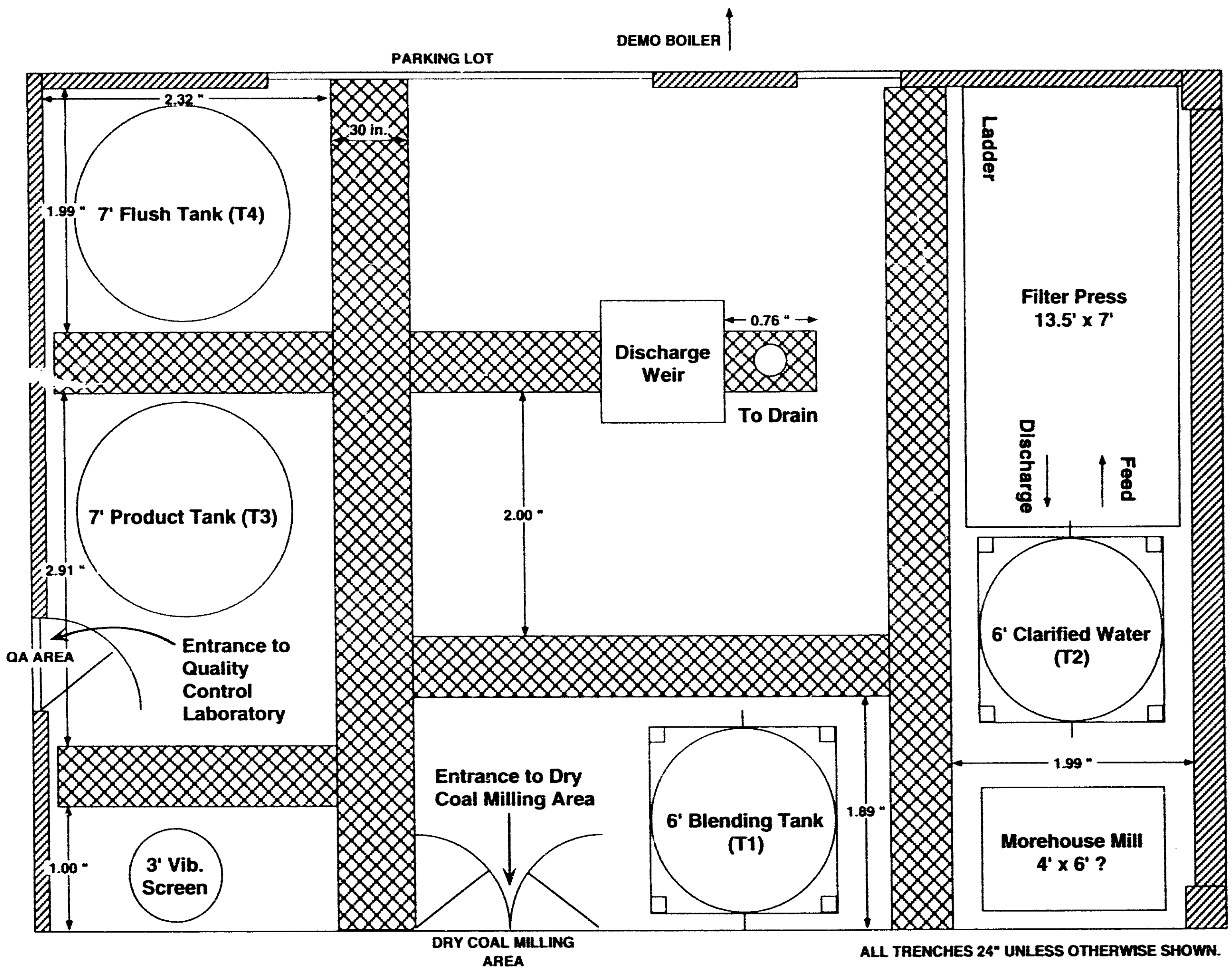

Figure 9. Plan View of the CWSF Preparation Circuit in the Fuel Preparation Facility

- "Combustion Performance of a Coal-Water Slurry Fuel in an Off-the-Shelf 15,000 lb Steam/h Oil-Fired Industrial Boiler" authored by Scott A. Britton, Sarma V. Pisupati, Bruce G. Miller, and Alan W. Scaroni.

A three volume technical report was prepared for DOE detailing the results from Phases I-III.

The Ninth Annual Coal Preparation, Utilization, and Environmental Control Contractors Conference was attended in Pittsburgh, Pennsylvania. A paper was prepared by Bruce G. Miller and Alan W. Scaroni discussing the status of the program and was presented.

7.0 NEXT SEMIANNUAL PERIOD ACTIVITIES

During the next reporting period, the following will be completed:

- Installation and shakedown of the CWSF preparation circuit;
- Installation of the superheater;

8.0 REFERENCES

Kinneman, W.P., R.T. Wincek, B.G. Miller, A.W. Scaroni, and R.G. Jenkins, "Conversion of a 1000 lb/h Steam Boiler to Fire Coal Water Slurry Fuel," *Thirteenth Int. Conf. on Coal and Slurry Tech.*, Denver, Colorado, p.725 (April 12-15, 1988).

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Wincek, R.T., W.P. Kinneman, B.G. Miller, A.W. Scaroni, D. Shefet, and F. Kal, "Combustion Control System for a Coal-Water Slurry Fuel-Fired Boiler," *AIChE Spring National Meeting*, Houston, Texas (April 2-6, 1989).

9.0 ACKNOWLEDGMENTS

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