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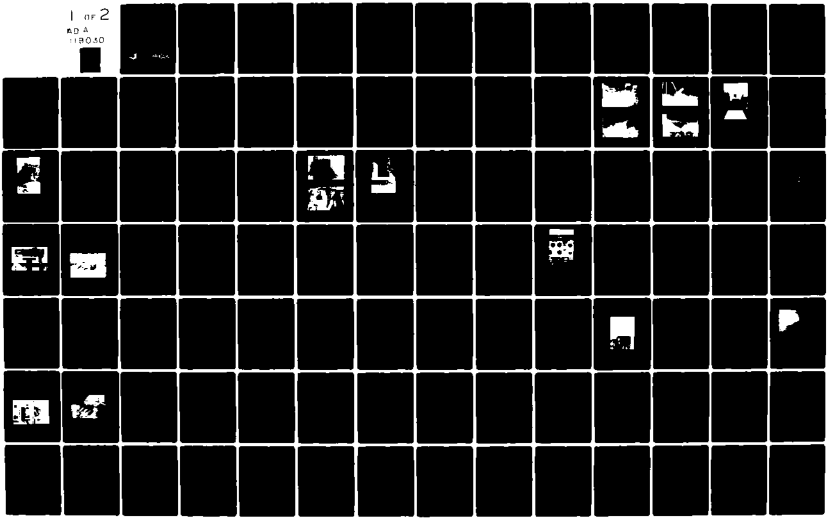

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ESL-TR-81-57

A FIELD TEST USING dRDF IN A SPREADER STOKER HOT WATER GENERATOR

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AUGUST 1981

FINAL REPORT
SEPTEMBER 1980 - JULY 1981

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The objective of this report was to provide an evaluation of boiler performance and environmental emissions when combusting densified forms of refuse-derived fuels (dRDF) in a military scale (40 - 300 MBTUH capacity) spreader stoker fired boiler. The boiler tested was located in Building 1240, Heating Facility at Wright-Patterson Air Force Base, Ohio. The field tests were desinged to investigate: (1) the material handling characteristics of RDF; (2) boiler performance, i.e., boiler efficiency, spreader limitations, HTHW production, combustion properties, slagging, fouling, and clickering; and, (3) environmental

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emissions, i.e., electrostatic precipitator performance, particulate emissions (size, mass rate, and resistivity), gaseous emissions, and trace metal emissions.

The test demonstrated that firing unblended dRDF can be performed with minimal impact on the operational performance of a military hot water generator operated at one-third of its capacity. The boiler burned well with adequate fuel burnout and boiler response. A three-and-one-half percent decrease in efficiency occurred during RDF firing. There was no significant change in electrostatic precipitator removal of particulate emissions as a result of firing RDF compared with coal. Some heavy metal emissions (nickel, zinc, chromium) were higher for RDF than coal.

SUMMARY

This field test had the overall objective of evaluating boiler performance and environmental emissions when combusting densified forms of refuse-derived fuels (dRDF) in a military scale (40×10^6 to 300×10^6 Btu/hr capacity) spreader stoker fired boiler. The boiler tested was located in the Building 1240 Heating Facility at Wright-Patterson Air Force Base, Ohio. This boiler operated in a closed loop, high temperature hot water (HTHW) system. Four hundred forty tons of dRDF were combusted over a 160-hr period. An additional 72 hours of coal testing were completed to provide a basis for comparison of the test results.

The field tests were designed to investigate (1) the material handling characteristics of dRDF; (2) boiler performance, i.e., boiler efficiency, spreader limitations, HTHW production, combustion properties, slagging, fouling, and clinkering; and (3) environmental emissions, i.e., electrostatic precipitator (ESP) performance, particulate emissions (size, mass rate, and resistivity), gaseous emissions (SO_x, NO_x, CO, carbonyls, and HC), and trace metal emissions.

This test demonstrated that firing unblended dRDF can be performed with minimal impact on the operational performance of a military hot water generator operated at one-third of its capacity. The boiler performed well with adequate boiler response and fuel burnout. A three and one-half percent decrease in boiler efficiency occurred during dRDF firing. This decrease was attributed to the high moisture and hydrogen content of the dRDF. There was no significant change in ESP removal of particulate emissions as a result of firing dRDF compared with coal. ESP collection efficiency was about 98 percent. Some heavy metal emissions (nickel, zinc, and chromium) were higher for dRDF than coal. Sulfur and nitrogen oxides emissions decreased when dRDF was substituted for coal.

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PREFACE

This report was prepared by SYSTECH Corporation, 245 North Valley Road, Xenia, Ohio 45385, under contract No. USAF MIPR N-80-47 with Headquarters Air Force Engineering and Services Center, HQ AFESC/RDVA, Tyndall AFB, FL 32403, and the U.S. Environmental Protection Agency (EPA), Contract No. 68-01-6071, Work Assignment No. 8.

The work was begun 1 January 1981 and completed 30 July 1981 and was sponsored by the Resource Recovery Division of the U.S. Environmental Protection Agency and Headquarters Air Force Engineering and Services Center, Department of the Air Force.

On behalf of SYSTECH Corporation, the authors gratefully acknowledge the direction and cooperation of the EPA Project Officer, Mr. Randolph L. Chrismon; the USAF Project Officer, Mr. Stephen A. Hathaway; and Mr. Thomas Shoup, Chief of the Environmental Planning Section, 2750th DEEX, Wright-Patterson Air Force Base.

The authors are also grateful for close coordination and assistance of the following members of the 2750th Civil Engineering Group: for engineering and design support, Mr. Dennis Ruschau and Mr. John Fuller; for fuel tracking and analysis information, Ms. Pat Stewart and Ms. Susan Schmidt; for plant operational coordination, Mr. Billy Jones, Mr. Arthur Johnson, and Mr. Harold Edmiston; and for unlimited details on plant equipment and boiler operations, Mr. Paul Youck, Mr. Ralph Brown, Mr. Harold Jones, Mr. Charles Louricella, and the many other Building 1240 operational personnel who assisted with the test.

The author is also indebted to Mr. Dennis de Breuil for U.S. Army Corps of Engineers area engineering support.

This report was reviewed and approved for publication by the Resource Recovery Division of the U.S. Environmental Protection Agency and Headquarters Air Force Engineering and Services Center, Department of the Air Force. Approval does not signify that the contents necessarily reflect the views and policies of the U.S. Environmental Protection Agency or the Department of the Air Force, nor does the mention of trade names or commercial products constitute endorsement or recommendations for use.

This report has been reviewed by the Public Affairs Office and is releasable to the National Technical Information Service (NTIS). At NTIS it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

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SECTION I

INTRODUCTION

BACKGROUND

In October 1980 a joint agreement was made between the U.S. Environmental Protection Agency (EPA) and the U.S. Air Force (USAF) to test and evaluate the burning of various mixtures of coal and Teledyne-produced densified refuse-derived fuel (dRDF). SYSTECH Corporation was subsequently awarded EPA Contract No. 68-01-6071, Task No. 8, to determine boiler efficiency, electrostatic precipitator (ESP) performance, and air pollutant emissions while burning dRDF in Boiler 3 in Building 1240 at Wright-Patterson Air Force Base (WPAFB). Where possible, the data are compared to data from dRDF tests at other locations such as Erie, Pennsylvania, and Hagerstown, Maryland.

The Air Force portion was funded under Research and Development Program Element 64708F, Project 2054, Task 5, "Aerospace Facility Power Systems," performed for Air Force Systems Command by the Air Force Engineering and Services Laboratory (HQ AFESC/RD), Tyndall AFB, Florida. Mr. Steven A. Hathaway (HQ AFESC/RDVA) was the program manager, and Lt. Paul C. Vitucci (HQ AFESC/RDVA) served as the project officer. The work was carried out under the general administrative supervision of Lt. Colonel Michael J. Ryan, Chief of the Environics Division (HQ AFESC/RDV) and Colonel Francis B. Crowley III, director of the Engineering and Services Laboratory (HQ AFESC/RD). The laboratory will publish the report as technical report ESL-81-57.

USAF and EPA Interests as Co-sponsors

Under the Department of Defense (DOD) Federal Agency Fuel Substitution Program the USAF has initiated several projects designed to convert existing heating and power plants from gas or oil fuels to a multifuel (including biomass) firing capability. Of immediate interest was the acquisition of technical data to develop design criteria involving the use of dRDF as a primary or secondary fuel in military heating and power systems in the 40×10^6 to 300×10^6 Btu/hr capacity range per boiler and in the 100×10^6 Btu/hr and 800×10^6 Btu/hr capacity range per plant.

Simultaneously the EPA has a program to provide information in published reports that can be used by decision makers in comparing proposed resource recovery systems. To prepare these reports, comprehensive environmental, technical, and economic evaluations are performed on various resource recovery systems. These evaluations require rigorous analysis of operational waste-to-energy systems similar to the WPAFB firing of dRDF.

Previous Co-Firing Tests

Perhaps the first summary of the early programs to investigate the feasibility of burning dRDF with coal was a report published in 1965 by R. T. Stirrup, Fellow of the Institute of Public Cleansing and Director of Public Cleansing, City of Southford, England. Specifically, this describes programs in England and Europe during the 1956 to 1960 period which prepared briquettes out of mixed refuse.

Since then, the testing of dRDF as an alternative fuel became an objective of many test programs conducted in the United States. Table 1 provides an overview of these programs.

OBJECTIVES

The original objective of this investigation was to analyze the effects of firing various blends of coal and dRDF as well as to investigate the effects of operating the boiler at different loads for each blend. However, various limitations of the closed loop, high temperature hot water (HTHW) system resulted in the inability of the boiler to attain loads greater than 30 percent of the maximum design rated output of 100×10^6 Btu/hr. Also, the absence of a suitable bulk weight measuring device (such as a belt scale) in the fuel conveying system made it impossible to quantitatively blend coal and dRDF. Therefore, the high load and co-firing tests were deleted.

All testing was conducted at a nominal boiler load of 30×10^6 Btu/hr, since this was the load where the system was able to maintain steady state test conditions. Furthermore, all tests were performed while firing dRDF alone or coal alone. The following paragraphs summarize the revised objectives of the test plan. The data and experience acquired from testing boiler efficiency and precipitator performance at this heating facility should be of interest to future developmental efforts for new military and industrial type boilers capable of firing various alternative fuels such as dRDF.

Boiler Performance

The boiler efficiency was determined for dRDF and compared with that for coal while firing the boiler at a nominal steady state load. Efficiency determinations were made in accordance with instrumentation and procedures as specified in the American Society of Mechanical Engineers (ASME) Power Test Codes (PTC), particularly ASME PTC 4.1, Steam Generating Units. In performing the efficiency tests, mass and energy balances for the various process streams of the boiler were also completed.

Emissions Performance

The efficiency of the electrostatic precipitator in reducing particulate matter in the stack effluent was determined. The effects of burning dRDF on the solid and gaseous emissions of the boiler plant were also determined.

Table 1. Chronological Summary of Previous Co-firing Tests.

	Location of test	Test sponsor	dRDF manufacturer	Date of test	Type of dRDF	Vol blend coal:dRDF	Amt dRDF (mg)	fired (tons)	Test duration (hours)
1.	Fort Wayne, IN Municipal Power Plant	National Recycling Center		1972	cubette 1 1/2" × 1 1/2" × 2"	3:1	36	40	--
2.	Eugene Water & Electric Board	Sandwell International, Inc.	Vista	1974	3/8" pellets	---	19	21	[illegible]
3.	Sunbury Steam Electric Station, Pennsylvania Power & Light		Elo & Rhodes	1975	5/8" pellets	---	73	80	[illegible]
4.	Piqua, OH Municipal Power Plant	Black-Clawson Fibreclaim, Inc.		1975	3/8" pellets	1:1	20	22	7
5.	Wright-Patterson AFB Building 770	Air Force Black-Clawson Fibreclaim, Inc.		1975	3/8" pellets	1:1 1:2	36	40	[illegible] 6
6.	Chanute AFB	U.S. Army CERL	Vista	1975	1 1/8" pellets	1:1 and 0:1	136	[illegible]	
7.	Stockertown, PA	Hercules Cement	Vista	1975	1 1/8" & 5/8" pellets	---	182	201	168
8.	Univ. of Wisconsin Oshkosh, WI	Wisconsin Solid Waste Recycling Authority	Vista	1976	1 1/8" pellets	1:1, 1:3, and 0:1	19	21	--
9.	Appleton Division	Wisconsin Solid Waste Recycling Authority	Grumman	1976	3/4" pellets	---	36	[illegible]	8
10.	Menasha Paperboard Mill	Wisconsin Solid Waste Recycling Authority	Grumman	1976	3/4" pellets	3:2	19	21	--
11.	Waupun, WI	Wisconsin Solid Waste Recycling Authority		1976	3/4" pellets	20%, 30%, and 40% by heating value	19	21	--
12.	Green Bay, WI	Ft. Howard Paper	Grumman	1976	3/4" pellets	1:3 and 1:2	36	40	--
13.	Hagerstown, MD	Maryland General Services	National Center for Resource Recovery	1977	1/2" × 3/4" pellets	1:1 1:2 0:1	258	[illegible]	[illegible]
14.	Erie, PA	General Electric	National Center for Resource Recovery	1979	1/2" × 1" pellets	1:1 1:2 1:4	1585	[illegible]	[illegible]

TEST SITE BACKGROUND

The decision to test the effects of firing dRDF at WPAFB Building 1240 heating facility was based on the following considerations.

Fuel Availability and Storage

dRDF

The WPAFB Building 1240 heating facility had been co-firing coal and dRDF in routine boiler operations for several months prior to the initiation of this program. The Air Force had contracted for dRDF to be manufactured and supplied by Teledyne National at the Baltimore County Solid Waste Disposal System and Reclamation Project in Cockeysville, Maryland. Truck shipments of dRDF could be arranged and deliveries received at one or two truckloads (approximately 20 to 40 tons) per day. Ample storage was available in an open coal yard, in storage silos, and in two buildings.

Coal

Railcar shipments of coal were received from mines in Kentucky and West Virginia. In addition, an abundance of reserve coal was always available from a nearby site on base.

Ash Handling

A separate ash silo was available and dedicated to the test. A pneumatic transport system was routed from the test boiler system to the dedicated ash silo. This dedicated silo permitted the weighing of all boiler bottom ash and ESP fly ash generated by Boiler 3. The two ash types could not be separated and had to be mixed in the same silo.

Heat Demand and Hot Water Flow Restrictions

As previously explained, this heating facility supplies a limited demand in a closed loop, high temperature hot water heating system. The configuration of this loop prevented the operation of the test boiler at maximum rated capacity because heat demand was extremely low. Most of the hot water was returned from the loop with about a 50° to 75°F drop in temperature. To complicate matters, pump capacity and boiler tube restrictions prevented any significant increase in water flow which would have been necessary to put an additional load on the test boiler. Flashing steam or releasing heat elsewhere would have increased the heat output less than 10×10^6 Btu/hr. Such an action was not considered worth the excessive noise to the local population, the energy waste, and possible damage to the boiler system components. In view of these considerations, maximum load testing was dropped altogether, and a steady state load of 30×10^6 Btu/hr was established for all tests.

Boiler Conditions and Configuration

The general condition of the boiler was inspected, photographed, and cold tested prior to firing coal and dRDF. Leaks in the casing were sealed after detection by smoke bomb tests. These leaks were found mainly in the breech area above the boiler. The grates and interior tubes were in excellent condition. While preparing the boiler for testing, a water tube which had been damaged previously by air from a soot blower was replaced and sent to the National Bureau of Standards for analysis. In addition, another undamaged tube was sectioned out (for comparison with the damaged tube) and replaced with a new tube section for future corrosion studies.

The configuration of the boiler system allowed easy access for flue gas tests through existing ports on the breech, roof (before the ESP), and stack. Additional temperature, pressure, and gas monitoring sensors were installed on the inlet or outlet sides of the boiler.

TEST APPROACH

Program Phases

The overall test involved a logical sequence of events to ensure timely installation and calibration of test equipment, check out of boiler control mechanisms, execution of the field tests, analysis of all samples taken, data reduction, and reporting of results. The general test matrix is given in Table 2, and detailed test procedures are given in Section 3 of this report.

Site Preparation Phase

This phase involved installation of thermocouples and manometers on the main boiler inlet and outlet ducts, hookup of continuous monitors for temperature and flue gas composition data records, location of critical plant process control gauges for hourly data recording, and calibration of the fuel scale and test instrumentation. Also, leak checks on the boiler casing were conducted to identify tramp air input. Trial burns were conducted to determine the best control settings for fuel input and proper adjustment of grate speed, overfire air, and underfire air for dRDF and coal.

Field Tests

The field tests involved the following general activities:

- Visual observation and documentation of control roo process instrumentation data.
- Hourly inspection and data recording during the test period of all operating equipment and associated meters and gauges that could effect a change in test conditions.
- Fuel and mixed ash sampling, moisture determinations, and bulk weight determinations.

Table 2. General Test Matrix.

	Week 1				Week 2				Week 3			Week 4
Test	dRDF				dRDF				Coal			dRDF
EPA Method 5												
Particulate ESP inlet			X	X	X	X	X	X	X	X	X	X
ESP efficiency, stack			X	X	X	X	X	X	X	X	X	X
Particle size Inertial cascade impactor												X
Carbonyls												X
EPA Method 6 - SO_x					X	X	X	X	X	X	X	
EPA Method 7 - NO_x						X	X	X	X	X	X	
Hydrocarbons (C_1 to C_6) Gas chromatography (GC)					X	X	X	X	X	X	X	X
Orsat					X	X	X	X	X	X	X	X
Continuous monitors CO_2, CO, O_2, SO_x, and NO_x					X	X	X	X	X	X	X	
Coal analysis									X	X	X	
dRDF analysis		X	X		X	X	X	X				X
Bottom ash analysis	X	X	X	X	X	X	X	X	X	X	X	X
ESP fly ash analysis		X	X									
Silo ash weight	X	X	X	X		X	X	X		X	X	X
Boiler data	X	X	X	X	X	X	X	X	X	X	X	X

- Sampling of dry bottom ash and dry fly ash for combustible content and bulk density determinations.
- Flue gas sampling and continuous monitoring of the stack effluent.

As field tests were conducted, all samples were identified and logged according to date, time, and fuel type used.

Laboratory Analysis Phase

Fuel and ash physical and chemical properties that were analyzed included moisture content, bulk density, size distribution, ultimate analysis, combustible content, resistivity, and trace metal analysis.

Data Analysis and Reporting Phase

The data from the above sampling, observations, and analysis were summarized, correlated, and compared in Section IV of this report. Conclusions and recommendations for future analysis and testing are in Section V of this report.

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SECTION II

DESCRIPTION OF PLANT AND SITE PREPARATIONS

GENERAL PLANT DESCRIPTION

The boiler selected for this test and evaluation is located in the HTHW Heating Facility, Building 1240, Wood City Area, WPAFB. The Heating Facility is approximately 15 miles northeast of Dayton, Ohio, on State Route 444.

The HTHW supply system consists of five boilers with a total plant capacity of 610 × 10^6 Btu/hr. Boilers 4, 5, and 6 (Figure 1) were added to the plant in 1976. Each of these newer boilers are rated at 150 × 10^6 Btu/hr and may be used to relieve either or both of the older boilers (Boilers 2 and 3 in Figure 1) through a heat exchanger. Boiler 3 is a 100 × 10^6 Btu/hr unit which serves A and B system HTHW demands. Boiler 3 was selected as the test boiler.

FUEL HANDLING SYSTEM

The fuel handling system is designed to transfer coal or dRDF from the shaker house to the boilers or to the various storage locations. Figure 2 is a plan view of the fuel handling system. The shaker house is a receiving area equipped to handle both railcar and truck deliveries of fuel. This shaker house also contains the control room for the entire fuel handling system. Fuel storage is provided by an open coal yard and by four silos (Figures 3 and 4). Via the various conveyors fuel can be routed from the shaker house to the boilers from the shaker house to the coal yard or silos, or from the coal yard and silos to the boilers.

A typical truck delivery from the Teledyne dRDF production facility in Baltimore is shown in Figure 5. These deliveries were either stored in the open yard or removed by an end loader (Figure 6) to a protected storage area in the shaker house (Figure 7).

Once the fuel was conveyed inside the plant, it was dropped to either a coal pile or dRDF pile on one side or the other of the fuel bunker. On either side of the dump loader scale the coal or dRDF could be fed by opening one of four available gates and closing the other three (Figure 8). The bunker and conveyor/weighing system is located on the second level of the boiler room (see Figure 9).

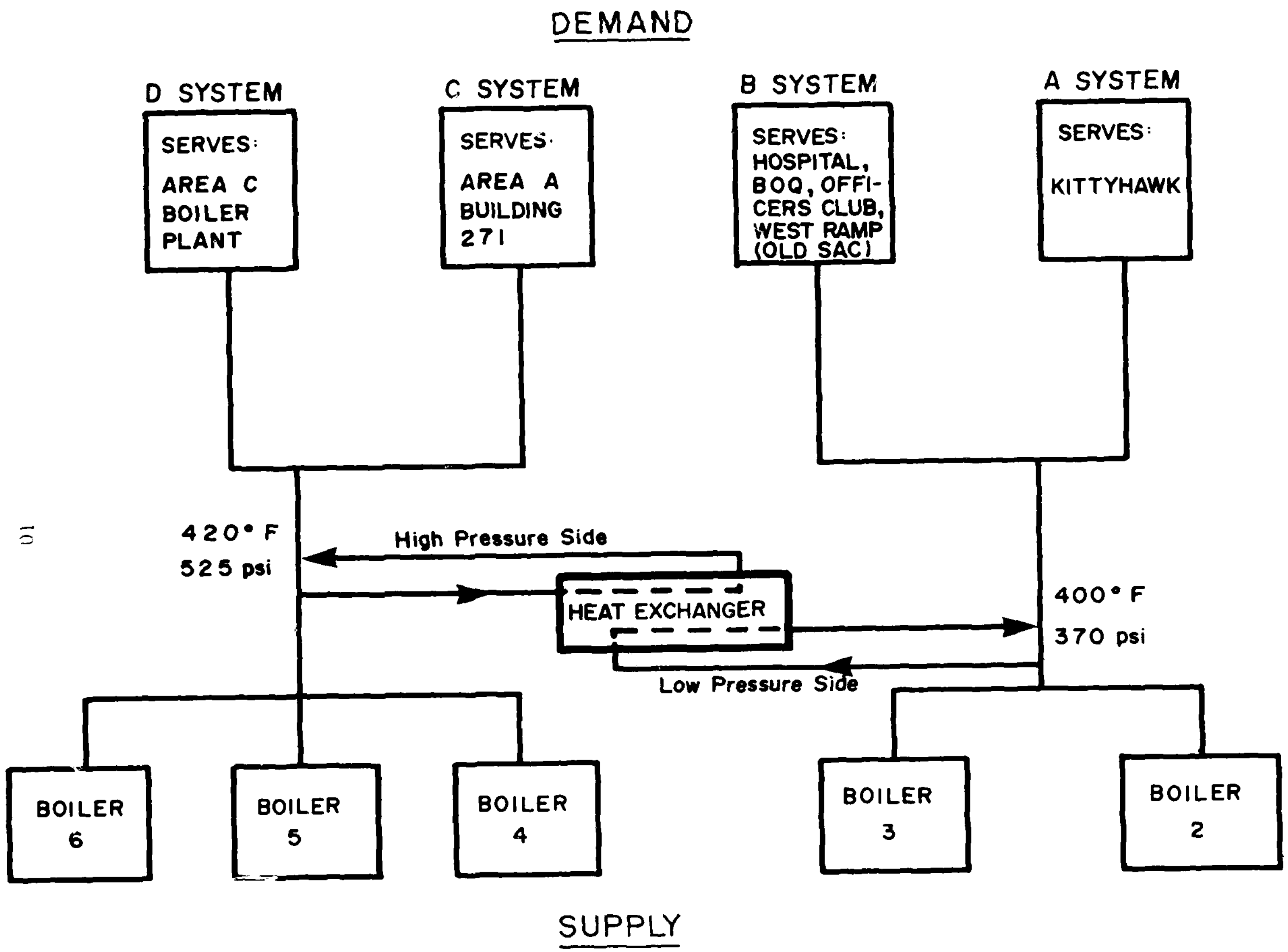

Figure 1. The Building 1240 Hot Water Loop.

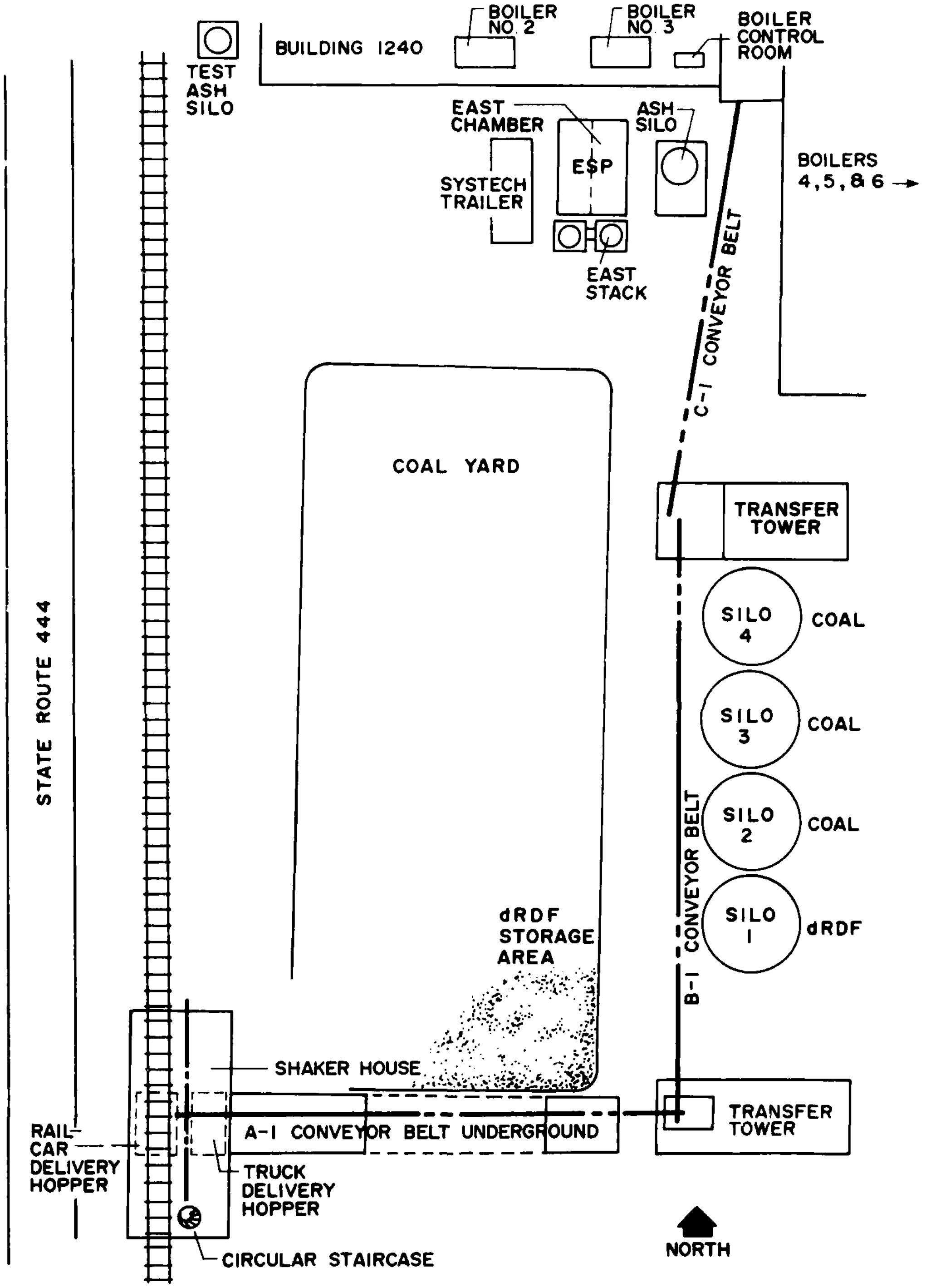

Figure 2. Building 1240 Plant Layout.

Figure 3. Test Stack, Coal Yard, and Shaker House.

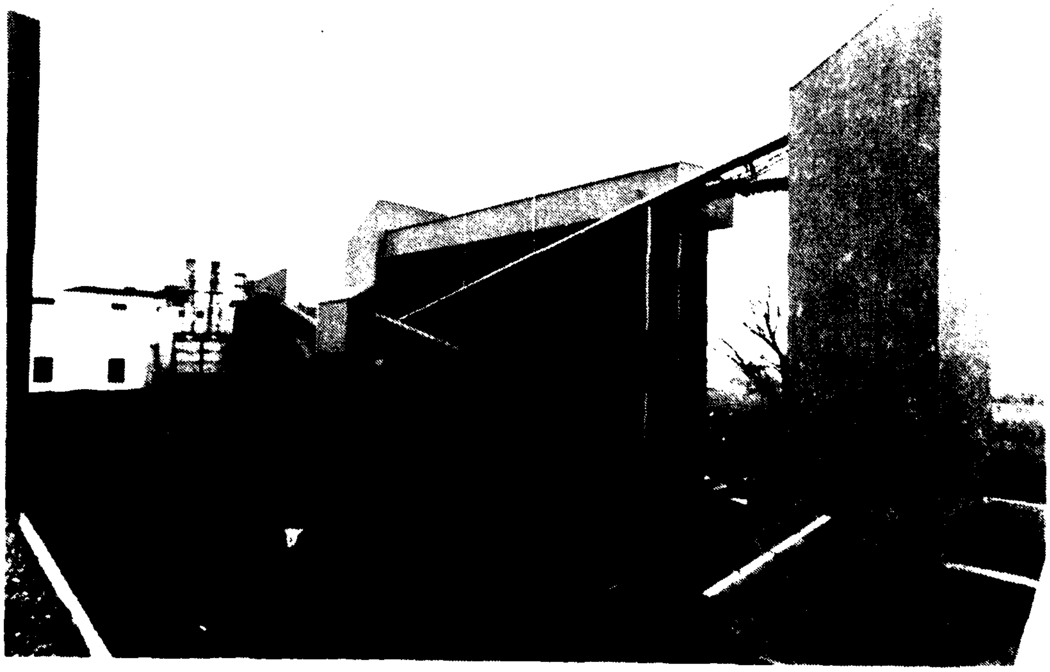

Figure 4. Fuel Storage Silos and Conveyor System.

Figure 5. A dRDF Truck Delivery.

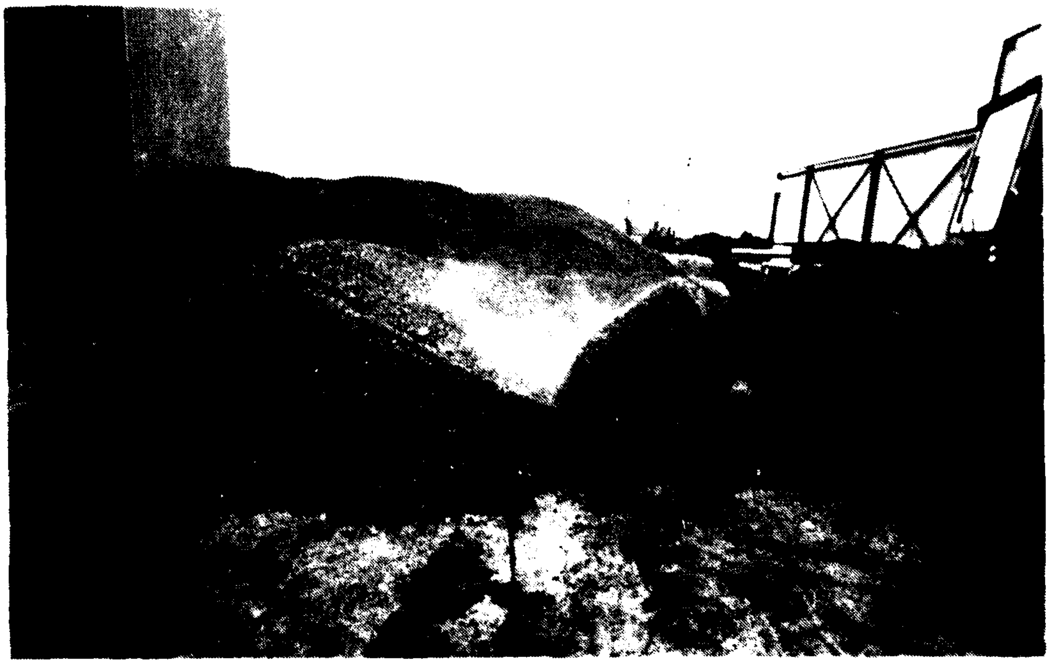

Figure 6. Front End Loader Used to Move dRDF Pellets.

Figure 7. dRDF Stored in the Shaker House.

TEST BOILER SYSTEM

The major components of the boiler system include the boiler tubes and furnace section, the rotograte stoker, the air preheater, the associated air fans and blowers, the multiclone dust collector, the breech, and the ash removal system. A cross-sectional side view of the boiler system is illustrated in Section 3. The predicted performance design specifications were supplied by courtesy of the Babcock & Wilcox Company (Tables 3 and 4).

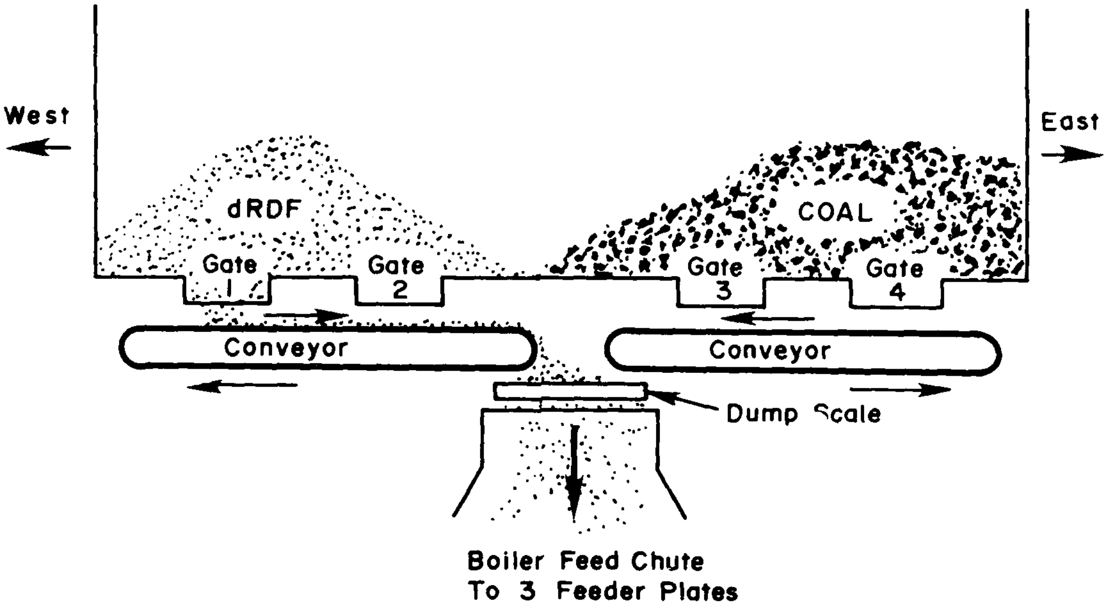

Figure 8. Side View of the Fuel Bunker.

Boiler Description

The furnace section of the boiler is a Babcock & Wilcox design with a volume of 3,270 ft^3. The four walls are lined with 1 1/2-in. o.d. tubes for a waterwall surface of 1,150 ft^2. Total heating surface available from the walls and boiler heating surface is 10,000 ft^2 (Table 3). The maximum design pressure rating is 275 psi (Table 4). Actual pressure at the boiler outlet during the test burns was 250 psi.

Previous plant operational experience (not during this test) with the test boiler revealed that the actual maximum attainable throughput of hot water through the boiler is 1,440 gallons per minute (gpm). This flow rate is slightly higher than the designed rate of 582,000 lb/hr or 1,168 gpm. Under test conditions the boiler was operated between 1,040 and 1,200 gpm. During the test the circulating water entered the boiler at about 340°F and exited at about 400°F, yielding a heat output of 25×10^6 to 35×10^6 Btu/hr as recorded on an integrator chart in the boiler control room.

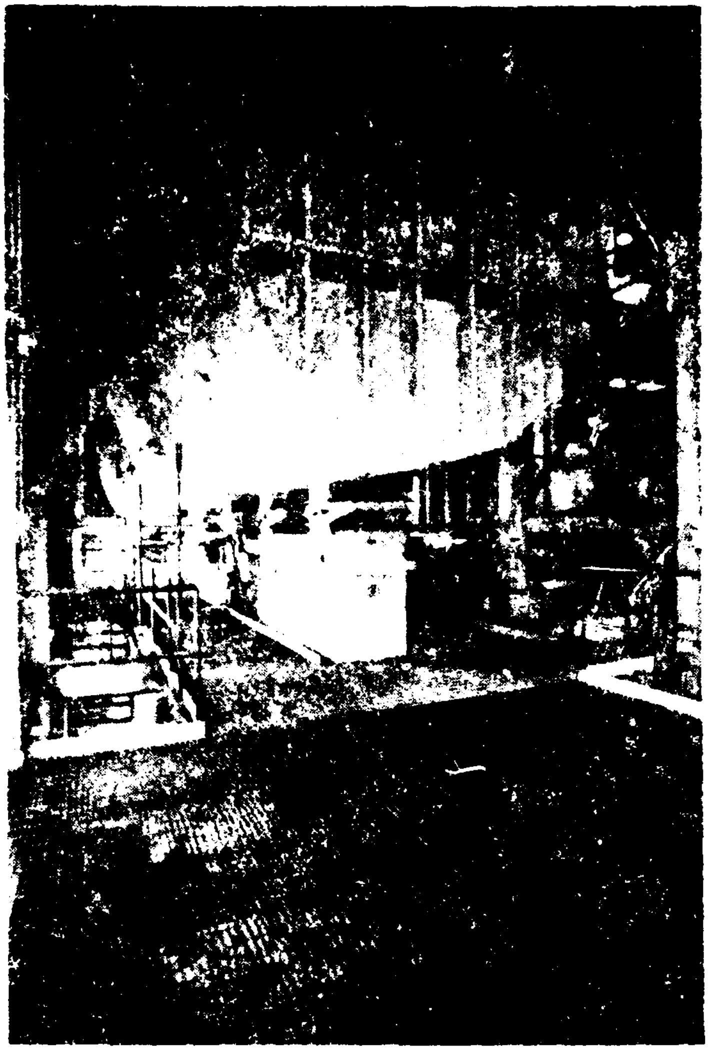

Figure 9. Fuel Bunker and Dump Scale.

Rotograte Stoker Description

Coal is dropped in 200-lb [illegible] from a [illegible] bunker [illegible] under-coal [illegible] fuel [illegible] for [illegible] spreaders of the stoker [illegible]. The fuel bed is carried [illegible] furnace front [illegible] stoker [illegible].

Table 3. Boiler No. 3 Fuel and Design Specifications.*

AS-FIRED FUEL RECOMMENDED SPECIFICATIONS SUPPLIED BY WPAFB

Bituminous Coal:	Proximate analysis (percent)		Ultimate analysis (percent)	
	2.4	Moisture	0.9	Sulfur
	33.7	Volatile matter	5.0	Hydrogen
	55.4	Fixed carbon	75.5	Carbon
	8.5	Ash	1.3	Nitrogen
			6.4	Oxygen
	100.0	TOTAL	10.9	Ash & moisture†
			100.0	TOTAL

Heat content 13,450 Btu/lb

BOILER DESIGN SPECIFICATIONS

Boiler heating surface 8,850 ft^2

Waterwall heating surface 1,150 ft^2

Design pressure - 400 psi

Furnace volume - 3,270 ft^3

Net grate surface - 187 ft^2

* Courtesy of the Babcock & Wilcox Company.

† Ash in fuel is 8.5 percent, and moisture in fuel is 2.4 percent.

Ash Handling System

Located beneath the rotograte system is a three section ash pit. The ashes are taken from each of the three grate zones by manually shoveling or raking the ashes into the pneumatic ash removal system (Figure 11). A vacuum is used to transport the ashes from the test boiler through an 8-in. line to the ash silo (Figure 12). This ash silo was also used to store ESP fly ash and was solely dedicated to test Boiler 3.

Table 4. Predicted Performance of Boiler 3.*†

Predicted performance (not guaranteed)	Minimum rating	Maximum rating
Heat output	20×10^6 Btu/hr	100×10^6 Btu/hr
HTHW flow	582,000 lb/hr	582,000 lb/hr
Blowdown	0	0
Excess air leaving boiler	80 percent	28 percent
Flue gas leaving boiler	-	122,000 lb/hr
Air leaving air heater	-	105,000 lb/hr
Pressures (psi)		
Water at boiler outlet	-	275
Drop through boiler	-	20
Temperature (°F)		
Flue gas leaving boiler		524
Flue gas leaving air heater	273	381
Water entering boiler	382	250
Water leaving boiler	414	414
Air entering air heater	-	70
Air leaving air heater	-	245
Draft losses (in. of water)		6.4
Air resistance (in. of water)		5.1
Heat losses		
Dry gas	-	7.6 percent
H_2 and H_2O in fuel	-	4.2 percent
Moisture in air	-	0.2 percent
Unburned combustibles	-	1.1 percent
Radiation	-	0.7 percent
Other	-	1.5 percent
TOTAL	Not estimated	15.3 percent
Predicted efficiency (heat loss method)		84.7 percent

* Based on fuel and design specifications of Table 3.

† Courtesy of the Babcock & Wilcox Company.

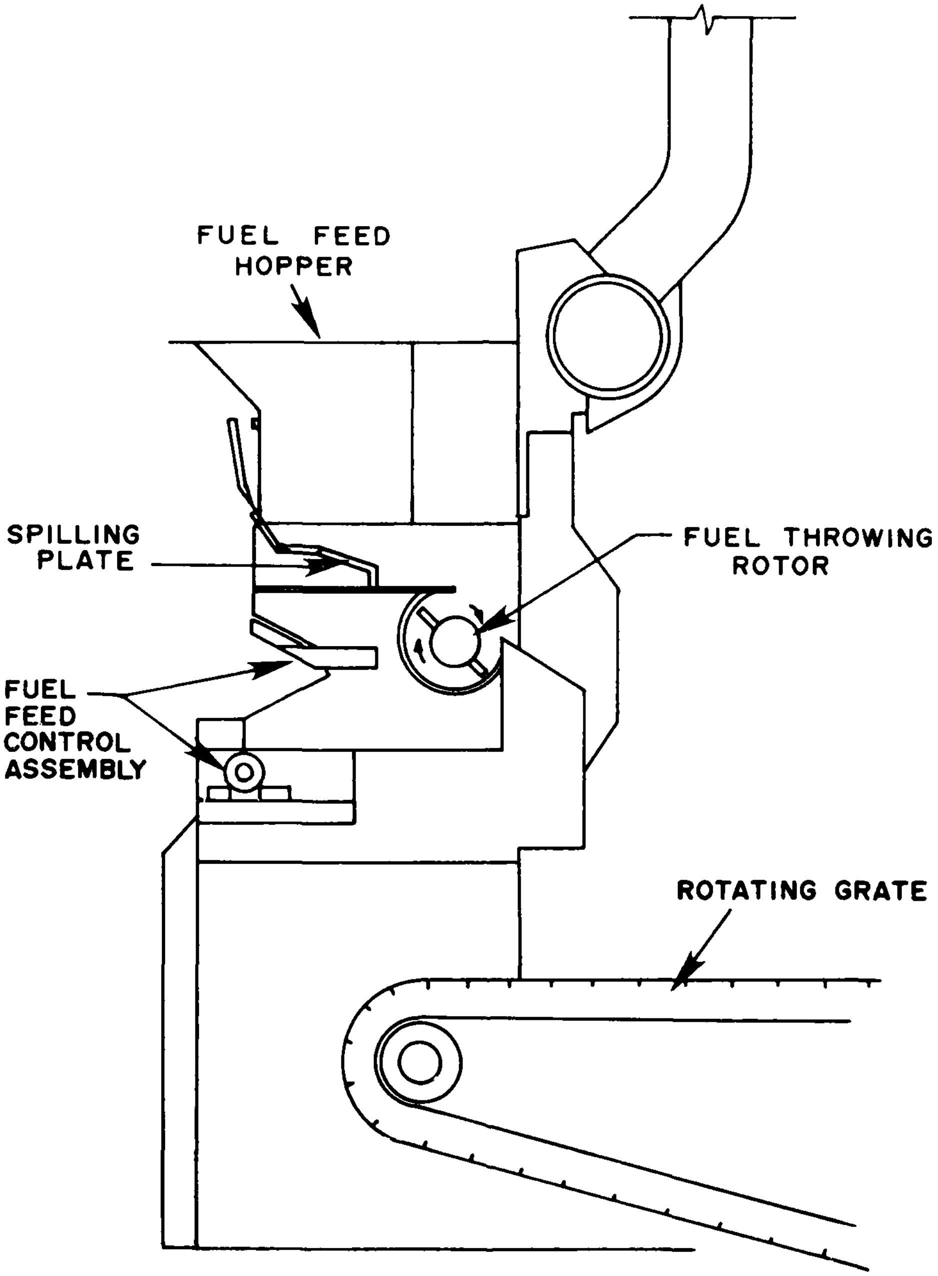

Figure 10. Cross-Sectional View of Detroit Rotograte Stoker.

Table 5. Description of Detroit Rotograte Spreader Stoker.

Number of spreaders	3
Feeder size	27 in
Spreader type	reciprocating overthrow
Volumetric capacity total	360 ft^3/hr
Forward traveling grate	
Grate width	11 ft
Grate length	17 ft
Grate area	187 ft^2

ESP DESCRIPTION

The precipitator system is a Unitrell Modular Electrostatic Precipitator fabricated by the Western Precipitation Company. It is divided into two separate chambers with two fields (labeled A and B) in each chamber. The A and B field compartments are insulated, under positive pressure, and heated. The fly ash collecting surfaces are 9- × 20-ft plates with 13 gas passages spaced 9 in. apart in each field. Maximum capacities of the system are 90,000 actual cubic feet per minute (ACFM), 15 in. H_2O operating pressure, 444°F temperature, and 0.19 gr/ft^3 inlet loading. Since one chamber was shut down, maximum flue gas output was reduced to 40,000 ACFM. The test gas emission rate was measured at approximately 30,000 ACFM, or 75 percent of capacity. The power supply is a 480-V, 60-Hz, 3-phase system. An automatic rapper system removes dust from the walls during operation.

The precipitator is located just outside the south side of Building 1240 (Figure 13) in front of Boiler 3. Ash hopper sampling ports were accessible at ground level, but manual removal of fly ash samples was hazardous. Fly ash was removed using the pneumatic ash removal system to the dedicated ash silo. There the fly ash was mixed with bottom ash, wetted down, and later trucked to a nearby landfill.

PLANT MODIFICATIONS

The most significant plant modification consisted of isolating the test boiler system from existing flue gas and ash systems interconnected with

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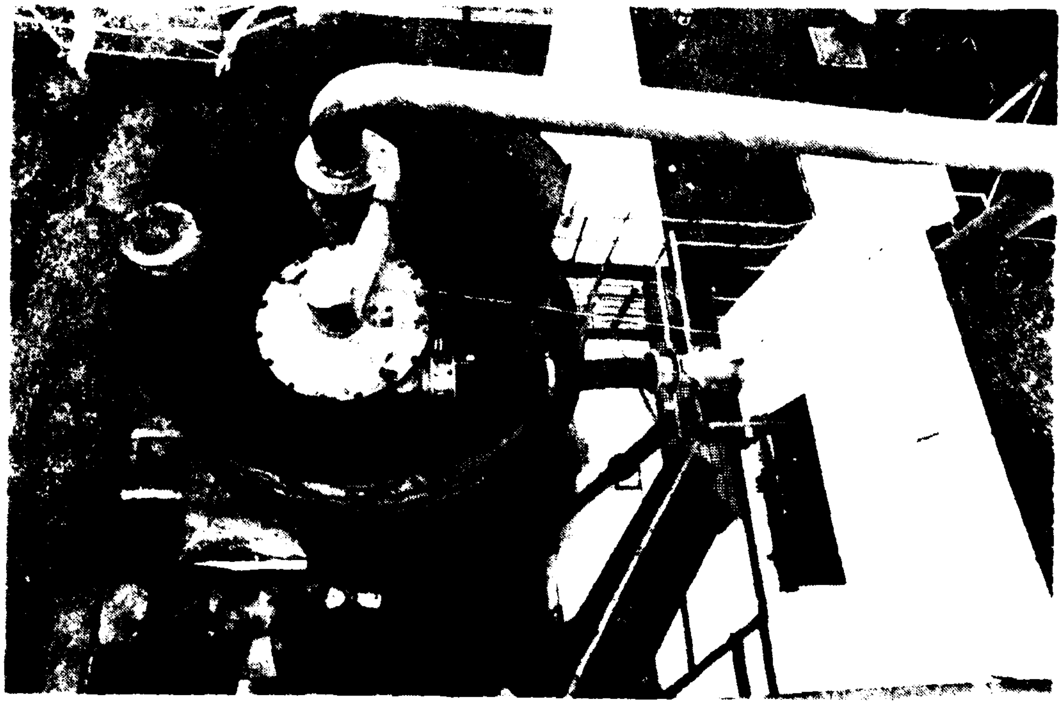

Figure [illegible]

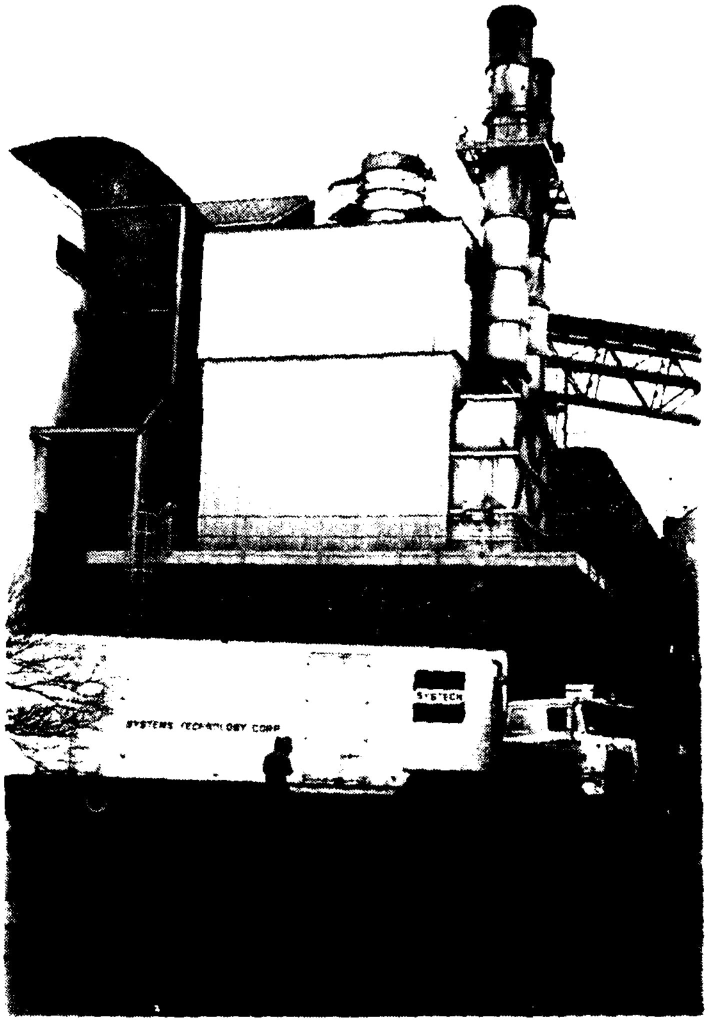

Figure 13. Unitrell Electrostatic Precipitator.

Boilers 2, 4, 5, and 6. Specific changes consisted of (1) isolating the test boiler flue gas outlet to flow uninterrupted through one side of the dual-chamber ESP system, (2) changing the fly ash and bottom ash routing from the new ash silo system to a dedicated ash silo, and (3) establishing manual operating procedures to ensure that the bunker fuel feed and weighing system would be properly controlled during the test periods.

SYSTEM PREPARATION

Before firing up the test boiler, it was inspected for possible air and water leaks; for fuel feed rates and distribution patterns; and for the overall condition of the casing, rotors, and grates. These cold tests are an important basis for explaining variations in combustion phenomena, corrosion, slagging, and clinkering which may occur during subsequent test firings for comparing the effects of coal and dRDF fuels. The test boiler was found to be in very good internal and external condition. See Section 3 for the procedures used to check fuel distribution patterns and Section 4 for the results of these feeder tests.

Fuel Feed Rate and Distribution Tests

The purpose of the cold fuel feed test was to verify satisfactory performance in feeding dRDF into the boiler. Potential problems which could be encountered during combustion tests include bunker or chute flow problems, jams in the feeding system, segregation of pellets, or incorrect spatial distribution of the coal or dRDF over the grate. The cold fuel feed test permitted proper preliminary settings of the stoker mechanism prior to actual boiler tests. The initial boiler tests then proceeded with little interference from feed system problems.

Rotograte Speed

The length of time for the grate to travel from the back of the boiler to the front has a direct effect on the depth of the ash bed and residence time of the fuel to achieve complete combustion. The speed adjustments were checked to provide better control of ash removal and to compare what speed changes, if any, would be required when shifting from coal to dRDF.

Smoke Bomb Tests for Tramp Air

Smoke bomb tests revealed no major tramp air leaks in the lower part of the boiler casing other than at the view ports in front of the boiler. Some leaks were found in the upper section around the breeching. These leaks were sealed.

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SECTION III

TEST PROCEDURES

OVERVIEW

This section describes the sampling locations and general field test procedures that were used to acquire suitable data for evaluation of the boiler performance while firing dRDF.

Test Matrix and Schedule

The test matrix and sampling schedule is outlined in Table 6. This scheduled was used for the acquisition of fuel, bottom ash, fly ash, and gas emission samples. The schedule was also used for the collection of hourly process data.

Data Recording and Sampling Locations

All process streams in the test boiler and ESP system were identified with respect to a mass and energy balance. Each stream was numbered, the measurements were described, the data recording frequency was determined, and the proper test and sampling procedures (e.g., ASTM Power Test Code, ASTM Standard, or EPA Method) were selected for application in the test program. A complete outline of the measurements taken is presented in Table 7. The stream numbers in Table 7 are related to the process flow diagram in Figure 14.

System Temperature and Pressure Measurements and Instrument Locations

The exhaust gas temperature was measured continuously at the boiler breech using a Type K thermocouple and recorded on a multipoint recorder. Also, the inlet and outlet hot water temperatures, overfire air, and boiler skin temperatures were monitored with thermocouples. The thermocouple and pressure gauge locations are given in Figure 15.

FUEL WEIGHT DETERMINATION, SAMPLING, AND ANALYSIS

The amount of fuel consumed during the test period is an important part of the mass and energy balance. The procedures for determining the quantity and quality of both coal and dRDF fuel types are the same.

Fuel consumption rate and total weight determination were easily monitored on the Richardson dump loader with digital readout which serves

Table 6. Detailed Test Matrix and Sampling Dates.

	March				March		April		April			April
	2	3	4	5	30	31	1	2	6	7	8	16
	Week 1				Week 2				Week 3			Week 4
Test	dRDF				dRDF				Coal			dRDF
EPA Method 5												
Particulate ESP inlet			X	X	X	X	X	X	X	X	X	X
Particulate ESP outlet			X	X	X	X	X	X	X	X	X	X
Particle size (ESP inlet)												X
Carbonyls												X
EPA Method 6 - SO_x					X	X	X	X	X	X	X	
EPA Method 7 - NO_x						X	X	X	X	X	X	
Hydrocarbons (C_1 to C_6) Gas chromatography					X	X	X	X	X	X	X	X
Orsat					X	X	X	X	X	X	X	X
Continuous monitors CO_2, CO, O_2, SO_x, and NO_x					X	X	X	X	X	X	X	
Coal sampling									X	X	X	
dRDF sampling	X	X	X	X	X	X	X	X				X
Bottom ash sampling	X	X	X	X	X	X	X	X	X	X	X	X
ESP fly ash sampling		X	X									
Silo ash (H_2O determination)	X	X	X	X		X	X	X		X	X	X
Boiler efficiency	X	X	X	X	X	X	X	X	X	X	X	X

Table 7. Process Stream Measurements.

Stream No. & description (see Fig. 14)	See Fig. 15 for code location	Measurement parameter	Measurement frequency	Measurement method used
1. Makeup water		flow rate	hourly	Uncalibrated water meter
2. HTHW, return	T-4	temperature	continuous	ASME PTC 19.3*
	P-4	pressure	hourly	Bourdon gauge
3. Fuel	V/O	input rate	hourly	ASME 4.1, Par. 4.03, 4.1, Par. 4.03
		ultimate	hourly composited to daily	ASTM D3176-74
		proximate		ASTM D3172-73
		Btu		ASTM D2015-66
		moisture		ASTM D3303-74 modification
		size dist.		ASTM D410-38 modification
		bulk density		ASME PTC 19-16 modification
4. Overfire air	T-3	temperature	continuous	ASME PTC 19.3*
	P-2, P-3	pressure	hourly	ASME PTC 19.2, Par. 3.11
5. Underfire air	T-2	temperature	continuous	ASME PTC 19.3*
	P-1	pressure	hourly	ASME PTC 19.2, Par. 3.11
6. Flue gas, boiler outlet at breech	T-5	temperature	continuous	ASME PTC 19.3*
		pressure	hourly	Manometer
7. Flue gas, ESP inlet		flow	2/day	EPA Method 5
		temperature	2/day	EPA Method 5
		pressure	2/day	EPA Method 5
		particulate conc.	2/day	EPA Method 5
		particulate size dist.	2/test	Intertial cascade impactor

* Type K thermocouple.

Table 7. Process Steam Measurements (Concluded).

Stream No. & description (see Fig. 14)	See Fig. 15 for code location	Measurement parameter	Measurement frequency	Measurement method used
8. Flue gas, stack		flow	2/day	EPA Method 5
		temperature	2/day	EPA Method 5
		pressure	2/day	EPA Method 5
		particulate conc.	2/day	EPA Method 5
		composition	2/day	EPA Method 3
		O_2 conc.	continuous	Electrochemical cell
		CO_2 conc.	continuous	Nondispersive infrared
		CO conc.	continuous	Nondispersive infrared
		NO_x conc.	continuous	Electrochemical cell
		NO_x conc.	2/day	EPA Method 7
		SO_x conc.	continuous	Electrochemical cell
		SO_x conc.	1/day	EPA Method 6
		carbonyls	4/test	Sodium bisulfite capture, MM 5 28, Par. 4.05
9. Fly ash, ESP		bulk density		ASME PTC 19.16 modification
		% combustibles		ASTM D3174-73 modification
		resistivity		ASME PTC 28, Par 4.05
		size dist.		ASTM D410-38 modification
10. Bottom ash		bulk density	2/day	ASME PTC 19.16 modification
		% combustibles	2/day	ASTM D3174-73 modification
		size dist.	2/day	ASTM D410-38 modification
11. Silo ash		weight	1/day	Truck sales
		% moisture	1/day	ASTM D3303-74 modification
12. HTHW outlet	T-6	flow rate	continuous	Orifice flow met
		temperature	continuous	ASME PTC 19.3*
		pressure	hourly	ASME PTC 19.2 Bourdon gauge

* Type K thermocouple.

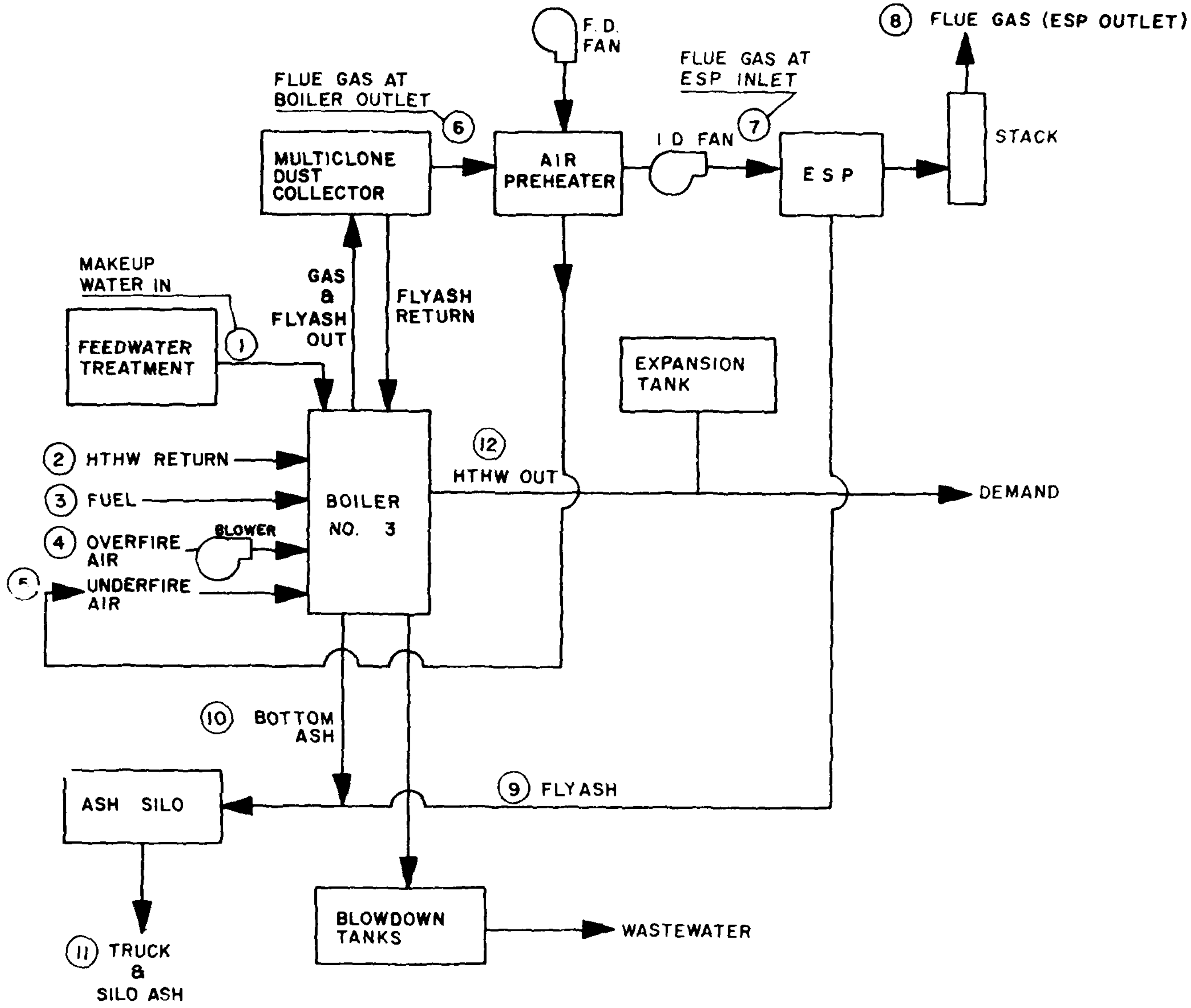

Figure 16. Test Boiler System Process Flow Diagram.

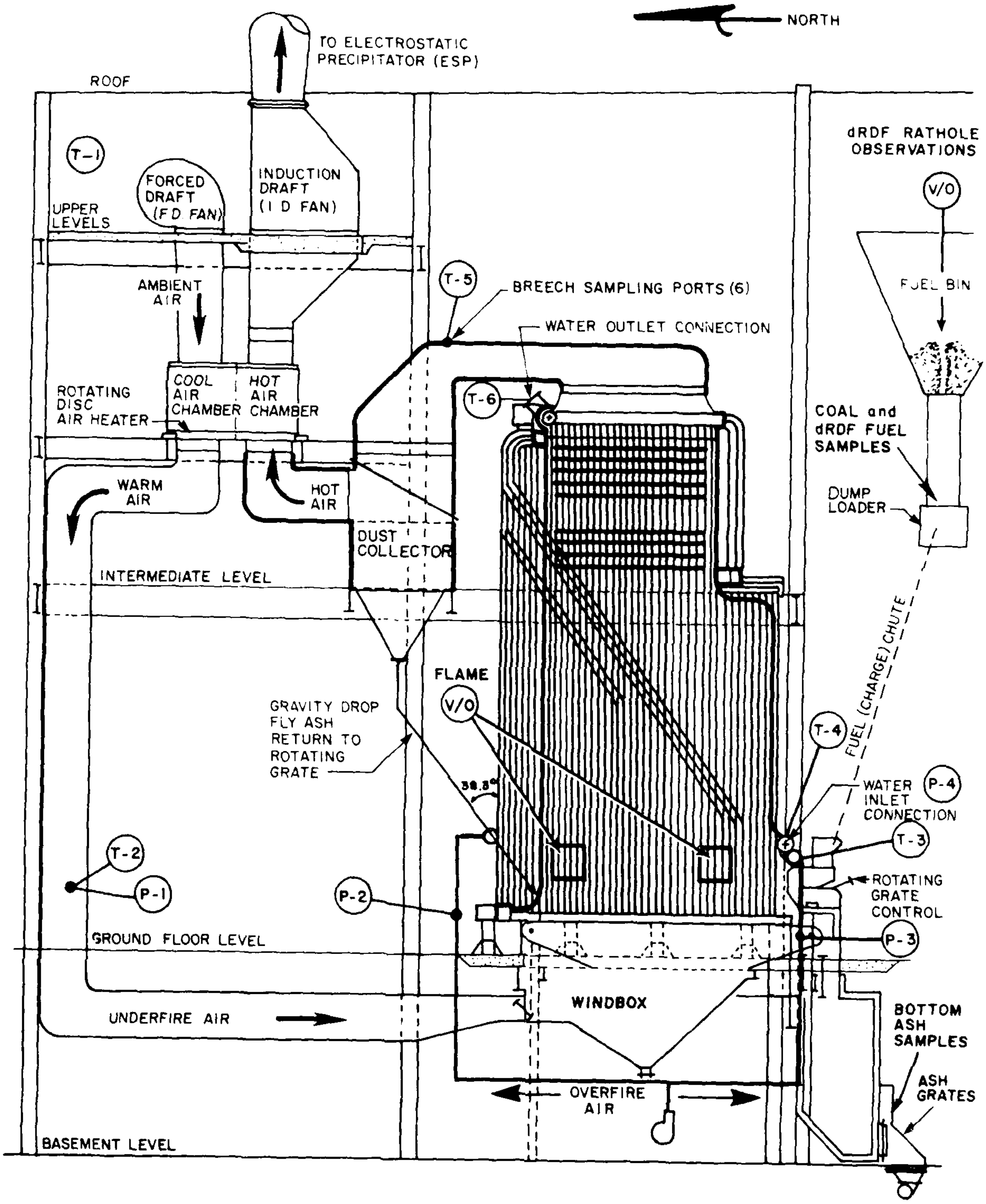

Figure 15. Location of SYSTECH Temperature (T) and Pressure (P) Gauges.

as a totalizer (Figure 16). Readings of the number of charges were taken hourly and multiplied at the end of the test period by the precalibrated weight per charge ([illegible] lb for RDF and [illegible] lb for coal). The scale was calibrated before each week of test burns by using preweighed quantities of fuel. The results are listed in Table 4. Also, fuel samples were taken hourly (Figure 17) at the dump loader for on-site bulk density determination, moisture content, and size analysis.

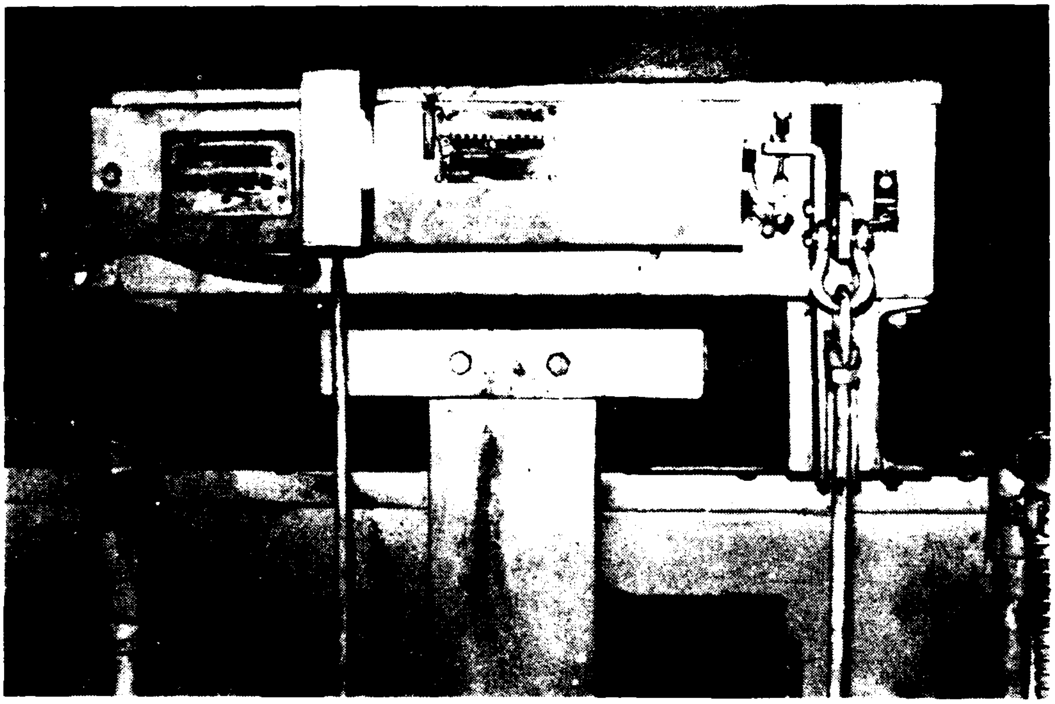

Figure 16. Richardson Dump Loader Scale.

At the end of each day all hourly fuel samples were split and combined to form a composite sample of equal weights from each hourly sample. The splitting and compositing procedure is shown in Figure 18.

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Figure 7. Raw Sample Taken From the Conveyor Belt.

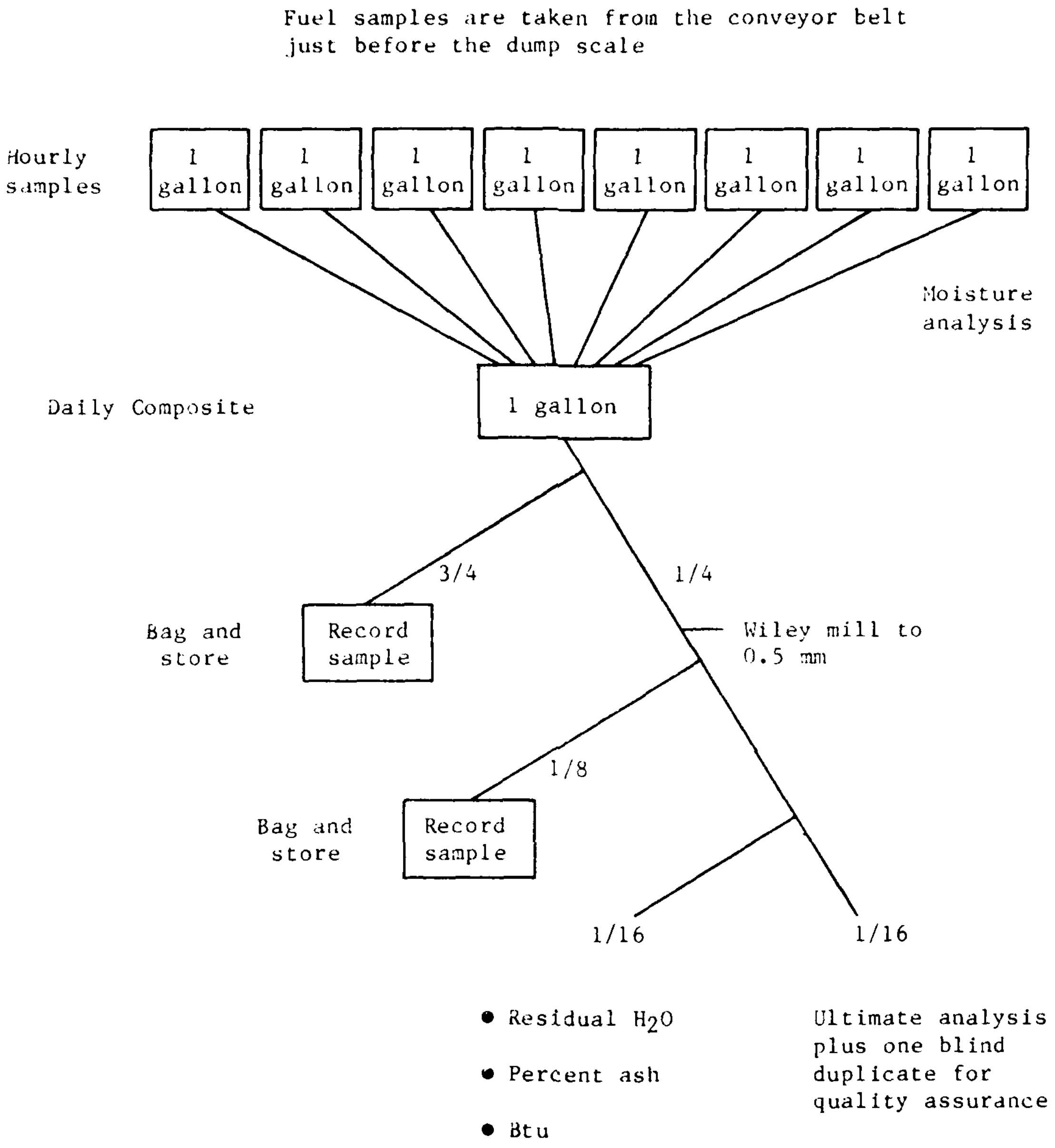

Figure 18. Fuel Sample Split Procedure.

The accuracy of the measurements used for the first three dRDF calibration measurements in Table 8 was determined as follows:

$$\text{uncertainty in weight } (\Delta) = \frac{\text{standard deviation (s)} \times \text{probability (t)}}{\text{number of samples}}$$

$$\Delta = \frac{s \cdot t}{n} ;$$

where: $t = 2.92$ at 95 percent confidence level from the t-distribution curve.

$s = 2.623$

$n = 3$

then: $\Delta = 4.4$ lb

$$\text{Percent uncertainty} = 100 \times \frac{\Delta}{\text{Avg wt}} = \frac{4.4}{93.6} \times 100$$

$$= \pm 5 \text{ percent accuracy}$$

ASH MEASUREMENTS

Direct weight measurement of bottom ash mixed with fly ash was possible on a weekly basis to use as verification of mass and energy balance calculations. The ash silo was emptied at the beginning of the test and left to fill during the test. At the end of the test the ash was removed by truck and weighed on a scale. Because this procedure was performed on a daily basis and periods when the boiler load was not carefully controlled were included, actual hourly rates could not be determined. In the mass balance the ash output rates were calculated from fuel usage rates, ultimate analysis, and EPA Method 5 data.

Ash was pulled pneumatically from the boiler (bottom ash) and from the ESP (fly ash). Ash pulls were usually accomplished in the morning prior to starting gas emission testing. Dry ash samples were collected at this time from the boiler before the bottom ash was mixed with the fly ash and wetted in the ash silo. Dry samples for bulk density determination were taken from all three ash pit doors beneath grate Zones 1, 2, and 3. The sampling procedure consisted of filling a 3-gal bucket with ash from each zone and weighing the bucket for a bulk density determination. Then a composite sample was formed for later combustibles and heat content analysis (see Figure 19).

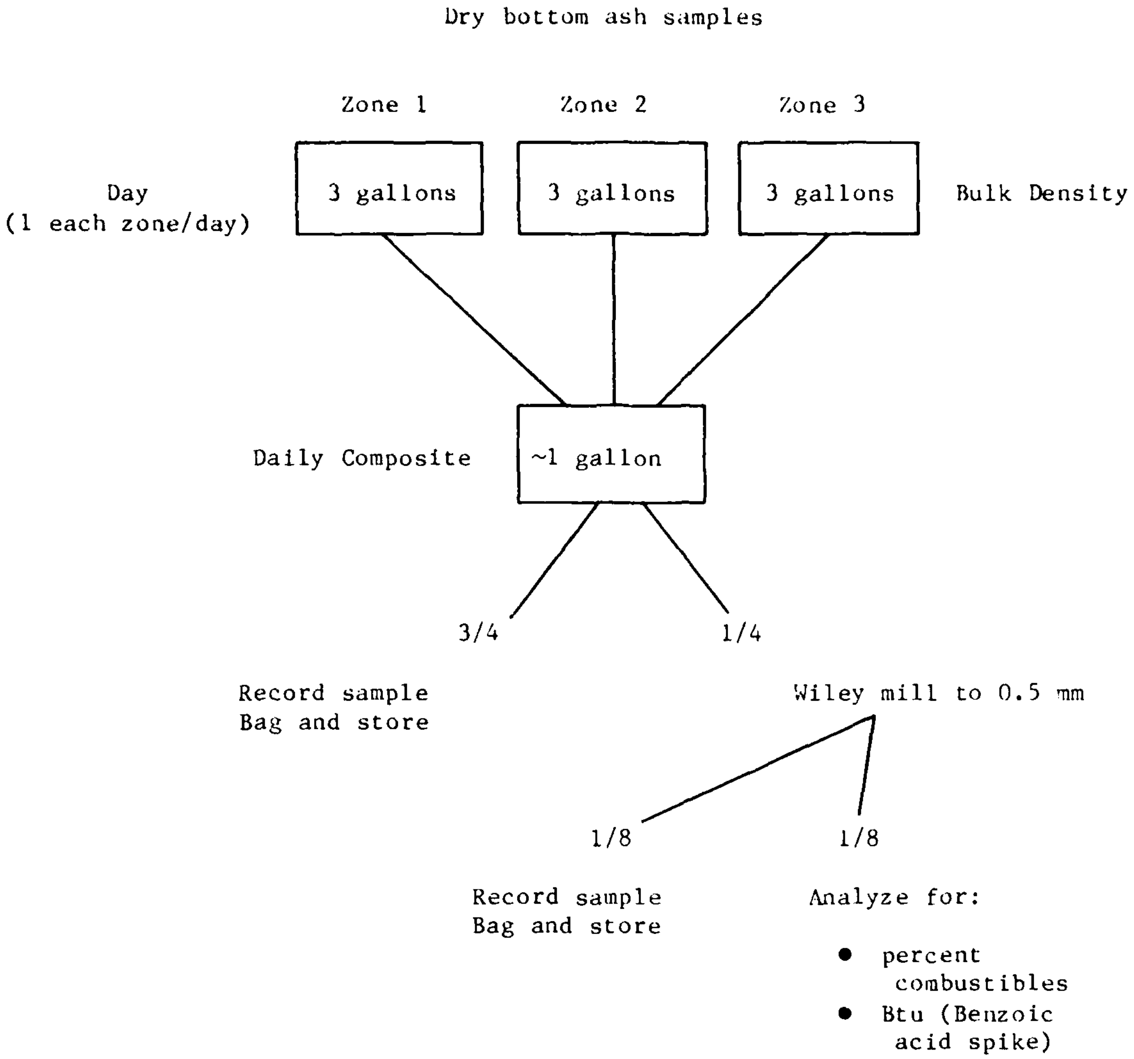

Figure 19. Bottom Ash Sample Split Procedure.

The amount of water added to ashes in the silo was determined by meter readings taken at the time of ash removal. The water meter was calibrated by filling a 5-gal pail from the outlet of the meter.

During removal of ash from the silo, 1-gal ash samples were taken for subsequent physical and chemical analysis. These 1-gal samples were then taken to SYSTECH's main laboratory for the analysis.

The 1-gal laboratory sample of bottom ash was mixed and quartered. Three quarters of the sample was returned to the original sample container and kept as a record sample. One quarter of the sample was ground to 0.5-mm size in a Model No. 4 Wiley mill. Half of this ground sample was retained as a record sample. A 1-gram sample (approximately) of the ground bottom ash was dried in a drying oven for 1 hour at 103°C, cooled in a desiccator, and weighed. This dried, weighed sample was then ignited in a muffle furnace which was brought to 750°C and maintained at that temperature for 1 hour. The sample was then cooled, desiccated, and reweighed to the nearest 0.1 mg. The weight loss of this sample was reported as percent combustible matter.

Dry fly ash samples for bulk density, combustible content, and resistivity analysis were taken from beneath the B-field section of the precipitator only once during each week of testing. The procedure used in splitting the fly ash sample is shown in Figure 20.

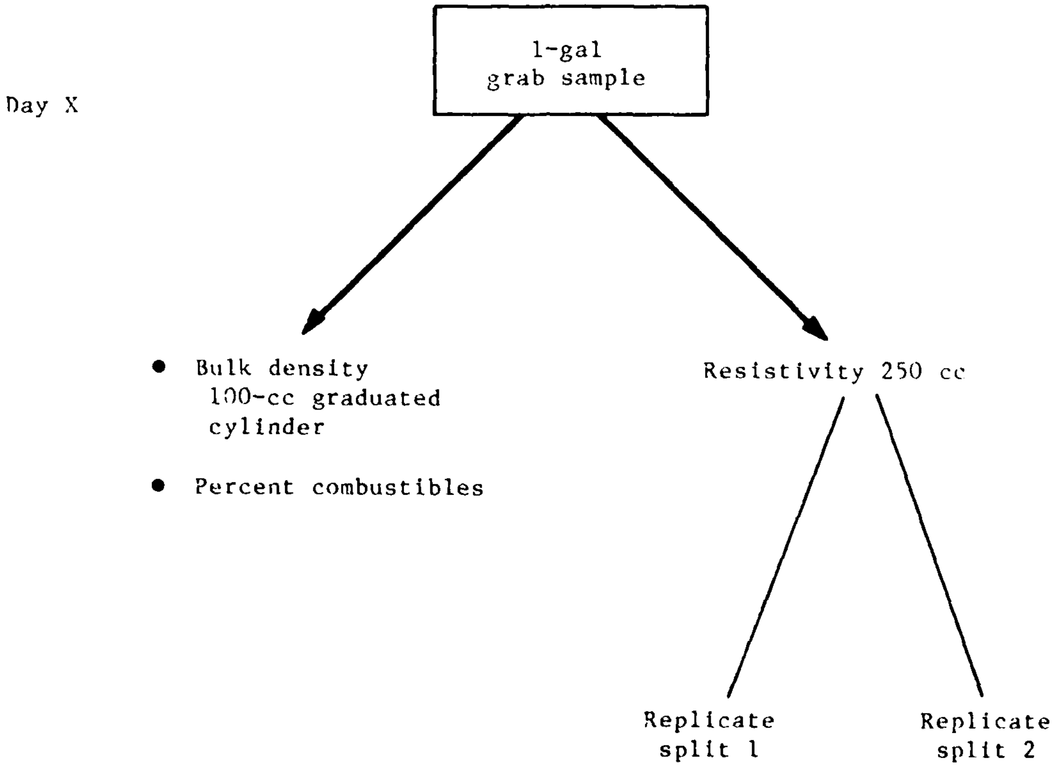

Figure 20. Fly Ash Split Procedure.

MASS AND ENERGY BALANCE

Both mass and energy balances require physical characterization of input and output streams to the system. Also, thermal properties must be determined to do energy loss analysis. Common losses in any combustion boiler system include sensible heat of dry flue gas and latent heat of vaporization of moisture in the flue gas, unburned combustibles in bottom and fly ash, and radiative and convective losses from the boiler and ductwork surfaces. All data used in mass and energy balance calculations are presented in Appendix A. Calculation methods and equations for the mass and energy balances are given in Appendix B.

BOILER EFFICIENCY

Sufficient data were collected to determine the boiler thermal efficiency by both the input-output method and the heat loss method as described in the ASME PTC 4.1. The precision in the HTHW heat output measurement system was not adequate for input-output efficiency determinations. Also, the hourly rate of fuel usage was documented to a sensitivity of ±5 percent. In view of these potential sources of error, boiler thermal efficiency was determined by the loss (heat balance) method which is not sensitive to either the measurement of HTHW production or the fuel input rate. Furthermore, ASME PTC 4.1 recommends that the efficiency of HTHW generators be determined by the heat loss method.

The heat balance efficiency is determined by the equation

$$\text{Efficiency} = 100 \quad 1 - \frac{\text{heat losses}}{\text{heat inputs}}$$

The values applied to this equation are determined from the following measurements:

1. Fuel properties (to determine heat input)

   Ultimate analysis
   Higher heating value
   Moisture content
   Fuel usage rate

2. Flue gas properties (to determine heat loss)

   Boiler outlet O_2 concentration
   Preheater outlet flue gas temperature (ESP inlet)
   Fly ash concentration at ESP inlet

3. Ash properties (to determine heat loss)

Combustibles content of collected ESP fly ash
Combustibles content of bottom ash

The heat losses accounted for include the following:

1. Wet flue gas loss--determined from the fuel moisture content, hydrogen content, fuel input rate, and ESP inlet (boiler outlet) gas temperature. Humidity in the combustion air was neglected.

2. Dry flue gas losses--from fuel input rate, stoichiometric air:fuel ratio, excess air determination, and boiler outlet gas temperature. It was assumed that all combustion air was at 70°F.

3. Fly ash losses--unburned combustibles in the collected ESP fly ash. Mass rate determined by the EPA Method 5 at ESP inlet.

4. Bottom ash losses--from difference in ash input rate and measured fly ash rate. Unburned combustibles in bottom ash samples for heating value.

5. Radiative/convective losses--from American Boiler Manufacturers Association (ABMA) Standard Radiation Loss Chart, ASME PTC 4.1, p. 67.

Any other losses were considered negligible or unaffected by fuel type.

Heat input is the product of the fuel feed rate and fuel higher heating values. Other sensible heat credits were neglected. For results of the calculation, see Data Columns 201 through 269 in Appendix B.

BOILER OPERATION

Pertinent boiler operating data were collected every hour throughout the daily test period. Typical data collected included: HTHW output rate, makeup water input, relative air flows, temperatures and pressures of the steam and feedwater, and water level in the steam drum. Also, the static pressures throughout the stoker and boiler system were recorded to indicate any abnormal operating conditions in the gas flow path. Flue gas temperatures were continuously monitored at the boiler outlet on the breech. Also, thermocouples were located (Figure 15) to indicate any shifts in flue gas temperature or hot water input and output. All these temperature sensors were Type K thermocouples and were attached to a multipoint temperature recorder

Rotograte Speed

Since the length of time for the grate to travel from the back of the boiler to the front has a direct effect on the depth of the ash bed and fuel combustion residence time, the rotograte speed was checked with chalk markings and a stop watch at maximum and half speed. The optimum speed adjustment, in combination with overfire and underfire air adjustments, provided more complete combustion of the fuel and reduced clinker formation on the ash bed. Boiler flames and ash bed depth as well as general bottom ash appearance were photo documented at various times during the tests. General observations about the flame color, ash bed depth, and bottom ash appearance were also recorded.

Control Room and Boiler Process Instruments

In the Building 1240 control room much of the process data was readily available from charts and sight gauges (Figure 21). All instrumentation was carefully checked or calibrated prior to the tests. All of the temperature and pressure gauges were verified by SYSTECH instruments to within ±0.5 percent. Hourly instrument readings were recorded by SYSTECH engineers and compared later with separate hourly plant records to ensure reliability and completeness.

PARTICULATE EMISSIONS

Particulate Mass Emission Rate

Particulate emissions to the atmosphere were determined by analyzing the stack effluent in accordance with the Code of Federal Regulations (CFR), Section 40, Sampling Methods 1 through 5. These tests were conducted twice per day and also yielded data on flue gas flow rates, moisture levels, and temperatures which were used in particulate emissions calculations. Sampling was performed at locations indicated in Figure 22. Figure 23 is an illustration of the Method 5 sampling train.

Particle Size

An inertial cascade impactor manufactured by Meteorology Research Incorporated was used to determine particulate size distribution at the ESP inlet. Seven collection stages yield seven size fractions spanning from "greater than 30" to "less than 0.4 microns." The particulate sample was collected and sized aerodynamically in the ESP inlet duct at isokinetic conditions. A schematic of the cascade impactor train is shown in Figure 24.

Trace Metals Analysis

Filters and probe rinses from all Method 5 tests run at the ESP outlet were composited by fuel type and analyzed for trace metal content by Inductively Coupled Plasma (ICP) spectroscopy. The eight dRDF and three coal

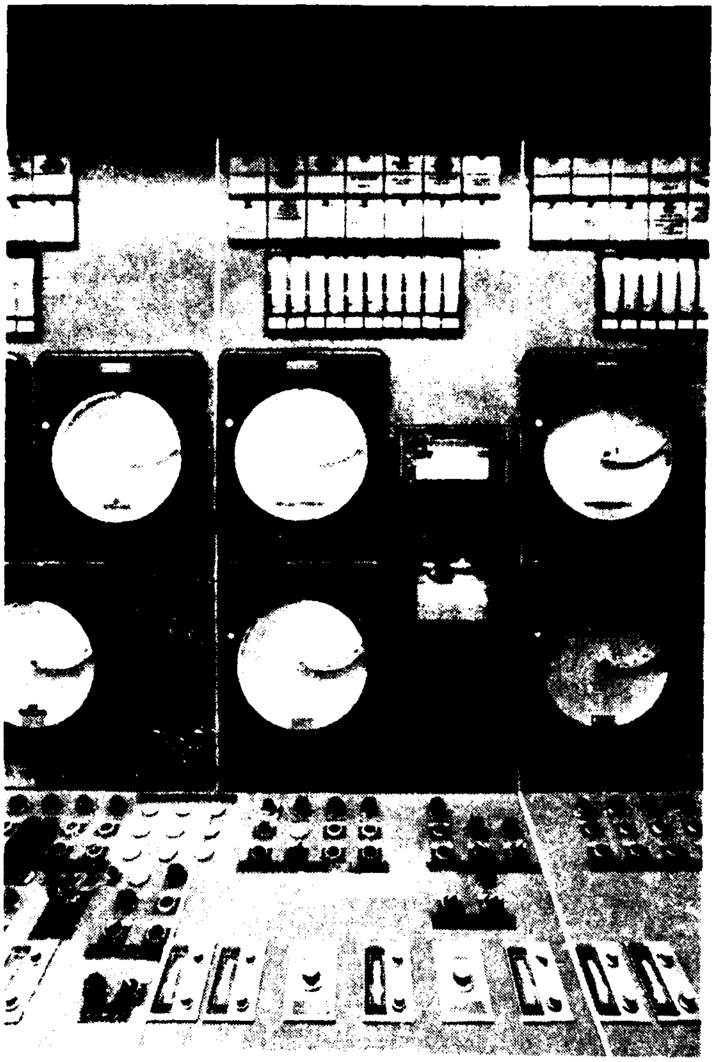

Figure 21. Process Control Panel for the Test Boiler.

particulate samples were sent to Monsanto Research Corporation's Dayton laboratory where they were composited into two analytical samples and analyzed by ICP for the following metals.

Silver	Ag	Magnesium	Mg
Aluminum	Al	Manganese	Mn
Boron	B	Molybdenum	Mo
Barium	Ba	Nickel	Ni
Beryllium	Be	Lead	Pb
Calcium	Ca	Antimony	Sb
Cadmium	Cd	Tin	Sn
Cobalt	Co	Strontium	Sr
Chromium	Cr	Titanium	Ti
Copper	Cu	Vanadium	V
Iron	Fe	Zinc	Zn

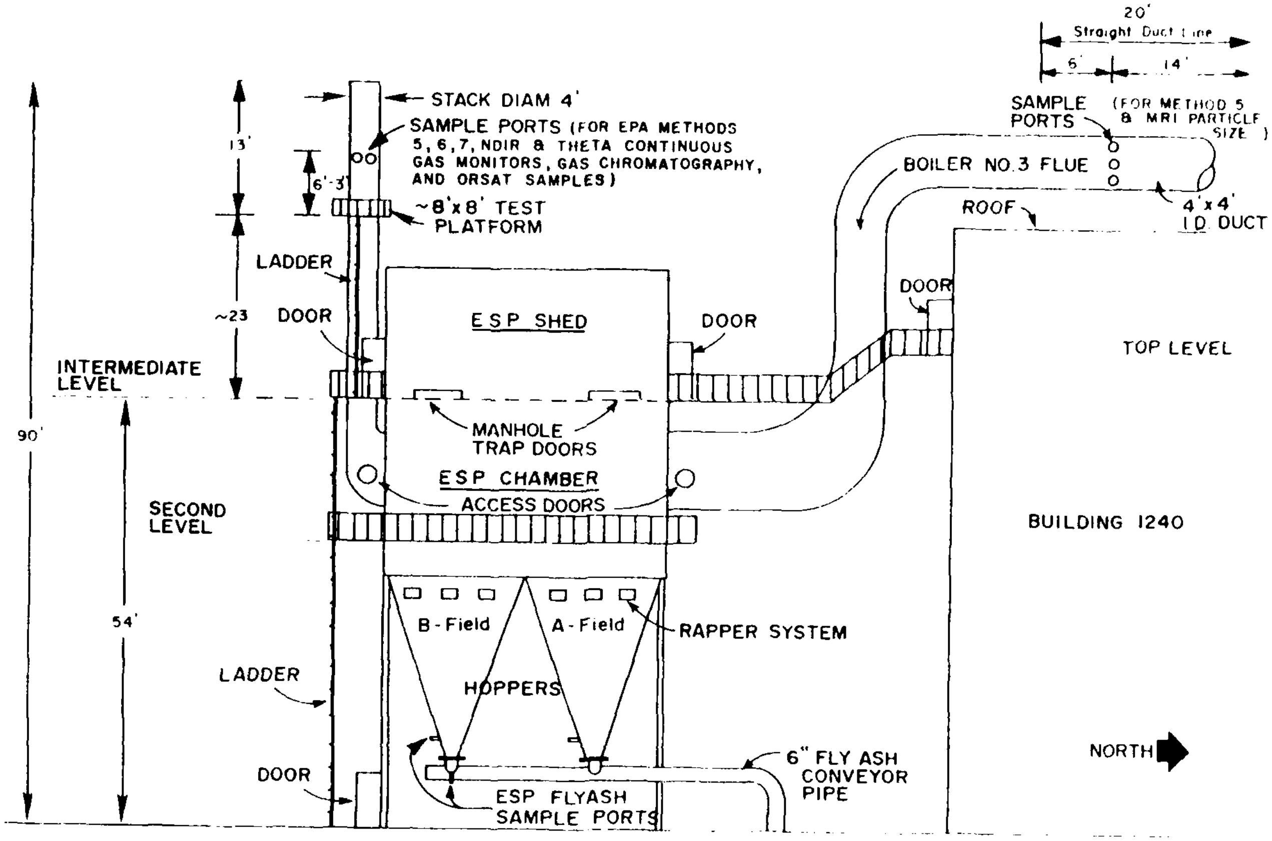

Figure 22. Cross Section of the ESP and Roof Ductwork.

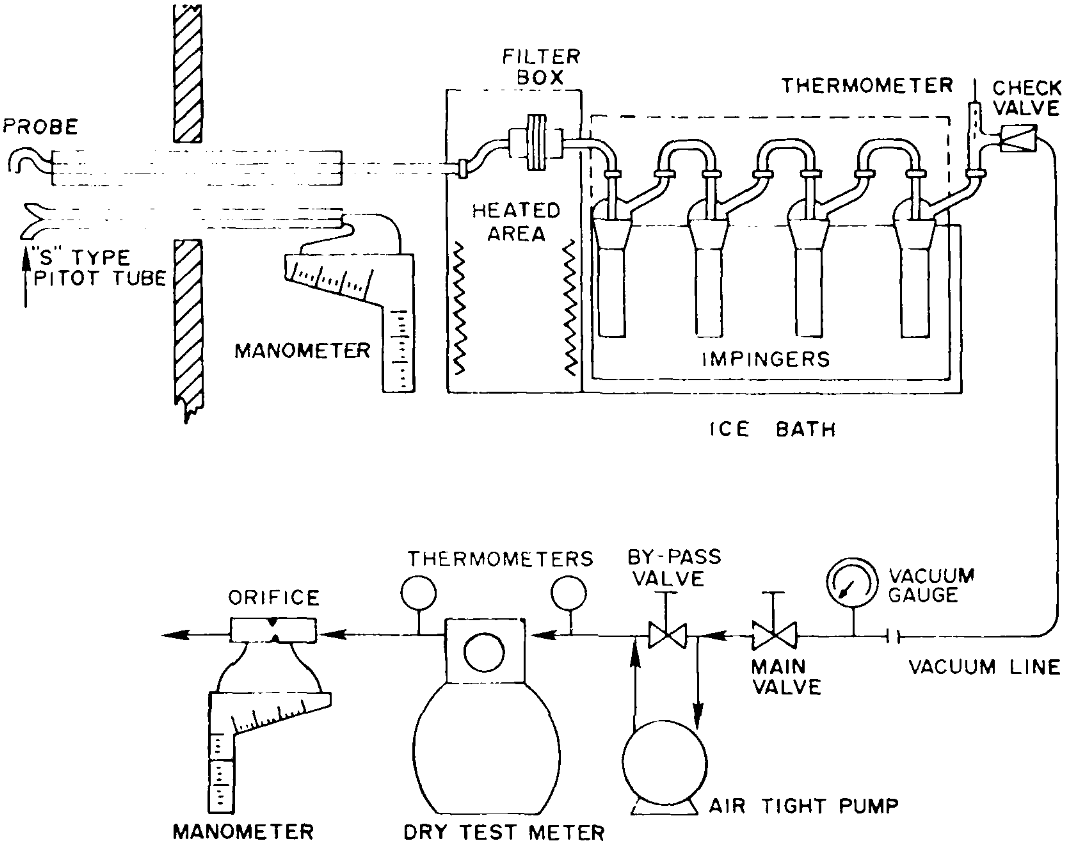

Figure 23. Schematic of EPA Method 5.

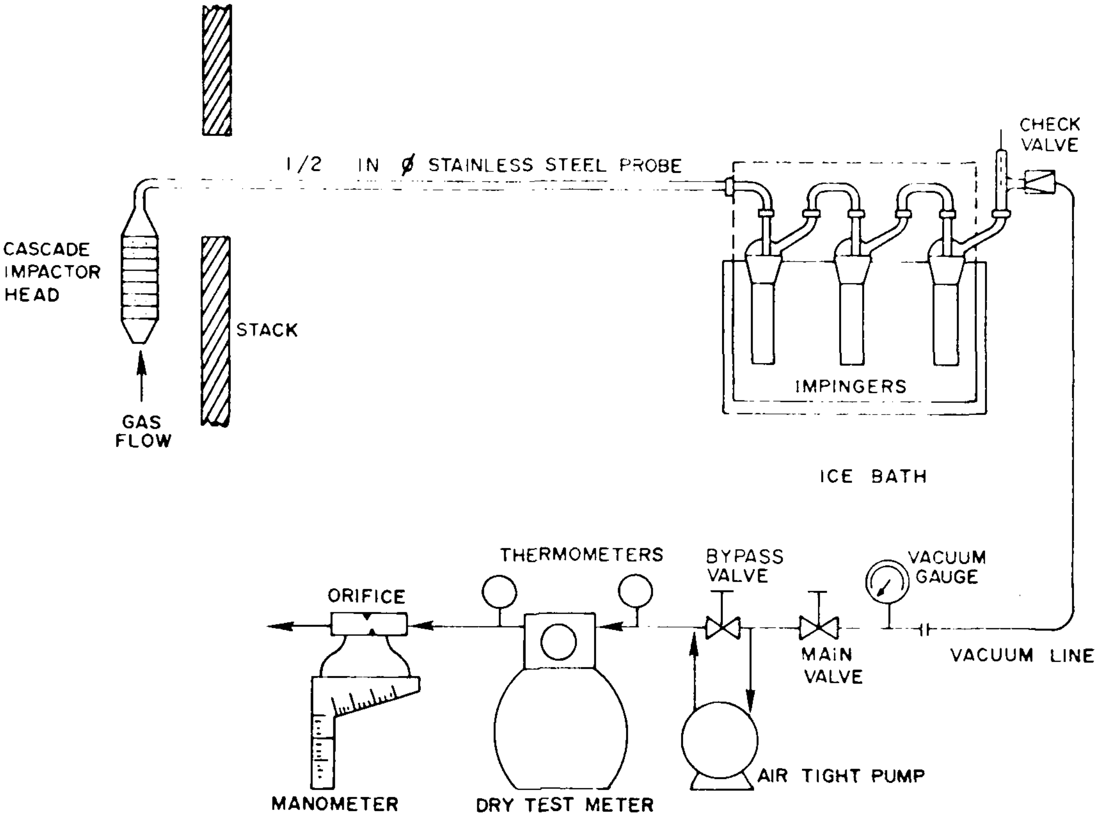

Figure 24. Schematic of Inertial Cascade Impactor.

Precipitator Performance

Particulate emissions were measured twice daily. To measure precipitator efficiency, simultaneous measurements of particulate concentrations were made upstream and downstream of the electrostatic precipitator. Figure 22 shows the sampling port locations.

Particulate concentrations at the ESP inlet and outlet were both determined in accordance with CFR 40, Methods 1 through 5. These data were used as the fly ash mass rate in the mass balances.

Gaseous Emissions

Boiler exhaust gases were periodically sampled using EPA methods and continuously monitored at the electrostatic precipitator outlet. Monitoring and sampling methods at the ESP outlet were interpreted to determine the emissions to the environment.

CO_2, CO, SO_x, NO_x, and O_2 (Continuous Monitors)

The composition of the stack flue gases emitted to the atmosphere were monitored continuously for CO_2, CO, SO_x, NO_x, and O_2. The stack gases were drawn from the stack and conditioned prior to entering the analytical instruments by removing the particulate matter and water vapor via a sintered metal filter and an ice bath condensing chamber. The conditioned gas sample was transported via Teflon tubing to the SYSTECH mobile laboratory which was located at the base of the stack.

Carbon dioxide and carbon monoxide levels in the flue gas were monitored during the daily test periods with Beckman Model 864 Infrared Analyzers. Within each analyzer two equal energy infrared beams are directed through two optical cells, a flow-through sample cell, and a sealed reference cell. Solid state electronic circuitry continuously measures the difference between the amount of infrared energy absorbed in the two cells. This difference is a measure of the concentration of the component of interest in the sample stream. The manufacturer's specifications on these instruments indicate an accuracy of 1 percent of full scale with zero and span drifts of ±1 percent of full scale for 24 hours. The electronic response time for deflection of 90 percent of scale is 0.5 seconds. The response time due to sample transportation from the stack is approximately 3 minutes.

Other gaseous emissions of interest were monitored on a Theta Sensor Source Monitor, Series 7213, Model 1940. This instrument monitors O_2, SO_x, and NO_x simultaneously through the use of three separate electrochemical transducers connected in series. The principle of operation of this instrument is based on the combined use of a semipermeable membrane and selective oxidation-reduction reactions within completely sealed electrochemical transducers. The electrical signals generated by these transducers are directly proportional to the concentrations of the gases being monitored. The response is linear over the entire analytical range. The accuracy stated by the manufacturer is ±2 percent of full scale. The stated zero drift for NO_x and SO_x is 2 percent for 24 hours with a span drift of 1 percent for 24 hours. The oxygen cell is stated to have 0.5 percent zero drift for 24 hours with a span drift of 1 percent. The NO_x and SO_x cells give a 90 percent deflection within 60 seconds while the oxygen cell responds in less than 20 seconds. In all cases instrument response is considerably less than the delay due to the sample transfer from the stack.

After the instruments were set up at the field test site and every day prior to the start of an 8-hr test period, each instrument was subjected to a two point calibration consisting of a zero gas nitrogen (N_2) and a calibration gas which is equivalent to a 90 percent of scale reading. A morning and evening zero and span calibration procedure was employed to verify that no significant changes in instrument response had occurred during the test period. The instrument response obtained on these morning and evening calibrations was averaged to obtain a daily calibration correction factor which was applied to the data recorded during that day for each instrument.

The electrical outputs from the continuous monitoring instruments were channeled to a Leeds & Northrup SPEEDO-MAX® W Multipoint Strip Chart Recorder with a six channel capability. The trace for each instrument was analyzed for maximum reading, minimum reading, and the mean of all 5-min points during that day's test period.

Orsat Analysis

The Orsat was run only as a quality control check. Single point grab samples of combustion gases from the stack were analyzed for percent O_2, CO_2, and CO by Method 3, CFR 40 dated 18 August 1977, using an Orsat analyzer. These Orsat measurements were used as a check of the continuous monitors for those gases. Orsat samples were drawn directly into a collapsible gas sampling bag at the stack by means of a hand squeeze bulb.

SO_x (EPA Method 6)

Although SO_x emissions were monitored continuously, the data which are reported in Section 4 were acquired in accordance with CFR 40, Method 6. Samples were taken once per day at the stack through an extra sampling port with a Method 6 sampling train manufactured by Nutech Incorporated.

NO_x (EPA Method 7)

NO_x emissions were determined by EPA Method 7 which is detailed in the Code of Federal Regulations. Two sets of three grab samples were taken at the stack each test day.

C_1 through C_6 Hydrocarbons by Gas Chromatography

The presence of hydrocarbons in the flue gas is an indicator of the incompleteness of the combustion process. Combustion gases from the stack were analyzed for volatile hydrocarbons (C_1 through C_6) by a GC. A Perkin-Elmer Sigma 2 GC was outfitted with a flame ionization detector and used for this analysis. Ten-mℓ aliquots were delivered to the GC from the Orsat gas sampling bag by means of a gas-tight syringe. Separation was accomplished with a well conditioned 6 ft × 1/8 in. stainless steel Porapak Q column using a temperature program suitable for identification of organic compounds with boiling points of -160° to +90°C.

All sample responses were bracketed with calibration gas standards. This calibration gas mixture consisted of 15 parts per million (ppm) each of methane, ethane, n-propane, n-butane, n-pentane, and n-hexane. The results of the sample analyses are reported as total hydrocarbon concentration observed in the six boiling ranges corresponding with methane through hexane (-160° to -100°C, -100° to -50°C, -50° to 0°C, 0° to 30°C, 30° to 60°C, and 60° to 90°C). This methodology permits an unknown compound to be identified as having the same retention time as one of the six standard compounds.

Carbonyls

The carbonyl group (made up of the double bond carbon and oxygen, C=0) can form highly toxic gases such as phosgene ($COCl_2$) or toxic liquids such as bromophosgene ($COBr_2$). Therefore, the stack dRDF effluent was tested for carbonyls at the request of the Air Force.

Carbonyls were collected via a Method 5 type impinger train. Sampling for carbonyls was conducted during the last day of the steady state dRDF firing mode. The sampling duration was approximately 60 minutes. The carbonyls sampling train consisted of a stainless steel probe connected with Teflon tubing to four impingers connected in a series. The first two impingers (Greenburg-Smith) contained a 1 percent sodium bisulfite solution. The third impinger was empty, and the fourth impinger was filled with silica gel. The impinger train was partially immersed in an ice bath. The final impinger is connected to an EPA Method 5 meter box. The sampling train was leak checked before and after each test. Analysis was performed as soon as possible after completion of sampling, usually within 60 minutes.

Carbonyls were analyzed immediately after sampling by a starch-iodine titrametric procedure. The impingers from the carbonyl sampling train were also analyzed for the presence of the specific carbonyl compound formaldehyde. No formaldehyde was identified by spectrophotometric analysis after complexing with chromotropic acid reagent (4,5-dihydroxy-2,7-naphthalenedisulfonic acid disodium salt).

SECTION IV

RESULTS

DATA REDUCTION

Section IV is a presentation of analytical data that were summarized from boiler testing. The more detailed data are presented in Appendix A and are referenced in the following sections.

FUEL PROPERTIES

The fuel properties for the coal and the 1/2-in. diameter pellets of dRDF used in this test are presented in Table 9 on an as-tested basis to indicate the actual moisture content at the time of combustion. The daily sample test results are presented in Tables A-1 and A-2 for coal and dRDF, and the ultimate analysis averages for both fuels on a dry weight basis are given in Table A-3.

TABLE 9. Fuel Physical Property Averages (As-Tested Basis).

Parameter	Coal*	dRDF†
Carbon percent	79.60	44.23
Hydrogen percent	5.14	5.60
Oxygen percent	5.97	35.99
Nitrogen percent	1.66	0.34
Sulfur percent	0.67	0.21
Ash percent	5.54	9.65
As-tested moisture percent	5.03	11.42
Higher heating value (Btu/lb)	13,051	7,164
Bulk density (lb/ft^3)	53.61	32.60

* Average of three coal samples.

† Average of eight dRDF samples.

The 0.67 percent sulfur content of this coal is extremely low. Purchasing low sulfur coal is the technique used by this plant to minimize SO_2 emissions as required by law. A check of independent analysis by two other laboratories (Blue Diamond and Kenwill) confirmed the low sulfur content in the bituminous coals used in this test.

Based on the fuel properties presented in Table 9 the differences in fuel characteristics between dRDF and coal are readily apparent. The dRDF has a very high oxygen content compared with other fossil fuels such as coal. This increased oxygen content results in dRDF having a lower air-to-fuel ratio.

Additional observations that can be made by comparing the fuel properties presented in this table are as follows:

1. The dRDF produces 13.46 pounds of ash per 10^6 Btu or three times the amount of ash per equivalent heat input as coal which produces 4.24 pounds of ash per 10^6 Btu.
2. The input of sulfur is .29 lb/10^6 Btu for dRDF and .51 lb/10^6 Btu for coal. Therefore, dRDF contains less sulfur than even low sulfur coal.
3. The dRDF is a low nitrogen fuel; therefore, it could be expected to produce low NO_x emissions.
4. The dRDF is higher in moisture than coal at 15.94 lb/10^6 Btu for dRDF and 3.85 lb/10^6 Btu for coal. Thus higher wet flue gas losses are expected when burning dRDF.
5. The dRDF has a lower bulk density than coal. The measured density of coal was 53.61 lb/ft^3 or .70 × 10^6 Btu/ft^3, and the dRDF was 32.60 lb/ft^3 or .23 × 10^6 Btu/ft^3. Thus a larger volume of dRDF must be handled to produce the same boiler heat output.

Overall, the pellets that were used in this test had a higher heating value (Btu/lb) than the dRDF tested at either Erie or Hagerstown. This finding is consistent with the fact that the pellets used in this test were lower in ash and moisture content than the pellets tested in Erie[1] or Hagerstown.[2]

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[1] Gerald H. Degler, A Field Test Using Coal:dRDF Blends in Spreader Stoker-Fired Boilers, U.S. Environmental Protection Agency, Cincinnati, 1980.

[2] Ned J. Kleinhenz, Coal:dRDF Demonstration Test in an Industrial Spreader Stoker Boiler. Use of Coal-dRDF Blends in Stoker-Fired Boilers, National Technical Information Service, Springfield, VA, 1981, Volumes I and II.

BOTTOM ASH PROPERTIES

Average bottom ash properties of combustible content, higher heating value, and bulk density are given in Table 10; data calculated on a daily basis are given in Table A-4. The samples were removed while dry from the ash hopper of each of the three rotograte zones (see Table A-5 for bulk density results and Table A-6 for combustible content analysis).

Table 10. Bottom Ash Properties.

Fuel	Average combustibles (weight percent)	Average higher heating value (Btu/lb)	Average density (lb/ft^3)
dRDF	1.17	163*	29.1
Coal	6.13	868	28.2

* Bomb calorimeter results show 633 Btu/lb for dRDF bottom ash. Heating value reported here is based on assumption that remaining combustibles in ash are carbon.

Densities ranged from 26.4 to 32.2 lb/ft^3 for bottom ashes of both coal and dRDF. The average density of all dRDF bottom ash was 29.1 lb/ft^3 with a standard deviation of 1.9 lb/ft^3. The average for coal was 28.2 lb/ft^3 with a 2.2 lb/ft^3 standard deviation. Therefore, there is no significant change in bottom ash bulk density caused by dRDF.

FLY ASH PROPERTIES

Fly ash samples were taken from the ESP hopper during two dRDF test burns (3 March and 4 March) and one coal test burn (8 April). The samples were analyzed for combustible content and density. Each of these three samples was split for a total of six resistivity determinations. The results of these analyses are shown in Table 11.

The resistivities are less than the ASME PTC 28, paragraph 4.05, recommended minimum measurable level of 1×10^7 ohm-cm; therefore, the results are not considered reliable because of lack of instrument sensitivity in this range. One of the causes of low resistivities is the presence of a high unburned carbon in the fly ash. The unburned carbon levels in the fly ash were not abnormally high, i.e., 22 to 26 percent for dRDF and 33 percent for coal. At low resistivity levels fly ash particles normally collect on

Table 11. ESP Fly Ash Physical Properties.*

Test date	Fuel	Sample No.	Combustibles percent	Density (g/mℓ)	Resistivity (Ohm-cm)
3/3/81	dRDF	1	26.31	0.188	2.23×10^5
		2			1.86×10^5
3/4/81	dRDF	3	21.75	0.149	3.35×10^5
		4			3.35×10^5
4/8/81	Coal	5	32.55	0.145	6.52×10^3
		6			4.46×10^3

* All resistivity determinations were performed in accordance with ASME PTC 28.

the precipitator walls, lose their charge, and re-enter the gas stream. This did not occur during testing since ESP fly ash removal efficiency was high (over 97 percent) for both coal- and dRDF-generated fly ash. While these low resistivities are suspect, the trend of resistivity increasing when changing fuel from coal to dRDF is consistent with the results from Erie and Hagerstown.

MASS BALANCE

The mass balance consists of measurements and calculations of the input rates of combustion air and fuel and the output rates of flue gas, fly ash (particulates), and bottom ash. The input and output requirements to sustain a 30 × 10^6 Btu/hr HTHW load are summarized in Table 12 for coal and dRDF. As expected, the boiler required almost twice as much dRDF fuel as coal, which again emphasizes the need for a large volume fuel handling system when using dRDF. Because dRDF has about half the air-to-fuel ratio of coal but also about half the heating value of coal, both dRDF and coal require approximately equal amounts of combustion air to release equal amounts of heat. Also, a considerable increase in the output of moisture with the flue gas can be expected when combusting dRDF. The dry flue gas and fly ash output were about the same for both fuels. The bottom ash output of dRDF was over four times greater than the ash output of coal; thus the need to ensure that the ash handling system can handle this increased amount of bottom ash from the boiler is emphasized. More detailed input and output data are given in Table A-7.

BOILER EFFICIENCY

Boiler efficiency was calculated using the heat loss method according to the ASME PTC 4.1. Table 13 is a presentation of the results of these calculations. These results are derived from details given in Table A-7.

Table 12. Mass Balance.*

	Coal (lb/10^6 Btu heat output)	dRDF (lb/10^6 Btu heat output)
Inputs:		
Fuel	96	183
Air	2,655	2,593
Total in	2,751	2,776
Outputs:		
Dry gas	2,697	2,644
Wet gas	49	113
Fly ash	1.2	1.2
Bottom ash	4.1	17.7
Total out	2,751.3	2,775.9

* Calculations are based on overall averages of 159 percent excess air, 30 × 10^6 Btu heat output, and boiler efficiency at 76.45 percent for dRDF and 80 percent for coal.

It should be noted that there is about a 3.5 percent drop in efficiency when burning dRDF compared with coal (Table 13). This shift compares well with the Erie results where a 2 percent drop in efficiency occurred when switching from coal to a 1:2 coal-to-dRDF blend.

ENERGY BALANCE

The summary of inputs and outputs for the energy balance is given in Table 14 in percentages of heat input. The heat values shown in this table are derived from the heat loss method details given in Table A-7. Dry flue gas, bottom ash, and radiation/convection heat losses were about the same for both fuels. However, the heat loss in flue gas moisture by dRDF fuel was over twice the heat loss from coal combustion. But, the heat loss of dRDF-generated fly ash was half that of coal-generated fly ash. This reduction can be attributed to the reduced combustibles content in dRDF fly ash.

Table 13. Boiler Efficiency Results.

Date	Fuel	Efficiency (percent) heat loss
3/2	dRDF	75.9
3/3	dRDF	75.0
3/4	dRDF	76.2
3/5	dRDF	76.7
3/30	dRDF	76.7
3/31	dRDF	76.8
4/1	dRDF	76.6
4/2	dRDF	77.7
Average efficiency		76.45
Standard deviation		0.69
4/6	Coal	80.5
4/7	Coal	79.8
4/8	Coal	79.7
Average		80.0
Standard deviation		0.36

Stoker Operation

Most adjustments occurred during fuel changeover from coal to dRDF, or vice versa, and during the subsequent 4- to 8-hr boiler stabilization period. Generally, no significant variations in operating procedures, stabilization time, and stoker adjustments were caused by the firing of dRDF compared with coal. The boiler response to a rotor or grate speed adjustment was fairly rapid (within a minute or two) and required communication between the boiler operator and the control room to determine when the proper setting had been reached.

The rotor feeder throw test results at medium rotor speed are shown in Table 15. These measurements are the result of the cold flow tests which were made prior to firing up the boiler. Also, Figure 25 is a comparison of the fuel throw distribution patterns for coal and dRDF from the front of the boiler to the rear. The grate speed varied from a low setting of 24 in./hr to a high setting of 40 in./hr.

Fuel Bed Conditions

Before starting the first week of dRDF testing, the fuel bed consisted of 100 percent coal. The flame height for a steady coal burn at a boiler load

Table 14. System Energy Balance.*

	Coal (percent fuel heat input)	dRDF (percent fuel heat input)
Input:		
Fuel, air, and HTHW return	100.00	100.00
Output:		
HTHW out	80.01	76.50
Dry flue gas	12.65	11.20
Water vapor in flue gas	4.55	10.00
Bottom ash	0.28	0.21
Fly ash	0.81	0.39
Radiation and convection	1.70	1.70
	100.00	100.00

* These percentages were determined at one average boiler load of 30 × 10^6 Btu/hr for three coal runs and eight dRDF runs.

Excess air level of 169 percent for coal.
Excess air level of 160 percent for dRDF.

Table 15. Results of Fuel Throw Tests for Three Stoker Spreaders at Medium Feeder Setting.

Measurement parameter	Coal	dRDF
Density, lb/ft^3	42.20	27.60
Feed rate, ft^3/min	6.12	6.03
Feed rate, lb/hr	15,500	10,000

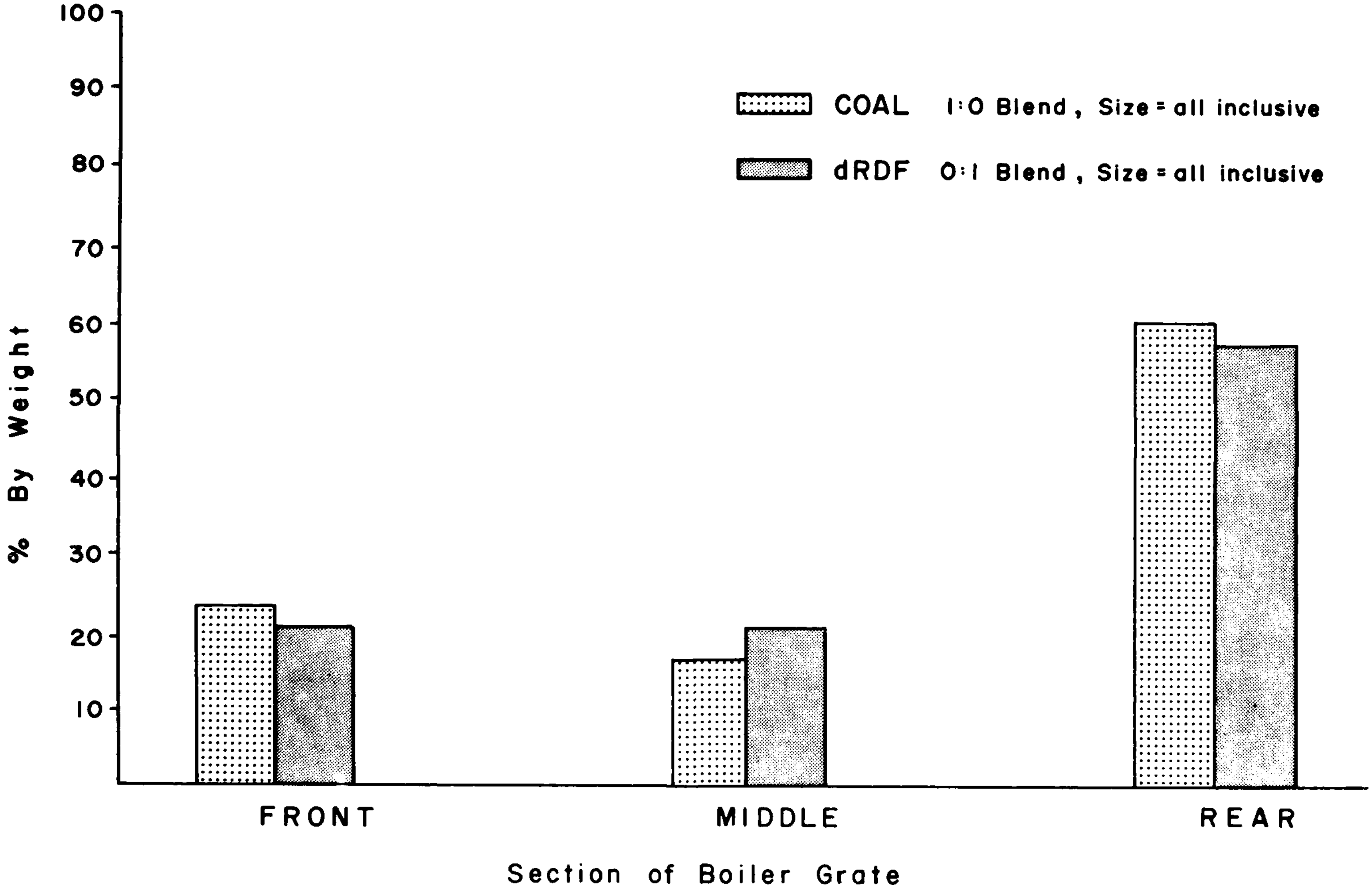

Figure 25. Fuel Distribution on Grate.

of 30 × 10^6 Btu/hr was [illegible] blue and white in color [illegible] excess air rating for [illegible] of 160 percent.

When the transition [illegible] dRDF [illegible] steadily increased [illegible] an orange colored [illegible] ft up the [illegible] Figure 26 shows the dRDF [illegible]

Figure 26. dRDF Flame Pattern Near Rear of Boiler.

shortly after stabilization. During the transition the fly ash reinjected into the furnace from the multiclone dust collector increased, resulting in a deeper ash bed around the injection port. Clinkering from 3 to 6 in. above the ash bed was observed. These problems occured during the first 4 hours of stabilization until the operators located the proper combustion control settings.

Ash Removal

There was no noticeable difference between coal and dRDF bottom ash removal procedures. About the same length of time (approximately 30 minutes) and frequency (usually two to three times per day) were required to rake all three zones of bottom ash through a grate screen for removal of clinkers. More clinkers were found for dRDF than for coal during stabilization firing. A photograph of the raking of dRDF bottom ash is shown in Figure 11. Once steady state combustion conditions were achieved, there was minimal clinkering using dRDF or coal. Fly and bottom ash were both removed without any plugging of the pneumatic removal system.

FUEL HANDLING

Storage and handling of coal and dRDF fuels have their problem areas, such as dust accumulation from both fuels along the conveyor lines, dRDF buildup and jamming in the fuel bunker, and heat buildup in dRDF piles even on cold winter days. The following sections describe some of the observations in operating the fuel transport system from delivery through combustion.

Fuel Storage Containers

The dRDF storage silo was never more than one-third full. As the fuel level was dropped, a layer of dRDF was left clinging to the wall (Figure 27). It appeared that this layer could be removed by rodding or blasting with an air hose. The dRDF stored in the silo was delivered by trucks with pellets aged not more than 2 to 3 days. To preclude the possibility of jamming during storage, dRDF was dispensed at a daily rate of 1 ton over a 15-min period from the silo to the bunker above Boiler 3.

The fuel storage bunker, which was under observation during this test, was the source of most of the funnel formation and dispensing problems that were experienced when using dRDF. The 2- × 2-ft opening to the feed chutes of the stoker was controlled by a sliding gate which was difficult to open or close without the aid of a toe bar applied to the gate control wheel. When dispensing coal, the gate was much easier to manually open and close, often without the aid of the toe bar.

Inside the fuel bunker an undesirable dRDF piping effect was commonplace as the dRDF was dispensed (Figure 28). A funnel shaped cavity would always form with walls often over 10 ft high and with funnel shaped bases ranging from as little as 2 ft to 8 ft in diameter depending on the height of the dRDF pile. After 2 months of storage in the bunker, dRDF surface

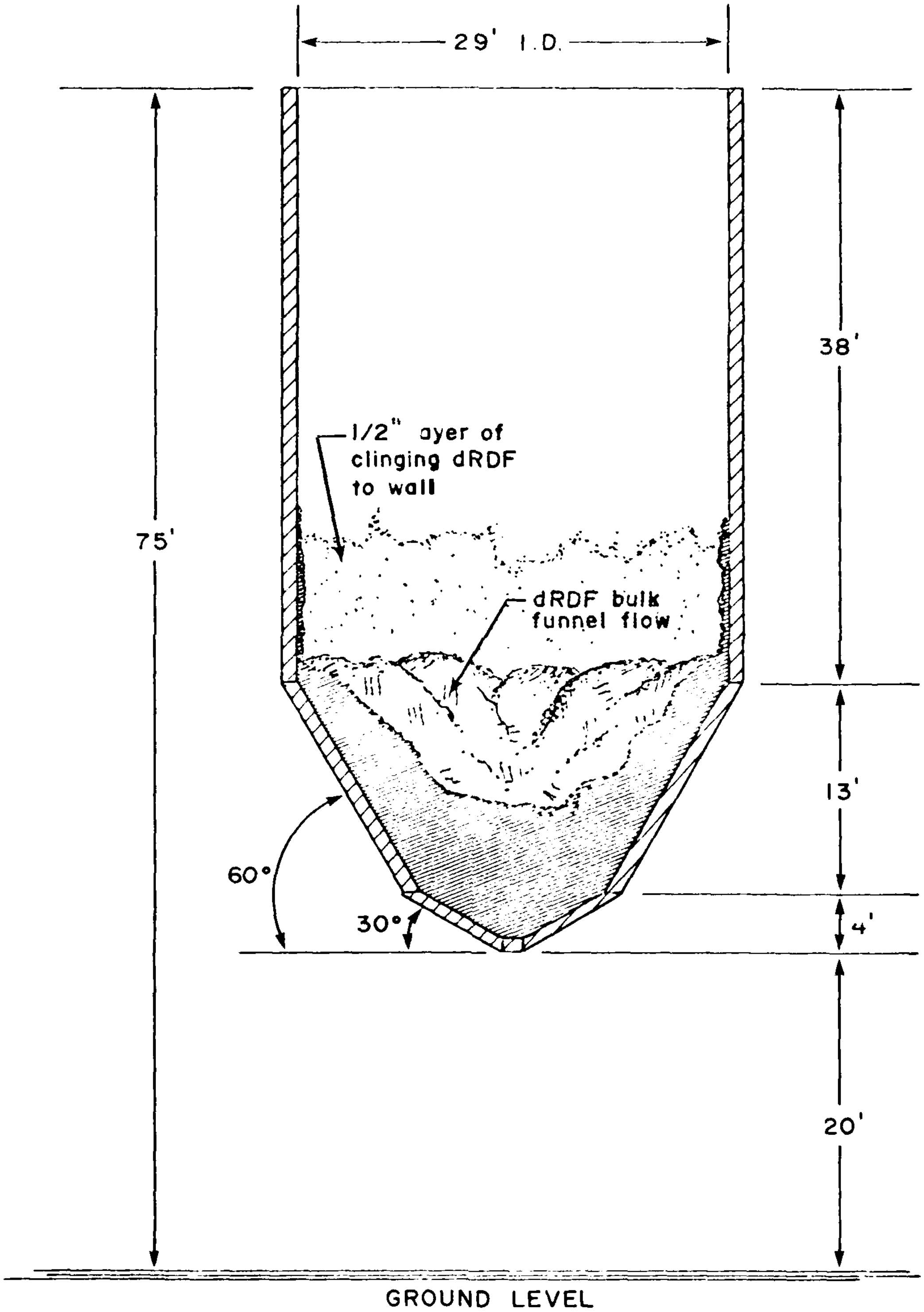

Figure 27. dRDF Storage Silo.

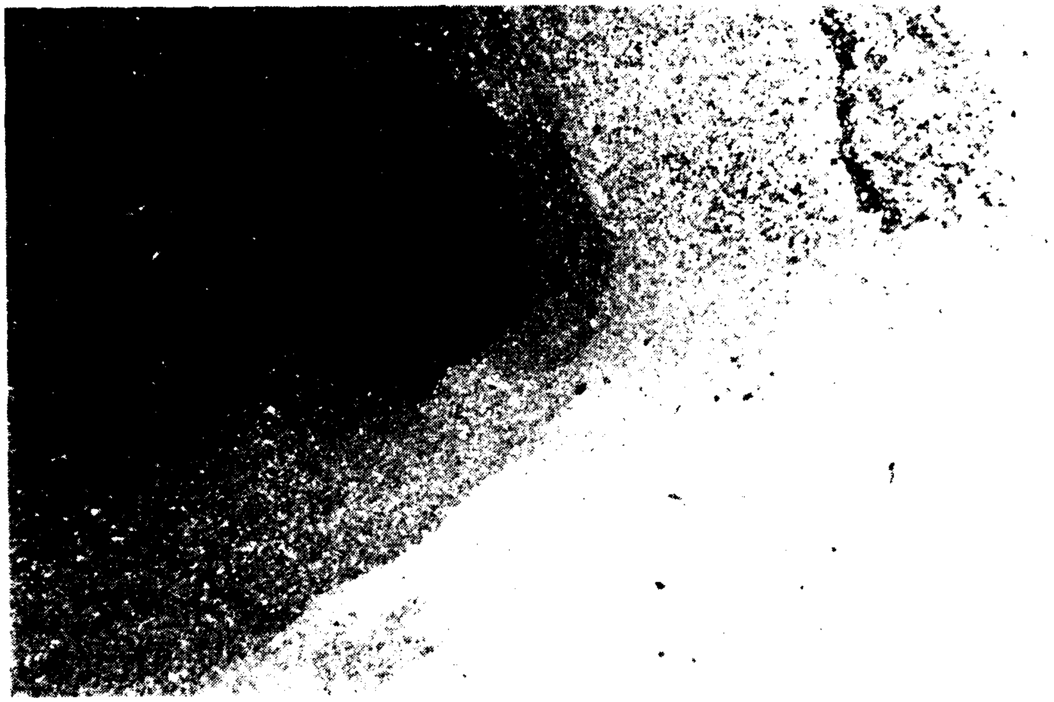

Figure 28. Typical dRDF Funnel Formation in Fuel Bunker.

temperatures as high as 105°F (41°C) were observed in 4 to 5 ft high hardened piles that were broken up while shoveling, and an increase in rigidity and resistance to flow was very common.

Transport Equipment

Trucks delivered the dRDF from the Teledyne production facility near Baltimore, Maryland. Front-end loaders were used at the test site to move both coal and dRDF to the shaker house hoppers for conveyor feeding direct to the parabolic bunkers in Building 1240 or to interim storage in one of the four available silos. Very little pellet breakup was observed in direct movement of the dRDF from the yard to the conveyor feed hoppers. However, if the front-end loader plowed or "bulldozed" a pile to gain yard space, considerable breakup occurred.

Conveyor systems in the Building 1240 fuel handling system were nominally 2 ft (0.6 m) wide. Some breakup did occur in dRDF pellets over the many 3- to 6-ft drops in the system (an estimated total of 50 to 75 ft in combined drops). For the parts of the conveyor line located outside Building 1240, dRDF fines were observed being blown around in great quantities on a day in March when winds gusted from 35 to 40 mph. Also, considerable dRDF dust buildup was observed along various transfer points. This build-up required clearing away every 2 to 3 months depending on dRDF fuel consumption. Dust accumulation can pose many equipment and respiratory problems, especially inside the plant (Figure 29).

Open Storage Conditions

Flow characteristics of dRDF were observed to be improved by good pellet integrity (resistance to breakdown into fluff). Pellets that remained intact and maintained their cylindrical shape were observed to flow quite freely if

Figure 29. dRDF Dust Accumulation.

are stored in one place for more than 2 or 3 days. Long storage periods [illegible] the open yard were found [illegible] plant due to settling. Under these conditions, the fuel required manual removal from the fuel bin or be shoveled. Exposure to various weather conditions in open storage piles resulted in pellet deterioration to a crust at depths up to 6 in. After 2 months of open yard storage each dRDF pile formed a crust. However, the characteristics of samples taken under the crust indicated that the crust formed a protective cover for the pellets below. The crust was photographed in the open yard pile in [illegible] (Figure 30). The dRDF was piled [illegible] ft in height and was subject to heat buildup. A temperature [illegible] was read about 6 in. below the crust of a [illegible]-ft high pile one day in February [illegible] the outside temperature was recorded at 33 F. During January and February cold weather temperatures ranged from -[illegible] to 34 F (see Table A-[illegible]).

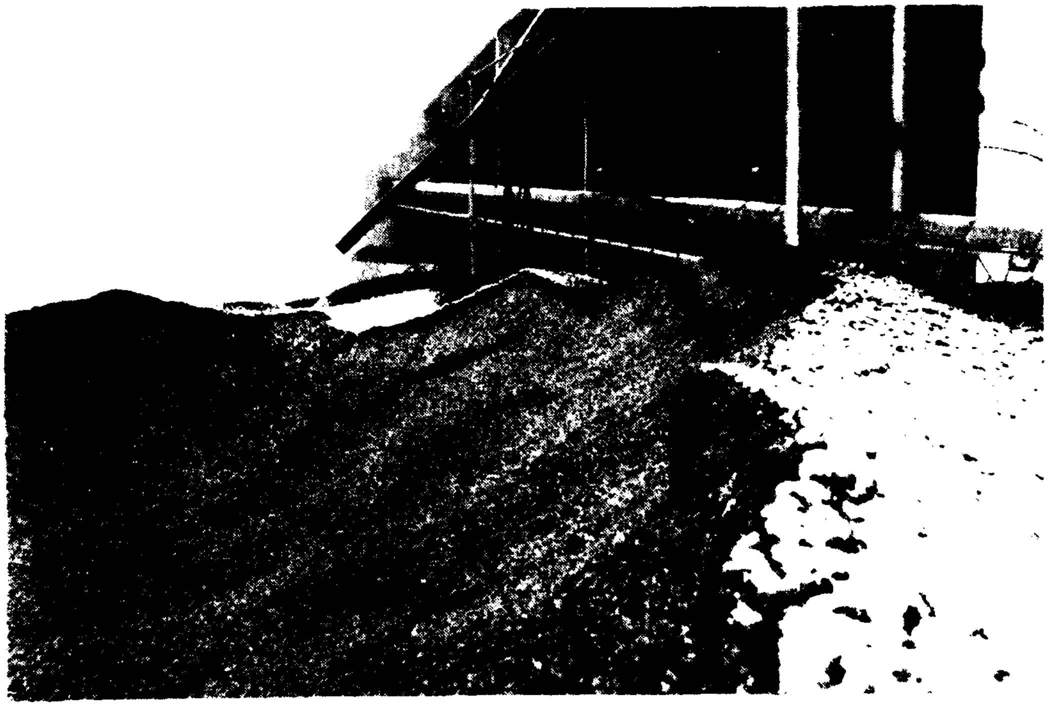

Figure 30. Crust Formation on dRDF Piles in Storage.

EMISSIONS

Emissions are classified in this report as particulate or gaseous. Overall, particulate and gaseous emissions were found to be within federal and state emission limits. Table 16 is a summary of the overall particulate and gaseous emission results as measured using methods described in Section 3.

Table 16. Stack Emissions (lb/10^6 Btu).

	dRDF	Coal	Maximum permissable*
Particulate			
ESP inlet	.925	.933	--
ESP outlet	.019	.023	.10
HC	.04	.04	--
CO	.22	.24	--
SO_x	.38	.80	1.2
NO_x	.45	.66	.70
Carbonyls	.005	†	--
Formaldehyde	N.D.§	N.D.	--

* 40 CFR 60.

† Not tested.

§ None detected above the detection limit of 1 × 10^{-6} g/sec.

Particulate Emissions

Particulate emissions are discussed in this section with respect to mass rate, particulate size, trace metal analysis, and precipitator performance.

Mass Rate

The particulate flow data for both inlet and outlet sides of the ESP are presented in Table 17 for each fuel type. The fly ash mass rate at the boiler outlet was almost exactly the same for both coal and dRDF. These results indicate that at low heat output rates the multiclone dust collector and electrostatic precipitator experienced no decrease in performance as a result of firing dRDF.

Table 17. ESP Performance Summary.

	dRDF	Coal
Inlet particles (lb/10^6 Btu)	0.925	0.933
Inlet particles standard deviation (lb/10^6 Btu)	0.354	0.137
Outlet particles (lb/10^6 Btu)	0.019	0.023
Outlet particles standard deviation (lb/10^6 Btu)	0.009	0.015
Collection efficiency (percent)	97.98	97.62
Resistivity		
Humidity (percent by volume)	7.50	4.00
Resistivity (Ohm-cm)	2.70×10^5	5.49×10^3
Breakdown (volts-cm)	6.2×10^2	1.4×10^1
Deutch drift vel. (ft/min)	717.11	823.43
A-Field		
Volts	318.6	258.5
Amps	87.3	54.4
Power (kW)	27.81	14.06
B-Field		
Volts	273.2	260.4
Amps	51.8	40.6
Power (kW)	14.15	10.57
Average total ESP power (kW)	41.96	24.63

Particle Size

The size distribution of the fly ash at the boiler outlet was tested for the dRDF burn on 16 April. This size distribution was measured with an inertial cascade impactor inserted in the duct upstream of the ESP. The results are given in Figure 31 for the morning test and in Figure 32 for the afternoon test. These results indicate a mean particle size of 5 to 10 μm which is larger than the mean size of 2 μm found in the Hagerstown tests.

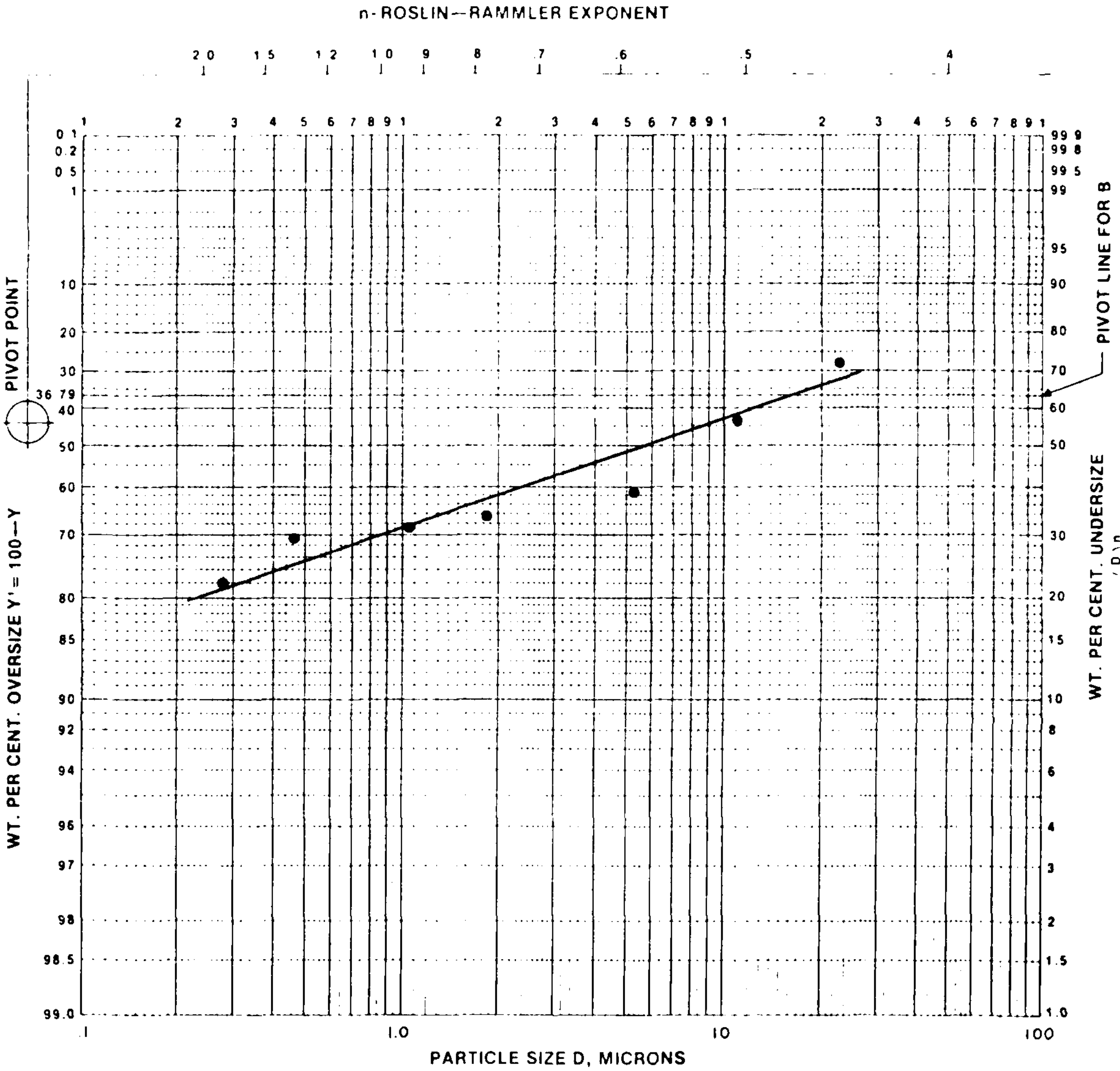

Figure 31. Particle Size (16 April 1981 Morning) of Fly Ash at the ESP Inlet.

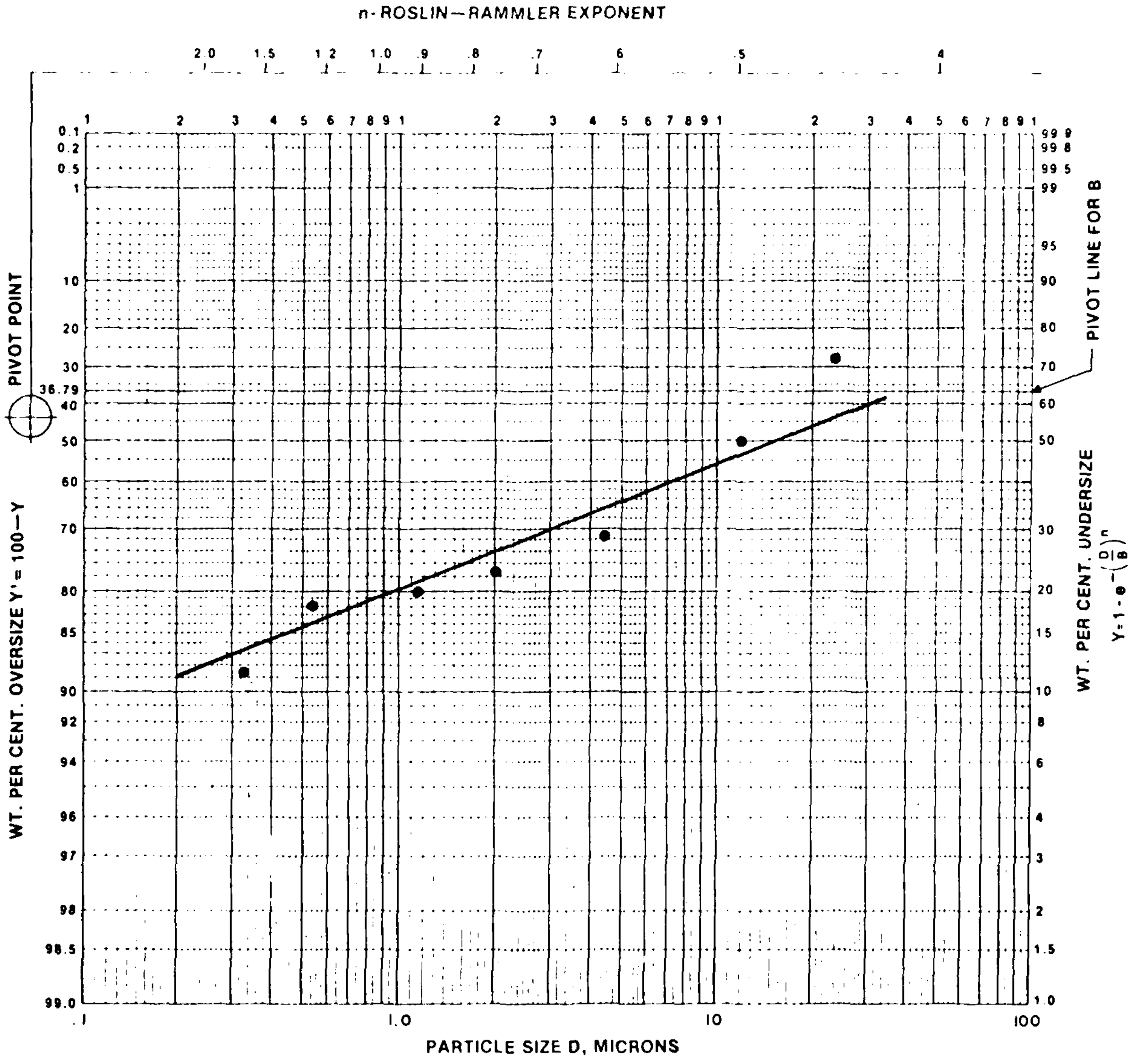

Figure 32. Particle Size of (16 April 1981 Afternoon) Fly Ash at the ESP Inlet.

Trace Metal Analysis

Results of ICP analysis of ESP outlet fly ash are given in Table 18. On a per unit weight of particulate matter basis there was an increase in the concentrations of chromium, manganese, nickel, titanium, and zinc when firing dRDF. There was also an increase in the iron concentration, but iron emissions present no notable hazard to the environment. However, there was no measurable increase in the stack emissions of lead or cadmium usually associated with RDF combustion. This indicates the ESP was effective in removing these metals.

Table 18. Trace Metal Results for Particulate Samples at ESP Outlet.

	dRDF (μg/g of sample)	Coal (μg/g of sample)
Ag	<14.2	<15.5
Al	281	331
B	39.4	133
Ba	5.4	2.3
Be	<0.2	<0.2
Ca	306	609
Cd	<1.1	<1.2
Co	<0.75	<0.82
Cr	12.2	3.4
Cu	<5.8	10
Fe	114	30.8
Mg	<12.5	54.7
Mn	5.8	0.57
Mo	<8	<8.8
Ni	10.8	<6.7
Pb	<18.7	<20.5
Sb	<20.8	<22.8
Sn	<20.8	<22.8
Sr	1.2	1.2
Ti	35.8	9.1
V	<6.2	<6.8
Zn	20.2	5.7

* < indicates that the amount present was less than the minimum detection limit.

Precipitator Performance

Precipitator performance was monitored at the maximum available boiler load of 30×10^6 Btu/hr. Particulate concentrations were measured at both the inlet (roof) and outlet (stack) of the ESP. Fly ash removal from the flue gas stream for both coal and dRDF was better than 98 percent efficient. The ESP required manual valve and blower settings only when the pneumatic fly ash removal system was activated after the tests were completed. More detailed tabular data for EPA Method 5 particulate test results are presented in Tables A-9 and A-10.

Electrical voltage in the precipitator is automatically controlled by the spark rate. Test results indicate that dRDF firing permitted higher voltages and therefore higher power usage by the precipitator (Table 17) because the increased resistivity caused a decreased spark rate.

Precipitator performance is usually analyzed through use of the Deutch Equation which is expressed as follows:

$$w = \frac{Q}{A} \log_e \frac{1}{P}$$

where:

w = drift velocity (ft/min)

Q = volumetric flow rate (ACFM)

A = electrode plate area (ft^2)

$P = \frac{\text{outlet particulate rate}}{\text{inlet particulate rate}}$

This form of the equation expresses the apparent drift velocity of particulate within the precipitator. Drift velocity is a measure of how effectively a precipitator causes particles to migrate toward the collector plates (perpendicular to the gas flow). This measure is commonly used to compare precipitator performance. The results for this analysis show that the drift velocity decreased slightly when shifting from coal to dRDF. In conclusion, results show that dRDF required more precipitator power but maintained a slightly higher particulate collection efficiency.

Gaseous Emissions

Flue emissions from the boiler were monitored for two reasons (1) to characterize the boiler outlet gases for mass and energy balance determinations and (2) to characterize the environmental impact of the effluent from the ESP outlet. The stack effluent was monitored continuously for CO_2, CO, O_2, SO_x, and NO_x. The results of these continuous monitors are summarized in Table 19, and detailed daily emissions are given in

Tables A-11 through A-14. The SO_x and NO_x continuous monitors did not operate reliably during the test, therefore data from these monitors are not presented here.

Table 19. Continuous Gas Monitor Data.

Excess air* percent	Fuel	Average concentrations O_2 percent	 CO_2 percent	 CO ppm
160	dRDF	13.00	6.90	116.50
169	Coal	13.27	6.50	128.67

* Excess air was calculated stoichiometrically using the continuous monitor CO_2 and O_2 readings.

The amount of excess air is calculated from the CO_2 and O_2 data that are presented in Table 19. Concentrations of CO_2 and O_2 resulting from the combustion process show little variation between coal and dRDF. Therefore, no significant differences could be noted in the amount of excess air required to burn the two fuels. Coal and dRDF were both fired at excess air levels ranging from 156 to 178 percent. Adjustments in underfire and overfire balance were minor.

Carbon Monoxide (CO)

The CO emissions for 4 days of dRDF burning averaged 0.22 lb/10^6 Btu and for 3 days of coal burning averaged 0.24 lb/10^6 Btu. Therefore, no significant variation of CO emissions was evident between the two fuels.

Sulfur Oxides (SO_x)

The extremely low sulfur content of the fuels is reflected in the sulfur dioxide gas emissions. As expected, a higher SO_x emission rate for coal at 0.80 lb/10^6 Btu was experienced compared with 0.38 lb/10^6 Btu for dRDF. This 52 percent reduction in sulfur oxide emissions is a direct result of the 69 percent lower sulfur content in the dRDF.

Nitrogen Oxides (NO_x)

The nitrogen oxide emission rate averaged 0.66 lb/10^6 Btu for coal compared with 0.45 lb/10^6 Btu for dRDF. The reduction in nitrogen oxide emissions can possibly be attributed to the lower nitrogen content of dRDF.

Carbonyls (C=O)

The level of carbonyls detected was negligible. Formaldehyde was not detected above 1 μg/sec, which is the minimum detection limit of the analysis method. These results are shown in Table 20.

Table 20. Carbonyl and Formaldehyde Emissions, 16 April 1981, Burning dRDF Fuel.

Run no.	Sample volume scm	mg CH_2O	CH_2O mg/m^3	CH_2O g/sec
Carbonyls				
1	1.529	5.02	3.28	0.027
2	1.524	4.40	2.89	0.024
3	1.438	2.72	1.89	0.016
4	1.390	1.29	0.93	0.008
Formaldehyde - emission limit 5.04 g/sec				
1	1.529	interference problem		
2	1.524	interference problem		
3	1.438	0.14	0.099	$<10^{-6}$*
4†	1.390	ND§	ND	$<10^{-6}$

* The detection limit for formaldehyde is 1 × 10^{-6} g/sec; formaldehyde was not detected at this level.

† Spike recoveries

20 mℓ + 1 μg → 87 percent
10 mℓ + 1 μg → 87 percent

§ None detected

Hydrocarbons

Volatile hydrocarbons from C_1 to C_6 were analyzed by gas chromatography. The results are given in Table A-14. Of the three grab samples analyzed during dRDF firing, only one showed any indication of volatile hydrocarbons above the 0.5 ppm detection limit. This sample, taken from the stack at 1133 hours on 2 March, shows a reproducible peak of 10 ppm with a retention time of 4.3 minutes which corresponds to Boiling Range 4 (n-butane). During the coal firing test five samples from the stack were analyzed for volatile hydrocarbons, and positive results were found twice. Sampling at 1600 hours on the first day of the test yielded a peak of 10 ppm in Boiling Range 4 (n-butane), and the sample at 1640 hours on the third day yielded another peak of 1 ppm in boiling Range 5 (n-pentane). In general it can be concluded that volatile hydrocarbons are of little significance as gaseous emissions when burning either dRDF or coal at this facility.

SECTION V

SUMMARY AND CONCLUSIONS

SUMMARY

The boiler and emissions performance testing at the WPAFB Building 1240 heating facility consisted of more than 215 hours of test firing. During actual test firing the boiler load was controlled for a 6- to 8-hr period each day at 30×10^6 Btu/hr ($\pm 5 \times 10^6$ Btu/hr). In 160 hours of testing 440 tons of dRDF alone were test fired. Coal baseline tests consisted of another 55 hours of combusting 75 tons of coal. Parameters monitored during these test periods included fuel and ash characteristics, boiler and ESP performance, and flue gas and particulate emissions. The test results showed that 100 percent dRDF can be fired in a spreader stoker boiler HTHW heating system without significantly decreasing boiler or ESP performance when fired at low loads. During this test half the ESP was operated near its maximum rated capacity with a demonstrated a collection efficiency of 98 percent when burning coal or dRDF. Fuel handling and storage problems of the dRDF were experienced due to pellet deterioration caused by rough handling and 2 week long periods of storage.

Coal Characterization

Fuel properties of the coal indicated that it was of very good quality. The coal fired at this heating facility had an average as-tested density of 53.6 lb/ft^3, a heat content of 13,051 Btu/lb, and a sulfur content of 0.67 percent. Moisture content averaged 5 percent.

dRDF Characterization

The Teledyne dRDF pellets had an average as-tested heat content of 7,164 Btu/lb, a bulk density of 32.6 lb/ft^3, and a sulfur content of 0.21 percent. Moisture content averaged 11.5 percent.

Bottom Ash Characterization

Firing with 100 percent dRDF reduced the combustibles in the bottom ash (when compared with coal firing) by a factor of six. The ashes from both fuels had the same average bulk density of 27 lb/ft^3.

SYSTEM PERFORMANCE

The overall system performance was evaluated at a fairly stable load of 30×10^6 Btu/hr $\pm 5 \times 10^6$ Btu/hr. The effects of burning coal and dRDF are compared in the following paragraphs with respect to boiler efficiency, operation, ESP performance, and emissions of particulate and gasous pollutants.

Boiler Efficiency

The boiler efficiency was reduced about 3.5 percent by firing dRDF instead of coal. The most significant heat loss increase was in the latent heat of vaporization of the moisture in the flue gas.

Boiler Operation

Clinkering of the fuel bed occurred when transitioning from coal to dRDF firing. However, these clinkers were eventually eliminated once proper grate speed, fuel feed, and excess air adjustments were made. Once stabilized, the boiler usually was taken off manual control and placed on automatic settings for both fuel types.

Precipitator Efficiency

The precipitator efficiency for both coal and dRDF particulate (fly ash) removal was in excess of 98 percent. Thus, no change in ESP performance was detected by firing dRDF.

Emissions

Particulates and Metals

The combustion of dRDF produced about the same particulate emission rate at the boiler outlet as coal. The dRDF produced 0.94 lb/10^6 Btu in particulates while coal produced 0.97 lb/10^6 Btu in particulates. Trace metal emissions of chromium and zinc (20.2 μg/g) from dRDF were four times higher than those emissions from coal; beryllium (0.2 μg/g), cadmium (1.2 μg/g), and lead (20 μg/g) emissions were the same for both fuels while twice as much nickel (10.8 μg/g) was emitted from dRDF as from coal.

Gaseous Emissions

Flue gas temperatures at the boiler outlet were essentially the same for both fuels, i.e., 305°F for coal compared with 301°F for dRDF. There was no significant difference between dRDF and coal emissions of CO and CO_2; however, SO_x emissions of .38 lb/10^6 Btu for dRDF were of only half the coal SO_x emissions of .80 lb/10^6 Btu. The NO_x emissions were 1.5 times greater for coal than dRDF (.45 lb/10^6 Btu for dRDF and .66 lb/10^6 Btu for coal). Hydrocarbon emissions were negligible, and carbonyl (including formaldehyde) emissions were not detected at all.

CONCLUSIONS

It has been demonstrated that 100 percent dRDF can be combusted in an existing spreader stoker at the same excess air levels as coal at 30 percent boiler loads. With proper control of the grate clinkering is not caused by dRDF, and ash burnout is significantly improved. There was no adverse impact on the environment from firing dRDF. In fact, when compared with coal, dRDF produced less sulfur and nitrogen oxides. The disadvantages of burning dRDF lie in the storage and handling of twice as much dRDF as coal to sustain the same boiler heat output rate and a 3.5 percent decrease in boiler thermal efficiency.

RECOMMENDATIONS

It is recommended that additional spreader stoker tests be performed at maximum continuous rating (MCR) boiler load and various coal:dRDF blend conditions at WPAFB Building 770 rather than Building 1240. Building 770 has steam generating boilers that are capable of operating near rated maximum capacity. Further analysis is recommended of the fly ash collected by the precipitator to determine which metals are removed by the precipitator and which metals are emitted to the environment.

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APPENDIX A

TEST DATA TABLES

Table A-1(a). dRDF Fuel Physical Properties (As-Tested Basis).

Date Sample number	3/2 R-1	3/3 R-2	3/4 R-3	3/5 R-4	3/30 R-5	3/31 R-6	4/1 R-7	4/2 R-8	Average
Carbon percent	43.80	44.10	43.80	45.00	44.80	44.70	43.70	43.90	44.23
Hydrogen (excluding H in moisture) percent	5.36	5.62	5.67	5.41	5.66	5.90	5.55	5.60	5.60
Oxygen (excluding O in moisture) percent	35.50	35.80	36.50	36.20	35.30	35.80	36.00	36.80	35.99
Nitrogen percent	0.36	0.41	0.28	0.35	0.22	0.31	0.39	0.38	0.34
Sulfur percent	0.25	0.17	0.41	0.12	0.25	0.18	0.08	0.22	0.21
Ash percent	10.10	10.20	9.95	8.49	9.91	9.93	9.37	9.24	9.65
As-tested moisture percent	12.50	11.42	13.85	12.50	10.72	9.42	10.76	10.18	11.42
Heat content Btu/lb	7,223	7,549	7,132	7,305	7,245	7,593	6,304	6,955	7,164

(Continued)

Table A-1(b). Coal Fuel Physical Properties (As-Tested Basis) (Concluded).

Date Sample number	4/6 C-1	4/7 C-2	4/8 C-3	Average
Carbon percent	84.80	77.50	76.50	79.60
Hydrogen (excluding H in moisture) percent	5.50	5.01	4.92	5.14
Oxygen (excluding O in moisture) percent	0.74	8.20	8.97	5.97
Nitrogen percent	1.79	1.63	1.55	1.66
Sulfur percent	0.56	0.79	0.67	0.67
Ash percent	5.22	5.48	5.91	5.54
As-tested moisture percent	5.08	5.47	4.53	5.03
Heat content Btu/lb	12,805	13,187	13,161	13,051

Table A-2. Fuel Percent Sulfur and Heat Content (Dry Basis) Bomb Calorimetry Results.

Sample	Date	ΔT (°C)	Titrants (mℓ)	Sample weight (gram)	Fuse length ignited (cm)	Sulfur (percent)	HHV cal/gram (constant volume)	HHV Btu/lb (constant volume)	HHV Btu/lb (contant pressure)
R-1	3/2	1.822	7.8	.9436	7.5	.205	4,614	8,306	8,321
R-1	3/2	1.847	9.3	.973	5	.205	4,541	8,174	8,189
R-2	3/3	1.836	8.5	.9282	7.5	.205	4,726	8,507	8,522
R-3	3/4	1.874	9.4	.9768	5	.205	4,589	8,261	8,277
R-3	3/4	1.82	7	.9483	6	.205	4,591	8,264	8,280
R-4	3/5	1.95	9	1.0095	2	.205	4,629	8,333	8,348
R-5	3/30	2.136	9.5	1.1345	8.5	.205	4,500	8,099	8,115
R-6	3/31	1.994	7.5	1.0255	8	.205	4,648	8,367	8,383
R-7	4/1	1.505	6.4	.9192	5	.205	3,916	7,049	7,064
R-8	4/2	1.868	7	1.0407	6.5	.205	4,293	7,728	7,743
C-1	4/6	3.108	20	.9678	5	.713	7,467	13,442	13,457
C-1	4/6	3.151	18.1	1.0058	5	.713	7,505	13,509	13,524
C-2	4/7	2.818	15.7	.875	5	.713	7,713	13,883	13,893
C-2	4/7	2.871	17.5	.893	5	.713	7,699	13,858	13,871
C-2	4/7	3.186	17.9	.9756	7	.713	7,819	14,074	14,087
C-3	4/8	2.927	9.6	.915	5.5	.713	7,668	13,803	13,816
C-3	4/8	3.181	19.1	.9968	7	.713	7,640	13,752	13,755

Table A-3. Fuel Ultimate Analysis Averages (Dry Weight Basis).

Parameter	Fuel	
	dRDF	Coal
Carbon percent	49.93	84.05
Hydrogen percent	6.32	5.43
Oxygen percent	40.63	6.30
Nitrogen percent	0.38	1.75
Sulfur percent	0.24	0.71
Ash percent	10.89	5.85
Higher heating value, Btu/lb	8,088	13,781

Table A-4. Bottom Ash Properties.

	Date	Fuel	Combustibles percent	HHV Btu/lb	Average density lb/ft^3
Week 1					
	3/2	dRDF	2.54	830	Not sampled
	3/3	dRDF	3.55	1,656	31.40
	3/4	dRDF	1.49	781	28.40
	3/5	dRDF	0.65	428	30.40
Week 2					
	3/30	dRDF	Not sampled	Not sampled	Not sampled
	3/31	dRDF	0.09	336	28.70
	4/1	dRDF	0.09	245	31.40
	4/2	dRDF	0.41	298	26.70
Averages			1.17	633	25.40
Week 3					
	4/6	Coal	4.63	514	Not sampled
	4/7	Coal	7.84	1,199	26.90
	4/8	Coal	5.93	891	29.40
Averages			6.13	868	28.40
	4/16	dRDF	0.43	487	26.40

Table A-5. Dry Bottom Ash Bulk Density.

		Grate Zone			Average bucket weight		Density
	Date (time)	1 grams	2 grams	3 grams	grams	lbs	lb/ft^3
Week 1	3/3 (1330)	5,590	6,210	5,290	5,697	12.6	31.4
	3/4 (1100)	5,440	4,810	5,310	5,186	11.4	28.4
	3/5 (1005)	5,570	5,690	5,370	5,543	12.2	30.4
Week 2	3/31 (1020)	5,630	4,550	5,510	5,230	11.5	28.7
	4/1 (0820)	5,860	5,360	5,890	5,703	12.6	31.4
	4/2 (1330)	4,880	4,780	4,920	4,860	10.7	26.7
Week 3	4/7 (0815)	4,900	5,210	4,620	4,910	10.8	26.9
	4/7 (1605)	5,260	4,580	4,840	4,893	10.8	26.9
	4/8 (0800)	5,240	5,360	5,380	5,327	11.7	29.2
	4/8 (1300)	6,640	5,620	5,280	5,847	12.9	32.2
	4/8 (1630)	4,680	5,400	4,600	4,893	10.8	26.9
Week 4	4/16	4,970	4,590	4,830	4,797	10.6	26.4

Note: Density Averages: dRDF - 29.1 lb/ft^3, standard deviation 2.1
Coal - 28.4 lb/ft^3, standard deviation 2.3

Table A-6. Bottom Ash Heat Content (Dry Basis) Bomb Calorimetry Results.

Sample	Date	Total sample (grams)	Benzoic acid (C_6H_5COOH) (grams)	Bottom ash (grams)	ΔT Total sample (°C)	ΔT due to C_6H_5COOH (°C)	ΔT due to bottom ash (°C)	Titrants (Mℓ)	Fuse length burnt (cm)	Gross heat of combustion (Hg) constant volume (cal/g)	Hg (Btu/lb)
B-1	3/2	.9655	.48275	.48275	1.374	1.274	.100	3.8	6	461	830
B-2	3/3	.9862	.4931	.4931	1.497	1.301	.196	4.6	5.5	920	1,656
B-3	3/4	.9786	.4893	.4893	1.388	1.291	.097	4.6	7	434	781
B-4	3/5	.9754	.4877	.4877	1.343	1.287	.056	4.9	6	238	428
B-5	3/31	.9836	.4918	.4918	1.342	1.2979	.044	3.5	4.5	187	336
B-6	4/1	.9836	.4918	.4918	1.333	1.2979	.035	3.3	6	136	245
B-7	4/2	.9760	.4880	.488	1.330	1.2879	.042	4	7	166	299
B-8	4/6	.9866	.4933	.4933	1.369	1.302	.067	4	7	286	514
B-9	4/7	.9836	.4918	.4918	1.441	1.2979	.143	3.2	5.5	666	1,199
B-10	4/8	.9780	.489	.489	1.399	1.291	.109	3.8	7	495	891
B-11	4/16	.9902	.4951	.4951	1.370	1.307	.063	3.7	6	270	487

Assume: No sulfur present in bottom ash.
Sample weight divides evenly between benzoic acid and bottom ash.
.9871 gram C_6H_5COOH raises temperature 2.605°C in calorimeter.

Table A-7. Mass and Energy Balance Data.

Date (1)	Time (2)	A-R* coal input lb/hr (3)	A-R pellet input lb/hr (4)	Coal moisture percent (5)	Pellet moisture percent (6)	Coal input dry basis lb/hr (7)	Pellet input dry basis lb/hr (8)	Carbon input lb/hr (9)
3/2		--	5,128	--	12.64	--	4,480	2,237
3/3		--	4,129	--	12.64	--	3,607	1,801
3/4		--	5,628	--	12.64	--	4,917	2,455
3/5		--	5,250	--	12.64	--	4,586	2,290
3/30		--	4,162	--	10.27	--	3,735	1,865
3/31		--	5,173	--	10.27	--	4,642	2,318
4/1		--	4,615	--	10.27	--	4,141	2,068
4/2		--	5,487	--	10.27	--	4,923	2,458
4/6		2,913	--	5.03	--	2,766	--	2,325
4/7		2,731	--	5.03	--	2,594	--	2,180
4/8		2,755	--	5.03	--	2,616	--	2,199
4/9		2,850		5.03	--	2,707	--	2,275
4/16		--	4,755	--	8.14	--	4,368	2,181

(Continued)

* As received.

Table A-7. Mass and Energy Balance Data (Continued).

Date	Hydrogen input lb/hr (10)	Sulfur input (fuel) lb/hr (11)	Oxygen input (fuel) lb/hr (12)	Nitrogen input (fuel) lb/hr (13)	Ash input (inerts) lb/hr (14)	Heat input (fuel) 10^6 Btu/hr (15)	Moisture input lb/hr (16)	Bottom ash unburnt carbon lb/hr (19)
3/2	283	10.75	1,820	17.02	487.90	36.23	648	11.71
3/3	228	8.66	1,466	13.71	392.80	29.17	522	13.68
3/4	311	11.80	1,998	18.68	535.50	39.77	711	7.52
3/5	290	11.01	1,863	17.43	499.40	37.09	664	3.13
3/30	236	8.96	1,518	14.19	406.70	30.21	427	0.77
3/31	293	11.14	1,886	17.64	505.50	37.54	531	0.42
4/1	262	9.94	1,682	15.74	451.00	33.49	474	0.37
4/2	311	11.82	2,000	18.71	536.10	39.82	564	2.07
4/6	150	19.64	174	48.41	161.80	38.12	147	5.21
4/7	141	18.42	163	45.40	151.70	35.74	137	9.20
4/8	142	18.57	165	45.78	153.00	36.05	139	7.57
4/9	147	19.22	171	47.37	158.40	37.31	143	
4/16	276	10.48	1,775	16.60	475.70	35.33	387	

(Continued)

Table A-7. Mass and Energy Balance Data (Continued).

Date	Fly ash unburnt carbon lb/hr (20)	Δ hr (24)	Fuel input dry basis lb/hr (25)	HHW generation rate 10^3 lb/hr (30)	HHW enthalpy gain Btu/lb (31)	Measured HHW heat output MMBTU/hr (32)	Stoichiometric air requirement lb/lb (33)
3/2	12.14	8	4,480	537.10	66	36.00	6.183
3/3	6.63	8	3,607	470.50	39	18.00	6.183
3/4	12.14	8	4,917	522.50	61	32.75	6.184
3/5	6.63	8	4,586	522.00	48	26.00	6.185
3/30	6.63	8	3,735	528.90	45	24.00	6.182
3/31	13.43	8	4,642	530.60	61	32.50	6.181
4/1	12.14	8	4,141	523.80	53	32.50	6.187
4/2	10.84	8	4,923	542.90	64	34.75	6.182
4/6	26.25	6	2,766	441.60	70	32.75	11.296
4/7	21.06	8	2,594	463.30	66	30.00	11.299
4/8	15.85	8	2,616	498.20	64	31.50	11.297
4/9	--	8	2,707	508.60	61	33.50	11.296
4/16	--	8	4,368	515.50	64	33.75	6.183

Table A-7. Mass and Energy Balance Data (Continued).

Date	Excess air percent (34)	Air flow into boiler 10^3/lb/hr (35)	Bottom ash lb/hr (36)	Fly ash lb/hr (37)	Total inerts lb/hr (38)	R/C energy percent (39)	R/C energy losses MMBtu/hr (40)	Input & output efficiency percent (41)
3/2	159	71.743	461.30	50.50	487.90	1.40	0.51	99.37
3/3	159	57.762	385.50	27.60	397.80	2.60	0.76	61.11
3/4	159	78.753	504.70	50.50	535.50	1.60	0.64	82.35
3/5	159	73.464	481.60	27.60	499.40	1.80	0.67	70.10
3/30	159	59.803	386.50	27.60	406.70	2.05	0.62	79.44
3/31	152	72.304	463.40	55.90	505.50	1.60	0.60	86.57
4/1	159	66.357	413.00	50.50	451.00	1.60	0.54	97.04
4/2	133	70.911	503.90	45.10	536.70	1.40	0.56	87.27
4/6	161	81.549	112.60	80.70	161.80	1.60	0.64	85.91
4/7	165	77.670	117.30	64.70	151.70	1.65	0.63	83.94
4/8	178	82.157	127.70	48.70	153.00	1.62	0.58	87.38
4/9	--	--	--	--	158.40	1.45	0.54	89.79
4/16	--	--	--	--	475.70	1.45	0.51	95.53

Table A-7. Mass and Energy Balance Data (Continued).

Date	Boiler load percent (42)	Bottom ash heat loss MMBtu/hr (43)	Fly ash heat loss MMBtu/hr (44)	CO_2 output rate lb/hr (45)	H_2O output rate lb/hr (46)	SO_2 output rate lb/hr (47)	Oxygen output rate lb/hr (48)
3/2	36	0.1650	0.1711	8,115.80	3,195.00	21.50	10,361.18
3/3	18	0.1900	0.0935	6,534.45	2,574.00	17.32	8,341.34
3/4	33	0.1060	0.1711	8,934.90	3,510.00	23.60	11,351.98
3/5	26	0.0440	0.0935	8,364.46	3,274.00	22.02	10,568.14
3/30	24	0.0109	0.0935	6,812.26	2,551.00	17.92	8,602.63
3/31	33	0.0059	0.1894	8,449.54	3,168.00	22.28	10,234.88
4/1	33	0.0052	0.1711	7,537.70	2,832.00	19.88	9,557.33
4/2	35	0.0292	0.1528	8,967.47	3,363.00	23.64	9,503.10
4/6	33	0.0735	0.3701	8,409.97	1,497.00	39.28	11,841.23
4/7	30	0.1300	0.2969	7,883.76	1,406.00	36.84	11,382.20
4/8	31	0.1070	0.2235	7,974.22	1,417.00	37.14	12,355.75
4/9	--	--	--	--	--	--	--
4/16	--	--	--	--	--	--	--

Table A-7. Mass and Energy Balance Data (Continued).

Date	N_2 output rate lb/hr (49)	Flue gas at boiler outlet temperature °F (50)	Total dry flue gas output 10^3 lb/hr (51)	Dry flue gas loss MMBtu/hr (52)	Enthalpy in flue gas moisture @ 1 PSI Btu/lb (53)	Wet flue gas loss MMBtu/hr (54)
3/2	55,043.90	304.00	73.54	4.17	1,197.54	3.70
3/3	44,317.16	300.00	59.21	3.30	1,195.70	2.98
3/4	60,422.23	300.00	80.73	4.50	1,195.70	4.06
3/5	56,364.32	292.50	75.32	4.06	1,192.28	3.78
3/30	45,883.09	297.50	61.32	3.38	1,194.56	2.95
3/31	55,474.81	305.00	74.18	4.22	1,198.00	3.67
4/1	50,911.56	302.50	68.03	3.83	1,196.85	3.28
4/2	54,407.45	310.00	72.90	4.24	1,200.30	3.91
4/6	62,596.49	300.00	82.89	4.62	1,195.70	1.73
4/7	59,618.29	306.25	78.92	4.52	1,198.58	1.63
4/8	63,060.20	305.00	83.43	4.75	1,198.00	1.64
4/9	--	302.50	--	--	1,196.85	--
4/16	--	301.25	--	--	1,196.28	--

AD-A119 030   SYSTEMS TECHNOLOGY INC XENIA OH   F/G 13/1
A FIELD TEST USING DRDF IN A SPREADER STOKER HOT WATER GENERATO--ETC(U)
AUG 81 P F CARPENTER, N J KLEINHENZ   MIPR-N-80-47
UNCLASSIFIED   AFESC/ESL-TR-81-57   NL

2 OF 2
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Table A-7. Mass and Energy Balance Data (Continued).

Date	Calculated boiler outlet H_2O percent volume (56)	Total losses MMBtu/hr (57)	Heat balance efficiency percent (58)	Heat input MMBtu/hr (62)	R/C loss percent (63)	Bottom ash loss percent (64)	Fly ash loss percent (65)	Dry flue gas loss percent (66)
3/2	6.65	8.72	75.93	36.23		0.46	0.47	11.51
3/3	6.65	7.31	74.95	29.17		0.66	0.32	11.31
3/4	6.65	9.46	76.21	39.77		0.27	0.43	11.32
3/5	6.65	8.64	76.72	37.09		0.12	0.25	10.95
3/30	6.38	7.05	76.65	30.21	2.05	0.04	0.31	11.19
3/31	6.54	8.69	76.84	37.54		0.02	0.50	11.24
4/1	6.39	7.83	76.62	33.49		0.02	0.51	11.44
4/2	7.03	8.89	77.69	39.82		0.07	0.38	10.65
4/6	2.88	7.44	80.49	38.12	1.60	0.19	0.97	12.12
4/7	2.84	7.20	79.84	35.74		0.36	0.83	12.65
4/8	2.71	7.32	79.70	36.05		0.29	0.62	13.18
4/9	--	--	--	37.31		--	--	--
4/16	--	--	--	35.33		--	--	--

Table A-7. Mass and Energy Balance Data (Concluded).

Date	Wet flue gas loss percent (67)	Loss percent (68)	Efficiency percent (69)	Inert rate input lb/10^6 Btu (70)	Sulfur rate input lb/10^6 Btu (71)	Nitrogen rate input lb/10^6 Btu (72)	R/C loss percent (63)
3/2	10.21	24.07	75.93	13.47	0.30	0.47	1.40
3/3	10.22	25.06	74.95	13.47	0.30	0.47	2.60
3/4	10.21	23.79	76.21	13.46	0.30	0.47	1.60
3/5	10.19	23.29	76.72	13.46	0.30	0.47	1.80
3/30	9.76	23.34	76.65	13.46	0.30	0.47	2.05
3/31	9.78	23.15	76.84	13.47	0.30	0.47	1.60
4/1	9.79	23.38	76.62	13.47	0.30	0.47	1.60
4/2	9.82	22.33	77.69	13.46	0.30	0.47	1.40
4/6	4.54	19.52	80.49	4.24	0.52	1.27	1.60
4/7	4.56	20.15	79.84	4.24	0.52	1.27	1.65
4/8	4.55	20.31	79.70	4.24	0.52	1.27	1.62
4/9	--	--	--	--	--	--	1.45
4/16	--	--	--	--	--	--	1.45

Table A-8. Open Yard dRDF Storage Environmental Conditions 14 January - 16 April 1981.

	Temperature								
	High		Low		Mean		Precipitation		Relative humidity
Date	(°F)	(°C)	(°F)	(°C)	(°F)	(°C)	(in.)	(cm)	percent
1/14	33	1	23	-5	28	-2	0		83
1/15	30	-1	23	-5	27	-3	.02	.05	82
1/16	28	-2	6	-14	17	-8	.02	.05	84
1/18	33	1	16	-9	25	4	0		78
1/19	44	7	22	-6	33	1	0		73
1/20	43	6	34	-1	38	3	0		67
1/21	36	2	39	-1	33	1	0		87
1/22	35	2	29	-2	32	0	0		89
1/23	35	2	30	-1	33	1	0		80
1/24	47	8	26	3	37	3	0		NR*
1/25	57	14	30	-1	44	7	0		54
1/26	51	11	32	0	42	6	0		76
1/27	39	4	31	-1	36	2	0		69
1/28	37	3	27	-3	33	1	0		58
1/29	31	-1	19	-7	25	-4	0		63
1/30	29	-2	13	-11	21	-6	0		68
2/01	39	4	33	1	36	2	.79	2.0	93
2/02	29	-2	7	-14	18	-8	.07	.18	64
2/03	13	-11	2	-17	8	-13	0		70
2/04	16	-9	6	-14	11	-12	0		73
2/05	24	-4	0	-18	12	-11	0		55
2/06	34	1	24	-4	29	-2	.01	.03	63
2/07	41	5	22	-6	32	0	0		NR
2/08	34	1	13	-11	19	-7	0		65
2/09	37	3	13	-11	25	-4	0		45
2/10	47	8	33	1	39	4	.55	1.4	93
2/11	49	9	-6	-21	26	-3	.83	2.1	66
2/12	15	-9	-6	-21	5	-15	0		53
2/13	34	1	6	-14	20	-7	0		50
2/14	46	8	16	-9	31	-1	0		NR
2/15	55	13	27	-3	41	5	0		56
2/16	49	9	38	3	44	7	.44	1.1	93
2/17	54	12	48	9	51	11	.02	.05	96
2/18	59	15	49	9	54	12	0		93
2/19	55	13	49	9	53	12	.28	.71	96
2/20	50	10	41	5	46	8	0		83
2/21	51	11	35	2	43	6	0		74
2/22	55	13	38	3	47	8	.02	.05	NR

* Not recorded.

Table A-8. Open Yard dRDF Storage Environmental Conditions
14 January - 16 April 1981 (Continued).

	Temperature								
	High		Low		Mean		Precipitation		Relative humidity
Date	(°F)	(°C)	(°F)	(°C)	(°F)	(°C)	(in.)	(cm)	percent
2/23	50	10	34	1	44	7	.21	.53	82
2/24	41	5	34	1	38	3	.01	.03	73
2/25	47	8	29	-2	38	3	0	0	65
2/26	36	2	25	-4	31	-1	0	0	75
2/27	48	9	28	-2	36	2	.03	.08	NR
2/28	53	12	41	5	47	8	.03	.08	NR
3/1	40	4	37	3	39	4	0	0	76
3/2	40	4	30	-2	36	2	0	0	56
3/3	40	4	24	-4	32	0	0	0	56
3/4	36	2	30	-1	33	1	.27	.69	89
3/5	37	3	31	-1	35	2	.42	1.07	78
3/6	36	2	22	-6	30	-1	.02	.05	82
3/7	32	0	20	-7	26	-3	trace		NR
3/8	42	6	29	-2	36	2	0	0	79
3/9	43	6	26	-3	35	2	0	0	76
3/10	46	8	33	1	30	-1	trace		70
3/11	39	4	27	-3	33	1	trace		67
3/12	55	13	28	-2	32	0	0	0	42
3/13	52	11	28	-2	41	5	0	0	48
3/14	45	7	21	-6	33	1	0	0	NR
3/15	59	15	31	-1	45	7	.01	.03	68
3/16	48	9	22	-6	35	2	.01	.03	38
3/17	45	7	28	-2	37	3	0	0	37
3/18	40	4	18	-8	29	-2	0	0	49
3/19	32	0	17	-8	25	-4	.03	.08	69
3/20	37	3	27	-3	32	0	.01	.03	64
3/21	49	9	27	-3	38	3	0	0	NR
3/22	47	8	29	-2	38	3	0	0	45
3/23	55	13	29	-2	40	4	0	0	45
3/24	60	16	27	-3	44	7	0	0	36
3/25	55	13	27	-3	41	5	0	0	34
3/26	67	19	36	2	52	11	0	0	38
3/27	51	11	40	4	46	8	.12	.30	58
3/28	51	11	39	4	43	6	0	0	NR
3/29	76	24	56	13	66	19	0	0	46
3/30	66	19	50	10	61	16	.29	.74	60
3/31	82	28	41	5	62	17	0	0	30

* Not recorded.

Table A-8. Open Yard dRDF Storage Environmental Conditions 14 January - 16 April 1981 (Concluded).

	Temperature								
	High		Low		Mean		Precipitation		Relative humidity
Date	(°F)	(°C)	(°F)	(°C)	(°F)	(°C)	(in.)	(cm)	percent
4/1	69	21	53	12	61	16	trace		38
4/2	72	22	38	3	55	13	0	0	27
4/3	76	24	52	11	64	18	.18	.46	76
4/4	70	21	57	14	64	18	.60	1.52	NR
4/5	56	13	36	2	42	6	trace		73
4/6	52	11	30	-1	42	6	0	0	39
4/7	68	20	33	1	51	11	0	0	33
4/8	75	24	54	12	65	18	trace		37
4/9	65	18	48	9	58	14	.02	.05	53
4/10	71	22	43	6	57	14	.02	.05	63
4/11	76	24	63	17	70	21	.54	1.37	NR
4/12	73	23	52	11	67	19	.82	2.08	90
4/13	76	24	50	10	63	17	trace		62
4/14	71	22	39	4	55	13	trace		50
4/15	56	13	33	1	45	7	0	0	44
4/16	65	18	36	2	51	11	trace		63

* Not recorded.

Table A-9. Particulate Emissions.

		Inlet gr/DSCF		Outlet gr/DSCF
<u>dRDF</u>				
3/30		.195		.00831
3/31		.249		.00450
3/31		.350		.00445
4/02		.203		.00302
	Average	.249	Average	.00507
<u>Coal</u>				
4/06		.292		.01146
4/06		.273		.00633
4/08		.241		.00489
4/08		.200		.00155
	Average	.252	Average	.00606

Table A-10. EPA Method 5 Data Summary.

General						
Test number	707-M5-I1	707-M5-01	707-M5-I2	707-M5-02	707-M5-I3	707-M5-03
Source	ESP Inlet	ESP Outlet	ESP Inlet	ESP Outlet	ESP Inlet	ESP Outlet
Date	3/30/81	3/30/81	3/31/81	3/31/81	3/31/81	3/31/81
"F" factor (DSCF/10^6 Btu)	9820	9820	9820	9820	9820	9820
Oxygen concentration (percent)	13	13	13	13	13	13
Measured gas flow data						
Stack area (ft^2)	49	13.1	49	13.1	49	13.1
Average velocity (FPM)	481	1,866	713	2,475	713	2,010
Flow rate (ACFM)	23,558	24,432	34,211	32,423	34,949	26,336
Temperature (°F)	298	279	330	289	328	291
Flow rate at standard conditions (SCFM)	16,488	17,564	22,974	22,966	23,428	18,524
Sample data						
Total particulate collected (mg)	817.6	66.4	1,170	19.5	1,639.9	15.2
Volume of gas sampled (DSCF)	64.5	123.3	72.5	66.9	71.9	52.7
Volume water vapor sampled (SCF)	5.7	8.9	6.1	5.5	5.1	3.9
Total gas sampled (SCF)	70.2	132.3	78.6	72.4	77.0	56.6
Isokinetic percentage	125	109	97	112	95	112
Results						
Particulate concentration						
gr/SCF	0.19545	0.00831	0.24907	0.00449	0.35192	0.00451
lb/hr	27.6	1.3	49.0	0.9	70.7	0.7
lb/10^6 Btu	0.725	0.031	0.924	1.016	1.31	0.017
Wet catch						
CH_2Cl_2 extract (mg)	6.2	11.3	15.3	12.6	18.5	21.1
Aqueous extract (mg)	9.8	49.3	46.9	27.4	55.1	27.0

Table A-10. EPA Method 5 Data Summary (Continued).

General						
Test number	707-M5-I4	707-M5-04	707-M5-I5	707-M5-05	707-M5-I6	707-M5-06
Source	ESP Inlet	ESP Outlet	ESP Inlet	ESP Outlet	EPS Inlet	ESP Outlet
Date	4/2/81	4/2/81	4/6/81	4/6/81	4/6/81	4/6/81
"F" factor (DSCF/10^6 Btu)	9820	9820	9820	9820	9820	9820
Oxygen concentration (percent)	13	13	13	13	13	13
Measured gas flow data						
Stack area (ft^2)	49	13.1	49	13.1	49	13.1
Average velocity (FPM)	809	3,270	801	2,158	808	1,645
Flow rate (ACFM)	39,658	42,841	38,229	28,274	39,579	21,550
Temperature (°F)	330	293	300	278	320	277
Flow rate at standard conditions (SCFM)	27,567	30,336	39,852	20,550	27,253	15,690
Sample Data						
Total particulate collected (mg)	1,150.2	15.5	1,829.6	44.7	1,741.6	20.4
Volume of gas sampled (DSCF)	87.242	79.238	96.6	60.183	98,128	49.7
Volume water vapor sampled (SC	6.404	7.47	3.3	2.61	3.36	1.4
Total gas sampled (SCF)	93.646	86.71	99.9	62.794	101.488	51.1
Isokinetic percentage	98.5	105.4	70.4	113.3	110.7	135
Results						
Particulate concentration						
gr/SCF	0.20343	0.00302	0.29224	0.01146	0.27385	.00633
lb/hr	48.1	0.8	99.8	2.0	64.0	0.9
lb/10^6 Btu	0.755	0.011	1.085	0.043	1.016	0.024
Wet catch						
CH_2Cl_2 extract (mg)	10.1	13.6	13.5	16.1	17.0	12.6
Aqueous extract (mg)	103.7	88.3	15.3	21.1	16.2	16.2

Table A-10. EPA Method 5 Data Summary (Concluded).

General				
Test number	707-M5-I7	707-M5-07	707-M5-I8	707-M5-08
Source	ESP Inlet	ESP Outlet	ESP Inlet	ESP Outlet
Date	4/8/81	4/8/81	4/8/81	4/8/8
"F" factor (DSCF/10^6 Btu)				
Oxygen concentration (percent)				
Measured gas flow data				
Stack area (ft^2)	49	13.1	49	13
Average velocity (FPM)	823	1,980	825	1,443
Flow rate (ACFM)	40,318	25,934	40,407	18,897
Temperature (°F)	340	281	340	280
Flow rate at standard conditions (SCFM)	25,987	18,047	25,742	13,557
Sample data				
Total particulate collected (mg)	1,498.8	17.2	292.7	3.8
Volume of gas sampled (DSCF)	95.981	54.242	22.650	37.711
Volume water vapor sampled (SCF)	3.49	2.13	1.0	1.85
Total gas sampled (SCF)	99.479	56.375	23.650	39.560
Isokinetic percentage	108.0	111.6	128.7	107.5
Results				
Particulate concentration				
gr/SCF	0.24095	0.00489	0.19939	.00155
lb/hr	53.6	0.8	44.0	0.2
lb/10^6 Btu	0.894	0.018	0.740	0.006
Wet catch				
CH_2Cl_2 extract (mg)	9.1	12.8	15.3	13.2
Aqueous extract (mg)	18.7	16.1	5.9	9.3

Table A-11. Daily Gaseous Emissions Summary.

		Carbon monoxide*	
		(ppm)	($lb/10^6$ Btu)
	3/30	160	0.30
	3/31	102	0.19
dRDF	4/01	100	0.19
	4/02	104	0.20
	Test period Avg	117	0.22
	4/06	122	0.23
	4/07	135	0.25
Coal	4/08	129	0.24
	Test period Avg	129	0.24

* Carbon monoxide emissions as measured on nondispersive infrared continuous monitor.

Table A-12. Sulfur Oxides (SO_x) Emissions.

		SO_x Method 6	
		(ppm)	(lb/10^6 Btu)
	3/30	103.3	0.45
	3/31	101.9	0.44
dRDF	4/01	72.2	0.31
	4/02	76.1	0.33
	Test period Avg	88.4	0.38
	4/06		
	4/07	185.5	0.80
Coal	4/08	193.9	0.84
		177.0	0.76
	Test period Avg		
		185.5	0.80

Table A-13. Nitrogen Oxides Emissions.

		NO_x Method 7	
		(ppm)	($lb/10^6$ Btu)
	3/30	---	---
	3/31	141.5	0.44
dRDF	4/01	152.5	0.47
	4/02	146.9	0.45
	Test period Avg	147.0	0.45
	4/06	249.9	0.77
	4/07	191.8	0.59
Coal	4/08	196.9	0.61
	Test period Avg	212.9	0.66

Table A-14. Hydrocarbon Emissions.

		Hydrocarbons C_1 and C_6	
		(ppm)	(lb/10^6 Btu)
	3/30	*	*
	3/31	9.0	0.04
dRDF	4/01	<0.5	<0.002
	4/02	0.0	<0.002
	4/06	10.0	0.04
	4/07	<0.5	0.002
Coal	4/08	0.7	0.003

* Not tested.

APPENDIX B

FORMULAS

Formulas (Continued).

The underlined numbers used in the formulae throughout Appendix B identify the numbered data columns of Appendix A.

1 Date

3 Fuel input as received (lb/hr)

$$W_{FA-R} = \frac{(S_f - S_i)\, S_{cf}}{224}$$

W_{FA-R} = weight of fuel as received (lb/hr)

S_f = final scale counter reading

S_i = initial scale counter reading

S_{cf} = scale calibration factor (lb/trip)

224 = hours in test period (hr)

5 Fuel moisture (%)

M_f = weekly average of daily moisture analysis

7 Fuel input dry basis (lb/hr)

$$W_f = \frac{1 - M_f}{100} W_{FA-R}$$

$$\frac{100 - \underline{5}}{100} \times \underline{3}$$

W_f = weight of fuel dry basis (lb/hr)

M_f = average fuel moisture (percent)

W_{FA-R} = weight of fuel as received (lb/hr)

9 Carbon input (lb/hr)	$W_c = \frac{W_f C_f}{100}$
$\frac{\underline{25} \times C_f}{100}$	W_c = carbon input rate (lb/hr) W_f = dry fuel input rate (lb/hr) C_f = average carbon content of fuel (percent)

10 Hydrogen input (lb/hr)	$W_H = \frac{W_f H_f}{100}$
$\frac{\underline{25} \times H_f}{100}$	W_H = hydrogen input rate (lb/hr) W_f = dry fuel input rate (lb/hr) H_f = average hydrogen content of fuel (percent)

11 Sulfur input (lb/hr)	$W_S = \frac{W_f S_f}{100}$
$\frac{\underline{25} \times S_f}{100}$	W_S = sulfur input rate (lb/hr) W_f = dry fuel input rate (lb/hr) S_f = average sulfur content of fuel (percent)

12 Oxygen input (lb/hr)	$W_O = \frac{W_f O_f}{100}$
$\frac{25 \times O_f}{100}$	W_O = oxygen input rate (lb/hr) W_f = dry fuel input rate (lb/hr) O_f = average oxygen content of fuel (percent)

13 Nitrogen input (lb/hr)	$W_N = \frac{W_f N_f}{100}$
$\frac{25 \times N_f}{100}$	W_N = nitrogen input rate (lb/hr) W_f = dry fuel input rate (lb/hr) N_f = average nitrogen content of fuel (percent)

14 Inert matter input (lb/hr)	$W_I = \frac{W_f I_f}{100}$
$\frac{7 \times I_f}{100}$	W_I = inert matter input rate (lb/hr) W_f = dry fuel input rate (lb/hr) I_f = average inerts content of fuel (percent)

$\underline{15}$ Heat input rate (10^6 Btu/hr)	$E_i = \frac{W_f HHV_f}{10^6}$
$\frac{\underline{7} \times HHV_f}{10^6}$	E_i = fuel energy input (10^6 Btu/hr) W_f = dry fuel input rate (lb/hr) HHV_f = average fuel higher heating value (Btu/lb)

$\underline{16}$ Moisture input rate (lb/hr)	$W_{WE} = \frac{W_{FA-R} f_m}{100}$
$\frac{\underline{3} \times \underline{5}}{100}$	W_{WE} = weight of moisture input (lb/hr) W_{FA-R} = as-received fuel input rate (lb/hr) f_m = average fuel moisture (percent)

19 Unburned carbon in bottom ash (lb/hr)	$UC_{BA} = \frac{W_{BA}C_{BA}}{100}$
$\frac{\underline{36} \times C_{BA}}{100}$	UC_{BA} = unburned carbon in bottom ash (lb/hr) W_{BA} = bottom ash output rate (lb/hr) C_{BA} = unburned combustibles in bottom ash (percent)
20 Unburned carbon in fly ash (lb/hr)	$UC_{FA} = \frac{W_{FA}C_{FA}}{100}$
$\frac{\underline{37} \times C_{FA}}{100}$	UC_{FA} = unburned carbon in fly ash (lb/hr) W_{FA} = fly ash output rate (lb/hr) C_{FA} = average unburned combustibles in fly ash (percent)
21 Efficiency test date	-------
Same as 1	-------

22 Start time (--)	-------
8:00 a.m.	-------

23 End time (--)	-------
	End of test period

24 Δt (hr)	Time end - time start
23 - 22	Elapsed time of efficiency test

30 HTHW generation rate (10^3 lb/hr)	$W_{HTHWE} = \frac{W_{HTHW}}{\Delta t}$
$\frac{W_{HTHW}}{24}$	W_{HTHWE} = HTHW generation rate (lb/hr) W_{HTHW} = total HTHW generated (lb) Δt = elapsed time of test (hr)

31 HTHW enthalpy gain (Btu/lb)	$\Delta h = h_o - h_i$
From 1967 ASME steam tables	Δh = enthalpy gain (Btu/lb) h_o = HTHW outlet enthalpy (Btu/lb) h_i = HTHW inlet enthalpy (Btu/lb)

32 Measured HTHW heat output (10^6 Btu/hr)	$Q_o = W_{HTHWE}\ \Delta h$
$\frac{\underline{30} \times \underline{31}}{1000}$	Q_o = HTHW heat output (10^6 Btu/hr) W_{HTHWE} = HTHW generation rate (10^3 lb/hr) Δh = steam enthalpy gain (10^3 Btu/lb)

33 Stoichiometric air requirement (lb/lb)

$$A\theta = 11.51C_f + 34.3\ H_f - \frac{O_f}{8} + 4.335S_f$$

$$11.51 \times \frac{\underline{9}}{\underline{7}} +$$

$$34.3 \times \frac{\underline{10}}{\underline{7}} - \frac{\underline{12}}{8 \times \underline{7}} +$$

$$4.335 \times \frac{\underline{11}}{\underline{7}}$$

$A\theta$ = theoretical air (lb/lb)

C_f = average carbon content of fuel (percent)

H_f = average hydrogen content of fuel (percent)

O_f = average oxygen content of fuel (percent)

S_f = average sulfur content of fuel (percent)

34 Excess air (%)

$$EA = \frac{O_2 - .5\ CO}{.264\ N_2 - (O_2 - .5\ CO)}$$

EA = excess air

$N_2 = 100 - CO_2 - O_2 - CO$

O_2 = daily average O_2 concentration at stack (percent)

CO_2 = daily average CO_2 concentration at stack (percent)

CO = daily average CO concentration at stack (percent)

$\underline{35}$ Air flow into boiler (10^3 lb/hr)

$$A_t = W_f A\theta' \;\; 1 + \frac{EA}{100}$$

$$\underline{7} \times \underline{33} \times \frac{100 + \underline{34}}{100}$$

A_t = total air flow (lb/hr)

W_f = dry fuel input rate (lb/hr)

$A\theta'$ = theoretical A:F ratio (lb/lb)

EA = excess air (%)

$\underline{36}$ Bottom ash output (lb/hr)

$$BA = \frac{W_I - (FA + UC_{FA})}{1 - \frac{C_{BA}}{100}}$$

$$\frac{\underline{14} - \underline{37} + \underline{20}}{1 - \frac{C_{BA}}{100}}$$

BA = bottom ash output (lb/hr)

W_I = inerts input rate (lb/hr)

FA = particulate rate ESP inlet (lb/hr)

UC_{FA} = fly ash unburned combustibles (lb/hr)

C_{BA} = bottom ash unburned combustibles (percent)

$\underline{37}$ Fly ash output (lb/hr)

FA = average daily or estimated fly ash emission at ESP inlet (lb/hr)

$\underline{39}$	R/C energy percent (%)	-------
	-------	From ABMA Standard Radiation Loss Chart (loss as percent of input heat)

$\underline{40}$	R/C energy losses (10^6 Btu/hr)	$L_\beta = R/C\ E_i$
	$\underline{15} \times \frac{\underline{39}}{100}$	L_β = radiation/convection losses (10^6 Btu/hr) R/C = loss rate (%) E_i = energy input (10^6 Btu/hr)

$\underline{41}$	Input-output efficiency (%)	$\eta_{I-O} = \frac{100Q_o}{E_i}$
	$\frac{\underline{32} \times 100}{\underline{15}}$	η_{I-O} = input-output efficiency (%) Q_o = measured HTHW output (10^6 Btu/hr) E_i = energy input (10^6 Btu/hr)

42	Boiler load (%)	$f = \frac{Q_o}{100 \times 10^6}$
	$\frac{\underline{32}}{100 \times 10^6}$	Q_o = energy output as HTHW (10^6 Btu/hr) f = boiler load (percent capacity)
43	Bottom ash heat loss (10^6 Btu/hr)	$L_{BA} = \frac{UC_{BA} \times HHV_{carbon}}{10^6}$
	$\frac{\underline{19} \times 14100}{10^6}$	L_{BA} = bottom ash heat loss (10^6 Btu/hr) UC_{BA} = bottom ash unburned combustibles (lb/hr) HHV_{carbon} = 14100 Btu/lb
44	Fly ash heat loss (10^6 Btu/hr)	$L_{FA} = \frac{UC_{FA}\ HHV_{carbon}}{10^6}$
	$\frac{\underline{20} \times 14100}{10^6}$	L_{FA} = fly ash heat loss (10^6 Btu/hr) UC_{FA} = fly ash unburned combustibles (lb/hr) HHV_{carbon} = 14100 Btu/lb

$\underline{45}$	CO_2 output rate (lb/hr)	$W_{CO_2} = \frac{44}{12} W_c - UC_{BA} - UC_{FA}$
	$3.667 \times (\underline{9} - \underline{19} - \underline{20})$	W_{CO_2} = CO_2 output rate (lb/hr) W_c = carbon input rate (lb/hr) UC_{BA} = bottom ash unburned combustibles (lb/hr) UC_{FA} = fly ash unburned combustibles (lb/hr)

$\underline{46}$	H_2O output rate (lb/hr)	$W_{H_2O} = W_{WE} + 9\ W_H$
	$\underline{16} + (9 \times \underline{10})$	W_{H_2O} = H_2O output rate (lb/hr) W_{WE} = fuel moisture inputs (lb/hr) W_H = hydrogen input (lb/hr)

47 SO_2 output rate (lb/hr)	$W_{SO_2} = 2\ W_S$
2 × 11	W_{SO_2} = SO_2 output rate (lb/hr) W_S = sulfur input rate (lb/hr)

48 O_2 output rate (lb/hr)	$W_{O_2} = .233\ A_t + W_O - .727\ W_{CO_2} - 8\ W_H - W_S$
(.233 × 35 × 1000) + 12 - (.727 × 45) - (8 × 10) - 11	W_{O_2} = O_2 output rate (lb/hr) A_t = total air input (lb/hr) W_O = oxygen input with fuel (lb/hr) W_{CO_2} = CO_2 output (lb/hr) W_H = hydrogen in fuel input (lb/hr) W_S = sulfur in fuel input (lb/hr)

49	N_2 output rate (lb/hr)	$W_{N_2} = .767 A_t + W_N$
	767 × 35 + 13	W_{N_2} = N_2 output rate (lb/hr) A_t = total air input (lb/hr) W_N = nitrogen input in fuel (lb/hr)

50	Temperature flue gas outlet (°F)	-------
	-------	Average of hourly observations.

51	Total dry flue gas rate (10^3 lb/hr)	$DFG = W_{CO_2} + W_{SO_2} + W_{O_2} + W_{N_2}$
	$\frac{45 + 47 + 48 + 49}{10^3}$	DFG = dry flue gas output (lb/hr) W_{CO_2} = weight of CO_2 output (lb/hr) W_{SO_2} = SO_2 output rate (lb/hr) W_{O_2} = oxygen output rate (lb/hr) W_{N_2} = nitrogen output rate (lb/hr)

$\underline{52}$ Dry flue gas sensible heat loss (10^6 Btu/hr)	$L_G = m\,Cp\Delta T$
$\frac{(\underline{50} - 70) \times \underline{51} \times .2423}{10^3}$	L_G = dry flue gas heat loss (Btu/hr) m = mass flow rate of dry flue gas (lb/hr) Cp = average specific heat of dry flue gas (Btu/lb °F) ΔT = Temperature of flue gas above 70°F reference
$\underline{53}$ Enthalpy of wet flue gas (Btu/lb)	-------
-------	According to ASME-PTC 4.1. Enthalpy of moisture in flue gas measured at flue gas outlet temperature and 1 psia. Superheated. From 1967 ASME Steam Tables.
$\underline{54}$ Wet flue gas loss (10^6 Btu/hr)	$L_{Wfg} = W_{H_2O}\,(h_{go} - h_i)$
$(\underline{53} - 38) \times \underline{46} \times 10^{-6}$	L_{Wfg} = loss due to moisture in flue gas (10^6 Btu/hr) W_{H_2O} = moisture output rate (lb/hr) h_{go} = enthalpy of superheated water vapor in flue gas (Btu/lb) h_i = enthalpy of liquid water at 70°F (Btu/lb)

56 Calculated boiler outlet H_2O (% vol)	$$H_2O = \frac{18W_{H_2O}}{29.5 \quad W_{H_2O} + DFG}$$
$\frac{100 \times \underline{46}}{\underline{46} + (610 \times \underline{51})}$	H_2O = moisture concentration (percent by volume) 18 = molecular weight of H_2O 29.5 = average molecular weight of flue gas W_{H_2O} = flue gas moisture rate (lb/hr) DFG = dry flue gas rate (lb/hr)

57 Total losses (10^6 Btu/hr)	$L_T = L_\beta + L_{BA} + L_{FA} + L_G + L_{Wfg}$
$\underline{40} + \underline{43} + \underline{44} + \underline{52} + \underline{54}$	L_T = total losses (10^6 Btu/hr) Other L's: see $\underline{40}$ through $\underline{54}$

58 Efficiency by heat balance (%)	$\eta = 1 - \frac{L_T}{E_i} \; 100$
$1 - \frac{\underline{57}}{\underline{15}} \times 100$	η = heat balance efficiency (%) L_T = total losses (10^6 Btu/hr) E_i = total energy input (10^6 Btu/hr)

64 Bottom ash loss (%)	$E_{BA} = \frac{L_{BA}}{E_i} \times 100$
$100 \times \frac{\underline{43}}{\underline{15}}$	E_{BA} = percent of input lost in bottom ash (%) L_{BA} = bottom ash losses (10^6 Btu/hr) E_i = energy input (10^6 Btu/hr)

65 Fly ash loss (%)

$$E_{FA} = \frac{L_{FA}}{E_i} \times 100$$

$$100 \times \frac{44}{15}$$

E_{FA} = percent of input lost in fly ash (%)

L_{FA} = fly ash losses (10^6 Btu/hr)

E_i = energy input (10^6 Btu/hr)

66 Dry flue gas loss (%)

$$E_G = \frac{L_G}{E_i} \times 100$$

$$100 \times \frac{52}{15}$$

E_G = percent of input lost in dry flue gas (%)

L_G = dry flue gas losses (10^6 Btu/hr)

E_i = energy input (10^6 Btu/hr)

67 Wet flue gas loss (%)	$E_{Wfg} = \frac{L_{Wfg}}{E_i}$
$100 \times \frac{\underline{54}}{\underline{15}}$	E_{Wfg} = percent of input lost in wet flue gas (%) L_{Wfg} = wet flue gas losses (10^6 Btu/hr) E_i = energy input (10^6 Btu/hr)

68 Total loss (%)	$E_{Loss} = \frac{L_T}{E_i} \times 100$
$100 \times \frac{\underline{57}}{\underline{15}}$	E_{Loss} = percent of input energy lost (%) L_T = total of losses (10^6 Btu/hr) E_i = energy input (10^6 Btu/hr)

70 Inert input rate (lb/10^6 Btu)	$A_I = \frac{W_I}{E_i}$
14 15	A_I = inert matter input rate (lb/10^6 Btu) W_I = inert matter input rate (lb/hr) E_i = heat input rate (10^6 Btu/hr)

71 Sulfur input rate (lb/10^6 Btu)	$A_S = \frac{W_S}{E_i}$
11 15	A_S = sulfur input rate (lb/10^6 Btu) W_S = sulfur input rate (lb/hr) E_i = heat input rate (10^6 Btu/hr)

72 Nitrogen in fuel input rate (lb/10^6 Btu)	$A_N = \frac{W_N}{E_i}$
13 15	A_N = nitrogen input rate (lb/10^6 Btu) W_N = nitrogen input rate (lb/hr) E_i = heat input rate (10^6 Btu/hr)

APPENDIX C

ENGLISH UNITS TO SI UNITS

To convert from	To	Multiply by
in.	mm	25.40
in.^{2}	mm^2	645.2
ft	m	0.3048
ft^2	m^2	0.09290
ft^3	m^3	0.02832
lb	kg	0.4536
lb/hr	Mg/s	0.1260
lb/10^6 Btu	ng/J	430
Btu	J	1056
Btu/lb	J/kg	0.002328
Btu/lb	W	0.2929
Btu/ft/hr	W/m	0.9609
Btu/ft/hr	J/h/m	3459
Btu/ft^2/hr	W/m^2	3.152
Btu/ft^2/hr	J/h/m^2	11349
Btu/ft^3/hr	W/m^3	10.34
Btu/ft^3/hr	J/h/m^3	37234
psi	Pa	6895
in. H_2O	Pa	249.1
Rankine	Celsius	$C = (5/9R) - 273$
Fahrenheit	Celsius	$C = 5/9(F - 32)$
Celsius	Kelvin	$K = C + 273$
Rankine	Kelvine	$K = 5/9R$
mm	in.	.03937
mm^2	in.^{2}	.00155
m	ft	3.281
m^2	ft^2	10.764
m^3	ft^3	35.315
kg	lb	2.2056
Mg/s	lb/hr	7.937
ng/J	lb/10^6 Btu	0.00233

ENGLISH UNITS TO SI UNITS (continued)

To convert from	To	Multiply by
J	Btu	0.000948
J/kg	Btu/lb	4.303
J/h/m	Btu/ft/hr	0.000289
$J/h/m^2$	$Btu/ft^2/hr$	0.0000881
$J/h/m^3$	$Btu/ft^3/hr$	0.0000269
W	Btu/hr	3.414
W/m	Btu/ft/hr	1.041
W/m^2	$Btu/ft^2/hr$	0.317
W/m^3	$Btu/ft^3/hr$	0.0967
Pa	psi	0.000145
Pa	in. H_2O	0.004014
Kelvin	Fahrenheit	F = 1.8K - 460
Celsius	Fahrenheit	F = 1.8C + 32
Fahrenheit	Rankine	R = F + 460
Kelvin	Rankine	R = 1.8K