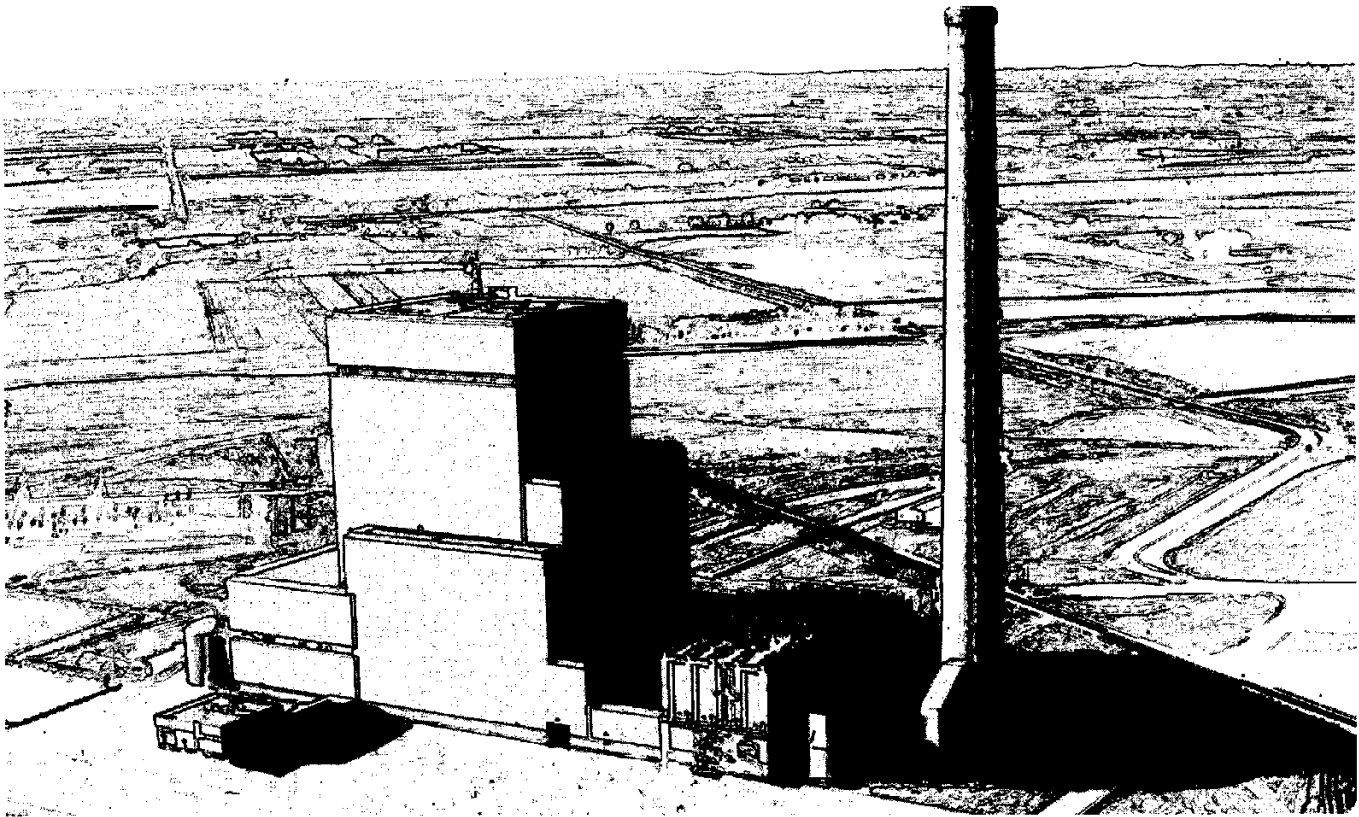


Results of Combustion and Emissions Testing when Co-Firing Blends of Binder-Enhanced Densified Refuse-Derived Fuel (b-dRDF) Pellets and Coal in a 440 MW_e Cyclone Fired Combustor

Volume 1: Test Methodology and Results



A Joint Effort



**Energy Systems Division
Argonne National Laboratory**

Operated by the University of Chicago
for the U.S. Department of Energy
under Contract W-31-109-Eng-38
Author: O. Ohlsson



**National Renewable
Energy Laboratory**

Managed by Midwest Research Institute
for the U.S. Department of Energy
under Contract DE-AC36-83CH10093
Technical Monitor: Philip B. Shepherd

Argonne National Laboratory and the National Renewable Energy Laboratory
are part of the national laboratory system of the **U.S. Department of Energy**.

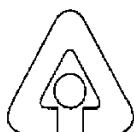
Results of Combustion and Emissions Testing when Co-Firing Blends of Binder-Enhanced Densified Refuse-Derived Fuel (b-dRDF) Pellets and Coal in a 440 MW_e Cyclone Fired Combustor

Volume 1: Test Methodology and Results

**O. Ohlsson
Energy Systems Division
Argonne National Laboratory
9700 South Cass Avenue
Argonne, Illinois 60439**

Technical Monitor: Philip B. Shepherd

A Joint Effort



**Energy Systems Division
Argonne National Laboratory**

Operated by the University of Chicago
for the U.S. Department of Energy
under Contract W-31-109-Eng-38



**National Renewable
Energy Laboratory**

Managed by Midwest Research Institute
for the U.S. Department of Energy
under Contract DE-AC36-83CH10093

This report was prepared under Task #WM41.1010
and Subcontract #DA-1-11157-1

July, 1994

This publication was reproduced from the best available camera-ready copy submitted by the subcontractor and received no editorial review at NREL.

NOTICE

This report was prepared as an account of work sponsored by an agency of the United States government. Neither the United States government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States government or any agency thereof.

Available to DOE and DOE contractors from:
Office of Scientific and Technical Information (OSTI)
P.O. Box 62
Oak Ridge, TN 37831
Prices available by calling (615) 576-8401

Available to the public from:
National Technical Information Service (NTIS)
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161
(703) 487-4650



Printed on paper containing at least 50% wastepaper including 10% postconsumer waste

Foreword

This report contains the test data from the co-firing of b-dRDF pellets and coal in a 440-MW_e cyclone-fired combustor. These tests were conducted under a Cooperative Research and Development Agreement (CRADA). The CRADA partners included the U.S. Department of Energy (DOE); the National Renewable Energy Laboratory (NREL); Argonne National Laboratory (ANL); Otter Tail Power Company; Green Isle Environmental, Inc.; XL Recycling Corporation; and Marblehead Lime Company. The report is made up of three volumes. Volume 1 contains a description of the test facility, the test program, test results, and study conclusions and recommendations; Volume 2 contains the field data and laboratory analysis of each individual run. Volume 3 contains other supporting information, quality assurance documentation, and safety and test plans. This multi-volume approach enables readers to find information at the desired level of detail, depending on individual interest or need.

Acknowledgements

The author would like to acknowledge the contributions of the following organizations that participated in the DOE/NREL/ANL tests: Otter Tail Power Company's Big Stone Plant of Big Stone City, South Dakota, which provided the test facility and necessary operations and engineering personnel; the Eden Prairie Recycling (Reuter, Inc.) facility of Minneapolis, Minnesota, which supplied approximately 620 tons of binder (lime) enhanced dRDF pellets; XL Recycling of Crestwood, Illinois, which supplied about 655 tons of binder-enhanced dRDF pellets; the Marblehead Lime Company of Chicago, Illinois, which furnished the lime binder additive; and Interpoll Laboratories of Circle Pines, Minnesota, which, under contract to ANL, conducted the stack gas sampling and emission determinations and analyses of the feedstock and ash sample.

Additionally, the author would like to acknowledge the contributions that the following individuals made to the successful accomplishment of the combustion tests: Roger Davis and John Boquist of Eden Prairie Recycling; Edward Prium and Peter Brown of XL Recycling; Dean Pawlowski, Stu Schreurs, and Mark Rolfes of the Big Stone City generation station; Lance Olson of Marblehead Lime Company; and Daniel Despen of Interpoll Laboratories. I also wish to express my appreciation to Mr. Simon Friedrich, Program Manager, Municipal Solid Waste, U.S. DOE; Mr. B.P. Gupta, Program Manager of the Municipal Solid Waste Program at NREL; and Mr. Philip Shepherd of NREL for their support and direct assistance in these studies.

Executive Summary

As part of the U.S. Department of Energy's (DOE) Municipal Solid Waste (MSW) Program, Argonne National Laboratory (ANL) conducted a multi-phase research study on the use of low-cost binder additives for improving densified refuse-derived fuel (dRDF) pellets. The laboratory test phase of this study, completed in 1985, examined more than 150 potential binders and binder combinations. The 13 most promising candidates from this laboratory testing were selected for field testing. The field work, was conducted in cooperation with the U.S. Navy at the Naval Civil Engineering Laboratory's test facility in Jacksonville, Florida during 1986. The results of these tests indicated that calcium hydroxide was the top-ranked binding agent.

As the third and final phase of the multi-phase study, ANL conducted two full-scale co-fired combustion tests of calcium hydroxide-enhanced dRDF pellets and coal. The first test was conducted in 1987 in ANL's spreader-stoker combustion unit.

With the successful completion of the ANL tests, it appeared desirable to consider the feasibility of co-firing binder-enhanced dRDF (b-dRDF) pellets and coal in a cyclone-fired combustor since these combustors are more extensively used in the industrial and electric utility market place than the older, smaller spreader-stoker units.

Commercial-scale tests for this study were conducted at Otter Tail Power Company's 440-MW_e cyclone-fired generating station located at Big Stone City, South Dakota. These tests were conducted under a cooperative research and development agreement (CRADA). The CRADA participants included two national laboratories and three industrial partners.

The facility uses a Babcock & Wilcox lignite-fired cyclone furnace with a balanced-draft, forced-circulation, radiant-reheat boiler. This boiler has a maximum continuous rating of 3.25×10^6 lb/hr steam at 2620 psig and 1005°F at the superheater outlet. Twelve water-cooled cyclone furnaces are located on the front and back sides of the boiler at two elevations. Each cyclone consists of a storage silo, a coal crusher located directly below the silo, turbine-driven forced-draft fans, pumps, air heaters, glycol-air preheaters, and a soot blowing system. The coal crushers reduce the coal size from 0.75 inch into 0.25 inch or less before it enters the cyclone furnaces that fire the main boiler. The coal usage is approximately 365 tons/hr and the design heating value is 6255 Btu/lb. The steam exiting the superheater powers a Westinghouse 500-MVA turbine-generator unit, which produces a maximum guaranteed electrical output of 414,588 kWh. The effluent combustion gases from the boiler pass through an electrostatic precipitator (ESP) where the flue gas flyash is removed. The ESP consists of four collection chambers, flyash is collected in hoppers located beneath each chamber. Combustion flue gases exiting the ESP are discharged to the atmosphere via a 498-foot stack. The ash-handling system collects and removes the ash from the furnace bottom, economizer hoppers, air heater hoppers, and precipitator hoppers. Furnace bottom ash, economizer ash, and air preheater ash are collected and conveyed in a wet state to the ash service pond. Precipitator flyash is conveyed by an air transport system to a storage silo for disposal by truck to the plant ash landfill.

This study was designed to determine the following:

1. The amount of pollutants, both gaseous and ashes, released during the co-firing of binder-enhanced dRDF pellets with coal in a cyclone-fired combustor;
2. Boiler efficiencies when combusting b-dRDF/coal blends; and
3. The effect of firing b-dRDF/coal blends on plant operations.

This study involved two testing periods. The first test period was conducted on October 26, 1992, during which time the plant was operated only with coal to provide a benchmark of typical plant performance. On the following day, October 27, 1992, the plant was operated using a blend of 12% (by weight) b-dRDF pellets and 88% coal. Each of the two tests were conducted over a 10-hour test period. Contamination encountered in the b-dRDF pellets during the blended b-dRDF/coal test caused an inconsistent fuel feed to the silos resulting in unstable boiler operation. Stable boiler conditions were not achieved until approximately the last 3 hours of the test run. However, all gaseous and ash emissions were below U.S. Environmental Protection Agency (EPA) regulatory limits during both the unstable and stable test conditions.

Approximately 1275 tons of dRDF pellets, containing 4% (by weight) calcium hydroxide binder, were produced at the 400-ton/day Eden Prairie Recycling (EPR) processing facility located at Minneapolis, Minnesota, and at the 400-ton/day XL Recycling facility in Crestwood, Illinois. Pellets were delivered to the test site by 58 trucks, which were scheduled to arrive either the day before or the morning of the first test day to minimize outdoor storage time. After delivery, the pellets were stored adjacent to a reclaim hopper normally used to feed coal from the dead coal storage pile in the event coal is not available from the live storage facility. During the blended b-dRDF/coal test day the b-dRDF pellets were fed onto the conveying system by a large front-end loader and mixed with coal (simultaneously fed from live storage via a separate conveyor) at the transfer house. The transfer house, which contains both primary and redundant hammermill crushers, reduced the mixture to 0.75 inch top size. The blended pellet and coal mixture then entered the boiler building on a single conveyor where the fuel mixture was fed into the 12 silos. Upon exiting the silos, the mixture was further reduced to 0.25 inch before being fed into the cyclone furnaces.

During each test period, combustion gases were sampled at the stack using manual sampling trains and a continuous-emission monitoring system. Manually sampled pollutants included particulate matter, PCDD, PCDF, PAHs, PCBs, Cl, HCl, HF, HBr, trace metals (14), BTX, and opacity. SO₂, NO_x, CO₂, O₂, CO, and THC were sampled by the continuous-emission monitoring system.

Combustion residues including bottom ash, economizer ash, and flyash were collected and analyzed separately. These ash residue samples were analyzed for metals (14), chlorides, sulfates, pH, H₂, mineral content, and PCDDs/PCDFs. Toxicity Characteristic Leaching Procedure (TCLP) tests also were conducted on the bottom ash, economizer ash, and flyash samples.

Individual coal and b-dRDF pellet samples were collected and analyzed and blended b-dRDF/coal samples were collected. These feedstock samples were analyzed for trace metals (14), total chlorine, ash fusion temperature, and bulk density. Ultimate and proximate analyses also were conducted.

All gaseous emissions and ash were analyzed according to the provisions of standard U.S. Environmental Protection Agency (EPA) methods cited in Code of Federal Regulations (CFR) Title 40, Part 60, Appendix A and other special purpose EPA methodologies reported elsewhere in the literature.

Analysis of the data yields several significant conclusions:

1. An overall beneficial reduction in the major priority pollutants in the flue gas was observed. The blended b-dRDF/coal tests produced lower emissions of SO₂, NO_x, and CO compared to coal only tests. CO₂, HF, and HBr emissions were essentially unchanged. HCl, THCs, and particulate matter increased, but increases were small.
2. For both tests, PCDD/PCDF levels in the flue gas were small and below federal regulatory limits.

3. Small increases in metal concentrations in the flue gas were observed during blended tests.
4. Metal concentrations in the ash (bottom ash and flyash) increased during the blended fuel tests.
5. The concentration of metals were more predominant in the flyash than in the bottom ash. Nine metals (Sb, As, Ba, Cd, Cr, Cu, Pb, Ag and Zn) exhibited higher concentrations in the flyash during the blended tests compared to the coal only tests. However, higher concentrations of four (Ba, Pb, As, Cd) of the nine metals were probably due to the higher levels of these metals existing in the coal used in the blended fuel tests. Three metals (Be, Hg, Ni) concentrations were about equal, one metal (Tl) was below detectable levels for both tests, and one metal (Se) was lower in the blended test for flyash.

Three metals (Sb, Hg, Cu) exhibited higher concentration levels in the bottom ash during the blended b-dRDF/coal tests and the coal tests. Concentrations of three metals (Be, Cd, Pb) were about equal, while three metals (Se, Ag, Tl) were below detectable levels for both the blended b-dRDF/coal tests and the coal only tests. Five metals (As, Zn, Ni, Cr, Ba) exhibited lower concentrations during the blended fuel tests compared to the coal only tests.

6. PCBs, BTX, and PAHs (except naphthalene and phenanthrene) were below detectable levels for both tests. Emissions of naphthalene and phenanthrene decreased during the blended fuel test.
7. No ash samples showed toxicity by the Toxic Characteristic Leaching Procedure (TCLP) test.
8. Fabricators of b-dRDF pellets must be attuned to the specific needs of potential users of their product. It is extremely important that these fuel pellets be tailored to meet individual furnace requirements. In the case of the cyclone-fired combustion system, particle size must be restricted to no more than 1-1.5 inches, or smaller if possible, to preclude potential operational problems. It is equally as important to remove as much film plastic material as possible prior to the densification process.

Contents

| | <u>Page</u> |
|---|-------------|
| Foreword | iii |
| Acknowledgements | iii |
| Executive Summary | iv |
| 1.0 Background | 1 |
| 2.0 Introduction | 3 |
| 3.0 Study Approach | 5 |
| 3.1 Introduction | 5 |
| 3.2 Test Facility Description | 6 |
| 4.0 Fuel Preparation | 9 |
| 4.1 Binder-Enhanced dRDF Pellets | 9 |
| 4.2 Coal | 9 |
| 4.3 Fuel Blending Procedures | 9 |
| 5.0 Sampling and Analysis Methodology | 15 |
| 5.1 Sampling and Analytical Procedures - Flue Gas | 15 |
| 5.2 Sampling and Analytical Procedures - Ash Residues | 17 |
| 5.3 Sampling and Analytical Procedures - Feedstock | 17 |
| 6.0 Test Results and Discussion | 20 |
| 6.1 Flue Gas Emissions | 20 |
| 6.1.1 Particulate Matter | 20 |
| 6.1.2 Opacity | 21 |
| 6.1.3 Sulfur Dioxide (SO ₂) | 21 |
| 6.1.4 Nitrogen Oxides (NO _x) | 21 |
| 6.1.5 Carbon Monoxide (CO) | 22 |
| 6.1.6 Carbon Dioxide (CO ₂) | 22 |
| 6.1.7 Total Hydrocarbons (THC) | 22 |
| 6.1.8 Benzene, Toluene, Xylene (BTX) | 22 |
| 6.1.9 Hydrogen Chloride (HCl) | 23 |
| 6.1.10 Hydrogen Fluoride and Hydrogen Bromide | 23 |
| 6.1.11 PCDD and PCDF | 23 |
| 6.1.12 PAH and PCB | 23 |
| 6.1.13 Trace Metals | 25 |

Contents (continued)

| | <u>Page</u> |
|---|-------------|
| 6.2 Ash Analysis | 25 |
| 6.2.1 TCLP Analysis | 25 |
| 6.2.2 Metals, PCDD/PCDF, and Physical Characteristics | 27 |
| 6.3 Feedstock Analysis | 30 |
| 6.4 General Operational Observations | 35 |
| 6.5 Boiler Efficiency | 39 |
| 7.0 Conclusions and Recommendations | 41 |
| 7.1 Flue Gas Emissions | 41 |
| 7.2 Solid Waste Residuals | 42 |
| 7.3 Recommendations | 42 |
| 8.0 Abbreviations | 43 |
| 9.0 References | 45 |

List of Tables

| | <u>Page</u> |
|---|-------------|
| 2-1 Test and Operating Conditions | 4 |
| 3-1 Combustor Design Performance | 8 |
| 4-1 Sampling and Analysis Methods - Flue Gas | 13 |
| 5-1 Sampling and Analysis Methods - Ash Residue | 18 |
| 5-2 Sampling and Analysis Methods - Feedstock | 18 |
| 6-1 Summary of Flue Gas Particulate Emission and Opacity Determinations | 20 |
| 6-2 Summary of Continuous Emission Monitoring of SO ₂ , NO _x , CO, CO ₂ , O ₂ , and THC Concentrations in Flue Gas | 22 |
| 6-3 Summary of Flue Gas BTX, CL ₂ , HCl, HBr, and HF Concentrations | 23 |
| 6-4 Summary of Flue Gas PCDD/PCDF Homolog Determinations | 24 |
| 6-5 Summary of Flue Gas PAH Determinations | 24 |
| 6-6 Summary of Flue Gas PCB Determinations | 25 |
| 6-7 Summary of Flue Gas Trace Metals Concentrations | 26 |
| 6-8 Summary of TCLP Test Results of Bottom Ash | 26 |
| 6-9 Summary of TCLP Test Results of Economizer Flyash | 27 |
| 6-10 Summary of TCLP Test Results of ESP Flyash | 28 |
| 6-11 Summary of Metals, PCDD/PCDF, and Physical Characteristics of Bottom Ash | 29 |
| 6-12 Summary of Metals, PCDD/PCDF, and Physical Characteristics of Economizer Flyash | 30 |
| 6-13 Summary of Metals, PCDD/PCDF, and Physical Characteristics of ESP Flyash | 31 |
| 6-14 Summary of Bottom Ash Mineral Analysis | 32 |
| 6-15 Summary of ESP Flyash Mineral Analysis | 32 |
| 6-16 Coal Sources and Characteristics - Test 1 | 33 |
| 6-17 Coal Sources and Characteristics - Test 2 | 33 |
| 6-18 Coal Ultimate and Proximate Analysis | 34 |

List of Tables (continued)

| | <u>Page</u> |
|--|-------------|
| 6-19 b-dRDF Pellet Ultimate and Proximate Analysis | 35 |
| 6-20 Feedstock Ultimate and Proximate Analysis | 36 |
| 6-21 b-dRDF Pellet Metals Analysis | 37 |
| 6-22 Coal Metals Analysis | 37 |
| 6-23 Feedstock Metals Analysis | 38 |
| 6-24 Metals Variation in Feedstock | 38 |
| 6-25 Feedstock Ash Fusion Temperature Analysis | 39 |
| 6-26 Heat Losses and Boiler Efficiency | 40 |
| 6-27 Comparison of Facility Permitted Levels vs. Test Levels | 40 |

List of Figures

| | <u>Page</u> |
|--|-------------|
| 3-1 Big Stone Steam Plant - Unit No. 1 | 7 |
| 4-1 EPR Pellets | 10 |
| 4-2 XL Recycling Pellets | 10 |
| 4-3 Plan View of b-dRDF/Coal Feed System | 11 |
| 4-4 Test Sampling Station Locations | 12 |
| 4-5 Aerial View of Test Facility | 12 |

1.0 Background

The disposal of municipal solid waste (MSW) is of increasing concern for municipalities and state governments throughout the United States. The U.S. Environmental Protection Agency (EPA) has estimated that the United States generated approximately 196 million tons of MSW in 1990.¹ Further, it projected that the amount of MSW generated by the year 2000 would be 225 million tons per year. Approximately 75-80% of this material is combustible and could be burned efficiently to produce energy for steam or electricity generation. Even using a conservative estimate that 35% of this combustible fraction can be successfully recycled, we are left with about 100 million tons per year of MSW that could be combusted. This waste represents approximately 1.1 quads of energy, roughly equivalent to 40 million tons of bituminous coal, or 4.5% of all the coal consumed by the U.S. economy in 1990.

The two basic technologies used in MSW combustion are mass burn and refuse-derived fuel (RDF) systems. Mass burn systems are usually large, field-erected facilities that burn unprocessed MSW (i.e., as received from collection vehicles). Prior to combustion, bulk items such as major appliances and materials hazardous to plant operations or the environment are removed. RDF systems are generally large facilities, ranging from 400 tons per day (tpd) to 3000 tpd. These facilities remove non-combustible materials (some of which are recycled) and process the remaining MSW into a more homogeneous fuel. The resulting RDF is either marketed to outside users or combusted in dedicated boilers or co-fired with other fuels in existing furnaces.

Two general types of RDF products are being produced. The first is a "fluff" type RDF, which has a low bulk density (about 2-4 lbs/ft³), is difficult and costly to handle and transport, and has a limited storage time. The second type of RDF product, known as densified RDF (dRDF), is produced by further processing the fluff RDF into a densified fuel product. To produce dRDF, the fluff material is extruded under pressure to create pellets, typically 2-3 inches in length, and 0.625-0.75 inch in diameter. Densified RDF has a bulk density of about 20-35 lbs/ft³ and an energy content of approximately 5500-7000 Btu/lb. Typically, the dRDF that was produced in the late 1970s and early 1980s lacked mechanical strength and exhibited the same limited storage time as fluff RDF.

In an attempt to alleviate the problems encountered with dRDF as a feedstock, Argonne National Laboratory (ANL) and the University of North Texas (UNT), under the sponsorship of the U.S. Department of Energy (DOE), began investigating the development of a low-cost binder that would improve dRDF pellets.² Initially, more than 150 binders were screened based on economics, projected environmental considerations, and effectiveness. This screening process eliminated many candidates, and the remaining binders, about 60, were subjected to a more detailed analysis, including laboratory testing.

Thirteen binder candidates from this laboratory testing were field tested in a joint agreement with the U.S. Navy's pilot-scale facility at Jacksonville Naval Air Station in Florida. The pellets that were produced from 53 individual test runs were subjected to a battery of chemical and physical tests that indicated calcium hydroxide (Ca(OH)₂) was the most effective binding agent.

In addition to the advantages that calcium hydroxide provided as a physical binding agent, it also had potential to reduce air quality emissions when combusted with coal. In order to investigate this premise, two full-scale co-fired combustion tests of calcium hydroxide-enhanced dRDF pellets and coal were undertaken. The first test was conducted in 1987 in ANL's traveling grate, spreader stoker unit. With the successful completion of this test³, it appeared desirable to consider the feasibility of co-firing binder-enhanced dRDF pellets and coal in a cyclone-fired combustor since these combustors are used extensively in the industrial and electric utility market place.

Commercial-scale co-fired combustion tests were conducted at Otter Tail Power Company's 440-MW_e cyclone-fired generating station located at Big Stone City, South Dakota on October 26-27, 1992. These tests were conducted under a cooperative research and development agreement (CRADA). The CRADA partners included DOE; ANL; the National Renewable Energy Laboratory (NREL); Otter Tail Power Company; Green Isle Environmental, Inc.; XL Recycling Corporation; and Marblehead Lime Company.

2.0 Introduction

This report describes the co-combustion testing of b-dRDF pellets and coal blends that were conducted at Otter Tail Power Company's 440-MW_e cyclone-fired power generation station in Big Stone City, South Dakota on October 26-27, 1992.

The objectives of this program were to:

1. Quantify the emissions that are released during the co-firing of b-dRDF pellets with coal in a cyclone-fired combustor;
2. Determine boiler efficiencies when combusting b-dRDF/coal blends; and
3. Evaluate the effect of firing b-dRDF/coal blends on plant operations.

The results of these combustion tests, coupled with the combustor performance evaluations developed concurrently with the emission testing are expected to:

1. Allow the industrial sector and the electric utility industry to develop operating, technical, and financial data, which will enhance and expand the commercial use of b-dRDF pellets;
2. Provide the data necessary to allow state regulatory agencies to evaluate methods for permitting and monitoring such units in the future; and
3. Provide a database for equipment manufacturers.

The combustion tests were conducted over a 2-day period. The sampling test periods were a one 10-hour test period in which 100% coal was fired and a second 10-hour test period in which a blend of 12% b-dRDF pellets and 88% coal was fired.

Flue gas emissions, ash and feedstock samples were collected and analyzed during each test day. Additionally, flue gas emissions were monitored by continuous emission monitoring systems. Combustor performance evaluations were developed concurrently with the emissions testing. The test and operating parameters for the 2-day test period are shown in Table 2-1.

This report covers a detailed description of the test facility, the test program, test results, and study conclusions. A discussion of the process operating data and the sampling and analysis methodologies is given. The results of the feedstock, flue gas, and ash residues sampling and analysis are presented, along with study conclusions. Volume 2 contains field and laboratory data, and Volume 3 provides other supporting information, quality assurance documentation, and the safety plan.

Table 2-1. Test and Operating Conditions

| Test condition | Test 1 | Test 2 |
|-----------------------------|---------------------|---------------------|
| | 100% coal | Blended b-dRDF/coal |
| Fuel ratio (coal/b-dRDF) | | |
| Mass | 100/0 | 88/12 |
| Btu | 100/0 | 89.2/10.8 |
| Fuel feed (tons/hr) | | |
| Coal | 369 | 341 |
| b-dRDF | 0 | 47 |
| Total | 369 | 388 |
| Fuel feed (10^6 Btu/hr) | | |
| Coal | 4562.8 | 4266.9 |
| b-dRDF | 0 | 518.5 |
| Total | 4562.8 ^a | 4785.4 ^a |
| Heating value (Btu/lb) | | |
| Coal | 6185 ^b | 6250 ^c |
| b-dRDF | NA ^d | 5570 ^e |
| Steam rate (% of max. load) | 100 | 100 |

^a Reference Appendix I of Volume 3.

^b Data from one sample.

^c Average of four samples.

^d Not applicable.

^e Average of three samples.

3.0 Study Approach

3.1 Introduction

The Big Stone Plant is located in Grant County in northeastern South Dakota. A railroad spur is provided for unit train coal delivery, and service is provided by the Burlington Northern railroad. The plant is served by U.S. Highway 12 and State Highway 15.

The Big Stone Plant is jointly owned by the Montana-Dakota Utilities Company of Bismarck, North Dakota; Northwestern Public Service Company of Huron, South Dakota; and the Otter Tail Power Company of Fergus Falls, Minnesota. Under the terms of the joint-ownership agreement, operation of the plant is the responsibility of the Otter Tail Power Company. As a participant in the CRADA under which the co-fired dRDF/coal tests were performed, Otter Tail Power Company provided the test facility, necessary operations and engineering personnel, capability for off-loading pellet trucks, and storage and conveyance facilities for the pellets. Otter Tail engineering personnel also determined combustor efficiencies for each of the test days.

Commercial quantities (1275 tons) of lime-enhanced dRDF pellets were jointly supplied by Eden Prairie Recycling (EPR) of Minneapolis and XL Recycling of Crestwood, Illinois. The lime binder additive was furnished to EPR and XL Recycling by Marblehead Lime Company of Chicago, Illinois. The fuel pellets and lime additive were provided at no cost to the project.

Interpoll Laboratories, Inc., under subcontract to ANL, conducted the stack gas manual and instrumental emission determinations and the analyses of the feedstock and ash samples.

ANL, under subcontract to NREL, completed the following major work elements:

- Prepared a project test plan, that was reviewed and approved by all CRADA participants prior to initiation of the tests.
- Arranged for the manufacture and transportation of b-dRDF pellets.
- Prepared and executed necessary purchase requisitions to fund transportation costs of b-dRDF pellets from the fabricator's facilities to the test site. Prepared purchase requisitions to cover transportation costs of the binder additive (lime) to the pellet fabricators.
- Provided contract technical oversight for conducting the combustion tests. Assisted Otter Tail personnel in collecting bottom ash, flyash, and feedstock samples.
- Assumed overall responsibility for testing at the site.
- Prepared a draft final report and submitted copies to CRADA participants for review and approval.
- Incorporated review comments and/or revisions and prepared the final report.

Under the CRADA agreement, NREL conducted the following work elements:

- Provided overall contract management for the CRADA.
- Provided funding for all transportation costs associated with providing the required quantity of calcium hydroxide binder additive to the pellet fabricators and transporting the b-dRDF pellets to the test site.

- Witnessed testing at the site.
- Together with ANL, identified barriers to commercial implementation of the technology. In addition, NREL and ANL developed a strategy for disseminating the test results and encouraging other utilities and industrial facilities to use the b-dRDF pellets and coal co-firing technology.

3.2 Test Facility Description

The steam generator, shown in Figure 3-1, is a Babcock & Wilcox lignite-fired cyclone furnace with a balanced-draft, forced-circulation, radiant-reheat boiler. The boiler has a maximum continuous rating of 3.25×10^6 lb/hr steam at 2620 psig and 1005°F at the superheater outlet. Twelve water-cooled cyclone furnaces are located on the front and back sides of the boiler at two elevations, six cyclones at each elevation. Each cyclone consists of a crushed fuel (lignite) supply, an oil lighter, and an oil burner. Other major equipment includes two turbine-driven forced-draft fans, four motor-driven induced-draft fans, two gas recirculation fans, four boiler circulation pumps, two regenerative air heaters, two glycol-air preheaters, and a soot blowing system. The coal use is approximately 365 tons/hr, and the design heating value of the coal is 6255 Btu/lb. Combustor design performance data is given in Table 3-1.

A Lurgi Wheelabrator-Frye electrostatic precipitator removes flue gas flyash leaving the boiler. The precipitator consists of four collection chambers which may be individually isolated during plant operation for maintenance. Flyash is collected in hoppers located beneath each chamber.

Combustion flue gases exiting the electrostatic precipitator are discharged to the atmosphere via a 498-ft tapered concrete stack. The stack has a base diameter of 42 ft and an upper diameter of 26 ft. Monitoring ports (4) are located at an elevation of 285 ft above the base.

The main electrical power system consists of a Westinghouse 500-MVA turbine-generator unit connected to a Westinghouse 460-MVA main transformer. Maximum guaranteed output is 414,588 kW at rated steam conditions of 2400 psig and 1000°F. Extraction steam from the turbine is used to drive two boiler feed-pump turbines and two boiler forced-draft for auxiliary turbines. Each turbine is rated at 10,738 horsepower. The pumps have a rated capacity of 4190 gpm at 7100 ft total head. Maximum calculated output is 455,783 kW with governor valves open and 5% overpressure.

The ash handling system, supplied by United Conveyor Corporation, collects and removes the ash from the furnace bottom, economizer hoppers, air heater hoppers, and precipitator hoppers. Furnace bottom ash, economizer ash, and air heater ash is collected and conveyed in a water slurry to the ash service pond. Precipitator flyash is conveyed by an air transport system to a storage silo for disposal by truck to the plant ash landfill.

Cooling pond makeup water is pumped from Big Stone Lake, located approximately 2 miles from the plant, to the cooling pond adjacent to the facility. The cooling pond consists of the main pond, covering 320 acres and containing approximately 5500 acre-ft of water, and the 10-acre plant makeup pond.

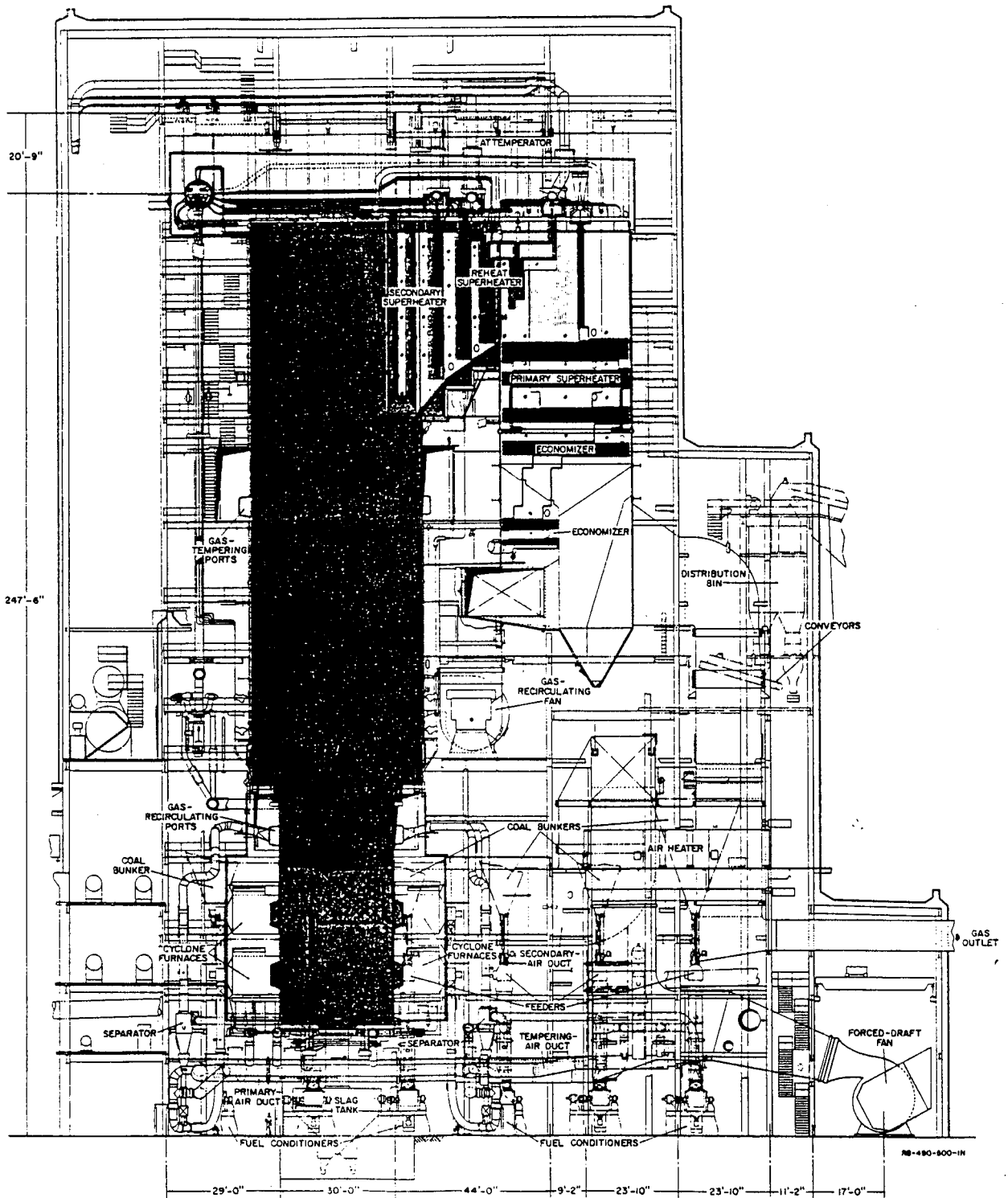


Figure 3-1 Big Stone Steam Plant- Unit No. 1

Table 3-1. Combustor Design Performance

| Parameter | Value |
|--|-----------|
| Steam leaving superheater (mlb/hr) | 3250 |
| Excess air leaving economizer (%) | 28 |
| No. of cyclones in operation | 12 |
| Fuel Input (MBtu/hr) | 4560 |
| Heat available, fuel & heated air (MBtu/hr) | 4793 |
| Steam pressure at superheater outlet (psig) | 2620 |
| Steam temperature at superheater outlet (°F) | 1005 |
| Heat loss (%) | 18.37 |
| Boiler efficiency (%) | 81.63 |
| Ash softening temp., °F (reducing) | 2060-2570 |
| Proximate analysis of coal | |
| Moisture, Total | 41.30 |
| Volume of matter | 25.24 |
| Fixed carbon | 27.00 |
| Ash | 6.46 |
| Total | 100.00 |
| Ultimate analysis of coal | |
| Ash | 6.46 |
| Sulfur | 0.82 |
| Hydrogen | 2.54 |
| Carbon | 37.25 |
| H ₂ O | 41.30 |
| N ₂ | 0.42 |
| O ₂ | 11.21 |
| Total | 100.00 |
| Design heating value as fired (Btu/lb) | 6255 |
| Ash analysis | |
| SiO ₂ | 17.1 |
| Al ₂ O ₃ | 12.6 |
| TiO ₂ | 0.2 |
| Fe ₂ O ₃ | 6.6 |
| CaO | 23.3 |
| MgO | 7.9 |
| Na ₂ O | 3.8 |
| K ₂ O | 0.3 |
| SO ₃ | 27.0 |

4.0 Fuel Preparation

4.1 Binder-Enhanced dRDF Pellets

The required quantity of 1275 tons of dRDF pellets, all containing a (lime) calcium hydroxide binder additive, were produced at the 400 tpd EPR, Inc. processing facility located in Eden Prairie, Minnesota, and at the 400 tpd XL Recycling facility in Crestwood, Illinois.

EPR produced a total of 620 tons of dRDF pellets containing a lime binder content of 4% (by weight) during October 1992. The pellets were nominally 0.625 inch in diameter by 2-2.5 inches in length. The pellets were stored in a warehouse prior to delivery to the test site on October 25-27, 1992. The EPR processing facility uses equipment supplied by Buhler-Miag, Inc. A photo of the pellets is shown in Figure 4-1.

XL Recycling fabricated approximately 655 tons of dRDF pellets (with a 4% lime binder) during September-October 1992; these were delivered to the test site on October 26-27, 1992. The pellets were approximately 1.25 inches square by 2.5-3 inches in length. This facility uses a modified National Recovery Technologies (NRT) processing line. Figure 4-2 shows a photo of the XL Recycling pellet.

4.2 Coal

The Big Stone facility burns lignite coal from the Knife River Coal Mining Company's Gascoyne mine in North Dakota. The coal is delivered to the plant site in two, 115-car trains, then conveyed to a 28,000-ton live storage building that provides approximately 60 hours of storage capacity based on a maximum flow rate of 365 tons/hr. A rotary flow feeder, rated at 550-tons/hr, feeds a conveyor that takes the coal from the live storage building to a transfer house containing magnetic separators and two 550-tons/hr crushers. Crushed coal (0.75-inch top size) is delivered to the power building by one of two parallel conveyors. Once inside the plant, the coal flows into a distribution bin, then into 12 storage silos. From the silos, the coal is fed into 12 crushers located directly below each silo. These crushers reduce the coal into 0.25 inch or less pieces before it enters the cyclone furnaces that fire the main boiler. A schematic of the coal feed system is given in Figure 4-3.

4.3 Fuel Blending Procedures

Delivery of the pellets to the test site was scheduled so that the approximately 58 trucks would arrive either the day before or the morning of the first test day, in order to minimize outdoor storage time. All truck unloadings were observed by ANL or Otter Tail Company personnel. After delivery, the pellets were stored adjacent to a reclaim hopper normally used to feed coal from the 30-day dead coal storage pile in the event coal is not available from live storage. During the blended test day, the dRDF pellets were fed onto conveyor #5, as shown in Figure 4-3, by a large front-end loader and mixed with coal (being simultaneously fed from live storage, via conveyor #4) at the transfer house. The transfer house, which contains two hammermill crushers, a primary and redundant hammermill, reduced the mixture 3/4-inch top size. The blended pellet and coal mixture then entered the boiler building on a single conveyor (conveyor #6), and the fuel mixture was fed into the 12 silos. Upon exiting the silos, the mixture was further reduced to 0.25-inch top size before being fed into the cyclone furnaces.

All flue gas manual and instrumental emission determinations were conducted according to the provisions of standard EPA methods cited in CFR Title 40, Part 60, Appendix A (revised July 1, 1990), and other special purpose EPA methodologies reported elsewhere in the literature. Feedstock and ash sampling



Figure 4-1. EPR Pellets



Figure 4-2. XL Recycling Pellets

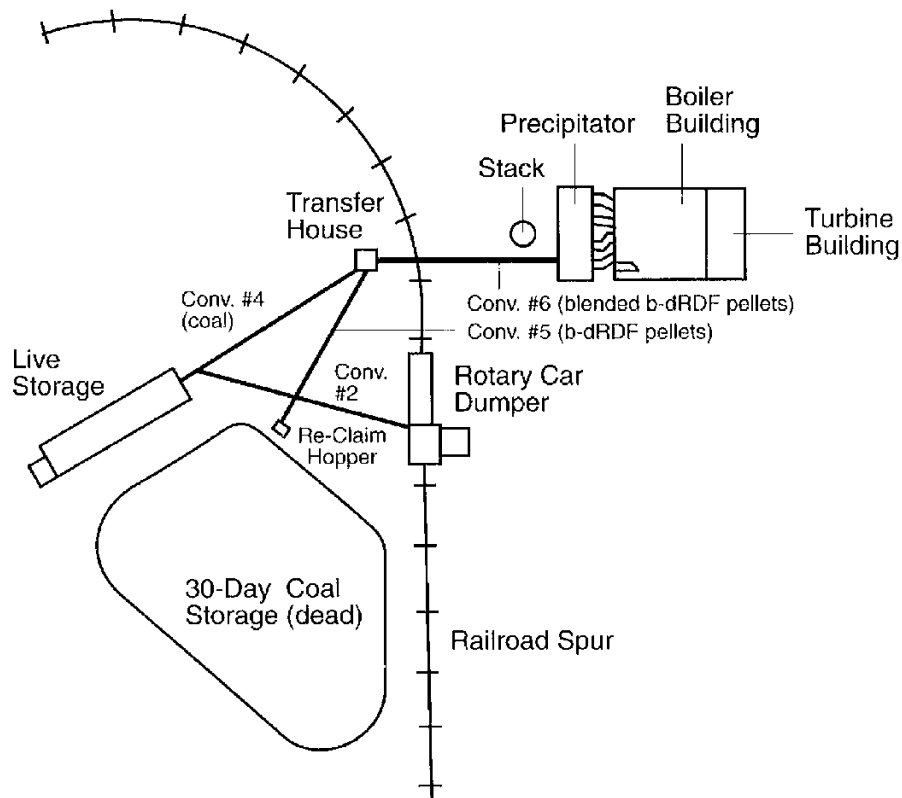


Figure 4-3. Plan View of b-dRDF/Coal Feed System

and analysis were conducted in accordance with ASTM and standard EPA methods cited in CFR Title 40, Part 60, Appendix A.

The sampling station locations are shown in Figure 4-4. Figure 4-5 is an aerial view of the test facility. Sampling and analysis of the flue gas emissions were performed by Interpoll Laboratories under subcontract to ANL. Feedstock and ash samples were collected by Otter Tail Power Company and ANL personnel. Interpoll Laboratories performed analyses of the feedstock and ash samples.

The combustion tests were conducted on October 26-27, 1992. The sampling test periods were composed of two 10-hour periods, one on each day. On the first test day, 100% coal was fired. On the second test day, a blend of 12% b-dRDF pellets and 88% coal was fired. Each test period started at 9:00 a.m. and continued until 7:00 p.m.

Operational problems that developed during the blended-fuel test day resulted in a delay in sampling activities until approximately 3:00 p.m. However, in most cases, an adequate number of samples were collected during the remaining testing period. Section 6.4 provides further discussion of the problems encountered.

Polychlorinated dibenzo-p-dioxins (PCDD) and dibenzofurans (PCDF) analyses were performed by Triangle Laboratories of Durham, North Carolina. A copy of Triangle Laboratories' analytical data, along with quality documentation and chain of custody sheets, is provided in Appendices G and H.

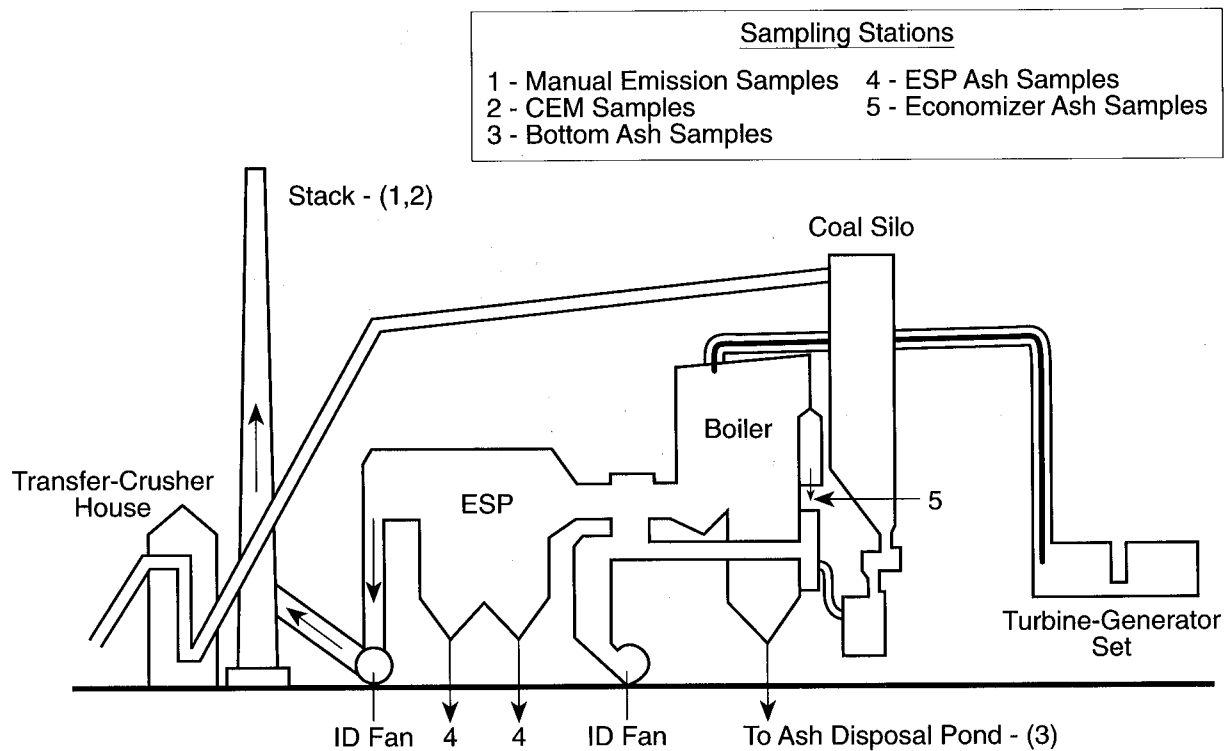


Figure 4-4. Test Sampling Station Locations



Figure 4-5. Aerial View of Test Facility

Table 4-1. Sampling and Analysis Methods - Flue Gas

| Constituent | Sampling Location^a | Sampling Runs^b | Methods |
|--|--------------------------------------|----------------------------------|--|
| Particulate | 1 | 3-1 Hr | EPA 1-5 |
| SO ₂ | 2 | Continuous | EPA 6C |
| NO _x | 2 | Continuous | EPA 7E |
| CO ₂ , O ₂ | 2 | Continuous | EPA 3A |
| CO | 2 | Continuous | EPA 10 |
| THC | 2 | Continuous | EPA 25A |
| CO ₂ , O ₂ , N ₂ , H ₂ O | 1 | 9-3 Hr | EPA 3-4 |
| PCDD/PCDF | 1 | 3-2 Hr (4 samples) | EPA MM5 & EPA 23 |
| PAH/PCB | 1 | 3-2 Hr | EPA MM5, EPA 8270 (PAH) EPA 8080 (PCB) |
| Cl, HCl, HF, HBr | 1 | 3-1 Hr | EPA 26 |
| Trace metals (14) | | 3-2 Hr | EPA4M5 & EPA 0010 (SW 846) |
| BTX | 1 | 3-1 Hr | EPA 18 & GC/FID |
| Opacity | 1 | 3-6 Min. | EPA 9 |

^a See Figure 4-4.

^b Number of samples and duration of each sampling run for each test day.

Tables 4-1, 5-1, and 5-2 present a summary tabulation of the pollutants analyzed from the flue gas, feedstock, and ash samples that were collected during each of the two test days. Also shown are the locations from which the samples were collected, the number of sampling runs made, duration of each run, and the methods used to collect and analyze each sample.

A test protocol, shown in Appendix M, was prepared by ANL and submitted to all CRADA participants for review and approval. Copies of the test protocol were also submitted for review to the regulatory agencies of Minnesota, Wisconsin, South Dakota, Illinois, and California.

Unless otherwise noted, all test results contained in the various tables of Volume 1 of this report are the average of at least three individual test runs as presented in Volumes 2 and 3.

In the case of flue gas, continuous emission monitoring data (both data logger and strip charts) are presented for SO₂, NO_x, CO, CO₂, THC, and O₂. The SO₂ readings for the blended b-dRDF/coal test (October 27) exhibited a discrepancy between the data logger and the strip charts. The data collected on the strip chart is considered valid and is the data reported by Interpoll. All other data logger parameters were cross-checked and found to be valid. Emission concentration levels for SO₂, NO_x, CO, and O₂ for the coal only test on October 26 were recorded at 15-minute intervals beginning at 9:45 a.m. and concluding at 7:00 p.m. Concentration levels for NO_x, CO, and O₂ for the blended test on October 27 were recorded at 5-minute intervals beginning at 3:05 p.m. and continuing until 5:55 p.m. Strip charts and data logger results are given in Appendix E of Volume 3.

Raw data for PCDD/PCDF emission levels, as prepared by Triangle Laboratories under subcontract to Interpoll Laboratories, is given in Appendix F of Volume 3.

Other miscellaneous data, including additional analysis of coal sulfur content for the coal only test (October 26); bulk density analysis of the coal and b-dRDF samples; and concentrations of cadmium, lead, and mercury in the coal samples collected during the coal only test are shown in Appendix P of Volume 3.

5.0 Sampling and Analysis Methodology

5.1 Sampling and Analytical Procedures—Flue Gas

Particulate determinations were performed in accordance with EPA Methods 1-5, CFR Title 40, Part 60, Appendix A (revised July 1, 1992). A preliminary flow-rate determination was used to select the appropriate nozzle diameter required for isokinetic sample withdrawal. Method 5 sampling trains were used to extract particulate samples by means of heated glass-lined probes. Wet catch samples were collected in the back half of the Method 5 sampling train and analyzed for condensable organics.

Sampling for PCDDs, PCDFs, PAHs, and PCBs was conducted using an EPA Modified Method 5 (MM5) sampling train with purified XAD-2 resin in accordance with EPA Method 23. Triangle Laboratories added a spike (two-component mixture of isotopically labeled dioxin and furan surrogates) to the top of the XAD-2 resin cartridge at the time the cartridges were packed. Upon return to Interpoll Laboratories, these cartridges also were spiked with 20 ug of d_{10} -fluoranthene. The pre-sample spikes provide an overall evaluation of the accuracy of sampling and analysis. A field-biased blank was collected by loading the entire sampling train, leak checking it, and then recovering the sample in a manner identical to that used for the field samples. The contents of the Adsorbent Module, Container No. 1, and Container No. 2 samples were extracted and combined to give a single extract for each flue gas sampling. Appendix F provides details on the sample extraction procedures employed by Triangle Laboratories in preparing these samples.

The recovered PCDD/PCDF, PAH, and PCB samples were stored over ice, returned to the laboratory, packed, and then shipped to Triangle Laboratories where they were carefully extracted to yield a two-part sample; one half was returned to Interpoll Laboratories for PAH and PCB analyses, and the other half was analyzed by Triangle Laboratories for tetra- through octachlorodibenzodioxin and chlorodibenzofuran homolog groups as well as for all of the 2, 3, 7, 8-chlorinated dibenzodioxin and dibenzofuran isomers as per EPA Methods 23 and 8290 using HRGG/HRMS. Quantitation was performed through isotope dilution mass spectrometry by Triangle Laboratories; thus, the reported dioxin and furan masses and concentrations have already been corrected for the recoveries of internal quantification standards.

The PAH aliquots were analyzed in accordance with EPA Method 8270 by HRGG/LRMS using electron impact with total ion monitoring. Quantification was performed using the six EPA Method 8270 internal standards. After cleanup, the PCB aliquots were analyzed by GC/ECD for mono through deca congeners as per EPA Method 8080. All data was carefully checked to ensure that the appropriate multipliers for aliquoting were applied.

Trace metal sampling was performed in accordance with EPA Method 0012 (SW846 3rd Ed.). The Multi-Metal Modified Method 5 (4M5) sampling train, described in this method, was used to isokinetically collect solid- and vapor-phase trace metals from the exhaust gas stream. The aerosol- or solid-phase trace metal samples were collected on Pallflex® Type 2500 QAT ultra-pure filters. The vapor-phase trace metals were collected in an all-glass impinger train. The first and second impingers each contained 100 cc of a mixture of 5% HNO_3 and 10% H_2O_2 . The third and fourth impingers each contained 100 cc of a mixture of 4% KMnO_4 and 10% H_2SO_4 . These impingers collect any elemental mercury that might penetrate the first two impingers. The recovered four-part samples were returned to the laboratory where the probe rins, filter, nitric acid impinger catcher and potassium permanganate impinger catcher were combined, dissolved in acid (including the quarter filter) and analyzed for trace metals by inductively coupled argon plasma emission spectrometry (ICP). Arsenic, beryllium, lead, antimony, selenium, and thallium were all reanalyzed by graphite furnace atomic absorption (GF/AA) to obtain greater sensitivity. Two field-biased blanks were collected and recovered for each test and analyzed for trace metals with the field samples.

Chlorine, hydrogen chloride, hydrogen fluoride, and hydrogen bromide samples were collected from the exhaust gas stream as per EPA Method 26. The samples were collected at a constant flow rate using a three-point traverse. After the samples were collected, the 0.1 N H₂SO₄ and 0.1 N NaOH impinger catchers were quantitatively recovered into separate all-glass sample containers closed with teflon-lined caps. The samples were returned to the laboratory; diluted (if necessary); and analyzed for chloride, fluoride, and bromide by automated ion chromatography as per EPA Method 300.3 (SW 846). The samples were analyzed using a Dionex Model 400i Ion Chromatograph equipped with an automatic sampler, a micro membrane suppression system, and a temperature-compensated conductivity detector. Quantification was based on the peak area using a five-point external standard curve.

Continuous emission monitoring was conducted for sulfur dioxide, oxides of nitrogen, carbon monoxide, carbon dioxide, total hydrocarbons, and oxygen. The measurements were performed in accordance with EPA Methods 3A, 6C, 7E, and 10. A slip stream of exhaust gas was drawn from the exhaust gas stream using test port(s) provided by the plant. The sample was drawn from a test port on the stack using a heat-traced probe and filter assembly. After passing through the filter, the gas passed through two VIA condenser-type moisture removal systems operating in series. The particulate-free dry gas was then transported to the analyzers and the excess gas was exhausted to the atmosphere through a calibrated orifice used to ensure that the flow from the stack exceeded the requirements of the analyzers. A three-way valve on the probe was used to introduce standard gas for the "system bias check." The analog response of each analyzer was recorded with a computer data logger and backed up with a strip chart recorder. The analyzers were calibrated with Scott Specialty and Linde Gases standard gases.

Total hydrocarbon (THC) determinations were performed in accordance with EPA Method 25A. Total gaseous hydrocarbon concentrations were determined instrumentally using a Ratfish Model RS 55 heated flame ionization detector (HFID) calibrated against propane in air standards. The THC concentration was continuously monitored by extracting a slipstream of exhaust gas by means of a heated probe and filter holder. A heat-traced teflon line transported the sample gas from the filter holder outlet to the analyzer inlet. The analog response was recorded using a strip chart recorder.

An integrated flue-gas sample was extracted simultaneously with each of the above-mentioned sampling trains using a specially designed gas sampling system. Integrated flue-gas samples were collected in 44-liter Tedlar bags housed in a protective aluminum container. After sampling was complete, the bags were sealed and returned to the laboratory for Orsat analysis. Prior to sampling, the Tedlar bags were leak checked at 15 inches of mercury (in.Hg) vacuum with an in-line rotameter. Bags with any detectable in leakage were discarded.

Benzene, toluene, and xylene (BTX) samples were collected from the flue gas as per EPA Method 18, Section 7.4. Charcoal tube sampling on three 1-hour samples and a field blank sample was done using gas chromatography with flame ionization detectors (GC/FID) analysis and a silica gel dessicant tube in front of the charcoal tube.

Testing on the boiler stack was conducted from four test ports at 90 degrees. These test ports are located approximately nine stack diameters downstream of the stack breeching, and nine stack diameters upstream of the stack exit.

Major results of the test are summarized in Section 6.1. Detailed results are presented in Volume 2. Field data and all other supporting information are presented in Appendices A through O in Volume 3.

5.2 Sampling and Analytical Procedures—Ash Residues

A total of 18 bottom ash, flyash, and economizer ash samples were collected by ANL and Otter Tail Power Company personnel, nine samples for each of the two test days. Because of project funding constraints, only 12 of the 18 samples collected were analyzed by Interpoll Laboratories: two bottom ash, three flyash, and one economizer ash sample for each of the two test days.

Bottom ash samples were collected for each test day during the two scheduled daily purging cycles. Flyash samples were collected from each of the four chambers of the electrostatic precipitator at 2-hour intervals during each of the two test periods. These samples were then composited into three gross samples, one containing samples taken from the first 4 hours of testing, the second containing samples taken from the 4-7 hours of testing, and the third containing samples taken from the 7-10 hours of testing. The same techniques also were used to collect the samples from the economizer.

A total of 12 bottom ash, flyash, and economizer ash samples were subjected to the TCLP tests. These leachates were analyzed for concentrations of 14 metals, including antimony, arsenic, barium, beryllium, cadmium, chromium, copper, lead, mercury, nickel, selenium, silver, thallium, and zinc. The pH of the ash and leachate, alkalinity, sulfate, chlorides, and total dissolved solids (TDS) were also determined per applicable EPA methodologies as specified in SW-846 (3rd edition) and EPA methods 150.1, 160., 300.0, and 310.1.

Trace metals and anion compositional analyses were performed on ten bottom ash, flyash, and economizer ash samples. The 14 metals analyzed were the same as those analyzed in the TCLP tests described above. Concentrations of chlorides and sulfates also were determined.

A mineral analysis including silica, alumina, titania, ferric oxide, lime, magnesia, potassium oxide, sodium oxide, sulfur trioxide, phos. pentoxide, manganese oxide and barium oxide was made on ten (10) samples.

Triangle Laboratories, under contract to Interpoll Laboratories, analyzed four samples and one field blank sample for total tetra-through octa-chlorinated dibenzo-p-dioxins and dibenzofurans.

Physical ash characteristics were evaluated for 12 ash samples. The characteristics included moisture content, percent combustibles, and pH.

Test results are summarized in Section 6.2. Detailed individual sample results are given in Volume 2. Field data and all other supporting information are presented in Appendices A through O in Volume 3.

Table 4 presents a summary tabulation of the ash constituents that were analyzed, together with sampling locations, number of samples collected, number of sampling runs, duration of each test run, and methods used to collect and analyze each sample.

5.3 Sampling and Analytical Procedures—Feedstock

Twelve feedstock samples were collected by ANL/Otter Tail Power Company personnel, three during the 100% coal-fired test on October 26, 1992, and nine during the blended-fuel tests on October 27, 1992.

During the coal only test day, samples were collected from the coal sampler at 1-hour intervals during the 10-hour testing period. These samples were then composited into three gross samples equally split over the 10-hour test period.

Table 5-1. Sampling and Analysis Methods—Ash Residue

| Constituent | Sampling Location ^a | Number of Samples | Methods |
|---|--------------------------------|-------------------|---|
| TCLP ^c | 3,4,5 | 6 | SW-846, EPA 150.1 160.1, 300.0 & 310.1 |
| Total metals (14), chlorides, sulfates | 3,4,5 | 5 | SW-846 & EPA 300.0 |
| pH, H ₂ O, loss on ignition | 3,4,5 | 6 | SW-846-9045 (pH) ASTM D3173 (H ₂ O) ASTM D3174 (loss on ignition) |
| Minerals (12) | 3,4,5 | 5 | ASTM D3682 & ASTM D1757 (ICP) |
| PCDD/PCDF (bottom & flyash) | 3,4 | 2 | Approved EPA method (Triangle Labs procedure) |

^a See Figure 4-4.

^b TCLP tests conducted on bottom ash, flyash, and economizer ash samples.

Table 5-2. Sampling and Analysis Methods—Feedstock

| Test | Sampling Location ^a | Number of Samples | Methods |
|---------------------------|------------------------------------|------------------------------|--|
| Ultimate analysis | Coal sampler & Conveyors #4, #5 | 4 (coal only) 7 (blended) | ASTM D3173, 3174, 3178, 3177 & 3179 |
| Proximate analysis | Coal sampler & Conveyors #4, #5 | 4 (coal only) 7 (blended) | ASTM D3173, 3174, 3175, 3177 & 2015 |
| Total chlorine | Coal sampler & Conveyors #4, #5 | 2 (coal only) 7 (blended) | ASTM E776-87 |
| Trace metals (14) | Coal sampler & Conveyors #4, #5 | 3 (coal only) 7 (blended) | SW-846 |
| Ash fusion temperature | Coal sampler & Conveyors #4, #5 | 1 (coal only) 6 (blended) | ASTM D1857 |

^a See Figure 4-4.

During the blended b-dRDF/coal tests, individual coal and b-dRDF pellet samples were collected from conveyors #4 and #5, respectively, at 1-hour intervals. Blended b-dRDF/coal samples were similarly samples from the coal sampler. The individual coal, b-dRDF pellets, and blended b-dRDF/coal samples were then composited into three gross samples equally split over the 10-hour test period.

Eight of the 12 samples collected were analyzed for the following:

1. Ultimate and proximate analysis, including chlorine and heating value.
2. Trace metals, including Ag, As, Ba, Be, Cd, Cr, Cu, Hg, Ni, Pb, Sb, Se, Tl, and Zn.
3. Bulk density.
4. Ash fusion analysis, including initial deformation (IT), softening temperature (ST), hemispherical temperature (HT), and fluid temperature (FT). The analysis of each of the four parameters was conducted for both an oxidizing atmosphere and a reducing atmosphere.

Test results are summarized in Section 6.3. Detailed individual sample results are given in Volume 2. Field data and all other supporting information are presented in Appendices A through O in Volume 3.

Table 5-2 provides a tabulation of the feedstock pollutants that were analyzed, together with sampling locations, total number of samples collected, sampling runs, duration of each run, and methods used to collect and analyze each sample.

6.0 Test Results and Discussion

This section presents summaries for all feedstock, ash residue, and flue-gas emission tests performed. The results presented in these summary tables consist of the average of all runs conducted on October 26 during the coal only test and the average of the blended b-dRDF pellets and coal runs conducted during the stable operation runs on October 27. Results of individual runs can be found in Volume 2 of this report.

6.1 Flue Gas Emissions

Table 6-1 through Table 6-7 provide summaries for all flue-gas emission tests performed. Complete test results for each individual run are given in Volume 2.

6.1.1 Particulate Matter

The stack sampling data for total particulate emissions is summarized in Table 6-1. Sampling and analytical procedures are described in Section 5.1 and Table 4-1. Table 6-1 contains the particulate concentrations for each test day, expressed as grains per dry standard cubic foot (gr/dscf). Mass emission rates for particulate matter also are given in units of lb/hr and lb/MMBtu.

Table 6-1. Summary of Flue Gas Particulate Emission and Opacity Determinations

| Parameter | Test 1 | Test 2 ^a |
|---|-----------|---------------------|
| Date of test | 10/26/92 | 10/27/92 |
| Fuel ratio (coal/pellets) | 100/0 | 88/12 |
| Heat input (10 ⁶ Btu/hr) | 4563 | 4785 |
| Volumetric flow | | |
| Actual (acfm) | 2,171,000 | 2,159,000 |
| Standard (dscfm) | 1,250,000 | 1,211,000 |
| Gas temperature (°F) | 294 | 304 |
| Moisture content (%v/v) | 14.03 | 14.73 |
| Gas composition (%v/v, dry) | | |
| Carbon dioxide ^c | 12.6 | 11.5 |
| Oxygen ^b | 7.9 | 8.4 |
| Nitrogen | 79.5 | 80.1 |
| Isokinetic variation (%) | 99.1 | 100.3 |
| Particulate concentration | | |
| Actual (gr/acf) | 0.00509 | 0.00710 |
| Standard (gr/dscf) | 0.00886 | 0.0138 |
| Standard (gr/dscf @ 7% O ₂) | 0.00947 | 0.0153 |
| Particulate emission rate (lb/hr) | 95 | 143 |
| Particulate emission rate (lb/MMBtu) | 0.021 | 0.031 |
| Opacity (%) | 10.4 | 10.0 ^c |

^a Data from one sample.

^b Data from multiple observations.

^c CO₂ and O₂ values shown are from manual sampling runs and do not agree with values shown in Table 6-2 (see note for Table 6-2).

Particulate emissions are influenced by a number of factors, the most important being the fuel composition, the method of firing (i.e., excess air, underfire and overfire air), and the collection system used.

The higher particulate concentration levels for the blended-fuel test compared to the coal-only test (0.0153 gr/dscf @ 7% O₂ versus 0.00947 gr/dscf @ 7% O₂) are related to the fuel composition since the firing method and the collection system used were the same for both tests. The higher mass fraction of ash in the pellets compared to the coal (approximately 11.95% versus 7.80%) and the lower heat content of the pellets compared to coal (approximately 5570 Btu/lb versus 6250 Btu/lb) combined to yield approximately twice the ash mass per Btu input for b-dRDF pellets compared to coal. The particulate matter from firing a blend of pellets and coal was approximately 1.5 times the ash mass per Btu input when firing coal-only [Table 6-1].

6.1.2 Opacity

The stack opacity as given in Table 6-1 was somewhat lower during the blended-fuel tests relative to the coal-only tests. The opacity value for the coal-only test was 10.4% compared to 10.0% for the blended tests. Detailed individual opacity observations are given in Volume 2.

6.1.3 Sulfur Dioxide (SO₂)

The SO₂ emissions were continuously monitored during the two 10-hour tests using EPA Method 6C. As shown in Table 6-2, the SO₂ emissions from the b-dRDF/coal co-firing tests were approximately 17.3% less than for coal-firing alone.

The reduced SO₂ emission rates can be explained by the fuel composition and by the reaction and removal of the SO₂ combustion product by the lime binder. The lower sulfur content of the b-dRDF compared to the coal certainly reduced the mass emission rates. A more important factor in decreased SO₂ emission rates, however, was the heterogeneous (gas phase-solid phase) reaction of SO₂ with the calcium hydroxide (Ca(OH)₂) in the lime binder to form calcium sulfate (CaSO₄). This assumption is based upon the fact that if the low sulfur content of the b-dRDF pellet was merely diluting the sulfur contained in the coal, the SO₂ decrease would have been linear and proportional to the mass fraction of sulfur in the b-dRDF pellets. This result is in agreement with previous spreader-stoker tests conducted by ANL⁴ and by Old Dominion University's Department of Civil Engineering tests⁵.

6.1.4 Nitrogen Oxides (NO_x)

NO_x emissions were continuously monitored during the two 10-hour test days using EPA Method 7E for sampling and analysis procedures. As can be seen from Table 6-2, the NO_x emissions from the pellet/coal co-firing tests were slightly less (approximately 556 ppm, d @ 7% O₂ versus 566 ppm, d @ 7% O₂) than the coal-only tests.

NO (nitric oxide) and NO₂ (nitrogen oxide) are often referred to as NO_x. Three kinds of NO are produced by combustion: thermal NO, prompt NO, and fuel NO. Thermal NO is produced regardless of what fuel is used. If the combustion flame contains excess oxygen, then the amount of NO that is formed depends on the concentration of O atoms produced from the dissociation of O₂ in the flame and the residence time in the flame region. Prompt NO results from flame reactions where hydrogen cyanide is formed as an intermediate. It applies to all types of fuel and is the major pathway to NO formation in fuel-rich flames. Although prompt NO exhibits a temperature dependence, low temperatures and short residence times seem to favor its formation. Fuel NO is formed from the combustion of fuel that contains bound nitrogen.

Table 6-2. Summary of Continuous Emission Monitoring of SO₂, NO_x, CO, CO₂, O₂, and THC Concentrations in Flue Gas

| Parameter | | Test 1 | Test 2 |
|-----------------|-------------------------------|----------|----------|
| Date of test | | 10/26/92 | 10/27/92 |
| Sulfur dioxide | (ppm, d) | 968 | 819 |
| | (ppm, d @ 7% O ₂) | 1051 | 869 |
| Nitrogen oxide | (ppm, d) | 521 | 524 |
| | (ppm, d @ 7% O ₂) | 566 | 556 |
| Carbon monoxide | (ppm, d) | 3.5 | 0.4 |
| | (ppm, d @ 7 %O ₂) | 3.8 | 0.4 |
| THC as carbon | (ppmC,w) | 6.5 | 12.3 |
| | (ppm, d @ 7% O ₂) | 7.1 | 13.0 |
| Carbon dioxide | (%v/v, d) | 13.1 | 13.2 |
| Oxygen | (%v/v, d) | 8.1 | 7.8 |

Note: Carbon dioxide and oxygen values represent average of continuous monitoring data.

The reduced NO_x emissions (about 2% to 3%) experienced during the blended-fuel test compared to the coal-only test is probably the result of the reduced (7%) bound nitrogen contained in the b-dRDF pellets. Although the Otter Tail plant has no means of measuring combustion temperature, it is estimated to be approximately 2600°F. Most researchers suggest that at combustion temperatures greater than 1900°F, the formation of NO exhibits a very weak dependence on temperature. It was assumed that the combustion temperature remains essentially constant for both tests, but even with a variation of about 25%, the formation of NO by thermal means would be negligible.

6.1.5 Carbon Monoxide (CO)

As shown in Table 6-2, the carbon monoxide concentrations were extremely low during both tests. These low values are indicative of the good combustion practices of the plant operators since CO emissions are related to combustion efficiencies.

6.1.6 Carbon Dioxide (CO₂)

Though not considered a regulated pollutant, carbon dioxide combustion emissions are indicative of the fuel-to-energy conversion efficiency. The CO₂ levels, as given in Table 6-2, were identical for both test days.

6.1.7 Total Hydrocarbons (THC)

Total hydrocarbons, although not regulated under current federal regulations, are regulated under some state statutes because of their smog-forming potential. Concentrations observed during the two tests were very low: 7.1 ppm, d @ 7% O₂ for the coal-only tests and 13.0 ppm, d @ 7% O₂ for the blended-fuel tests.

6.1.8 Benzene, Toluene, Xylene (BTX)

The BTX concentrations shown in Table 6-3 were below detectable levels for all samples collected during the coal-only and blended-fuel tests.

Table 6-3. Summary of Flue Gas BTX, Cl₂, HCl, HBr, and HF Concentrations

| Parameter | | Test 1 | Test 2 |
|-------------------|-------------------------------|----------|----------|
| Date of test | | 10/26/92 | 10/27/92 |
| Benzene | (ppm, d) | <0.008 | <0.008 |
| | (ppm, d @ 7% O ₂) | <0.0087 | <0.0085 |
| Toluene | (ppm, d) | <0.007 | <0.007 |
| | (ppm, d @ 7% O ₂) | <0.0076 | <0.0074 |
| Xylene | (ppm, d) | <0.006 | <0.006 |
| | (ppm, d @ 7% O ₂) | <0.0065 | <0.0064 |
| Hydrogen chloride | (ppm, d) | 3.0 | 35.0 |
| | (ppm, d @ 7% O ₂) | 3.3 | 37.1 |
| Chlorine | (ppm, d) | 1.20 | <0.1 |
| | (ppm, d @ 7% O ₂) | 1.30 | <0.11 |
| Hydrogen fluoride | (ppm, d) | 1.70 | 2.50 |
| | (ppm, d @ 7% O ₂) | 1.84 | 2.65 |
| Hydrogen bromide | (ppm, d) | 0.02 | 0.10 |
| | (ppm, d @ 7% O ₂) | 0.022 | 0.11 |

6.1.9 Hydrogen Chloride (HCl)

Hydrogen chloride emissions were found to increase, as expected, during the blended-fuel tests. This increase in HCl emissions was due to the increased chlorine content found in the b-dRDF pellets. However, the increase was small (30 ppm).

6.1.10 Hydrogen Fluoride and Hydrogen Bromide

Concentrations of HF and HBr given in Table 6-3 were higher in the blended-fuel tests than in the coal-only tests. However, the concentration levels for both HF and HBr were extremely low for both tests, ranging from 1.84 ppm HF for the 100% coal test to 2.65 ppm HF for the blended tests, and from 0.022 ppm HBr for the coal-only tests to 0.11 ppm of HBr emissions in the blended-fuel tests.

6.1.11 Polychlorinated dibenzo-p-dioxin (PCDD) and Polychlorinated dibenzofuran (PCDF)

The results of the PCDD/PCDF determinations are summarized in Table 6-4. The total tetra- through octa-chlorinated dibenzo-p-dioxins and dibenzofurans for the coal-only test day were all below detectable levels. The total tetra- through octa-homolog groups for PCDDs and PCDFs were 0.025 mg/Nm³ for the blended-fuel test day, well below federal and state regulated levels. Most of the increase in total PCDDs/PCDFs during the blended-fuel test day occurred in the octa-dioxin group. Refer to Volume 2 for all PCDD/PCDF individual test data and results.

6.1.12 Polycyclic Aromatic Hydrocarbon (PAH) and Polychlorinated Biphenyl (PCB)

Tables 6-5 and 6-6 contain the PAH and PCB results, respectively. All PAHs were below detectable levels except two compounds, naphthalene and phenanthrene, both of which were reduced during the blended-fuel tests. All PCB emissions were below detectable levels for both test days.

Table 6-4. Summary of Flue Gas PCDD/PCDF Homolog Determinations

| Parameter | Test 1 | Test 2 |
|-------------------------------------|--------------------|--------------------|
| Date of test | 10/26/92 | 10/27/92 |
| Concentration (ng/Nm ³) | | |
| TCDD | <0.008 | <0.011 |
| PeCDD | <0.008 | <0.014 |
| HxCDD | <0.008 | <0.018 |
| HpCDD | <0.025 | <0.028 |
| OCDD | <0.193 | 0.20 |
| TCDF | <0.008 | 0.046 |
| PeCDF | <0.006 | <0.011 |
| HxCDF | <0.008 | <0.014 |
| HpCDF | <0.008 | <0.018 |
| OCDF | <0.014 | <0.035 |
| TOTAL PCDD/PCDF | 0.286 ^a | 0.395 ^a |

^a Worst-case values since detection levels were used in computing totals.

Table 6-5. Summary of Flue Gas PAH Determinations

| Parameter | Test 1 | Test 2 |
|-------------------------------------|----------|----------|
| Date of test | 10/26/92 | 10/27/92 |
| Concentration (ug/Nm ³) | | |
| Naphthalene | 1.4 | 0.12 |
| Acenaphthylene | <0.032 | <0.031 |
| Acenaphthylene | <0.036 | <0.035 |
| Fluorene | <0.036 | <0.035 |
| Phenanthrene | 0.15 | 0.078 |
| Anthracene | <0.029 | <0.028 |
| Fluoranthene | <0.043 | <0.042 |
| Pyrene | <0.054 | <0.053 |
| Benzo-a-anthracene | <0.065 | <0.063 |
| Chrysene | <0.033 | <0.032 |
| Benzo-b-fluoranthene | <0.036 | <0.035 |
| Benzo-k-fluoranthene | <0.061 | <0.060 |
| Benzo-a-pyrene | <0.043 | <0.042 |
| Dibenzo-a,h-anthracene | <0.032 | <0.031 |
| Benzo-g,h,i-perylene | <0.043 | <0.042 |
| Indeno-1,2,3-g,d-pyrene | <0.033 | <0.032 |

Table 6-6. Summary of Flue Gas PCB Determinations

| Parameter | Test 1 | Test 2 |
|-------------------------------------|----------|----------|
| Date of test | 10/26/92 | 10/27/92 |
| Concentration (ug/Nm ³) | | |
| Chlorinated hydrocarbons (Arochlor) | | |
| 1016 | <0.014 | <0.014 |
| 1221 | <0.014 | <0.014 |
| 1232 | <0.014 | <0.014 |
| 1242 | <0.014 | <0.014 |
| 1248 | <0.014 | <0.014 |
| 1254 | <0.014 | <0.014 |
| 1260 | <0.014 | <0.014 |
| Total PCB | <0.014 | <0.014 |

6.1.13 Trace Metals

Table 6-7 summarizes the results of the trace metal determinations. These metal emission concentrations are directly related to the rate of generation of particulate matter and the fraction passing through the air pollution control equipment. The current New Source Performance Standards (NSPS) reflect a rationale of controlling the overall solid-phase emissions through particulate matter limits rather than through limits on individual metals. Specific metals, including mercury, lead, and cadmium may have emission levels included in upcoming NSPS revisions.

Six metals, including As, Ar, Be, Cd, Se, and Ag were below detection levels for both tests. Three others, Ba, Pb, and Zn were present in higher levels in the blended-fuels tests than in the coal-only tests. However, the lead and zinc concentrations in the coal used during the blended test were significantly higher than the concentrations present in the coal used during the coal-only test day.

Lead concentrations in the coal used in the blended tests were 123 ug/g compared to 29 ug/g of lead in the coal used during the coal test day. Zinc concentrations in coal were 107 ug/g for the blended-fuel test compared to 23 ug/g for the 100% coal test. Levels of barium were higher during the blended-fuel tests.

6.2 Ash Analyses

A summary of the ash analyses performed is presented in this section. The average values obtained for each of the tests (coal-only and blended-fuel) are given in Tables 6-8 through 6-13. Individual analyses are presented in Volume 2.

6.2.1 TCLP Analysis

Results of the TCLP leachate analysis performed on bottom ash, economizer ash, and fly ash samples are shown in Tables 6-8, 6-9, and 6-10, respectively. All test samples successfully passed the TCLP criteria for hazardous waste definition. In fact, all metals passed with substantial margins of safety relative to the regulatory levels.

Table 6-7. Summary of Flue Gas Trace Metals Concentrations

| Parameter | Test 1 | Test 2 ^a |
|-------------------------------------|----------|---------------------|
| Date of test | 10/26/92 | 10/27/92 |
| Concentration (ug/Nm ³) | | |
| Antimony | <0.35 | <0.54 |
| Arsenic | <0.70 | <1.08 |
| Barium | 5.42 | 20.01 |
| Beryllium | <0.01 | <0.02 |
| Cadmium | <0.36 | <0.54 |
| Chromium | 0.86 | 1.94 |
| Copper | 2.26 | 8.50 |
| Lead | 0.76 | 5.99 |
| Mercury | 19.23 | 22.75 |
| Nickel | 1.06 | 1.88 |
| Selenium | <6.42 | <6.45 |
| Silver | <0.35 | <0.54 |
| Zinc | 27.88 | 56.95 |

^a Data from one sample.

Table 6-8. Summary of TCLP Test Results of Bottom Ash

| Parameter | Test 1 | Test 2 |
|----------------------------------|----------|----------|
| Test date | 10/26/92 | 10/27/92 |
| Fuel weight ratio (coal/pellets) | 100/0 | 88/12 |
| TCLP leach (mg/L) | | |
| Antimony | <0.2 | <0.2 |
| Arsenic | <0.006 | <0.006 |
| Barium | 4.73 | 2.88 |
| Beryllium | <0.02 | <0.02 |
| Cadmium | <0.02 | <0.02 |
| Chromium | <0.02 | <0.02 |
| Copper | <0.02 | 0.15 |
| Lead | 0.064 | 0.06 |
| Mercury | <0.0001 | <0.0001 |
| Nickel | 0.027 | 0.05 |
| Selenium | <0.02 | 0.03 |
| Silver | <0.02 | 0.03 |
| Thallium | <8.0 | <8.0 |
| Zinc | 0.42 | 0.21 |
| pH | 5.0 | 5.1 |
| Alkalinity | 1530 | 1485 |
| Sulfates | 9.95 | 41 |
| Chloride | 0.66 | 0.29 |
| Total dissolved solids | 5585 | 5610 |

Table 6-9. Summary of TCLP Test Results of Economizer Flyash

| Parameter | Test 1 | Test 2 |
|----------------------------------|----------|----------|
| Test date | 10/26/92 | 10/27/92 |
| Fuel weight ratio (coal/pellets) | 100/0 | 88/12 |
| TCLP leach (mg/L) | | |
| Antimony | <0.2 | <0.2 |
| Arsenic | 0.19 | 0.22 |
| Barium | 0.51 | 0.364 |
| Beryllium | <0.02 | <0.02 |
| Cadmium | <0.02 | <0.02 |
| Chromium | <0.022 | <0.02 |
| Copper | <0.02 | <0.02 |
| Lead | <0.06 | <0.06 |
| Mercury | <0.0001 | <0.0001 |
| Nickel | 0.06 | 0.18 |
| Selenium | <0.02 | <0.12 |
| Silver | <0.02 | <0.02 |
| Thallium | <8.0 | <8.0 |
| Zinc | 0.02 | 0.274 |
| pH | 8.9 | 7.3 |
| Alkalinity | 1540 | 2940 |
| Sulfates | 940 | 1200 |
| Chloride | 0.17 | 1.3 |
| Total dissolved solids | 9770 | 9950 |

6.2.2 Metals, PCDD/PCDF, and Physical Characteristics

A summary of the bottom ash analysis is given in Table 6-11. No major differences were observed between the two tests on the bottom ash. Selenium, silver, and thallium were below detection levels in all samples for both test days. Antimony and mercury concentrations were higher for the blended-fuel test day, while the remaining 9 metals were either lower or the same concentration as for the coal-only tests. Sulfates were higher both in the leachate and compositional analysis for the blended-fuel test day. Chlorides were about the same for the two tests. PCDD/PCDF (in ppt) were about the same for the two tests. Moisture content, percent combustibles, and pH levels were essentially the same for both tests.

A summary of the economizer ash analyses are given in Table 6-12. Three of the 14 metals analyzed were below detection levels. These metals included Se, Ag, and Tl. Arsenic and barium levels were lower, and Sb, Cd, Cr, Cu, Pb, and Ni were higher for the blended-fuel tests. Beryllium and mercury levels were about the same for both tests. Most of the higher concentration levels for lead and zinc are probably due to the higher levels of these metals existing in the coal used during the blended-fuel tests, compared to the coal used in the coal-only tests. Sulfates and chloride levels were higher in the blended-fuel tests. The levels were also significantly higher than those in the bottom ash samples. Moisture and pH levels were similar in both tests. However, the moisture level was an order of magnitude less than the moisture content of the bottom ash, while the pH was somewhat higher (8.4-9.1 for bottom ash and 10.9-11.2 for economizer ash).

Table 6-10. Summary of TCLP Test Results of ESP Flyash

| Parameter | Test 1 | Test 2 |
|----------------------------------|----------|----------|
| Test date | 10/26/92 | 10/27/92 |
| Fuel weight ratio (coal/pellets) | 100/0 | 88/12 |
| TCLP leach (mg/L) | | |
| Antimony | <0.2 | 0.27 |
| Arsenic | 0.14 | 0.10 |
| Barium | 0.96 | 1.14 |
| Beryllium | <0.02 | <0.02 |
| Cadmium | <0.02 | <0.02 |
| Chromium | 0.18 | 0.35 |
| Copper | <0.02 | <0.02 |
| Lead | <0.06 | <0.06 |
| Mercury | 0.00013 | 0.00013 |
| Nickel | 0.03 | <0.02 |
| Selenium | 0.45 | 0.59 |
| Silver | <0.02 | <0.02 |
| Thallium | <8.0 | <8.0 |
| Zinc | 0.023 | <0.02 |
| pH | 8.9 | 9.2 |
| Alkalinity | 3200 | 3170 |
| Sulfates | 1700 | 1500 |
| Chloride | 0.62 | 13.3 |
| Total dissolved solids | 11,100 | 10,700 |

The ESP flyash results are summarized in Table 6-13. One metal, thallium, was below detectable levels. Three metals, including Pb, Be, and Hg were at similar concentrations for both tests. Only one metal, selenium, exhibited a lower concentration for the blended-fuel tests. As expected, nine metals, including Sb, As, Ba, Cd, Cr, Cu, Pb, Ag, and Zn, had enriched concentration levels in the flyash. The concentrations of all these metals were higher in the ESP flyash than in the bottom ash. Sulfates and chloride levels were higher in the blended tests, and were higher than levels in either the bottom ash or economizer ash. Moisture content, percent combustibles, and pH were similar for both test days. The moisture content and combustible percentage were lower than the levels noted in either the bottom ash or the economizer ash. pH levels were about 12.1, compared to 11.0 for the economizer ash and 8.5 for the bottom ash.

An overall review of the ash samples indicates that there probably was not any net increase or decrease in the composition of the total ash stream. Increases in one parameter for one type of ash appear to be offset by a comparable decrease of that parameter in one or both of the other ash types.

PCDD/PCDF levels were reduced during the blended-fuel tests compared to the coal-only tests.

Table 6-11. Summary of Metals, PCDD/PCDF, and Characteristics of Bottom Ash

| Parameter | Test 1 | Test 2 |
|---------------------------------------|----------|----------|
| Test date | 10/26/92 | 10/27/92 |
| Fuel weight ratio (coal/pellets) | 100/0 | 88/12 |
| Metal composition (ug/g) ^a | | |
| Antimony | 9.0 | 11.0 |
| Arsenic | 7.8 | <1.0 |
| Barium | 4780 | 3760 |
| Beryllium | 2.1 | 1.9 |
| Cadmium | 1.8 | 1.3 |
| Chromium | 47.6 | 45.7 |
| Copper | 270 | 276 |
| Lead | 19.0 | 19.7 |
| Mercury | <0.005 | 0.024 |
| Nickel | 23.7 | 22.9 |
| Selenium | <0.47 | <0.49 |
| Silver | <0.90 | <0.90 |
| Thallium | <470.0 | <490.0 |
| Zinc | 76.7 | 72.3 |
| Sulfates | 73 | 110 |
| Chlorides | 1 | 2 |
| PCDD/PCDF (ppt) ^b | | |
| TOTAL | 24.3 | 25.7 |
| Characteristics ^c | | |
| Moisture content (% w/w) | 5.17 | 4.92 |
| Combustibles (% w/w) | 1.0 | 0.97 |
| pH | 8.4 | 9.1 |

^a Data from one sample.

^b Reference Appendix F of Volume 3.

^c Data from two samples.

The results of the mineral analyses conducted on the bottom ash and ESP flyash samples are shown in Tables 6-14 and 6-15. The mineral test results for both the bottom ash and ESP flyash yielded almost identical results for both test days. The silica content in the bottom ash was somewhat higher (34.22% vs. 33.74%) in the blended test than in the coal-only test. Ferric oxide was lower (8.97% vs. 9.82% w/w) in the blended test than in the coal-only test.

The ash distribution percentage for the coal-only test was 60% bottom ash, 5% economizer ash, and 35% ESP flyash. Although no actual measurements could be made of the ash distribution for the blended-fuel days, the plant engineers and operators determined that the ash distributions did not vary significantly from the 100% coal, based on samples collected and visual observations.

Table 6-12. Summary of Metals, PCDD/PCDF, and Characteristics of Economizer Flyash

| Parameter | Test 1 | Test 2 |
|---------------------------------------|------------------|------------------|
| Test date | 10/26/92 | 10/27/92 |
| Fuel weight ratio (coal/pellets) | 100/0 | 88/12 |
| Metal composition (ug/g) ^a | | |
| Antimony | <6.9 | 16 |
| Arsenic | 32.1 | 6.1 |
| Barium | 5730 | 4490 |
| Beryllium | 2.5 | 2.3 |
| Cadmium | 1.7 | 3.4 |
| Chromium | 28.9 | 48.1 |
| Copper | 36 | 366 |
| Lead | 22 | 62.8 |
| Mercury | 0.017 | 0.018 |
| Nickel | 18 | 25.9 |
| Selenium | <0.49 | <0.44 |
| Silver | <0.90 | <0.88 |
| Thallium | <490.0 | <440.0 |
| Zinc | 80.4 | 191 |
| Sulfates | 27,000 | 23,000 |
| Chlorides | 4 | 19 |
| PCDD/PCDF (ppt) | | |
| TOTAL | N/A ^b | N/A ^b |
| Characteristics ^a | | |
| Moisture content (% w/w) | 0.08 | 0.05 |
| Combustibles (% w/w) | 0.96 | 1.37 |
| pH | 11.1 | 10.9 |

^a Data from one sample.

^b Not applicable.

6.3 Feedstock Analyses

Key parameters resulting from the individual analyses of coal and b-dRDF pellet samples collected during the trial burns are given in Tables 6-14 and 6-15, respectively.

The characteristics of the coal fired during the two test days are shown in Tables 6-16 and 6-17. As shown in Table 6-16, the coal combusted during the 100% coal tests was obtained from six different seams within the mine. A total of 9348 tons were delivered to the test site. Various parameters, including sulfur, sodium, moisture, ash content, and HHV of the coal are shown. These parameters represent data measured at the mine prior to shipment of the coal to the test site. The same information described above is given in Table 6-17 for the coal used during the blended test day. The fact that the coal came from many different coal seams probably accounts for the large variability in the metals content of the coal samples analyzed.

Table 6-13. Summary of Metals, PCDD/PCDF, and Characteristics of ESP Flyash

| Parameter | Test 1 | Test 2 |
|----------------------------------|----------|----------|
| Test date | 10/26/92 | 10/27/92 |
| Fuel weight ratio (coal/pellets) | 100/0 | 88/12 |
| Metal composition (ug/g) | | |
| Antimony | 8.1 | 20 |
| Arsenic | 11.4 | 36 |
| Barium | 2410 | 3040 |
| Beryllium | 2.5 | 2.2 |
| Cadmium | 1.5 | 3.8 |
| Chromium | 29.9 | 37.3 |
| Copper | 82.3 | 385 |
| Lead | 48.7 | 148 |
| Mercury | 0.354 | 0.369 |
| Nickel | 24.6 | 28.3 |
| Selenium | 1.3 | 0.77 |
| Silver | 0.43 | 3.0 |
| Thallium | <463 | <477 |
| Zinc | 106 | 386 |
| Sulfates | 30,000 | 37,000 |
| Chlorides | 13.9 | 247 |
| PCDD/PCDF (ppt) | | |
| TOTAL | 28.8 | 1.2 |
| Characteristics | | |
| Moisture content (% w/w) | 0.07 | 0.05 |
| Combustibles (% w/w) | 0.69 | 0.70 |
| pH | 12.1 | 12.2 |

Ultimate and proximate (including heating value) analyses of coal, b-dRDF pellets, and blended b-dRDF pellets and coal are given in Tables 6-18 through 6-20. Briefly, the ultimate (or elemental) analysis is used for combustion calculations and determination of boiler efficiency. The proximate analysis (volatile matter, ash, fixed carbon, and moisture) is used to evaluate the suitability of furnace geometry to accommodate the firing of a given feedstock. An examination of the ultimate analyses of coal and b-dRDF pellets presented in Table 6-18 and 6-19, respectively, shows that the b-dRDF pellet was considerably lower in carbon, sulfur, and moisture, slightly lower in nitrogen, higher in ash and hydrogen, and much higher in chlorine and oxygen content than was the coal. The low carbon and high oxygen content of b-dRDF is the main reason for the relatively low heating value of this fuel. Oxygen in fuels in combination with carbon or hydrogen represents a reduction in the fuel's potential heat energy. However, in this particular case, the reduction in heating value is only 10% compared to the heating value of the coal (lignite). Table 6-20 summarizes the ultimate and proximate (including heating value) analyses of the feedstock used during the coal-only tests and the blended b-dRDF pellet and coal tests. The data presented for the blended b-dRDF/coal test were prepared by mathematically combining the coal analyses for the Test 2 data in Table 6-18 and the b-dRDF pellet analyses in Table 6-19 for direct comparison with the fuel results from the coal-only tests.

Table 6-14. Summary of Bottom Ash Mineral Analysis

| Parameter | Test 1 | Test 2 ^a |
|---|----------|---------------------|
| Test date | 10/26/92 | 10/27/92 |
| Fuel weight ratio (coal/pellets) | 100/0 | 88/12 |
| Mineral composition (%) | | |
| Silica (SiO ₂) | 33.74 | 34.58 |
| Alumina (Al ₂ O ₃) | 13.92 | 14.69 |
| Titania (TiO ₂) | 0.70 | 1.19 |
| Ferric oxide (Fe ₂ O ₃) | 9.82 | 8.82 |
| Lime (CaO) | 23.02 | 22.88 |
| Magnesia (MgO) | 8.35 | 7.43 |
| Potassium oxide (K ₂ O) | 0.24 | 0.23 |
| Sodium oxide (Na ₂ O) | 2.41 | 2.56 |
| Sulfur trioxide (SO ₃) | 0.85 | 0.85 |
| Phos. pentoxide (P ₂ O ₅) | 0.36 | 0.40 |
| Manganese oxide (Mn ₃ O ₄) | 0.23 | 0.23 |
| Barium oxide (BaO) | 0.72 | 0.59 |
| Not determined | 5.64 | 5.86 |
| TOTAL | 100.00 | 100.00 |

^a Data after 1500 hours on October 27, 1992.

Table 6-15. Summary of ESP Flyash Mineral Analysis

| Parameter | Test 1 | Test 2 |
|---|----------|----------|
| Test date | 10/26/92 | 10/27/92 |
| Fuel weight ratio (coal/pellets) | 100/0 | 88/12 |
| Mineral composition (%) | | |
| Silica (SiO ₂) | 32.95 | 31.46 |
| Alumina (Al ₂ O ₃) | 13.68 | 13.47 |
| Titania (TiO ₂) | 0.67 | 0.84 |
| Ferric oxide (Fe ₂ O ₃) | 4.93 | 4.36 |
| Lime (CaO) | 19.94 | 20.17 |
| Magnesia (MgO) | 7.20 | 6.91 |
| Potassium oxide (K ₂ O) | 0.97 | 1.10 |
| Sodium oxide (Na ₂ O) | 5.96 | 6.56 |
| Sulfur trioxide (SO ₃) | 0.85 | 0.85 |
| Phos. pentoxide (P ₂ O ₅) | 0.38 | 0.40 |
| Manganese oxide (Mn ₃ O ₄) | 0.22 | 0.22 |
| Barium oxide (BaO) | 0.54 | 0.46 |
| Not determined | 11.73 | 13.20 |
| TOTAL | 100.00 | 100.00 |

Table 6-16. Coal Sources and Characteristics^a - Test 1 (October 26, 1992)

| Sources | Number of Loads | Tons | S (% w/w) | Na (% w/w) | Moisture (% w/w) | Ash (% w/w) | HHV (Btu/lb) |
|---------------------------------------|--------------------------------|-------------|----------------------|-----------------------|-----------------------------|------------------------|-------------------------|
| Red Reimer #19, Station 4-Seam C | 35 | 3408 | 0.85 | 3.00 | 44.83 | 6.72 | 6021 |
| Red Reimer #19, Station 9-Seam A-B | 20 | 1947 | 0.75 | 2.45 | 43.12 | 6.54 | 6215 |
| Yellow #17, Station 5-Seam C | 5 | 487 | 0.76 | 1.50 | 42.77 | 8.17 | 6045 |
| Blue #14, Station 25-Seam B | 10 | 974 | 1.01 | 6.70 | 43.78 | 7.25 | 6111 |
| Blue #14, Station 26-Seam B | 16 | 1558 | 0.85 | 7.70 | 43.71 | 6.58 | 6148 |
| Blue #15, Station 14-Seam A | 10 | 974 | 1.70 | 3.40 | 43.59 | 7.50 | 6051 |

^a Data as measured at mine.**Table 6-17. Coal Sources and Characteristics^a - Test 2 (October 27, 1992)**

| Sources | Number of Loads | Tons | S (% w/w) | Na (% w/w) | Moisture (% w/w) | Ash (% w/w) | HHV (Btu/lb) |
|--|--------------------------------|-------------|----------------------|-----------------------|-----------------------------|------------------------|-------------------------|
| Red Reimer #19, Station 4-Seam C | 28 | 2715 | 0.85 | 3.00 | 44.83 | 6.72 | 6021 |
| Red Reimer #19, Station 5-Seam C | 8 | 776 | 1.21 | 2.50 | 44.15 | 6.72 | 6090 |
| Red Reimer #19, Station 10- Seam A-B | 11 | 1066 | 0.75 | 2.45 | 43.19 | 6.49 | 6213 |
| Yellow #17, Station 5-Seam C | 5 | 485 | 0.76 | 1.50 | 42.77 | 8.17 | 6054 |
| Blue #14, Station 26-Seam B | 25 | 2424 | 0.85 | 7.70 | 43.71 | 6.58 | 6148 |
| Blue #14, Station 14 | 10 | 969 | 1.70 | 3.40 | 43.59 | 7.50 | 6051 |

^a Data as measured at mine.

Table 6-18. Coal Ultimate and Proximate Analysis (as received –w/w)

| Parameter | Test 1 | Test 2 |
|------------------------------------|-----------------------|-----------------------|
| Date of test | 10/26/92 ^a | 10/27/92 ^b |
| Fuel weight ratio (coal/pellets) | 100/0 | 88/12 |
| Ultimate analysis | | |
| Moisture, Total | 40.73 | 40.73 |
| Ash | 9.57 | 8.28 |
| Carbon | 36.45 | 37.10 |
| Hydrogen | 2.02 | 1.99 |
| Nitrogen | 0.58 | 0.58 |
| Chlorine | 0.008 | 0.0053 |
| Sulfur | 0.79 | 0.76 |
| Oxygen | <u>9.85</u> | <u>10.56</u> |
| TOTAL | 100.00 | 100.00 |
| HHV (Btu/lb) | 6185 | 6250 |
| Bulk density (lb/ft ³) | 44.65 | 45.80 |
| Proximate analysis | | |
| Moisture, Total | 40.73 | 40.73 |
| Ash | 9.57 | 8.28 |
| Volatile matter | 27.29 | 27.11 |
| Fixed carbon | <u>22.42</u> | <u>23.89</u> |
| TOTAL | 100.00 | 100.00 |

^a Data from one sample except sulfur content. Three additional sulfur tests were conducted; see Appendix P of Volume 3.

^b Data is average from two samples.

The metals (14) analyses of coal, b-dRDF pellets, and blended b-dRDF/coal samples are provided in Tables 6-21 through 6-23, respectively. As shown in Table 6-24, the concentrations of metals in the coal were much greater and exhibited larger variations than the concentrations and variability of those same metals found in the b-dRDF pellets. An examination of Tables 6-21 and 6-22 indicates that the b-dRDF pellets are richer than coal in the following elements: Sb, Cr, Cu, Hg, Ag, and Zn. Coal has higher concentrations of the following metals: As, Ba, Be, Pb, Se, and Tl. Concentrations of cadmium and nickel are similar in both coal and b-dRDF pellet samples. Overall, the metal content of the b-dRDF pellets is less than that of the coal (638 ug/g for coal and 438 ug/g for b-dRDF pellets). Thallium was deleted from both the pellet and coal samples in the above comparison since the thallium data are not conclusive due to the very high detection limits associated with the analysis of this element.

The fusion temperature of the coal and b-dRDF ashes for both an oxidizing and reducing atmosphere are given in Table 6-25. The ash fusion temperature (reducing) data were found to be somewhat of a surprise. The hemispherical temperature of the b-dRDF pellet was higher (2350°F) than that of the coal (2130°F).

**Table 6-19. b-dRDF Pellet Ultimate and Proximate Analysis
(as received -w/w)**

| Parameter | Test 2 ^a |
|------------------------------------|---------------------|
| Date of test | 10/27/92 |
| Fuel weight ratio (coal/pellets) | 88/12 |
| Ultimate analysis | |
| Moisture, Total | 18.80 |
| Ash | 12.44 |
| Carbon | 33.99 |
| Hydrogen | 4.22 |
| Nitrogen | 0.54 |
| Chlorine | 0.123 |
| Sulfur | 0.22 |
| Oxygen | <u>29.67</u> |
| TOTAL | 100.00 |
| HHV (Btu/lb) | 5570 |
| Bulk density (lb/ft ³) | 19.86 |
| Proximate analysis | |
| Moisture, Total | 18.80 |
| Ash | 12.44 |
| Volatile matter | 55.27 |
| Fixed carbon | <u>13.49</u> |
| TOTAL | 100.00 |

^a Data from one sample. Data from run made between 1000-1300 hours on October 27, 1992, is approximately 96-98% of values shown above.

The reason for this is not clearly understood; however, other researchers, for example in the test at the Oscar Meyer facility, Madison, Wisconsin, in 1981⁶, experienced the same phenomenon. The high ash fusion temperature of the pellet ash might explain why no serious bottom ash clinkering problems occurred.

A comparison of facility permitted levels and test levels is presented in Table 6-26.

6.4 General Operational Observations

Otter Tail Power Company has been active in firing alternative fuels at the Big Stone Plant for a number of years. The company's alternative fuels policy states that it "encourages the use of alternative fuels when the burning of such alternative fuels can be done as a way to both lower fuel costs and provide an environmentally acceptable disposal mechanism of the fuel in question." The plant had been co-firing blends of b-dRDF pellets and coal for approximately 1 year at the time these tests were conducted. Approximately 32,000 tons had been fired as of January 1, 1993, with a firing ratio of pellets to coal. Only minor housekeeping problems had been encountered, primarily due to pieces of film plastic

Table 6-20. Feedstock Ultimate and Proximate Analysis (received -w/w)

| Parameter | Test 1 | Test 2 |
|------------------------------------|--------------|--------------|
| Date of test | 10/26/92 | 10/27/92 |
| Fuel weight ratio (coal/pellets) | 100/0 | 88/12 |
| Ultimate analysis | | |
| Moisture, Total | 40.73 | 38.10 |
| Ash | 9.57 | 8.78 |
| Carbon | 36.45 | 36.73 |
| Hydrogen | 2.02 | 2.26 |
| Nitrogen | 0.58 | 0.57 |
| Chlorine | 0.008 | 0.019 |
| Sulfur | 0.79 | 0.70 |
| Oxygen | <u>9.85</u> | <u>12.85</u> |
| TOTAL | 100.00 | 100.00 |
| HHV (Btu/lb) | 6185 | 6168 |
| Bulk density (lb/ft ³) | 44.65 | 42.7 |
| Proximate analysis | | |
| Moisture, Total | 40.73 | 38.10 |
| Ash | 9.57 | 8.78 |
| Volatile matter | 27.29 | 30.49 |
| Fixed carbon | <u>22.42</u> | <u>22.65</u> |
| TOTAL | 100.00 | 100.00 |

becoming airborne and littering the plant area. Other problems occurred as a result of the airborne plastic becoming entrained with the combustion air and collected on the preheater coils in the forced draft fan ductwork.

Several operational problems developed during the blended pellet and coal-fired tests conducted on October 27, 1992. The main problem was contamination by film plastic "stringers" approximately .75-in. wide and 12-15-in. long becoming entangled with the primary hammermill crusher in the transfer house. These "stringers" caused an inconsistent feed to the plant and required the primary hammermill to be shut down and clean out. While the primary hammermill was cleaned out, the pellet feed was rerouted to the redundant hammermill. This problem was traced to the fuel pellets provided by XL Recycling and was solved by firing only pellets supplied by EPR, Inc.

The inconsistent fuel feed resulting from the contamination in the XL Recycling pellets also caused several cyclones to trip because pellets were building up on the sides of the silos.

The cofired b-dRDF/coal tests indicated:

1. b-dRDF pellets can replace a high percentage (approximately 20%) of coal in an existing unmodified cyclone-fired combustor,

Table 6-21. b-dRDF Pellet Metals Analysis (concentration - ug/g)

| Parameter | Test 2 ^a |
|--------------|---------------------|
| Date of test | 10/27/92 |
| Fuel ratio | 88/12 |
| Metals | |
| Antimony | 19 |
| Arsenic | <0.19 |
| Barium | 81.2 |
| Beryllium | <0.19 |
| Cadmium | 1.1 |
| Chromium | 26 |
| Copper | 132 |
| Lead | 16 |
| Mercury | 0.190 |
| Nickel | 10.7 |
| Selenium | <0.095 |
| Silver | 1.3 |
| Thallium | <190 |
| Zinc | 190 |

^a Data from sample #7328-119.

Table 6-22. Coal Metals Analysis (concentration - ug/g)

| Parameter | Test 1 ^a | Test 2 ^b |
|-----------|---------------------|---------------------|
| Metals | | |
| Antimony | <5.9 | 12 |
| Arsenic | 3.63 | 4.3 |
| Barium | 1090 | 273 |
| Beryllium | 0.98 | 0.66 |
| Cadmium | <0.8 | 1.5 |
| Chromium | 18 | 12 |
| Copper | 29 | 15 |
| Lead | 29 | 206 |
| Mercury | 0.087 | <0.005 |
| Nickel | 11 | 6 |
| Selenium | <0.4 | 0.23 |
| Silver | 0.99 | <0.3 |
| Thallium | <840 | <330 |
| Zinc | 23 | 107 |

^a Data from sample #7328-113.

^b Data from sample #7328-117.

Table 6-23. Feedstock Metals Analysis (concentration - ug/g)

| Parameter | Test 1 | Test 2 |
|--------------|----------|----------|
| Date of test | 10/26/92 | 10/27/92 |
| Fuel ratio | 100/0 | 88/12 |
| Metals | | |
| Antimony | <5.9 | 13 |
| Arsenic | 3.63 | 3.81 |
| Barium | 1090 | 250 |
| Beryllium | 0.98 | 0.60 |
| Cadmium | <0.8 | 1.5 |
| Chromium | 18 | 13.7 |
| Copper | 29 | 29.0 |
| Lead | 29 | 183 |
| Mercury | 0.087 | <0.027 |
| Nickel | 11 | 6.6 |
| Selenium | <0.4 | <0.21 |
| Silver | <0.99 | <0.42 |
| Thallium | <840 | <313 |
| Zinc | 23 | 117 |

Table 6-24. Metals Variation in Feedstock (concentrations - ug/g)

| Metals | b-dRDF Pellets | Coal (Test 2) | Coal (Test 1) |
|-----------|---------------------------|------------------|---------------|
| Antimony | 19-62 (3.26) ^a | 2.5-12 (4.80) | <5.9 |
| Arsenic | <0.19-2.27 (11.94) | 0.53-4.3 (8.11) | 3.63 |
| Barium | 81.2-173 (2.13) | 228-2800 (12.28) | 10.90 |
| Beryllium | <0.17-<0.19 (1.12) | 0.66-0.99 (1.50) | 0.98 |
| Cadmium | 1.0-1.1 (1.1) | <0.3-1.5 (5.00) | <0.8-<1.0 |
| Chromium | 19-34.5 (1.82) | 12-26.5 (2.21) | 18 |
| Copper | 132-201 (1.52) | 15-64 (4.27) | 29 |
| Lead | 13-16.8 (1.29) | 12-206 (17.17) | <2.5-29 |
| Mercury | 0.107-0.675 (6.31) | <0.005 | 0.087-0.18 |
| Nickel | 9.6-10.7 (1.11) | 6-13 (2.17) | 11 |
| Selenium | <0.09 | <0.2-0.47 (2.35) | <0.4 |
| Silver | 0.84-4.5 (5.36) | <0.3-0.97 (3.23) | 0.99 |
| Thallium | 170-190 (1.12) | <290-<460 (1.59) | <840 |
| Zinc | 124-190 (1.53) | 22-123 (5.59) | 23 |

^a () Indicates factor variation.

Table 6-25. Feedstock Ash Fusion Temperature Analysis^a

| 1. Coal Ash Fusion Temperatures (Test Day 1 - coal only) | | |
|---|-------------------------------|---------------------|
| Parameter | Fusion Temperature of Ash, °F | |
| | Oxidizing Atmosphere | Reducing Atmosphere |
| Initial deformation | 2163 | 2100 |
| Softening temperature | 2198 | 2120 |
| Hemispherical temperature | 2210 | 2130 |
| Fluid temperature | 2250 | 2173 |
| 2. b-dRDF Pellet Ash Fusion Temperature (Test Day 2) | | |
| Parameter | Fusion Temperature of Ash, °F | |
| | Oxidizing Atmosphere | Reducing Atmosphere |
| Initial deformation | 2305 | 2280 |
| Softening temperature | 2330 | 2319 |
| Hemispherical temperature | 2369 | 2350 |
| Fluid temperature | 2408 | 2395 |
| 3. Coal/b-dRDF Pellets (Fuel Ratio 88/12) Ash Fusion Temperature (Test Day 2) | | |
| Parameter | Fusion Temperature of Ash, °F | |
| | Oxidizing Atmosphere | Reducing Atmosphere |
| Initial deformation | 2180 | 2122 |
| Softening temperature | 2214 | 2144 |
| Hemispherical temperature | 2129 | 2156 |
| Fluid temperature | 2269 | 2199 |

^a Combustor Design Ash Fusion Temperature (Reducing) = 2060-2570°F

2. b-dRDF pellets must be tailored to meet individual furnace requirements. In the case of a cyclone-fired combustor, the pellet particle size must be no larger than 1 to 1-1/2 inches, and as much of the film plastic must be removed as possible.

6.5 Boiler Efficiency

Boiler efficiency testing was carried out according to ASME Power Test Code 4.1, with gross efficiency calculated by the heat loss method. System parameters and instrumentation necessary to measure the Power Test Code 4.1 parameters were calculated and/or provided by on-line plant instrumentation. The heat losses and resulting boiler efficiencies for the two test days are shown in Table 6-26. The largest losses were for dry gas and moisture in the fuel. Boiler efficiency for the blended b-dRDF/coal test was approximately 1% less than the efficiency for the coal-only test.

Table 6-26. Comparison of Permitted Levels vs. Test Levels

| Pollutant | Permit Levels | Test 1 | Test 2 |
|----------------------------|----------------------|---------------|---------------|
| SO ₂ (lb/MMBtu) | 3.0 | 2.56 | 2.12 |
| Particulates (lb/MMBtu) | 0.26 | 0.021 | 0.031 |
| Opacity (%) | 20 | 10.4 | 10 |

Table 6-27. Heat Losses and Boiler Efficiency

| % Heat Losses Due to | Test 1 (coal only) | Test 2 (pellet/coal blend) |
|---------------------------------------|-------------------------------|---------------------------------------|
| Dry gas | 6.85 | 7.55 |
| Moisture in fuel | 7.79 | 7.53 |
| H ₂ O from combustion of H | 3.45 | 3.84 |
| Combustion air moisture | 0.02 | 0.03 |
| Air preheat | (+)0.64 | (+)0.71 |
| Radiation and convection | 0.15 | 0.15 |
| Total heat loss (%) | 17.62 | 18.39 |
| Boiler efficiency | 82.38 | 81.61 |

7.0 Conclusions and Recommendations

On the basis of the test program discussed in the previous sections, the key conclusions and recommendations regarding the co-firing of b-dRDF pellets with coal in a commercial-scale cyclone-fired combustor are listed in this section. General conclusions include the following:

1. An overall beneficial reduction in the major priority pollutants was observed. During blended tests, SO₂, and CO emissions were reduced compared to coal-only tests. CO₂, HF, and HBr emissions were unchanged. HCl, THCs, and particulates increased, but increases were small.
2. PCDD/PCDF levels for both tests were small.
3. PAHs (except two compounds), PCBs, and BTX were below detectable levels for both tests.
4. Small increases in metal concentrations were measured during blended tests.
5. All ash samples were not toxic by the TCLP tests.
6. Concentrations of some metals in the ash samples increased during blended tests.

Specific findings and conclusions related to the study are presented below.

7.1 Flue Gas Emissions

1. Sulfur dioxide (SO₂) emissions from combustion of b-dRDF/coal blends decreased by approximately 17.3% from the coal-only tests. This reduction was due to the lime-SO₂ reaction and subsequent removal, as well as the b-dRDF pellet's lower sulfur content.
2. Nitrogen oxides (NO_x) and carbon monoxide (CO) levels from combustion of b-dRDF/coal blends decreased compared to the coal-only tests.
3. Carbon dioxide (CO₂) emissions were similar for both tests. Hydrogen fluoride (HF) and hydrogen bromide (HBr) emissions were very low for both tests, less than 3 ppm for HF and 0.1 ppm for HBr.
4. Emissions of hydrogen chloride (HCl) and particulate matter (PM) increased during the blended-fuel tests. Both increases were related to the mass fraction of the b-dRDF pellet in the fuel. In the case of HCl, the increase was due to the increased chlorine found in the pellets. However, the increase was small (~30 ppm). The PM increase was due to the higher ash content and lower heat content of the pellets. The increase was small, 0.01 lb/MMBtu over the emission rate of the coal-only tests.
5. Total hydrocarbons (THC), although not federally regulated are regulated under some state statutes. Total emission levels for both tests were small, about 7 ppm for the coal-only tests, and 13 ppm for the blended-fuel tests.
6. PAHs (except for two compounds), PCBs, and BTX were below detectable levels for both tests. The two PAH compounds above detection levels were naphthalene and phenanthrene. Emissions of both compounds decreased during the blended-fuel tests.
7. PCDD/PCDF levels for both tests were small, less than 0.025 ng/Nm³ for the coal-only tests and 0.395 ng/Nm³ for the blended tests.

8. Only small increases in metal concentrations were observed in the blended-fuel tests compared to the coal-only tests. The enrichment of barium (Ba), copper (Cu), and zinc (Zn) were most noticeable. Six of the 14 metals analyzed were below detection levels.

7.2 Solid Waste Residuals

1. All bottom, economizer, and flyash samples passed the TCLP tests, most by many orders of magnitude, the smallest by a factor of four.
2. As expected, metal concentrations increased during the blended-fuel tests in both the flyash and bottom ash samples. These metals include Sb, Ba, Cd, Cr, Cu, Pb, Ag, and Zn. Higher concentrations of Ba, Cd, and Pb are probably due to the higher levels of these metals existing in the coal used in the blended-fuel tests. The concentration of all of the metals were more predominant in the flyash than in the bottom ash.
3. PCDD/PCDF levels in the flyash were reduced in the blended-fuel tests compared to the coal-only tests.
4. Mineral content for both bottom ash and flyash yielded almost identical results for both blended-fuel and coal-only tests.

7.3 Operational and Conclusions

1. Boiler efficiency for the blended b-dRDF/coal test was approximately one percent less than the efficiency for the coal-alone tests. This was the result of slightly higher blended day gas losses and moisture in the blended fuel compared to the coal only losses.
2. Several operational problems developed during the blended fuel tests. The main problem encountered were film plastic "stringers" approximately 3/4" in width and 12 inches in length which became entangled within the primary hammermill crusher. These "stringers" caused an inconsistent fuel feed to the plant and required the hammermill to be shutdown and the "stringers" removed. Other problems occurred as a result of airborne plastic becoming entrained in the combustion air which then collected on the preheater coils in the forced draft fan ductwork. Both of these problems were a result of inadequate particle size reduction during the fabrication of the pellets supplied by XI Recycling. The supplier has corrected the problem by the addition of a second air classifier and hammermill in the processing system.

7.4 Recommendations

In light of the foregoing conclusions, the following recommendations are made:

1. The primary benefit of co-firing technology to potential users is emissions reduction. Comprehensive emission testing has been conducted in two types of combustion systems, a grate-fired unit and a cyclone-fired combustor, both of which emitted lower levels of the major priority pollutants. It is now important to accurately map the emissions of fluidized-bed combustion units and suspension-fired units, both of which are widely used in the electric utility and industrial marketplace.
2. The manufacturers of b-dRDF pellets must be attuned to potential users of their product. These fuel pellets must be tailored to meet individual furnace requirements. In the case of a cyclone-fired combustion system, particle size must be restricted to no more than 1-1.5 inches and smaller, if

possible, to preclude potential operational problems. It is equally as important to remove or size-reduce, film plastic material prior to the densification process.

3. The mechanisms behind various types of corrosion are not well understood. For example, high-temperature, liquid-phase corrosion is caused by molten alkali-metal sulfates, but the exact mechanism has not been verified. The mechanism behind corrosion by hydrogen chloride (HCl) is also unclear. Thus, research is needed to investigate the effects of acid gas formation on boilers metals performance on a long-term basis.
4. Because suspension-fired combustors are extensively used in the electric utility industry, research should be conducted to evaluate the implications of pulverizing b-dRDF pellets with coal to increase the market for this technology.

8.0 Abbreviations

| | |
|------------------------|--|
| < | ≤ (when following a number) |
| %v/v | percent by volume |
| %w/w | percent by weight |
| ACFM | actual cubic fee per minute |
| ANL | Argonne National Laboratory |
| ASTM | American Society for Testing and Materials |
| b-dRDF | binder (lime) entranced densified refuse derived fuel |
| Btu | British Thermal Unit |
| BTX | benzene, toluene, and xylene |
| cc (ml) | cubic centimeter (milliliter) |
| CEM | continuous emission monitoring |
| CFR | Code of Federal Regulations |
| CRADA | Cooperative Research and Development Agreement |
| DEG-F (°F) | degrees Fahrenheit |
| DOE | U.S. Department of Energy |
| dRDF | densified refuse-derived fuel |
| DSCFM | standard cubic foot of dry gas per minute |
| DSCM | standard cubic meter of dry gas per minute |
| EPA | U.S. Environmental Protection Agency |
| EPR | Eden Prairie Recycling |
| ESP | electrostatic precipitator |
| ft/sec | feet per second |
| g | gram |
| g/dscm | grams per dry standard cubic meter |
| GC/ECD | |
| GF/AA | graphite furnace atomic absorpion |
| GR/DSCF | grains per dry standard cubic foot |
| GR/ACF | grains per actual cubic foot |
| hr | hour |
| HRGG/HRMS | |
| HRGG/LRMS | |
| ICP | inductively coupled Argon plasma emission spectrometry |
| in. | inch |
| in.Hg | inches of mercury |
| in.wc | inches of water |
| kW | kilowatt |
| lb | pound |
| lb/dscf | pounds per dry standard cubic foot |
| lb/hr | pounds per hour |
| lb/MMBtu | pounds per million british thermal units heat input |
| lb/10 ⁶ Btu | pounds per million british thermal units heat input |
| ltpd | long tons per day |
| mg/DSCM | milligrams per dry standard cubic meter |
| min. | minutes |
| MM5 | modified method 5 sampling train |
| MSW | municipal solid waste |
| MW | megawatt |
| ng | nanogram (1 gram x 10 ⁻⁹) |
| NO _x | nitrogen oxides |

| | |
|-------|--|
| NREL | National Renewable Energy Laboratory |
| NRT | National Recovery Technologies |
| PAH | polynuclear aromatic hydrocarbons |
| PCB | Polychlorinated biphenyls |
| PCDD | polychlorinated dibenzo-p-dioxins |
| PCDF | polychlorinated dibenzo-p-dioxins |
| PM | particulate matter |
| PPH | pounds per hour |
| ppm | parts per million |
| ppmC | parts per million carbon |
| ppm,d | parts per million, dry |
| ppm,w | parts per million, wet |
| ppt | parts per trillion |
| psi | pounds per square inch |
| QAT | |
| RDF | refuse-derived fuel |
| TCLP | Toxicity Characteristic Leaching Procedure |
| TDS | total dissolved solids |
| THC | total hydrocarbon |
| tpd | tons per day |
| ug | microgram |
| um | micrometer |
| UNT | University of North Texas |

Standard conditions are defined as 68°F (20°C) and 29.92 in. of mercury pressure.

9.0 References

1. Franklin Associates, Ltd. (1980). *Characterization of MSW in the United States: 1990 Update*, Prepared for the U.S. EPA.
2. Ohlsson, O.O., K.E. Daugherty and B.J. Venables. (1986). *Densified Refuse-Derived Fuel: An Alternative Energy Source*, Proceedings of the American Association of Energy Engineers, 9th World Energy Engineering Congress, Atlanta, Georgia, pp. 593-597.
3. Ohlsson, O., K.E. Daugherty and B.J. Venables. (1988). *Emissions Resulting from the Full-Scale Co-firing of Pelletized Refuse-Derived Fuel and Coal*, Proceedings of the Tenth Annual Industrial Energy Technology Conference, Houston, Texas, pp. 311-316.
4. Daugherty, K.E., O. Ohlsson, B.J. Venables, P. Moore, M. Paslusny, B. Attili, Jen-Fon Jen and Chia-Hui Tai. (1988). *Raw Data for Determining Acid Gases, Trace Metals and Organics from Co-firing Blends of Coal and Densified Refuse-Derived Fuels (dRDF)*, ANL Interim Report, Vols 1 through 4, Argonne National Laboratory.
5. Culkin, G.W. and J.M. Marchello. (1991). *RDF Test Burns at a Steam Boiler*, Final Report prepared under CIT Contract BIO-92-001, Old Dominion University Research Foundation.
6. Vetter, R.J., M.L. Smith and K.W. Ragland. (1978). *Test Firing Refuse-Derived Fuel in an Industrial Coal-Fired Boiler*, Alternative Technologies Division, Hazardous Waste Engineering Research Laboratory, Cincinnati, Ohio, Grant No. R806328-01-3.

REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

| | | | | |
|---|---|--|--|--|
| 1. AGENCY USE ONLY (Leave blank) | | 2. REPORT DATE July 1994 | 3. REPORT TYPE AND DATES COVERED Final Report | |
| 4. TITLE AND SUBTITLE Results of Combustion and Emissions Testing when Co-Firing Blends of Binder-Enhanced Densified Refuse-Derived Fuel (b-dRDF) Pellets and Coal in a 440 MW, Cyclone Fired Combustor: <i>Volume 1: Test Methodology and Results.</i> | | | 5. FUNDING NUMBERS (C) DA-1-11157-1 (TA) WM41.1010 | |
| 6. AUTHOR(S) O. Ohlsson | | | | |
| 7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Energy Systems Division Argonne National Laboratory Argonne, Illinois | | | 8. PERFORMING ORGANIZATION REPORT NUMBER DE94000283 | |
| 9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Renewable Energy Laboratory 1617 Cole Boulevard Golden, CO 80401-3393 | | | 10. SPONSORING/MONITORING AGENCY REPORT NUMBER NREL/TP-430-6322a ANL/ESD-22 | |
| 11. SUPPLEMENTARY NOTES | | | | |
| 12a. DISTRIBUTION/AVAILABILITY STATEMENT National Technical Information Service U.S. Department of Commerce 5285 Port Royal Road Springfield, VA 22161 | | | 12b. DISTRIBUTION CODE UC-1414 | |
| 13. ABSTRACT (<i>Maximum 200 words</i>) This research project characterized the effects of burning a combination of binder-enhanced densified refuse-derived fuel (b-dRDF) pellets and coal in a commercial-scale electrical generating facility. Pelletized b-dRDF has been burned in coal combustors, but only in quantities of less than 3% in large utility systems. This research investigated using b-dRDF in quantities up to 20%. Through this research, project participants gained operating, technical, and economic viability data that will be critical for the near-term commercial use of b-dRDF. | | | | |
| 14. SUBJECT TERMS Municipal solid waste, refuse-derived fuel, boilers, power generation, cogeneration | | | 15. NUMBER OF PAGES 60 | |
| | | | 16. PRICE CODE A04 | |
| 17. SECURITY CLASSIFICATION OF REPORT | 18. SECURITY CLASSIFICATION OF THIS PAGE | 19. SECURITY CLASSIFICATION OF ABSTRACT | 20. LIMITATION OF ABSTRACT | |

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102