COFIRING BIOMASS WITH LIGNITE COAL

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COFIRING BIOMASS WITH LIGNITE COAL

ABSTRACT

The University of North Dakota Energy & Environmental Research Center, in support of the U.S. Department of Energy's (DOE) biomass cofiring program, completed a Phase 1 feasibility study investigating aspects of cofiring lignite coal with biomass relative to utility-scale systems, specifically focusing on a small stoker system located at the North Dakota State Penitentiary (NDSP) in Bismarck, North Dakota. A complete biomass resource assessment was completed, the stoker was redesigned to accept biomass, fuel characterization and fireside modeling tests were performed, and an engineering economic analysis was completed. In general, municipal wood residue was found to be the most viable fuel choice, and the modeling showed that fireside problems would be minimal. Experimental ash deposits from firing 50% biomass were found to be weaker and more friable compared to baseline lignite coal. Experimental sulfur and NO_x emissions were reduced by up to 46%. The direct costs savings to NDSP, from cogeneration and fuel saving, results in a 15- to 20-year payback on a \$1,680,000 investment, while the total benefits to the greater community would include reduced landfill burden, alleviation of fees for disposal by local businesses, and additional jobs created both for the stoker system as well as from the savings spread throughout the community.

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COFIRING BIOMASS WITH LIGNITE COAL

EXECUTIVE SUMMARY

In support of the U.S. Department of Energy's (DOE) biomass cofiring program, the University of North Dakota Energy & Environmental Research Center (EERC) completed a Phase 1 feasibility study investigating the aspects of cofiring lignite coal with biomass relative to utility-scale systems and, specifically, for a small stoker system located at the North Dakota State Penitentiary (NDSP) in Bismarck, North Dakota.

A complete biomass resource assessment led to the selection of municipal wood residue as the most viable fuel choice in terms of quantity, cost, quality, availability, and reliability. Wood residues can be delivered to the NDSP facility from tree service and municipal haulers at no cost per ton, avoiding a \$10.00 per ton tipping fee at the landfill and an unnecessary landfill burden. The fuel-handling design includes a complete receiving station, with segregation, grinding, and drying capability. Modifications to the stoker include dual-fuel Detroit stokers and a vibratory grate. Fireside issues were addressed by completing fuel characterization, modeling of fireside behavior, test burns relative to utility-scale systems, and grate-fired testing to evaluate clinker formation. In general, all results indicated that fireside issues would be minimal and decrease in severity with increased blending of biomass with lignite coal. Specifically, despite the increased percentage of Ca, K, and P in biomass ash, the lower amounts of ash resulted in experimental tube fouling deposits that were more friable and weaker in strength. Modeling results were in agreement with experimental results. Measured emissions from 50% blends indicated decreases in sulfur and NO_x at 46% and 33%, respectively. Clinker formation from biomass blended at 75% with coal was minimal to nonexistent. Environmental permitting will require minimal modification to an existing air permit for NDSP and in no way affects the economics of the project. Cogeneration of electricity, in combination with fuel cost savings, produces a 15- to 20-year payback on a \$1,680,000 investment. These are the direct costs to the NDSP facility and do not take into account the much larger benefits to the community that are obtained by utilizing biomass residues.

The specific benefits of this project are outlined below, and the benefits realized from the support of the DOE biomass cofiring program are summarized. The NDSP, through the results of this study, has the potential to move forward with a cofiring application that can achieve the following for the local community and the facility:

- Reduced sulfur and NO_x emissions and zero net gain of carbon dioxide
- Reduction of landfill burden and associated taxpayer costs
- Alleviation of tipping fees for disposal from local businesses
- Additional jobs at NDSP, and potentially other businesses, benefiting from lower disposal costs

- Reduction in energy costs, which will benefit taxpayers in the long term
- Increased energy reliability and security
- No significant change to the NDSP air quality permit
- 15- to 20-year return on investment

In many cases, the infrastructure and market conditions are available to take advantage of cofiring biomass; however, various factors inhibit the progress for biomass utilization. DOE's support helps to overcome barriers resulting in viable projects that would not move forward otherwise. This project is a case in point, and the following barriers addressed by this study are outlined as follows:

- District energy systems, approximately 5800 of them throughout the United States, provide an appropriately sized infrastructure for utilizing biomass. The primary concern for facility managers is usually a consistent supply of energy. Cost is secondary. State-funded institutions provide very limited incentives to lower energy costs through investigation of alternative fuels or fuel diversification. This forces facility managers to focus budget justification efforts on maintenance upgrades as opposed to exploring nontraditional solutions to lower costs. DOE-funded studies can help facility managers see specific cases that could reduce costs by cofiring biomass.
- Biomass is site-specific, case-specific, and nontraditional. These attributes create greater difficulty evaluating biomass relative to fossil fuels. Typical energy-related engineering firms realize the technical and market difficulties of biomass and tend to focus on more reliable, profitable fossil energy solutions. The result is a low availability of off-the-shelf equipment and knowledge of how to take advantage of biomass fuels. Compared to fossil energy, significant work must be done to verify biomass resource availability prior to implementation, since biomass may come from a variety of sources. DOE-funded studies help to alleviate the effort of resource evaluation by employing knowledgeable research facilities. Resulting case studies help to demonstrate how to seek available resources and provide detailed information on equipment that is unique for biomass applications.
- Potential biomass fuel suppliers are not significant drivers of the market and do not have the benefit of the infrastructure of fossil fuels. Natural gas and coal are brokered commodities made available from the supplier and marketed to a target audience. The industries have been well developed over time and operate at peak efficiencies to provide competitive costs. Biomass, a relatively immature industry, lacks procurement efficiency. Many potential fuel suppliers pay to dispose of material or have found some low-value-added markets for residues. Small businesses that generate wood residues do not have the resources to collaborate and convince energy users to utilize their waste. The DOE's support of this study helped to link the generators of waste material to an energy consumer.

COFIRING BIOMASS WITH LIGNITE COAL

INTRODUCTION

The U.S. Department of Energy (DOE) cofiring program released solicitation DE-PS26-00NT40775 on February 23, 2000, to support cost-shared applications for research and development of technologies for cofiring biomass feedstocks with fossil fuels. The interest on behalf of DOE was for five critical areas of research:

- Biomass cofiring as an emission reduction technique
- Gasification-based cofiring strategies
- Closed-loop biomass cofiring
- Low-rank coal cofiring – subbituminous and lignite
- University and college cofiring applications

This project represents support of activities under low-rank coal cofiring. The justification on behalf of DOE for funding this area of research, as taken from the solicitation, is as follows. “The DOE has, in the past, cooperated with power producers in testing and analyzing biomass cofiring in coal-fired boilers that use bituminous and some subbituminous coals. However, the program has not tested cofiring biomass in a lignite-fired boiler or extensively demonstrated subbituminous coals. Through this subtopic, the biomass cofiring program intends to add lignite and subbituminous coals to the fossil fuels being demonstrated in other projects. The United States has a significant resource base of these fuels. Cofiring of lignite with biomass can be significantly different than cofiring subbituminous or bituminous coals because of the ash chemistry and moisture and other factors. A potentially attractive feature of cofiring biomass with lignite is that the boilers are designed for a fuel with low heat and high moisture content that is consistent with the properties of biomass. As such, DOE is seeking, through this solicitation, to demonstrate the viability of cofiring biomass with lignite or subbituminous coal for application within the fossil-fuel industry.”

As part of typical business activity, the Energy & Environmental Research Center (EERC) contacted various local lignite- and subbituminous-fired utilities. Very little interest could be found among the commercial sector in funding a project. The EERC did, however, get significant interest from smaller users of lignite coal. The EERC was able to respond to the solicitation with a proposal to demonstrate cofiring biomass with lignite coal. The research project was designed to provide data to both utility-scale and small-scale systems. The DOE highlights under Subtopic E how small-scale, typically stoker-fired systems, are more likely to adapt to the use of biomass fuels. This project was performed to provide a feasibility study to a small stoker-fired system, conduct experimental combustion research, and proceed with a Phase 2 demonstration of the small stoker system to extrapolate data to large-scale utilities. The project achieves multiple objectives set forth by DOE and represents an excellent economical demonstration of biomass fuel use.

Objectives

The overall objectives of the project are to complete a technical and economic feasibility study on cofiring wood waste with lignite at the North Dakota State Penitentiary (NDSP), obtain the first research data on the impact of cofiring biomass fuels with lignite coal, provide a demonstration to other state institutions and small stoker-fired systems, and provide research data for lignite utilities.

Methodology

This project provides the opportunity to explore the cofiring of biomass with lignite coal. Factors such as the dispersion of resources and the physical properties of biomass can make biomass fuel expensive to transport, handle, and feed into conventional systems. While the economics may not justify cofiring biomass at large-scale utility plants, smaller facilities, which may be located close to biomass resources and pay a higher price for coal, can economically justify using biomass as a fuel. Additionally, these smaller facilities provide a unique opportunity to learn about the properties and benefits of cofiring biomass with lignite. Basic research and demonstration at the smaller scale are applicable to larger utility systems. This project provides a case study for the estimated 5800 district energy systems throughout the United States and provides a jump-start for lignite utilities, when future developments improve the economics for cofiring biomass.

The EERC discovered a unique opportunity existing in Bismarck, North Dakota. The NDSP is interested in reducing the cost of operation of its lignite-fired steam plant. The City of Bismarck currently landfills 13,000 tons/yr of combustible wood residue. By cofiring biomass with lignite, NDSP can potentially convert its existing steam heat plant from a 2800-ton/yr, 7-month operation to a year-round steady-load cogeneration facility that would operate at a net profit. Considering the monetary value of environmental costs associated with clean air and landfilling, the benefit of the proposed project is equal to \$854,000 annually. This exciting opportunity benefits the landfill, city government, the penitentiary, state government, and the biomass and lignite coal industries and meets DOE objectives. The project demonstrates how other similar facilities could use biomass to improve the cost-effectiveness of their operation and possibly increase the use of local biomass resources and lignite coal.

Participating Organizations

Participating organizations included the EERC, Grand Forks, North Dakota; the North Dakota Department of Corrections and Rehabilitation, Bismarck, North Dakota; the North Dakota Division of Community Services (DCS), Bismarck, North Dakota; King Coal Furnace Corporation, Bismarck, North Dakota; and K.J. Schwartz Engineering (KJSE), Bismarck, North Dakota. This project was made possible by funding from DOE's National Energy Technology Laboratory and cost share provided by DCS and the North Dakota Department of Corrections and Rehabilitation.

North Dakota State Penitentiary Background

Shown in Figure 1, NDSP is one of four prison divisions in North Dakota under the Department of Corrections. Located in East Bismarck, NDSP is the main prison complex and houses

Figure 1. NDSP boilerhouse and facilities.

715 maximum to minimum high-custody inmates representing 68% of the state's inmate population. The facility covers 400,000 square feet of building space, and 180 acres of ground. Currently, the NDSP uses 2600 to 2800 tons/yr of lignite coal to provide steam heat to its facility. The steam is produced by a Zurn Industries boiler installed in 1982. The boiler is fed by a spreader stoker and removes ash with a dump grate. Steam is produced at 100 psig, saturated. The boiler has the capacity to produce 200 psig at 28,000 lb/hr and operates at an efficiency of about 72%. The fuel currently being fired is 2-in. stoker coal with 34% moisture, 6% ash, 43% carbon, 3% hydrogen, 0.3% sulfur, 0.7% nitrogen, 13% oxygen, and 7240 Btu/lb. The boiler operates 7 months out of the year, with shutdown May through October. The annual cost of operation is approximately \$48,000/yr, firing about 2600 tons/yr at \$18.50/ton. The boiler is fitted with an electrostatic precipitator (ESP) and backed up with two gas boilers.

Prior to the project, some prefeasibility work was completed to conceptualize a possible cofiring scenario at the penitentiary facility. A case was run assuming the penitentiary could collect a \$10/ton tipping fee for biomass, as the local landfill requires the same amount. At this rate, even a modest cogeneration system (250 kW) would provide a very attractive return on investment. However, as we moved forward into the project, we found that tree service companies and waste haulers would only haul direct to the NDSP if a \$0/ton rate were available. This changed the economics and engineering focus to come up with a system that could achieve an attractive rate of return based on offsetting fuel and electricity costs for the NDSP at \$20/ton and \$0.05/kWh respectively. During prefeasibility work, we found that the Bismarck Landfill (located just down the road from the NDSP) was receiving at least 5000 tons/yr of usable wood fuel. Further efforts found twice the wood resource locally available to justify the project. In order to create a positive

impression of our research results and sustain a useful demonstration for Phase 2, we considered attractive economics to be paramount in our Phase 1 efforts.

All inmates are sentenced to the Department of Corrections and Rehabilitation and are expected to work during their incarceration. Projects performed at NDSP provide rehabilitative benefits of holding a job and instilling the work ethic. Job assignments include janitorial, grounds maintenance, food services, laundry, property, and Rough Rider Industries (RRI). The Job Placement Committee coordinates the assignment of inmates to various jobs with the individual work supervisors. Inmates are expected to work 8 hours a day and are paid a daily wage for every day they work.

RRI is the industrial work program for the Prisons Division. The purpose of this program is to give inmates the opportunity to be productive with their time through meaningful work experience. Inmates who make an honest effort to address their treatment and education needs and fill their remaining time with meaningful work have been far more successful in staying out of prison once they are released. It is for this reason that compliance with treatment and education, as well as exhibiting proper behavior, are requirements to work at RRI. At NDSP, RRI has a furniture and upholstery factory, a sign shop, a license plate shop, and a metal factory. This project will result in jobs for inmates to support a biomass-receiving station with general operation and maintenance activities.

EXPERIMENTAL

Goal

The EERC, working with King Coal Furnace Corporation and KJSE, is providing a feasibility study and demonstration project that will provide scientific information on the cofiring of biomass with lignite coal and lead to a successful commercial application for the North Dakota Department of Corrections and Rehabilitation's penitentiary facility.

Objectives

- Complete analysis to determine the technical and economic feasibility of cofiring biomass fuels at NDSP's lignite-fired steam plant. The analysis will include assessment of local biomass resources in terms of quantity, preparation requirements, and delivered costs; design of a biomass cofired system; evaluation of fireside performance; evaluation of design modifications required for cofiring; evaluation of environmental issues; reassessment of land/energy demand; and economic analysis.
- Complete bench-scale testing to provide data to DOE on cofiring biomass with lignite to support technical and economic decisions.
- Demonstrate to other state institutions and users of stoker-fired systems the performance and potential economic and environmental advantages of cofiring biomass with lignite.

- Demonstrate at a smaller scale the cofiring of biomass with lignite and how it applies to utility-scale systems.

Summary of the Approach

The proposed project involves two phases. A Phase 1 feasibility study would determine the technical and economic feasibility of cofiring biomass at the NDSP and scientifically evaluate cofiring biomass and lignite through bench-scale studies. A Phase 2 demonstration project would make a documented case study available to other institutions, small stoker systems, and lignite utilities that are considering cofiring biomass. Research data would be collected during both phases to quantify the effects of several lignite–biomass mixtures.

Tasks were designed to carry out the above objectives and are described below:

Task 1 – Local Biomass Resource Assessment

The focus of this task was to assess local biomass resources, their availability, quantities, ease of access, and delivered projected cost. The EERC has developed a method for generating quantities of potential collectible biomass resources pertaining to small power systems. This estimating method, based on documented resources for wood residuals, agricultural residuals, animal waste, sludge, and municipal solid waste (MSW) was used to get a broad picture of the potential resource within 100 miles of the site. Other specific resources were identified and evaluated for use. All costs associated with preparation and handling were taken into consideration prior to selecting the most appropriate biomass cofiring resource.

Task 2 – Fuel-Handling Issues

Technical issues related to fuel-handling transportation, storage, drying, size reduction, metering, and feeding were addressed. This task in combination with Task 1 addressed costs for various fuel preparation methods. A direct comparison of systems was used to select the most economical and technically viable solution for handling and feeding biomass fuel. A complete system design and preliminary equipment specification were developed.

Task 3 – Fireside Issues

The focus of the task was to address technical and operational issues related to biomass cofiring combustion, such as needed residence time for complete combustion, slagging, fouling, corrosion, heat rate, efficiency, and steam production rates. Preliminary bench-scale tests were performed to assist in evaluation of these issues.

The primary objectives of the small-scale testing were as follows:

- To fully characterize the inorganic and ash-forming constituents of the lignite and wood biomass fuels that will be part of this program using conventional and advanced analytical techniques.

- To determine the fundamental ash behavior and ash interactions between inorganic components in the lignite and biomass during combustion using small-scale combustion testing facilities and predictive modeling.
- To determine the overall fireside performance of 100% lignite compared to a blend of 20% or more of wood biomass with lignite, which included, at a minimum, determining fouling, slagging, grate clinkering, and fine-particulate generation levels under varied combustion conditions.
- To assess air toxic emissions for the lignite–biomass blends, including NO_x, SO_x, mercury, and other significant trace elements.
- To make suggestions as to proper boiler design and operation, possibly including fuel preparation and feeding, air distributions, and deposit removal systems to maximize fireside boiler performance.

Analysis

One lignite sample and the two most common types of waste wood that could be supplied to the NDSP were acquired for analysis and combustion testing. The fuels were analyzed to fully characterize the inorganic and ash-forming constituents using conventional techniques and advanced techniques. Each sample received was submitted for analysis of particle size, bulk density, particle density, heating value, proximate–ultimate analysis, chlorine, major oxide chemistry (i.e., SiO₂, Fe₂O₃, etc.), and trace element analysis (As, Hg, Cd, Cr, Pb, and Se). Advanced fuel analysis using chemical fractionation (CHF) and computer-controlled scanning electron microscopy (CCSEM) was done under this project. CCSEM is used to determine the size, composition, and association of the mineral species in fuel that are greater than 1 μm in diameter. CHF quantifies organically bound inorganics and minerals that are less than 1 μm in size. Organically bound inorganics are found only in low-rank fuels, and they comprise the bulk of the inorganics that are less than 1 μm in size. Together, CCSEM and CHF give a complete inorganic characterization of any type of fuel; this information is crucial for identifying the fuel-related root causes of ash deposit formation in a boiler and is also used in predictive modeling.

Modeling

The data produced by the advanced and conventional fuel analyses were used as input for running predictive models or indices. Two models were used in this project to assess ash deposition. The model termed Predictive Coal Quality Effects Screening Tool, PCQUEST, is a computer program designed to output a series of indices that rank fuels according to predicted performance with respect to slag deposit formation, high- and low-temperature-region fouling, fly ash collectibility, slag tapping, and ash erosion. This model requires CCSEM and CHF data as input; therefore, should these data not be available, this model will not be run. A model called the FACT (Facility for the Analysis of Chemical Thermodynamics) code is another computer-based model that is used for assessing fuel quality effects on ash behavior in a boiler. FACT is a thermodynamic equilibrium model that predicts molar fractions (partial pressures) of all gas, liquid, and solid stable

components in a system by Gibbs free energy minimization. Output from FACT includes quantities, compositions, and viscosities of liquid and solid mineral phases; therefore, the code works well for predicting the behavior of fuel ash, including biomass-derived ash for different boiler temperature regimes. This model is especially useful for extrapolating to different temperature regions in a boiler to assess potential slag or fouling deposit formation, and it is also useful for performing blend evaluations.

Combustion Testing

Combustion testing for this project involved firing lignite and two lignite–biomass blends in a drop-tube furnace (DTF) system and in a small grate–stoker combustion system. Combustion tests in the DTF are relatively low-cost bench-scale combustion simulations of gas temperature, gas composition, particle residence time, and entrained ash aerodynamics. Tests in the DTF assessed fouling and fine particulate generation, and testing in the small grate–stoker combustion system assessed clinkering or slagging.

Combustion testing in the small grate-stoker combustion system focused primarily on evaluating low-viscosity slag development that could induce clinker formation. The lignite and two lignite–biomass blends were fired in the bench-scale stoker furnace using an excess air level, gas temperature, and gas composition similar to that which is used in the NDSP system. The lignite and blend samples were compared, and an assessment of clinker potential was derived.

Task 4 – Environmental Issues

The focus of this task is to address technical and operational issues that may potentially impact emissions released from the plant to the environment. These include air, water, and solid emissions/releases. Most of the data were collected during Task 3. Gas analyzers were used to measure CO, CO₂, O₂, NO_x, and SO_x concentrations from bench-scale combustion equipment. The particle-size distribution of the fly ash and the corresponding carbon carryover or loss-on-ignition quantity were determined in the DTF. The size and composition distribution of the fly ash was also determined by CCSEM analysis. This information was used to assess potential particulate emissions for the lignite–biomass blends. Emissions of mercury and other significant trace elements measured in the fuels were estimated using the in-house predictive models for these emissions based on fuel analyses.

Task 5 – Energy Production Assessment

The focus of this task was to determine and quantify the impact that biomass firing will have on energy (steam/heat) production and define options and/or firing strategies that will result in optimal use of biomass for energy production. The potential exists to convert the penitentiary's steam heat facility to a cogeneration plant and provide steam for other uses such as absorption chillers. These opportunities affect the decisions that go into equipment selection, process flow arrangement, and various cycle analysis. The completion of this task was necessary to identify the most beneficial application of technology for the various opportunities that cofiring of biomass offers for the penitentiary facility.

Task 6 – Engineering Economic Analysis

An economic analysis was carried out using guidelines set forth by the state of North Dakota in evaluating new projects. Specific considerations for utility rate schedules and requirements for budgeting at state facilities were factored into the economic analysis. These considerations make the document useful for the end user.

TASK 1 – LOCAL BIOMASS RESOURCE ASSESSMENT

The first and most important step in the process of any biomass-related feasibility study is identifying a secure biomass fuel resource. With respect to the NDSP needs, identifying an available low-cost source of biomass was paramount to creating an attractive economic scenario. The scope of this task consisted of looking at theoretically available biomass supplies in order to narrow-down the search for specific viable resources. This helped to minimize time and effort and allowed for a detailed focus on the most promising resources. The results of this task were presented to the NDSP, DCS, and potential fuel suppliers. Meaningful discussion during the presentation helped to direct our efforts and corroborate data.

The EERC has developed methods for estimating national biomass resources as described in Schmidt and Pinapati (1). These methods were used to estimate biomass residues located within 100-mile radius of Bismarck, North Dakota. A 100-mile radius, shown in Figure 2, was chosen because costs to transport biomass greater than 100 miles can require delivered biomass fuel costs exceeding delivered coal costs. Lignite coal of similar heating value to wood is delivered to NDSP at

Figure 2. Counties within 100-mile radius of Bismarck, North Dakota.

approximately \$20/ton. Hauling estimates provided by several vendors suggested rates of about \$15/ton for a 75-mile distance. Unless unique circumstances are present, the 100-mile radius provides a good rule of thumb. The results of the theoretical estimates are presented in Table 1. Details of how these estimates are calculated are found in Schmidt and Pinapati (1).

Table 1. Theoretically Available Biomass Within 100-mile Radius of Bismarck

Theoretically Available Biomass (all sources combined)		2.6 million tons/yr
Woody Residues	Agricultural Residues	Human Residues
2.3% of total	91.3% of total	6.4% of total
Normalized Subtracting Crop Residues		
13.2% of total	50.2% of total	36.6% of total

The biomass types shown in Table 1 are defined as follows. Woody residues are made up of sawdust from primary and secondary processors or mills and manufacturers, respectively; forest residues from logging activity; and municipal wood supplied from residential, industrial, construction, and demolition sources. Agricultural residues consist of crop residue left on the field in excess of what is required for soil stabilization, processing residues, and animal manure. Human residues are made up of segregated MSW and sewage sludge. All of these materials are potential biomass fuels for the NDSP facility.

We began our resource investigation by analyzing the above data and eliminating the least promising possibilities. On the surface, the results of the theoretical data tended to indicate that agricultural sources might be available in large quantity and should be the first point of focus. It was found that crop residues comprised the majority of total available biomass: 82%! However, crop residues are widely dispersed, and the logistics of gathering the resource are difficult since each individual farmer must supply the resource. Costs cannot compete with coal. This is the problem that energy crop researchers face, and as data indicate from studies with switchgrass (typical hay crop) (2), \$40.00 to \$60.00 per ton is the expected delivery costs. Even the most promising studies investigating the use of corn stover estimate \$23/dry ton delivered (3), which is more than the cost of lignite coal delivered to NDSP. Although these data were discouraging relative to NDSP, based on the sheer quantity of crop residues in North Dakota, the state should consider future research efforts, which could decrease logistical barriers, and costs for using crop residues as fuel.

The data were normalized eliminating crop residue in the count. The results indicated that agricultural residues comprised 50% of the total, with human residues at 37% and woody residues at 13%. In light of these data, we examined the subcategories and eliminated the small contributors for potential further investigation. Sewage sludge, mill residue, and forest residue were the lowest quantities, accounting for less than 4% of the normalized total; hence they were eliminated. Animal manure, although accounting for over 13% of the normalized total, was eliminated because of logistics, odor, and handling issues. This left the categories shown in Table 2 for detailed investigation of various attributes, including quantity, cost, availability, reliability, and quality.

Table 2. Theoretical Quantities of the Most Promising Biomass Resources Within 100-mile Radius of Bismarck, ND

Biomass Fuel Type	Theoretical Quantity
1. Municipal Woody Residues	56,846 tons/yr
2. Agricultural Processing Residues	171,853 tons/yr
3. Municipal Solid Waste	156,139 tons/yr

The theoretical numbers provided in Table 2 exceed consumption requirements of the NDSP and were deemed appropriate estimates in which to embark on obtaining further information on the above resources. NDSP consumes approximately 2500 tons/yr of lignite coal for heating purposes, operating only 7 months out of the year. If the current boiler were operated at full capacity 100% of the year, it could potentially consume approximately 20,000 tons/yr of lignite coal. MSW was eliminated from the list for further investigation. Permitting and fuel-handling characteristics cause MSW to be extensively more difficult to implement than wood or ag-processing residues. Therefore, data on wood and ag-processing residues were the only detailed information collected.

Agricultural Processing Residues

North Dakota maintains its reputation as the leading cereal crop producer in the nation. According to the U.S. Department of Agriculture (4), North Dakota is ranked the No. 1 producer of spring wheat, durum wheat, sunflowers, barley, dry edible beans, pinto beans, canola, and flaxseed. North Dakota is ranked No. 2 for production of all wheat, oats, navy beans, dry edible peas, and honey. North Dakota is ranked No. 3 for sugar beets and lentils. All of the above crops require processing. The opportunity was to identify local processors and determine the waste residues that may be used as fuel.

In the Bismarck area, agricultural processors were interviewed to obtain data on processing residues. Processors of sunflowers and sugar beets are primarily located in the Red River Valley of North Dakota outside the 100-mile radius of Bismarck. All the other crops listed are generally handled by local grain elevators and then shipped to out-of-state distributors or processors. Twenty-five grain elevators or processors were contacted concerning potential residues. A detailed list is provided in Appendix A. About 5000 tons/yr of material was verified as available. However the average cost was about \$20 per ton, not including delivery. Primarily grain elevator screenings, these residues are sold to farmers for cattle feed. Archer Daniels Midland Corporation is the only significant processor in the region. The plant produces no usable waste of any significant quantity. Therefore, the investigation of agricultural processing residues did not yield a significant economically usable fuel resource for the NDSP.

Municipal Woody Residues

This category proved to be the most successful for securing an economically viable fuel resource for the NDSP. The data suggest that there is approximately 30,000 tons/yr of wood available within 100 miles of Bismarck. This number is based on actual conversations with landfills, tree services, municipal waste haulers, and commercial industry. The amount of material that was

confirmed by specific sources within the immediate Bismarck area such as tree services and industry was 8000 tons/yr. A detailed breakdown is provided in Appendix A. This amount was estimated by the specific haulers through telephone interviews and is considered a conservative approximation of the amount of material we could expect to be delivered to the NDSP. Other data supporting these estimates were gathered from local landfills and is summarized in Table 3.

Table 3. Landfill Summary

Landfill/Distance from NDSP	Notes on Resource
Bismarck Landfill/Bismarck	7900 tons/yr
Mandan Landfill/5–10 miles from NDSP	5000 tons/yr
County Landfill/91 miles – Glenham, SD	600 tons/yr can segregate and grind
Mercer County/50 miles – Stanton, ND	Quantity not recorded, \$21/ton tipping fee
McDaniel Landfill/100 miles – Sawyer, ND	Quantity not recorded
Jahner Sanitation/60 miles – Linton, ND	Not contacted
City of Dickinson Landfill/100 miles	Estimated 3000 tons/yr
City of Jamestown Landfill/100 miles	Estimated 3000 tons/yr
City of Minot Landfill/100 miles	Estimated 3000 tons/yr

The landfill data tend to support the quantities suggested by the local tree services and industries. The groups hauling woody debris to the local landfills (Bismarck and Mandan) are comprised of tree services, municipal waste haulers, and miscellaneous private industries. All of these haulers pay a \$10 per ton tipping fee to the landfill for woody debris. Haulers typically drive past the NDSP to get to the Bismarck landfill, which is within 5 miles of NDSP. Mandan area haulers take material directly to the Mandan landfill on the opposite side of the city. Interviews suggest that haulers would be interested in dropping off material at NDSP if there were no tipping fee. Haulers in the Mandan area would be interested in driving the extra 10 miles across town to deliver material to NDSP only if there were no fee. A \$5/ton tipping fee was discussed, but considered an unattractive option to all haulers.

The data concerning municipal wood supply in the Bismarck/Mandan area are summarized here with detailed information available in Appendix A. Detailed investigation was required to ensure an adequate fuel supply to the NDSP. Telephone interviews provided information from each individual supplier on aspects of wood residue costs, quantity, quality, availability, and reliability. Potential suppliers attended a meeting held at the NDSP February 1, 2001, and provided additional input. In general, we discovered the following.

Cost

All suppliers are willing to deliver wood residue material to the NDSP for free. The delivered fuel cost assumption is \$0/ton. Most suppliers are not willing to pay any tipping fee. Most likely, if a tipping fee of \$5/ton were imposed, we would lose half the potential fuel supply. Haulers in the Mandan area would not deliver to NDSP if a tipping fee were imposed.

Quantity

8000 tons/yr of material was verified through interviews. The reliability of this information should be fairly accurate. Although suppliers did not have recorded data by weight, they could easily estimate the amount of material hauled on a weekly basis by volume, or they knew what their landfill tipping fees totaled. From these numbers, a weight was calculated. Assumptions included 15 lb/ft³ bulk density of wood and a \$10/ton tipping fee to arrive at the approximate weights. The wood residue haulers agreed at the February meeting that once the NDSP project was implemented, significantly greater amounts of wood waste would probably become available and that the estimate of 8000 tons/yr could be considered a good conservative estimate. Landfill records seem to support the quantification given that the Bismarck Landfill registered 7900 tons per year and the Mandan landfill estimated receiving a similar amount.

Quality

Given a quantity of 8000 tons/yr, 52% is expected to come from tree services. This material would include all parts of the tree leaves, branches, bark, trunks, and stumps. A large majority is from the city trees comprising cottonwood, elm, box elder, and oak. The second largest supply would come from primarily from one local municipal waste hauler. This amount accounts for 32% of the total and is made up of construction and demolition (C&D) debris and commercial wood waste. The hauler indicated segregation would be required. By eliminating the tipping fee at the landfill, the municipal hauler could offer greater services to their customer, and segregation may be on behalf of the customer, the hauler, or at the NDSP receiving site. An approach for sorting and segregation of received materials is provided in the Task 2 section of this report. The municipal hauler did not view segregation as a significant issue, as long as the NDSP site was set up to keep truck traffic moving efficiently. The remaining wood residue resource would be supplied by private industries that haul their own waste to the landfill. The quality of this resource is quite high, consisting of clean sawdust, 2 × 4 edgings, and pallets. In all cases, material must be screened and ground in order to process in the boiler at the NDSP.

In general, the collected wood waste can be expected to have an average delivered moisture content of 25% to 35%. Even the wettest wood should not exceed 50% moisture. Delivered heating value will be approximately 7500 Btu/lb; once dry, the wood has a heating value of over 8000 Btu/lb. Comparatively, lignite coal is 6700 Btu/lb @ 36.8% moisture. Also, wood will have 4 times less sulfur and over 3 times less ash than lignite coal. Other fireside performance issues are explained in the Task 3 section of this report. In general, we expect improved environmental performance, similar fuel consumption rates, and improved fireside performance.

Availability

Availability can be described as the ability to obtain the resource. In all cases of resource supplied from tree services, municipal haulers, or private companies, the parties agreed that dropping material at the NDSP site would be attractive. Municipal haulers seemed to have the highest level of need since many of their customers currently do not segregate material. In cases where fuel cannot be segregated in advance, the NDSP will have the capability of segregating fuel on-site prior to processing. Unwanted debris can then be transferred to the Bismarck landfill. It will be paramount

for the NDSP to determine whether a truck should unload on-site or be passed on to the Bismarck landfill in the event that too much noncombustible material is present. Outdoor and indoor storage of biomass fuel will be available. An easy-access drive-through approach is designed that is amenable to self-dumping trucks.

Reliability

Reliability of the resource is defined as the cyclical nature of supply whether on an annual basis or projected future yearly basis. In general, the expected reliability of the municipal woody biomass is excellent. The majority of the resource is from tree service companies. It can be expected that fuel availability will increase during the summer and decrease in the winter. However, all the local tree services work year-round and claim that their residue deliveries would be fairly consistent. Also, the amount available in future years is expected to be consistent. The municipal haulers get material from a variety of sources, and volume follows a similar summer/winter cycle as do tree services. Future supply can be linked to population statistics. Bismarck is a city of 52,000, and the surrounding counties grew 10%–15% in the last year. The private suppliers of wood waste include two truss manufacturers and a pallet recycler. The supply is based on the viability of the business, which is expected to be good. Their supply is, again, higher in the summer but fairly consistent throughout the year. In no case is the volume of woody residues expected to decrease or be diverted to other higher value uses. The tree services do chip material and sell as bedding; however, the value does not provide a significant profit or comprise a significant percentage of their business.

TASK 2 – FUEL-HANDLING ISSUES

Task 2 was initiated upon the completion of Task 1. Once the most promising fuel resource was identified, the design of the fuel-handling system could be completed. The kickoff of this task included input provided by the potential fuel suppliers, since a handling and receiving site would be required. A complete design package is included in Appendix B. The package includes site plan drawings, equipment specifications, and costs. Highlights have been pulled from the drawings in Appendix B and are presented in the figures that follow.

The site plan in Figure 3 shows the layout of a fuel preparation site adjacent to the NDSP boiler house. Trucks are intended to enter the site via the lift station road and leave using industries road. Trucks may approach the site using either road, but traffic through the site is one way. Two outdoor storage piles with the capacity to store 375 tons of material (1 week at maximum capacity) each are planned. One pile is designated for separated commercial debris and the other of tree limbs, branches, etc. These piles constitute unconditioned large-diameter material. Clean presized or preconditioned debris will be received directly into the 80' × 100' fuel storage building. Approximately 120 tons can be stored in this preconditioned receiving station. Unconditioned fuel is processed in a CBI Grizzly Mill. Specifications are in Appendix B. A front-end loader transfers material from the unconditioned piles to the Grizzly Mill. The material will be screened using a 1" taper slot screen manufactured by Action Equipment Company and integral to the CBI equipment. Undersized material will be discarded in a rolloff dumpster and hauled to the landfill. After screening and metal separation, the fuel is ground to nominal 2" diameter with the hammer mill. The

Figure 3. Proposed site plan.

fuel is conveyed into a building for storage. Approximately 170 tons can be stored at the discharge of the Grizzly Mill. Both conditioned indoor fuel storage piles will automatically be conveyed overhead across the lift station road to a bunker drying bin for the boiler. The bunker drying bin is aerated and can use waste heat from the exhaust stack if necessary. The bunker drying bin has a capacity of 9391 ft³ or 3 days of fuel storage. The bunker drying bin is fully automated and feeds material to a surge hopper which then feeds the stoker. Finally, a dual-fuel stoker will supply material to the boiler. These stokers are a commercially proven technology provided by Detroit Stoker Company. For an equipment budget and visual representation of the process, see the process flow diagram and specifications presented in Appendix B.

In order for the old stoker to handle wood chips, modifications are planned for the boiler. A hydrograte will be installed. A hydrograte produced by Detroit Stoker Company is a vibratory, sloped, water-cooled grate. This new grate will replace the existing chain grate which currently is less tolerant of higher volatility fuels. Dry wood chips react faster inside the boiler and contain less ash. These two attributes create higher potential for exposure of the grate surface to excessive temperatures. Water-cooled hydrogrates eliminate this potential operational problem. In order to install the hydrograte, the boiler will need to be raised 3 feet.

The previous description of the process design was based on the handling issues and requirements relative to the most promising source of biomass supply for the NDSP. The theoretical requirements for design are summarized in Table 4.

TASK 3 – FIRESIDE ISSUES

Fireside issues are defined as the implications of fuel combustion on boiler maintenance. Fireside issues relative to the NDSP and utility-scale systems were addressed in this task through characterization of fuel components, modeling, and bench-scale testing. The results are summarized and presented as follows.

Fuel Characterization and Modeling

Introduction and Description of Samples and Analysis Data

A sample of the lignite coal fired at the NDSP was obtained for analysis, along with samples of mixed wood chips and chipped tree wood. These are referred to in the report as the lignite, wood chips, and tree wood, respectively. Proximate analyses were performed using American Society for Testing and Materials (ASTM) procedure D5142-90, ultimate analyses using ASTM D5373-93 and D5016-89, and the bulk ash chemistry of the fuels determined using ASTM procedure D4326-94. The EERC as-received proximate and ultimate results for the samples are given in Table 5. The EERC bulk ash chemistry results are given in Table 6.

The PCQUEST calculations to predict slagging and fouling behavior also required CCSEM analysis, image analysis (IMA), and CHF analysis. CCSEM analysis is used to determine the size

Table 4. Design Philosophy

Requirement	Result
Most promising biomass choice based on cost, quantity, quality, availability, and reliability.	Municipal woody residue consisting of cut trees, chips, sawdust, edgings, pallets, C&D debris
Design Requirements	Results
1. 1 week of fuel-receiving capacity	Large outdoor pile storage and some indoor surge storage.
2. Efficient load transfer and heavy truck traffic flow	Site plan was arranged for easy dump access and one-way through-site traffic with access from any outside direction.
3. Minimal on-site sorting, some required, manual labor can be utilized at low costs	Outdoor storage piles can be sorted manually; however, efforts to preseggregate materials on behalf of the municipal haulers will have to be implemented to minimize unwanted materials.
4. Screening	CBI ¼" screen for removing fines prior to the hammer mill. Oversized material that cannot feed to the hammer mill will be reduced with chain saws. No oversized screen is required after the hammer mill.
5. Metal separation	Three locations are provided for pulley magnets. 1) prior to the hammer mill, 2) at the discharge of the hammer mill conveyor, and 3) at the discharge into the dryer.
6. Low intensity drying	Indoor storage of 1-day capacity is provided for air drying, and a continuous dryer with the potential for using hot flue gas is provided.
7. Fuel conveying to boiler	Rapat cleated belt conveyors and augers are specified.
8. Fuel stoking for wood chips/blending control with coal	A Detroit dual-fuel stoker is specified. PLC logic will provide settings for automatically controlled blend ratios.
9. Ash handling for biomass	A Detroit hydrograte is specified.

and composition of the mineral species in a fuel that are greater than 1 µm in diameter, along with IMA to determine the association of the mineral species. CHF analysis quantifies inorganic materials, which are ion-exchangable, and minerals that are less than 1 µm in size. Organically bound inorganics are found only in low-rank fuels such as lignite and comprise the bulk of the inorganics that are less than 1 µm in size. Together, CCSEM and CHF give a complete inorganic characterization of a fuel. A complete description of the PCQUEST model is given in Appendix C.

A summary of the CCSEM size distribution of mineral phases is given in Table 7 and a summary of the CHF results in Table 8. The complete CCSEM and CHF analysis results are given in Appendix C.

Table 5. Proximate and Ultimate Analysis

	Lignite	Tree Wood	Wood Chips
Proximate Analysis, as received (wt%)			
Moisture	36.8	6.8	7.3
Volatile Matter	30.06	75.87	76.82
Fixed Carbon	27.25	15.40	15.25
Ash	5.89	1.93	0.63
Ultimate Analysis, as received (wt%)			
Hydrogen	6.75	6.37	6.12
Carbon	40.95	45.13	46.85
Nitrogen	0.96	0.83	0.17
Sulfur	0.74	0.19	0.18
Oxygen	44.72	45.55	46.05
Ash	5.89	1.93	0.63
Heating Value, Btu/lb	6700	7801	8274

Table 6. Bulk Ash Chemistry

Oxide, wt%	Lignite	Tree Wood	Wood Chips
SiO ₂	19.8	7.1	27.7
Al ₂ O ₃	11.3	1.3	11.0
Fe ₂ O ₃	10.7	2.0	10.0
TiO ₂	0.4	0.1	0.5
P ₂ O ₅	0.1	8.2	1.4
CaO	20.3	44.5	28.4
MgO	5.6	8.3	5.9
Na ₂ O	7.9	0.1	4.9
K ₂ O	0.8	25.8	7.6
SO ₃	23.2	2.6	2.5

Fireside Modeling Predictions

The PCQUEST program developed at the EERC determines combustion performance indices, including the potential for furnace wall slagging and convective pass fouling of various fuels. Slag is defined as the more fluid-type of ash material that forms only in the hottest temperature radiant section of a boiler. Fouling deposits are formed only in the cooler temperature regions of a boiler in the region of the secondary and primary superheaters and reheaters. Slagging deposits would form on radiant zone waterwalls in a pulverized coal-fired system or on the burning bed of fuel in a stoker-fired boiler, while fouling deposits would form on heat-transfer tubes in the convective pass of a boiler. The indices are on a scale of 0–100, with 0–33 being low, 34–66 being medium, and 67–100

Table 7. CCSEM Mineral Distribution, wt%

Mineral Fraction:	Lignite	Tree Wood	Wood Chips
	5.889	2.534	1.467
Mineral			
Quartz	10.9	7.3	6.7
Iron Oxide	1.4	4.2	27.4
Calcite	0.3	27.5	0.6
Dolomite	0.3	5.0	0.0
Kaolinite	7.9	0.2	2.8
K Al-Silicate	6.6	3.2	6.5
Fe Al-Silicate	3.5	1.0	2.0
Mixed Aluminosilicate	7.7	0.8	6.4
Fe Silicate	0.0	0.0	4.0
Ca Silicate	0.1	1.6	0.2
Pyrite	2.2	0.0	0.0
Pyrrhotite	35.4	0.0	0.8
Oxidized Pyrrhotite	1.0	1.0	8.1
Gypsum/Aluminosilicate	0.4	2.5	1.8
Silica-Rich	3.1	2.7	2.4
Unknown	14.4	37.9	23.5

Table 8. Chemical Fractionation Analysis

Amount Soluble in Water and Ammonium Acetate, wt%			
	Lignite	Tree Wood	Wood Chips
Si	0	53	76
Al	0	55	75
Fe	12	71	66
Ti	6	66	67
P	27	90	79
Ca	74	70	97
Mg	77	92	96
Na	99	57	96
K	19	100	90
S	71	60	6

being a high or severe value. The resolution of the calculations is such that differences of 2–3 index units indicate effectively the same performance.

PCQUEST calculations were performed on the pure lignite, tree wood, and wood chip fuels as well as on calculated blends to determine the effect of blend ratio. Indices for these blends were calculated at 10% increments by weight. The calculations were performed using parameters for the boiler, which was assumed to be at 100% load. The results of PCQUEST index calculations are

given in Figures 4 and 5 for the low- and high-temperature fouling, slagging, and opacity indices for the lignite–tree wood and the lignite–wood chip blends, respectively.

The proximate–ultimate analysis results show that the tree wood and wood chip samples are characterized by a significantly lower moisture and ash content than the lignite coal, along with a much higher volatile matter content. The lower moisture results in a 16%–20% higher heating value for the biomass fuels than for the lignite coal. This, along with the lower ash content, makes them attractive as fuels.

The bulk ash chemistry of the two wood fuels differs significantly, with the tree wood having high levels of calcium, potassium, and phosphorus with little silica, alumina, or iron, while the wood chips contains a greater amount of silica than the lignite, with comparable alumina and iron levels. The wood chips also have a moderately higher level of potassium. Both the tree wood and wood chips contain substantially less sulfur than the lignite coal. The high calcium and potassium levels, combined with the sulfur in the lignite, may form calcium and potassium sulfate deposits in low-temperature regions (below 1800EF) of the boiler when cofired.

The major mineral phases identified by CCSEM in the lignite coal are quartz, clays (kaolinite, potassium aluminosilicate, and aluminosilicate), and pyrite compounds. The tree wood contains considerable calcite (CaCO_3) along with some quartz and clay materials. The wood chips contain a high level of iron oxide, calcite, and pyrite compounds along with some clay minerals. Both biomass samples have a large amount of “unknown” inorganic material arising from the wood structure which does not fit the normal mineral classifications. It is believed that the high iron content of the wood chips is a result of treatment and processing of the material from the furniture plant from which it was received.

The CHF analysis shows that the majority of all elements in the tree wood and wood chips are soluble or ion-exchangable. For elements of concern which tend to form fine particulate leading to fouling deposits (Ca, Na, and K), the biomass samples have soluble or ion-exchangable values similar to, or somewhat higher than, the lignite coal. However, these higher values are compensated for by the lower ash content of the biomass samples.

The PCQUEST indices (low-temperature fouling, high-temperature fouling, slagging, and opacity) for blends of the tree wood with lignite coal predict no significant change in the low-temperature fouling index and a slight decrease in the high-temperature fouling index with increasing tree wood blend levels. There is a moderate increase in the slagging index as well as in the opacity index with an increasing percentage of tree wood in the blend. All of the indices remain in the “low” range, except for the opacity index at 100% tree wood. The PCQUEST results for the wood chips show slight decreases in the high-temperature fouling and opacity indices with increasing wood chip blend levels. There is no significant change in the low-temperature fouling or slagging indices. Overall, the PCQUEST results predict that blends of both biomass fuels with the lignite coal will produce only small changes in slagging, fouling, and opacity relative to the lignite coal itself and that these changes slightly improve fireside performance.

Figure 4. PCQUEST calculation results for various lignite and tree wood blends.

Figure 5. PCQUEST calculation results for various lignite and wood chip blends.

Equilibrium Thermodynamic and Viscosity Calculations

The FACT is a set of programs developed to calculate the thermodynamic equilibrium of complex many-component equilibria. Once the initial system composition and pressure is set, FACT determines equilibrium concentrations of solid, liquid, and gas species over a specified temperature range. A more detailed description of the FACT calculations is given in Appendix C.

The sample analyses used in the FACT calculations consisted of the bulk ash chemistry analyses and estimated ultimate analyses. FACT calculations were performed at 25EC intervals from 500E–1500EC (932E–2732EF) to determine the percentage of liquid phases present as a function of temperature and to provide input for viscosity calculations. Viscosities for the liquid-phase material as a function of temperature were then calculated using a modified form of the Urbain equation in a spreadsheet for each sample. A summary of the results of the FACT calculations are given in Figure 6. Because of the computational time required by FACT, calculations were performed at 20% weight percent increments for the lignite–tree wood and lignite–wood chips blends. The complete FACT calculation results are given in Appendix C, which contain numerical listings of viscosity, liquid phases, and the percentage of solid sulfates as a function of temperature.

The FACT calculation results appear promising for the behavior of lignite–wood cofiring. The results predict a consistent decrease in liquid-phase ash viscosity as the level of tree wood in the blends increases. This results in a lowering of the T_{250} temperature (temperature at which the ash viscosity is 250 poise) by approximately 150EF. However, the lower ash viscosity is compensated for by a concurrent decrease in the amount of liquid-phase ash predicted to be present. The reduced amount of liquid-phase ash results in a “dry” deposit with very little strength. This effect has been seen previously with blends of a bituminous and a subbituminous coal with wheat straw, alfalfa stems, and hybrid poplar wood (5). In these previous experiments, the blend deposits were significantly weaker than deposits formed from either the coal or biomass. FACT calculations for the wood chips indicate very little decrease in viscosity and a small decrease in the percentage of liquid-phase ash with increasing wood chip blend levels. The slagging and fouling behavior of wood chip blends is thus expected to be similar to that of the lignite coal. Neither the tree wood nor wood chip blends are seen to present particular problems when blended with the lignite.

FACT predictions of solid sulfate phases which is indicative of low-temperature sulfate-based fouling shows that the total percentage of solid sulfates formed remains the same with increasing tree wood blend level, although the sulfates do form at a higher temperature. The percentage of solid sulfates forming for blends of the wood chips does show an increase at high blend levels (80% and 100% wood chips). Blends at lower wood chip levels have percentages of solid sulfates equal to or lower than that of the lignite coal.

The conclusions drawn from the PCQUEST modeling and FACT calculation results were that 1) no significantly increased high-temperature fouling or slagging would occur at any blend level of the lignite coal with the tree wood or the wood chips, and increasing the amount of biomass cofired with lignite generally provides slight improvement in fireside performance; 2) the changes in predicted fouling, slagging, and opacity vary directly with the amount of biomass in the blends, with

Figure 6. Results from FACT modeling.

no “optimum” blend level; and 3) opacity and low-temperature fouling behavior may only be moderately adverse at very high biomass blend levels (80% biomass or greater).

The general linear behavior of the PCQUEST and FACT results with biomass blend level resulted in the selection of a 50% lignite coal–50% biomass blend for the combustion tests to generate high-temperature fouling deposits. This blend level would allow interpolation to lower blend levels suitable for large power generating plants as well as extrapolation to higher blend levels in stoker boilers. A blend level of 25% lignite coal–75% biomass was selected for the grate clinking tests. This level would best represent the stoker boiler operation proposed for the NDSP, where high biomass blend levels produce desirable economics.

Utility-Related Fireside Performance

Samples of Beulah lignite and 50% blends with tree wood and pallet wood were combusted in the EERC’s optical drop tube furnace (ODTF). The samples were analyzed for their propensity to produce convective pass deposits. The chemical nature of these deposits and fly ash was also determined with SEM/energy-dispersive spectrometry techniques and Malvern analysis.

The coal sample was pulverized to 70% ! 200 mesh. Both wood samples were reduced to a size of 1/8" and then further reduced in a micro-cutter mill. All fuels were characterized with x-ray fluorescence (XRF), CCSEM, and proximate–ultimate analyses prior to combustion.

A schematic diagram of the ODTF is seen in Figure 7 below. The ODTF has provisions for an optical section, which allows visual and video monitoring of deposit formation and in situ deposit

Figure 7. Schematic diagram of the ODTF.

adhesion strength measurements on the probe. The optical access section also allows in situ temperature measurements by optical pyrometry and entrained particle-size determinations by near-forward-angle laser scattering, as well as the capacity to add additional nonintrusive optical diagnostics shown in the schematic in Figure 7. The ODTF is especially designed to assess the fouling and slagging tendencies of coal. A cylindrical deposition probe with a controlled skin temperature can be inserted into a heated deposition zone, and the initial slagging temperature, deposit adhesion strength, and deposit growth rates can be determined. The heated zones in the furnace reactor tube can be customized to reflect temperature regimes in a real utility boiler. The maximum temperature that can be achieved is 1650EC (3002EF).

The fuel analysis of the Beulah lignite was very typical of a North Dakota lignite coal. The as-received heating value was approximately 6700 Btu/lb at 37% moisture. The CCSEM analysis indicated the presence of primarily pyrrhotite (35.4%), an iron sulfide compound, mixed aluminosilicate clays, and quartz. The ash content of the coal was 5.89% at 37% moisture. An XRF analysis on the fuel indicated the same elements as the CCSEM analysis. The major elements reported as oxides are Al_2O_3 (11.3%), SiO_2 (19.8%), Fe_2O_3 (10.7%), CaO (20.3%), SO_3 (23.2%), and Na_2O (7.9%).

The tree wood sample had a heating value of approximately 7800 Btu/lb at 6.8% moisture. The CCSEM and XRF analyses indicated a slightly different association of the potential ash material in the tree wood. The major mineral phase was calcite (27.5%) with mixed levels of aluminosilicates. The aluminosilicate material is likely due to sample contamination from soil. The XRF data show CaO (44.5%) and K_2O (25.8%) as the predominant elements in the ash. The tree wood had an ash content of 1.9% at 6.8% moisture.

Again, the characteristics of the wood chip sample were slightly different than the previously described samples. The heating value was approximately 8200 Btu/lb at 7.3% moisture. The CCSEM analysis indicated iron oxide (27.4%) as the major mineral phase with the same aluminosilicate clays mixed in minor concentrations. The XRF data show CaO (28.4%) as the major oxide. The ash content is 0.6% at 7.3% moisture. All three fuel samples had properties similar to other samples of a similar nature previously examined at the EERC.

Ash Samples

CCSEM analysis was performed on all ash samples generated in the DTF facility. The CCSEM will give the particle-size distribution and chemical composition of the ash produced.

The Beulah lignite fly ash had a high number of unclassified particles (46.4%). This simply means the particles did not meet the criteria for one of the specified bins in the CCSEM analysis. The unclassified particles were calcium-rich with traces of Si, Al, and Fe. The other major phases included quartz (7.6%), iron oxide (10.1%), calcium-rich (8.8%), and mixed aluminosilicates making up the balance of the fly ash. It is interesting to note that the large and small mineral grains present in the fuel combined and fragmented to produce the majority of fly ash particles from 4.6 to 46 μm (Table 9).

Table 9. Results of CCSEM Analysis on Fly Ash from Lignite, Lignite–Pallet Wood, and Lignite–Green Wood Blends, mass %

Phase	Lignite	Lignite–Tree Wood	Lignite–Wood Chips
Quartz	7.6	4.2	8.6
Iron Oxide	10.1	9.5	12.3
Calcite	1.9	6.7	1.7
Dolomite	6.9	11.7	9.5
Ankerite	5.0	4.2	2.9
Na Al-Silicate	4.7	–	1.8
Mixed Al-Silica	–	–	1.7
Ca Aluminate	3.8	3.6	4.2
Si-Rich	1.8	1.4	1.9
Ca-Rich	8.8	9.2	5.6
Unclassified	46.4	44.9	47.9

The fly ash from a 50/50 blend of lignite and tree wood produced ash relatively similar to the pure lignite. Some of the major differences include a higher calcite and calcium-rich content. The most striking difference is in the particle-size distribution of the ash. Figure 8 shows a particle-size distribution of fly ash from all three tests, as determined by CCSEM. Both biomass blends produced larger-sized ash than the pure lignite. The larger ash size will only aid in fly ash collection.

Figure 8. Particle-size distribution for fly ash from lignite, lignite–tree wood, and lignite–wood chips determined by CCSEM.

Fly ash from the 50/50 blend of lignite and wood chips was also similar to that from the pure lignite. The major differences are in the quartz, iron oxide, calcium-rich, and dolomite content. The calcium rich phases are due to the increased amount of calcium in the wood fuel.

Deposit Samples

Deposits were also generated in the EERC's DTF facility. A scanning electron microscopy point count (SEMPC) was performed on each of the deposits. This analysis gives an idea of the mineral transformations taking place during combustion. The results can also be used to "flag" potential problems that the burning of the tested fuel may cause.

The first sample tested was the Beulah lignite. This fuel is currently being fired at the State Penitentiary. The deposit formed was very loosely adhered to the deposit probe and was easily removed. An SEMPC analysis of the deposit indicated that most of the deposit material was calcium-rich. The results of the SEMPC analysis are found in Table 10; only phases making up more than 1% of the deposit are reported in the table.

Table 10. Results of SEMPC Analysis on Deposits from Lignite, Lignite-Pallet Wood, and Lignite-Green Wood Blends, frequency %

Mineral Phase	Lignite	Lignite-Tree Wood	Lignite-Wood Chips
Calcium Oxide	1.0	3.5	4.0
Iron Oxide	1.4	9.3	15.6
Mixed Oxide-Rich	2.1	7.5	8.0
Mixed Sulfur-Rich	3.1	2.2	1.2
Calcite	23.0	4.4	—
Ankerite	4.1	—	—
Mixed Metal-Rich	6.9	—	—
Quartz	1.7	—	—
Albite	—	—	1.2
Anorthite	1.0	—	2.8
Montmorillonite	1.0	—	1.2
Pyroxene	1.4	—	1.2
Calcium Silicate	4.8	2.2	4.4
Spurrite	1.0	2.2	—
Mixed Silicon-Rich	13.7	11.5	12.4
Unknown	26.1	54.4	44.0

Both lignite-wood blends produced deposits similar to the deposit formed by firing 100% lignite. The deposits were again loosely adhered to the deposit probe and easily removed. The chemical composition of the deposits was similar with the exception of an increased amount of unknown phases. The unknown phases consist of mixed calcium aluminosilicates. The deposits had the following strengths: lignite, 19 psi; lignite-wood chips, 20 psi; and lignite-tree wood, 12 psi.

A more detailed SEM analysis of the deposits revealed the material holding the deposit together. Figure 9 below is an SEM photomicrograph of the deposit formed by firing 100% lignite coal, while Table 11 gives its morphology analysis for the identified points. The rest of the morphology data can be found in Appendix C.

Based on the results presented above, the addition of either wood sample tends to increase the overall size of fly ash particles. This result will aid in the collection of fly ash by particulate collection devices. This may be due to the assimilation of fine quartz particles into the deposit matrix, hence shifting the ash distribution.

The results of SEM analysis of the deposits indicate that the material holding the deposits together consists of a calcium aluminosilicate compound. This compound is formed by the

Figure 9. SEM micrograph of a deposit formed from Beulah lignite.

Table 11. Lignite Deposit Morphology Analysis Results

Point	Description	Na	Mg	Al	Si	S	Ca	Fe
1	Matrix	0.4	26.3	5.0	6.6	1.8	43.4	16.2
2	Matrix	3.9	3.6	5.8	32.6	ND ¹	42.5	11.1
3	Matrix	3.2	5.0	7.4	2.4	9.8	50.9	19.5
4	Bright particle	1.4	1.5	1.6	2.1	ND	6.9	86.2
5	Matrix	2.3	ND	4	37	ND	52.8	1.7

¹ Not detected.

incorporation of calcite and dolomite-type fly ash particles reacting with silicate phases. The calcium likely originated in the organic portion of the fuel and is not evident in the CCSEM analysis of the fuel samples but can be recognized in the XRF data.

Some major differences seen between the three samples are as follows. All three fuels produce fly ash with iron oxide as a major phase. The iron oxide can be incorporated into the deposit matrix or can stay in the fly ash fraction. The 100% lignite fuel maintained most of the iron in the fly ash and not in the deposit. The iron being assimilated into the deposit may or may not have a long-term effect on the deposits characteristics. The lignite and lignite–wood chip samples had deposits with similar strengths (20 psi), while the lignite–tree wood sample had a much lower strength (12 psi). It is also interesting to note that the lignite–wood chips deposit grew at a slightly higher rate than the other two, the lignite–tree wood deposit having the lowest sticking potential.

The SEM analysis also indicates the possible potential for the lignite–wood chip deposit to produce slightly “nastier” deposits. The presence of anorthite, pyroxene, and increased calcium silicates lends one to believe a higher degree of sintering has occurred and possibly produced some crystalline phases. These types of deposits tend to have a higher strength and be harder to remove.

It is also important to note that the lignite has a high amount of iron sulfide compounds and all three samples have a high amount of alkali elements organically associated in all of the fuels. This combination is highly favorable to the formation of sulfate phases in portions of the boiler that have lower temperatures.

The two lignite biomass blends tested in this project should not severely decrease fireside performance. Blending with wood chips and tree wood shifts the particle-size distribution of fly ash to larger sizes. This will aid in fly ash collection. Emissions measured during the runs showed on average a 46% reduction in sulfur and a 33% reduction in NO_x. Specific data are provided in Appendix C.

The deposits produced by a lignite–tree wood blend had characteristics that were slightly more favorable than the pure lignite or the lignite–wood chips blend. The favorable blend had a deposit that was less sintered, a lower crushing strength, and less potential to melt and produced crystalline phases and stronger deposits.

Clinkering Potential for Grate-Fired Systems

Combustion testing in the small grate-stoker combustion system focused on evaluating the propensity for low-viscosity slag development, which could induce clinker formation. The lignite and blends of 25% lignite–75% tree wood and 25% lignite–75% pallet wood by weight were fired in the bench-scale stoker system under conditions approximating those in the NDSP boiler. The blend level was selected to be in the range of what would be fired at the NDSP facility.

The lignite, tree wood, and wood chip samples were ground and sieved to provide material suitable for introduction into the auger of the combustor. The lignite was crushed to ! 3/8" + 1/8", and the tree wood and wood chips ground and sieved to ! 3/8" + 1/8".

At the start of each test, a bed of the fuel was placed on the grate and ignited with a propane torch. Once the fuel bed was ignited, the fuel feed rate and combustor draft were adjusted to maintain stable steady-state burning. The individual tests were run for 4 hours for the lignite, 3.5 hours for the 25% lignite–75% tree wood blend, and 4 hours for the 25% lignite–75% wood chip blend. The fuel feed was then terminated, the remaining fuel on the grate allowed to burn out and cool, and the residual ash on the grate inspected for evidence of slagging and clinker formation.

Observations of the ash formed by the lignite coal itself indicated that although numerous ash agglomerates resembling clinkers had formed, these were very friable and crumbled when touched. A few ¼" to ¾" agglomerates were harder and were collected for subsequent examination. Photographs are provided in Appendix C.

Observations during the test of the 25% lignite–75% tree wood blend noted that the difference in fuel density resulted in the lignite being sparsely dispersed in the tree wood fuel and that only very infrequently would two coal particles be in contact on the grate. Effectively, ash from the coal particles only contacted ash from the biomass, without larger agglomerations forming from interactions between coal ash particles. The temperature during the test was somewhat lower, because of the lower heating value of the biomass. The great majority of the ash remaining at the conclusion of the test was very fine, with no agglomerations formed as had occurred during the test with the lignite coal alone. A few small firm agglomerates were found on the grate, although these were much smaller than those from the test of the lignite coal, being only approximately ⅛" in size. Similar results were seen for the 25% lignite–75% wood chips blend.

The clinkers produced during testing were mounted in epoxy and cross-sectioned for examination of their morphology and chemistry using a scanning electron microscope (SEM).

Appendix C-19 shows typical cross sections of the 100% lignite, the 25% lignite–75% tree wood, and the 25% lignite–75% pallet wood, respectively. Indicated in the figures are major chemical constituents for selected areas analyzed. The clinker deposits are quite porous, which is consistent with the observation of the high friability of the clinkers during the combustion tests.

Appendix C-20 compares the predicted ash composition based on the bulk inorganic chemistry of the fuels with the actual average chemical compositions determined during the SEM morphological examination. The clinkers formed from the 100% lignite fuel were significantly enriched in iron, with corresponding depletion of silica, sulfur, magnesium, sodium, and potassium. In contrast, although the 25% lignite–75% tree wood and 25% lignite–75% pallet wood blends are also enriched in iron, there is also a large enrichment of sulfur. Of interest is the increased sulfur retention, although alkali and alkaline-earth species (CaO, MgO, Na₂O, and K₂O), which might be expected to capture sulfur, are depleted in the blend clinkers. The association of the sulfur appears to be primarily with iron either as a sulfate or sulfide, although some areas analyzed indicate the presence of sulfur in association with alkali and alkaline-earth elements.

It would appear that under the combustion conditions used, much of the alkali and alkaline-earth species in the biomass form a fine light ash which is entrained by the air flow through the grate and removed without interacting with the iron and other lignite-derived ash minerals. Even with the

lignite ash, the lighter material seems to be removed, leaving the denser, iron-rich ash on the grate. This iron-rich material also appears to be quite effective at sulfur capture for the lignite–biomass blends. Although the clinkers formed were friable under the combustion conditions used, a sufficiently higher fuel bed temperature could result in more problematic grate clinkers because of the high iron and sulfur content.

The bench-scale stoker test results showed that the lignite coal alone formed larger agglomerates than did either of the two blends tested. The agglomerates of the lignite coal alone were also larger and harder than the ash from the blends, although the lignite coal agglomerates were generally very weak. The tests indicate that the blending of either the tree wood or wood chips with the lignite will not produce increased clinker formation and may even reduce clinker formation at high biomass blend levels. This is consistent with the low ash content of the biomass and the predictions of the PCQUEST and FACT calculations.

TASK 4 – ENVIRONMENTAL ISSUES

Changes in Boiler Emissions and Their Effect on Permitting

Air Emissions

Switching fuel from coal to biomass or a blend of coal and biomass typically has a beneficial impact with regard to stack emissions. Most biomass sources are low in sulfur and result in substantially lower SO₂ emissions for the same fuel input. Wood wastes typically have lower ash content, resulting in lower amounts of uncontrolled particulate emissions; however, the particulates generated from burning biomass are typically finer than coal ash and may or may not lead to lower stack emissions. When burned wet, biomass will also reduce flame temperatures during combustion and can produce lower levels of NO_x.

The NDSP operates its current boilers under North Dakota Department of Health (NDDH) Air Pollution Control Permit to Operate Number F83007. Condition 7.C of the permit sets the stack emission limits for the Zurn spreader stoker at 0.52 lb/MMBtu for particulate matter (PM), an opacity of 20%, and 3.0 lb/MMBtu for sulfur dioxide. The coal-fired boiler currently meets the stack particulate emissions and opacity requirements. The boiler modifications that are recommended to accommodate firing the blend of coal and wood wastes (primarily feed method, grate design, and overfire air control) are expected to reduce the amount of PM that leaves the boiler. Therefore, it is anticipated that particulate emissions and opacity will not change substantially from the current level. Current SO₂ emissions, based upon U.S. Environmental Protection Agency (EPA) AP-42 Emission Factors and the level of sulfur in the coal (0.74%) are estimated to be 1.4 lb/MMBtu. The lower sulfur content in the blend (0.32%) would reduce the estimated SO₂ emissions to 0.6 lb/MMBtu.

Of more importance to this feasibility study is Condition 7.J, which deals with alterations, modifications, or changes. This condition states that “any alteration, rebuilding, repairing, expansion, change in the method of operation, or change of location of the source which results in the emission of an additional type or greater amount of air contaminants or which results in an increase in the

ambient concentration of any air contaminant must be reviewed and approved by the Department prior to the start of such alteration, rebuilding, repairing, expansion, change in method of operation, or change of location.” The boiler modifications proposed are not expected to change the ambient concentration of any pollutant and should reduce ambient SO₂ concentrations. Since only untreated wood will be accepted as fuel, no new air contaminants should be emitted. However, changing the annual hours of operation from the equivalent of 1095 to 8322 will increase the total amount of air contaminants emitted each year. Table 12 presents the current and expected annual uncontrolled emissions from the Zurn boiler currently in operation at the State Penitentiary. Of primary concern are the SO₂ and NO_x emissions. PM is controlled by the existing ESP, so the factors listed here represent an estimate of PM entering the ESP, rather than the total emitted.

A primary factor in determining whether the proposed modifications and change in operation trigger reclassification of the Zurn boiler as a new source are its emissions relative to Title V and Prevention of Significant Deterioration (PSD) limits. Subsection b of Section 3 of Section 33-15-14-02 of the North Dakota Air Pollution Rules lists exceptions to those cases where boiler modifications an/or changes in operating procedures require establishment of a new source. Since the proposed changes will result in increasing the firing rate to the boiler’s rated capacity, the total hours of annual operation will increase significantly. The two appropriate conditions to be considered that exclude classification of a new source for Title V or PSD are:

- If increasing the firing rate does not exceed the operating design capacity of the source and it is not limited by a permit condition, reclassification to Title V or PSD may be avoided.
- If increasing the hours of operation is not limited by a permit condition, reclassification to Title V or PSD may be avoided.

Therefore, provided the changes will not trigger a limitation executed by the existing permit, or by state and federal standards, the unit should not require classification as a new source. As shown in Table 12, the triggers for permit reclassification are 250 tn/yr of a single pollutant based on PSD and 100 tn/yr based on Title V. The annual emissions of SO₂ are expected to increase from the current level of approximately 29 to 94 tn/yr for the base case (75–25 wood–coal blend at a 95% capacity factor). NO_x annual emissions are expected to increase from 7.7 to 53 tn/yr. The base case is below these triggers for all pollutants. The only scenario that may require reclassification of the boiler under Title V is the case where the amount of biomass available is less than the optimal 75–25 wood–coal blend and the unit is fired at 95% capacity. At the 95% capacity factor, Title V restrictions would kick in at a blend ratio of 70–30 wood–coal blend.

Required Air-Related Permit Actions

Air permit actions are minimal for the case where the annual emissions are maintained below the trigger levels for Title V (100 tn/yr per pollutant). As stated above, this is the case for all scenarios using the 75–25 wood–coal blend. If annual pollutant levels do not trigger Title V, the State Penitentiary will be required to inform the NDDH in writing of the proposed changes, including the expected emissions under the new operating scenario. Upon review of this letter, the NDDH will issue a response granting authorization to proceed with the planned modifications. This

Table 12. Emission Estimates for Given Blends from the State Correctional Center

<u>Common Factors</u>						
Design Feed Rate, lb/hr	4,605					
Current Coal Usage, tn/yr	2,600					
Design HHV, Btu/lb	7,440					
Design Heat Input, Btu/hr	34261200					
Design Input, MW (check factor)	10					
Current Availability	12.9%					
HHV New Coal, Btu/lb	6,700					
HHV Wood, Btu/lb	8,274					
Coal S	0.74					
Wood S	0.18					
Coal Ash	5.9					
Wood Ash	1.9					
<u>Emission Factors for Overfed Stoker Based on EPA AP-42</u>						
	lb/ton coal					
PM from Boiler (factor × ash)	8					
PM from ESP (factor × ash)	0.07					
SO ₂ (factor × S)	30					
NO _x	5.8					
<u>Calculated Uncontrolled Emissions – Base Case</u>						
PM from Boiler, tn/yr	61					
PM with ESP, tn/y	1					
SO ₂ , tn/yr	29					
NO _x , tn/yr	8					
<u>Input for New Scenarios*</u>	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>	<u>6</u>
Pct Coal in Blend	0.25	0.25	0.3	0.25	0	1
Pct Biomass in Blend	0.75	0.75	0.7	0.75	1	0
Availability	0.95	0.74	0.95	1	0.95	0.95
Coal Feed, lb/hr	1278	1278	1534	1278	0	5114
Biomass Feed, lb/hr	3106	3106	2899	3106	4141	0
Coal Feed, tn/yr	5319	4144	6383	5599	0	21278
Biomass Feed, tn/yr	12922	10066	12061	13603	17230	0
<u>Calculated Uncontrolled Emissions – New Blend</u>						
PM from Boiler, tn/yr	224	174	242	236	131	502
PM with ESP, tn/y	2	2	2	2	1	4
SO ₂ , tn/yr	94	73	103	99	47	236
NO _x , tn/yr	53	41	53	56	50	62
<u>Triggers for Permit Reclassification</u>						
	<u>PSD</u>		<u>Title V</u>			
PM ₁₀ , tn/yr	250		100			
SO ₂ , tn/yr	250		100			
NO _x , tn/yr	250		100			
Average Sulfur of Blend	0.32	0.32	0.348	0.32		

- * 1 Base case for retrofit.
2 Change availability with constant blend to reduce biomass to 10,000 tn/yr.
3 Change blend with constant availability to reduce biomass to 10,000 tn/yr.
4 Change availability with constant blend to reduce SO₂ to less than 100 tn/yr.
5 Emissions for 100% biomass at 95% availability.
6 Emissions for 100% coal at 95% availability.

authorization would be expected to be granted within 1 to 2 weeks. The NDDH will require stack testing to verify the estimated emission levels once boiler modifications are complete. A final permit modification will be granted based upon the results of these stack tests. All existing conditions of Permit F83007 will be expected to remain in effect.

If the recommendation of this feasibility study and the plans of the State Penitentiary are to operate the boiler at a 95% capacity factor at a blend ratio of 70%–30% wood–coal or lower, then a Title V permit will be required. Procedures for obtaining a Title V Permit to Construct and Permit to Operate are given in Section 33-15-14 of the North Dakota Air Pollution Rules. An application for a permit to construct requires 30 days for review by the state and another 45 days for review by the EPA. A Title V permit requires additional monitoring, recording, and record keeping for NO_x, CO, PM, and SO₂. The NO_x and CO monitoring could be met using a portable analyzer with testing performed every 6 months. This is currently done at the University of North Dakota Steam Plant to partially meet its Title V requirements. SO₂ emissions can be calculated based on an analysis of the sulfur in the fuel. For coal, this is typically done on a per shipment basis. An acceptable method would need to be devised to deal with a potentially wide variety of sources for wood waste. PM is periodically checked using on-site personnel who are trained and certified to estimate the opacity of the gases leaving the stack of the boiler. While the Title V permit requirements will add to the work load of operations/supervisory staff at the State Penitentiary, these requirements should be minimal both in terms of staffing and cost. Therefore, because the economical impact of Title V requirements are minimal, they should not be used as a criteria for selecting the optimal blend ratio or capacity factor.

Solid Waste Considerations

The State Penitentiary is not required to have a solid waste permit under its current mode of operation. Small facilities are typically allowed to dispose of their ash and other residues directly to the landfill. Under the current mode of operation, approximately 150 tn/yr of ash is generated that must be disposed of at the landfill. Under the baseline scenario, this would increase to approximately 550 tn/yr and still would be considered a small amount not requiring a solid waste permit.

The current mode of operation at the State Penitentiary is to stockpile ash for a considerable amount of time prior to hauling the ash to the landfill. Under the new scenario, it is recommended that the ash be hauled to the landfill on a monthly basis.

Water Quality/Storm Water Runoff

Under the proposed modified operations, wood waste will be received with provisions for some outside storage of unprocessed wood. Once the wood is dried and processed (chipped), it is stored inside the feed bins until it is consumed in the boiler. No processed material will be stored with exposure to the elements. Therefore, since no processed fuel will be stored outside, no special permitting is required. Also, ash is planned to be stored on-site in closed vessels, eliminating the need for a leachate water quality permit.

If processed fuel and/or ash is stored exposed to the elements, the type of material to be stored will need to be identified, along with the potential material in the runoff. Based on this information, a pollution prevention plan will need to be prepared. Sampling will be required once or twice per year for biological oxygen demand, chemical oxygen demand, nitrates, and others based upon the material that is being stored. The NDDH will set permit discharge levels.

Transfer Station Permitting

Under some scenarios, a site receiving a waste material must obtain a transfer station permit. Recyclable/reuse material is typically granted an exemption, since this material, if recycled or reused, is not itself a waste. In the case of the proposed project with the State Penitentiary, an exemption from transfer station permitting is expected since the proposed wood is not a true waste. Additionally, many states encourage this type of operation since it significantly reduces the burden on the landfill.

Economic Considerations Relative to Permitting

An important aspect for economic consideration of cogeneration projects is the value of producing excess electricity to put back on the grid versus internal use of all electricity generated. A utility company is required to buy electricity from a Qualifying Facility (QF) as defined under 18 CFR, Part 292. The question becomes whether the profits generated from this sale offset the additional costs associated with the sale.

Typically, utility companies will have rate agreements that are applicable for facilities like the State Penitentiary that would not be dispatchable and would provide energy and capacity on an “as available” basis. For this type of facility, the utility would pay the avoided cost of producing electricity. This avoided cost for utilities in North Dakota is rather low, approximately \$0.013 to \$0.175/kWh. The higher price is typical of peaking power, with the lower representing off-peak pricing. Both rates would be specified in an agreement including a definition of peak and nonpeak hours. In addition, a nominal metering charge would be applied.

To ensure the reliability and safety of the electrical grid, the utility will require a number of provisions to be met prior to entering into an agreement with a QF. The most important in terms of the overall economic viability of a project are the requirements that the QF install metering and switchgear required for synchronous power transmission onto the grid. The cost of this equipment in many cases more than offsets any anticipated profits from power sales.

TASK 5 – ENERGY PRODUCTION ASSESSMENT

Several options were investigated for the coproduction of electricity and heat for the NDSP. The options primarily center on the application of steam turbines and their relationship to the existing thermal and electrical loads. The physical and economic constraints that apply to the production of energy are as follows:

1. Electric power production must remain captive to achieve significant return on investment.
2. Existing thermal loads must be met at current steam conditions (100 psig saturated vapor). Lowering or raising steam pressure is possible, but was not considered because of the uncertainty for adequate alternative pressures to meet flow and equipment requirements.
3. Boiler output is limited to 200 psig saturated vapor and 25,000 lb/hr @ 72% efficiency.

Energy use for the NDSP was obtained from monthly billing records. Average monthly loads were computed and used to determine a baseline for the energy production assessment. Figures 10 and 11 summarize the load profiles for electricity and thermal energy.

Options included considering extraction, condensing, back pressure, and small turbines applied to distributed pressure-reducing stations. The following describes the considerations used to determine the appropriate cogeneration configuration:

1. Extraction turbine consideration – Although a single extraction turbine could provide both back pressure to the system and condense auxiliary steam for electricity production, the cost was prohibitive. Separate condensing and back-pressure turbines can be purchased for 2.5 times less than the cost of a single extraction turbine. Therefore, one condensing turbine and one back-pressure turbine were chosen to provide power. Both turbines can be operated in either mode, which provides good redundancy for the power plant and increases availability.
2. It was discovered that 100 psig steam is produced and distributed to pressure-reducing stations throughout the facility. The pressure is reduced to 15 psig before being used. Small pressure-reducing turbines were investigated to apply to this otherwise lost energy.

Performance data were obtained from Dresser Rand Corporation for the turbines. Quotations are included in the equipment specifications in Appendix B for the steam turbines. Performance data for the turbines are as follows. The condensing turbine follows a performance curve provided in Figure 12. Since the back-pressure turbine contributes only a small portion of the total electricity, the performance was calculated using a straight isentropic efficiency of 35%. The performance of the small pressure reduction turbines is 45 lb/hr-kW.

The configuration of the system was modeled and is provided in Figure 13. The system is designed to provide consistent steam production year-round at 25,000 lb/hr, 200 psig saturated steam. A single 200 psig header supplies both the back pressure and condensing turbine. A back pressure of 100 psig is maintained for the system, and the condensing turbine exhausts at 20 psig. The pressure-reducing turbines were not modeled; however, calculations were performed separately and added later. The model was used to calculate average monthly performance of the system based on various thermal load requirements. The results of the calculations are provided in Tables 13 and 14, and detailed mass and energy balances are included in Appendix D.

Figure 10. Electricity load profile.

Figure 11. Energy consumption profile.

Figure 12. Condensing turbine performance.

Figure 13. Energy production model, process flow diagram.

Table 13. Monthly Electrical Generation

Electrical Generation, kWh			Parasitic Loss	15%
Month	CT	CT + BPT	CT+BPT+PRTs	Net Power
Jan	321846	353840	399922	339934
Feb	386359	411608	447977	380780
Mar	378869	405487	443826	377252
Apr	481163	493488	511240	434554
May	570011	571628	571966	486171
Jun	521669	529174	530741	451130
Jul	547425	552775	553892	470808
Aug	553129	557537	558457	474689
Sep	551947	556550	557511	473884
Oct	438053	457860	486391	413433
Nov	314406	347876	396085	336672
Dec	315932	349100	396875	337344
			5854883	4976651

Table 14. Monthly Average Peak Thermal Load Case

System Performance for November Average Month Heat Load (based on billing)	
Firing Rate	37,775 kBtu/hr
Condensing Turbine Output	431 kW
Back-Pressure Turbine Output	46 kW
Total Power Output	477 kW
Pumping Requirement	5.5 kW
Other Parasitic Loads 5%	24 kW
Net Power Out	447 kW
Heat Load	9,184 kBtu/hr
System Energy Efficiency	28%

An analysis was performed to determine the cost-effectiveness of the back-pressure turbine since its output is marginal as shown in Figure 14. A relative simple payback analysis was used to compare costs, as shown in Table 15.

New and used turbines can be procured for the project, and their costs were taken into consideration. The condensing turbine, whether purchased new or used, appears to have an attractive payback. The back-pressure turbine payback is higher by a factor of 4 to 10 years. As a percentage of project investment, the cost of acquiring a back-pressure turbine and the effect on overall project payback were considered. If we are targeting a 7-year payback period, it appears that the purchase of a used back-pressure turbine will only slightly impact the total project economics. Therefore, the benefits of turbine redundancy and flexibility are worth the marginal economics of purchasing a used back-pressure turbine.

Figure 14. Contribution of back-pressure turbine to load.

Table 15. Relative Payback Analysis for the Back-Pressure Turbine

Simple Payback Analysis		Simple Payback as % of Project Investment	
Condensing Turbine		Total Project Cost	\$1,800,000
Cost New	\$200,000	CT New	11%
Cost Used	\$50,000	CT Used	3%
Payback New	1.3 years	BPT New	6%
Payback Used	0.19 years	BPT Used	3%
Back-Pressure Turbine		Effect of Purchase on Payback	
Cost New	\$110,000	Total Project Payback Period, 10 years	
Cost Used	\$50,000	CT New	11.6 months
Payback New	11 years	BPT New	! 0.65 months
Payback Used	5.0 years	Used BPT	1.68 months
		Total Project Payback Period, 7 years	
		CT New	7.6 months
		BPT New	! 2.85 months
		Used BPT	0.68 months

TASK 6 – ENGINEERING ECONOMIC ANALYSIS

An engineering economic analysis was performed to assess the viability of the proposed project, determine the factors that are most critical to the success of the project, and determine alternative cases that may improve the likelihood of economic success. Presented here are the results of the economics, a discussion of the calculations and assumptions, and potential alternative economic scenarios.

The base case economic scenario was conceived from the following calculations and assumptions described in Figure 15. The peak load (1) is 784 kW, and this is calculated from the highest average monthly electrical production primarily based on the potential output from the condensing turbine in the summer months. Gross electrical and net electrical production was calculated from the average monthly projected power outputs from Task 5. A load factor of 1, availability of 90%, and a parasitic loss of 15% were applied. It is reasonable to assume that availability could be 90%, leaving a 1-month downtime because two steam turbines will be installed. Both turbines will have the capability of operating in either condensing or back-pressure mode, and while one is down, the other could be operated a full output. Steam output was assumed at 25,000 lb/hr, which is the continuous rating of the NDSP boiler. It was assumed that 75% biomass will be fired with 25% coal. This ratio tends to be the most economically viable and within reason based on the resource assessment. The best scenario is to fire 100% biomass; however, resources may not be available to support this level of biomass firing, and the flexibility of some regular coal supply is necessary to ensure that in an emergency enough coal will be available for heating purposes.

Cash flow calculations for the base case are presented in Figure 16 and discussed. The costs are shown as current facility costs, cost reductions with cogeneration, and cost additions due to cogeneration, and debt service. The electricity cost includes demand and service charges. Natural gas and electricity are escalated at 3% per year, primarily because the state of North Dakota allows a 3% increase on utility budgets at state agencies and previous studies presented to the state for energy efficiency projects have used the same assumptions. Coal is escalated at 1.5%, based on the same criteria and inflation at 2.7% (6). An alternative case is presented later where escalations are in line with energy information administration predictions of close to 0% (7). All current costs were provided by the NDSP. Cost reductions are primarily achieved by offsetting electricity costs and natural gas. Cost additions occur because of increased personnel requirements, specified by the NDSP, and operation and maintenance specified by the equipment manufacturers. Also, increased chemical usage and ash disposal are expected. The debt service is based on 5.05% bond financing, which is currently available. The results show a negative savings in the first few years; however, advanced payments from increased savings in the later years can be used to pay off debt early.

The results of the base case economic analysis show how a \$1,680,000 investment financed with a 20-year municipal bond at 5.05% can be paid back in 15 years based on the energy savings and the above assumptions. Figure 17 shows the advanced payment schedule of the 20-year bond.

A sensitivity analysis shown in Figure 18 was performed to identify the parameters that have the most significant effect on the economics. It can be seen that the availability of the plant is the

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PLANT GENERATION:**Turbine Generator Performance**

Peak Load (1)*	784 kW
Condensing Turbine Heat Rate (4)	38 lb/hr-kW
Back Pressure Turbine Heat Rate	190 lb/hr-kW
Pressure Reducing Turbines Heat Rate	45 lb/hr-kW
Gross Annual Electricity (100% availability) (2, 3, 5)	5,854,883 kWh
Load Factor	1
Load	784 kW
Availability	90%
Parasitic Losses	15%
Net Annual Electricity	4,478,985 kWh

Boiler Performance

Steam Supply, consistent output	25,000 lb/hr
Steam Heat Rate	26,750,000 Btu/hr
Boiler Efficiency	72%Btu/lb
Firing Rate	37,152,778 Btu/hr

Fuel Requirements

	<u>Moisture Content</u>	<u>Ratio</u>	
HHV Coal	36.8%	25%	6,700 Btu/lb
HHV Biomass	7.3%	75%	8,274 Btu/lb
Fuel Flow Dry Coal		29%	1,386 lb/hr
Fuel Flow Dry Biomass		71%	3,368 lb/hr
Tonnage Required, coal	36.8%	25%	5,465 tons/yr
Tonnage Required, biomass	25.0%	75%	16,409 tons/yr
Truckloads Wood Per Year @	20 tons/load		820 truckloads
Truckloads Wood Per Day @	240 days/yr		3 truckloads/day

* NOTES

1. The peak load is determined from the highest estimated monthly electrical generation.
  2. Electricity production was determined from turbine specifications and load profiles.
  3. Generated using modeling results based on monthly fuel billing records.
  4. The condensing turbine heat rate was varied with output. BPT and PRTs remained constant.
  5. Calculations on a monthly basis are provided in Appendix D.
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Figure 15. Base case scenario calculations.

most significant factor and plays an important role once the project is up and running. Next in order of significance is coal price, followed by blend ratio of biomass and electricity price. Although all factors have some effect on economics, it can be concluded that equipment maintenance and volatile gas prices will have little impact. A final conclusion drawn from the sensitivity analysis is that in no case can adjustment of a single factor result in paybacks of 5 years or less. Return on investment will most likely be limited to 15% even in the most attractive set of scenarios.

Some alternative economic cases were calculated to determine relative return on investment or payback. A best case scenario was developed by adjusting the most significant factors from the sensitivity analysis. Availability was adjusted to 92%, cofiring rate to 90%, capital investment at \$1,550,000, and the cost of coal at \$22.00 per ton. The results show the investment could be paid

Figure 16. Cash Flow Analysis.																						
CURRENT COSTS:	YEAR		2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
	YEAR		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Natural Gas (1)																						
Interruptible gas consumption	\$	5.18 per DKT	\$60,751	\$62,574	\$64,451	\$66,384	\$68,376	\$70,427	\$72,540	\$74,716	\$76,958	\$79,266	\$81,644	\$84,094	\$86,616	\$89,215	\$91,891	\$94,648	\$97,488	\$100,412	\$103,425	\$106,527
Firm gas consumption	\$	11,728 DKT	\$42,390	\$43,662	\$44,972	\$46,321	\$47,710	\$49,142	\$50,616	\$52,134	\$53,698	\$55,309	\$56,969	\$58,678	\$60,438	\$62,251	\$64,119	\$66,042	\$68,023	\$70,064	\$72,166	\$74,331
Subtotal gas		6,243 DKT	\$103,141	\$106,235	\$109,422	\$112,705	\$116,086	\$119,569	\$123,156	\$126,850	\$130,656	\$134,576	\$138,613	\$142,771	\$147,054	\$151,466	\$156,010	\$160,690	\$165,511	\$170,476	\$175,591	\$180,858
Coal																						
Present consumption	\$	19.42 per ton	\$57,056	\$57,912	\$58,780	\$59,662	\$60,557	\$61,465	\$62,387	\$63,323	\$64,273	\$65,237	\$66,216	\$67,209	\$68,217	\$69,240	\$70,279	\$71,333	\$72,403	\$73,489	\$74,592	\$75,710
		2,938 tons																				
		39,369 MMBtu																				
Electricity (2)																						
Purchase price from utility	\$	0.0500 per kWh	\$268,290	\$276,339	\$284,629	\$293,168	\$301,963	\$311,022	\$320,352	\$329,963	\$339,862	\$350,058	\$360,559	\$371,376	\$382,517	\$393,993	\$405,813	\$417,987	\$430,527	\$443,442	\$456,746	\$470,448
Present consumption		5,365,800 kWh	\$428,487	\$440,486	\$452,832	\$465,535	\$478,606	\$492,056	\$505,896	\$520,137	\$534,791	\$549,870	\$565,388	\$581,356	\$597,789	\$614,699	\$632,102	\$650,011	\$668,441	\$687,408	\$706,928	\$727,017
Subtotal energy																						
Operation and Maintenance Costs																						
Maintenance (3)																						
Labor current staff (4)		4 people	\$124,800	\$128,170	\$131,630	\$135,184	\$138,834	\$142,583	\$146,432	\$150,386	\$154,447	\$158,617	\$162,899	\$167,298	\$171,815	\$176,454	\$181,218	\$186,111	\$191,136	\$196,296	\$201,596	\$207,039
Ash disposal, \$32/ton		165	\$5,280	\$5,423	\$5,569	\$5,719	\$5,874	\$6,032	\$6,195	\$6,362	\$6,534	\$6,711	\$6,892	\$7,078	\$7,269	\$7,465	\$7,667	\$7,874	\$8,087	\$8,305	\$8,529	\$8,759
Repairs, ash gates			\$9,000	\$9,243	\$9,493	\$9,749	\$10,012	\$10,282	\$10,560	\$10,845	\$11,138	\$11,439	\$11,748	\$12,065	\$12,390	\$12,725	\$13,069	\$13,421	\$13,784	\$14,156	\$14,538	\$14,931
Repairs, misc.			\$325	\$334	\$343	\$352	\$362	\$371	\$381	\$392	\$402	\$413	\$424	\$436	\$447	\$460	\$472	\$485	\$498	\$511	\$525	\$539
		Fuel Consumption																				
Chemicals, \$0.10/MMBtu		55,323 MMBtu	\$5,800	\$5,957	\$6,117	\$6,283	\$6,452	\$6,626	\$6,805	\$6,989	\$7,178	\$7,372	\$7,571	\$7,775	\$7,985	\$8,201	\$8,422	\$8,649	\$8,883	\$9,123	\$9,369	\$9,622
Subtotal O&M			\$145,205	\$149,126	\$153,152	\$157,287	\$161,534	\$165,895	\$170,374	\$174,974	\$179,699	\$184,551	\$189,534	\$194,651	\$199,906	\$205,304	\$210,847	\$216,540	\$222,387	\$228,391	\$234,558	\$240,891
A Subtotal current costs			\$573,692	\$589,611	\$605,984	\$622,822	\$640,140	\$657,951	\$676,270	\$695,111	\$714,490	\$734,421	\$754,921	\$776,007	\$797,695	\$820,003	\$842,949	\$866,551	\$890,828	\$915,799	\$941,486	\$967,908
COST REDUCTIONS																						
Interruptible gas consumption	\$	5.18 per DKT	\$60,751	\$62,574	\$64,451	\$66,384	\$68,376	\$70,427	\$72,540	\$74,716	\$76,958	\$79,266	\$81,644	\$84,094	\$86,616	\$89,215	\$91,891	\$94,648	\$97,488	\$100,412	\$103,425	\$106,527
		11,728 DKT																				
Electrical Generation (5)																						
Cogen. system generation		4,478,985 kWh	\$223,949	\$230,668	\$237,588	\$244,715	\$252,057	\$259,619	\$267,407	\$275,429	\$283,692	\$292,203	\$300,969	\$309,998	\$319,298	\$328,877	\$338,743	\$348,906	\$359,373	\$370,154	\$381,259	\$392,696
Net supplied power		886,815 kWh																				
% of present consumption		83%																				
Power sold to the utility		0 kWh																				
B Subtotal			\$284,700	\$293,241	\$302,039	\$311,100	\$320,433	\$330,046	\$339,947	\$350,145	\$360,650	\$371,469	\$382,613	\$394,092	\$405,915	\$418,092	\$430,635	\$443,554	\$456,860	\$470,566	\$484,683	\$499,224
COST ADDITIONS																						
Additional labor (4)		2.5 people	\$78,000	\$80,106	\$82,269	\$84,490	\$86,771	\$89,114	\$91,520	\$93,991	\$96,529	\$99,135	\$101,812	\$104,561	\$107,384	\$110,283	\$113,261	\$116,319	\$119,460	\$122,685	\$125,998	\$129,400
Coal Purchase (delivered) (6)	\$	19.42 per ton	\$49,070	\$49,806	\$50,553	\$51,312	\$52,081	\$52,863	\$53,655	\$54,460	\$55,277	\$56,106	\$56,948	\$57,802	\$58,669	\$59,549	\$60,442	\$61,349	\$62,269	\$63,203	\$64,151	\$65,114
Future consumption total		5,465 tons																				
Additional		2,527 tons																				
Ash disposal \$32/ton		306 tons	\$9,779	\$10,043	\$10,314	\$10,592	\$10,878	\$11,172	\$11,474	\$11,784	\$12,102	\$12,428	\$12,764	\$13,109	\$13,463	\$13,826	\$14,199	\$14,583	\$14,977	\$15,381	\$15,796	\$16,223
		Additional Fuel Consumption																				
Chemicals, \$0.10/MMBtu additional		33,859 MMBtu	\$3,386	\$3,477	\$3,571	\$3,668	\$3,767	\$3,868	\$3,973	\$4,080	\$4,190	\$4,303	\$4,420	\$4,539	\$4,661	\$4,787	\$4,917	\$5,049	\$5,186	\$5,326	\$5,469	\$5,617
Feed System Maintenance (7)		\$1.00 per ton	\$16,409	\$16,852	\$17,307	\$17,774	\$18,254	\$18,747	\$19,253	\$19,773	\$20,307	\$20,855	\$21,418	\$21,996	\$22,590	\$23,200	\$23,826	\$24,470	\$25,130	\$25,809	\$26,506	\$27,221
C Subtotal			\$156,643	\$160,284	\$164,014	\$167,836	\$171,752	\$175,764	\$179,875	\$184,088	\$188,405	\$192,828	\$197,361	\$202,007	\$206,767	\$211,646	\$216,646	\$221,770	\$227,022	\$232,404	\$237,920	\$243,575
D Savings before financing			\$128,057	\$132,957	\$138,025	\$143,264	\$148,681	\$154,282	\$160,072	\$166,058	\$172,245	\$178,641	\$185,252	\$192,085	\$199,147	\$206,446	\$213,989	\$221,784	\$229,839	\$238,162	\$246,763	\$255,649
DEBT SERVICE (8):																						
Project Cost		\$1,680,000																				
Downpayment		0%																				
Amount Financed		\$1,680,000																				
Rate		5.05%																				
Term		20 years																				
E Annual Payment		(\$135,380)	\$135,380	\$135,380	\$135,380	\$135,380	\$135,380	\$135,380	\$135,380	\$135,380	\$135,380	\$135,380	\$135,380	\$135,380	\$135,380	\$135,380	\$135,380	\$23	\$0	\$0	\$0	\$0
Boilerhouse Operational Costs (9)	A-B+C+E		\$581,015	\$592,034	\$603,339	\$614,938	\$626,838	\$639,049	\$651,578	\$664,433	\$677,624	\$691,160	\$705,049	\$719,302	\$733,928	\$748,937	\$764,340	\$644,790	\$660,989	\$677,637	\$694,723	\$712,258
Savings		(\$1,680,000)	(\$7,323)	(\$2,422)	\$2,645	\$7,884	\$13,302	\$18,902	\$24,692	\$30,678	\$36,865	\$43,261	\$49,872	\$56,705	\$63,768	\$71,066	\$78,609	\$221,761	\$229,839	\$238,162	\$246,763	\$255,649

- NOTES: ( )
- Fuel costs based on actual usage for facility.
  - Electricity rate includes monthly demand charge. Increases at 3% per year.
  - Maintenance includes labor and materials, increasing at 2.7% per year. O&M costs were provided by the NDSP.
  - Labor cost increase is 2.7% per year.
  - Electricity charge includes monthly standby charge.
  - Fuel cost incese is 3% per year.
  - Maintenance is based on costs provided by CBI. 2.7% escalation is provided.
  - Debt Service is for capital costs.
  - Net Cash Flow = Total fuel Cost Savings - O&M Costs - Finance Costs.

Payment Schedule Using Advanced Payments from Energy Savings								
Key Figures			Inputs		Calculated Numbers			
Annual Loan Payment	\$135,380	Loan Principal Amount	\$1,680,000	Effective Annual Interest	5.05			
Payment per Year	\$135,380	Annual Interest Rate, %	5.05	Effective Period Interest	5.05			
Payment Amount	\$135,380	Loan Period	20	$(1+I)^N$		2.67868185		
Interest in First Year		# of Pay Periods/yr	1	A/P Factor		0.08058313		
Total Interest		Compounding Freq.	1					
Total Payments	20	Starting Year of Loan				135379.654		
Total Amount Paid (I+P+F)		Starting Month of Loan						
Payment Number	Begin Balance	Payments	Principal	Interest	Cumulative Principal	Cumulative Interest	Ending Balance	
1	\$1,680,000	\$128,057	\$43,217	\$84,840	\$43,217	\$84,840	\$1,636,783	
2	\$1,636,783	\$132,957	\$50,300	\$82,658	\$93,517	\$167,498	\$1,586,483	
3	\$1,586,483	\$138,025	\$57,907	\$80,117	\$151,424	\$247,615	\$1,528,576	
4	\$1,528,576	\$143,264	\$66,071	\$77,193	\$217,495	\$324,808	\$1,462,505	
5	\$1,462,505	\$148,681	\$74,825	\$73,857	\$292,319	\$398,665	\$1,387,681	
6	\$1,387,681	\$154,282	\$84,204	\$70,078	\$376,523	\$468,742	\$1,303,477	
7	\$1,303,477	\$160,072	\$94,246	\$65,826	\$470,770	\$534,568	\$1,209,230	
8	\$1,209,230	\$166,058	\$104,991	\$61,066	\$575,761	\$595,634	\$1,104,239	
9	\$1,104,239	\$172,245	\$116,481	\$55,764	\$692,242	\$651,398	\$987,758	
10	\$987,758	\$178,641	\$128,759	\$49,882	\$821,001	\$701,280	\$858,999	
11	\$858,999	\$185,252	\$141,873	\$43,379	\$962,874	\$744,659	\$717,126	
12	\$717,126	\$192,085	\$155,870	\$36,215	\$1,118,744	\$780,874	\$561,256	
13	\$561,256	\$199,147	\$170,804	\$28,343	\$1,289,548	\$809,218	\$390,452	
14	\$390,452	\$206,446	\$186,728	\$19,718	\$1,476,276	\$828,936	\$203,724	
15	\$203,724	\$213,989	\$203,701	\$10,288	\$1,679,977	\$839,224	\$23	
16	\$23	\$24	\$23	\$1	\$1,680,000	\$839,225	\$0	

Figure 17. Loan payments from energy savings.

back in 9 years. A second case was run to determine how much the capital investment would have to be reduced in order to have an attractive return if 0% escalation was assumed for all energy-related costs. In this case, all assumptions are the same as the base case except for escalation and capital investment. It is assumed that the dryer and hydrograte could be eliminated from the fuel-handling system. The total capital is then reduced to \$1,069,834. The resulting payback period from the energy savings is 15 years and provides a positive scenario given a more realistic energy escalation assumption (0% vs. 3%).

RESULTS AND DISCUSSION

The results of this feasibility study were presented to the NDSP and the DCS. The NDSP is very pleased with the results of the study and wants to pursue implementation. Moving forward with this project will benefit the NDSP from several aspects:

Sensitivity Analysis				Annualized Savings		Advanced Payback on Debt (years)		Sensitivity
				Base	\$82,877	Base	15	
Variable	Base	High	Low	High	Low	High	Low	% effect/ % change
Coal Price	\$19.42	\$20.00	\$15.00	\$65,811	\$96,395	16	14	6.89
Gas Price	\$5.18	\$8.00	\$3.50	\$119,588	\$61,006	13	16	0.81
Electricity Price	\$0.05	\$0.07	\$0.04	\$205,627	\$21,502	10	19	3.7
Availability @ 75–25 cofire	92%	95%	70%	\$148,000	\$44,670	14	17	24.1
Wood Tonnage	16773	17320	12762					
% Wood Cofired @ 92% availability	75%	100%	65%	\$200,892	\$35,671	10	18	4.27
Wood Tonnage	16773	22364	14537					
Feed System O&M, \$/ton	\$1.00	\$3.00	\$0.50	\$39,246	\$93,785	18	14	0.26
Capital Investment	\$1,680,000	\$1,800,000	\$1,400,000	\$74,586	\$102,223	15	13	1.4
Additional Labor, no. of people	3	4	0	\$22,008	\$184,325	19	10	1.22

Figure 18. Sensitivity analysis.

1. Energy cost savings can be achieved and used to pay back a typical municipal bond, while obtaining upgrades to NDSP's energy system.
2. Skilled new hires will have employment, and work will be available for prisoner personnel.
3. The long-term energy costs for the NDSP will decrease.
4. The public image of the Department of Corrections will improve by enabling its agency to apply public funds to an environmentally and economically beneficial project that affects the general public directly and is not limited to inmates.

The specific results from the various tasks are summarized below.

Task 1 – Local Biomass Resource Assessment

1. Municipal wood residue is the most viable biomass resource in terms of quantity, cost, quality, reliability, and availability. It was determined that 30,000 tons/yr could be obtained within 100 mile radius of Bismarck, which is twice the amount required for the project. Also, at least half of the required wood resource (8,000 tons/yr) was confirmed to be available from local haulers in the Bismarck and Mandan area. Delivered cost is expected to be \$0.00 per ton, since haulers must currently pay \$10.00 per ton to dispose of wood residues at the local landfill.

Task 2 – Fuel-Handling Issues

2. Wood residues will require adequate bulk storage, handling, sizing, segregation, and potential drying. All of these issues have been addressed with a robust mechanical fuel receiving and feed system design optimized to reduce cost.

Task 3 – Fireside Issues

3. Fuel characterization supports the notion that wood residue may be favored over lignite coal because of its lower moisture, lower sulfur, and lower ash content. However, ash constituents that contribute to tube fouling problems exist in higher concentrations than in coal ash, namely, calcium, potassium, and phosphorus.
4. Modeling of the fouling, slagging, and opacity potentials for lignite coal and wood blends resulted in a low index value, indicating favorable performance. In general, the greater the percentage of biomass fired with lignite, the better the results. No optimum blend ratio was determined, although blend ratios of greater than 85% could be problematic from an opacity standpoint.
5. DTF tests were completed to provide data with respect to utilities on the cofiring of wood and lignite coal. Tests run at a 50% blend ratio indicated that no decrease in fireside performance will result from cofiring wood residue. Samples collected from tree service companies show better results than wood collected from hardwood sawdust. Tree wood samples produced less sintered deposits with half the crushing strength of lignite coal deposits. Also, the particle size of the fly ash from the biomass blends tended to be larger, which would result in better capture efficiency. The average reduction in SO_x and NO_x emissions was 46% and 33%, respectively.
6. Cofiring tests were conducted in a bench-scale grate-fired furnace to obtain information regarding clinker formation relative to stoker-fired systems. A blend of 75% wood fired with lignite coal was compared to baseline lignite. At this time, results are not available from the advanced analysis; however, we visually observed that clinker formation decreased with the addition of wood fuel.

Task 4 – Environmental Issues

7. An environmental emission study determined that the firing of biomass at the NDSP will not adversely affect the economics from an air quality permitting standpoint. Also, no other permitting issues will limit application of the technology, such as transfer station permitting, solid waste considerations, and water quality issues.

Task 5 – Energy Production Assessment

8. The energy production assessment revealed that offsetting electrical costs will be the most beneficial economic aspect of the project. The best method to achieve this goal is to apply used condensing and back-pressure steam turbines. This will allow for some redundancy since both turbines can be operated in either mode and will optimize electrical production output.

Task 6 – Engineering Economic Analysis

9. The economics show a 15- to 20-year return on investment for the NDSP facility depending on various factors. An investment of \$1,680,000 would be required for the complete project. Depending on the final decision of NDSP on proper escalation factors, this investment may have

to be reduced to \$1,250,000 and would eliminate a nonessential fuel dryer or result in the purchase of used versus new fuel-handling equipment. The 20-year return on investment is acceptable to the Department of Corrections, which is a publicly funded agency that values the benefit to the community that results from utilizing a resource that would otherwise be buried in the landfill.

CONCLUSION

This study presents a clear case that cofiring biomass with lignite coal can be beneficial to both small stoker-fired institutions and utility-scale installations. The primary hurdle for utility-scale systems is more of an economic and resource-based issue. It can be difficult to locate sufficient quantities of biomass at costs that economically benefit large utilities. This is not the case with small stoker-fired institutions, as in this study we identified a resource available at \$0.00/ton and in sufficient quantity to supply 100% of the capacity. The results from this study indicate that cofiring wood residues will produce favorable fireside performance in boilers and the greater the amount cofired, the better the results. Care must be taken in the mechanical feed system design to address the sizing and handling issues relative to specific biomass fuels. The NDSP, through the results of this study, has the potential to move forward with a cofiring application that can achieve the following for the local community and the facility:

- Reduced sulfur and NO_x emissions and zero net gain of carbon dioxide.
- Reduction of landfill burden and associated taxpayer costs.
- Alleviation of tipping fees for disposal from local businesses.
- Additional jobs at NDSP and potentially other businesses benefiting from lower disposal costs.
- Reduction in energy costs, which will benefit taxpayers in the long term.
- Increased energy reliability and security.
- No significant change to the NDSP air quality permit.
- 15- to 20-year return on investment.

Support of feasibility studies for cofiring biomass on behalf of DOE should be continued. In many cases, the infrastructure and market conditions are available to take advantage of cofiring biomass; however, various factors inhibit the progress for biomass utilization. DOE's support helps to overcome barriers resulting in viable projects that would not move forward otherwise. This project is a case in point, and the following barriers addressed by this study are outlined as follows:

1. District energy systems, approximately 5800 of them throughout the United States, provide an appropriately sized infrastructure for utilizing biomass. The primary concern for facility managers is usually a consistent supply of energy. Cost is secondary. State-funded institutions provide very limited incentives to lower energy costs through investigation of alternative fuels or fuel diversification. This forces facility managers to focus budget justification efforts on maintenance upgrades as opposed to exploring nontraditional solutions to lower costs. DOE-funded studies can help facility managers see specific cases that could reduce costs by cofiring biomass.
2. Biomass is site-specific, case-specific, and nontraditional. These attributes create greater difficulty evaluating biomass relative to fossil fuels. Typical energy-related engineering firms realize the technical and market difficulties of biomass and tend to focus on more reliable, profitable fossil energy solutions. The result is a low availability of off-the-shelf equipment and knowledge of how to take advantage of biomass fuels. Compared to fossil energy, significant work must be done to verify biomass resource availability prior to implementation, since biomass may come from a variety of sources. DOE-funded studies help to alleviate the effort of resource evaluation by employing knowledgeable research facilities. Resulting case studies help to demonstrate how to seek available resources and provide detailed information on equipment that is unique for biomass applications.
3. Potential biomass fuel suppliers are not significant drivers of the market and do not have the benefit of the infrastructure of fossil fuels. Natural gas and coal are brokered commodities made available from the supplier and marketed to a target audience. The industries have been well developed over time and operate at peak efficiencies to provide competitive costs. Biomass, a relatively immature industry, lacks procurement efficiency. Many potential fuel suppliers pay to dispose of material or have found some low-value-added markets for residues. Small businesses that generate wood residues do not have the resources to collaborate and convince energy users to utilize their waste. DOE's support of this study helped to link the generators of waste material to an energy consumer.

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APPENDIX A

BIOMASS RESOURCES

BIOMASS RESOURCES

A-1. Grain Elevators/Contacts

Ag Processors

<u>Source</u>	<u>Contact</u>	<u>Phone #</u>	<u>Price per ton</u>	<u>Quantity (tons/yr)</u>	<u>Quality</u>	<u>Reliability</u>	<u>Availability</u>
Mandan Farmers Elevator	Jerry Janz	(701) 663-3710	\$30		Mostly wheat screenings, very seldom barley or oats except in spring	Most during harvest, least in December and January	Currently more than 50% ground for cattle feed, remainder mostly for hogs
Farmers Union	Duane Rudland	(701) 734-6780	\$25		Mix of wheat, barley, oats	Most during harvest	Sold to local cattle farmers
South Central	Bill Schauer	(701) 387-4506	\$20		Screenings	Most during harvest	Sold for feed
Falkirk Farmers Elevator	Jeremy Rademacher, Assistant Manager	(701) 462-8572	\$10–\$20	520	Wheat screenings	Most during harvest, least right before harvest	Sold to local cattle farmers
Raleigh Grain Company	Mike Himmelspach	(701) 597-3571	\$25	200	70% wheat screenings, remainder barley	Most during harvest, least in January	70% sold for cattle, remainder mostly for sheep
Steele Farmers	Clayton Martin	(701) 475-2334	\$15		Wheat screenings, pigeon grass	Most during feed cleaning, least in January, February	Sold for calves, mixed with corn and oats; some to turkeys in Larimore
Ada Supply		(701) 475-2128			Removal service; they don't actually handle screenings		
Tuttle Farmers	Ed Bickle	(701) 867-2559	\$20		Wheat screenings	Varies	Cow and calf feed
Dakota Grain	Jim Meyer	(701) 584-2660	\$35	400	Wheat screenings	Varies	Sold for cattle feed
Benson-Quinn	Dean Ash, Laborer	(701) 442-3204	N/A	100 tons off ground; 700–800 tons sold	13% picked up off ground, remainder wheat screenings	Varies	N/A
Coop Elevator	Brian Larson	(701) 363-2529	\$25	400	80% wheat, 10% durham, 10% other	Most in harvest, least in winter months	Mostly sold to local cattle farmers, some to nearby turkey farmers

Farmers Elevator	Jeff	(701) 748-2355	\$25	700	Mostly wheat screenings, some durham	Varies	N/A
Equity Elevator	Jeremy, Assistant Manager	(701) 448-2461	\$20	300	N/A	N/A	N/A
Hepper Grain, Inc.		(701) 422-3351			Phone number not in service		
Tappen Grain	Melissa Johnson	(701) 327-4254	\$20–\$25	30	Mostly wheat and flax, some oats	Most in harvest, least in late winter, when it's all been sold	Sold to local livestock farmers
Goodrich Farmers Co-Op Association	Mike	(701) 884-2707	\$20	350	Wheat screenings	Most in harvest, least in late winter, when it's all been sold	Sold locally as cattle feed
Beulah Farmers Union Elevator		(701) 873-4413			No contact		
Southwest Grain Co-Operative	Kenny	(701) 584-2152	\$25	100	Wheat screenings	N/A	N/A
Hebron Farmers Elevator	Bonnie, Bookkeeper	(701) 878-4462	\$30	N/A	Wheat screenings		
Hurdsfield Grain Inc.	Heidi, Bookkeeper	(701) 962-3344	\$25	117	Wheat screenings		
Modern Grain Inc.	Tim Meuchel	(701) 878-4525	\$30	500	Wheat screenings		
New Leipzig Grain Company	Jeff, Secondman	(701) 584-3830	\$25–\$30	75	Wheat screenings		
Garrison Farmers Union Elevator Company	Clint, Assistant Manager	(701) 463-2251	\$20	200	Wheat screenings		
Bentley Equity Exchange	Lyle	(701) 824-2600	\$20	N/A	Wheat screenings		
ADM	Tim Bourdeau, Plant Engineer	(701) 338-2491		4692	Processor; only deal with screened material and recycling, no waste		ADM plant in Enderlin, ND, that deals with waste, but too far away for our purposes

A-2. Municipal Woody Residues/Contacts

Municipal Woody Residue

<u>Source</u>	<u>Contact</u>	<u>Phone #</u>	<u>Price</u>	<u>Quantity</u>	<u>Quality</u>	<u>Reliability</u>	<u>Availability</u>
B & V Tree & Yard Service	Vira Doll, Manager	(701) 255-1035	Free	No estimate	Anything from tree, including branches, leaves, etc.	VERY INTERESTED; willing to give away everything they have	Can have it all; summer only
Belohlavek Landscaping & Tree	Jim Belohlavek, Owner	(701) 663-5124	Free	More than 500 tons every summer	All branches	Willing to give away everything they have	Can have it all; summer only
Dakota Tree Movers & Nursery	Rosemary W., Owner	(701) 223-5223	N/A	None	N/A	N/A	N/A
Dan's Repair & Tree Service	Dan, Owner	(701) 222-2214	N/A	None	N/A	N/A	N/A
Ellingson	N/A	Unlisted	N/A	N/A	N/A	N/A	N/A
Outdoor Services	Kim, Secretary	(701) 222-3889	N/A	None	N/A	N/A	N/A
Rohrich Tree Service	N/A	Disconnected	N/A	N/A	N/A	N/A	N/A
S&B Landscaping & Nursery	Steve Becker, Manager	(701) 224-0100	Free	2000 pallets/yr	Ground waste and pallets	VERY INTERESTED; say it would be best to take pallets once a year rather than make frequent visits	Can have it all; once a year – will even grind it for us **MANAGER IS ON CITY BOARD**
Seibel's Tree Service Bismarck Landfill	Justin Seibel, Owner Keith Hunke	(701) 255-1680 (701) 222-6431	N/A Free	None 7900	N/A 38% clean, 49% C&D wood, 13% firewood	N/A More in summer less in winter but fairly consistent	N/A Would have to arrange transportation or send haulers to State Penitentiary instead
Mandan Landfill	Pete Snider	(701) 667-3240	Free	5000	Tree trimmings, did not provide numbers on C&D debris	More in summer less in winter but fairly consistent	Would have to arrange transportation or send haulers to State Penitentiary instead
Garbage +	Darrell Lauer	(701) 223-5343	Free	120–180	As high as 50% paper, cardboard, mostly sawdust.	Consistent year-round	Available for drop-off via roll-off container
A1 Tree Service	Pat Bosch	(701) 258-8517 (701) 221-4622	Free	700	Tree trimmings, separates firewood but doesn't have to	Busy May–August, slower in winter, but does business year-round	100%

Waste Management	Wayne Becker	(701) 223-2295	Free	5200	C&D debris, have to sort	Consistent year-round	100%
Bullinger Tree Service	Leonard Bullinger	(701) 663-5121	Free	3600	Tree trimmings and chips	Consistent year-round	80%, some chips may not be available
Lesmeister Transportation	Barry Lesmeister	(701) 258-9494	Free	400	Very clean, hardwood	Consistent year-round	85%, burns some of his own
Truss Systems	Wayne Friesz	(701) 222-1353	Free	260	Clean 2x4 edgings	Consistent year-round	Contract with waste management
Capital City Roof & Floor	Richard Sander	(701) 663-2331	Free	75	Clean 2x4 edgings	Consistent year-round	100%
J S Specialties	Jeff Scherr	(701) 224-8060	Free	20	Wood + cardboard	Consistent year-round	Contract with waste hauler
Eagle Ridge Spans	Bob Harper	(701) 224-1877		N/A	Plywood glues	N/A	Need more information
				Total = 8255 tons/yr			

A-3. Theoretical Biomass Resource by County

Estimate for Entire State	Population	Mill Residue	Forest Residues	Urban Wood	Industrial Wood	Urban C&D Wood	Animal Manure	Crop Residue	Agricultural Processing Waste	MSW	Sludge	Total of All Biomass
(all figures in tons/yr)												
North Dakota	633,666	5,250	28,637	34,693	25,347	57,030	1,551,141	3,602,931	384,615	300,990	26,283	6,016,916

Biomass Resources (counties within 100-mile radius of Bismarck, ND)

										Agricultural			Total	
North Dakota			Mill	Forest	Urban	Industrial	Urban	Animal	Crop	Processing			of All	
Co. No.	County	Population	Residue	Residues	Wood	Wood	C&D Wood	Manure	Residue	Waste	MSW	Sludge	Biomass	
1	Adams	2,644	0	0	159	106	238	25,578	31,243		1,381	121	58,826	
2	Benson	6,781	0	0	408	271	610	20,947	106,106		3,543	309	132,195	
3	Burleigh	67,371	0	0	4,057	2,695	6,063	49,375	58,011		35,201	3074	158,477	
4	Dickey	5,662	0	0	341	226	510	34,701	153,526		2,958	258	192,521	
5	Dunn	3,457	0	762	208	138	311	71,850	50,260		1,806	158	125,494	
6	Eddy	2,765	0	0	167	111	249	11,823	47,914		1,445	126	61,834	
7	Emmons	4,302	0	0	259	172	387	56,077	95,573		2,248	196	154,913	
8	Foster	3,787	0	0	228	151	341	13,000	68,425		1,979	173	84,297	
9	Grant	2,854	0	0	172	114	257	51,798	55,794		1,491	130	109,756	
10	Hettinger	2,839	0	0	171	114	256	20,221	65,145		1,483	130	87,519	
11	Kidder	2,798	0	0	169	112	252	54,669	38,855		1,462	128	95,647	
12	LaMoure	4,700	0	0	283	188	423	27,747	146,301		2,456	214	177,613	
13	Logan	2,268	0	0	137	91	204	37,353	48,627		1,185	103	87,700	
14	McHenry	5,962	0	100	359	238	537	60,601	67,537		3,115	272	132,759	
15	McIntosh	3,397	0	0	205	136	306	36,307	51,303		1,775	155	90,186	
16	McLean	9,603	0	0	578	384	864	35,907	121,767		5,018	438	164,956	
17	Mercer	9,210	0	0	555	368	829	25,582	35,319		4,812	420	67,885	
18	Morton	24,568	0	12.5	1,480	983	2,211	92,857	82,656		12,837	1121	194,157	
19	Oliver	2,158	0	0	130	86	194	35,784	33,368		1,128	98	70,789	
20	Pierce	4,594	0	0	277	184	413	21,112	66,969		2,400	210	91,565	
21	Sheridan	1,665	0	0	100	67	150	17,886	65,145		870	76	84,293	
22	Sioux	4,156	0	0	250	166	374	24,982	13,641		2,171	190	41,774	
23	Stark	22,490	0	1187	1,354	900	2,024	50,347	55,166		11,751	1026	123,755	
24	Stutsman	21,090	0	0	1,270	844	1,898	50,359	142,712		11,019	962	209,064	
25	Ward	58,360	0	2350	3,515	2,334	5,252	37,470	136,545		30,493	2663	220,622	
26	Wells	5,094	0	0	307	204	458	16,859	127,314		2,662	232	148,036	
South Dakota														-
27	Campbell	1,847	0	0	111	74	166	31,952	55,679		965	84	89,031	
28	Corson	4,104	0	0	247	164	369	52,119	41,412		2,144	187	96,643	
29	McPherson	2,693	0	0	162	108	242	63,293	43,753		1,407	123	109,088	
30	Walworth	5,614	0	0	338	225	505	31,473	74,632		2,933	256	110,362	
										(estimated 6.5%)				-
100-mile radius total		298,833	-	4,412	17,997	11,953	26,895	1,160,030	2,180,697	239,977	156,139	13,634	3,811,734	

A-4. Crop Residue and Animal Manure by County

Collectible Assumptions

Crop	Residue Generation Factor	Residue Collection Factor	Livestock	Tons/Dry Manure/ Animal/Year	Percent Collectible	Tons/Dry Manure/ Animal/Year	Conversions lbs/bu	Poultry
Corn Grain	1	0.55	Animal/Year				Corn Grain	56
Barley	1.5	0.55	Cattle and calves	0.73	100%	0.73	Barley	48
Oats	1.4	0.5	Milk cows/dairy cattle	2.13	80%	1.7	Oats	38
Sorghum	0.9	0.5	Hogs and pigs	0.27	100%	0.27	Sorghum	
Wheat	0.9	0.25	Chickens	0.01644	100%	0.01644	Wheat	60
Peanuts	1.25	0.3	Sheep and lambs	0.106	50%	0.053	Peanuts	
Sunflower	1.5	0.3					Soybeans	60
Soybeans	0.83	0.25					Sunflower	28

Crop		1999					Number of Animals			
County	Corn Grain, bu	Barley, bu	Oats, bu	Sunflower, lb	Wheat, bu	Soybeans, bu	Cattle and Calves	Milk Cows/ Dairy Cattle	Hogs and Pigs	Sheep and Lambs
Adams	151,600	252,000	229,000	18,740,000	2,467,700	0	34,000	0	0	14,300
Benson	323,800	2,718,000	382,000	70,860,000	3,879,200	15,100	27,000	500	1,100	1,700
Burleigh	886,200	468,000	720,000	37,150,000	2,469,000	79,800	67,000	0	800	4,700
Dickey	6,765,900	451,000	303,000	55,020,000	2,641,500	989,800	43,000	800	6,500	3,700
Dunn	111,600	846,000	943,000	5,550,000	2,666,600	0	94,000	1,400	2,600	2,800
Eddy	187,500	1,024,000	129,000	46,510,000	1,862,300	0	16,000	0	0	2,700
Emmons	801,600	1,108,000	1,296,000	82,380,000	3,675,300	114,000	65,000	4,900	1,100	0
Foster	388,800	1,347,000	117,000	70,980,000	2,595,800	115,500	17,000	0	1,400	4,000
Grant	568,700	447,000	881,000	31,710,000	2,855,000	10,000	65,000	2,000	3,000	2,600
Hettinger	123,600	367,000	237,000	18,110,000	7,221,900	0	23,000	1,000	6,000	2,100
Kidder	843,800	327,000	659,000	17,240,000	950,000	53,000	71,000	1,300	800	7,800
LaMoure	3,429,300	1,521,000	285,000	89,830,000	4,197,800	1,773,000	28,000	2,000	14,000	2,400
Logan	258,700	782,000	535,000	45,210,000	1,710,200	52,700	47,000	1,600	1,000	1,000
McHenry	126,000	1,452,000	424,000	46,390,000	3,077,000	0	77,000	2,300	800	5,000
McIntosh	318,800	569,000	629,000	64,220,000	1,707,800	126,000	44,000	2,200	1,500	800
McLean	287,800	1,900,000	340,000	27,600,000	10,201,700	19,500	46,000	1,300	0	2,200
Mercer	62,100	600,000	458,000	4,690,000	2,272,000	0	35,000	0	0	600
Morton	716,500	1,248,000	1,197,000	42,870,000	3,148,000	15,500	109,000	7,000	4,000	5,800
Oliver	91,100	644,000	521,000	8,220,000	1,546,000	0	45,000	1,200	2,800	2,600
Pierce	91,700	1,663,000	255,000	47,750,000	2,702,000	41,100	27,000	800		800
Sheridan	39,200	1,633,000	254,000	45,120,000	2,767,000	0	22,000	900	900	1,000
Sioux	122,000	35,000	365,000	7,800,000	648,000	13,700	34,000	0	600	0
Stark	70,400	598,000	671,000	6,650,000	4,714,200	0	60,000	3,100	4,100	3,200
Stutsman	823,000	2,540,000	289,000	128,460,000	6,249,400	773,500	61,000	2,900	2,700	3,200
Ward	59,700	3,126,000	234,000	44,480,000	8,979,400	0	46,000	1,800	2,700	1,900
Wells	513,500	2,416,000	207,000	115,200,000	6,314,000	44,400	23,000	0	0	1,300
South Dakota										
Campbell	1,559,000		587,000	48,720,000	1,622,600	313,000	39,442	1,342	2,711	2,757
Corson	527,000		756,000	18,355,000	2,831,300	0	68,794	638	2,139	4,476
McPherson	1,108,000		580,000	36,360,000	1,175,000	460,000	71,202	1,756	30,440	2,105
Walworth	2,151,000		328,000	64,160,000	2,934,400	466,000	37,227	458	12,921	564

Collectable Residue (tons)
Crop 1999

County	Corn Grain	Barley	Oats	Sunflower	Wheat	Soybeans	Cattle and Total Calves	Milk Cows/ Dairy Cattle	Hogs and Pigs	Sheep and Lambs	Total		
Adams	2,335	4,990	3,046	4,217	16,657	-	31,243	24,820	0	0	758	25,578	
Benson	4,987	53,816	5,081	15,944	26,185	94	106,106	19,710	850	297	90	20,947	
Burleigh	13,647	9,266	9,576	8,359	16,666	497	58,011	48,910	0	216	249	49,375	
Dickey	104,195	8,930	4,030	12,380	17,830	6,162	153,526	31,390	1,360	1,755	196	34,701	
Dunn	1,719	16,751	12,542	1,249	18,000	-	50,260	68,620	2,380	702	148	71,850	
Eddy	2,888	20,275	1,716	10,465	12,571	-	47,914	11,680	0	0	143	11,823	
Emmons	12,345	21,938	17,237	18,536	24,808	710	95,573	47,450	8,330	297	0	56,077	
Foster	5,988	26,671	1,556	15,971	17,522	719	68,425	12,410	0	378	212	13,000	
Grant	8,758	8,851	11,717	7,135	19,271	62	55,794	47,450	3,400	810	138	51,798	
Hettinger	1,903	7,267	3,152	4,075	48,748	-	65,145	16,790	1,700	1,620	111	20,221	
Kidder	12,995	6,475	8,765	3,879	6,413	330	38,855	51,830	2,210	216	413	54,669	
LaMoure	52,811	30,116	3,791	20,212	28,335	11,037	146,301	20,440	3,400	3,780	127	27,747	
Logan	3,984	15,484	7,116	10,172	11,544	328	48,627	34,310	2,720	270	53	37,353	
McHenry	1,940	28,750	5,639	10,438	20,770	-	67,537	56,210	3,910	216	265	60,601	
McIntosh	4,910	11,266	8,366	14,450	11,528	784	51,303	32,120	3,740	405	42	36,307	
McLean	4,432	37,620	4,522	6,210	68,861	121	121,767	33,580	2,210	0	117	35,907	
Mercer	956	11,880	6,091	1,055	15,336	-	35,319	25,550	0	0	32	25,582	
Morton	11,034	24,710	15,920	9,646	21,249	96	82,656	79,570	11,900	1,080	307	92,857	
Oliver	1,403	12,751	6,929	1,850	10,436	-	33,368	32,850	2,040	756	138	35,784	
Pierce	1,412	32,927	3,392	10,744	18,239	256	66,969	19,710	1,360	0	42	21,112	
Sheridan	604	32,333	3,378	10,152	18,677	-	65,145	16,060	1,530	243	53	17,886	
Sioux	1,879	693	4,855	1,755	4,374	85	13,641	24,820	0	162	0	24,982	
Stark	1,084	11,840	8,924	1,496	31,821	-	55,166	43,800	5,270	1,107	170	50,347	
Stutsman	12,674	50,292	3,844	28,904	42,183	4,815	142,712	44,530	4,930	729	170	50,359	
Ward	919	61,895	3,112	10,008	60,611	-	136,545	33,580	3,060	729	101	37,470	
Wells	7,908	47,837	2,753	25,920	42,620	276	127,314	16,790	0	0	69	16,859	
South Dakota										0		0	
Campbell	24,009	-	7,807	10,962	10,953	1,948	55,679	28,793	2,281	732	146	31,952	
Corson	8,116	-	10,055	4,130	19,111	-	41,412	50,220	1,085	578	237	52,119	
McPherson	17,063	-	7,714	8,181	7,931	2,864	43,753	51,977	2,985	8,219	112	63,293	
Walworth	33,125	-	4,362	14,436	19,807	2,901	74,632	27,176	779	3,489	30	31,473	
Total	362,022	595,624	196,986	302,925	689,054	34,086	2,180,697	1,053,145	73,430	28,785	34,031	4,669	1,160,030
										Statewide			

APPENDIX B

EQUIPMENT SPECIFICATIONS

EQUIPMENT SPECIFICATIONS

B-1. Process Flow Diagram

Biomass Cofiring With Lignite Coal Phase 1 Study

**ND Dept. of Corrections
State Penitentiary Facility
Bismarck, ND**

PROPOSED SITE PLAN

DATE: 08/31/2001

PREPARED BY:

EERC

ENERGY & ENVIRONMENTAL RESEARCH CENTER UNIVERSITY OF NORTH DAKOTA

K.J. Schwartz Engineering, Inc.
CONSULTING ENGINEERS
233 West Rosser Ave., P.O. Box 2361 Bismarck, North Dakota 58502
Phone: (701) 222-0520
Fax: (701) 222-3770

KING COAL FURNACE CORPORATION

Mailing Address: PO. BOX 2151
PUGHKISS, MO 65680

Factory Location: 100E. I-40, PUNK
3 MI. S.W. I-40-EXIT 167
PUGHKISS, MO

(701) 255-6408
(405) 791-395-0246

SHEET NO: DOC - 1

PROCESS FLOW DIAGRAM

NO SCALE

LEGEND

TPH - TONS PER HOUR
PPH - STEAM FLOW POUNDS PER HOUR
PSIG - PRESSURE - POUNDS PER SQ. IN. GAUGE

B-2. Site Plan

- 1 PROPOSED MODIFICATIONS TO EXISTING SITE PLAN
- 2

Biomass Co-firing With Lignite Coal Phase 1 Study	
ND Dept. of Corrections State Penitentiary Facility Bismarck, ND	
PROPOSED SITE PLAN	
DATE: 08/31/2001	PREPARED BY:
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SHEET NO: DOC - 2	

B-3. Equipment Layout

**Biomass Cofiring With Lignite Coal
Phase 1 Study**

**ND Dept. of Corrections
State Penitentiary Facility
Bismarck, ND**

PROPOSED FLOOR PLAN

DATE: 08/31/2001

PREPARED BY:

EERC

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SHEET NO: DOC - 3

B-4. Equipment Elevation

B-5. Equipment Specifications

EQUIPMENT SPECIFICATIONS:
PROJECT: COFIRING BIOMASS & COAL
DATE: 8-31-01
LOCATION: North Dakota State Penitentiary
Bismarck, ND

1. **FUEL PREPARATION**

Wood fuel is generally transported via trucks with 40- or 50-ft vans holding between 18 and 40 tons. This is the most economical way to transport bulk materials over the short distances normally traveled between fuel source and boiler plant.

Self-unloading vans, dump trucks and conventional semitrailers are used to haul wood fuel. The most economical choice for small plants requiring only a few loads per day is either the self unloading van or rear dump trucks.

The fuel unloading system is designed to unload fuel as quickly as possible in the receiving area. The system will handle the daily fuel consumption in a 4-hour period. This equals 25 tons per hour. Fuel-handling equipment will be capable of reliable operation year round under dusty conditions moving a material that is abrasive, can freeze solid, and has virtually a negative angle of repose.

Traffic flows are indicated on the modified Site Plan Sheet. Increased traffic will be necessary to deliver the quantities of fuel required. On the average, there will be two (2) to four (4) trucks per day carrying 25 tons each. Arborists or tree trimming operation and loads hauled from the landfill after sorting will also affect the number of loads, or vehicles, in the area.

2. **WOOD FUEL HANDLING**

The wood fuel is removed from the transport vehicle to storage piles for sorting, continuing to the charging hopper, and then metered to a screen that splits the stream into two fractions. Screened materials are sent to a grinder or "hog" for sizing to correct fuel size. Dirt and particles of reject size bypass the mill are conveyed to a dumpster for disposal.

Tramp iron is removed from the fuel stream by magnets. Once the fuel has been screened or sized, and the metal removed, it is conveyed to storage in the Condition Fuel building pile or to Drying Bunder building with a live bottom floor.

Screen removes dirt from the fuel stream before entering the the wood grinder.
Chosen is a vibrating type screen.

Screen Specifications:

VIBRATING SCREENS

Action Equipment Company, Inc. has received worldwide recognition for its screening expertise and has been awarded a United States and Canadian patent for various unique features of the non-blinding TAPER-SLOT®® Screen. **The technologically advanced TAPER-SLOT®® Screen overcomes the shortcomings of other standard screening devices such as perforated screens, wire mesh screens, finger screens, disc screens, and rotary trommels.** Distinctly different and unmatched in performance, the TAPER-SLOT®® Screen is a shining example of innovative screening technology that not only looks good on paper - it is technology that performs.

TAPER-SLOT®® Screen with Patented Lateral Wedge Members

U.S. & Canadian Patents 5,746,322 and
2,206,981 Other Patents Pending

Unlike conventional finger screens, the highly sophisticated TAPER-SLOT® Screen offers three distinct benefits new to the vibratory industry:

- 1) HANG-UP ELIMINATION** - Lateral wedge deflectors prevent material from shifting laterally and catching under or wrapping around finger tips, thus allowing the screen to remain clean for maximum screening efficiency.
- 2) ACCURATE SIZING** - Lateral wedge deflectors prevent longer, often oversized materials from shifting sideways under a finger tip and falling into the accepts, resulting in more accurate sizing of two dimensional flat materials.
- 3) ULTRA-RIGID** - Lateral wedge deflectors prevent undesirable "finger bending" and function as gussets under each finger to provide the ultimate in rigidity for long screen life.

Screen Size: 1"

Dimension: 30' long x 48" Wide

Minimum Flowrate: 25 Tons per hour.

Motors: 2 - 10 HP

30'-0" long x 48" wide balanced and isolated 1" TAPER-SLOT® Screen with 12" vertical drop to remove fines from overs.

Powerful Magnetic Trap

The Action Magnetic Trap successfully catches small pieces of tramp helping to prevent machinery damage, costly shutdowns, spark induced fires, explosions, and reduces labor costs by eliminating the need for continual metal detector monitoring with undesirable sensitivity adjustments.

Permanent Plate Separator Magnets

Action's industrial strength plate magnets provide a permanent magnetic power source to help protect against the hazards of fine iron and tramp iron contamination in free-flowing materials.

3. **HORIZONTAL GRINDER**

Oversized wood fuel is reduced to manageable, relatively uniform pieces by shredding in a rotary mill.

CBI 3636 STATIONARY
BIOMASS RECOVERY SYSTEM
Electric

EQUIPMENT: CBI 36 X 36 GRIZZLY MILL

MAIN FRAME

- S Consists of Upper and Lower Housing. All cross members formed and 100% welded. **All stress relieved** for maximum life and strength. Main Frame **line bored** and all holes equipped with **replaceable bushings**.
- S Equipped with four lifting eye brackets.

ROTOR (Offset Helix)

- S Solid Steel Rotor made of machined plate, welded together to make one unit with **four alternately angled** rows of rebuildable / replaceable Striker Plates.
- S Rotor Diameter complete is 36".
- S Rotor Length is 60".
- S Rotor locked to shaft by Ringfeder.

STRIKER PLATES (20 pieces)

- S Machined plates made of 400 BHN Abrasive Resistant alloy and hard-coated with tungsten carbide.
- S Weight = 35 lbs. each.

SHAFT

- S Made of high strength alloy **6" diameter**.
- S Drilled and tapped in both ends for bearing, bearing sleeve removal

BEARINGS (2)

- S **SKF 22234 Spherical** Roller Bearings

BEARING HOUSINGS

- S Machined of thick steel plate recessed into side plates for **exact positioning** and full support. Bolted on to main frame. Grease filled.
- S One fixed and one floating.
- S Labyrinth seal on inside.
- S Lip seal on outside in removable bearing cap.

ANVIL

- S 5" thick, supported at the top with 2" hinge pins, drilled and tapped for pull hammer. and at the bottom with 2" diameter shear pins machined to suit the application.
- S Anvil equipped with **adjustable** blocks to support shear pins, allowing anvil / rotor clearance to be adjusted, and shear pins to be easily replaced.
- S Anvil equipped with lifting eye bracket.

ANVIL LINER

- S Made of 1 1/4" thick, **500 BHN** Abrasive Resistant alloy. - Liner **bolted** to the Anvil.

SIDE LINERS

- S Made of .625" thick, 400 BHN Abrasive Resistant alloy, bolted in place. - Liners **cover 100%** of the wear area.
- S Top and Bottom sideliners can be removed with rotor in place.

GRATE

- S Designed for super high strength and the industry's longest life.
- S Grate Liner made of **1.25" thick, 400 BHN** Abrasive Resistant alloy, **180 degree cutting surface** with diamond holes for maximum throughput.
- S Supported by four 1.5" pins equipped with shear groove.
- S **Adjustable** in two positions.
- S Grate available in various sized openings.

HYDRAULICS

Two hydraulic Cylinders for opening the Upper Housing to access the Rotor. Cylinder Bore 4" x Rod 2" x Stroke 14"

BONNET

The Chute includes the Grizzly Mill feed chute (bonnet over mill) of 1/2"- 3/8" plate construction with flat bar stiffeners on the outside. The chute will match feed conveyor head end section. Primed and painted CBI yellow.

BASE

Base to tie together mill and motor with adjustable motor platform. I-Beam frame to tie together Hog, motor, hydraulic power unit, discharge conveyor, as well as, supporting feed conveyor designed to be placed on elevated concrete pad/foundation.

POWER UNIT

One, 400 HP, 480V, TEFC high efficiency, TECO motor.

DRIVE Complete V-belt Drive including belt guard.

FEED CONVEYOR

60" wide x 40' long belt with heavy structural steel conveyor frame with 18" deep sides and 8'x 10' loading hopper. Cross members under conveyor bed; 1/4" plate in bed under conveyor belt at loading end. The conveyor belt is to be heavy-duty impact resistant. Drive to be large diameter, 3/8 lagged pulley with a 2 15/16 shaft with a Dodge gearbox with 10 HP. Heavy-duty tail pulley with take-up brackets on pillow block bearing. Four, 4" diameter heavy-duty return idlers to carry conveyor belt. Conveyor to have hood section built-on head pulley end to fit hood section on hog.

HYDRAULICS SYSTEM:

A 20 HP electric motor mounted on a 120-gallon hydraulic tank with filters. Variable displacement piston pump for feed conveyor and mill opener. Two-directional electric over hydraulic solenoid valve for feed conveyor. Manual valve bank for mill opener. Oil cooler.

DISCHARGE CONVEYOR:

The 60" x 40' Discharge Conveyor complete as follows: the conveyor belt rides in a steel trough protected with liners; cleated belt #220 - 2 ply; head pulley with shaft and bearings; self-cleaning tail pulley with shaft and bearings; return idlers; and screw takeups. The drive guard and tail pulley guards are included. The head pulley is powered by an electric motor through gearbox.

CBI GRIZZLY MILL DRIVE CONFIGURATIONS

Mill Size	Rotor Dia.	Rotor Lgth.	Rotor Wt.	Total Weight	RPM	HorsePower Electrical / Deisel	Shaft	Capacity TPH
36x36	36	36	6470	16600	750	200 - 300	6	25

Note: Specifications are to be used as a general guide. HP and Capacity figures are based on log yard debris and will vary depending on materials to be processed and desired size of finish product.

4. **MECHANICAL CONVEYORS**

Mechanical conveyors selected include belt, drag, and twin screw conveyors.

- A. *Belt.* Fuel will be transported from the fuel processing area to the storage/drying building by belt conveyors because they are less costly to operate, can carry fuel of all sizes and quality, have high carrying capacity, can be installed over virtually unlimited distances, can be easily maintained and repaired, and are highly reliable.

RAPAT CTR 40024 CONVEYOR	1
• 400' Mild Steel Conveyor 6" x 8.2# Structural Channel	390
• 24" Wide Rubber Belt 220 PIW	
• Precision 18" Vulcanized Head Pulley with 10: Snub Pulley	
• Precision 14" Tail Pulley	
• Dodge S-2000 Head and Tail Bearings	
• Precision CEMA C 5" Diameter 35 Degree Idlers on 4' Centers	
• Precision CEMA C 5" Diameter Flat Return Idlers on 10' Centers	
• 2 15/16" Drive Shaft	
• 2 7/16" Tail Shaft	
• 14 Gauge Tail Pulley Guard	
• Full Galvanized Smooth Covers	400
• Skirting 20' @ Inlet	20
• Emergency Stop Switch with Full Length Cord	1
• Suspended Gravity take-up	1
• Painted Grey Enamel	
• Rated Capacity 10 TPH @ 35 PPCF	
• 7.5 HP TEFC Three Phase Electric Motor	1
• Dodge T 4 Shaft Mount Reducer	1
• Catwalk and Supports Desinged to Span 50' Running form Grade to a 35' Discharge Height	1

- B. *Drag.* 12" wide drag conveyors are also capable of handling a wide variety in the quality and quantity of wood fuel, and they are located in the fuel stream where unprocessed fuel enters the system-between the fuel receiving and the screen and grinder and the fuel storage to the conveyor feeding the active storage and drying. Units to have box-link chains in single strands. Unit will work on inclines up to 20°, have modest power requirements, and can take more abuse (such as overloading) than other conveyors.
- C. *Screw.* Twin screw conveyors are often used as feeders to the fuel-metering bin at the boiler front. With sufficient care, screw conveyors operate with a high degree of reliability.

Twin Screw Conveyor - Boiler Fuel Feed

- S 3/8" thick flighting - 5 1/2" diameter contra rotating
- S Housing Dimensions: 14" x 8".
- S Electric Motor: 5 HP
- S Variable Frequency Drive Speed Control
- S Interconnect to Boiler Control Panel

TWIN SCREEN AUGER FOR FUEL FEED

TWIN SCREW PICKUP AT BIN DISCHARGE

TWIN SCREW AUGER - CONVEYING FUEL
(TOP COVER OFF)

BIOMASS SURGE HOPPER & TWIN SCREW FUEL FEED

NOT TO SCALE

**RAPAT SERIES ECTR:
THE COMPLETELY ENCLOSED
TROUGHING ROLLER CONVEYER**

With today's tight safety regulations and environmental concerns, completely enclosed conveyors are becoming more common. Whether it is to reduce environmental contaminants, provide a safer working environment for employees, or to maintain the integrity of your products by reducing contamination, the Rapat ECTR line of heavy-duty conveyors have the features you're looking for.

No matter what your material handling or overall capacity requirements, Rapat has a system that is easily and affordably custom tailored to suit your needs.

Above: CCMA standard U-Pol Troughing rollers carry the load.
Left: Snap-on cover attachment system means quick, easy enclosure access!

Series ECTR Conveyors have access hatches located at every critical inspection point, allowing easier inspection, maintenance and repair.

Series ECTR Conveyor shown with top covers removed.

INSPECTION DOORS
Target inspection doors located along the conveyor allow quick and easy access for maintenance and inspection.

HEAD PULLEY
Loaded for positive drive without slipping.

HEAVY DUTY BEARINGS
Most bearings are externally mounted, meaning easier maintenance without conveyor disassembly.

COMPUTER ENGINEERED BOLT-TOGETHER DESIGN

Through the use of 3-D Solid Modeling software, we're able to maintain tighter tolerances—giving you a system that installs faster, lasts longer and is easier to maintain.

ADJUSTABLE TAKE-UP
Conveyor belt adjustment with off-conveyor take-up externally mounted.

WE'VE GOT YOU COVERED

Different installations have different requirements. Maybe you would like to keep the wind and weather away from your product, and require enclosure on the sides and top only? Our ECTR Conveyor will suit you perfectly! Or perhaps your installation is in a dust-sensitive area, and you need to keep potentially hazardous dust to a minimum—requiring a fully enclosed and sealed conveyor. In this instance the Rapat ECTR conveyor will provide the containment you need without sacrificing durability or performance.

Series ECTR Conveyor shown with top covers installed for weather-tight operation.

TROUGHING ROLLERS CARRY THE LOAD

Our Troughing Roller system is designed to reduce friction and shape the belt to form a "U" shaped trough, allowing higher capacities and lower maintenance.

MOTOR AND DRIVE

Shown with standard shaft-mounted reducer. Many options available, including right angle, inline, and gear motor drives.

SERIES ECTR FEATURES

- Enclosure keeps dust and emissions contained within the enclosure for a safer, cleaner work environment.
- Inspection doors located at head and tail as well as throughout the enclosure to provide quick, simple access for inspection, cleanout and maintenance.
- Allows for dusty, dirty or dangerous products to be moved without affecting the environment immediately surrounding the conveyor.
- Can be supplied with or without bottom covers for a partially enclosed or totally enclosed system.
- Utilizes CEMA standard components such as carrying & return idlers and head and tail pulleys.
- Conveyor frame is built in 10' sections for easy handling, shipping and installation. Each 10' frame section is jig welded with structural angle flanges to ensure a strong, square fit consistently on every section.
- Head & tail shafts are sealed with UHMW & felt seals to prevent excess dust and product from escaping through the shafts.

INTAKE AND DISCHARGE FEATURES

FORMED AND WELDED FRAME
12 gauge mild steel standard, A3 line optional

UHMW RETURN RAILS
Reduce friction and noise of chain movement.

SLACK CHAIN SWITCH
Provides warning of problem with chain

INTAKE END

DISCHARGE END

GEAR REDUCER DRIVE

OPTIONAL SPLIT SPROCKET
Sprocket is bolted together, allowing easy chain repair or replacement.

ADJUSTABLE CHAIN TAKE UP
Allows for chain adjustment and reduces problems associated with slack chain assemblies.

EXTERNAL BEARINGS
Easy maintenance and inspection with externally mounted bearings. Mounted with air gap for longer bearing life and added safety.

PLUG SWITCH
Stops conveyor operation if material plugs conveyor.

CONVEYOR CROSS SECTION

8" and 12" wide conveyors have single rail return as shown.
16" wide and larger conveyors have three rail returns.

DRIVE SYSTEM (left)
Shaft mounted gear reducer with V-belt or HTD belts. Drive motor gear box drive with no belt or pulleys also available.

INTAKE SYSTEM (right)
Intake may be located in nearly any position along conveyor length. Designed for easy connection to your new or existing material handling system.

5. **BUNKER DRYING AND LIVE BOTTOM FLOOR FUEL HANDLING**

Before any fuel can burn, the moisture it contains must be evaporated. Virtually all biomass fuel steam generators have furnaces designed to drive off all the water from wood with moisture contents up to 55 percent moisture content wet basis (mcwb). But with moisture contents any higher than that, combustion becomes problematical.

One solution is to cofire a higher-quality solid fuel such as hardwood chips, coal, tire-derived fuel, or hogged pallets and reels. The existing boiler is designed for this cofiring, however, the stoker must be replaced.

Preheating all combustion air (underfire, overfire, and fuel distributor air) will enable the boiler to burn up to 60 percent moisture content.

This system will use hot flue gases to dry green fuel by direct or indirect contact to 40 percent mcwb or lower. Excess heat in flue gases is also used in the preheating of combustion air.

Wood fuel is stored in the Bunker Drying bin and the conditioned and pre-conditioned fuel poiles. The quantity of fuel processed is designed to sustain boiler operations through a weekend.

1

Boiler feedrate @ 2500PPH steam flow is 4300 LB/HR (2.55 Tons/Hr).

Fuel active storage volume = 2.55 TPH x 3 days x 24 Hrs/Day x 50% mix coal and biomass = 91.5 Tons.

A significant benefit of storing fuel for 2 to 4 weeks before firing is moisture content stabilizes so that the fuel has a much more consistent heating value. This more consistent fuel allows the combustion controls to maintain much lower CO and NO_x emissions.

Fuel seasoned for 2 to 4 weeks produces fewer material-handling problems.

Processed Fuel could be stored in the long term storage pile located in the proposed new building.

The Bunker Drying building will be constructed from masonry materials and concrete with precast concrete roof. This construction method minimizes steel or other metals subject to rust and corrosion from high moisture.

---

¹ Elliot, Chen, Swanekamp, Standard Handbook of Power Plant Engineering

6. Processed Fuel Storage and Handling Structure

Titan Series 3 Building include the following:

- 80 FT x 100 FT
- Patented 12.5 ounce flame retardant DuraWeave II polyethylene cover
- Trusses consist of 4" diameter tubes spaced 32" apart and strengthened by 1.9" continuous webbing
- 20' on center arch spacing
- 30 lbs. Roof snow load, 110 mph wind load
- Choice of color
- Two endwalls with steel support system and fabric
- 4 - 16' x 16' Duratrak doors installed (2 per endwall)
- 4 - walk through service doors installed
- Labor installation and equipment

PROPOSED PROCESSED FUEL BUILDING STYLE

The boiler fuel feed system, which transfers wood from storage to fuel stokers, is a critical component of the powerplant. It must reliably deliver a controlled amount of fuel to the fuel feeders consistent with signals from the combustion controls. It must also prevent tramp air from entering the furnace via the fuel distributor.

Wood-fired plant will incorporate a live-bottom metering bin holding about 20 min worth of fuel (1100 lb) and located at the boiler. Multiple screws will discharge fuel into the stokers at a rate determined by the combustion controls.

WOOD DRYING SYSTEM - MODULAR FUEL HANDLING & STORAGE

Project: DOC State Pen
 Location: Bismarck, ND
 Date: 08/27/2001

Prepared by: K. J. Schwartz Engineering, Inc

VOLUME OF WOOD STORAGE

OPERATION DAYS STORAGE:	3 DAYS
MAX FUEL FEEDRATE: 75% x 4000 LB/HR	3,000 LB/HR
BURNER ON TIME:	100%
AVERAGE FUEL FEEDRATE:	3000 LB/HR
FUEL DENSITY:	23 LB/CU. FT.
VOLUME REQUIRED:	9,391 CUBIC FT.
STORED HEIGHT:	12 FT.
FLOOR AREA REQUIRED:	783 SQ. FT.
NUMBER OF MODULES:	7
MODULE WIDTH:	4 FT.
MODULE LENGTH:	28.0 FT.

WOOD FUEL DATA

MOISTURE CONTENT:	50% (1)
DRIED FUEL MOISTURE	25% (2)
HEAT CONTENT @ (1)=	4250 BTU/LB
HEAT CONTENT @ (2)=	7650 BTU/LB
SPECIFIC HEAT=	0.65 BTU/LB-DEG F
MOISTURE REMOVAL RATE (MRR):	750.0 LB/HR

DRYER MASS & ENERGY BALANCE

EVAPORATION TEMP:	125 DEG F
BOILER ROOM AIR @ 70F w1 =	0.0159 LBm/LBa
EVAPORATION TEMP @ 125 F w2 =	0.0954 LBm/LBa
AIR DENSITY @ 70 F =	0.075 LB/CU. FT.

MINIMUM AIRFLOW REQUIRED=
 $MRR / (w2-w1) \times \text{AIR DENSITY} \times 60 \text{ MIN/HR} =$ 2097 CFM

MOISTURE EVAPORATION HEAT @ 125 F= 1022.9 BTU/LB

HEAT TO EVAPORATE MOISTURE @ 125 F= 767,175 BTU/HR
 HEAT TO RAISE WOOD FROM 30 DEG F = 92,625 BTU/HR
 HEAT TO RAISE MOISTURE IN WOOD FROM 30 DEG F = 142,500 BTU/HR
 HEAT FOR RADIANT LOSSES (DUCT & BIN) @ 10 BTU/C.F.= 93,913 BTU/HR

HEAT REQUIRED FOR DRYING = 1,096,213 BTU/HR
 DRYER EFFICIENCY= 70%
TOTAL HEAT REQUIRED FOR DRYING = 1,566,019 BTU/HR

GAS TEMPERATURE FROM STACK HEAT RECOVERY= 280 DEG F
 DRYING AIR SUPPLY TEMPERATURE= 250 DEG F
TOTAL AIR SUPPLY= 8019 CFM

DRYER GRATE AREA

GRATE FREE AREA 5%
 VELOCITY LEAVING GRATE 500 FPM
 GRATE FREE AREA REQUIRED = 16.04 SQ. FT.
 TOTAL GRATE AREA= 320.7 SQ. FT.
 7 MODULES@ 28 FT & 2 ROWS PER MODULE @ 5.74 INCH WIDTH GRATES

7. **COMBUSTION**

The burning process is divided into three phases: evaporation of moisture, distillation, and oxidation of volatiles and fixed carbon. In other words, the fuel absorbs heat which first drives off water and then drives off hydrocarbons, hydrogen, and carbon monoxide, which burn and sustain the combustion reaction. When most of the volatile elements are gone, the highly reactive surface of the remaining fixed carbon is oxidized.

Semisuspension Firing

Also known as *spreader stoker firing*, semisuspension burning involves distributing hogged fuel along with coal over a grate installed in the bottom of the furnace. Some of the fuel is consumed in suspension, but the larger, wetter fuel pieces land on the grate where they burn in a thin bed. The type of distributors or spreaders are four types of grates.

- Fuel distributors are most commonly designed to use medium-pressure air, pre-heated combustion air from the overfire air system, to propel fuel into the furnace. A combination feeder will be installed to replace the existing mechanical fingers distributors.
- Vibrating water-cooled grates are easier to maintain, permit cofiring of other solid fuels; feature continuous ash discharge. and rapid load response; allow very high combustion air temperatures; and enjoy very high grate heat-release rates.

Combustion Air

Bone-dry wood fuel requires less air than other carbon fuels because a significant amount of oxygen is chemically bound in cellulose. [In fact, the theoretical flame temperature of bone-dry wood fuel exceeds 3600/F (1982/C).] However, in practice, all hogged fuel boilers require relatively large amounts of excess air to drive off the water in green fuel. Theoretically, 25 to 35 percent excess air is possible, but the combustion air system is sized for 50 to 60 percent excess air to accommodate the lowest quality-available fuel under furnace upset conditions.

Moreover, the combustion air system is designed so that the ratio of overfire to underfire air can be varied widely. The placement and amount of overfire air are important in maintaining efficient combustion and critical in maintaining low CO emissions. The ratio of underfire to overfire air can range from 20:80 to 60:40 depending on the steaming rate, fuel quality, and other variables. It is the overfire air that allows operators to maintain the "three T's" of clean, efficient combustion: time, temperature, and turbulence.

COMBINATION RECIPROCATING FEEDER

AMS109

Combination Reciprocating Feeder

AMS106
2/11/93

The best of both worlds... in one fuel feeder

THE DETROIT COMBINATION FEEDER

The newly redesigned Detroit Combination Fuel Feeder combines the many features and benefits of Detroit's Air Swept Distributor Spout and the Detroit' Underthrow Fuel Distributor.

The Detroit Air Swept Distributor Spout was designed specifically for Biomass and Refuse fuels. Many industrial processes result in solid waste streams of high calorific value, which is ideally suited for energy recovery. Waste products such as bark, wood waste, sawdust, bagasse, grain hulls, coffee refuse, RDF, and tire chips, have all been burned successfully utilizing Detroit's Air Swept Distributor Spout technology.

The Detroit Underthrow Fuel Distributor is used primarily for coal distribution for spreader stokers. The underthrow design of the rotor coupled with pneumatic assistance is a revolutionary change for fuel distributors. Due to the unique design, operators have been able to reduce their fuel cost by utilizing less expensive, run-of-mine coals which contain a high amount of fines. Due to the high fines and varying moisture content these fuels have traditionally been difficult to distribute evenly and consistently over the fuel bed using

conventional coal feeder technology. The Underthrow has been found to be the ideal choice for solving this problem.

In the past it was not uncommon for stoker operators using two different fuels to require separate fuel distributors for each fuel type. With this being the case one distributor would often be mounted higher than the other distributor and the fuel entry points would be at different elevations within the boiler. With one distributor high in the boiler, excessive suspension burning and carry over occurs resulting in less ash cover to protect the grate surface.

The new Detroit Combination Fuel Feeder design allows for both fuels, coal and refuse, to be introduced into the boiler at an elevation that allows the fuels to be spread evenly over the entire stoker grate surface. Fine particles are rapidly burned in suspension while heavier particles are spread evenly burning fuel bed. The combination of suspension burning and fast burning bed improves combustion which can improve furnace efficiency, emissions and makes the stoker extremely responsive to load demand.

Features & Benefits:

! Combination Hopper / Distributor can be retrofitted to existing DSC coal feeders.

! Baffle design in air chamber of spout provides even air distribution across the width of the distributor.

! New combination feeder design provides better fuel distribution by lowering the air outlet point closer to the exit point of the distributor.

! Rugged construction/superior materials - stainless steel for areas susceptible to heat. Chromium carbide used at wear points. Factory constructed, assembled and tested.

! Distributes fuel more consistently and evenly than other feeders.

! Improved distribution of fuel promotes less carry-over resulting in lower loss of ignition.

! Innovative design makes the Combination Feeder the ideal choice for increasing fuel flexibility.

! Utilizes the smallest furnace opening possible to alleviate damage caused by radiant heat.

! Ideal for distributing fuels inconsistent in size and moisture content.

ILLUSTRATED FEATURES OF THE COMBINATION FEEDER

1. BAFFLED AIR CHAMBER

in the distributor spout maintains uniform air distribution across the entire width of the distributor.

2. AIR OUTLET LOCATION

has been lowered closer to the exit point in the furnace to provide better fuel distribution over the stoker grate surface.

3. ADJUSTABLE DISTRIBUTOR PLATE

directs the fuel by the position of an adjustable plate. It can be rotated from the horizontal position up to a 10 degree incline to project fuel to the rear of the stoker.

4. MOTORIZED ROTARY SL, BIASED AIR DAMPERS

controls the air to each air swept spout by alternately increasing and decreasing both volume and pressure of the air assuring even fuel distribution within the furnace. The action of these dampers varies the trajectory and spread of the fuel front to rear.

5. CHAIN CONVEYOR CARRIAGE

measures the fuel feed by varying the speed of the motor from the combustion control system.

6. CARRIAGE DRIVE AND ROTOR DRIVE

are separate for each distributor and driven by a 1 HP motor. Each distributor is controlled independently through the use of an A.C. variable frequency drive or through mechanical devices.

7. DISTRIBUTING UN13ERTHROW ROTOR

spreads the fuel in the furnace evenly, longitudinally and laterally, over the stoker grate surface.

8. AIR COOLED APRON TUYERES

line the bottom of the distributor discharge opening into the furnace to prevent the buildup of fines which could interfere with proper fuel distribution.

Performance Specification

No. of Units	2
Feedrate (modulating 0 to 100%)	
Coal (7000 BTU/LB)	48000 LB/HR
Biomass (5000 BTU/LB)	6720 LB/HR
Motor	2 HP

THE DETROIT® HYDROGRATE **WoodPak** patent pending

Energy From Biomass Combustion

Recycling and reduction of our world's waste stream is not only environmentally necessary, it also makes good business sense. Many industrial processes produce solid wastes of high heating value ideally suited for energy recovery. With today's high cost of conventional fuels, extraction of useful energy from otherwise non-recyclable materials represents recycling at its finest.

The Detroit Hydrograte WoodPak is designed for the forestry and wood working industries, to provide a long term answer for biomass utilization and environmental responsibility. The WoodPak is suitable for a wide variety of biomass fuels containing up to 60% moisture.

Renewable Fuels - Today's Environmental Choice

Biomass fuels are considered CO₂-neutral because the carbon dioxide emitted during combustion is used in the growth cycle of renewable fuel sources. This process makes biomass the world's largest renewable supply of energy. Furthermore, biomass fuels produce insignificant emission levels when compared to the fossil fuels they replace.

CO₂-neutral, biomass combustion does not contribute to the buildup of green house gases.

DESIGN FEATURES

The Detroit WoodPak system's unique design features solve many of the combustion problems associated with biomass burning such as ash accumulation, equipment wear and component overheating. The WoodPak's simple design and few moving parts reduce maintenance time and cost. The water-cooled surface intermittently vibrates for automatic ash discharge and permits continuous operation without shutdowns to clean grates. Because the stoker is water-cooled, its firing can be based on combustion conditions rather than cooling air requirements. This makes it possible to maintain higher combustion air temperatures necessary for burning high moisture, low ash biomass fuels without damage to the grate surface.

The WoodPak units are shop assembled and can be applied to most types of steam boilers, hot water boilers, heat exchangers, or other drying applications in capacities from 10 MBtu/hr. to 120 MBtu/hr. (3 to 35 MWt).

For more information about the WoodPak or other Detroit Stoker combustion products call: 300-STOKER-4 or (734) 241-9500.

BENEFITS

- IDEAL FOR HIGH MOISTURE/LOW ASH FUELS
- HIGHER EFFICIENCY
- LOWER EMISSIONS
- REDUCED MAINTENANCE COSTS
- HIGHER AVAILABILITY
- AUTOMATIC ASH DISCHARGE
- FEW MOVING PARTS
- NO LUBRICATION PROBLEMS
- MINIMIZES UNDERGRATE AIR
- REDUCED INSTALLATION TIME

WoodPak

Detroit Stoker Company • 1510 East First Street • Monroe, Michigan 48161 • USA

www.detroitstoker.com e-mail: sales@detroitstoker.com

Specification

Feedrate (modulating 0 to 100%)

Coal	(7000 BTU/LB)	48000 LB/HR
Biomass	(5000 BTU/LB)	6720 LB/HR
Grate Area =		160 SQ. FT.
Dimensions =		7.5 Ft. Wide x 24 Ft. Long
Motor		10 HP

8. SINGLE STAGE STEAM TURBINE GENERATOR

RLHA/RLHB Horizontal Single Stage Turbines

Engineered for higher efficiencies and in place maintenance. RLHA turbines are available in four frame sizes offering a horsepower range of 10 to over 4,000 (7.5 to 2984+ kW). This series is designed for higher efficiencies, operating conditions and steam flows than those accommodated by the RLA. The RLHA's design meets the standards of API611.

Common applications: process pumps, compressors and fans; cogeneration markets.

Features:

- Axially split construction.
- Choice of sleeve or antifriction journal bearings.
- Pedestal centerline support.
- Balanced, cage-guided governor valve.
- Positive-seating trip valve.

Benefits:

- Allows fast, easy, in place maintenance
- Allows customer a choice based on lubrication preference.
- Isolates bearing housings from forces due to pipe stress and minimum thermal movements.
- Minimizes actuating force and optimizes control.

DRESSER RAND
BOX 19188
HOUSTON, TEXAS 77224-9188
PHONE (713) 973-5368 FAX (713) 935-3490

TO: KJ C SCHWARTZ ENG.
233 WEST ROSSER AVE.
BISMARK, N.D. 58501

DATE: MARCH 10, 2001

ATT: KEN SCHWARTZ

FAX: (701) 222-3770

FROM: FOSTER KNEELAND

SUBJ: DEPT. OF CORRECTIONS
BISMARK, ND.

KEN;
THANK YOU FOR YOUR PHONE CALL OF TODAY'S DATE AND YOUR INTEREST IN
DRESSER-RAND. AS REQUESTED, WE ARE PROVIDING AN ESTIMATE ON A TURBINE
GENERATOR SET AS SHOWN BELOW:

GIVEN: 20,000 #1HR OF 200-SAT-15 STEAM

MODEL: 703E STEAM TURBINE

PERFORMANCE: 410 KW AT THE GENERATOR LEADS

PRICE: \$100-110,000 FOB WELLSVILLE NY DEPENDENT ON FINAL
SPECIFICATIONS

SHIPMENT: 22-24 WEEKS AFTER RECEIPT OF ORDER WITH FULL RELEASE

ENVELOPE DIMENSIONS: 16' L X 6' W X 6' H

SCOPE OF SUPPLY: TURBINE, GEAR REDUCER, 480V GENERATOR, BASEPLATE,
ELECTRONIC GOVERNOR

EXCLUDED FROM SCOPE: GENERATOR CONTROLS, OR ANY ITEM UPSTREAM I
DOWNSTREAM OF TURBINE FLANGES SUCH AS EXPANSION JOINTS, SHUT-OFF VALVES,
RELIEF VALVES, ETC.

UNDER SEPARATE COVER AND IN TODAY'S MAIL IS SOME DESCRIPTIVE LITERATURE AND
MY BUSINESS CARD.
THANK YOU AGAIN FOR YOUR INTEREST.

CC WELLSVILLE-JIM SMITH I JIM FELTZ

DRESSER-RAND

The Americans

1200 W. Sam Houston Parkway N. (77043-4009)

P.O. Box 19188

Phone: 713-973-5368

Fax: 713-935-3490

August 24, 2001

K.J. Schwartz Eng.
233 West Rosser Ave.
Bismark, ND 58501

Attention: Ken Schwartz

Fax: (701) 222-3770

Subject: Department Of Corrections
Bismark, ND

Ken:

Thank you for your phone call of today's date and your interest in Dresser-Rand. As requested, we are providing as estimate on a Turbine Generator Bet as shown below:

Given: 25,000# I Hr of 200-SAT-10" HGA Steam

Model: 703LPE Steam Turbine

Performance: 800 KW at the generator leads

Price: \$175,000-\$200,000 FOB Wellsville, NY dependent on final specifications.

Shipment: 22-24 weeks after receipt of order with full release

Envelope Dimensions: 18'L X 6"VV X i3'H'

Scope Of Supply: Turbine, Gear Reducer, 480V Generator, Baseplate te, Electronic Governor,
Condenser

Excluded From Scope: Generator Controls, or any item Upstream/Downstream of Turbine Flanges
such as expansion joints, shut-off valves, relief valves, etc.

In the event you have further questions, you may contact our local representative -- Power Process Co. in Chanhassen, Minnesota; Jim Myers ~ (952) 975-5662.

Thank you again for your interest.

Cordially,

DRESSER-RAND COMPANY The Americas

Foster Kneeland Account. Mgr.

FAK:mc
cc Wellsville-U.Covell Power Process-J.Myers

B-6. Equipment Budget

PROBABLE PROJECT COSTS						
PROJECT:		ND STATE PENITENTIARY				
		CO-FIRING DEMONSTRATION PROJECT				
DATE:		14-Mar-01				
		Rev. 1 1-Jun-01				
		Rev. 2 5-Sep-01				
						BUDGET
1	New Vibrating Grate Stoker to replace existing Dump Grate					\$ 300,000
	A Existing Equipment removal and new Equipment installation					\$ 60,000
	B Raise Boiler 3 ft. for new stoker installation including piping modifications and support structure					\$ 40,000
2	Fuel Conditioning/Preparation Grinder & Screening with Conveyors					\$ 275,000
	A Installation					\$ 20,000
	B Electrical					\$ 12,000
3	Biomass Fuel Handling Systems					
	Conveyors	400 LF	\$ 155.00	Per LF		\$ 62,000
	Installation & Supports					\$ 16,000
4	Existing Coal Fuel Handling System Modifications					\$ 5,000
5	Fuel Metering Systems - Coal & Wood - (PLC)					\$ 7,000
	Installation					\$ 6,000
6	Ash Handling System Modifications					\$ 8,000
7	Condensate Storage Tank & Pumps					\$ 8,000
	Installation					\$ 2,000
8	Steam Turbine/Generators & Switchgear					
	1 Recond	600 KW	Cond.			\$ 50,000
	1 Recond	450 KW	BP			\$ 50,000
	1050 KW Total					
	Installation		\$ 50.00	Per KW		\$ 52,500
Qty.	Equipment	Equipment Cost	Piping			
			Lin. Ft.	Cost/ft		
	6" Steam Piping		60	\$ 30.00		\$ 1,800
	8" Steam Piping		85	\$ 40.00		\$ 3,400
	1 Cooling Tower & Support	\$ 22,000	120	\$ 38.00		\$ 26,560
	Installation					\$ 12,000
	1 Heat Exchanger					
	1 Condenser Water Pump	\$ 3,600.00				\$ 3,600
	Installation					\$ 2,967
	Misc. Piping: Air Compressor, water, Fittings, Valves					\$ 5,000
	Automatic Controls Systems					\$ 6,000
	Electrical					\$ 20,000
9	General Construction					
	A. Fuel Process Building	8000 S.F.	\$ 7.00	Per S.F.		\$ 56,000
	Foundation & Concrete					\$ 24,000
	Sitework	4400 C.Y.	\$ 11.00	Per C.Y.		\$ 48,400
	Electrical					\$ 6,500
	B. Existing Building Modifications					
	Misc. Patch & Paint					\$ 5,000
	Steel					\$ 2,000
	Concrete					\$ 6,000
	C. Biomass Fuel Drying Bunker Building					
	G-M-E 28' x 20' x 20'	11200 C.F.	\$ 4.50	Per C.F.		\$ 50,400
	D. Turbine Generator Building					
	G-M-E 28' x 26' x 16' x 2	23296 C.F.	\$ 5.50	Per C.F.		\$ 128,128
10	Biomass Fuel Drying System					
Qty.	Equipment	Equipment Cost	Flue Gas Ducting			
			Lin. Ft.	Cost/ft		
	1 Heat Transfer Fan	\$ 4,600.00				\$ 4,600
	Flue Gas Ducting		140	\$ 95.00		\$ 13,300
	2 Exhaust Fans	\$ 1,100.00				\$ 2,200
	Floor Scrape & Fuel Drying					\$ 30,000
	Installation					\$ 8,000
	Automatic Controls Systems					\$ 6,000
	Electrical					\$ 6,550
11	SUBTOTAL=					\$ 1,451,905
	Contingency		5%			\$ 72,595
	Engineering		10%			\$ 152,450
TOTAL PROBABLE PROJECT COST=						\$ 1,676,950

APPENDIX C

FIRESIDE DATA

FIRESIDE DATA

C-1. Description of PCQUEST Model

PCQUEST Modeling

PCQUEST Input

The PCQUEST (Predictive Coal Quality Effects Screening Tool) model input requires a standard American Society for Testing and Materials as-received proximate analysis (% moisture, volatile matter, fixed carbon, and ash), as-received ultimate analysis (% hydrogen, carbon, nitrogen, sulfur, oxygen, and ash), and bulk ash chemistry (% SiO₂, Al₂O₃, Fe₂O₃, TiO₂, P₂O₅, CaO, MgO, Na₂O, K₂O, and SO₃). The FACT (Facility for the Analysis of Chemical Thermodynamics) model requires only the as-received ultimate and bulk ash chemistry analyses.

The PCQUEST calculations also require computer-controlled scanning electron microscopy (CCSEM) analysis, image analysis (IMA), and chemical fractionation (CHF) analysis as well as proximate, ultimate, and bulk ash chemistry analysis of the coal. IMA is automatically performed as part of the CCSEM analysis.

The CCSEM analysis is used to determine the size and composition of the mineral grains in a fuel that are greater than 1 µm in diameter, along with IMA analysis to determine the association of the mineral grains, i.e., whether mineral grains are embedded in the coal particles (included minerals) or are free grains not attached to the coal particles (excluded minerals). This association of mineral grains has a significant effect on the formation of fly ash and ash deposits, with included mineral grains much more likely to combine with each other than the free excluded mineral grains.

The CHF analysis is a series of selective chemical leachings that quantifies organically bound inorganics and minerals that are less than 1 µm in size. Organically bound inorganics are found only in low-rank fuels and comprise the bulk of the inorganics that are less than 1 µm in size. Low-rank subbituminous and lignite coals act as ion-exchange materials, with alkali and alkaline-earth elements such as Ca⁺⁺, Na⁺, and K⁺ attaching to carboxylic acid groups in the coal. Up to half the calcium and all of the sodium and potassium present in the coal ash may be bound in this way. When the coal is burned, these highly dispersed elements have a high propensity to interact with other minerals present as well as form very fine ash.

PCQUEST Output

Eight indices are calculated: grindability, high-temperature fouling, low-temperature fouling, slagging, slag tapping, sootblowing, erosion, and opacity, either for a specific power station using the input boiler parameters or for a generic boiler.

The predicted grindability corresponds to the Hardgrove grindability and was developed for western subbituminous coals. Grindability of western coals is especially susceptible to moisture, and the predicted values may not reflect actual determined grindabilities well. The grindability index is best used as an indication of relative changes in grindability rather than as actual Hardgrove values. The high-temperature fouling index is a measure of fouling occurring at the front part of the convective pass in the secondary superheater and reheater region. Such fouling is primarily silicate based and is strongly dependent on the furnace exit gas temperature (FEGT).

The low-temperature fouling index is a measure of fouling occurring in the primary superheater and economizer region of the convective pass. Such deposition is primarily calcium-based, forming smooth, very hard calcium sulfate deposits. The sootblowing index is related to the high-temperature fouling index and is an indication of the ease of removal of the high-temperature deposits. The slagging index is a measure of slagging propensity on walls in the radiant section of the boiler. Depending on the FEGT, the slagging region may extend to include platen superheater and reheater surfaces suspended over the furnace box and surfaces at the entrance to the convective pass. The slag-tapping index gives an estimation of the ease of slag flow from the cyclone barrels of a cyclone-fired boiler. The tube erosion index provides a relative indication of the ash abrasiveness based on the ash hardness and kinetic energy, which is dependent on the gas velocity selected as input in the boiler parameters. This index value reflects the abundance of large, hard quartz and pyrite mineral particles in the coals, but has not been calibrated against actual field observations of erosion. The opacity index provides an indication of the difficulty of ash collectibility, based on the relative abundance of fine hard-to-collect minerals and organically bound minerals in the coal. This value is indicative only of the difficulty of collecting fine ash, in this case reflecting the resistivity of the ash. A well-functioning collection device may effectively control even apparently fine particulate emissions.

The indices, except for the grindability index, are on a scale of 0–100, with 0–33 being low, 34–66 being medium, and 67–100 being a high or severe value. The resolution of the calculations is such that differences of 2–3 index units indicate effectively the same performance. PCQUEST is best used to evaluate the relative performance of coals and is most effective if a coal with known fireside performance is included as a “benchmark.”

Boiler Inputs

In addition to fuel analyses, the model requires some rudimentary boiler information. The boiler inputs are as follows:

Flue gas velocity (m/s, convective pass): 1.6

Particulate collection device, indicate one of the following:

Baghouse _____

Cold-side electrostatic precipitator (ESP) _____, av. operating temp. _____ EC

Hot-side ESP X , av. operating temp. 208EC

Scrubber _____

Furnace box cross-sectional area (ft²) 89

Design maximum continuous rating firing rate (lb/hr) 4665

Design coal heating value (Btu/lb) 7240

Design coal ash content (% of coal) 6.28

Burner design, pick one of the following:

Conventional burners X

Low-NO_x burners _____

pc-fired _____ or cyclone-fired X

C-2. Description of FACT Code

FACT Modeling

FACT (Facility for the Analysis of Chemical Thermodynamics) is an integrated thermodynamic database coupled to programs developed to calculate multicomponent multiphase equilibria based on a minimization of Gibbs' free energy. Once the initial system composition and pressure are set, FACT determines equilibrium concentrations of solid, liquid, and gas species over a specified temperature range. It should be noted that FACT calculates equilibrium concentrations independently at each temperature. Depending on the kinetics of the reactions occurring, these equilibrium concentrations may or may not be achieved. FACT is also constrained by the number of elements selected as input and by the compounds available and selected to be considered in the calculations from the thermodynamic database. The sample analyses used in the FACT calculations consisted of the bulk ash chemistry analyses and as-received ultimate analysis. FACT may also be used on blends, with the input being a calculated blend ultimate and ash chemistry analysis. Because the FACT calculations and postprocessing of the results are quite labor-intensive, only a limited number of blend scenarios are performed.

FACT determines the equilibrium amounts of gas, liquid, and solid compounds as a function of temperature. Calculations are normally performed at 45EF (25EC) intervals from 932E–2732EF (500E–1500EC). Note that the calculation at each temperature is independent of the previous or subsequent calculations and that each calculation represents an equilibrium condition which may not be kinetically or physically achieved. The compounds considered are approximately 30 or more major and minor gas species of highest concentration (FACT needs about this many gas species to allow the matrices to converge), a silicate-based liquid slag, and a solid calcium–magnesium sulfate solution which is indicative of potential low-temperature calcium-based fouling, and all pure solid species in the FACT database.

Calculations are performed on a weight basis to determine the percentage of liquid phases present as a function of temperature. A second calculation is performed on a mole basis to provide input for viscosity calculations. Viscosities for the liquid-phase material as a function of temperature are subsequently calculated using a modified form of the Urbain equation in a spreadsheet for each sample.

Both the viscosity and the amount of liquid phases present are important in predicting the amount of slagging and fouling which can occur. For example, at a given temperature, a coal with a higher percentage of liquid phases with lower viscosity would be expected to show more severe fouling behavior relative to a baseline coal. Although these calculated rates may not accurately reflect the actual magnitude of deposition experienced in a full-scale boiler, they give an indication of the relative fouling behavior.

The PCQUEST and FACT models complement each other, together providing a reasonable prediction of relative fireside performance. The advantage of PCQUEST is that ash partitioning between bottom ash and fly ash is accounted for in the model algorithms, while FACT uses the bulk coal ash composition. However, FACT provides predictions as a function of temperature, while the PCQUEST model implicitly assumes a “typical” boiler with an FEGT of approximately 2200EF.

C-3. Lignite CCSEM Mineral Distribution

Table C-3. Lignite CCSEM Mineral Distribution, wt%

Mineral Fraction:	5.889							
Size Bins:	1.0–2.2	2.2–4.6	4.6–10	10–22	22–46	46–100	Total	% Excluded
Quartz	1.8	2.4	2.9	2.4	1.3	0.1	10.9	64.4
Iron Oxide	0.1	0.2	0.1	0.0	0.0	1.1	1.4	96.2
Periclase	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Rutile	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100.0
Alumina	0.0	0.0	0.0	0.1	0.0	0.0	0.1	0.0
Calcite	0.0	0.0	0.0	0.1	0.2	0.0	0.3	100.0
Dolomite	0.0	0.1	0.1	0.0	0.1	0.0	0.3	100.0
Ankerite	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Kaolinite	0.8	1.8	1.8	1.3	0.8	1.3	7.9	48.2
Montmorillonite	0.3	0.7	0.2	0.1	0.0	0.0	1.3	31.0
K Al-Silicate	1.1	1.7	0.9	0.3	0.5	2.2	6.6	81.3
Fe Al-Silicate	1.2	1.2	0.4	0.2	0.2	0.3	3.5	61.5
Ca Al-Silicate	0.4	0.1	0.2	0.3	0.1	0.1	1.2	38.1
Na Al-Silicate	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Aluminosilicate	0.0	0.0	0.1	0.1	0.1	0.0	0.3	73.0
Mixed Aluminosilicate	1.2	2.1	0.7	1.3	0.8	1.7	7.7	73.9
Fe Silicate	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Ca Silicate	0.0	0.0	0.0	0.0	0.0	0.0	0.1	18.6
Ca Al-Silicate	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Pyrite	0.0	0.2	0.4	0.4	1.1	0.1	2.2	93.3
Pyrrhotite	1.4	4.1	6.0	10.0	8.3	5.7	35.4	91.8
Oxidized Pyrrhotite	0.1	0.1	0.2	0.5	0.1	0.0	1.0	96.5
Gypsum	0.1	0.2	0.1	0.0	0.0	0.0	0.4	28.3
Barite	0.1	0.1	0.3	0.4	0.2	0.0	1.1	100.0
Apatite	0.1	0.0	0.1	0.2	0.0	0.0	0.4	84.1
Ca Al-Phosphate	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
KCl	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Gypsum/Barite	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Gypsum/Aluminosilicate	0.2	0.0	0.0	0.1	0.1	0.1	0.4	45.7
Silica-Rich	0.4	0.5	0.5	0.5	0.4	0.8	3.1	71.6
Ca-Rich	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Ca–Si-Rich	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Unknown	4.0	3.7	1.8	0.3	1.5	3.1	14.4	67.3
Totals	13.5	19.2	16.7	18.6	15.6	16.4	100.0	

C-4. Lignite CCSEM % of Excluded Minerals

Table C-4. Lignite CCSEM Percentage of Excluded Minerals, wt%

Size Bins:	1.0–2.2	2.2–4.6	4.6–10	10–22	22–46	46–100
Quartz	39.3	69.3	71.4	67.9	65.1	100.0
Iron Oxide	27.3	100.0	100.0	0.0	0.0	100.0
Periclase	0.0	0.0	0.0	0.0	0.0	0.0
Rutile	0.0	0.0	100.0	0.0	0.0	0.0
Alumina	0.0	0.0	0.0	0.0	0.0	0.0
Calcite	0.0	0.0	100.0	100.0	100.0	0.0
Dolomite	0.0	100.0	100.0	0.0	100.0	0.0
Ankerite	0.0	0.0	0.0	0.0	0.0	0.0
Kaolinite	21.4	33.3	53.0	42.7	52.0	81.8
Montmorillonite	29.3	15.1	56.5	100.0	48.2	0.0
K Al-Silicate	43.9	69.8	91.2	100.0	97.6	100.0
Fe Al-Silicate	31.9	62.6	78.2	100.0	100.0	100.0
Ca Al-Silicate	0.0	0.0	25.1	100.0	12.7	100.0
Na Al-Silicate	0.0	0.0	0.0	0.0	0.0	0.0
Aluminosilicate	0.0	0.0	54.2	100.0	78.0	0.0
Mixed Aluminosilicate	33.0	47.9	94.6	100.0	89.5	100.0
Fe Silicate	0.0	0.0	0.0	0.0	0.0	0.0
Ca Silicate	0.0	0.0	50.9	0.0	0.0	0.0
Ca Al-Silicate	0.0	0.0	0.0	0.0	0.0	0.0
Pyrite	100.0	100.0	100.0	100.0	85.9	100.0
Pyrrhotite	74.1	69.4	93.1	94.1	96.1	100.0
Oxidized Pyrrhotite	60.8	100.0	100.0	100.0	100.0	0.0
Gypsum	31.6	0.0	75.3	0.0	0.0	0.0
Barite	100.0	100.0	100.0	100.0	100.0	0.0
Apatite	65.6	0.0	100.0	100.0	0.0	0.0
Ca Al-Phosphate	0.0	0.0	0.0	0.0	0.0	0.0
KCl	0.0	0.0	0.0	0.0	0.0	0.0
Gypsum/Barite	0.0	0.0	0.0	0.0	0.0	0.0
Gypsum/Aluminosilicate	14.8	0.0	0.0	100.0	55.4	100.0
Silica-Rich	38.2	14.8	74.3	100.0	92.1	100.0
Ca-Rich	0.0	0.0	0.0	0.0	0.0	0.0
Ca–Si-Rich	0.0	0.0	0.0	0.0	0.0	0.0
Unknown	31.9	58.8	87.6	100.0	88.3	98.4

C-5. Tree Wood CCSEM Mineral Distribution

Table C-5. Tree Wood CCSEM Mineral Distribution, wt%

Mineral Fraction:	2.534							
Size Bins:	1.0–2.2	2.2–4.6	4.6–10	10–22	22–46	46–100	Total	% Excluded
Quartz	0.5	2.0	1.1	0.2	0.7	2.9	7.3	NA
Iron Oxide	0.5	1.5	0.6	1.6	0.1	0.0	4.2	NA
Periclase	0.0	0.0	0.0	0.0	0.0	0.0	0.0	NA
Rutile	0.0	0.4	0.2	0.0	0.0	0.0	0.6	NA
Alumina	0.0	0.0	0.0	0.0	0.0	0.0	0.0	NA
Calcite	4.0	6.8	7.0	7.9	1.7	0.0	27.5	NA
Dolomite	0.5	0.7	0.7	1.0	0.7	1.4	5.0	NA
Ankerite	0.0	0.0	0.0	0.0	0.0	0.0	0.0	NA
Kaolinite	0.1	0.0	0.0	0.0	0.0	0.0	0.2	NA
Montmorillonite	0.0	0.0	0.0	0.0	0.0	0.0	0.0	NA
K Al-Silicate	1.7	0.9	0.4	0.0	0.2	0.0	3.2	NA
Fe Al-Silicate	0.0	0.2	0.2	0.7	0.0	0.0	1.0	NA
Ca Al-Silicate	0.4	0.1	0.1	0.0	0.0	0.0	0.6	NA
Na Al-Silicate	0.0	0.3	0.1	0.3	0.0	0.0	0.7	NA
Aluminosilicate	0.0	0.0	0.0	0.0	0.0	0.0	0.0	NA
Mixed Aluminosilicate	0.0	0.4	0.4	0.0	0.0	0.0	0.8	NA
Fe Silicate	0.0	0.0	0.0	0.0	0.0	0.0	0.0	NA
Ca Silicate	0.4	1.2	0.1	0.0	0.0	0.0	1.6	NA
Ca Al-Silicate	0.0	0.0	0.0	0.0	0.0	0.0	0.0	NA
Pyrite	0.0	0.0	0.0	0.0	0.0	0.0	0.0	NA
Pyrrhotite	0.0	0.0	0.0	0.0	0.0	0.0	0.0	NA
Oxidized Pyrrhotite	0.0	0.0	0.0	1.0	0.0	0.0	1.0	NA
Gypsum	0.1	0.2	0.0	0.7	0.0	0.0	1.0	NA
Barite	0.0	0.0	0.0	0.0	0.0	0.0	0.0	NA
Apatite	0.1	0.1	0.0	0.0	0.0	0.0	0.3	NA
Ca Al-Phosphate	0.1	0.0	0.1	0.0	0.0	0.0	0.1	NA
KCl	0.0	0.0	0.0	0.0	0.0	0.0	0.0	NA
Gypsum/Barite	0.0	0.0	0.0	0.0	0.0	0.0	0.0	NA
Gypsum/Aluminosilicate	0.2	1.5	0.5	0.3	0.1	0.0	2.5	NA
Silica-Rich	0.2	0.8	0.4	0.7	0.5	0.2	2.7	NA
Ca-Rich	0.6	0.4	0.2	0.0	0.1	0.0	1.4	NA
Ca–Si-Rich	0.1	0.2	0.0	0.0	0.0	0.0	0.2	NA
Unknown	10.1	16.9	8.4	1.5	1.1	0.0	37.9	NA
Totals	19.6	34.6	20.3	15.8	5.1	4.5	100.0	

C-6. Wood Chips CCSEM Mineral Distribution

Table C-6. Wood Chips CCSEM Mineral Distribution, wt%

Mineral Fraction:	1.467							
Size Bins:	1.0–2.2	2.2–4.6	4.6–10	10–22	22–46	46–100	Total	% Excluded
Quartz	0.1	0.0	5.1	1.3	0.2	0.0	6.7	NA
Iron Oxide	0.1	0.0	23.3	3.6	0.5	0.0	27.4	NA
Periclase	0.1	0.0	0.0	0.0	0.0	0.0	0.0	NA
Rutile	0.1	0.0	0.2	0.0	0.0	0.0	0.2	NA
Alumina	0.1	0.0	0.7	0.0	0.0	0.0	0.7	NA
Calcite	0.1	0.0	0.6	0.0	0.0	0.0	0.6	NA
Dolomite	0.1	0.0	0.0	0.0	0.0	0.0	0.0	NA
Ankerite	0.1	0.0	0.2	0.0	0.0	0.0	0.2	NA
Kaolinite	0.1	0.0	2.8	0.0	0.0	0.0	2.8	NA
Montmorillonite	0.1	0.0	0.8	0.0	0.0	0.0	0.8	NA
K Al-Silicate	0.1	0.0	4.1	2.1	0.2	0.1	6.5	NA
Fe Al-Silicate	0.1	0.0	1.7	0.0	0.3	0.0	2.0	NA
Ca Al-Silicate	0.1	0.0	1.4	0.6	0.0	0.0	2.0	NA
Na Al-Silicate	0.1	0.0	0.3	0.2	0.0	0.0	0.5	NA
Aluminosilicate	0.1	0.0	0.0	0.0	0.1	0.0	0.1	NA
Mixed Aluminosilicate	0.1	0.0	5.1	0.9	0.4	0.0	6.4	NA
Fe Silicate	0.1	0.0	2.9	1.1	0.0	0.0	4.0	NA
Ca Silicate	0.1	0.0	0.2	0.0	0.0	0.0	0.2	NA
Ca Al-Silicate	0.1	0.0	0.3	0.0	0.1	0.0	0.4	NA
Pyrite	0.1	0.0	0.0	0.0	0.0	0.0	0.0	NA
Pyrrhotite	0.1	0.0	0.8	0.0	0.0	0.0	0.8	NA
Oxidized Pyrrhotite	0.1	0.0	5.8	2.3	0.0	0.0	8.1	NA
Gypsum	0.1	0.0	0.8	0.0	0.0	0.0	0.8	NA
Barite	0.1	0.0	0.0	0.0	0.0	0.0	0.0	NA
Apatite	0.1	0.0	0.0	0.0	0.0	0.0	0.0	NA
Ca Al-Phosphate	0.1	0.0	0.0	0.0	0.0	0.0	0.0	NA
KCl	0.1	0.0	0.0	0.0	0.0	0.0	0.0	NA
Gypsum/Barite	0.1	0.0	0.0	0.0	0.0	0.0	0.0	NA
Gypsum/Aluminosilicate	0.1	0.0	1.7	0.0	0.1	0.0	1.8	NA
Silica-Rich	0.1	0.0	1.3	1.0	0.1	0.0	2.4	NA
Ca-Rich	0.1	0.0	0.4	0.0	0.0	0.0	0.4	NA
Ca–Si-Rich	0.1	0.0	0.6	0.0	0.0	0.0	0.6	NA
Unknown	0.1	0.3	15.8	4.9	2.3	0.2	23.5	NA
Totals	3.3	0.3	77.0	18.0	4.4	0.3	100.0	

C-7. Chemical Fractionation Analysis

Table C-7. Chemical Fractionation Analysis, %

Lignite

	Water	Removed by NH ₄ OAc	HCl	Remaining
Si	0	0	0	100
Al	0	0	0	100
Fe	12	0	19	69
Ti	6	0	6	88
P	10	17	55	18
Ca	6	68	26	0
Mg	9	68	15	8
Na	11	88	0	1
K	0	19	8	73
S	19	52	29	0

Tree Wood

	Water	Removed by NH ₄ OAc	HCl	Remaining
Si	36	17	29	18
Al	29	26	33	12
Fe	66	5	28	1
Ti	34	32	25	9
P	50	40	9	1
Ca	19	51	30	0
Mg	32	60	7	1
Na	57	0	11	32
K	48	52	0	0
S	28	32	39	1

Wood Chips

	Water	Removed by NH ₄ OAc	HCl	Remaining
Si	76	0	1	23
Al	75	0	13	12
Fe	66	0	25	9
Ti	67	0	0	33
P	61	18	13	8
Ca	76	21	2	1
Mg	84	12	2	2
Na	87	9	2	2
K	90	0	10	0
S	52	44	4	0

C-8. Summary of FACT Lignite–Tree Wood Viscosities

Table C-8. Summary of FACT Lignite–Tree Wood Viscosities

Blend %							
Lignite	100	80	60	40	20	0	
Tree Wood	0	20	40	60	80	100	
Temperature, °C Viscosity, log10 poise							
1500	0.70	0.63	0.53	0.44	0.26	0.07	
1475	0.76	0.69	0.59	0.50	0.32	0.13	
1450	0.83	0.75	0.65	0.57	0.38	0.19	
1425	0.90	0.82	0.73	0.65	0.45	0.37	
1400	0.97	0.89	0.81	0.72	0.52	0.52	
1375	1.04	0.96	0.89	0.79	0.59	0.64	
1350	1.11	1.06	0.97	0.86	0.70	0.76	
1325	1.19	1.14	1.05	0.93	0.80	0.94	
1300	1.28	1.22	1.13	1.00	0.91	1.05	
1275	1.36	1.30	1.24	1.11	1.01	1.15	
1250	1.47	1.42	1.35	1.21	1.13	1.24	
1225	1.58	1.54	1.47	1.32	1.44	1.34	
1200	1.70	1.66	1.58	1.44	1.52	1.43	
1175	1.81	1.76	1.69	1.57	1.61	1.52	
1150	1.91	1.84	1.80	1.69	1.69	1.61	
1125	2.04	1.96	1.88	1.81	1.79	1.71	
1100	2.18	2.10	1.97	2.10	1.90	1.81	
1075	2.31	2.23	2.10	2.26	2.07	1.92	
1050	2.41	2.31	2.23	NA	2.23	2.02	
1025	2.53	2.48	2.40	NA	2.39	2.13	
1000	2.62	2.68	2.63	2.54	2.51	2.24	
975	2.88	2.81	2.88	2.70	2.64	2.36	
950	3.09	3.03	3.07	2.93	2.77	2.47	
925	3.32	3.25	3.21	3.20	2.90	2.58	
900	3.51	3.48	3.43	NA	3.04	2.69	
875	3.75	3.64	3.63	NA	3.17	2.79	
850	NA	NA	NA	NA	3.31	2.88	
825	NA	NA	NA	NA	3.45	2.95	
800	NA	NA	NA	NA	3.59	2.98	
775	NA	NA	NA	NA	3.71	2.96	
750	NA	NA	NA	NA	3.80	2.76	
725	NA	NA	NA	NA	3.82	3.44	
700	NA	NA	NA	NA	3.72	3.66	
675	NA	NA	NA	NA	3.95	3.49	
650	NA	NA	NA	NA	4.05	3.15	
625	NA	NA	NA	NA	4.14	2.95	
600	NA	NA	NA	NA	4.47	NA	
575	NA	NA	NA	NA	4.60	NA	
550	NA	NA	NA	NA	4.74	NA	
525	NA	NA	NA	3.96	3.98	NA	
500	NA	NA	NA	4.23	3.66	NA	

C-9. Summary of FACT Lignite–Wood Chip Viscosities

Table C-9. Summary of FACT Lignite–Wood Chips Viscosities

Blend %						
Lignite	100	80	60	40	20	0
Wood Chips	0	20	40	60	80	100
Temperature, °C	Viscosity, log10 poise					
1500	0.70	0.70	0.71	0.71	0.71	0.67
1475	0.76	0.77	0.77	0.77	0.78	0.73
1450	0.83	0.83	0.83	0.84	0.84	0.80
1425	0.90	0.90	0.90	0.91	0.91	0.87
1400	0.97	0.97	0.97	0.98	0.98	0.94
1375	1.04	1.04	1.04	1.05	1.05	1.01
1350	1.11	1.11	1.12	1.12	1.13	1.09
1325	1.19	1.19	1.19	1.20	1.20	1.16
1300	1.28	1.27	1.27	1.29	1.32	1.27
1275	1.36	1.36	1.38	1.41	1.45	1.41
1250	1.47	1.48	1.51	1.54	1.58	1.56
1225	1.58	1.60	1.63	1.66	1.71	1.73
1200	1.70	1.72	1.75	1.79	1.84	1.89
1175	1.81	1.84	1.87	1.92	1.98	2.05
1150	1.91	1.94	1.98	2.03	2.11	2.21
1125	2.04	2.04	2.08	2.14	2.24	2.38
1100	2.18	2.18	2.18	2.24	2.35	2.54
1075	2.31	2.31	2.32	2.33	2.46	2.72
1050	2.41	2.42	2.43	2.44	2.54	2.89
1025	2.53	2.54	2.52	2.54	2.60	3.04
1000	2.62	2.63	2.64	2.66	2.68	3.14
975	2.88	2.87	2.85	2.81	2.81	3.16
950	3.09	3.08	3.07	3.06	3.11	3.16
925	3.32	3.32	3.32	3.32	3.40	3.42
900	3.51	3.51	3.54	3.55	3.58	3.62
875	3.75	3.75	3.78	3.82	3.83	NA
850	NA	NA	NA	NA	NA	NA
825	NA	NA	NA	NA	NA	NA
800	NA	NA	NA	NA	NA	NA
775	NA	NA	NA	NA	NA	NA
750	NA	NA	NA	NA	NA	NA
725	NA	NA	NA	NA	NA	NA
700	NA	NA	NA	NA	NA	NA
675	NA	NA	NA	NA	NA	NA
650	NA	NA	NA	NA	NA	NA
625	NA	NA	NA	NA	NA	NA
600	NA	NA	NA	NA	NA	NA
575	NA	NA	NA	NA	NA	NA
550	NA	NA	NA	NA	NA	NA
525	NA	NA	NA	NA	NA	NA
500	NA	NA	NA	NA	NA	NA

C-10. Summary of FACT Lignite–Tree Wood Liquid Phases

Table C-10. Summary of FACT Lignite–Tree Wood Liquid Phases

Lignite	100	80	60	40	20	0
Tree Wood	0	20	40	60	80	100
Temperature, °C % of Liquid Phases						
1500	84.95	85.79	86.98	84.83	83.35	51.60
1475	84.96	85.80	86.97	83.84	82.25	50.42
1450	84.99	85.81	86.97	82.85	81.27	49.28
1425	85.02	85.84	86.07	81.86	80.30	21.97
1400	85.05	85.87	84.95	80.95	79.41	14.52
1375	85.09	85.90	83.76	80.95	78.48	11.55
1350	85.13	83.61	83.20	80.97	67.12	9.35
1325	84.36	83.25	82.67	81.01	59.71	6.09
1300	84.16	83.29	82.21	79.82	54.08	5.10
1275	84.02	82.73	78.62	74.37	49.46	4.82
1250	81.82	78.14	74.00	69.69	43.23	4.66
1225	77.84	74.44	70.10	64.93	19.31	4.57
1200	75.12	71.48	66.89	60.79	19.02	4.51
1175	73.54	69.34	64.72	56.70	18.92	4.49
1150	72.99	68.83	62.21	50.23	16.63	3.73
1125	70.60	65.41	59.86	46.58	14.94	3.30
1100	67.72	61.41	55.43	30.80	13.65	3.02
1075	66.37	59.56	49.53	27.84	12.44	2.87
1050	64.59	56.66	42.20	0.00	11.69	2.70
1025	63.03	52.82	38.45	0.00	9.21	2.53
1000	63.36	49.75	35.32	0.48	5.15	2.42
975	60.25	49.18	33.15	14.27	3.47	2.33
950	60.26	50.89	33.69	15.96	2.78	2.27
925	57.20	50.33	35.82	15.15	2.51	2.23
900	49.72	36.66	11.13	0.00	2.41	2.22
875	43.23	3.93	12.04	0.00	2.38	2.23
850	0.00	0.00	0.00	0.00	2.37	2.29
825	0.00	0.00	0.00	0.00	2.36	2.42
800	NA	0.00	0.00	0.00	2.30	2.70
775	NA	0.00	0.00	0.00	2.28	3.42
750	NA	0.00	0.00	0.00	2.27	4.22
725	0.00	0.00	0.00	0.00	2.28	3.07
700	0.00	0.00	0.00	0.00	2.35	2.13
675	0.00	0.00	0.00	0.00	7.28	1.57
650	0.00	0.00	0.00	0.00	7.09	1.56
625	0.00	NA	NA	0.00	6.92	1.87
600	NA	NA	NA	0.00	11.47	NA
575	NA	NA	NA	0.00	11.46	NA
550	NA	0.00	NA	0.00	11.70	NA
525	NA	0.00	NA	10.19	17.19	NA
500	NA	NA	NA	10.28	22.29	NA

C-11. Summary of FACT Lignite–Wood Chip Liquid Phases

Table C-11. Summary of FACT Lignite–Wood Chips Liquid Phases

Lignite	100	80	60	40	20	0
Wood Chips	0	20	40	60	80	100
Temperature, °C	% of Liquid Phases					
1500	84.95	85.03	85.17	85.47	86.15	88.91
1475	84.96	85.04	85.17	85.44	86.07	88.58
1450	84.99	85.06	85.18	85.43	86.01	88.33
1425	85.02	85.09	85.20	85.44	85.98	88.13
1400	85.05	85.12	85.22	85.45	85.97	87.99
1375	85.09	85.16	85.25	85.47	85.97	87.88
1350	85.13	85.20	85.29	85.50	85.98	87.81
1325	84.36	84.83	84.92	85.13	85.61	87.42
1300	84.16	84.71	84.96	83.93	81.13	83.75
1275	84.02	84.24	81.63	78.81	76.03	77.32
1250	81.82	79.51	77.33	74.65	71.90	71.20
1225	77.84	75.96	73.86	71.26	68.51	65.97
1200	75.12	73.31	71.18	68.53	65.69	61.85
1175	73.54	71.62	69.33	66.48	63.39	58.01
1150	72.99	70.94	68.43	65.22	61.61	53.69
1125	70.60	71.18	68.52	64.88	60.48	50.33
1100	67.72	67.91	68.59	65.51	60.17	47.67
1075	66.37	66.40	66.74	67.03	60.82	45.29
1050	64.59	64.67	65.44	66.84	62.41	43.82
1025	63.03	62.89	64.25	65.19	64.34	42.95
1000	63.36	63.41	63.29	63.86	65.19	43.32
975	60.25	59.31	60.48	62.66	64.43	43.69
950	60.26	60.81	61.69	62.78	61.48	34.77
925	57.20	57.45	57.93	58.89	56.45	28.54
900	49.72	47.79	46.16	43.90	38.64	18.62
875	43.23	45.23	43.59	40.35	12.28	0.00
850	0.00	0.00	0.00	0.00	0.00	0.00
825	0.00	0.00	0.00	0.00	0.00	0.00
800	NA	0.00	NA	0.00	0.00	0.00
775	NA	NA	NA	NA	0.00	0.00
750	NA	NA	NA	NA	0.00	0.00
725	0.00	0.00	0.00	0.00	0.00	0.00
700	0.00	NA	NA	0.00	0.00	0.00
675	0.00	NA	NA	0.00	0.00	0.00
650	0.00	NA	NA	NA	0.00	0.00
625	0.00	0.00	NA	NA	0.00	0.00
600	NA	NA	0.00	NA	NA	0.00
575	NA	NA	NA	NA	NA	0.00
550	NA	NA	NA	NA	NA	0.00
525	NA	NA	NA	NA	NA	0.00
500	NA	NA	NA	NA	NA	0.00

C-12. Summary of FACT Lignite–Tree Wood Solid Sulfates

Table C-12. Summary of FACT Lignite–Tree Wood Solid Sulfates

Lignite	100	80	60	40	20	0
Tree Wood	0	20	40	60	80	100
Temperature, °C	% Solid Sulfates					
1500	0.00	0.00	0.00	0.00	0.00	0.00
1475	0.00	0.00	0.00	0.00	0.00	0.00
1450	0.00	0.00	0.00	0.00	0.00	0.00
1425	0.00	0.00	0.00	0.00	0.00	0.00
1400	0.00	0.00	0.00	0.00	0.00	0.00
1375	0.00	0.00	0.00	0.00	0.00	0.00
1350	0.00	0.00	0.00	0.00	0.00	0.00
1325	0.00	0.00	0.00	0.00	0.00	0.00
1300	0.00	0.00	0.00	0.00	0.00	0.00
1275	0.00	0.00	0.00	0.00	0.00	0.00
1250	0.00	0.00	0.00	0.00	0.00	0.00
1225	0.00	0.00	0.00	0.00	0.00	0.00
1200	0.00	0.00	0.00	0.00	0.00	0.00
1175	0.00	0.00	0.00	0.00	0.00	0.00
1150	0.00	0.00	2.07	6.81	12.54	16.81
1125	1.12	2.44	5.82	11.51	21.09	26.79
1100	2.63	5.61	9.82	17.34	29.23	34.14
1075	3.92	7.51	12.55	19.75	32.87	37.96
1050	5.30	9.07	14.89	28.44	35.21	39.89
1025	8.03	13.26	18.42	31.87	37.68	40.88
1000	9.68	18.15	22.95	32.21	40.16	41.40
975	18.92	20.02	27.37	33.08	41.29	41.67
950	23.96	25.98	30.28	34.76	41.79	41.80
925	26.36	29.10	31.56	36.55	42.01	41.87
900	29.59	32.67	38.01	40.78	42.10	41.91
875	31.38	39.66	38.79	41.65	42.13	41.92
850	40.85	40.73	41.28	42.00	42.14	41.93
825	41.15	40.88	41.44	42.13	42.15	41.92
800	NA	40.94	41.50	42.19	42.17	41.90
775	NA	40.96	41.53	42.20	42.18	41.86
750	NA	40.97	41.54	42.21	42.19	38.22
725	41.34	41.02	41.97	42.21	42.20	38.12
700	41.35	41.02	41.89	42.21	42.20	37.99
675	41.35	40.99	41.75	42.21	41.89	37.18
650	41.35	40.99	41.75	42.21	41.84	37.14
625	41.35	NA	NA	42.21	41.79	37.11
600	NA	NA	NA	42.21	41.10	NA
575	NA	NA	NA	42.21	40.86	NA
550	NA	41.59	NA	42.21	40.47	NA
525	NA	41.59	NA	41.14	40.70	NA
500	NA	NA	NA	41.12	40.02	NA

C-13. Summary of FACT Lignite–Wood Chip Solid Sulfates

Table C-13. Summary of FACT Lignite–Wood Chips Solid Sulfates

Lignite	100	80	60	40	20	0
Wood Chips	0	20	40	60	80	100
Temperature, °C	% Solid Sulfates					
1500	0.00	0.00	0.00	0.00	0.00	0.00
1475	0.00	0.00	0.00	0.00	0.00	0.00
1450	0.00	0.00	0.00	0.00	0.00	0.00
1425	0.00	0.00	0.00	0.00	0.00	0.00
1400	0.00	0.00	0.00	0.00	0.00	0.00
1375	0.00	0.00	0.00	0.00	0.00	0.00
1350	0.00	0.00	0.00	0.00	0.00	0.00
1325	0.00	0.00	0.00	0.00	0.00	0.00
1300	0.00	0.00	0.00	0.00	0.00	0.00
1275	0.00	0.00	0.00	0.00	0.00	0.00
1250	0.00	0.00	0.00	0.00	0.00	0.00
1225	0.00	0.00	0.00	0.00	0.00	0.00
1200	0.00	0.00	0.00	0.00	0.00	0.00
1175	0.00	0.00	0.00	0.00	0.00	0.00
1150	0.00	0.00	0.00	0.00	0.00	0.00
1125	1.12	0.02	0.00	0.00	0.00	0.00
1100	2.63	1.78	0.40	0.00	0.00	0.00
1075	3.92	3.02	1.82	0.00	0.00	0.00
1050	5.30	4.61	3.35	0.03	0.00	0.00
1025	8.03	7.43	4.66	0.09	0.00	0.00
1000	9.68	8.67	8.11	0.20	2.28	0.00
975	18.92	17.40	15.21	3.42	6.83	0.00
950	23.96	23.66	23.15	15.47	19.73	11.14
925	26.36	26.36	26.25	19.33	27.12	35.23
900	29.59	30.51	31.42	28.85	34.75	43.49
875	31.38	31.85	33.16	30.92	44.46	51.21
850	40.85	41.85	43.36	29.81	48.35	52.30
825	41.15	42.20	43.80	30.46	48.85	52.64
800	NA	42.35	NA	30.70	48.94	52.83
775	NA	NA	NA	NA	50.10	54.41
750	NA	NA	NA	NA	50.12	54.46
725	41.34	42.44	44.08	30.80	51.06	56.45
700	41.35	NA	NA	30.79	51.52	56.64
675	41.35	NA	NA	30.78	51.68	57.06
650	41.35	NA	NA	NA	51.72	57.75
625	41.35	42.44	NA	NA	51.74	59.18
600	NA	NA	43.91	NA	NA	60.84
575	NA	NA	NA	NA	NA	63.26
550	NA	NA	NA	NA	NA	68.48
525	NA	NA	NA	NA	NA	69.69
500	NA	NA	NA	NA	NA	69.69

C-14. CCSEM Deposit Analysis of 50% Pallet Wood and Lignite

Table C-14. Pallet Wood Blend

Point	Description	Na	Mg	Al	Si	P	S	Ca	Fe	Ti
1	Matrix	ND	12.5	18.0	1.2	ND	4.7	55.2	7.0	ND
2	Matrix	ND	2.6	21.4	0.5	ND	7.5	60.0	6.3	ND
3	Matrix	6.1	1.4	13.3	38.2	ND	ND	34.1	5.1	ND
4	Matrix	3.2	ND	1.6	35.5	ND	ND	55.3	2.1	ND
5	Bright inclusion	ND	11.2	13.6	11.8	ND	ND	38.4	24.2	ND
6	Matrix	ND	0.5	1.6	18.9	1.2	ND	72	4	1

ND = Not detected.

C-15. CCSEM Deposit Analysis of 50% Tree Wood and Lignite

Table C-15. Green Wood Blend

Point	Description	Na	Mg	Al	Si	S	K	Ca	Fe	Ba	Ti
1	Matrix	ND	23.5	16.4	1.0	0.7	ND	53.6	4.0	ND	ND
2	Matrix	0.7	1.3	20.9	1.4	6.9	2.0	50.2	15.3	ND	1.1
3	Matrix	6.7	1.3	20.5	33.9	ND	16.7	13.4	5.0	2.0	ND
4	Bright inclusion	1.5	0.6	0.5	0.7	ND	ND	2.7	92.3	1.1	ND
5	Bright inclusion	ND	6.3	4.0	1.5	ND	ND	28.2	59.3	ND	ND
6	Bright inclusion	ND	ND	2.7	1.8	ND	ND	43.1	50.9	ND	ND

ND = Not detected.

C-16. Gas Analysis of Drop-Tube Furnace Runs

Table C-16. Gas Analysis for Drop-Tube Furnace Runs, averages for all runs

Sample	O ₂ , %	CO ₂ , %	CO, ppm	SO ₂ , ppm	NO _x , ppm
100% Lignite	2.0	2.3	1.9	89.7	83.5
50/50 Lignite–Green Wood	2.1	1.9	2.0	59.9	65.5
50/50 Lignite–Pallet Wood	0.6	1.1	3.3	36.0	47.0

C-17. Photographs of Lignite Fuel, Grate Combustion, Collected Ash

Figure C-17A. Lignite coal.

Figure C-17B. Burn on grate.

Figure C-17C. Clinkers.

C-18. Photographs of 75% Wood Blend, Grate Combustion, Collected Ash

EERC DS19673.CDR

EERC DS19674.CDR

C-19. Cross Sections of Lignite and Lignite Blends

Figure C-19A. SEM image of 100% lignite.

Figure C-19B. SEM image of 25% lignite-75% tree wood blend.

Figure C19-C. SEM image of 25% lignite–75% pallet wood blend.

C-20. Comparison of Predicted and Actual Clinker Composition

Table C-20. Comparison of Predicted and Actual Clinker Composition

DMC 01/04/02

Oxide, wt %	Predicted Lignite	Actual Lignite Clinker	Predicted	Actual	Predicted	Actual
			25 % Lignite 75 % Tree Wood	25 % Lignite 75 % Tree Wood	25 % Lignite 75 % Pallet Wood	25 % Lignite 75 % Pallet Wood
SiO ₂	19.8	6.6	13.7	10.0	21.7	14.1
Al ₂ O ₃	11.3	11.1	6.5	7.1	11.2	0.9
Fe ₂ O ₃	10.7	33.9	6.5	18.4	10.5	23.6
TiO ₂	0.4	0.5	0.3	0.3	0.4	0.0
P ₂ O ₅	0.1	0.1	4.0	0.0	0.4	5.7
CaO	20.3	25.4	32.0	11.2	22.3	11.0
MgO	5.6	1.7	6.9	1.6	5.7	1.1
Na ₂ O	7.9	5.0	4.1	4.1	7.2	1.3
K ₂ O	0.8	0.2	12.9	1.9	2.5	0.3
SO ₃	23.2	15.4	13.3	45.4	18.2	42.0
Sulfur-Free Basis						
SiO ₂	25.8	7.8	15.8	18.3	26.5	24.3
Al ₂ O ₃	14.7	13.1	7.5	13.0	13.7	1.5
Fe ₂ O ₃	13.9	40.1	7.5	33.8	12.9	40.7
TiO ₂	0.5	0.6	0.3	0.5	0.5	0.0
P ₂ O ₅	0.1	0.1	4.6	0.1	0.5	9.9
CaO	26.4	30.1	36.9	20.5	27.2	19.0
MgO	7.3	2.0	8.0	2.9	6.9	1.8
Na ₂ O	10.3	5.9	4.8	7.5	8.8	2.2
K ₂ O	1.0	0.3	14.8	3.5	3.0	0.6

APPENDIX D

ENERGY CALCULATIONS

Monthly Cases

Case	Stream	From	To	Temperature °F	Pressure psia	Flow lb/hr	Enthalpy Btu/lb	Quality	Case Description and Calculation Summary			
1, JAN	S1	CND1	PUMP1	162	5	25,003	130	0%	System Performance for January Average Monthly Heat Load (based on billing)			
1, JAN	S13	SP1	ST1	388	215	8,348	1200	100%	Firing Rate	37,775 kBtu/hr	CT Heat Rate	37.8 lbs/hr - kW
1, JAN	S14	BOIL1	SP1	388	215	25,003	1200	100%	Condensing Turbine Output	441 kW	BPT Heat Rate	190 lbs/hr - kW
1, JAN	S15	ST2	CND1	162	5	16,655	1110	98%	Back Pressure Turbine Output	44 kW	Parasitic Loss total	6% % of Output
1, JAN	S2	SP1	ST2	388	215	16,655	1200	100%	Total Power Output	485 kW		
1, JAN	S3	-	BOIL1	3018	15	37,900	808	0%	Pumping Requirement	5.5 kW		
1, JAN	S4	HX1	CND1	338	115	8,348	566	29%	Other Parasitic Loads	5% 24 kW		
1, JAN	S5	ST1	HX1	338	115	8,348	1182	99%	Net Power Out	455 kW		
1, JAN	S6	PUMP1	BOIL1	163	215	25,003	131	0%	Heat Load	8,779 kBtu/hr		
1, JAN	S7	-	HX1	100	10	5,000	68	0%	System Energy Efficiency	27%		
1, JAN	S8	HX1	-	193	10	5,000	1097	95%				
1, JAN	S9	BOIL1	-	485	15	37,900	103	0%				
2, FEB	S1	CND1	PUMP1	162	5	25,003	130	0%	System Performance for February Average Monthly Heat Load (based on billing)			
2, FEB	S13	SP1	ST1	388	215	6,588	1200	100%	Firing Rate	37,775 kBtu/hr	CT Heat Rate	34.8 lbs/hr - kW
2, FEB	S14	BOIL1	SP1	388	215	25,003	1200	100%	Condensing Turbine Output	529 kW	BPT Heat Rate	190 lbs/hr - kW
2, FEB	S15	ST2	CND1	162	5	18,415	1102	97%	Back Pressure Turbine Output	35 kW	Parasitic Loss total	6% % of Output
2, FEB	S2	SP1	ST2	388	215	18,415	1200	100%	Total Power Output	564 kW		
2, FEB	S3	-	BOIL1	3018	15	37,900	808	0%	Pumping Requirement	5.5 kW		
2, FEB	S4	HX1	CND1	338	115	6,588	401	10%	Other Parasitic Loads	5% 28 kW		
2, FEB	S5	ST1	HX1	338	115	6,588	1182	99%	Net Power Out	530 kW		
2, FEB	S6	PUMP1	BOIL1	163	215	25,003	131	0%	Heat Load	6,928 kBtu/hr		
2, FEB	S7	-	HX1	100	10	5,000	68	0%	System Energy Efficiency	23%		
2, FEB	S8	HX1	-	193	10	5,000	1097	95%				
2, FEB	S9	BOIL1	-	485	15	37,900	103	0%				
3, MAR	S1	CND1	PUMP1	162	5	25,003	130	0%	System Performance for March Average Monthly Heat Load (based on billing)			
3, MAR	S13	SP1	ST1	388	215	6,945	1200	100%	Firing Rate	37,775 kBtu/hr	CT Heat Rate	34.8 lbs/hr - kW
3, MAR	S14	BOIL1	SP1	388	215	25,003	1200	100%	Condensing Turbine Output	519 kW	BPT Heat Rate	190 lbs/hr - kW
3, MAR	S15	ST2	CND1	162	5	18,058	1102	97%	Back Pressure Turbine Output	36 kW	Parasitic Loss total	6% % of Output
3, MAR	S2	SP1	ST2	388	215	18,058	1200	100%	Total Power Output	555 kW		
3, MAR	S3	-	BOIL1	3018	15	37,900	808	0%	Pumping Requirement	5.5 kW		
3, MAR	S4	HX1	CND1	338	115	6,945	441	15%	Other Parasitic Loads	5% 28 kW		
3, MAR	S5	ST1	HX1	338	115	6,945	1182	99%	Net Power Out	522 kW		
3, MAR	S6	PUMP1	BOIL1	163	215	25,003	131	0%	Heat Load	7,304 kBtu/hr		
3, MAR	S7	-	HX1	100	10	5,000	68	0%	System Energy Efficiency	24%		
3, MAR	S8	HX1	-	193	10	5,000	1097	95%				
3, MAR	S9	BOIL1	-	485	15	37,900	103	0%				
4, APRIL	S1	CND1	PUMP1	162	5	25,003	130	0%	System Performance for April Average Monthly Heat Load (based on billing)			
4, APRIL	S13	SP1	ST1	388	215	3,216	1200	100%	Firing Rate	37,775 kBtu/hr	CT Heat Rate	33.1 lbs/hr - kW
4, APRIL	S14	BOIL1	SP1	388	215	25,003	1200	100%	Condensing Turbine Output	659 kW	BPT Heat Rate	190 lbs/hr - kW
4, APRIL	S15	ST2	CND1	162	5	21,787	1097	97%	Back Pressure Turbine Output	17 kW	Parasitic Loss total	6% % of Output
4, APRIL	S2	SP1	ST2	388	215	21,787	1200	100%	Total Power Output	676 kW		
4, APRIL	S3	-	BOIL1	3018	15	37,900	808	0%	Pumping Requirement	5.5 kW		
4, APRIL	S4	HX1	CND1	211	115	3,216	180	0%	Other Parasitic Loads	5% 34 kW		
4, APRIL	S5	ST1	HX1	338	115	3,216	1182	99%	Net Power Out	637 kW		
4, APRIL	S6	PUMP1	BOIL1	163	215	25,003	131	0%	Heat Load	3,382 kBtu/hr		
4, APRIL	S7	-	HX1	100	10	5,000	68	0%	System Energy Efficiency	15%		
4, APRIL	S8	HX1	-	193	10	5,000	713	56%				
4, APRIL	S9	BOIL1	-	485	15	37,900	103	0%				

5, MAY	S1	CND1	PUMP1	162	5	25,003	130	0%	System Performance for May Average Month Heat Load (based on billing)				
5, MAY	S13	SP1	ST1	388	215	422	1200	100%	Firing Rate	37,775 kBtu/hr	CT Heat Rate	31.5 lbs/hr - kW	
5, MAY	S14	BOIL1	SP1	388	215	25,003	1200	100%	Condensing Turbine Output	781 kW	BPT Heat Rate	190 lbs/hr - kW	
5, MAY	S15	ST2	CND1	162	5	24,581	1092	96%	Back Pressure Turbine Output	2 kW	Parasitic Loss total	6% % of Output	
5, MAY	S2	SP1	ST2	388	215	24,581	1200	100%	Total Power Output	783 kW			
5, MAY	S3	-	BOIL1	3018	15	37,900	808	0%	Pumping Requirement	5.5 kW			
5, MAY	S4	HX1	CND1	211	115	422	180	0%	Other Parasitic Loads	5%	39 kW		
5, MAY	S5	ST1	HX1	338	115	422	1182	99%	Net Power Out	738 kW			
5, MAY	S6	PUMP1	BOIL1	163	215	25,003	131	0%	Heat Load	444 kBtu/hr			
5, MAY	S7	-	HX1	100	10	5,000	68	0%	System Energy Efficiency	8%			
5, MAY	S8	HX1	-	185	10	5,000	152	0%					
5, MAY	S9	BOIL1	-	485	15	37,900	103	0%					
6, JUNE	S1	CND1	PUMP1	162	5	25,003	130	0%	System Performance for June Average Month Heat Load (based on billing)				
6, JUNE	S13	SP1	ST1	388	215	1,958	1200	100%	Firing Rate	37,775 kBtu/hr	CT Heat Rate	32.2 lbs/hr - kW	
6, JUNE	S14	BOIL1	SP1	388	215	25,003	1200	100%	Condensing Turbine Output	715 kW	BPT Heat Rate	190 lbs/hr - kW	
6, JUNE	S15	ST2	CND1	162	5	23,045	1094	96%	Back Pressure Turbine Output	10 kW	Parasitic Loss total	6% % of Output	
6, JUNE	S2	SP1	ST2	388	215	23,045	1200	100%	Total Power Output	725 kW			
6, JUNE	S3	-	BOIL1	3018	15	37,900	808	0%	Pumping Requirement	5.5 kW			
6, JUNE	S4	HX1	CND1	211	115	1,958	180	0%	Other Parasitic Loads	5%	36 kW		
6, JUNE	S5	ST1	HX1	338	115	1,958	1182	99%	Net Power Out	683 kW			
6, JUNE	S6	PUMP1	BOIL1	163	215	25,003	131	0%	Heat Load	2,059 kBtu/hr			
6, JUNE	S7	-	HX1	100	10	5,000	68	0%	System Energy Efficiency	12%			
6, JUNE	S8	HX1	-	193	10	5,000	460	30%					
6, JUNE	S9	BOIL1	-	485	15	37,900	103	0%					
7, JULY	S1	CND1	PUMP1	162	5	25,003	130	0%	System Performance for July Average Month Heat Load (based on billing)				
7, JULY	S13	SP1	ST1	388	215	1,396	1200	100%	Firing Rate	37,775 kBtu/hr	CT Heat Rate	31.5 lbs/hr - kW	
7, JULY	S14	BOIL1	SP1	388	215	25,003	1200	100%	Condensing Turbine Output	750 kW	BPT Heat Rate	190 lbs/hr - kW	
7, JULY	S15	ST2	CND1	162	5	23,607	1092	96%	Back Pressure Turbine Output	7 kW	Parasitic Loss total	6% % of Output	
7, JULY	S2	SP1	ST2	388	215	23,607	1200	100%	Total Power Output	757 kW			
7, JULY	S3	-	BOIL1	3018	15	37,900	808	0%	Pumping Requirement	5.5 kW			
7, JULY	S4	HX1	CND1	211	115	1,396	180	0%	Other Parasitic Loads	5%	38 kW		
7, JULY	S5	ST1	HX1	338	115	1,396	1182	99%	Net Power Out	714 kW			
7, JULY	S6	PUMP1	BOIL1	163	215	25,003	131	0%	Heat Load	1,468 kBtu/hr			
7, JULY	S7	-	HX1	100	10	5,000	68	0%	System Energy Efficiency	10%			
7, JULY	S8	HX1	-	193	10	5,000	348	19%					
7, JULY	S9	BOIL1	-	485	15	37,900	103	0%					
8, AUG	S1	CND1	PUMP1	162	5	25,003	130	0%	System Performance for August Average Month Heat Load (based on billing)				
8, AUG	S13	SP1	ST1	388	215	1,150	1200	100%	Firing Rate	37,775 kBtu/hr	CT Heat Rate	31.5 lbs/hr - kW	
8, AUG	S14	BOIL1	SP1	388	215	25,003	1200	100%	Condensing Turbine Output	758 kW	BPT Heat Rate	190 lbs/hr - kW	
8, AUG	S15	ST2	CND1	162	5	23,853	1092	96%	Back Pressure Turbine Output	6 kW	Parasitic Loss total	6% % of Output	
8, AUG	S2	SP1	ST2	388	215	23,853	1200	100%	Total Power Output	764 kW			
8, AUG	S3	-	BOIL1	3018	15	37,900	808	0%	Pumping Requirement	5.5 kW			
8, AUG	S4	HX1	CND1	211	115	1,150	180	0%	Other Parasitic Loads	5%	38 kW		
8, AUG	S5	ST1	HX1	338	115	1,150	1182	99%	Net Power Out	720 kW			
8, AUG	S6	PUMP1	BOIL1	163	215	25,003	131	0%	Heat Load	1,209 kBtu/hr			
8, AUG	S7	-	HX1	100	10	5,000	68	0%	System Energy Efficiency	10%			
8, AUG	S8	HX1	-	193	10	5,000	298	14%					
8, AUG	S9	BOIL1	-	485	15	37,900	103	0%					

9, SEPT	S1	CND1	PUMP1	162	5	25,003	130	0%
9, SEPT	S13	SP1	ST1	388	215	1,201	1200	100%
9, SEPT	S14	BOIL1	SP1	388	215	25,003	1200	100%
9, SEPT	S15	ST2	CND1	162	5	23,802	1092	96%
9, SEPT	S2	SP1	ST2	388	215	23,802	1200	100%
9, SEPT	S3	-	BOIL1	3018	15	37,900	808	0%
9, SEPT	S4	HX1	CND1	211	115	1,201	180	0%
9, SEPT	S5	ST1	HX1	338	115	1,201	1182	99%
9, SEPT	S6	PUMP1	BOIL1	163	215	25,003	131	0%
9, SEPT	S7	-	HX1	100	10	5,000	68	0%
9, SEPT	S8	HX1	-	193	10	5,000	309	15%
9, SEPT	S9	BOIL1	-	485	15	37,900	103	0%
10, OCT	S1	CND1	PUMP1	162	5	25,003	130	0%
10, OCT	S13	SP1	ST1	388	215	5,168	1200	100%
10, OCT	S14	BOIL1	SP1	388	215	25,003	1200	100%
10, OCT	S15	ST2	CND1	162	5	19,835	1097	97%
10, OCT	S2	SP1	ST2	388	215	19,835	1200	100%
10, OCT	S3	-	BOIL1	3018	15	37,900	808	0%
10, OCT	S4	HX1	CND1	218	115	5,168	186	0%
10, OCT	S5	ST1	HX1	338	115	5,168	1182	99%
10, OCT	S6	PUMP1	BOIL1	163	215	25,003	131	0%
10, OCT	S7	-	HX1	100	10	5,000	68	0%
10, OCT	S8	HX1	-	193	10	5,000	1097	95%
10, OCT	S9	BOIL1	-	485	15	37,900	103	0%
11, NOV	S1	CND1	PUMP1	162	5	25,003	130	0%
11, NOV	S13	SP1	ST1	388	215	8,733	1200	100%
11, NOV	S14	BOIL1	SP1	388	215	25,003	1200	100%
11, NOV	S15	ST2	CND1	162	5	16,270	1110	98%
11, NOV	S2	SP1	ST2	388	215	16,270	1200	100%
11, NOV	S3	-	BOIL1	3018	15	37,900	808	0%
11, NOV	S4	HX1	CND1	338	115	8,733	593	32%
11, NOV	S5	ST1	HX1	338	115	8,733	1182	99%
11, NOV	S6	PUMP1	BOIL1	163	215	25,003	131	0%
11, NOV	S7	-	HX1	100	10	5,000	68	0%
11, NOV	S8	HX1	-	193	10	5,000	1097	95%
11, NOV	S9	BOIL1	-	485	15	37,900	103	0%
12, DEC	S1	CND1	PUMP1	162	5	25,003	130	0%
12, DEC	S13	SP1	ST1	388	215	8,654	1200	100%
12, DEC	S14	BOIL1	SP1	388	215	25,003	1200	100%
12, DEC	S15	ST2	CND1	162	5	16,349	1110	98%
12, DEC	S2	SP1	ST2	388	215	16,349	1200	100%
12, DEC	S3	-	BOIL1	3018	15	37,900	808	0%
12, DEC	S4	HX1	CND1	338	115	8,654	588	32%
12, DEC	S5	ST1	HX1	338	115	8,654	1182	99%
12, DEC	S6	PUMP1	BOIL1	163	215	25,003	131	0%
12, DEC	S7	-	HX1	100	10	5,000	68	0%
12, DEC	S8	HX1	-	193	10	5,000	1097	95%
12, DEC	S9	BOIL1	-	485	15	37,900	103	0%

System Performance for September Average Month Heat Load (based on billing)

Firing Rate	37,775 kBtu/hr	CT Heat Rate	31.5 lbs/hr - kW
Condensing Turbine Output	756 kW	BPT Heat Rate	190 lbs/hr - kW
Back Pressure Turbine Output	6 kW		
Total Power Output	762 kW		
Pumping Requirement	5.5 kW		
Other Parasitic Loads	5% 38 kW		
Net Power Out	719 kW		
Heat Load	1,263 kBtu/hr		
System Energy Efficiency	10%		

System Performance for October Average Month Heat Load (based on billing)

Firing Rate	37,775 kBtu/hr	CT Heat Rate	33.1 lbs/hr - kW
Condensing Turbine Output	600 kW	BPT Heat Rate	190 lbs/hr - kW
Back Pressure Turbine Output	27 kW		
Total Power Output	627 kW		
Pumping Requirement	5.5 kW		
Other Parasitic Loads	5% 31 kW		
Net Power Out	590 kW		
Heat Load	5,435 kBtu/hr		
System Energy Efficiency	20%		

System Performance for November Average Month Heat Load (based on billing)

Firing Rate	37,775 kBtu/hr	CT Heat Rate	37.8 lbs/hr - kW
Condensing Turbine Output	431 kW	BPT Heat Rate	190 lbs/hr - kW
Back Pressure Turbine Output	46 kW		
Total Power Output	477 kW		
Pumping Requirement	5.5 kW		
Other Parasitic Loads	5% 24 kW		
Net Power Out	447 kW		
Heat Load	9,184 kBtu/hr		
System Energy Efficiency	28%		

System Performance for December Average Month Heat Load (based on billing)

Firing Rate	37,775 kBtu/hr	CT Heat Rate	37.8 lbs/hr - kW
Condensing Turbine Output	433 kW	BPT Heat Rate	190 lbs/hr - kW
Back Pressure Turbine Output	45 kW		
Total Power Output	478 kW		
Pumping Requirement	5.5 kW		
Other Parasitic Loads	5% 24 kW		
Net Power Out	449 kW		
Heat Load	9,101 kBtu/hr		
System Energy Efficiency	28%		