MTI

Microbeam Technologies Incorporated

Matching Coal Quality and Boiler Operation

Applicants:

BNI Coal Ltd.
HC2, P.O. Box 230, Center, ND 58530-0230

Minnkota Power Cooperative, Inc.
P.O. Box 127, Center, ND 58530-0127

Microbeam Technologies Inc.
P.O. Box 14758, Grand Forks, ND 58208-4758

Co-Principal Investigators:
William Peterson, BNI Coal Ltd.
Richard Schwalbe, MPC
Steven Benson, MTI

January 1, 1998

Amount of Request: $260,050.49

Table of Contents

4. Abstract

BNI Coal Ltd., Minnkota Power Cooperative (MPC), and Microbeam Technologies Incorporated (MTI) propose to improve power plant performance by matching coal quality with boiler operation. The primary goal of the project is to determine the best solution to reducing oil consumption in cyclone-fired boilers by 1) increasing coal quality control, 2) optimizing boiler operations and 3) evaluating boiler design. The secondary goal is to evaluate changes in operations and/or coal quality on NO_X and SO_2 compliance, furnace slagging and fouling, and electrostatic precipitator performance. Test burns to evaluate good and marginal coals will be conducted over the course of the project. The project involves five tasks. The first task entitled "Validation of Coal Quality Relationships to Operational Performance" is aimed at validating methods used to predict the effects of coal quality on boiler efficiency with observed performance. The second task entitled "Evaluation of Potential Solutions" involves performing multivariate statistical analysis of plant operational and performance data with delivered coal quality, evaluating fuel blending and delivery scenarios to optimize cyclone performance and minimize wall slagging and convective pass fouling, and identifying potential boiler design modifications that could be used to minimize ash and slag related issues. The third task "Performance Optimization" will implement and test the potential solutions for their reliability. The efforts of task three will focus on the impact of fuel quality, boiler operation, and design options on overall system efficiency (economic evaluation), and emissions. The fourth task entitled "Training and Workshops" will provide training for mining as well as boiler operations staff regarding fuel quality and boiler operational impacts on the efficient operation of the power system. The fifth and final task entitled "Coordination" provides for the overall management of the program through Coal Quality Task Force meetings, preparation of progress reports, and participation in selected meetings and conferences.

The duration of the project is eighteen months, with a total cost of $1,227,415. Project participants include BNI, MPC and MTI as co-principal investigators. Two subcontractors will be involved. E.M. Griffin and Associates will provide expertise in cyclone-fired boiler operation, and the University of North Dakota Energy and Environmental Research Center (EERC), will provide viscosity measurement data and predictive models. Through the EERC's involvement, the U.S. Department of Energy will provide $25,435 as cost share.

5. Project Summary

The work proposed will determine the best solutions to reducing oil burning in cyclone-fired boilers through coal quality control, boiler operations, and boiler design. Methods such as coal selection/blending and optimizing cyclone operation will be tested to determine their reliability and effects on emissions. Relationships between coal quality and boiler operating conditions were developed in a previous project entitled "Coal Quality Management System" (CQMS). The CQMS yielded a useful performance model, which is currently being used by MPC, BNI and MTI to assess coal quality effects on plant performance. The work proposed here will focus on the following issues:

- Validate relationships between calculated coal quality performance and observed boiler performance based on as-fired coal analysis,
    - Determine optimum drill hole spacing in mine
    - Identification of methods to control coal quality
    - Perform test burns on acceptable and non-acceptable as-mined coal quality
    - Validation of viscosity predictions with measured slag viscosity
    - Test wall slagging and convective pass fouling indices
- Testing potential solutions to minimize the effects of poor slag flow and ash deposition,
    - Multivariate analysis of boiler operations, boiler performance, and as-fired coal quality – evaluation of overall performance during test burns
    - Identification of boiler design options to minimize effects of ash and slag
- Performance optimization
    - Determine reliability of measures to minimize the effects of coal quality/boiler operations of boiler performance and emissions
    - Test feasibility of potential design options
    - Perform economic evaluation of measure taken to optimize performance

The primary deliverables of the project will be methods that assist mine planning and boiler operations personnel in matching coal quality and boiler operations that result in the reliable and efficient operation of North Dakota lignite-fired boilers. These methods will provide more accurate definition of coal quality available for planning purposes and quality of coal delivered. Based on coal quality delivered, cyclone-boiler operations will be adjusted in anticipation of delivered coal quality to assure efficient and reliable operation. The protocols and relationships will be incorporated in the Coal Quality Management System. In addition, design options will be identified that have the potential to minimize oil burning.

6. Project Description

6.1 Goals and Objectives

The primary goal of the project is to determine the best solution to reduce oil consumption in cyclone-fired boiler systems by 1) increasing coal quality control, 2) optimizing boiler operations and 3) evaluating boiler design. The secondary goal is to evaluate the effects of changes in operations or coal quality on NO_x and SO_2 compliance, furnace slagging and fouling, and electrostatic precipitator performance. In addition, CQMS program improvements will be made based on validation of viscosity relationships and other ash performance parameters.

6.2 Work Plan

The project has been divided into the following tasks:

Task 1. Validation of Coal Quality Relationships to Operational Performance

Task 1.1 Determination of Optimum Drill Hole Spacing

The optimum spacing for coal quality drill holes will be determined by comparing the means and standard deviations of the various coal quality parameters taken from drill holes spaced at 200 feet apart, to drill holes spaced at other intervals (e.g. 400 feet). In addition, the variances or significant changes in coal quality will be examined in more detail through additional drilling if necessary. There may be optimum drill spacing unique to each coal quality parameter. For example, drill spacing may need to be closer to obtain representative samples for sulfur while representative samples for BTU's may be obtained from a larger spacing.

Another method to determine optimum drill hole spacing is to use BNI's Minex software to grid the various coal quality parameters using all drill holes, then re-grid using higher or lower density drill hole data. The grids can then be compared statistically to see if there is a significant difference between gridded data.

During the course of this project a total of 120 samples will be collected and characterized in addition to over 1000 data points currently available. All 120 samples will have proximate, heating value, and bulk ash composition determinations made. CCSEM analysis will be performed on selected drill core samples. Chemical fractionation will be performed on selected samples. (Descriptions of analytical techniques can be found in Appendix A).

Roles: BNI—drill core sampling and mapping, MTI—sample analysis.

Task 1.2 Identification of methods to control coal quality

This task will identify feasible methods of controlling coal quality delivered to the boiler based on core sample composition. Selected mining, blending and scheduling loading/unloading will be examined. This work will be performed in conjunction with Task 1.3. The composition of the core samples will be compared to the composition of as-fired coal samples. Samples of as-fired coal will be collected using the Coallector® samplers installed on Unit 2. Four on-line samplers have been installed on the coal-fired systems to cyclones which will assist in determination of lag time between coal delivery to the coal yard and delivery to the cyclones. Samples of coal will be collected at selected intervals based on coal feed rates and estimated silo fill rates. During the course of this project samples will be collected and characterized to determine proximate, heating value and ash composition. CCSEM analysis will be performed on selected samples. Chemical fractionation will be performed on selected samples.

Roles: MPC—as-fired coal sampling, MTI—sample and data analysis, BNI—mine sampling and monitoring coal deliveries.

Task 1.3 Test burns for acceptable/non-acceptable core quality for cyclone performance

During the testing conducted in Tasks 1.1 and 1.2 coals will be selected that have acceptable and non-acceptable cyclone performance based on CQMS predictions. A total of 48 test burns will be conducted. Test burns will be conducted with good and marginal coal quality. Twenty-four samples of as-fired coal and selected cyclone slags will be collected and analyzed for each test. Boiler operating conditions including coal feed rates, oil firing rates, excess air and other important parameters will be compiled during testing. Visual observation of cyclone performance will be made. Comparison of predicted coal quality effects (T_{250}/T_{cv}) with observed performance will be made and coordinated with Task 1.4 efforts (viscosity measurements). Samples of as-fired coal and slag will be collected and characterized. The coal characterization will include proximate, BTU and ash composition for a total of 1,152 samples. CCSEM analysis will be performed to determine size, abundance and composition of mineral grains for selected samples. Chemical fractionation will also be performed on selected samples to determine the abundance of organically associated inorganic elements. The slag will be analyzed to determine the bulk chemical composition, microstructure, and phase assemblages using x-ray diffraction and SEMPC (10 samples). Morphological analysis using the scanning electron microscope/microprobe will be used to provide images of the microstructural features of the slag (20 hours of SEM time).

Roles: BNI—test burn coal selections, MPC—collection of coal and slag samples, E.M. Griffin and Associates—monitoring and interpretation of cyclone performance, MTI—sample characterization and interpretation of coal and slag analysis results.

Task 1.4 Viscosity measurements - validate predictions

This task involves an in depth validation of the Urbain (1) and Sage and McIlroy (2) methods for calculating viscosities and T_{250} based on chemical composition and temperature for lignite-based slags. Based on the past project, CQMS, and a recent in-depth evaluation of viscosity methods by Folkedahl (3) the Urbain method provided reasonable results. The Sage and McIlroy method has been used for many years to predict slag behavior based on T_{250}. The core of the proposed work is actual slag viscosity measurements of twenty samples of Center slags. Actual slag samples of known performance from the Milton R. Young Station will be used. The viscosity of each slag will be measured using a rotating bob viscometer. T_{250} and T_{cv} values will be obtained for each slag. The measured viscosities will be compared to the values calculated using the Urbain and Sage and McIlroy methods, and the equations used will be revised as needed to match the empirical data.

As a complement to the validation work for the T_{250} calculation methods, calculations of T_{cv} (temperature of critical viscosity) will be performed for all of the slag samples. The initial T_{cv} calculations will be based on the method of Watt (4). The data set will be examined to determine the relative importance of T_{250} and T_{cv} in predicting slag behavior for different compositions. To aid in interpreting the T_{250} and T_{cv} results, the thermodynamic equilibria software package FACT (5) or SOLGASMIX (6) will be used to determine whether specific crystalline phases are likely to crystallize first from specific slags during cooling.

Steps to be taken under Task 1.4 include:

a. Selection of samples of cyclone slags for viscosity measurements

b. Performance of viscosity measurements and determination of T_{cv} and T_{250}

c. Comparison of viscosity calculation results with experimental viscosity data to develop better models.

d. Comparison of slag compositions with compositions of matching coal samples to assess the partitioning of inorganic components between coal and slag.

e. Comparison of T_{cv} with onset of crystallization determined using an equilibrium model.

The samples of slag will be characterized using x-ray diffraction (XRD) and SEMPC to determine the phases present in the slag (20 samples). SEM morphological analysis will be used to examine the microstructural features in the slag (20 samples at 1 hour per sample).

Roles: MPC—collection of slag samples, EERC—slag viscosity measurements/testing correlations and thermochemical equilibria calculations, MTI—slag analysis, incorporation of improved relationships in CQMS.

1.5 Ash Deposition Correlations

Indices for ash deposition on heat transfer surfaces have been calculated for radiant section wall slagging, high temperature silicate-based convective pass fouling, low temperature sulfate-based convective pass fouling, and deposit strength development. The indices will be calculated using CCSEM mineral analysis, bulk ash composition, and proximate/ultimate analysis. These indices will be compared to on-line measurements of boiler cleanliness. Boiler fireside performance will be monitored in terms of cleanliness factors for various boiler sections and coal types. The cleanliness factor information along with boiler operating conditions will be down loaded from MPC O.T.I.S. system. The cleanliness factors will be compared to fouling and slagging indices. All data will be collected in conjunction with other Task 1 efforts. A total of 15 wall slag and convective pass deposits will be collected and characterized. The characterization techniques include XRD, SEMPC, and SEM morphology (2 hours per sample).

Roles: MPC—download operating conditions and performance and collection of wall slag and convective pass deposits, MTI—calculation and comparison of indices, BNI—coal quality input.

Task 2 Evaluation of Potential Solutions

Task 2.1 Multivariate analysis of plant data

The multivariate analysis begins with the design of a data matrix containing all operational parameters and fuel characteristics believed to be of possible relevance to the occurrence of oil-burning, furnace wall slagging and fouling, and ESP performance. The data obtained in Task 1 will be utilized in the multivariate analysis. Data matrices will be subjected to a statistical evaluation. For all of the statistical work proposed here, the SPSS Advanced Statistics package (available for purchase from SPSS Inc.) will be used. Principal components analysis will be the type of multivariate statistical analysis applied to the data set. Based on the results of the preliminary principal components analysis, the data matrix will be revised to exclude the least-relevant parameters. The principal components analysis will then be re-run using the reduced data matrix. Results will be examined to ensure that the principal components vary similarly for each oil burning or ash deposition event. If this is not the case, the principal components analysis can be run again under slightly altered conditions.

Task 2.1.1 Managing coal quality to meet cyclone performance

Data representing both oil-burning and non-oil-burning periods, as well as times immediately preceding oil-burning events, will be included in the matrix. It will be critically important to design the matrix to include data representing a range of time intervals before the onset of each oil burn, in order to ensure that the statistical analysis will be able to discern the relevant variations in each parameter. The use of Coallector® samples will ensure accurate fuel quality information. Once the primary components are identified the optimum fuel quality and operating conditions will be determined. Emphasis will be placed on determining the range of coal quality necessary for cyclone operations as well as the range of cyclone operating conditions necessary for proper operation. A total of 5 additional samples will be characterized. The analyses will include proximate, heating values, ash composition, and CCSEM.

Roles: BNI—provide coal quality data, MPC—provide coal, ash, and slag samples, and boiler operating conditions, MTI—perform statistical analysis and fuel analysis.

Task 2.1.2 Statistical analysis of ash deposition on waterwalls and convective pass and characteristics of ash on air pollution control devices

Data representing ash deposition on waterwalls and convective pass and effects of ash on air pollution control devices will be included in the matrix. The data matrix include boiler operating conditions, sootblowing cycles, heat recovery after cleaning cycles, and opacity measurements. Higher opacity has been observed when firing coals with low T_{250} values. This is likely due to poor retention of ash in the cyclone resulting in increased ash loadings to the ESP. Data representing a range of time intervals will be compiled in order to ensure that the statistical analysis will be able to discern the relevant variations in each parameter. The use of Coallector®

samples will ensure accurate as-fired fuel quality information. Once the primary components are determined the optimum fuel quality and operating conditions will be identified. Data will be collected during test periods of selected coals and firing conditions. A total of 5 test burns will be conducted. The analysis will include proximate, heating values, ash composition, and CCSEM.

Roles: BNI—provide coal quality data, MPC—provide coal, ash, and slag samples, and boiler operating conditions, MTI—perform statistical analysis and fuel analysis.

Task 2.2 Boiler design options

Based on operations data and fuel quality options for cyclone and boiler design modifications will be identified.

Roles: Minnkota and EM Griffin and Associates

Task 3 Performance Optimization

Task 3.1 Reliability

Task 3.1.1 Identify and implement measures to minimize the impact of fuel quality

The range of coal quality parameters necessary to maintain reliable operations will be identified and field tested based on the results obtained in Tasks 1 and 2. Coal quality parameters will be mapped in the mine with BNI's GIS system. Various ranges in coal quality will be tested to determine reliability in operations as a function of coal quality. Validation of measures for five test burns of know/blended fuel quality will be conducted. Analysis of samples of coal in mine, delivered coal, slag, and deposits using CCSEM and SEMPC techniques will be conducted. A total of 10 coal samples will have the following analysis performed including: proximate, heating value, ash composition and CCSEM. In addition, two coals will be characterized using chemical fractionation. A total of 15 deposit and slag samples will be collected and characterized using SEMPC, XRD, and SEM morphology (5 hours per sample).

Roles: (see description at end of task 3.1.4).

Task 3.1.2 Identify and implement measures to minimize impact of boiler operation

The range of boiler operating parameters will be determined that are necessary to maintain reliable operations. This will be based on both operations and coal quality. The optimum operating conditions for various coal properties will be determined. The range operational parameters necessary to achieve good performance as a function of coal quality will be determined through test burning selected fuels. The boiler operation methodologies will be tested to determine the reliability of operation as a function of boiler operation. Slag samples and deposits will be collected and characterized using SEMPC and XRD to determine potential operational effects on slag deposit characteristics.

Roles: (see description at end of task 3.1.4).

Task 3.1.3 Identify impact of fuel quality and boiler operation measures on compliance/stack emissions

The impact of the implementation of fuel quality and boiler operation measures on emissions will be monitored to minimize potential problems. Two fly ash samples will be characterized to determine size and composition using CCSEM analysis.

Roles: (see description at end of task 3.1.4).

Task 3.1.4 Identify design options

Design options will be identified based on the testing conducted in the fuel quality and operational measures implemented. In addition, a review of the performance of lignite-fired cyclone furnaces will be made. An assessment of changes in design will be made relative to system reliability.

Roles: BNI—coal quality mapping, selecting optimum fuel properties; MPC—boiler operations, evaluation effects of coal quality and operations on boiler performance, MTI—coal analysis monitoring of coal quality and boiler performance, E.M. Griffin and Associates—cyclone-boiler operation assessment/boiler design.

Task 3.2 Economic evaluation

Task 3.2.1 Fuel costs

The cost of mining coal blending and other methods to maintain optimum fuel quality for proper boiler operation will be determined.

Task 3.2.2 Operating and maintenance costs

The effectiveness of the measures to minimize the effects of ash on boiler operating and maintenance costs will be compared with prior experience.

Roles: BNI—evaluation of mining costs, MPC—evaluation of boiler operating and maintenance costs.

Task 4. Training / Workshops

Training workshops will be held at two locations during the course of this project to inform mining and boiler operations personnel regarding methods to minimize the adverse effects of ash on boiler performance. Optimum mining procedures to obtain coal that will minimize operational problems will be discussed. In addition, boiler operating parameters that effect performance will be discussed.

Roles: MTI—overview of coal quality and boiler operations effects on cyclone-fired boiler operations and use of CQMS software.

Task 5. Coordination

Task 5.1 CQ meetings

Quarterly coordination meetings of the coal quality task force will be held.

Task 5.2 Reporting

Progress reports will be prepared on a six-month basis that will provide data, observations, interpretations, project status, and project direction.

Task 5.3 Participation in LEC/LRC conferences

The results of the project will be presented at meetings and conferences.

6.3 Facilities

6.3.1 Microbeam Technologies Inc.

MTI was established in November 1991. MTI serves coal-fired utilities, boiler manufacturers, environmental consultants, as well as public and private research institutions worldwide, providing advanced CCSEM analysis of coal and related materials to solve ash-related problems. By far the majority of MTI clients are utility companies already faced with ash-related problems; that is, those trying to make informed operational changes in order to reduce problems caused as the result of inadequate fuel planning.

MTI owns a JEOL JSM-IC845A scanning electron microscope/microprobe analysis system. The SEM is equipped with stage automation, digital beam control, backscatter electron detector, energy dispersive x-ray analysis system, TN5500 x-ray and image analysis system and additional computers for data manipulation. MTI also has a modern sample preparation laboratory, including ashing furnaces and chemical fractionation facilities. Software available for program development include Borland's C++™ for Windows™, ZaPP, and NeuroSolutions™ for Windows™. MTI will purchase a laptop computer to be dedicated to the project.

6.3.2 BNI Coal Ltd.

With more than 50 years' operating experience in the lignite industry, BNI Coal Ltd., has the distinction of being the lowest cost producer to a major lignite user in the State. BNI began operating in 1930 as Baukol-Noonan. In 1988, Baukol-Noonan became a wholly-owned subsidiary of Minnesota Power.

BNI has coal supply agreements with Minnkota Power and Square Butte Electric Cooperative until 2027 with a 15-year extension clause. The four million tons of coal BNI supplies the two units at the Milton R. Young Station annually is equivalent to approximately 160 mined acres.

BNI uses two UNIX workstations built by Sun Microsystems, complete with digitizing table and plotter. The Geographic Information System at BNI coal is part of a large integrated mine planning software package named MINEX. MINEX consists of various software features such as geologic modeling, mine reserves, mine scheduling, dragline simulator, land surveying, and others. Borehole data (including borehole collars, seam intervals, lithology, and coal analyses) are stored with x, y, z values and can be mapped along with digital base map data (e.g. topography, cultural features, -- roads, section lines, etc.; and geologic features -- faults, outcrops, etc.). A geologic model can be created on the computer and this model can be displayed along with the above mentioned base map data as plans, cross sections, and contour maps. Reports, data transfers, and statistics can also be run on the borehole database as well as the modeled data. Mining plans and schedules can then be run to optimize mixing of the coal seams.

6.3.3 Minnkota Power Cooperative Inc.

Minnkota, headquartered in Grand Forks, N.D., has been providing valuable, affordable electricity for people in eastern North Dakota and northwestern Minnesota for more than 50 years. It supplies electricity to 12 associated distribution cooperatives in a 35,000 square-mile area.

The Milton R. Young Station consists of two units. Unit 1, which began producing electricity in 1970, is owned and operated by Minnkota Power. It has the capacity to produce 234,550 kilowatts (kW) of electricity and is the main source of generation for more than 88,000 customers served by the 12 Minnkota-associated cooperatives.

Unit 2, with a 438,000-kW generating capacity, began operating in 1977. It is owned by private investors and leased to Square Butte Electric Cooperative and operated by Minnkota. Square Butte was formed by the

Minnkota associated cooperatives to meet the increasing electrical demand of their consumer-owners and to provide electricity to Minnesota Power, a utility based in Duluth, MN.

The Milton R. Young Station, named for the late United States senator from North Dakota, has been consistently rated one of the lowest-cost coal-fired electric generators in the United States by the Utility Data Institute, Washington, D.C. Innovative technologies, efficient operations and an abundant coal supply from the nearby mine at BNI Coal, Ltd., have contributed to the plant's success.

6.3.4 E. M Griffin and Associates.

E.M. Griffin and Associates. is a consulting firm based in Westfield Center, OH, that offers services to the fossil power industry. Before starting his consulting firm in 1982, Mr. Griffin had work for Babcock and Wilcox for thirty years and had risen to the position of Senior Vice President in charge of the Fossil Power & Construction Group at Babcock and Wilcox.

6.3.5 University of North Dakota's Energy and Environmental Research Center

The viscosity measurement experiments will be performed at the University of North Dakota's Energy and Environmental Research Center (EERC) in Grand Forks, North Dakota. The EERC is a comprehensive research facility with extensive laboratory and pilot plant equipment. Among its other expertise, the EERC has years of experience in making viscosity measurements for slags of varied compositions.

7. Standard of Success

The progress of the project will be evaluated on a quarterly basis. The primary standard of success for the proposed work will be the extent of the reduction in the amount of oil burned at Milton R. Young Station to maintain slag. This must be accomplished considering costs of mining, fuel blending/handling, and boiler operations. An economic evaluation of the overall impact of matching coal quality with boiler operations will be conducted and will provide for evaluating the overall success of the project.

8. Background

8.1 Ash and Slag Behavior

The effects of ash on the performance of conventional boilers depends upon the inorganic composition of the fuel and operating conditions. Ash in conventional power systems is known to be a major problem that results in the loss of millions of dollars annually as a result of decrease in efficiency, unscheduled outages, equipment failures, and cleaning. The many ways in which the detrimental effects of ash manifest themselves in a boiler system include fireside ash deposition, corrosion and erosion of boiler parts, and production of fine particulates that are difficult to collect. The literature on ash-related issues is immense. Overviews of ash-related issues and compilations of work by many investigators can be found by referring to the work of Baxter and Desollar (7), Couch (8), Williamson and Wigley (9), Benson and others (10), Benson (11), Bryers and Vorres (12), Raask (13,14), and Watt (4).

A major problem with coal use is the high variability and complex associations of the inorganic components in coal. The association and abundance of major, minor and trace elements in coal is dependent upon coal rank and depositional environment. The inorganic components in lower rank subbituminous and lignitic coals are associated with the organic and mineral portions of the coal matrix. The lower rank coals contain high levels of oxygen some of which are in the form of carboxylic acid groups that can act as sites for cations such as Ca^{2+}, Mg^{2+}, Na^{+1}, K^{+1}, Sr^{+2}, and Ba^{+2}. Unlike lower ranked coals, the inorganic components associated with bituminous and anthracite are primarily in the form of minerals. The major mineral groups include quartz, clay minerals, pyrite, and carbonates. The abundance and association of minerals in coal has been reviewed and published in *Fundamentals of Coal Combustion for Clean and Efficient Use* (10). The sulfur oxide emissions in power plants are derived from organic sulfur and mineral forms such as pyrite, gypsum, barite, and others. Many air toxic metals are associated with the minerals in coal. Many considered to be air toxic metals such as Hg, Cd, Pb, As, and others are associated with or as sulfides. The association, fate, and behavior of air toxic metals has been reviewed and published in a Special Issue of *Fuel Processing Technology* (15).

Ash deposits on fireside heat exchange surfaces of power plants significantly decrease plant efficiency and are aggravated by variability in coal quality. Deposit formation is related to coal quality (chemical and physical characteristics of the inorganic material), system operating conditions, and system design (9). Variations in coal quality can significantly influence ash deposition on heat transfer surfaces resulting in decreased plant performance and availability. Deposits in the radiant and convective pass heat transfer surfaces of the boiler require sootblowing and loadshedding for removal, both of which decrease plant efficiency and availability. Ash accumulations on heat transfer surfaces require annual or semi-annual shutdowns for cleaning which results in cleaning costs and lost revenues from being off-line. In addition, maintaining slag flow in wet bottom boilers and cyclone-fired boilers can require co-firing of other fuels and outages to remove frozen slag resulting in decreased efficiency and availability.

In cyclone-fired systems the coal is injected into the cyclone with the primary air. Secondary air is added tangentially at 300 ft/sec resulting in coal particles impinging on the walls and burning in the molten slag. Depending upon the coal, the temperature of the cyclone exceeds 1650 °C (3000 °F) which is sufficient to melt the coal ash, thus producing slag. The slag flows from the cyclone through the slag tap opening. The ability of a slag to flow is dependent on its viscosity which in turn is dependent upon the slag chemical composition and temperatures. A typical viscosity plot is shown in Figure 1.

The maximum viscosity at which slag can be tapped from a cyclone is 250 poise. The temperature at which the slag has a viscosity of 250 poise is called T_{250}. Generally, for a coal to be appropriate for cyclone-firing, it must have a slag viscosity of 250 poise at 2600 °F or lower. In addition, the slag must be of sufficient thickness to retain the burning coal particles thereby transferring the coal ash to the slag and completing the combustion in the cyclone. In order to keep slag flowing, a boiler has to be operated at a temperature higher than T_{250}.

Another factor that influences the flow of slag is crystallization. The temperature at which a sudden transition in viscosity occurs is called the temperature of critical viscosity (T_{cv}). The rapid increase in viscosity on cooling below this temperature is a result of crystallization. Crystallization can cause sluggish slag flow and must be considered in slags that exhibit such behavior. In estimating when a slag is completely molten, the following consideration should be used:

if $T_{250} > T_{cv}$, then slag removal temperature must be greater than T_{250};
if $T_{250} < T_{cv}$, then slag removal temperature must be greater than T_{cv}.

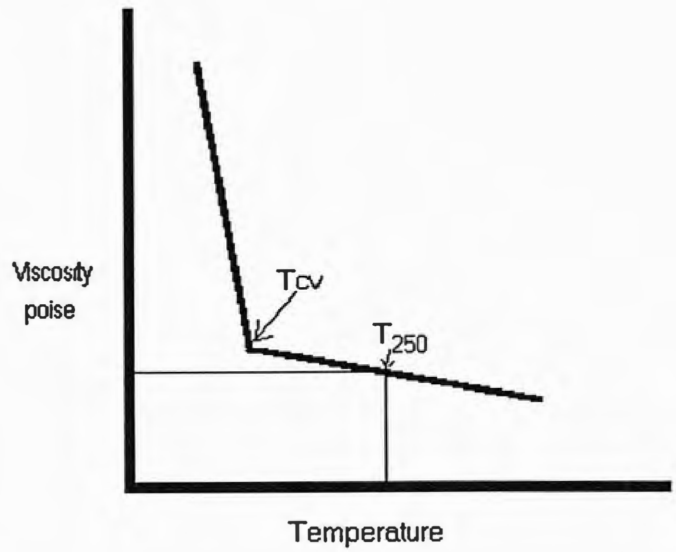

Figure 1. Viscosity plot for a typical coal slag plotted across a range of temperatures.

The major components of Center lignite slag are Si and Al. Aluminum in coal ash slag participates with the silicon oxide to increase the viscosity of the slag. Silicon dioxide is a good network former that produces slags with high viscosities. The more Si-O-Si bonds present, the higher the viscosity. Addition of Na^+, K^+, Mg^{++}, Ca^{++}, or Fe^{++} reduces the viscosity by breaking the Si-O-Si bonds and producing smaller silicate units.

There have been a number of methods developed to calculate viscosity based on slag composition and temperature. Some have been applied and tested on Center lignite and other lignites from the Northern Great Plains. MTI and BNI's CQMS model can provide viscosity calculations using both the Urbain model (1) and the Sage and McIlroy method (2). The Urbain method is based on the structure of silicate melts and has been tested extensively by some investigators. These methods have recently been reviewed by Folkedahl (3).

Upon combustion in a cyclone the mineral grains are much more likely to end up in the slag than the elements that are associated in the organic matrix because the minerals are larger in size and denser, causing them to impact the barrel of the cyclone. In order for the elements associated with the organic fraction to become incorporated into the slag, it is essential for the coal particle to burn in the molten slag thereby transferring the calcium, sodium, and other organically-associated elements into the slag. The elements associated with the mineral fraction of the coal (largely clay minerals and quartz) cause viscosity to increase and are sometimes difficult to dissolve into the molten slag. Previous work has shown that the chemical composition of the slag appears to differ significantly from the composition of the coal fired, indicating a partitioning effect. The slag is typically depleted in the Na, Mg, Ca and Fe and enriched in Al and Si as compared to the coal fired.

8.2 Predicting Ash Behavior

The prediction of ash behavior using conventional ASTM methods of analysis is severely limited because of the inadequacy of such methods to determine the chemical and physical characteristics of the inorganic components in the coal. Computer-controlled scanning electron microscopy (CCSEM) (16) is used to determine the size, composition, and abundance of minerals in coals. In lower ranked coals, chemical fractionation is used to determine the abundance of organically associated cations that are important to predict ash deposition behavior (17). The effects of these minerals on system performance and emissions can be predicted with a high degree of certainty using CCSEM and other advanced methods of analysis (18).

The components of the Coal Quality Management System are shown in Figure 2. The system operates on the Windows 95™ platform. Descriptions of the indices included in the software are listed below (see Appendix A for a description of the analysis techniques employed to provide the raw data for the CQMS software).

Advanced Boiler Performance Indices

MTI has developed a series of advanced indices that relates coal characteristics, as determined by CCSEM and chemical fractionation, to ash behavior in a coal-fired utility boiler. The indices appear promising, however, the database of coals and boiler types is still limited. In addition, problems with the viscosity calculations for certain types have been noted. Fuel performance is estimated in terms of slag flow behavior, abrasion and erosion wear, wall slagging, high temperature silicate-based convective pass fouling, and low temperature sulfate-based convective pass fouling. The following are the indices currently used by MTI to assess the effects of ash behavior on utility boiler performance:

- Convective Pass Fouling

  Sulfation Index: Indicates the propensity of a deposit to form in the convective pass of the utility boiler in the temperature range from 1000 to 1750 °F. This index is based on the availability of alkali (Na and K) and alkaline earth (Ca and Mg) elements to react with SO_2 and SO_3 to form sulfates. The sulfates are

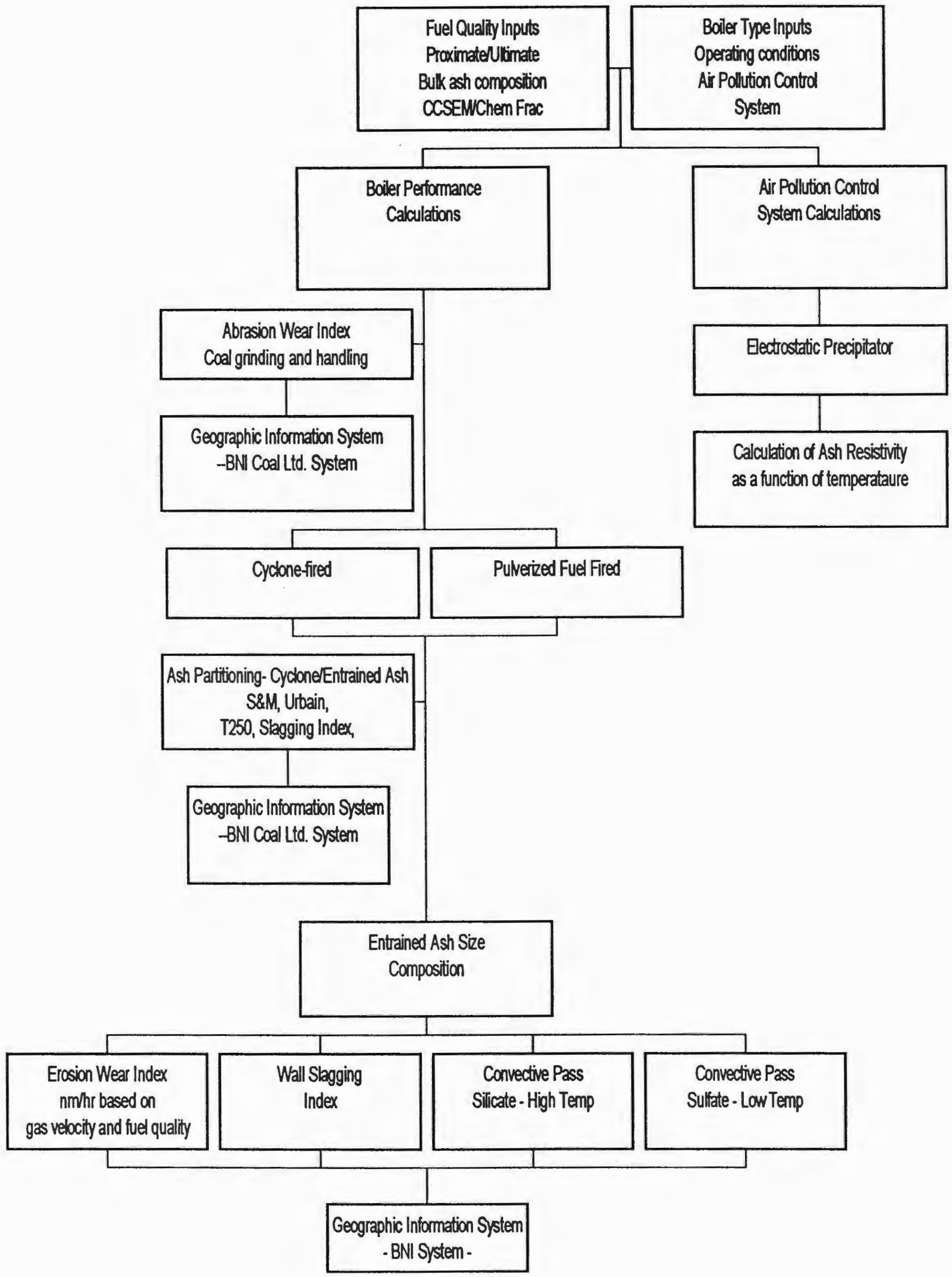

Figure 2. CQMS schematic diagram.

the primary materials that cause particle-to-particle bonding in high-calcium coals. The sulfates are thermodynamically stable at temperatures below about 1650 °F. Index values range from 1-low to 10-severe.

Silicate Index: Indicates the propensity of deposits to form from 1600 to 2400 °F. This index is related to the formation of deposits in which the silicate material is the primary component that bonds the deposits together. The information used to derive the index include the size of the minerals such as quartz and clay minerals, availability of alkali and alkaline earth elements, and the viscosity of the silicate liquid phase. Index values range from 1-low to 200-severe.

- Water Wall Slagging

  Slagging Index: Indicates the propensity of a deposits to form on the radiant walls from 2000 to 3000 °F. The basis of the slagging index is the size of the minerals (especially the illite, quartz, and pyrite), association of the calcium (calcite can contribute to slagging), and the viscosity of the silicate-based liquid phase. Index values range from 1 - low to 20 - severe.

- Wear Indices

  Abrasion Index: This index indicates the potential for wear of fuel preparation and handling equipment. The wear is related to the hardness of minerals in the coal. The primary minerals of concern include quartz and pyrite. The index values range from 0.1 - low to 10 - severe.

  Erosion Index: This index indicates the potential for wear of boiler parts due to the impaction of fly ash particles. The erosion index is dependent upon the size of each ash/mineral particle, and size and velocity of each particle. The index values range from 0.1 - low to 1.0 - severe.

- Cyclone Slagging Index: This index provides information on the slag flow behavior in cyclones. The factors that are included in this index include the partitioning of the ash in the cyclone based on size and association of the ash forming components in the coal. The partitioning of the ash between the slag and entrained ash can significantly influence the flow behavior of the slag. Standard partitioning criteria have been developed to provide the composition of the slag. The composition is used to estimate the viscosity of the slag as a function of temperature. The index values have several ranges as follows: 1 - low viscosity, 1.5-2.5 - optimum viscosity, >3.0 – slag freezing.

NOTE: The cyclone slagging index is related to the viscosity of the slag. The index is calculated based on the partitioning factors that indicate what materials are going to remain in the cyclone versus the materials that are likely to be entrained and leave the cyclone. The cyclone slagging index has been found to vary dramatically from 1.0 to over 4.0. The coals that have high indices for cyclone slag flow index (poor performance) have a low propensity for ash deposition in the radiant and convective pass fouling and vice versa.

- $\underline{T_{250}}$: This value represents the calculated temperature at which the slag viscosity will be 250 poise, based on ash composition. Given the fact that the upper limit of viscosity for slag fluidity is approximately 250 poise, the T_{250} is generally used as the maximum slag removal temperature. The cyclone temperature must be greater than the T_{250} in order for slag to flow from the cyclone.

  NOTES: The Sage and McIlroy method uses base-to-acid ratios to determine T_{250} values (2). Values are affected by reducing or oxidizing atmospheric conditions, with the slag viscosity profile being raised as the proportion of ferric iron decreases. The Sage and McIlroy method is considered to be valid for bituminous-type ash and for lignitic ash with acidic content over 60 percent.

  The Urbain method (1) categorizes slag constituents into three different groups: "glass formers," such as silicon and phosphorous, which tend to form the initial solid structures in molten slag; "modifiers," such as sodium, potassium, calcium, iron, and titanium, which extend the solid structure over a larger range; and "amphoterics," such as aluminum, boron, and iron, which can influence either the short-range or long-range solid structure of a slag. T_{250} for a given slag composition can be calculated based on the interactions of these three types of slag constituents. The Urbain method was originally applied to ceramics and has become an accepted technique for predicting viscosities for slicate-rich slags.

- <u>Strength Development Index</u>: The strength index is based on the ability of the deposited material to develop strength. Strength development is primarily dependent upon the abundance and viscosity of the liquid phase components in the deposits. Index values less than 0.25 indicate that the material will produce weak deposits, 0.25 to 0.34 weak-to-moderate strength deposits, 0.34-0.41 high-strength deposits, and >0.41 flowing slag.

- <u>Resistivity Calculations</u>: These calculations are based on Bickelhaupt's model (19) of ash behavior. The resistivity is calculated over a temperature range from 200 to 700 °F. The migration velocity of particles declines rapidly when the resistivity is higher than 2×10^{10} Ω-cm. The temperature at which the precipitator is operated and the chemical composition of the coal and resulting flue gas stream have a significant influence on the resistivity. In order for good precipitator performance the resistivity should be below 2×10^{10} Ω-cm.

Table 1 shows the summary of CQMS output data. Key parameters from the CCSEM and ASTM methods are presented with the calculated indices.

Table 1. Sample CQMS Output Data

MTI #	95-275	95-271	95-317	95-272	95-325	95-327	95-326	95-324	95-323	95-322	95-318	95-320
BNI #	**41-132HB**	**41-144KC**	**41-144 HA**	**41-144HB**	**41-168 KC**	**41-168 HA**	**41-168 HB**	**41-180 KC**	**41-180 HA**	**41-180 HB**	**41-192 KC**	**41-192 HA**
Total Quartz Content	3.1	17.0	18.8	9.8	30.3	8.7	8.8	11.4	20.0	3.9	15.0	17.4
Quartz < 10 microns	2.0	10.8	9.7	6.4	24.6	4.4	4.0	6.8	3.3	2.6	9.7	12.7
Total Kaolinite Content	5.8	10.6	16.7	10.8	7.7	6.4	1.7	9.5	4.4	2.4	14.3	28.0
Kaolinite Content < 10 microns	2.6	5.1	8.4	6.3	4.5	2.6	0.9	4.8	1.1	0.9	10.2	20.8
Total Montmorillonite	1.8	10.7	6.0	2.7	6.5	1.7	6.1	7.0	2.3	2.4	7.6	5.1
Total Illite	10.2	14.1	0.7	9.3	6.6	0.2	28.0	19.1	10.2	1.6	6.8	1.9
Total Pyrite	45.4	8.0	28.7	26.7	18.9	67.1	19.7	9.1	10.9	57.2	22.6	32.3
Pyrite Content < 10 microns	8.9	4.5	3.5	10.5	2.8	9.8	4.7	2.5	2.5	17.0	6.6	7.0
Gypsum Content	10.6	6.5	0.6	0.0	1.6	2.7	0.8	5.4	0.0	16.1	2.2	0.0
Proximate (as received)												
Total Moisture	36.50	30.95	40.62	41.66	36.24	38.23	37.50	37.90	37.99	38.21	37.85	39.52
Ash	7.39	10.30	4.80	4.63	9.26	6.22	7.58	9.05	8.1	4.37	6.88	5.91
Total Sulfur	1.49	0.94	0.55	0.55	1.49	1.08	0.75	0.99	0.64	0.86	0.90	0.85
Fixed Carbon	29.70	26.56	30.32	27.97	28.18	29.65	30.37	27.94	29.53	31.54	29.15	30.30
BTU/lb	7081	6597	6711	6593	6791	6957	6806	6584	6653	7194	6881	6835
Volatile Matter	26.41	27.26	24.26	25.74	26.32	25.90	24.55	25.11	24.42	25.88	26.13	24.27
Bulk Ash Composition												
% Moisture	36.50	30.95	40.62	41.66	36.24	38.23	37.50	37.90	37.99	38.21	37.85	39.52
% Ash (dry basis)	11.64	10.30	8.08	7.94	14.52	10.07	12.13	14.57	13.00	7.07	11.07	9.77
Na_2O	7.67	0.50	8.93	10.65	0.82	9.25	8.02	0.46	8.15	11.99	1.48	9.69
MgO	3.43	3.30	5.72	5.74	3.72	4.90	4.45	3.90	5.00	4.59	6.13	5.10
Al_2O_3	8.58	11.90	9.30	10.37	9.34	5.64	11.81	12.12	10.19	5.23	10.59	7.46
SiO_2	14.78	30.60	15.36	14.70	33.71	8.47	30.74	35.57	36.25	5.31	25.80	13.06
P_2O_5	0.22	0.20	0.43	0.06	0.15	0.42	0.25	0.07	0.26	0.23	0.25	0.24
SO_3	30.00	23.00	25.25	25.50	21.28	35.25	21.05	18.32	15.93	35.75	24.15	32.75
K_2O	0.65	1.20	0.50	0.96	0.47	0.62	1.52	1.03	1.22	0.47	0.55	0.60
CaO	13.86	16.80	23.51	21.00	15.31	18.94	12.10	17.15	14.87	15.43	20.01	18.98
TiO_2	0.27	1.30	0.27	0.39	0.72	0.29	0.40	0.51	0.29	0.16	0.48	0.28
MnO	0.02	0.20	0.08	0.03	0.07	0.05	0.04	0.10	0.07	0.04	0.07	0.12
Fe_2O_3	21.77	10.30	9.57	8.43	14.87	15.95	10.44	7.80	6.84	18.88	10.12	13.29
BaO	0.37	0.80	0.88	0.76	0.69	0.81	0.50	0.48	0.68	0.73	0.36	0.52
ADVANCED INDICES -												
Cyclone Slagging Index	1.33	2.77	1.2	1.28	2.5	1.1	2.6	3.3	2.9	0.4	2.2	1.3
Convective Pass Fouling												
silicate	132.05	0.71	82.44	102.43	29.47	108.33	109.93	16.29	176.22	137.49	14.19	149.54
sulfate	2.84	9.43	3.6	3.57	2.2	5.01	3.46	1.75	3.98	4.4	2.21	3.24
Wall Slagging Index	10.04	1.18	9.45	11	2.67	10.68	9.27	1.79	8.83	12.63	2.2	10.53
Erosion Index	0.17	0.19	0.19	0.15	0.17	0.19	0.22	0.21	0.27	0.17	0.17	0.17
Abrasion Index	2.53	2.14	1.08	0.71	6.46	1.55	1.41	2.25	1.93	0.83	1.75	1.68
Strength Index	0.46	0.32	0.63	0.66	0.35	1.11	0.35	0.3	0.33	1.32	0.43	0.63
T_{250} (Urbain) – °F	1980	2550	1950	1920	2590	1670	2500	2610	2520	1560	2300	1950
T_{250} (Sage and McIlroy) – °F	1962	2063	2317	2264	2021	2263	1960	2231	2020	2164	2169	2227

8.3 Mine Planning and Boiler Sampling

BNI coal currently conducts a pre-mining coring program where coal quality is determined in advance of dragline overburden removal activities and coal deliveries to the Young Station. The coring program consists of a core sample spacing of 200 feet parallel to the pits and for the length of the pits with a lateral spacing of 300 feet. Each core of each seam is analyzed for the proximate analysis plus mineral ash. This information is built into the coal quality data base and can be related back to the numerous applications and plots of coal quality in BNI's GIS system and the coal quality data base. Among these applications is a relationship of coal delivered by day, by pit and sample number, by unit, by time. Overall daily quality and interim quality can be determined for coal delivered to each unit. This information can then be compared to the oil burn data collected from the plant operations.

An as-fired coal sampling system, Coallector®, has been tested for its ability to collect unbiased coal samples for an as-fired system to an individual cyclone burner. Detailes of the sampling system is found in section 8.6 of this proposal.

Minnkota has purchased three additional coal samplers which have been installed on three cyclones of Unit 2 for continued sampling for as-fired coal quality. All four samplers will be used in the sample collection to determine coal quality going to the cyclones. Delivered coal quality and as-fired coal quality relationships and cyclone performance can then be compared and evaluated.

8.4 Previous Recent Work Determining Slag Viscosity of Center Lignite

T_{250} calculations to date have been performed using two methods, that of Urbain, and Sage and McIlroy. Discrepancies have been found between the two methods. In order to evaluate the viscosity models, five lignite slags of known performance were collected from the Milton R. Young Station's cyclone-fired furnaces. Table 2 shows the chemical composition of the slags and coals.

The calculated viscosities, as a function of temperature, are shown in Figure 3. The calculations are based on bulk composition and use the Urbain and Sage and McIlroy T_{250} methods. The calculated viscosities for the Unit #1 samples show some increases in the viscosity that appears to be related to oil firing. However, all the T_{250} for the Unit #1 slags were less than 2600 °F indicating proper operation. Based on the composition of the slags collected from Unit #1, no oil should have been required. The slag with the highest viscosity for Unit 1 was the slag that required oil firing. The increase in slag viscosity is attributed to the decrease in CaO content. The results indicate that the Unit #2 slags have a much higher viscosity because of the lower levels of calcium and other fluxing elements such as sodium, calcium, and magnesium. The calculation indicated that oil was required.

Table 2. Estimated Ash Composition of Coals that Produced Milton R. Young Station Slags. (wt.% equivalent oxide)

Calculated Ash Comp.	MTI 96-254 Slag Comp.	Fuel that Produced MTI 96-254	MTI 96-255 Slag Comp.	Fuel that Produced MTI 96-255	MTI 96-256 Slag Comp.	Fuel that Produced MTI 96-256	MTI 96-257 Slag Comp.	Fuel that Produced MTI 96-257	MTI 96-258 Slag Comp.	Fuel that Produced MTI 96-258
Na_2O	4.2	8.43	4.8	9.21	4.0	9.21	0.9	1.03	1.1	1.03
MgO	3.7	5.43	4.0	5.93	3.3	5.93	1.8	2.25	1.9	2.25
Al_2O_3	15.3	6.04	14.1	6.90	15.7	6.90	17.2	13.90	17.9	13.90
SiO_2	50.9	10.91	50.2	9.53	52.3	9.53	61.0	48.36	60.9	48.36
P_2O_5	0.0	0.61	0.1	6.25	0.1	6.25	0.0	0.20	0.1	0.20
SO_3	0.4	30.50	0.7	29.50	0.4	29.50	0.4	13.00	0.4	13.00
K_2O	1.8	0.49	0.9	0.53	1.9	0.53	2.4	1.98	2.2	1.98
CaO	14.2	22.25	14.3	25.67	12.5	25.67	6.5	7.02	6.6	7.02
TiO_2	0.7	0.16	0.5	0.65	0.6	0.65	0.7	0.65	0.7	0.65
MnO	0.1	0.04	0.1	0.07	0.1	0.07	0.1	0.05	0.1	0.05
Fe_2O_3	8.0	13.85	9.2	10.07	8.1	10.07	8.1	10.08	7.4	10.08
BaO	n.a.	0.72	n.a.	0.16	n.a.	0.16	n.a.	0.16	n.a.	0.16

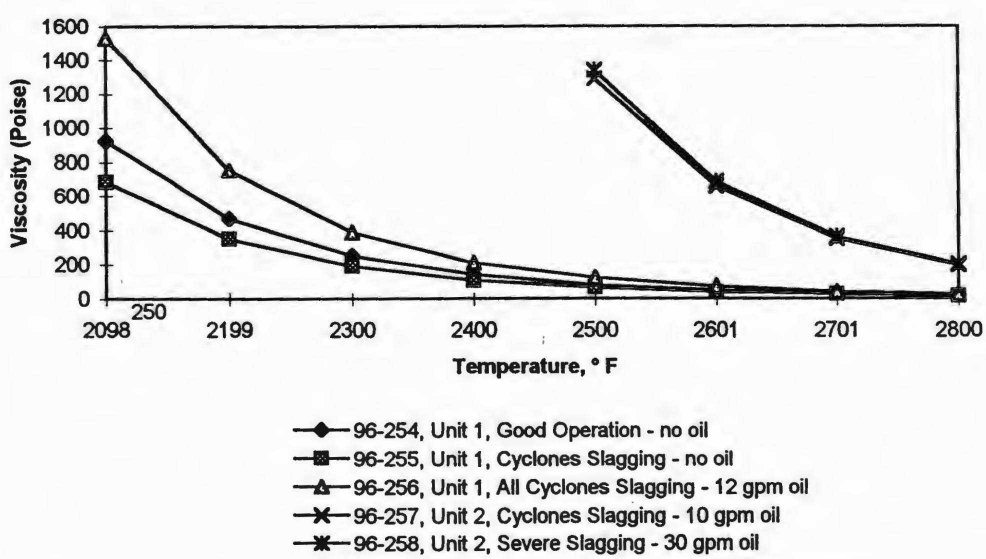

Figure 3. Calculated viscosities based on the chemical composition of the slag collected by Minnkota.

In order to better understand the differences in the viscosity calculation methods viscosities of the slags were measured using a rotating bob viscometer for Unit #1 (#1) MTI 96-254 and Unit #2 (#5) MTI 96-258. The results are shown in Table 3 and Figure 4. The viscosity of the Unit #1 slag was very low; it rapidly solidified at 2174 °F. This slag would be very liquid and easily flow from the cyclone. It may not provide a sufficient layer of slag for the coal particles to be retained during burning. The T_{cv} and T_{250} are the same. The Unit #2 slag was found to have a very high viscosity with a measured T_{250} of 2610 °F. The Unit #2 slag behaved as a glass and did not exhibit a T_{cv}. Comparison of the calculated viscosity at various temperatures shown in Figure 4, based on the Urbain, indicates general agreement with the measured data. The Urbain equation predicts T_{250} higher than measured.

The results of the Sage and McIlroy method T_{250} calculations for higher Si/Al ratios appear adequate. The Sage and McIlroy calculation method may not adequately predict the T_{250} when the slag is susceptible to crystallization resulting in rapid freezing of the slag as shown in Figure 4 for MTI 97-254. This slag has a definitive T_{cv}.

Table 3. Calculated and Measured T_{250} and Slagging Index

Sample #	Measured T_{cv}	Measured T_{250}	T_{250} (Urbain)	T_{250} (Sage & McIlroy)
MTI 96-254 (#1)	1190 °C (2174 °F)	1190 °C (2174 °F)	1260 °C (2300 °F)	(2050 °F)
MTI 96-255 (#2)	not measured	not measured	1238 °C (2260 °F)	not available
MTI 96-256 (#3)	not measured	not measured	1297 °C (2367 °F)	not available
MTI 96-257 (#4)	not measured	not measured	1518 °C 2764 °F	not available
MTI 96-258 (#5)	not detected	1432 °C 2610 °F	1520 °C (2768 °F)	(2675 °F)

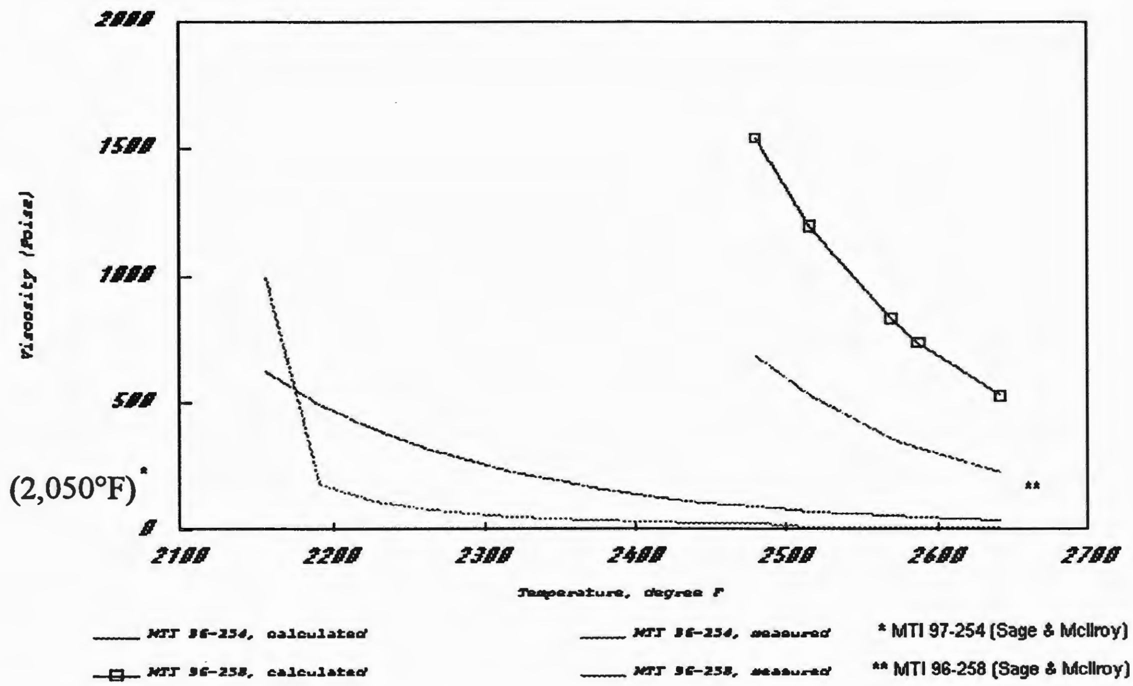

Figure 4. Measured and calculated viscosities as a function of temperature for a Unit 1 and a Unit 2 slag sample.

8.5 Identification of Oil Burning Trends

In previous work, plots of coal quality versus oil burning have been a primary focus of efforts in attempting to identify the causes of oil-burning events at Milton R. Young Unit 1. This has included plotting the major oxides present in the ash, sulfur, and ash base-to-acid ratios. The plots have not provided definitive information regarding specific ash components that contribute to oil burning although several trends have been noted. These trends are not reliable because the analyzed coal is not necessarily the same coal as fired in the utility boiler. The possible trends identified include:

- increase in oil burning with increase in the Al content of the ash in the coal fed.
- increase in oil burning with lower levels of Fe, possibly due to the fluxing action of iron.
- increase in oil burning with high base-to-acid ratio (high potential for crystallization) and low base-to-acid ratios (high viscosity slag). The trends for oil burning versus base-to-acid ratios are illustrated in Figure 5.

The difficulty in identifying trends was due to the inability to obtained as-fired coal samples.

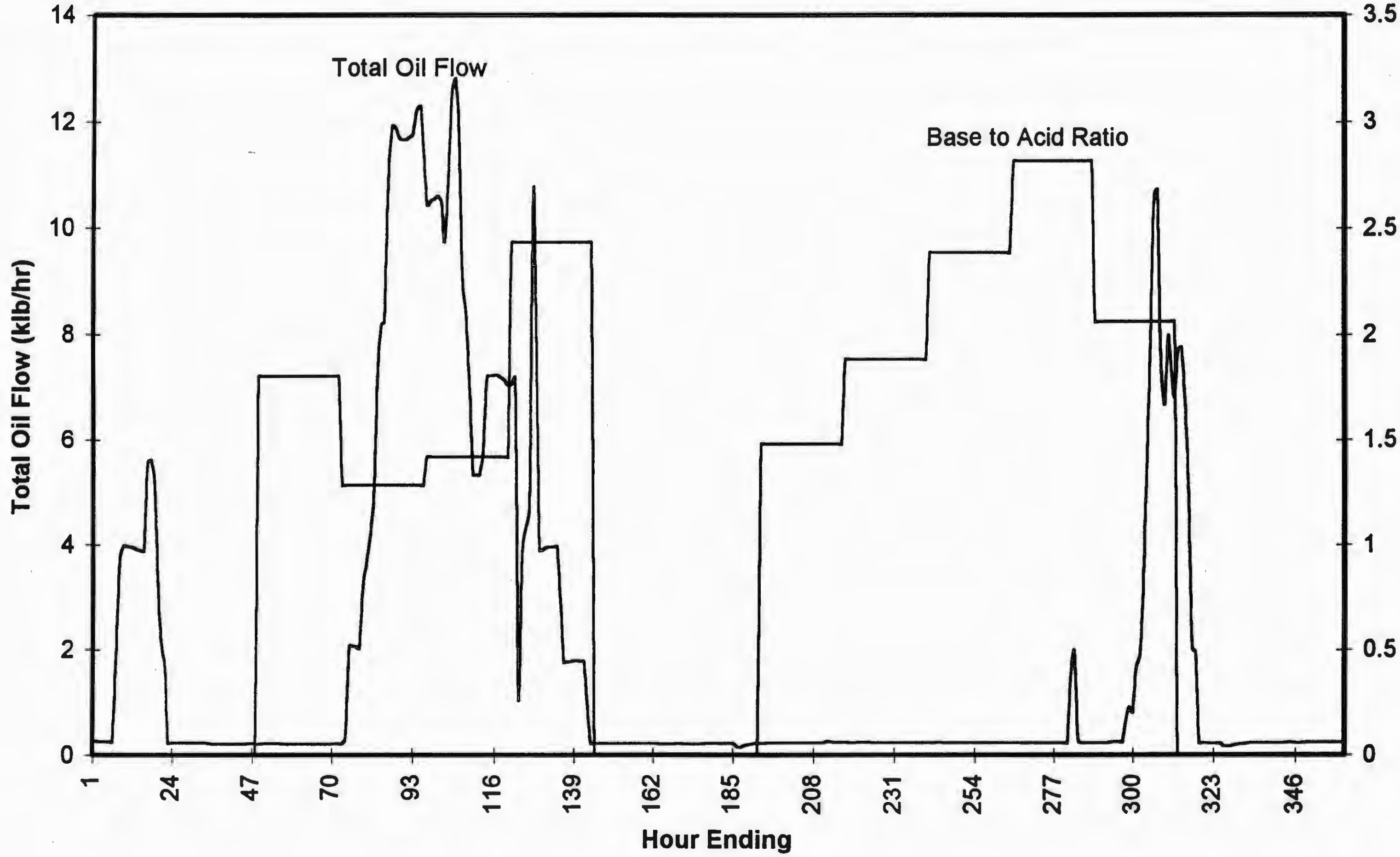

Figure 5. Unit 1—Base-to-acid ratio of coal delivered to coal yard vs. total oil flow, December 1-15, 1996.

8.6 Addition of As-fired Coal Sampling System

In order to make direct relationships between coal quality and cyclone boiler performance as-fired coal samples needed to be collected and related to boiler performance. A sampler designed to collect a coal sample prior to a cyclone was installed and tested. Stop belt coal samples and corresponding Coallector® samples were collected and analyzed. Bias testing was performed to determine if the sample collected in the sampler was biased in any way from the sample collected from the belt . The results indicated excellent agreement between the stop belt samples and the sampler samples. Figure 6 illustrates a comparison of the chemical composition of the belt and sampler samples.

The sampler system was used to collect coals during a cyclone slagging event that resulted in firing oil to melt the slag from the cyclone. The samples of coal were analyzed to determine the heating value and bulk ash composition. The bulk ash composition was used to calculate the T_{250}. During the testing the cyclone flame quality was visually monitored and recorded where a value of 7 is normal operation and a 5 is dark or oil firing mode. Figure 7a and 7b show the impact that increasing T_{250} has on cyclone burner performance. The T_{250} value is plotted along with oil burning and cyclone flame quality. The results indicate that high T_{250} values result in slag freezing and oil burning.

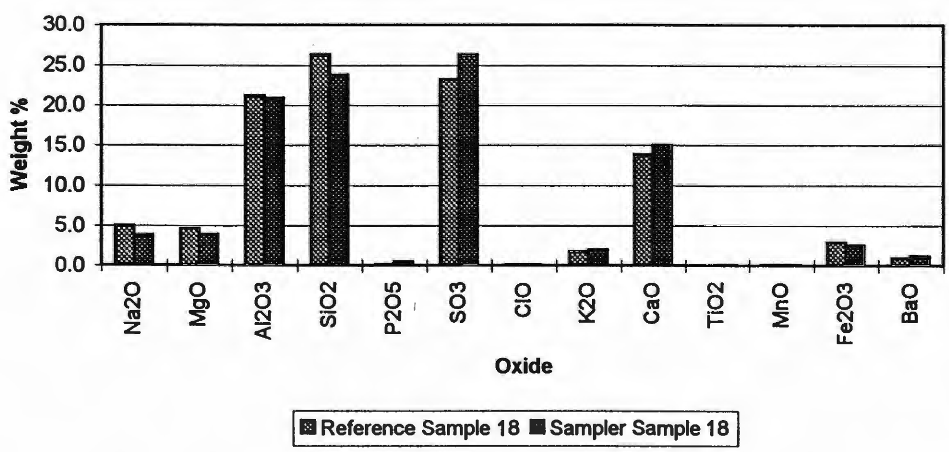

Figure 6. Ash composition comparisons between a Coallector® sample and reference sample.

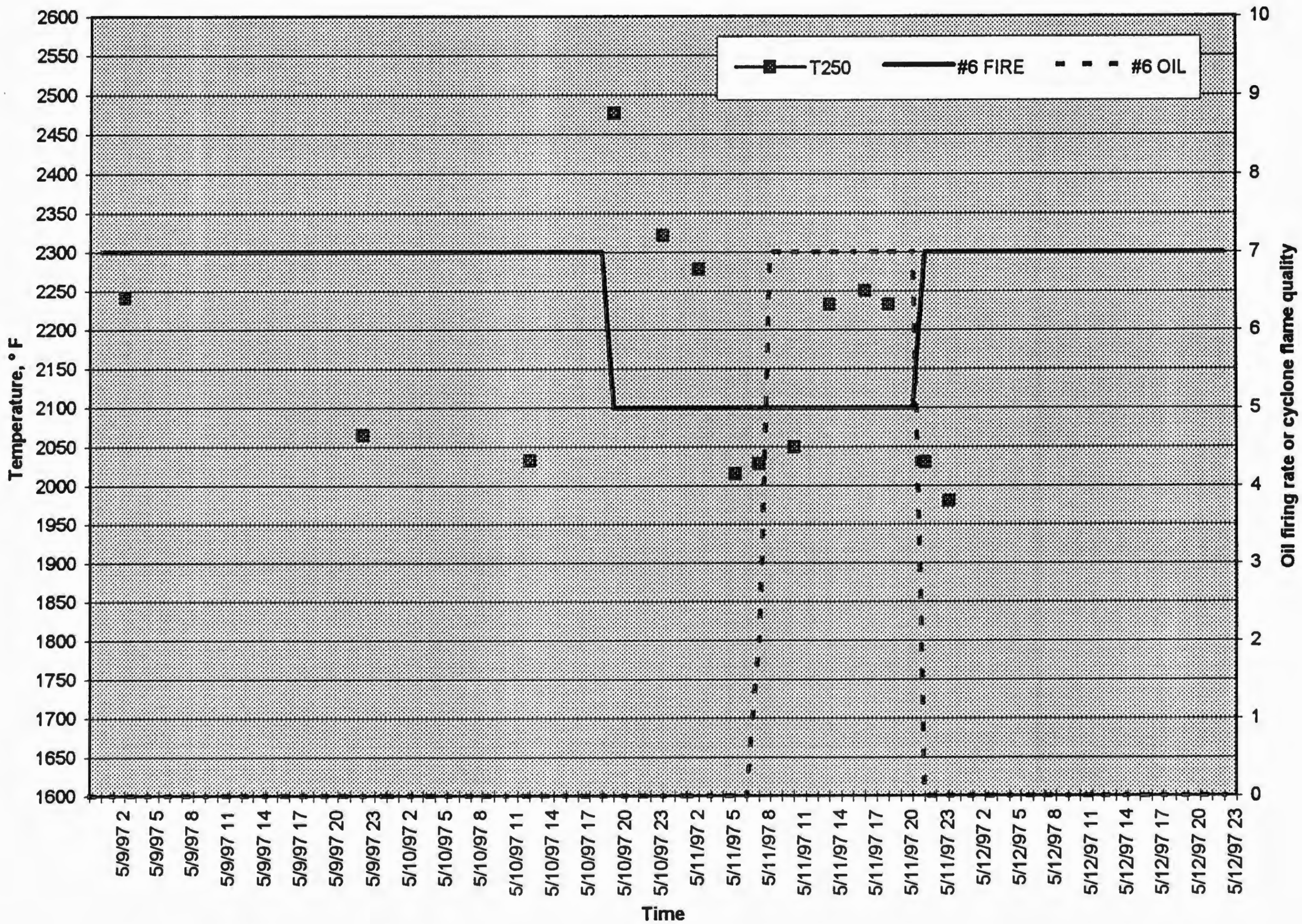

Figure 7a. Minnkota Power Unit #2—Coal feeder #6 (5/9/97 through 5/12/97).

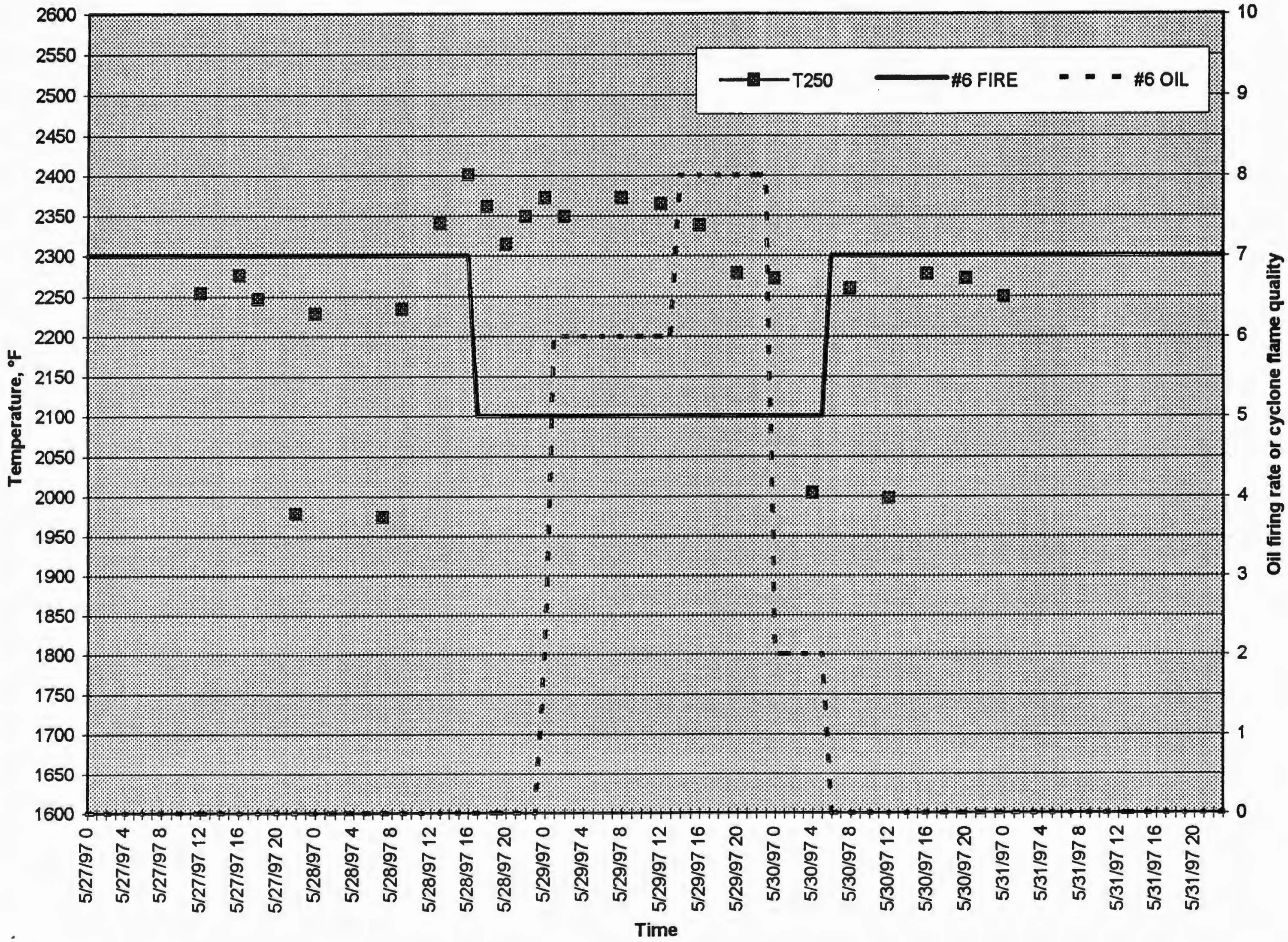

Figure 7b. Minnkota Power Unit #2—coal feeder #6 (5/27/97 through 5/31/97).

In some cases it was difficult to determine the potential for slag freezing solely based on T_{250} calculated from the bulk ash composition. Five samples of coal and corresponding slags were collected. The first sample of coal and slag corresponds to poor slag flow characteristics. The other four samples of coal and slag were collected when good slag flow was observed. The coals were analyzed to determine bulk chemical composition and size and abundance of minerals using CCSEM analysis. The CQMS software was used to calculate the fouling and slagging indices as well as the slag flow behavior of the coal ash slag using the Urbain and the Sage and McIlroy methods. T_{250} values were calculated on the coal ash composition and the slag composition using both methods. The CQMS summary data file is shown in Table 4.

The CQMS results indicate some very subtle differences between the characteristics of the coal and slag where difficulty was observed in maintaining slag flow and those where slag flow was good. The problematic coal MTI 97-226 and corresponding slag MTI 97-223 indicated very high T_{250} values based on the Urbain and low T_{250} values based on the Sage and McIlroy model. In general the Urbain method predicted higher viscosities than the Sage and McIlroy. In all but one case the T_{250} values of the slags were higher than the corresponding coal ash. This is due to the depletion of some elements such as sodium and magnesium as a result of volatilization and entrainment out of the cyclone during combustion.

The reason for the poor slag flow exhibited for MTI 97-223 is not evident from the bulk composition of the coal ash and the slag composition. The Urbain calculations of the T_{250} and the MTI slagging index indicated the potential for slag freezing for slag sample MTI 97-223 and the corresponding coal. The calculations based on the Urbain and MTI cyclone slagging index also indicated slag freezing for other coal ashes where good slag flow was observed. The most likely cause of the poor slag flow for MTI 97-223 is the presence of large clay minerals in the coal that are difficult to assimilate into the coal ash slag. The size of the aluminosilicate and silicate minerals is included in the calculation of the silicate convective pass fouling index. This index is related to the abundance of large aluminosilicate particles (mostly illite, kaolinite, and montmorrillonite clay minerals) that will accumulate on a heat transfer surface. The silicate index may also be used to assess the ability of the clay minerals to be incorporated into the slag melt. The silicate index was found to be the highest for the coal that produced the poor flowing slag. The index was found to be 137 as compared to the others that ranged from 65 to 126.

Table 4. CQMS Summary Data for Parent Coals and Slags.

MTI #	Coal 97-226	Slag 97-223	Coal 97-227	Slag 97-219	Coal 97-228	Slag 97-222	Coal 97-229	Slag 97-221	MTI 97-230	Slag 97-220
BNI #	073197 09		081497 10		081497 16		081597 10		081597 16	
Slag Flow	Poor		Good		Good		Good		Good	
Total Quartz Content	10.8		8.0		11.6		7.7		8.5	
Quartz < 10 microns	4.3		3.1		6.8		4.4		1.5	
Total Kaolinite Content	3.2		6.1		4.0		2.9		2.1	
Kaolinite Content < 10 microns	1.6		3.1		3.3		1.4		1.1	
Total Montmorillonite	4.0		6.4		2.1		3.9		2.1	
Total Illite	24.5		18.4		22.6		19.7		17.6	
Total Pyrite	15.7		16.9		18.1		16.7		40.0	
Pyrite Content < 10 microns	3.7		2.5		3.3		4.2		2.7	
Gypsum Content	1.1		.0		.0		.0		.0	
Proximate (as received)	13.1		11.0		8.6		12.0		12.7	
Total Moisture	34.59		36.09		36.67		36.69		36.03	
Ash	10.95		10.59		9.75		10.45		11.46	
Total Sulfur	0.94		1.26		0.94		1.08		1.09	
Fixed Carbon	28.14		28.04		26.78		27.67		26.97	
BTU/lb	6610		6581		6631		6539		6491	
Volatile Matter	26.32		25.28		26.80		25.19		25.54	
Bulk Ash Composition										
% Moisture	34.59		36.09		36.67		36.69		36.03	
% Ash (dry basis)	16.74		16.57		15.40		16.51		17.91	
Na2O	4.38	1.5	4.00	1.7	4.17	2.0	4.09	1.4	3.73	1.8
MgO	3.50	1.7	3.36	1.6	3.62	2.5	3.77	2.7	3.48	1.7
Al2O3	11.98	18.6	11.56	18.5	11.60	17.1	12.03	18.6	12.08	18.7
SiO2	38.46	50.0	38.92	51.7	37.28	45.8	39.01	49.3	41.12	53.3
P2O5	0.08	1.2	0.11	1.4	0.12	1.2	0.12	1.4	0.11	1.7
SO3	18.58	0.2	19.70	0.4	20.18	0.7	19.28	0.5	18.62	0.2
K2O	1.73	2.3	1.57	2.4	0.83	1.5	1.50	1.6	1.59	2.4
CaO	11.22	12.9	10.41	10.6	11.23	16.5	10.82	14.6	9.50	10.0
TiO2	0.47	0.9	0.44	0.8	0.45	0.8	0.48	0.8	0.51	0.8
MnO	0.07	0.0	0.06	0.0	0.06	0.0	0.06	0.0	0.06	0.0
Fe2O3	7.71	10.4	10.64	10.9	8.55	11.6	8.39	8.8	9.09	9.2
BaO	0.50	0.1	0.44	0.1	0.41	0.2	0.53	0.2	0.43	0.1
Cyclone Slagging Index	3.71	4.57	3.80	4.83	3.67	2.52	3.63	4.38	3.00	4.94
Convective Pass Fouling										
silicate	137.17		87.44		65.69		77.92		126.52	
sulfate	2.27		1.99		2.46		2.35		2.74	
Wall Slagging Index	8.61		7.22		6.91		7.36		10.28	
Erosion Index	0.23		0.26		0.24		0.27		0.32	
Abrasion Index	5.05		3.98		3.50		4.31		6.14	
Strength Index	0.28		0.28		0.29		0.29		0.35	
T_{250} (Urbain) – °F	2639	2877	2666	2944	2628	2246	2616	2827	2414	2969
T_{250} (Sage and McIlroy) – °F	2268	2396	2248	2434	2257	2057	2272	2386	2303	2487

References

1. Urbain, G., Cambier, F., Deletter, M., Anseau, M.R., 1981, "Viscosity of Silicate Melts," Transactions of the British Ceramic Society.
2. Sage, W.L., and McIlroy, J.B., "Relationship of Coal Ash Viscosity to Chemical Composition," *Combustion* 31(5): 41-48, Nov. 1959.
3. Folkedahl. B.C., "A Study of the Viscosity of Coal Ash and Slag." Ph.D. Thesis, Pennsylvania State University, 1997.
4. Watt, J.D., and Fereday, "The Flow Properties of Slags Formed from the Ashes of British Coals: Part I. Viscosity of Homogeneous Liquid Slags in Relation to Slag Composition," *Journal of the Institute of Fuel*, 42 (338): 99-103, March 1969.
5. Bale, C.W., A. D. Pelton, W.T. Thompson, "Facility for the Analysis of Chemical Thermodynamics (FACT)," CRCT, Ecole Polytechnique, De Montreal, P.O. Box 6079 Station "Downtown", Montreal, Quebec H3C 3A7, Canada.
6. Eriksson, G., "Thermodynamics Studies of High Temperature Equilibrium," XII, Chemica Scripta, 8, 100, 1975.
7. Baxter, L., and DeSollar, R. (Eds.)(1996). *Applications of Advanced Technology to Ash-Related Problems in Boilers*. New York: Plenum Press.
8. Couch, G., "Understanding Slagging and Fouling During pf Combustion," IEA Coal Research report; 1994.
9. Williamson, J., and Wigley, F. (Eds.) (1994). *The Impact of Ash Deposition on Coal Fired Plants: Proceedings of the Engineering Foundation Conference.* London: Taylor & Francis.
10. Benson, S.A., Jones, M.L. and Harb, J.N. Ash Formation and Deposition--Chapter 4. In: *Fundamentals of Coal Combustion for Clean and Efficient Use*, edited by Smoot, L.D. Amsterdam, London, New York, Tokyo: Elsevier, 1993, p. 299-373.
11. Benson, S.A. (Ed.) (1992). *Inorganic Transformations and Ash Deposition During Combustion.* New York: American Society of Mechanical Engineers for the Engineering Foundation.
12. Bryers, R.W.; Vorres, K.S., Eds. Proceedings of the Engineering Foundation Conference on Mineral Matter and Ash Deposition from Coal, Feb 22-26, 1988, Santa Barbara, CA, Unit Engineering Trustees Inc., 1990.
13. Raask, E. Erosion Wear in Coal Utility Boilers; Hemisphere: Washington, 1988.
14. Raask, E. Mineral Impurities in Coal Combustion; Hemisphere: Washington, 1985.
15. Trace Element Transformations in Coal-Fired Power Systems, Eds., S.A. Benson, E.N. Steadman, A.K. Mehta, and C.E. Schmidt, Special Issue, *Fuels Processing Technology*, Elsevier, 1994, vol. 39 (1-3), pp 489.
16. Zygarlicke, C.J. and Steadman, E.N., "Advanced SEM Techniques to Characterize Coal Minerals," Scanning Electron Microsc., Vol. 4, No. 3 (1990) pp. 579-590.
17. Benson, S.A.; Holm, P.L. "Comparison of Inorganic Constituents in Three Low-Rank Coals," Ind. Eng. Chem. Prod. Res. Dev. 1985, 24, 145.
18. Benson, S.A., Hurley, J.P., Zygarlicke, C.J., Steadman, E.N. and Erickson, T.A. Predicting Ash Behavior in Utility Boilers. *Energy & Fuels vol.*7 (6):746-754, 1993.
19. Bickelhaupt, R.E., Ed. Sparks, L.E. *A Study to Improve a Technique for Predicting Fly Ash Resistivity with Emphasis on the Effect of Sulfur Trioxide.* Washington, D.C.: U.S. Environmental Protection Agency, 1985.

9. Qualifications

Key Personnel:

William Peterson: Mr. Peterson holds the position of Geologist at BNI Coal, Ltd. in Center, North Dakota. Mr. Peterson has a bachelor's degree in geology, University of North Dakota. Mr. Peterson has twenty years of professional experience in the areas of environmental, geologic, and hydrogeologic assessments related to coal development and mining. Mr. Peterson has intensive experience with mine planning through the use of a GIS.

Richard Schwalbe: Mr. Schwalbe has been with Minnkota Power Cooperative Inc. for 27 years and currently holds the position of Senior Production Coordinator. Prior to his current position he was Operations Supervisor at Minnkota Power Cooperative Inc.

Steven A. Benson: Dr. Benson currently holds the position of President of MTI and Associate Director at the Energy and Environmental Research Center of the University of North Dakota. He has a Ph.D. in Fuel Science, Department of Materials Science and Engineering, The Pennsylvania State University. Dr. Benson has over 20 years of professional experience in the area of coal ash slagging and fouling, inorganic constituents in coals, scanning electron microscopy analysis and fundamentals of coal combustion. Dr. Benson is a member of several professional organizations and has written or co-written over 100 publications including two books and one more in press.

Karen A. Katrinak: Dr. Katrinak currently holds the position of SEM Applications Director at MTI. She has a Ph.D. in Geology from Arizona State University with an emphasis in electron microscopy of individual aerosol particles. Dr. Katrinak performed multivariate statistical analysis for aerosol particle characteristics. Before joining MTI, Dr. Katrinak was the manager of the Natural Materials Analytical Research Laboratory at the University of North Dakota Energy and Environmental Research Center. In addition to ten years of experience in scanning electron microscopy, Dr. Katrinak brings expertise in the development of new sample preparation and analytical procedures for coal, ash and other materials.

10. Value to North Dakota

The state of North Dakota will profit from the development of the proposed key performance tools in several ways. These tools will promote lignite use in North Dakota by reducing the need for burning oil in cyclone-fired systems that use lignite. The performance tools can be readily adapted to systems using other types of coal, and as such represent a promising new product that can be marketed to electrical utilities throughout the United States and internationally. Sales of this product will benefit North Dakota through increased salaries, taxes and support services.

11. Management

The overall project will be coordinated by the Coal Quality Task Force. Members of the Coal Quality Task force include represenatives of MPC, BNI, and MTI. In addition, a technical representative for the North Dakota Industrial Commission will be a member. Figure 8 illustrates how the management of the project will be accomplished.

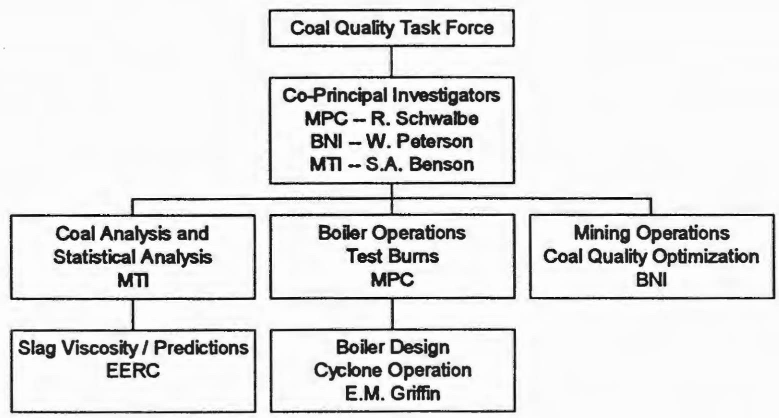

Figure 8. Management structure.

Meetings of the Coal Quality Task Force will be conducted on a minimum of a quarterly basis to monitor progress and provide directions for the project. Karen Katrinak will participate in the management of the statistical analysis of the boiler operation and coal quality data and the viscosity measurements at the EERC. Reporting will also be conducted on a quarterly basis to ensure all project team members are informed about the progress of the project. The project team has been working together for the past two and a half years.

12. Timetable

Project Start		**4/1/98**
		Completion Dates:
Task 1.	**Validation of Coal Quality Relationships to Operational Performance**	
1.1	Determination of optimum drill hole spacing	7/1/98
1.2	Determination of coal yard effects on as-fired coal quality	3/1/99
1.3	Test burns for acceptable/non-acceptable core quality for cyclone performance (T_{250} / T_{cv})	8/1/98
1.4	Viscosity measurements - validate predictions	12/1/98
1.5	Ash deposition correlations	12/1/98
Task 2	**Evaluation of Potential Solutions**	
2.1	Multivariate analysis of plant data	
2.1.1	Blending to meet cyclone performance	12/1/98
2.1.2	Operation of boiler related to ash deposition on waterwalls and convective pass and effects of ash on air pollution control devices	2/1/99
2.2	Boiler design options	5/1/99
Task 3	**Performance Optimization**	
3.1	Reliability	
3.1.1	Identify and implement measures to minimize the impact of fuel quality	6/1/99
3.1.2	Identify and implement measures to minimize impact of boiler operation	6/1/99
3.1.3	Identify impact of fuel quality and boiler operation measures on compliance/ stack emissions	7/1/99
3.1.4	Identify design options	7/1/99
3.2	Economic evaluation	
3.2.1	Fuel costs	8/1/99
3.2.2	Operating and maintenance costs	8/1/99
Task 4.	**Training / Workshops**	
4.1	Boiler operations personnel	10/1/98
4.2	Mining operations personnel	10/1/98
Task 5.	**Coordination**	
5.1	CQ meetings	Quarterly
5.2	Reporting	Quarterly
5.3	Participation in LEC / LRC conferences	Annually

Quarterly dates for reports and meeting are as follows: 7/1/98, 10/1/98, 1/1/99, 4/1/99, 7/1/99, and final report/meeting 10/1/99.

13. Budget

A breakdown of project costs by project year and by funding source is summarized in the attached budget. The itemized costs proposed to be funded by NDIC is labeled "NDIC share" in the attached budget. The amount of the subcontract to the University of North Dakota EERC is listed in the budget with NDIC and U.S. Department of Energy contributions itemized separately. The costs include the purchase of a laptop computer that will be used for the field testing of the performance tools and data reduction on site. The funding from NDIC is needed in this project to demonstrate the ability of the technology to be able to effectively predict and plan fuel quality, optimize boiler operating conditions, and identify boiler design options.

14. Matching funds

The matching funds include $967,364 from Minnesota Power Cooperative Inc. and BNI Coal Ltd. which includes a cash contribution of $40,000. The in-kind costs consists of BNI personnel time as well as sample collection costs, cost of ASTM sample analysis, and computer time.

An additional $25,435 in matching funds will be provided by the U.S. Department of Energy through its Jointly Sponsored Research Program, as part of the viscosity measurement work being subcontracted to the University of North Dakota's Energy and Environmental Research Center.

15. Tax Liability – see attached affidavit.

16. Confidential Information – none.

D[illegible]led Budget for "Matching Coal Quality and Boiler Operation" prop

	Year 1	Year 2	Subtotals	Total Project Costs	BNI Share Inkind/Cash	Minnkota Share Inkind/Cash	NDIC Share
Personnel							
Steven Benson, Project Manager	$10,174.14	$9,052.53	$19,226.67				
Karen Katrinak, Technical Manager	$15,535.00	$9,691.50	$25,226.50				
Computer Programmer	$7,905.40	$1,932.06	$9,837.46				
Student	$2,380.00	$1,249.50	$3,629.50				
BNI Manager	$39,658.00	$15,519.00	$55,177.00				
BNI Geologist	$36,210.00	$12,071.00	$48,281.00				
Minnkota Power Production Staff	$74,812.00	$37,406.00	112,218.00				
Minnkota Operator	$20,451.00	$10,225.00	$30,676.00				
Total Personnel	$207,125.54	$97,146.59		$304,272.13	$103,458.00	$142,894.00	$57,920.13
Fringe Benefits	$86,007.59	$39,330.85		$125,338.44	$46,556.10	$64,302.30	$14,480.04
Travel	$3,400.00	$2,100.00		$5,500.00	$0.00	$0.00	$5,500.00
Equipment	$4,500.00	$0.00		$4,500.00	$0.00	$0.00	$4,500.00
Supplies	$4,700.00	$1,350.00		$6,050.00	$500.00	$0.00	$5,550.00
Subcontracts	$90,658.00	$0.00		$90,658.00	$0.00	$52,500.00	$38,158.00
Construction	$0.00	$0.00		$0.00	$0.00	$0.00	$0.00
Other:							
Analysis:							
CCSEM	$52,000.00	$7,800.00					
Preps (grinding)	$6,000.00	$900.00					
XRD	$13,275.00	$7,375.00					
SEMPC	$24,300.00	$13,500.00					
BNI Coal Analyses	$120,000.00	$40,000.00					
MPC Coal Analyses	$94,279.50	$48,569.00					
Morphologies	$9,660.00	$690.00					
Chemical Fractionations	$9,570.00	$1,595.00					
Analysis Totals	$329,084.50	120,429.00	449,513.50				
BNI Computer Time	$3,000.00	$1,000.00	$4,000.00				
BNI Drilling Costs	$96,000.00	$30,000.00	126,000.00				
Other Total	$428,084.50	151,429.00		$579,513.50	$290,000.00	$142,848.50	$146,665.00
Total Direct Costs	$824,475.63	291,356.44		$1,115,832.07	$440,514.10	$402,544.80	$272,773.17
Indirect Charges	$82,447.57	$29,135.64		$111,583.21	$44,051.41	$40,254.48	$27,277.32
Total Direct and Indirect Costs	$906,923.20	320,492.08		$1,227,415.28	$484,565.51	$442,799.28	$300,050.49
BNI Cash Contribution					$40,000.00		($40,000.00)
Total Contributions					$524,565.51	$442,799.28	$260,050.49

Budget Breakdown by Task - Year

	Task 1	Task 2	Task .	Task 4	Task 5	Subtotals	Total Project Costs
Personnel							
Steven Benson, Project Manager	$3,350.52	$3,268.80			$3,554.82	$10,174.14	
Karen Katrinak, Technical Manager	$7,345.00	$4,680.00			$3,510.00	$15,535.00	
Computer Programmer	$6,542.40	$1,090.40			$272.60	$7,905.40	
Student	$1,890.00	$350.00			$140.00	$2,380.00	
BNI Manager	$24,138.00	$3,449.00	$6,897.00	$3,449.00	$1,725.00	$39,658.00	
BNI Geologist	$17,242.00	$3,449.00	$10,345.00	$3,449.00	$1,725.00	$36,210.00	
Minnkota Power Production Staff	$37,405.00	$21,461.00	$9,352.00	$4,676.00	$1,918.00	$74,812.00	
Minnkota Operator	$10,225.00	$2,557.00	$7,669.00	$0.00	$0.00	$20,451.00	
Total Personnel	$108,137.92	$40,305.20	$34,263.00	$11,574.00	$12,845.42		$207,125.54
Fringe Benefits	$44,836.48	$16,259.50	$15,418.35	$5,208.30	$4,284.96		$86,007.59
Travel	$2,040.00	$680.00	$0.00	$0.00	$680.00		$3,400.00
Equipment	$0.00	$4,500.00	$0.00	$0.00	$0.00		$4,500.00
Supplies	$3,500.00	$500.00	$500.00	$0.00	$200.00		$4,700.00
Subcontracts	$38,158.00	$26,250.00	$26,250.00	$0.00	$0.00		$90,658.00
Construction	$0.00	$0.00	$0.00	$0.00	$0.00		$0.00
Other:							
Analysis:							
CCSEM	$45,500.00	$6,500.00	$0.00	$0.00	$0.00	$52,000.00	
Preps (grinding)	$5,250.00	$750.00	$0.00	$0.00	$0.00	$6,000.00	
XRD	$13,275.00	$0.00	$0.00	$0.00	$0.00	$13,275.00	
SEMPC	$24,300.00	$0.00	$0.00	$0.00	$0.00	$24,300.00	
BNI Coal Analyses	$120,000.00	$0.00	$0.00	$0.00	$0.00	$120,000.00	
MPC Coal Analyses	$47,139.50	$23,570.00	$23,570.00	$0.00	$0.00	$94,279.50	
Morphologies	$9,660.00	$0.00	$0.00	$0.00	$0.00	$9,660.00	
Chemical Fractionation	$9,570.00	$0.00	$0.00	$0.00	$0.00	$9,570.00	
Analysis Totals	$274,694.50	$30,820.00	$23,570.00	$0.00	$0.00	$329,084.50	
BNI Computer Time	$1,500.00	$0.00	$1,500.00	$0.00	$0.00	$3,000.00	
BNI Drilling Costs	$96,000.00	$0.00	$0.00	$0.00	$0.00	$96,000.00	
Other Total	$372,194.50	$30,820.00	$25,070.00	$0.00	$0.00		$428,084.50
Total Direct Costs	$568,866.90	119,314.70	101,501.35	$16,782.30	$18,010.38		$824,475.63
Indirect Charges	$56,886.69	$11,931.47	$10,150.14	$1,678.23	$1,801.04		$82,447.57
Total Direct and Indirect Costs	$625,753.59	131,246.17	111,651.49	$18,460.53	$19,811.42		$906,923.20

Budget Breakdown by Task - Year ˜

	Task 1	Task 2	Task .	Task 4	Task 5	Subtotals	Total Project Costs
Personnel							
Steven Benson, Project Manager	$0.00	$0.00	$4,290.30	$2,445.47	$2,316.76	$9,052.53	
Karen Katrinak, Technical Manager	$0.00	$0.00	$5,323.50	$2,088.45	$2,279.55	$9,691.50	
Computer Programmer	$0.00	$0.00	$1,502.71	$286.23	$143.12	$1,932.06	
Student	$0.00	$0.00	$588.00	$588.00	$73.50	$1,249.50	
BNI Manager	$0.00	$0.00	$10,345.00	$3,449.00	$1,725.00	$15,519.00	
BNI Geologist	$0.00	$0.00	$6,897.00	$3,449.00	$1,725.00	$12,071.00	
Minnkota Power Production Staff	$0.00	$0.00	$30,812.00	$4,676.00	$1,918.00	$37,406.00	
Minnkota Operator	$0.00	$0.00	$10,225.00	$0.00	$0.00	$10,225.00	
Total Personnel	$0.00	$0.00	$69,983.51	$16,982.15	$10,180.93		$97,146.59
Fringe Benefits	$0.00	$0.00	$29,151.68	$6,560.34	$3,618.83		$39,330.85
Travel	$0.00	$0.00	$840.00	$840.00	$420.00		$2,100.00
Equipment	$0.00	$0.00	$0.00	$0.00	$0.00		$0.00
Supplies	$0.00	$0.00	$750.00	$500.00	$100.00		$1,350.00
Subcontracts	$0.00	$0.00	$0.00	$0.00	$0.00		$0.00
Construction	$0.00	$0.00	$0.00	$0.00	$0.00		$0.00
Other:							
Analysis:							
CCSEM	$0.00	$0.00	$7,800.00	$0.00	$0.00	$7,800.00	
Preps (grinding)	$0.00	$0.00	$900.00	$0.00	$0.00	$900.00	
XRD	$0.00	$0.00	$7,375.00	$0.00	$0.00	$7,375.00	
SEMPC	$0.00	$0.00	$13,500.00	$0.00	$0.00	$13,500.00	
BNI Coal Analyses	$40,000.00	$0.00	$0.00	$0.00	$0.00	$40,000.00	
MPC Coal Analyses	$0.00	$0.00	$48,569.00	$0.00	$0.00	$48,569.00	
Morphologies	$0.00	$0.00	$690.00	$0.00	$0.00	$690.00	
Chemical Fractionations	$0.00	$0.00	$1,595.00	$0.00	$0.00	$1,595.00	
Analysis Totals	$40,000.00	$0.00	$80,429.00	$0.00	$0.00	$120,429.00	
BNI Computer Time	$0.00	$0.00	$1,000.00	$0.00	$0.00	$1,000.00	
BNI Drillings Costs	$30,000.00	$0.00	$0.00	$0.00	$0.00	$30,000.00	
Other Total	$70,000.00	$0.00	$81,429.00	$0.00	$0.00		$151,429.00
Total Direct Costs	$70,000.00	$0.00	182,154.19	$24,882.49	$14,319.76		$291,356.44
Indirect Charges	$7,000.00	$0.00	$18,215.42	$2,488.25	$1,431.98		$29,135.64
Total Direct and Indirect Costs	$77,000.00	$0.00	200,369.60	$27,370.74	$15,751.74		$320,492.08

T[illegible] Budget Breakdown:

		Year 1					
		Task 1	Task 2	Task 3	Task 4	Task 5	Total
Trip to BNI/day:		3 Trips, 2 People, 3 Days	1 Trip, 2 People, 3 Days			1 Trip, 2 People, 3 Days	
Mileage/Car Rental	$100.00	$900.00	$300.00	$0.00	$0.00	$300.00	
Meals	$30.00	$540.00	$180.00	$0.00	$0.00	$180.00	
Hotel	$50.00	$600.00	$200.00	$0.00	$0.00	$200.00	
Parking, etc.	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	
Total Travel Year 1		$2,040.00	$680.00	$0.00	$0.00	$680.00	$3,400.00

		Year 2					
		Task 1	Task 2	Task 3	Task 4	Task 5	
Trip to BNI Conf./day:				2 Trips, 2 People 2 Days	2 Trips, 2 People 2 Days	1Trip, 2 People, 2 Days	
Mileage/Car Rental	$100.00	$0.00	$0.00	$400.00	$400.00	$200.00	
Meals	$30.00	$0.00	$0.00	$240.00	$240.00	$120.00	
Hotel	$50.00	$0.00	$0.00	$200.00	$200.00	$100.00	
Parking, etc.	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	
Total Travel Year 2		$0.00	$0.00	$840.00	$840.00	$420.00	$2,100.00

Equipment Budget Breakdown:

	Year 1					
	Task 1	Task 2	Task 3	Task 4	Task 5	Totals
Laptop Computer	$0.00	$4,500.00	$0.00	$0.00	$0.00	$4,500.00

	Year 2					
	Task 1	Task 2	Task 3	Task 4	Task 5	Totals
None	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00

Supplies Budget Breakdown:

	Year 1 Task 1	Task 2	Task 3	Task 4	Task 5	Totals
Office Supplies/Software (SPSS Advanced Statistics Package - $2,500.00)	$3,500.00	$500.00	$500.00	$0.00	$200.00	$4,700.00

	Year 2 Task 1	Task 2	Task 3	Task 4	Task 5	Totals
Office Supplies/Software	$0.00	$0.00	$750.00	$500.00	$100.00	$1,350.00

Subcontract Budget Breakdown:

	Year 1 Task 1	Task 2	Task 3	Task 4	Task 5	Totals
UND - see attached sheet	$38,158.00	$0.00	$0.00	$0.00	$0.00	$38,158.00
EM Griffin & Associates	$0.00	$26,250.00	$26,250.00	$0.00	$0.00	$52,500.00
Totals	$38,158.00	$26,250.00	$26,250.00	$0.00	$0.00	$90,658.00

	Year 2 Task 1	Task 2	Task 3	Task 4	Task 5	Totals
None	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Totals	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00

sis Breakdown: **Yea**

	Number/ Cost per Analysis	Task 1	Number/ Cost per Analyses	Task 2	Task 3	Task 4	Task 5	Totals
CCSEM	70/$650	$45,500.00	10/$650	$6,500.00	$0.00	$0.00	$0.00	$52,000.00
Preps (grinding)	70/$75	$5,250.00	10/$75	$750.00	$0.00	$0.00	$0.00	$6,000.00
XRD	45/$295	$13,275.00		$0.00	$0.00	$0.00	$0.00	$13,275.00
SEMPC	45/$540	$24,300.00		$0.00	$0.00	$0.00	$0.00	$24,300.00
BNI Coal Analyses		$120,000.00		$0.00	$0.00	$0.00	$0.00	$120,000.00
MPC Coal Analyses		$47,139.50		$23,570.00	$23,570.00	$0.00	$0.00	$94,279.50
Morphologies	70/$138	$9,660.00		$0.00	$0.00	$0.00	$0.00	$9,660.00
Chemical Fractionation	6/$1595	$9,570.00		$0.00	$0.00	$0.00	$0.00	$9,570.00
Analysis Totals		$274,694.50		$30,820.00	$23,570.00	$0.00	$0.00	$329,084.50
BNI Computer Time		$1,500.00		$0.00	$1,500.00	$0.00	$0.00	$3,000.00
BNI Drilling Costs		$96,000.00		$0.00	$0.00	$0.00	$0.00	$96,000.00
Other Total		$372,194.50		$30,820.00	$25,070.00	$0.00	$0.00	$428,084.50

Analysis Breakdown: **Year 2**

	Task 1	Task 2	Number/ Cost per Analysis	Task 3	Task 4	Task 5	Totals
CCSEM	$0.00	$0.00	12/$650	$7,800.00	$0.00	$0.00	$7,800.00
Preps (grinding)	$0.00	$0.00	12/$75	$900.00	$0.00	$0.00	$900.00
XRD	$0.00	$0.00	25/$295	$7,375.00	$0.00	$0.00	$7,375.00
SEMPC	$0.00	$0.00	25/$540	$13,500.00	$0.00	$0.00	$13,500.00
BNI Coal Analyses	$40,000.00	$0.00		$0.00	$0.00	$0.00	$40,000.00
MPC Coal Analyses	$0.00	$0.00		$48,569.00	$0.00	$0.00	$48,569.00
Morphologies	$0.00	$0.00	5/$138	$690.00	$0.00	$0.00	$690.00
Chemical Fractionations	$0.00	$0.00	1/$1595	$1,595.00	$0.00	$0.00	$1,595.00
Analysis Totals	$40,000.00	$0.00		$80,429.00	$0.00	$0.00	$120,429.00
BNI Computer Time	$0.00	$0.00		$1,000.00	$0.00	$0.00	$1,000.00
BNI Drillings Costs	$30,000.00	$0.00		$0.00	$0.00	$0.00	$30,000.00
Other Total	$70,000.00	$0.00		$81,429.00	$0.00	$0.00	$151,429.00