

**MERCURY OXIDATION VIA CATALYTIC BARRIER FILTERS:  
PHASE II**

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# MERCURY OXIDATION VIA CATALYTIC BARRIER FILTERS

## **Abstract**

The **goal** of this proposed project is to explore the feasibility of oxidizing elemental mercury in coal combustion flue gas using catalytic material impregnated onto barrier filters. Oxidizing elemental mercury will increase the effectiveness of control technologies for the removal of mercury from coal combustion flue gas prior to emission.

A Phase I project was designed as a proof-of-concept study, and demonstrated the feasibility of this concept. This Phase II project will further develop the feasibility of impregnated filters for mercury control. The success of the project will be indicated by the ability to impregnate the barrier filter material, to obtain high levels of mercury oxidation, to minimize the amount of SO<sub>3</sub> formation, and enhanced capture of mercury by fly ash on the fabric filter. Verification testing will be performed on a small-scale combustion test facility firing a range of coals.

The total cost of this 30 month project is \$245,000. The U.S. Department of Energy has committed \$200,000 toward the project and the University of North Dakota \$15,000. The project team is actively seeking \$15,000 from local utilities. The remaining \$15,000 for the project is being requested from the NDIC.

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## Table of Contents

Abstract.....	i
Project Summary.....	1
Introduction.....	3
Results from Phase I.....	5
Objective.....	6
Approach and Scope of Work.....	7
Standards of Success.....	7
Partnerships.....	8
Value to North Dakota.....	9
Management.....	9
Budget.....	12
Summary.....	13
Appendix A: Results from Phase I - Material in This Appendix is Confidential.....	15
Appendix B: Approach and Scope of Work - Material in This Appendix is Confidential.....	18
Appendix C – UND Chemical Engineering Combustion Research Facilities.....	26
Appendix D - Budget Details.....	30
Appendix E - Vita.....	33
Appendix F - Facilities.....	37
References.....	39

# MERCURY OXIDATION VIA CATALYTIC BARRIER FILTERS

## Project Summary

Development of mercury control technologies has been ongoing for the last decade. Implementation of EPA regulated controls for coal-fired power plants is scheduled for December 2007, yet there is currently no single best technology that can be applied broadly. Further, based on the current state of development, mercury control will be very costly, with estimates for its control as high as \$0.004/kWH (\$3-\$7 billion/yr). Injection of sorbents into the gas stream to capture the mercury is one of the most promising methods of control. Capture of mercury in wet scrubbers, the same devices that capture oxides of sulfur (acid rain precursors) also shows promise. Unfortunately, the performance of sorbents is reduced for elemental mercury while none of the current wet scrubber methods capture any appreciable elemental mercury. Thus, if mercury control targets are to be met and control costs reduced, methods to oxidize the elemental mercury to  $\text{Hg}^{2+}$  in the flue gases from coal-fired power plants must be developed.

The University of North Dakota (UND) Chemical Engineering Department has investigated the use of fabric filters as a method of contacting the mercury laden flue gas with the oxidation catalyst under a DOE UCR Innovative Concept Phase I grant. Preliminary data generated for catalytically impregnated barrier filters during the Phase I grant demonstrated between 85% and 95% oxidation of elemental mercury is possible through a catalyst-coated fabric. The Phase I project was designed as a proof-of-concept study. This Phase II project will further develop the feasibility of impregnated barrier filters for mercury control.

The feasibility of oxidizing elemental mercury in coal combustion flue gas using catalytic material impregnated onto barrier filters will be determined through two basic activities

1)investigating catalyst coating techniques and loadings, and 2)testing the performance of a catalytic barrier filter(s) under full combustion conditions. During the first activity, catalyst coating techniques and loadings will be investigated. The coated filter must be able to withstand frequent cleaning cycles and must exhibit a long life-time (2-3 years). During the second activity, the performance of barrier filter(s) utilizing the best catalyst and impregnating method at the optimal loading will be tested in UND's 17-kW furnace equipped with a small baghouse (one bag of 6" diameter and 30" in length). Coal will be fired in the furnace and the particulate laden flue gases ran through the baghouse. Mercury concentrations at the inlet and outlet of the baghouse will be determined using an online mercury analyzer to determine the extent of oxidation realized with the catalyst impregnated bags. Coal variability and the impact of flue gas components on oxidation levels will be explored.

# MERCURY OXIDATION VIA CATALYTIC BARRIER FILTERS

## Introduction

The **goal** of this proposed project is to explore the feasibility of oxidizing elemental mercury in coal combustion flue gas using catalytic material impregnated onto barrier filters. Oxidizing elemental mercury will increase the effectiveness of control technologies for the removal of mercury from coal combustion flue gas prior to emission.

Coal-fired utility boilers account for about 31% of the total U.S. anthropogenic mercury emissions (40 to 50 tons annually).<sup>1</sup> Oxidized gaseous and particulate forms of mercury are deposited near their source. However, the lifetime of elemental mercury in the atmosphere is estimated to be up to one year<sup>1</sup> and can be transported over trans-continental distances. While equilibrium calculations predict that elemental mercury should be almost completely converted to oxidized forms of gas or solid phase mercury ( $\text{Hg}^{2+}$ ) upon cooling, measurements of flue gas from boilers burning a variety of coals typically show only 35% to 95% oxidation<sup>9</sup>.

Development of mercury control technologies has been ongoing for the last decade. Implementation of EPA regulated controls for coal-fired power plants is scheduled for December 2007, yet there is currently no single best technology that can be applied broadly. Further, based on the current state of development, mercury control will be very costly, with estimates for its control as high as \$0.004/kWH (\$3-\$7 billion/yr).<sup>2</sup> Injection of sorbents into the gas stream to capture the mercury is one of the most promising methods of control. Capture of mercury in wet scrubbers, the same devices that capture oxides of sulfur (acid rain precursors) also shows promise. Partial capture is also accomplished in the baghouse by fly ash on the fabric filters. Unfortunately, the performance of sorbents and fly ash is reduced for elemental mercury<sup>1</sup> while

none of the current wet scrubber methods capture any appreciable elemental mercury.<sup>3</sup> Thus, if mercury control targets are to be met and control costs reduced, **methods to oxidize the elemental mercury to Hg<sup>2+</sup> in the flue gases from coal-fired power plants must be developed.**

Several researchers have focused on the oxidation of vapor-phase elemental mercury, primarily for enhanced mercury removal via wet flue-gas desulfurization (WFGD). WFGD systems are currently installed on about 25% of the coal utility generating capacity in the US. One of the more promising efforts by Radian International investigates catalytic oxidation<sup>4</sup>. Based on laboratory screening and field testing, between 70% to 96% of the elemental mercury can be oxidized utilizing Pd and or Pd-Carbon based catalysts. Tests with Pd-based pellets showed greater than 70% mercury oxidation at an area velocity over an order of magnitude greater than that typical of selective catalytic reduction (SCR) catalysts and nearly 100% oxidation at an area velocity about seven times greater, suggesting high mercury oxidation efficiencies could be achieved with a reactor much smaller than is typically required for SCR applications. Testing with honeycomb catalysts did not compare well with the oxidation by the pellets at the same area velocities. The honeycomb oxidized 51% of the Hg<sup>0</sup> while the Pd pellets showed 97% oxidation at similar conditions. The lower oxidation by the honeycomb could be a result of insufficient catalyst loading or inadequate flue gas contact with the catalyst surface. Results from the Radian work indicate that catalytic oxidation of mercury is possible at relatively low residence times, and that obtaining good flue gas/catalyst contact is important.

Other researchers have focused on alternate techniques to enhance mercury capture in the wet scrubber. Argonne National Laboratory (ANL) focused much of their initial work on “solution oxidation”, but found that the effectiveness of oxidants within the scrubber solution

were limited by gas- and liquid-film diffusion. They are currently pursuing NOXSORBJ, a chloric-acid oxidizing solution<sup>5</sup>. Babcock & Wilcox has been investigating scrubber additives including EDTA and H<sub>2</sub>S to enhance removal of Hg<sup>0</sup> in WFGD<sup>6</sup>. Other groups, such as ARCDIS are investigating the addition of oxidants to a variety of sorbents during their production process to increase the Hg<sup>0</sup> uptake capacity of the sorbent<sup>5</sup>.

Mercury capture across barrier filters as also been observed in both pilot and full scale testing. Certain ashes, such as those from lignite, show a higher potential for mercury capture than others. These “reactive ashes” are more effective at capturing oxidized than element mercury.

The positive results from catalytic oxidation testing, such as the work performed by Radian, inspired the University of North Dakota (UND) Chemical Engineering Department to propose the use of fabric filters as a method of contacting the mercury laden flue gas with the oxidation catalyst. Preliminary data have been generated for catalytically impregnated barrier filters through funding from a DOE UCR Innovative Concept Phase I grant. The Phase I project was designed as a proof-of-concept study. The current proposal will further develop the feasibility of impregnated barrier filters for mercury control.

## **Results from Phase I**

A Phase I scoping study has been completed using seed money from EPA and DOE. The University is currently seeking a patent on this process and considers those results confidential. Results from this work are therefore presented in Appendix A.

**Based upon the initial results from Phase I, we conclude that oxidation of mercury via catalytic barrier filters shows promise as a feasible technology for mercury emission control.** The high potential for development of a cost effective and technically efficient solution



for power plants employing filter-based ash removal systems suggests that further development activities are warranted.

## **Objective**

**The goal of this proposed Phase II project is to build upon the Phase I results so that we can determine the conditions under which oxidizing elemental mercury in coal combustion flue gas using catalytic material impregnated onto barrier filters is feasible.** Barrier filters will provide excellent contact between the mercury and catalyst and reduce the gas-film dependency observed for other contacting configurations. The excellent gas/catalyst contacting that can be provided by barrier filters is expected to overcome the current gas-diffusion limitations of competing technologies, i.e. packed beds and entrained injection. This should substantially reduce the amount of catalyst required to accomplish removal of elemental mercury (perhaps as much as 2 to 3 orders or magnitude compared to activated carbon entrained injection). Further, for existing and planned facilities utilizing barrier filters, this oxidation can be accomplished with virtually no additional capital expense. A secondary goal of this work is to determine the level of enhanced mercury capture by fly ash that can be achieved across a fabric filter containing an oxidizing catalyst.

This concept has been previously investigated for simultaneous control of NO<sub>x</sub> and particulates by Owens Corning and the UND Energy and Environmental Research Center (EERC)<sup>11</sup>. In their work, fabric samples were coated with SCR catalysts. NO<sub>x</sub> reductions of 90% were achieved while maintaining high particulate removal efficiencies. Variables that were studied that are of importance to the proposed work include catalyst deactivation, air-to-cloth ratio (residence time), SO<sub>2</sub> oxidation to SO<sub>3</sub>, catalyst coating technique, catalyst life, temperature cycling, fuel impacts, fabric cleaning, and filter performance/life. Several of these variables will

be examined in the proposed work, while others are more appropriate for a planned follow up demonstration-commercialization phase.

## **Approach and Scope of Work**

The University is currently seeking a patent on this process and considers the information in this section confidential. The approach and scope of work are therefore presented in Appendix B.

## **Standards of Success**

The success of the project will be indicated by the ability to impregnate the barrier filter material, to obtain high levels of mercury oxidation, to minimize the amount of SO<sub>3</sub> formation, and enhance capture of mercury by fly ash on the fabric filter.

The successful combination of mercury oxidation with particulate filtration has significant implications to coal-fired utilities as they begin formulating their mercury control strategies. While there are many possible control strategies, some of the more realistic options that are being considered include sorbent injection, capture in a wet scrubber, and packed-bed absorption<sup>9</sup>. Wet scrubbers are limited by their ability to capture only oxidized mercury. Oxidizing elemental mercury up stream of the scrubber would result in overall mercury removal efficiencies over 90%<sup>13</sup>. Packed-bed adsorption is expected to be high cost due to the high sorbent requirements dictated by poor adsorption of elemental mercury. Size and cost reductions of three to four times the current design are feasible by oxidizing the incoming mercury. Sorbent injection may be minimally affected by this technique, since a significant portion of the mercury occurs after the sorbent is captured on the fabric filter, and is enhanced for oxidized mercury<sup>9</sup>.

As discussed in the introduction, other researchers including Radian International have been conducting a variety of catalyst tests. These tests have focused primarily on conventional

packed-bed and honeycomb catalysts. In tests performed to date, the effectiveness of the honeycomb catalysts has been modest due to gas-diffusion limitations<sup>14</sup>. If determined feasible, impregnating the mercury oxidation catalyst on the barrier filter is expected to reduce the amount of catalyst by 2 to 3 orders of magnitude compared to the packed-bed.

Based upon success at this level, future work would involve a more rigorous investigation of impregnating techniques, filter materials, catalyst type and concentration, variability of gas composition, catalyst deactivation/poisoning, and catalyst life. Follow-on testing would be performed at a larger scale at the UND EERC with continued input from catalyst and baghouse vendors, DOE, and utility companies. This in turn will be followed by demonstration testing at a commercial facility.

## **Partnerships**

The UND Chemical Engineering Department is working with various project managers at the UND EERC. In particular, we are obtaining advice from personnel who managed projects that include catalytic coated bags for NO<sub>x</sub> control, the Advance Hybrid Particulate Collector, and the Center for Air Toxic Metals. They will play a lead role in any follow-on demonstration and commercialization work for the proposed concept. Also, during the preliminary phase of this project, the department has begun working with a baghouse supplier. The baghouse vendor, BHA Group, Inc. will help in proper selection of bag and designing experiments to adequately test the concept on the provided bags. In the proposed project, we will identify and establish a working relationship with a catalyst vendor, who will help finalize catalyst selection and provide input on the optimal methods for impregnating the bags with the selected catalyst.

## **Value to North Dakota**

The primary value of this concept is for those plants equipped with fabric filters. This limits its value in North Dakota somewhat, since a majority of the existing facilities utilize ESPs for particulate control. For the existing plant with the fabric filter, this concept offers an option to potentially meet upcoming mercury standards without adding major equipment to the plant. For future plants where an oxidation catalyst may be required as a part of the mercury control strategy, this concept offers an option that can significantly reduce the amount and subsequent cost of applying that catalyst.

## **Management**

The proposed project is a joint effort between three tenure-track faculty in the Chemical Engineering Department (resumes in Appendix D). Dr. Wayne Seames will have overall responsibility for project execution. He specializes in the mechanisms and control of trace elements generated during combustion. He will have specific responsibility to coordinate all of the combustion and analytical work performed under this project as well as overseeing the simulated flue gas-testing phase of the project. Dr. Seames has substantial experience in the design and execution of laboratory-scale coal combustion experiments including the types of gas doping experiments proposed in this project.

Dr. Michael Mann has worked in the area of power systems and environmental control for the past 20 years. He pioneered some of the early work on  $N_2O$  formation and control in the late 80's and early 90's. More recently he has been working with a pilot-scale wet scrubber simulator to enhance mercury control. He will be responsible for working with the baghouse vendor and ensuring proper filter selection and baghouse operation.

Dr. Darrin Muggli specializes in developing and evaluating catalytic processes. He has

developed a range of expertise and equipment to investigate transient reactions allowing him to more thoroughly investigate and manipulate mechanisms related to pollution control. Dr. Muggli will be responsible for the impregnation of catalyst onto barrier filter material.

Drs. Seames and Mann recently designed and built the 17-kw vertical downflow combustion system (commissioned in 2003) that forms the heart of this proposed work. This facility is equipped with two single bag baghouses that are operated in parallel, providing the flexibility required to successfully perform the proposed work. A machine shop is available for fabrication activities as required. This project will make use of an existing gas sampling system, particulate sampling probe including low-pressure impactors, cold-vapor attachment for flame atomic adsorption spectroscopy equipment, and glassware for an Ontario Hydro (modified EPA method 29) gas-phase mercury sampling train. The combustion furnace and particulate sampling methods are described in more detail in Appendix C. Analytical capabilities are described in the Facilities section of Appendix E.

Execution of this project will involve the purchase of an on-line mercury analyzer. The department is planning on purchasing an on-line analyzer with a dry mercury conversion system. The selection of this instrument will be based on experience and advice from the EERC. A similar analyzer (borrowed from the EERC) was used for much of the Phase I work, but is not expected to be available for the more extensive utilization proposed in this Phase II project.

The proposed project will be completed over a 30-month time frame. Specific milestones are shown on the project schedule in Figure 1.

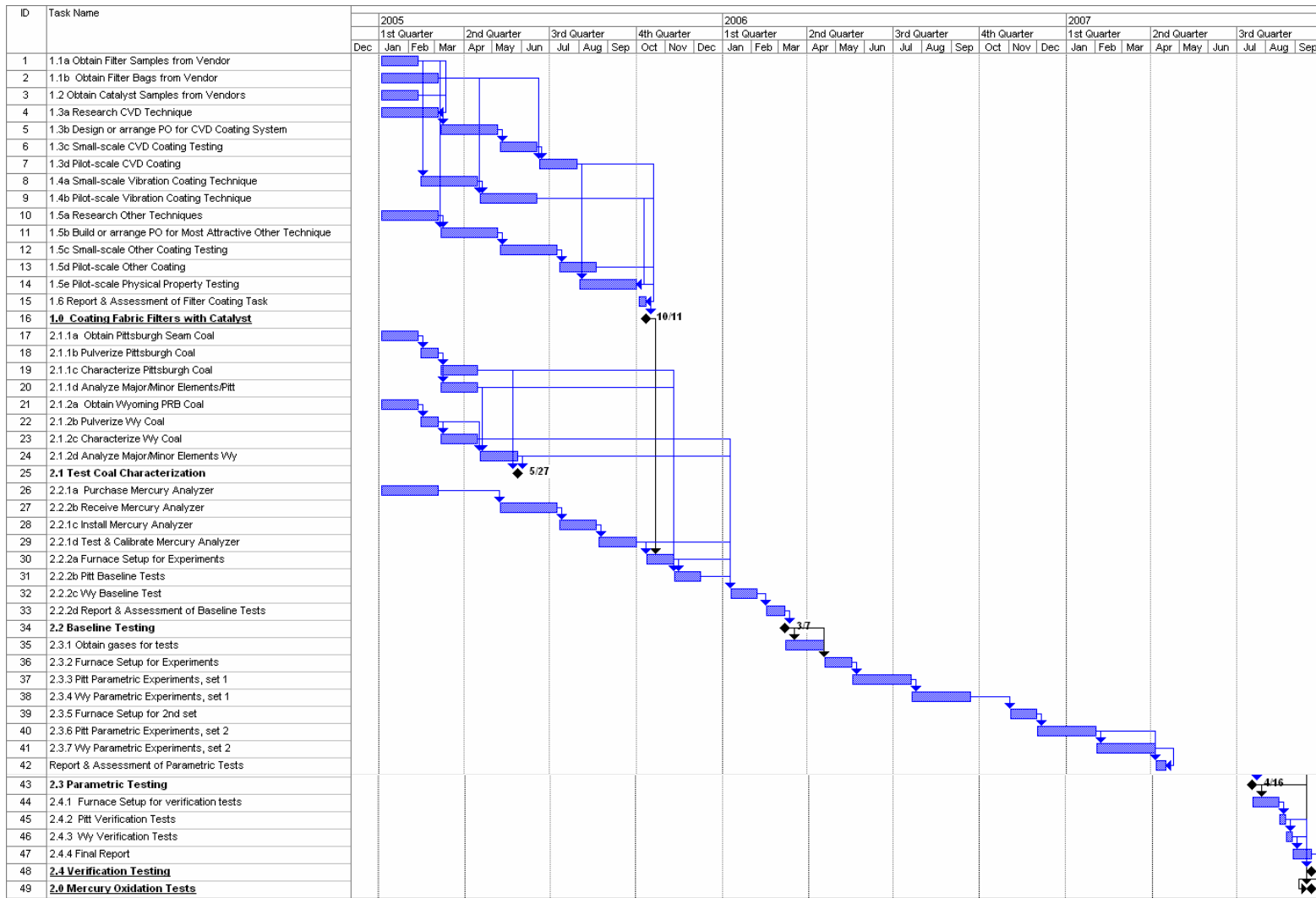


Figure 1. Work Breakdown Structure

## Budget

The budget for the project is presented in Table 1. The total cost of the project is \$245,000 as summarized in Table 1. The bulk of the personnel costs include student support at both the graduate and undergraduate level. This project will form the basis of a Ph.D. dissertation. The second year includes 0.25 months of summer faculty support. Operating supplies are primarily those to operate the test furnace and the required analytical support. The equipment to be purchased from this grant is an on-line mercury analyzer. Although the Chemical Engineering Department collaborates with the EERC on several projects, we do not have access to their mercury analyzers at the level required for successful completion of this project. Indirect costs are calculated at the University's standard rate. A more detailed discussion of each item in the budget is presented in Appendix D.

Table 1. Budget Summary

	Year 1	Year 2	Year 3	Total
Personnel	\$21,666	\$39,276	\$7,269	\$68,238
Operating Expenses	\$13,035	\$27,809	\$1,800	\$5,400
Equipment	\$90,000	\$0	\$0	\$90,000
Indirect Cost	\$13,950	\$26,566	\$3,602	\$44,118
Total Project Cost	\$123,651	\$93,651	\$12,698	\$245,000

A proposal has been submitted to and accepted for funding by the U.S. Department of Energy for the amount of \$200,000. The University has committed \$15,000 cash towards this project. We are currently working with the North Dakota utility community to raise an additional \$15,000. This request to the North Dakota Industrial Commission is for \$15,000, which would fully fund this project. A breakdown of the project funding is provided in Table 2.

Table 2. Project Funding Sources

<b>Source</b>	<b>Amount</b>
Department of Energy	\$200,000
University of North Dakota	\$15,000
Utility Support	\$15,000
NDIC	\$15,000
<b>Total</b>	<b>\$245,000</b>

## Summary

The goal of the proposed project is to determine the conditions under which oxidizing elemental mercury in coal combustion flue gas using catalytic material impregnated onto barrier filters is feasible. Oxidizing elemental mercury will increase the effectiveness of control technologies for the removal of mercury from coal combustion flue gas prior to emission. This concept, if feasible will substantially reduce the amount of catalyst required and the overall cost of mercury oxidation as compared to conventional pack-bed applications. An effective, low-cost option for oxidizing mercury greatly expands the viable options available for mercury control. This has significant implications to both utility and industrial coal-fired plants as they adapt mercury control strategies to meet the 2007 implementation of EPA's mercury control regulations.

The feasibility of oxidizing elemental mercury in coal combustion flue gas using catalytic material impregnated onto barrier filters will be determined through two basic activities 1) investigating catalyst coating techniques and loadings, and 2) testing the performance of a catalytic barrier filter(s) under full combustion conditions. During the first activity, catalyst coating techniques and loadings will be investigated. The coated filter must be able to withstand frequent cleaning cycles and must exhibit a long life-time (2-3 years). During the second activity, the performance of barrier filter(s) utilizing the best catalyst and impregnating method



at the optimal loading will be tested in UND's 17-kW furnace equipped with a small baghouse (one bag of 6" diameter and 30" in length). Coal will be fired in the furnace and the particulate laden flue gases ran through the baghouse. Mercury concentrations at the inlet and outlet of the baghouse will be determined using an online mercury analyzer to determine the extent of oxidation realized with the catalyst impregnated bags. Results will also quantify the level enhanced capture accomplished by the fly ash collected by the bags. Coal variability and the impact of flue gas components on oxidation levels will be explored.

The strong, balanced background of the three PI s and their successful experience on previous collaborative projects make them well suited for performing the proposed work.

## Appendix C – UND Chemical Engineering Combustion Research Facilities

### 17kW Downflow Laboratory Combustion System

The UND Chemical Engineering

Department vertical downflow combustion system was designed to allow well controlled and characterized solid fuel combustion experiments under realistic combustion conditions. The combustor's 15 cm internal diameter by 7 meter length provides a heterogeneous combustion environment and post-combustion residence/temperature profile that scales to commercial systems yet provides the well-defined transport properties necessary for mechanistic studies. The combustion zone is large

enough to allow heterogeneous effects (i.e. gas-particle, particle-particle, and liquid-particle interactions) to be studied; a task that is not possible in smaller drop-tube combustors.

The combustion zone can be operated under self-sustaining conditions or supplemental energy can be added through external heaters and/or natural gas. The external heaters are provided in the upper 2 meters of the furnace so that the combustion zone temperature can be manipulated independent from the coal feed rate. Facilities are also available to allow doping of

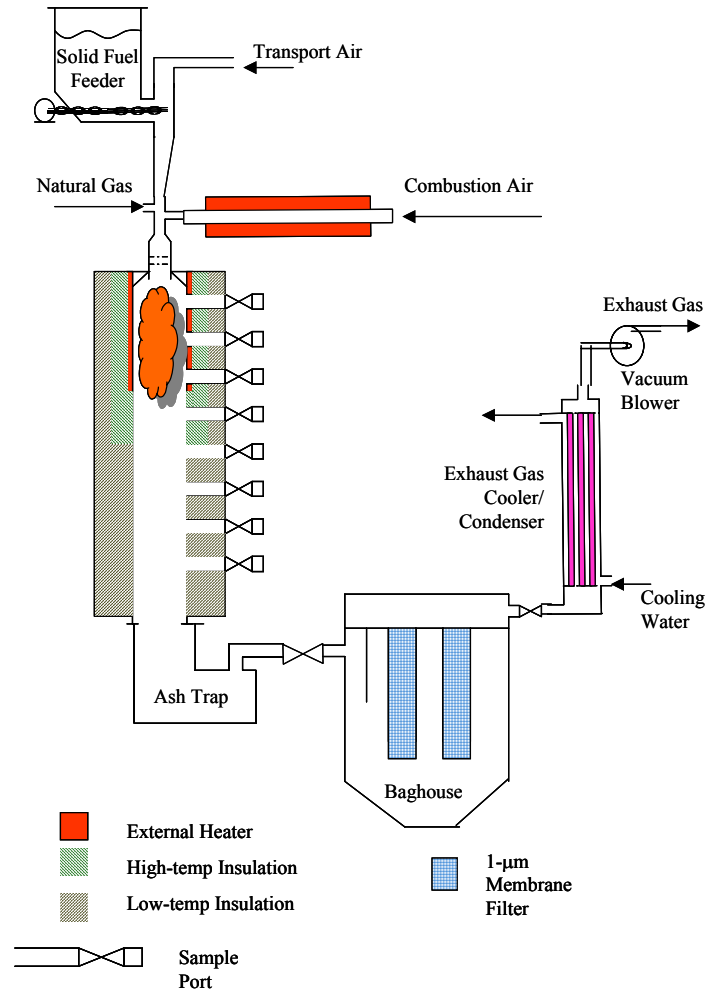


Figure 5. The University of North Dakota 17kW Downflow Vertical Combustion System

gases, liquids, and solids into the combustion environment.

A simplified schematic of the furnace system is provided in Figure 5. The top portion of the furnace is constructed of slag-resistant castable refractory. This is surrounded by the external heaters which are capable of heating the interior of the furnace to 1800 °C. The heaters are enclosed using Zircar SALI© unfired refractory cylinders and then kaowool blankets.

The lower portion of the furnace is constructed of unfired fibrous low-silica alumina cylinders insulated with kaowool blankets. Sample ports are located every 0.3m in the upper portion and every 0.46m in the lower portion of the furnace. Exhaust gases are routed through an ash trap and two parallel, single gas baghouses containing 6” ID by 30” long fabric or membrane filter elements.

### Gas and Particulate Sampling

Flue gas samples will be extracted from various sample ports using custom designed portable temperature, gas, and particle sample probes. Gas phase samples from the water-cooled probe are routed in heat traced sample tubing to a sample conditioning system and then to the on-line analyzers (paramagnetic oxygen analyzer, NDIR CO/CO<sub>2</sub> and SO<sub>2</sub> analyzers, and a chemiluminescent NO<sub>x</sub> analyzer). Included in this proposal is the purchase of an on-line mercury analyzer to

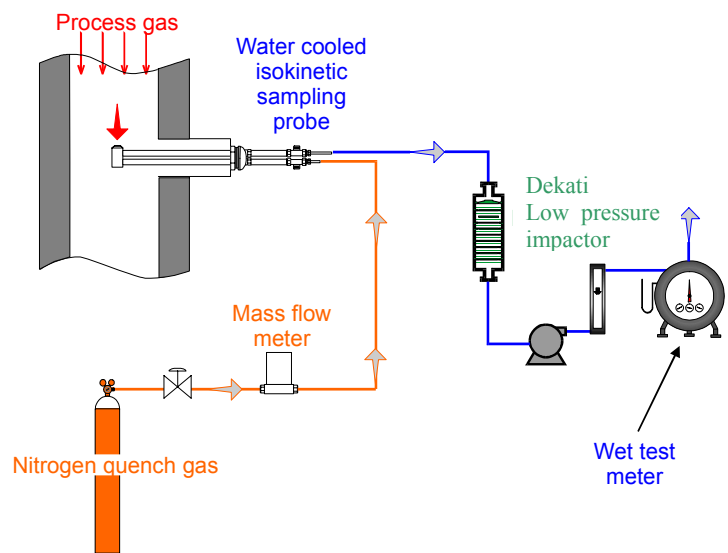


Figure 6. Size-segregated fly ash sampling system utilizing a Dekati low pressure impactor

improve the efficiency of gas-phase mercury concentration and oxidation state measurements.

Combined gas and fly ash samples are extracted isokinetically in a portable water-cooled sampling probe. The sample is diluted at the probe tip with nitrogen in the range of 20:1 to quench any further reaction. Water cooling is used to rapidly cool the sample, further reducing reactivity while inducing nucleation of gas-phase trace metals. The sample is routed through Tygon tubing and a Dekati low-pressure impactor (DLPI) using a high performance vacuum pump that maintains the DLPI outlet pressure at 8kPa. Flow rate is controlled through a critical flow orifice built into the impactor. A simplified schematic of the sampling system is shown in Figure 6.

The DLPI utilizes low pressure and high jet velocities to allow size segregation of particles in 13 collection plates of decreasing size as characterized by aerodynamic diameter D50% cutoff ranging from 10 to 0.030  $\mu\text{m}$ . Isokinetic sampling conditions are determined by comparing the  $\text{NO}_x$  concentration in the furnace to the  $\text{NO}_x$  concentration of the extracted sample.

A careful protocol will be followed to insure that an accurate particle size distribution is obtained from low mass DLPI ash samples. Polycarbonate membranes used in the DLPI will be coated with a high purity grease. The grease will be dissolved in hexane or toluene and applied using an air blast atomizer. The membranes will then be placed in petrie dishes and dried in an oven for at least 24 hours prior to use. Membranes will be preweighed shortly before loading into the DLPI on a microbalance with a resolution of 0.01 mg. New petrie dishes will be used to store the membranes after sample collection. These dishes will be preweighed on the microbalance and stored in a double layer of sealed polyethylene bags until use. After the membranes are placed into the preweighed dishes they will again be stored in a double layer of sealed polyethylene bags until they are weighed on the microbalance.

In order to obtain an accurate particle size distribution, samples must be collected both with and without an inlet cyclone on the DLPI. The cyclone is used to allow the longer sampling times (0.5-5 minutes) necessary to obtain sufficient mass on the submicron impactor stages without overloading the larger diameter stages. Sampling is repeated without the cyclone for a much shorter sampling time (5-20 seconds) to obtain a reasonable mass on the large diameter stages. By sampling back-to-back with two sets of impactor stages, a reasonable particle size distribution can be obtained.

## Appendix D - Budget Details

### 1. Personnel

Direct project salaries are estimated based on the scope of work and prior experience. Detailed calculations of Faculty and Student salaries are as follows:

<b>Senior Personnel</b>	
PI - W. Seames	0.25 month/yr taken in yr 2 @ \$6974/month
Co-Pi - M. Mann	0.25 month/yr taken in yr 2 @ \$7275/month
Co-PI - D.	0.25 month/yr taken in yr 2@\$6930/month
EARL Lab Manager	0.25 month/yr taken in yr 2@ \$3000/month
<b>Student Personnel</b>	
Grad Student Academic	1 @ \$12000/9 months
Grad Student Summer	1 @ \$4000/summer
Undergrad Summer	1 @ 40hrs/wk & \$7.0/hr

### 2. Fringe Benefits

Fringe benefits are estimated for proposal purposes only, on award implementation, only the true cost of each individual's fringe benefit plan will be charged to the project. Fringe benefits are comprised of the following: social security, state retirement, TIAA-CREF, health insurance, unemployment, worker's compensation, life insurance, and disability. Estimated rates are 26% for faculty, \$750/12 month year (\$700/academic year) for graduate students, and 0% for undergraduate students.

### 3. Travel

Travel is estimated based on UND travel policies, which include estimated GSA daily meal rates. Travel includes one annual review meeting per year for years 1 & 2 in Pittsburgh, PA and one technical conference at a location to be determined for year 3 at \$1800 per trip.

### 4. Contractual

No contracts are proposed in the performance of this work.

### 5. Equipment, Materials, and Supplies

An on-line mercury analyzer will be procured as a part of this project. This analyzer is estimated to cost \$90,000. The University of North Dakota will contribute \$15,000 towards

the cost of this analyzer. Laboratory and analytical-related supplies included in the “supplies” category includes laboratory supply items and minor equipment items including, but not limited to chemicals, consumable lab supplies, labware, and consumable gases. Office supplies include items specifically related to the proposed project and may be such items as pens, pencils, paper clips, printer paper and toner cartridges, notebooks (if needed), Post-It notes, computer diskettes, transparencies or other presentation materials, duplicating materials or charges, and other miscellaneous items required to complete the project.

**6. Other Direct Costs**

Includes analytical fees and combustion system operating fees. Analytical fees are estimated on a per sample basis with an average cost of \$8/sample. Combustion system operating fees are estimated at \$450 per day for 30 days.

**7. Indirect Costs**

The indirect cost rate included in this proposal is the federally approved rate for the University of North Dakota (40.2% in year 1 and 39.6% in years 2 and 3). Indirect costs are calculated based on the Modified Total Direct Costs (MTDC), defined as the Total Direct Costs of the project less individual items of equipment \$5,000 or greater and subcontracts in excess of the first \$25,000 for each award.

**8. Cost Participation**

The University of North Dakota will provide \$15,000 to share the cost for the purchase of the on-line mercury analyzer required for this project.

**9/10. Total Amount Requested / Matching Funds**

The source and amount of funds required to complete this project are provided below. The support from the Department of Energy and the University has been committed. We are currently seeking support from the utility community.

<b>Source</b>	<b>Amount</b>
Department of Energy	\$200,000
University of North Dakota	\$15,000
Utility Support	\$15,000
NDIC	\$15,000
<b>Total</b>	<b>\$245,000</b>

**UNIVERSITY OF NORTH  
BUDGET SUMMARY**

<b><u>PERSONNEL</u></b>	<b>Year 1</b>	<b>Year 2</b>	<b>Year 3</b>	<b>TOTAL</b>
SALARY - Faculty - PI	\$0	\$3,844	\$0	\$3,844
FRINGE	\$0	\$1,000	\$0	\$1,000
SALARY - Faculty - Other	\$0	\$7,648	\$0	\$7,648
FRINGE	\$0	\$1,989	\$0	\$1,989
SALARY - Research Personnel - Other	\$0	\$1,654	\$0	\$1,654
FRINGE	\$0	\$430	\$0	\$430
SALARY - Graduate Student	\$16,800	\$17,640	\$6,946	\$41,386
FRINGE	\$750	\$750	\$350	\$1,850
SALARY - Undergraduate Student	\$4,116	\$4,322	\$0	\$8,438
FRINGE	\$0	\$0	\$0	\$0
<b>TOTAL PERSONNEL</b>	<b>\$21,666</b>	<b>\$39,276</b>	<b>\$7,296</b>	<b>\$68,238</b>
<b><u>OPERATING EXPENSES</u></b>				
TRAVEL -	\$1,800	\$1,800	\$1,800	\$5,400
UTILITIES -				\$0
COMMUNICATIONS -	\$0	\$0	\$0	\$0
INSURANCE - Other				\$0
DATA PROCESSING -				\$0
RENTS & LEASES -				\$0
OFFICE - Supplies	\$0	\$0	\$0	\$0
REPAIRS - Other				\$0
SUPPLIES - Supplies	\$1,143	\$7,817	\$0	\$8,960
FEES - Other	\$10,092	\$18,192	\$0	\$28,284
SUBCONTRACT				\$0
INSTRUCTIONAL - Supplies				\$0
GENERAL - Other	\$0	\$0	\$0	\$0
<b>TOTAL OPERATING EXPENSES</b>	<b>\$13,035</b>	<b>\$27,809</b>	<b>\$1,800</b>	<b>\$42,644</b>
<b><u>EQUIPMENT</u></b>				
Mercury Analyzer	\$90,000			
<b>TOTAL EQUIPMENT COSTS</b>	<b>\$90,000</b>	<b>\$0</b>	<b>\$0</b>	<b>\$90,000</b>
<b>TOTAL DIRECT COST</b>	<b>\$124,701</b>	<b>\$67,085</b>	<b>\$9,096</b>	<b>\$200,882</b>
INDIRECT COST @ 40.2% OF	\$13,950			\$13,950
INDIRECT COST @39.6% OF		\$26,566	\$3,602	\$30,168
<b>TOTAL INDIRECT COST</b>	<b>\$13,950</b>	<b>\$26,566</b>	<b>\$3,602</b>	<b>\$44,118</b>
<b>TOTAL PROJECT COSTS</b>	<b>\$138,651</b>	<b>\$93,651</b>	<b>\$12,698</b>	<b>\$245,000</b>
UND COST	\$15,000	\$0	\$0	\$15,000
<b>TOTAL PROJECT COST</b>	<b>\$123,651</b>	<b>\$93,651</b>	<b>\$12,698</b>	<b>\$230,000</b>

Due to the limitations within the Universities accounting system, the system does not for accumulating and reporting of expenses at the detail level outlined above. The costs will accounted for and reported at the category level. The detail above is presented for evaluation purposes



## Appendix E - Vita

### WAYNE S. SEAMES

Assistant Professor, Department of Chemical Engineering,  
University of North Dakota (UND)

#### PRINCIPAL AREAS OF EXPERTISE

One of Dr. Seames' principal areas of expertise is investigating how to mitigate the impact of industrially generated particulates, heavy metals, and inorganic salts upon the environment. To date, his work in this area has primarily involved the emission of particulate and heavy metals in gaseous and solid waste streams during pulverized coal combustion. Other related work activities have involved heavy metals emissions from municipal sewage waste/biomass combustion and emissions from biologically derived diesel and jet fuels. Dr. Seames has expertise in current methods available for the elemental analysis of particulate matter, trace quantities of metals, and other inorganic components in highly heterogeneous media.

#### EDUCATION

2000, Ph.D. Chemical Engineering, University of Arizona  
Dissertation: The Partitioning of Trace Elements During Pulverized Coal Combustion  
1979, B.S. Chemical Engineering, University of Arizona  
30+ hours of Continuing Education Courses

#### PROFESSIONAL EXPERIENCE

2002 – Present      Director, Environmental Engineering Graduate Program, University of North Dakota, Grand Forks, ND  
2000 – Present      Assistant Professor, Department of Chemical Engineering, UND  
Director, Chemical Engineering Graduate Program, UND  
1995 – 2000      Independent Consultant, Seaway Consulting  
Graduate Instructor/Research Assistant, Dept. of Chemical Engineering, University of Arizona, Tucson, Az.  
1982 – 1995      Project Manager, Supervisor, Engineer, Saudi Arabian Oil Company, Houston, Tx. and Saudi Arabia.  
1979 – 1982      Chemical Engineer, Engineering Dept., Radian Corp., Austin, Tx.

#### PROFESSIONAL ACTIVITIES AND HONORS

- Member of AIChE, ISA, and ASEE professional societies.
- **Member of Chemical Engineering Magazine Product Research Council, 1985.**
- Received the "Award for Excellence at the Student Interface" from the Univ. of Arizona College of Engineering and Mines, 1999
- 1999-2000 T.K. Chapman Fellow

#### PUBLICATIONS

To date, Dr. Seames has published eight refereed papers. He has 11 additional, non-peer reviewed public publications and over 100 proprietary publications.

Publications relevant to the proposed research are provided beginning on page 28.

## **DR. MICHAEL D. MANN**

Associate Professor, Chemical Engineering Department  
Director, Engineering Doctoral Program  
University of North Dakota

### **PRINCIPAL AREAS OF EXPERTISE**

Advanced processes and technologies within the energy industry including multidisciplinary and integrated energy and environmental projects emphasizing a cradle-to-grave approach, i.e., development of energy strategies; selection of optimum utilization processes emphasizing clean coal technologies, integration of effluent treatment, and emission controls; and development of sustainable energy sources including wind and hydrogen.

### **EDUCATION**

- 1997 Ph.D., Energy Engineering, University of North Dakota, 1997.  
Dissertation: "Capture of Alkali During Pressurized Fluidized-Bed Combustion Using In-Bed Sorbents."  
1988 M.B.A., University of North Dakota  
1981 M.S., Chemical Engineering, University of North Dakota  
1979 B.S., Chemistry and Mathematics, Mayville State College (North Dakota)

### **PROFESSIONAL EXPERIENCE**

- 1999 – Present Associate Professor, Chemical Engineering, UND  
2000 – Present Director, Engineering Doctoral Program, UND  
1999 – Present Sr. Research Advisor, UND Energy & Environmental Research Center  
1994-1999 Sr. Research Manager, Advanced Processes and Technologies, UND  
EERC  
1985-1994 Research Manager, Combustion Systems, EERC  
1981-1985 Research Engineer, Wastewater Treatment and Reuse, EERC

### **PROFESSIONAL ACTIVITIES AND HONORS**

- American Institute of Chemical Engineering
- NSF CAREER Grant, 2001: Thermo-economic Modeling as a Tool for Advancing the Electric Power Industry
- U.S. Patent Number 6,053,954 Methods to Enhance the Properties of Hydrothermally Treated Fuels, 2000
- Link Foundation Energy Fellowship, 1996.
- Certificate of Recognition for Outstanding Training, U.S. Agency for International Development/ Institute of International Education, 1992.

### **PUBLICATIONS**

To date, Dr. Mann has published 18 refereed papers. He has over 100 other publications including conference papers, client reports and proprietary publications.

Publications relevant to the proposed research are provided beginning on page 28.

## PUBLICATIONS

Recent peer-reviewed publications related to the proposed research are provided below.

1. **Seames, W.S.**, "An Initial Study of the Fine Fragmentation Fly Ash Particle Mode Generated during Pulverized Coal Combustion", *Fuel Processing Technology*, 81, 2003
2. Dronen, L.C., Moore, A.E., Kozliak, E.I., and **Seames, W.S.**, "An Assessment of Acid Wash and Bioleaching Pretreating Options to Remove Mercury from Coal", *Fuel*, **83**, 181-186, 2003.
3. Linak, W.P., Miller, C.A., **Seames, W.S.**, Wendt, J.O.L., Ishinamori, T., Endo, Y., and Miyamae, S., "On Trimodal Particle Distributions in Fly Ash From Pulverized Coal Combustion", *Proc. Combust. Inst.*, 29, 2002.
4. **Seames, W.S.**, Fernandez, A.F., and Wendt, J.O.L., "A Study of Fine Particulate Emissions from Combustion of Treated Pulverized Municipal Sewage Sludge", *Environ. Sci. Technol.*, 36(12), 2772-2776, 2002.
5. **Seames, W.S.**, Sooroshian, J., and Wendt, J.O.L., "Assessing the solubility of inorganic compounds from size-segregated coal fly ash aerosol impactor samples", *J. Aerosol Science*, 33/1:77-90, 2001.
6. **Seames, W.S.** and J.O.L. Wendt, "The Partitioning of Arsenic, Selenium, Cadmium, and Cesium During Pulverized Coal Combustion in a 17kW Downflow Combustor", *Development in Chemical Engineering & Mineral Processing*, Fall, **9**, 231-239, 2001.
7. **Seames, W.S.** and J.O.L. Wendt, "The Partitioning of Arsenic during Pulverized Coal Combustion", *Proc. Combust. Inst.*, 28:2305-2312, 2000.
8. **Seames, W.S.** and J.O.L. Wendt, "Partitioning of Radionuclides During the Combustion of Pittsburgh and Illinois #6 Coals in a Self-Sustained Combustor", *Advances in Environmental Research*, **4**, 45-58, 2000.
9. Seames, W.S. and J.O.L. Wendt, "Partitioning of As, Se, And Cd During the Combustion of Pittsburgh and Illinois #6 Coals in a Self-Sustained Combustor", *Fuel Processing Technology*, 63:179-196, March, 2000.
10. Zhao, Y.X., **Mann, M.D.**; "Oxidation Of Mercury In The Simulated Flue Gas: A Focus On Mercury Chlorination", *Journal of Air & Waste Management* (in review)
11. Zhao, Y.X., **Mann, M.D.**; "Oxidation Of Mercury In The Simulated Flue Gas: Impact of Moisture on Mercury Oxidation", *Journal of Air & Waste Management* (in review)
12. Karki, S.; **Mann, M.D.**, Slahlefar, H.; "Energy and Environment in the ASEAN:

Challenges and Opportunities” *Energy Policy* **2003**, 33 (4), 499-509.

13. Knutson, R.Z.; **Mann, M.D.**; Erjavec, J.; Jacobson, J.P.; “Modeling Reaction Kinetics for a Transport Gasifier”, *Fuel* 83, **2003** 1643-1650.
14. Pavlish, J.P.; Sondreal, E.A.; **Mann, M.D.**; Olson, E.S.; Galbreath, K.C.; Laudal, D.L.; Benson, S.A. “A Status Review of Mercury Control Options for Coal-Fired Power Plants” *Fuel Process. Technol.* **2003**, 82: 89-165.
15. Timpe, R.C.; **Mann, M.D.**; Pavlish, J.H. “Organic Sulfur and HAP Removal from Coal Using Hydrothermal Treatment”. *Fuel Process. Technol.*, **2001**, 73 (2), 127-141.
16. Sondreal, E.A.; Benson, S.A.; Hurley, J.P.; **Mann, M.D.**; Pavlish, J.H.; Swanson, M.L.; Weber, G.F.; Zygarlicke, C.J. “Review of Advances in Combustion Technology and Biomass Firing”. *Fuel Processing Technology* **2001**, 71 (1-3), 7-38.
17. Kozliak, E.I; Sternberg, S.R.; Jacobson, M.L.; Kuether, K.W.; **Mann, M.D.** “Mercury Removal from Air by a Fiber-Based Bioreactor”. *Bioremediation J.* **1999**, 3 (4), 291-298.

Recent Federal reports related to the proposed research are provided below.

1. Senior, C.L., Huggins, F., Huffman, G.P., Shah, N., Yap, N., Wendt, J.O.L., **Seames, W.S.**, Ames, M.R., Sarofim, A.F., Swenson, S., Lighty., J.S., Kolker, A., Finkelman, R., Palmer, C.A., Mroczkowski, S.J., Helble, J.J. Mamani-Paco, R., Sterling, R., Dunham, G. and Miller, S., “Toxic Substances from Coal Combustion – a Comprehensive Assessment, Final Report, DOE Contract No. DE-AC22-95PC95101, July, 2001.
2. Senior, C.L., Bool III, L.E., Huggins, F., Huffman, G.P., Shah, N., Wendt, J.O.L., **Seames, W.**, Peterson, T., Shadman, F., Helble, J., Wornat, M., Sarofim, A., Olmez, I., Crowley, S., and Finkelman, R., “Toxic Substances from Coal Combustion -- A Comprehensive Assessment,” Phase I Final Report, DOE Contract DE-AC22-95PC95101, September, 1997.
3. **Mann, M.D.**, “Mercury and VOC Control using Fiber-Based Bioreactors”, Annual Report to the Environmental Protection Agency Contract No. R 824854-01; Energy & Environmental Research Center: Grand Forks, ND, December 2000.
4. **Mann, M.D.**, “Environmental Aspects of Hydrothermal Treatment” Annual Report to the Environmental Protection Agency, Contract No. R 824854-01; Energy & Environmental Research Center: Grand Forks, ND, December 2000.
5. **Mann, M.D.**, “Economic Evaluation of Mercury Control Options” Center for Air Toxics Final Technical Report, Environmental Protection Agency Contract No. R 824854-01; Energy & Environmental Research Center: Grand Forks, ND, January, 2001.

## Appendix F - Facilities

The University of North Dakota (UND) is one of the world's foremost facilities for Energy and Energy-related Environmental research and study. The laboratory facilities, specialized research equipment, analytical instrumentation, expertise, and support resources available at UND are ideally suited for this research program.

Specific facilities that will be utilized by this project include:

- Experimental work associated with this project will be conducted in existing research laboratory facilities assigned to the Department of Chemical Engineering by the University of North Dakota School of Engineering and Mines. Principal investigator, co-PI, and graduate student office resources, including personal computing are provided in existing Chemical Engineering Department facilities.
- Combustion experiments shall be performed in a newly commissioned solid fuels combustion research laboratory that includes a 17kw vertical downflow combustion system, dedicated on-line gas component analyzers for CO/CO<sub>2</sub>, O<sub>2</sub>, NO<sub>x</sub>, and SO<sub>2</sub>. A redundant EPA method 29/Ontario hydro impinger sampling train is also available. This combustion system is described in Appendix A of the project narrative section of the proposal. Supporting laboratory facilities are provided for impactor fly ash sampling including a microbalance capable of 0.01mg accuracy, membrane greasing facility, and a programmable oven. This laboratory is jointly maintained and utilized by Drs. Seames and Mann.
- Sample preparation facilities are also maintained by Drs. Seames and Mann. These facilities include an ultrapure water system, a test tube shaker for leaching experiments, and the infrastructure necessary for solvent and acid digestion of fly ash samples.
- Analytical work will be conducted in the UND School of Engineering and Mines Environmental Analytical Research Laboratory (EARL). The EARL's mission is to support research, research training, and projects involving aqueous chemistry, water resources investigations, and research into how solid phases, such as sediments, coal, fly ash, and municipal waste, may influence water and air quality. It is the only laboratory on the UND campus designated for multidisciplinary use by tenure-track faculty members and it is open to all campus departments. Fully equipped sample preparation facilities are available for materials and solids research. The EARL is staffed with a full time Laboratory Manager who works with graduate and undergraduate students to provide training, support, and data interpretation for analytical work using the laboratory's instruments. Dr. Seames serves on the steering committee overseeing the operation of the EARL. He is one of the two largest users of this laboratory's analytical capabilities.

Relevant to this research, AAS/GFAA analyses will be conducted on a ThermoElemental Solaar M-6 Graphite Furnace/Flame Atomic Absorption Spectrometer, with zeeman background correction.

- Coal feedstock pulverization and characterization (proximate, ultimate analyses, HHV,

moisture) will be accomplished by experienced laboratory technicians at the UND EERC Coal Analysis laboratory. The Coal Analysis Laboratory (CAL) is an integrated and fully equipped laboratory set up primarily for proximate and ultimate analyses of coal. In addition to performing proximate and ultimate analyses, the CAL provides a wide variety of testing: helium air pycnometry, surface area determination, laser particle sizing, dry and wet sieve analysis, and ash fusion. The lab analyzes coal samples from various state universities and institutions to determine the quality of the coal used in the boilers. The lab performs analyses according to American Society for Testing and Materials (ASTM).

The laboratory is equipped with instrumentation and equipment designed for the analysis and testing of coal and coal by-products including: a Leco TGA-501 analyzer for moisture, volatile matter, and ash analysis, a Leco 600 CHN analyzer for carbon and nitrogen content, a Leco SC-132 sulfur analyzer, a Leco AC-350 isoperibol calorimeter for heating value, a Fisher 307 low-temperature incubator for equilibrium moisture, a carbon-dioxide-in-coal analysis apparatus used to estimate the mineral matter content, particularly the  $\text{CaCO}_3$  and  $\text{MgCO}_3$ , of high-carbonate coals, a Malvern 2600 particle-size analyzer, a fusibility of coal and coke ash furnace, and facilities for sieving, grinding, and sample preparation.

- Execution of this project will involve the purchase of an on-line mercury analyzer. The department is planning on purchasing an on-line analyzer with a wet mercury conversion system. The selection of this instrument is based on experience and advice from the UND EERC which has performed evaluations of on-line mercury analyzers for the EPA.

## References

1. Brown, T.D.; Smith, D.N.; Hargis, R.A.; O'Dowd, W.J. Mercury Measurement and Its Control: What We Know, Have Learned, and Need to Further Investigate. *Journal of the Air and Waste Management Association*, June 1999, pp 1-97.
2. Jayaraman, K.R., Haydel, J.M., Venkatesh, B.N., Memorandum: Mercury Control Cost Calculations, September 2000
3. U.S. EPA. Mercury Study Report to Congress; EPA-452/R-97-003; U.S. EPA Office of Air Quality Planning and Standards, U.S. Government Printing Office, Washington, DC, December 1997.
4. Carey, T.R.; Skarupa, R.C.; Hargrove, O.W. Jr. Enhanced Control of Mercury and Other HAPs by Innovative Modification to Wet FGD Processes. Phase I Report to the U.S. Department of Energy, Contract DE-AC22-95PC95260, August 28, 1998.
5. Livengood, C.D.; Mendelsohn, M.H.; Huang, H.S.; Wu, J.M. Development of Mercury Control Techniques for Utility Boilers. In Proceedings of the Air and Waste Management Associations 88<sup>th</sup> Annual Meeting, San Antonio, Texas, Paper MP21.07
6. Amrhein, G.T.; Holmes, M.J.; Bailey, R.T.; Kudlac, G.A.; Downs, W.; Madden, D.A. *Advanced Emissions Control Development Program*, Phase III - Approved Final Report, DOE Contract DE-FC22-94PC94251, July 1999.
7. Galbreath, K.C. and C.J. Zygarlicke, Mercury transformations in coal combustion flue gas. *Fuel Processing Technology*, 2000. **65**: p. 289-310.
8. Senior, C.L.; Helble, J.J.; Sarofim, A.F. Predicting the Speciation of Mercury Emissions from Coal-Fired Power Plants. In Proceedings of the Conference on Air Quality II: Mercury, Trace Elements, and PM, September 19-21, 2000, McLean, Virginia, Paper A5-2.
9. Pavlish, J.P.; Sondreal, E.A.; Mann, M.D.; Olson, E.S.; Galbreath, K.C.; Laudal, D.L.; Benson, S.A. "A Status Review of Mercury Control Options for Coal-Fired Power Plants" *Fuel Process. Technol.* 2003, 82: 89-165.
10. Edwards, J., Srivastava, R.; A Study of Gas Phase Mercury Speciation using Detailed Chemical Kinetics. *J. Air and Waste Management Assoc.*, 51 (2001), 869-877.
11. Frederick, N., Agrawal, R.K., and Wood, S.C.; NO<sub>x</sub> Control on a Budget. *Power Engineering*. July 2003.
12. Bradford, M., Grover, R., and Paul, P.; Controlling NO<sub>x</sub> Emissions. *Chemical Engineering Progress*. March 2002, 42-46.

13. Holmes, M.J., Redinger, K.E., Evans, A.P., Nolar, P.S. ' Control of Mercury in Conventional Flue Gas Emissions Control Systems, Proceedings of the 4<sup>th</sup> International Conference on Managing Hazardous Air Pollutants, Washington, D.C., Nov 12-14, 1997.
14. Richardson, C., Blythe, G., Rhudy, R., Brown, T.; Enhanced Control of Mercury by Wet FGD Systems, Presented at the Air and Waste Management Association 93rd Annual Meeting and Exhibition, Salt Lake City, UT, 2000, Paper No. AE1B43.