MICROBEAM
TECHNOLOGIES, INC.
www.microbeam.com

October 1, 2014

Ms. Karlene Fine
Executive Director
North Dakota Industrial Commission
State Capitol – Fourteenth Floor
600 East Boulevard Avenue
Bismarck, ND 58505

Dear Ms. Fine:

Subject: Microbeam Technologies Proposal entitled "Managing Slag Flow Behavior in Combustion and Gasification Systems"

Microbeam Technologies Incorporated is pleased to submit this proposal to advance measures to predict slag flow behavior in combustion and gasification systems. Please find the subject proposal enclosed as well as the $100 application fee.

If you have any questions, please contact me by telephone at (701) 213-7070 or by e-mail at sbenson@microbeam.com.

Sincerely,

Steven A. Benson, Ph.D.
President

Shipping:
4200 James Ray Drive, Ste. 193
Grand Forks, ND 58203

Mailing:
PO Box 14758
Grand Forks, ND 58208-4758

Phone: 701-777-6530
Fax: 701-777-6532
info@microbeam.com

2. Title Page

A proposal for multiclient funding:

Managing Slag Flow Behavior in Combustion and Gasification Systems

APPLICANT

Microbeam Technologies Incorporated

PRINCIPAL INVESTIGATOR

Steven A. Benson, PhD

DATE OF APPLICATION

October 1, 2014

AMOUNT OF REQUEST

$245,065

3. TABLE OF CONTENTS

4. ABSTRACT

This project is aimed at advancing methods to predict slag flow behavior in high-temperature slagging combustion and gasification systems. During high-temperature combustion or gasification, the fuel impurities partition into vapors and particles (liquid and solid). The vapors and small particles contribute to the formation of the entrained ash, and the larger particles are captured as slag. This project involves integrating the chemical and physical processes involved in slag formation and flow behavior into a three-dimensional computation fluid dynamics (CFD) framework. The CFD will utilize key information derived on high-temperature partitioning of fuel impurities between slag and gas-phase entrained vapors and particles to predict slag layer formation, ash/char retention in slag, slag layer thickness, slag freezing, and slag flow. The CFD modeling efforts will be used to develop relationships that can be utilized on a day-to-day basis to predict slag behavior as a function of fuel properties, system design, and operating conditions. Current CFD modeling efforts of slag-flow behavior are based on bulk ash composition and do not consider ash partitioning (vapors and liquid/solid particles), ash/char particle retention in slag, chemical and physical properties of slag, and slag layering.

This project is aimed at improving the performance of cyclone-fired combustion systems and high-temperature slagging gasifiers.

The duration of the project will be two years. The total project cost is $785,065 that includes $300,000 of in-kind cost share, $240,000 cash cost share from project sponsors currently being identified, and $245,065 from NDIC. The project participants include: Clean Coal Solutions, University of North Dakota, Barr Engineering, and Microbeam Technologies Inc.

5. PROJECT SUMMARY

This project is aimed at advancing methods to predict slag-flow behavior in high-temperature slagging combustion and gasification systems. During high-temperature combustion or gasification, the fuel impurities are partitioned into vapors and particles (liquid and solid). The vapors and small particles contribute to the formation of the entrained ash, and the larger particles are captured as slag. This project involves integrating the chemical and physical processes involved in slag formation and flow behavior into a three-dimensional computation fluid dynamics (CFD) framework. The CFD will utilize key information derived on high-temperature partitioning of fuel impurities between slag and gas-phase entrained vapors and particles to predict slag-layer formation, ash/char retention in slag, slag-layer thickness, slag freezing, and slag flow. The CFD modeling efforts will be used to develop relationships that can be utilized on a day-to-day basis to predict slag behavior as a function of fuel properties, system design, and operating conditions. Current CFD modeling efforts of slag-flow behavior are based on bulk ash composition and do not consider ash partitioning (vapors and liquid/solid particles), ash/char particle retention in slag, chemical and physical properties of slag, and slag layering.

This project is aimed at improving the performance of cyclone-fired combustion systems and high-temperature slagging gasifiers. The specific challenges being addressed include:

- Combustion systems – current cyclone-fired plants have been modified to provide the ability to adjust the air distribution in the boiler in order to reduce NOx formation. As a result of these changes, plant personnel now operate cyclone burners under substoichiometric combustion conditions combined with adding air in the upper regions of the furnace to complete the combustion. Substoichiometric combustion conditions decrease NOx but also can change the partitioning of ash between the cyclone slag and gas-entrained vapors and particles leading to poor slag flow, refractory wear, water wall slagging, convective pass fouling, and fine particulate formation. Many utilities fire oil in order to melt the slag from the cyclone.

- Gasification systems - entrained flow and slagging fixed-bed gasification systems must maintaining slag flow, while protecting refractory and other system components. In low-ash fuels such as petroleum, coke materials are added to the fuel to ensure sufficient slag is produced to protect refractory and maintain operations.

The goal of this project is to develop methodologies that will allow designers and operators of high-temperature combustion and gasification systems to manage slag layer thickness and flow properties as a function of fuel composition, system design, and operating conditions. In order to meet the goal, the following specific objectives have been identified: 1) identify and develop three base cases (entrained flow gasifier, cyclone combustion (2)) for the study; 2) conduct sampling efforts at three selected locations (based on sponsor input); 3) characterize fuels, slags, and entrained ash materials; 4) develop CFD applications for the three base cases that includes ash partitioning, slag layer properties, freezing, and flow; 5) conduct model testing and compare to operational experience; 6) based on the models, develop useful relationships that plant operations personnel can utilize on a daily basis; and 7) manage and report the results of studies to project participants.

The project team includes Microbeam Technologies Inc., the University of North Dakota (UND) and Barr Engineering. Microbeam will be responsible for leading the effort. UND is responsible for conducted the CFD modeling, and Barr Engineering is responsible for collecting samples of entrained ash materials.

6. PROJECT DESCRIPTION

Goal:

The goal of this project is to develop a method that will allow designers and operators of high-temperature combustion systems to manage slag-layer thickness and flow properties as a function of fuel composition, system design, and operating conditions.

Objectives:

1. Identify and develop three base cases (cyclone combustion (2) and entrained flow gasifier) for the study. Additional plants may be added depending upon input from project sponsors.
2. Conduct sampling and analysis of fuels, slags, and entrained-ash materials efforts at three selected locations (based on sponsor input).
3. Develop CFD applications for the three base cases that include ash partitioning, slag layer properties, freezing, and flow.
4. Conduct model testing and compare to operational experience,
5. Based on the models, develop useful relationships or guidelines that plant operations personnel can utilize on a daily basis.

Scope of Work:

Task 1. Base Case Development

Three base case systems will be identified in a detailed study. The base case systems will need to represent the major technologies in slagging combustion and gasification systems. The systems will include two cyclone-fired systems, an entrained-flow gasification system, and an additional system of interest to project sponsors. Additional plants may be added depending upon input from project sponsors.

Task 2. Materials Sampling and Analysis

Three materials sampling campaigns will provide samples to assist in the CFD modeling development and validation. During the sampling campaigns, personnel from the host plant, Microbeam, and Barr Engineering will conduct sampling of fuel, entrained ash, and slag. Sampling of fly ash in combustion systems will be performed upstream of the ESP by Barr Engineering and Microbeam.

2a. Slag Formation Processes

The impact of ash-forming components on the processes involved in the formation of the slag will be determined through careful examination of as-fired fuel samples and slag. The coals will be characterized to determine the size, composition, and abundance of mineral grains present using computer controlled scanning electron microscopy (CCSEM), bulk ash composition, and basic coal properties. The slag will be characterized to determine bulk composition, homogeneity, crystalline phase types, and melting behavior.

2b. Partitioning of Impurities to form Slag and Fly Ash

The partitioning processes will be determined for selected coal blends during the week-long test campaigns. A state-of-the-art Dekati low pressure impactor (DLPI) will be used to aerodynamically classify and collect ash particle samples. The fly ash mass and composition will provide critical information needed to develop ash partitioning parameters as a function of the inorganic composition of the as-fired fuel and operating conditions. The partitioning data provides a better estimation of the slag composition and prediction of slag-flow behavior. In addition, the properties of the fly ash that end up down-stream in the system that have the potential to produce deposits on heat transfer surfaces can be determined using partitioning data. Further, this information is also important for fine particle formation that can have an impact on particulate control and ash handling.

2c. Slag Flow Properties

The chemical and physical properties of slag materials that allow for the assessment of flow behavior (crystallization, degree of assimilation, phase separation) will be determined using scanning electron microscopy morphological analysis and scanning electron microscopy point count analysis (SEMPC). The physical measurements will include viscosity (T_{250} using the crucible method), surface tension (sessile drop technique), porosity (SEM image analysis), and density. The chemical measurements determined with the SEMPC and morphological analysis will include bulk composition, microstructure, crystalline phases, and chemical homogeneity.

2d. Entrained Ash Properties

The mass/size and composition distribution of entrained-ash particles for selected coal blends will be analyzed. Ash collected on each stage from the DLPI in subtask 2b will be characterized to determine the overall composition. SEM imaging of the particles on each stage will be imaged to examine the microstructural features.

Task 3. Computational Fluid Dynamics (CFD) Applications Development

Building the CFD application for the three main cases will be the focus of UND combined with Microbeam's expertise on inorganic transformation and slag flow behavior.

3a. Geometry Building and Meshing

CAD files/drawings of the combustor or gasification system will be utilized to create a 3D geometric representation of the system geometry, which will then be meshed to an adequate resolution. This will enable accurate predictions of the particle tracks, combustion behavior and temperature inside the gasifier or combustor. An example is given for the cyclone barrel illustrated in Figure 1.

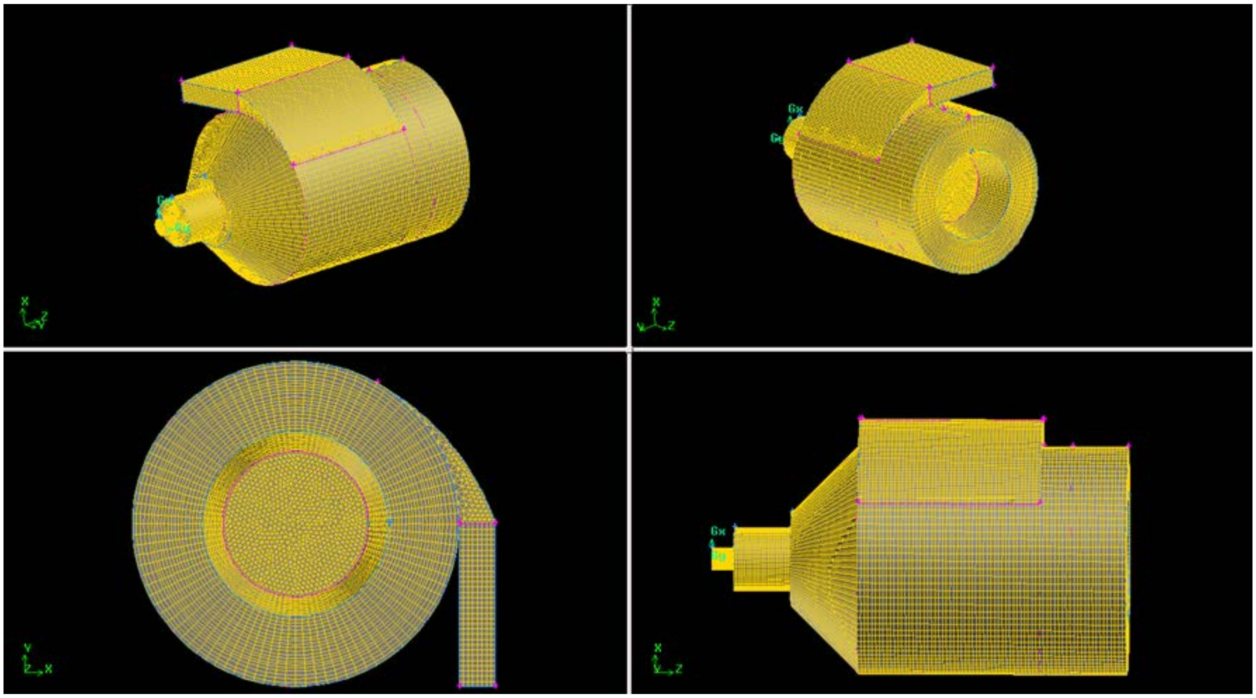


Figure 1. Geometry of a cyclone barrel simulated at UND.

3b. Modeling Inorganic Transformation Mechanisms

Our current capabilities allow for the determination of the partitioning of ash-forming components between the vaporized components and the super-micron particulate phase. The efforts will focus on quantifying the sub-micron component of the vaporized impurities resulting from the volatilized/vaporized inorganic components during gasification or combustion. The remaining residual ash-forming components are derived from the non-volatile minerals and organically associated elements, which go through a process of coalescence, fragmentation and shedding to produce the super-micron component. The coal/mineral particle tracks, resulting from the CFD simulation in conjunction with equilibrium thermodynamic relationships, are employed in a post-processing manner to quantify the fraction of vaporized ash.

3c. Slag Model Development and Refinement

The 3D slag-flow behavior inside each system will be predicted by employing a unique coupling between the Lagrangian particle-tracking method and a Volume-of-Fluid (VOF) modeling capability that tracks the interface between the slag layer and the combustion/gasification gases. The slag model will incorporate the impacts of fuel properties, system design, and operating parameters. The slag model will be based on partitioned ash materials (vapors and liquid and solid particles). The ability of the particles to be captured will be a function of the slag-layer properties (thickness, temperature, viscosity surface) and the particle properties. Viscosity models will be used to provide information on the temperature where the viscosity of the surface is sufficiently low to become sticky. The critical sticking viscosity was reported in a range from 10^5 Pa•s to 10^7 Pa•s.

If one of the two is non-sticky, the particle will be assumed to be trapped if the Weber number (the ratio of the kinetic energy and the interfacial surface tension energy) is smaller than unity or another pre-defined number. A combination of empirical correlations from the literature and models used at Microbeam (Kalmanovitch Urbain) will be employed to determine the important slag properties, like the critical viscosity and surface tension that are needed to estimate the Weber number. Once the 3D mass flux profiles of the sticking particles are estimated at the walls, the slag model will be coupled with the VOF to estimate the transient evolution of the slag-layer thickness along the walls. The model will be employed in a post-processing manner with the CFD simulations as illustrated in Figure 2.

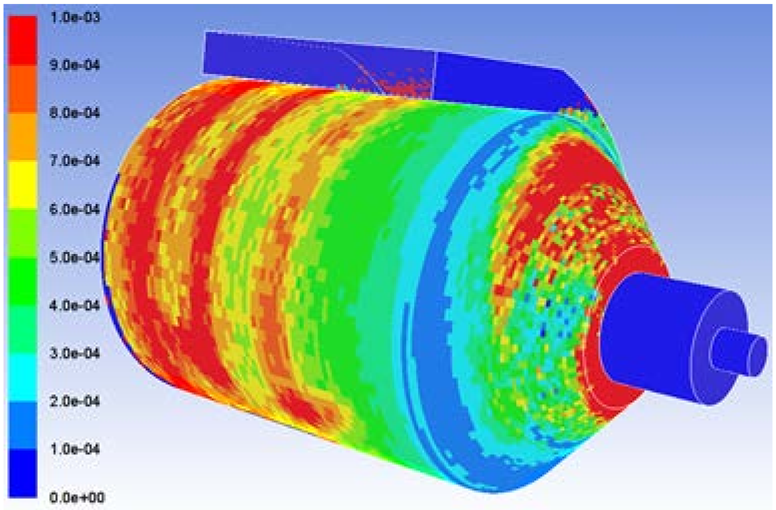


Figure 2. UND's slag model predictions of the average particle diameter of the depositing particles onto the slag layer within a cyclone barrel.

Task 4. CFD Model Testing

The key parameters that the CFD model will calculate based on a partitioned ash are slag layer thickness, slag flow rate, partitioning between slag and fly ash as a function of fuel composition, system design, and operating parameters. This information will be compared to measured values of slag layer and entrained ash properties as a function of fuel composition and system operating conditions. For example, Figure 3 shows measured data for the quantity of ash retained as slag and ash that produced fly ash. The results show that a very low viscosity slag produced from D3 fuel resulted in a thin layer of slag with the particle retention being low because of an insufficient layer available to retain the burning particle and ash particle. The high viscosity slag case for D4 fuel showed a high retention of ash as slag. The D2 fuel produced a layer that was estimated to be optimum because ash retention as slag was moderate with good slag flow.

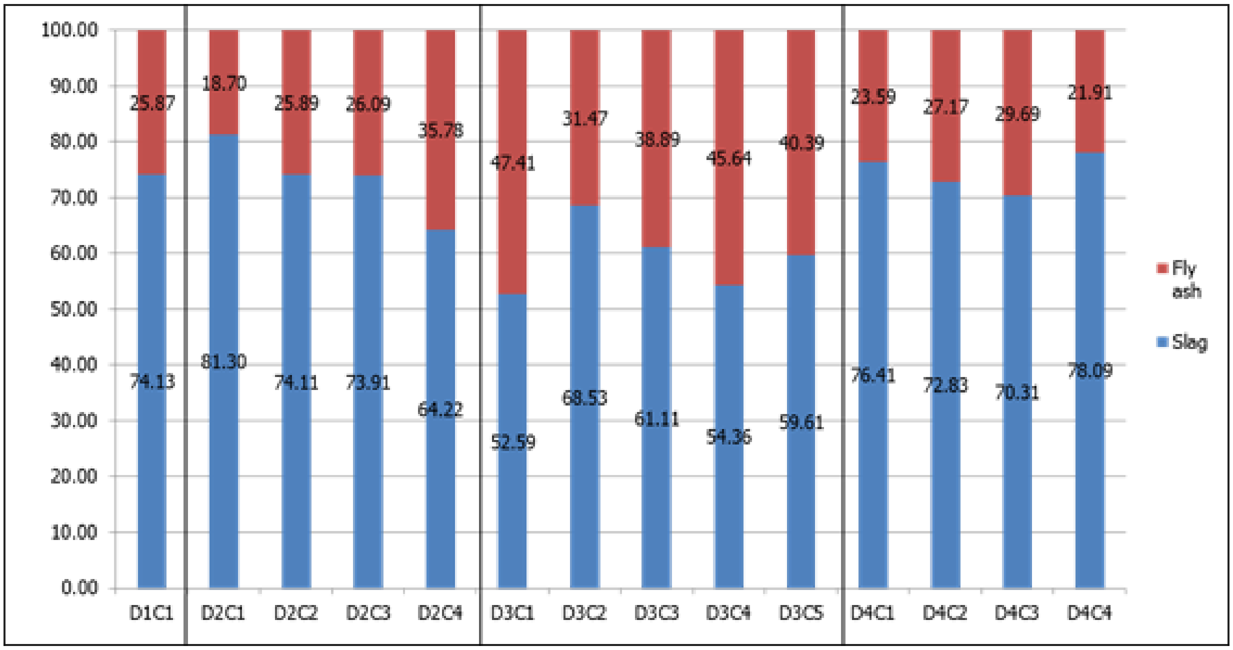


Figure 3. Measured percent of ash retained as slag and fly ash for a cyclone-fired boiler firing four different fuels (D1 and D2 – moderate viscosity slag, D3 – low viscosity slag, D4 – high viscosity slag) under varying air-to-fuel ratios (C1 to C4).

Based on project sponsor input, testing of the model will be conducted on various systems. For example, in combustion systems the impact of slag and ash properties assessing the effectiveness of NOx control strategies: over-fire air, re-burning, air-staging or SNCR methodologies towards NOx control, examining the flame impingement patterns, boiler fouling and heat transfer characteristics in front-wall fired furnaces, or estimating CO emissions and un-burnt carbon (UBC), will require comprehensive simulations of the entire boiler geometries. CAD files/drawings of the boiler will be utilized to create a 3D geometric representation of the boiler geometry, which will then be meshed to an adequate resolution. This will enable accurate predictions of the particle tracks and their residence times across different temperature zones within the boiler.

Task 5. Simplified Correlations – CFD Based

To investigate the impact of changes to the operating conditions and fuel variability on the fly-ash to bottom-ash distributions and other parameters calculated using the CFD code that include CO, NOx emissions and UBC, a range of CFD simulations corresponding to those conditions will be run to generate new particle tracks , and the post-processing using the slag model will be repeated.

The split of the ash in between slag and fly ash impacts the properties of both the slag and the fly ash. The partitioning is dependent upon the association of the ash-forming components in the fuel and operating conditions of the cyclone. The results of the CFD analysis of cyclone-slag and fly-ash samples for a range of coal properties will be used to determine the ash component partitioning. Based on these results, empirical correlations between coal properties and operating parameters will be developed to calculate the components that end up in the slag and fly ash. The composition of the slag will be used to calculate T_{250} and base-to-acid ratios.

Anticipated Results

Deliverables resulting from the proposed work will include the following:

1. Prediction methodologies for slag-layer properties in combustion and gasification systems.
2. Prediction of fly-ash and vapor-phase species that are not retained in fly ash.

3. Impact of a wide range of fuel properties and operating conditions on NOx formation, slag-flow behavior, fly-ash formation, water-wall slagging, convective-pass fouling, and fly-ash collection
4. Application to emerging and advanced combustion and gasification systems.

Facilities, Resources and Techniques

MTI has laboratory and office space located in the Center for Innovation at the University of North Dakota. . Our automated scanning electron microscope is equipped with x-ray microanalysis capabilities. The laboratory has sample preparation equipment, a small-scale fluidized bed combustor, a small-scale gasifier simulator equipped with a syngas cooler, a high-temperature 1700 ºC refractory testing furnace, an ash-fusion furnace, chemical-fractionation analysis equipment, and other laboratory equipment. The equipment is specifically designed and optimized to characterize coal and coal ash-related materials. In addition, MTI has developed numerous data analysis procedures designed to interpret the results of analysis of fuel and fuel-ash related materials for clients worldwide. These techniques are used to assist combustion and gasification facilities to improve reliability and decrease maintenance costs through fuel selection/blending and optimized operating conditions. MTI has conducted over 1450 projects that involve the analysis of fuel, ash, slag, and metal materials. Qualifications of Barr Engineering and UND are summarized in the Appendix.

Environmental and Economic Impacts

This project has the potential to economically improve the environmental performance of cyclone-fired boilers by managing lignite properties that will allow for optimum cyclone performance. Specific application of the results of this project will be cost effective measures to optimize NOx reductions through managed lignite properties.

Ultimate Technological and Economic Impacts

Managing the variability of lignite is a key challenge to overcome that will ensure the future use of lignite. Developing these tools will enable personnel associated with lignite mining and plant operations to operate the systems more efficiently.

Why the Project is needed

This project is needed to update tools used to manage cyclone-fired boiler performance in order to improve NOx reduction and plant efficiency. Lignite coals have slagging properties that can be optimized to provide for use in high efficiency advanced slagging combustors and gasifiers.

7. STANDARDS OF SUCCESS

The standards for success of the project include:

- Development of a CFD approach to predict slag flow, ash partitioning, boiler slagging/fouling, and emissions control.
- The development of CFD database information that includes the impact of fuel quality and system operating conditions.

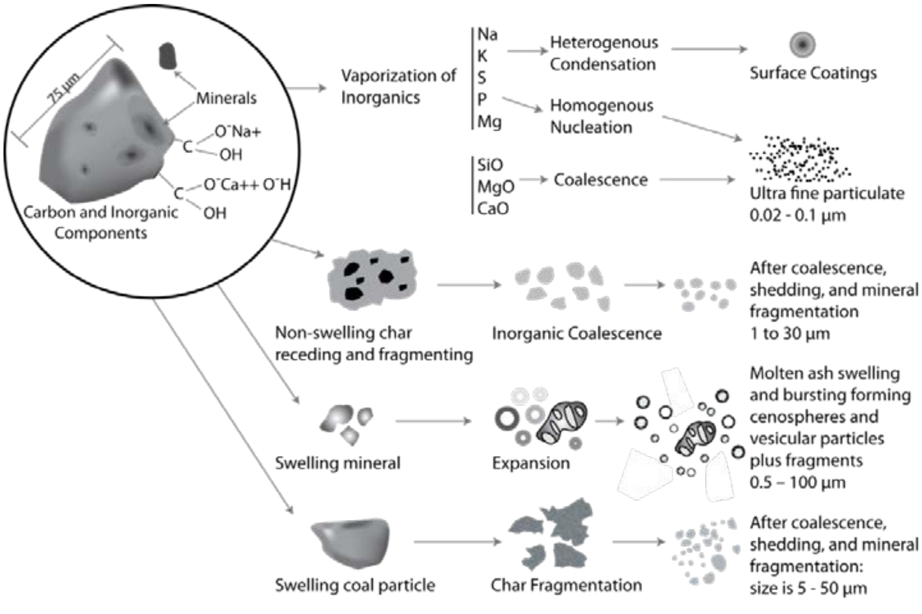
These standards will ensure the success of the project. The information will be used to develop guidelines for equipment developers and operations personnel.

8. BACKGROUND

Managing slag flow is essential in slagging combustion and gasification systems. The development of an accurate slag thickness and flow model requires accurate prediction of ash formation and partitioning of the ash/slag-forming constituents between the slag and entrained ash. Some of the ash-forming materials are vaporized or are in small particles and are not retained in the slag. Computational fluid dynamics (CFD) combined with accurate prediction of slag and entrained-ash composition offers the opportunity to more accurately assess slag-flow properties as a function of fuel properties, system design, and operating parameters. The following discussion includes the transformations of impurities to form ash materials, transport to form slag layers, viscous flow behavior of slag, and recent CFD applications to predict slag layer flow and thickness.

The physical transformations of the fuel-associated inorganic components during combustion and gasification to form intermediate solid and liquid particles and gas-phase species depend upon their form (organic or mineral association) and operating parameters. For example, the larger size particles resulting from the reactions of inorganic components can consist of organically associated cations, mineral grains that are included in coal particles, and excluded mineral grains. Physical processes involved in the formation of ash particles include: 1) melting and flow of the particles driven by viscosity of ash-forming materials, 2) coalescence of individual mineral grains within a char particle as the particle burns, 3) shedding of the ash particles from the surface of the chars driven by the melting point, 4) convective transport of ash from the char surface during devolatilization, 5) fragmentation of the inorganic mineral particles, and 6) vaporization and subsequent condensation of the inorganic components upon gas cooling. As a result of these interactions the inorganic components are partitioned in the gasification system. The degree of partitioning depends upon the severity of the combustion or gasification process. The mechanisms of transformations are illustrated in Figure 4.

The physical processes in transformations and partitioning are in part impacted by the chemical composition of the vapor phase and particulate materials. This partitioning influences the fate of the inorganic species in the gasification systems. For example, the more refractory components, such as silicon, aluminum, iron, and calcium, typically end up in the slag in high-temperature gasification systems. The more volatile components, such as sodium, potassium, sulfur, halogens, and some trace elements, end up being carried with the bulk gas flow of the system and upon gas cooling will condense to form various sizes of particles.



S.A. Benson and M.L. Laumb, 2007

Figure 4. Major physical transformations of ash components during combustion and gasification.

The potential to accumulate ash on surfaces inside a system to produce a slag is influenced by the size and density of the particles as well as the design and operating conditions of the combustion or gasification system. Particle stickiness and the stickiness of the surface (captive surface) will influence the formation of a slag layer. For example, ash particles of any composition and melting behavior impacting a surface containing molten silicate will stick and build up more rapidly than if the surface were “dry.” The viscosity slag layer will dictate the thickness of the layer as well as the stickiness. Figure 5 illustrates a thin slag layer produced from a slag with a low-viscosity slag with a high base-to-acid ratio (B/A), a moderate viscosity slag with a medium B/A ratio, and high-viscosity slag with a low B/A.

$(B/A = (Na_2O+CaO+MgO+K_2O+FeO)/(SiO_2+Al_2O_3+TiO_2))$

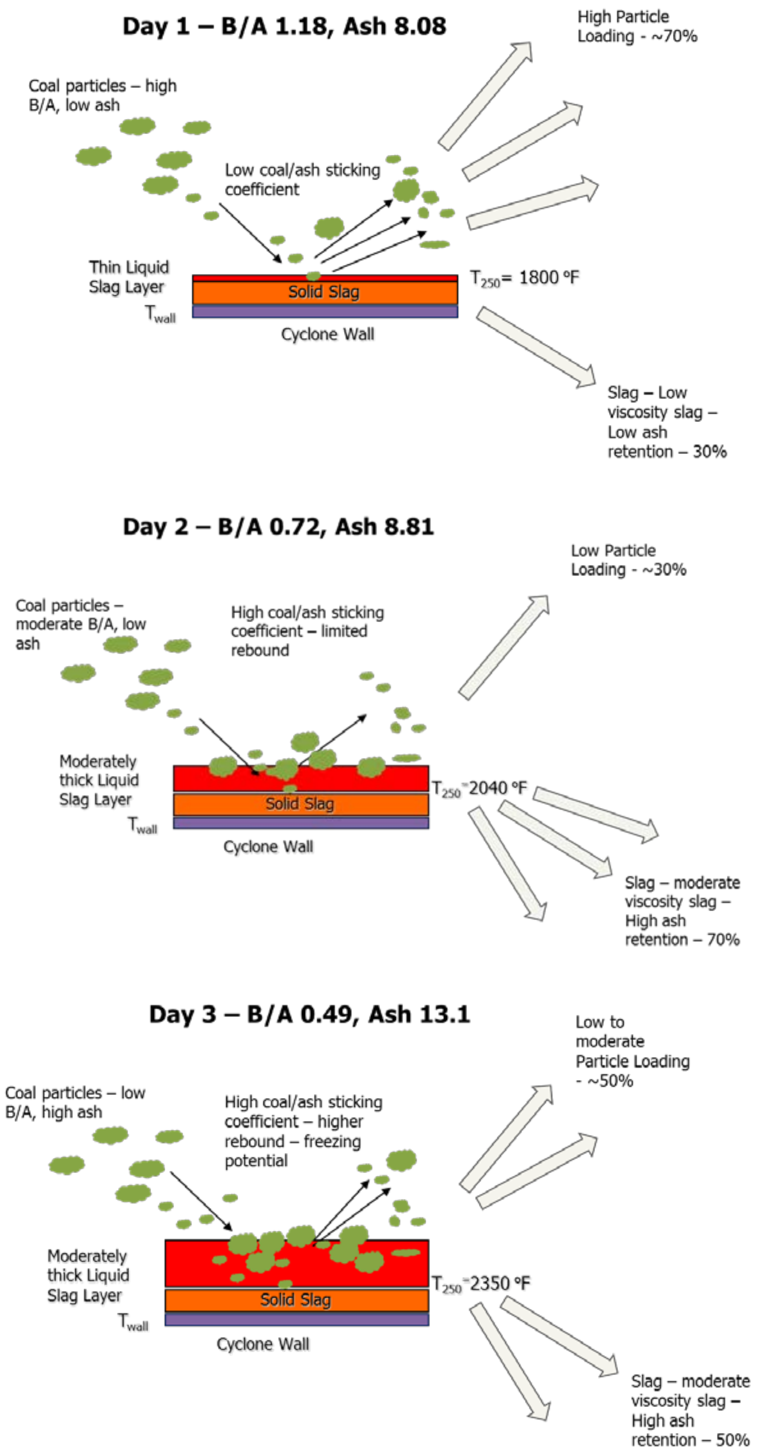


Figure 5. Slag layer thickness as a function of fuel properties.

For slagging systems, the bulk of the ash melt formed flows through a slag tap. In this case, the viscosity of the bulk material is a controlling factor. The bu1k viscosity will be dependent on the chemical composition and the temperature. Several relationships have been developed to define the ability of slag to flow as shown in Figure 6. The first is the T_{250} temperature which is where the viscosity is at 250 poise. In some cases a lower viscosity is required and the T_{80} value is used to determine the temperature required for slag to flow at 80 poise. In some cases, crystallization occurs within the melt, and the temperature at which it occurs is defined as the T_{cv} or the temperature of critical viscosity. This results in a rapid increase in viscosity that is due to the formation of crystalline phases. Crystallization has two effects: first it reduces the amount of liquid phase present; and second, it alters the chemical composition of the melt. Both these effects can alter the bu1k flow properties. Figure 7 provides a series of potential scenarios found in high-temperature slag flow in gasification systems. The best case is depicted by Scenario 1 where the viscosity follows a Newtonian or relatively linear increase with decreasing temperature. Scenario 2 shows the impact of the formation of some crystalline phases in the slag resulting in an increase in viscosity causing non-linearity in the viscosity-temperature relationships. Scenario 3 shows a very non-linear relationship due to the formation of likely a primary and secondary phase resulting in the freezing of the slag. Scenario 4 shows the result of significant crystallization and rapid freezing. Scenario 4 is typical of slags derived from high alkali and alkaline earth element–rich coals such as the North American lignite and subbituminous coals.

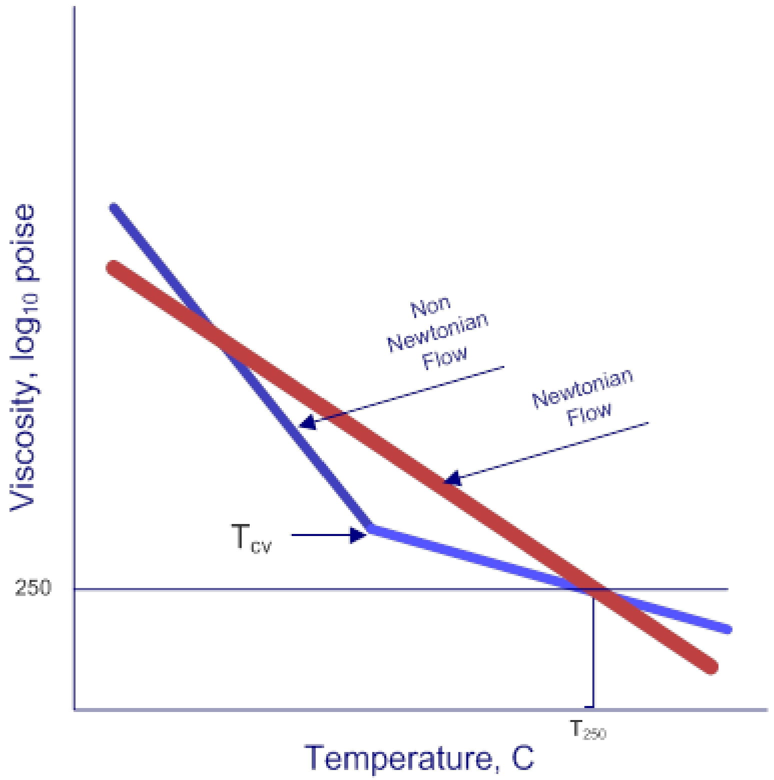


Figure 6. Slag flow behavior where T_{250} = temperature at 250 poise and T_{cv} = temperature of critical viscosity.

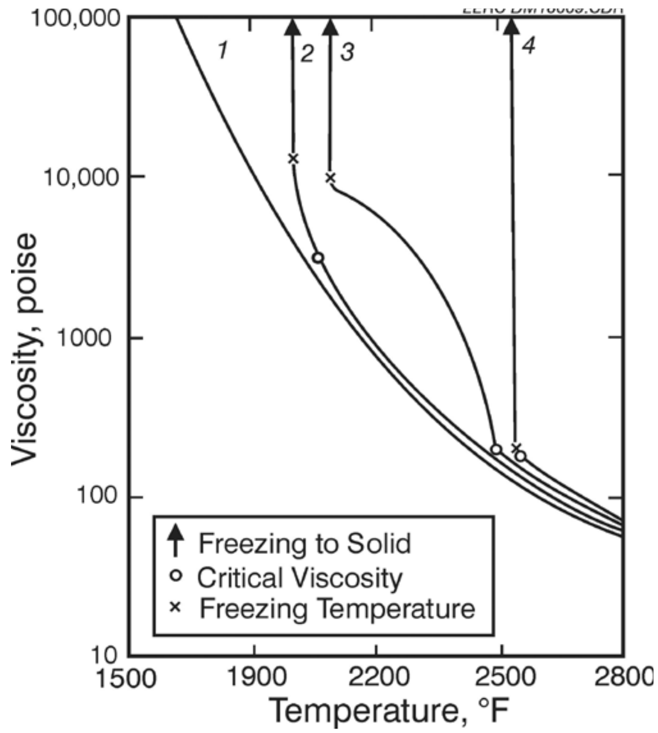


Figure 7. Illustration of the relationship between viscosity and temperature for high temperature showing 1) viscoelastic material with Newtonian flow properties, 2) a material with a critical viscosity and a freezing point likely due to crystallization, 3) a material with crystallization of a minor phase followed by crystallization/freezing due to the formation of a secondary phase, and 4) a material with major crystallization resulting in rapid freezing.

Ni and others (2010) modeled the formation of slag deposit and flow behavior of slag layers that form on membrane and refractory walls of gasifiers. The model considers multiple layers having solid and liquid phases. They consider the temperature of critical viscosity as it relates to the flow behavior of the slag in addition to the temperature where the slag flows. They utilized the bulk composition in their modeling efforts and did not consider the partitioned or fine ash in their work. The model developed by Ni and others (2010) is illustrated in Figure 8. Work has also been conducted by Chen and Ghomiem (2013) on 3-D computational slag-flow models for combustion and gasification in which they use bulk-ash properties and do not consider partitioned ash in their work. Additional work was conducted by Chen and others (2012) on slag-layer formation for oxy-coal fired systems.

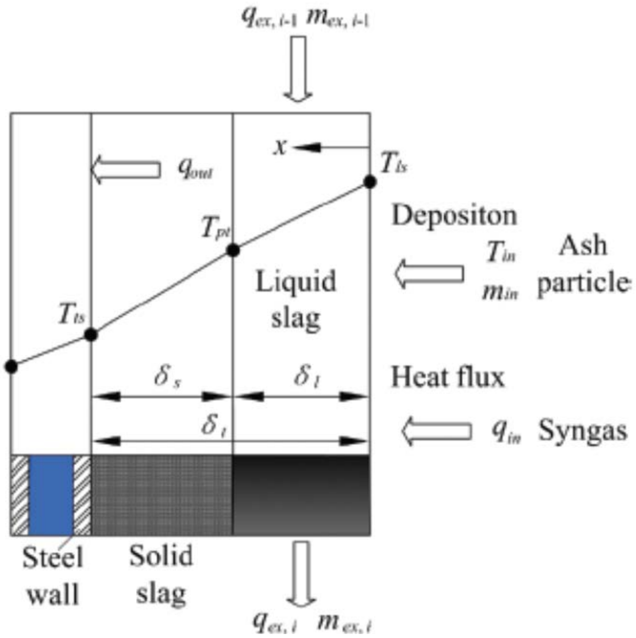


Figure 8. Model of slag-flow behavior on steel membrane surface in the radiant section of an entrained-flow gasifier (Ni and others, 2010).

References

Chen,L., Ahmed F. Ghoniem, Development of a three-dimensional computational slag flow model for coal combustion and gasification Fuel 113 (2013) 357–366.

Chen L, Yong SZ, Ghoniem AF. Oxy-fuel combustion of pulverized coal: characterization, fundamentals, stabilization and CFD modeling. Prog Energy Combust Sci 2012;38:156–214.

Ni J, Zhou Z, Yu G, Liang Q, Wang F. Molten slag flow and phase transformation behaviors in a slagging entrained flow coal gasifier. Ind Eng Chem Res, 2010;49:12302–10.

9. QUALIFICATIONS

The corporate mission of Microbeam Technologies Inc. (MTI) is to provide advanced analysis tools and technologies to minimize the impacts of inorganic components in solid fuels on power system performance. Since 1992, MTI has performed more than 1,450 commercial projects providing advanced analysis of coal, ash, ceramics, metals, and other materials, and has done consulting for researchers, power industry, boiler manufacturers, coal companies, and others. In 1999, MTI received a DOE Phase I SBIR on the abatement of corrosion and plugging of hot-gas filters in gasification systems. In 2002, MTI was awarded a National Science Foundation (NSF) Phase I SBIR on the use of gasification systems to recover valuable elements from the gas stream. Based on the results of the Phase I SBIR work, Phase II was awarded in 2004. MTI has completed Phase II research and development and is working on commercializing the technology.

MTI's core competency lies in the understanding of the combustion and environmental control technologies for coal, biomass, petroleum coke, and waste-fired systems. Efforts have been focused on behavior of fuel impurities in combustion and gasification systems as a function of fuel characteristics, system design, and operating conditions. The projects conducted on gasification and combustion systems have been aimed at matching fuel quality with plant design and developing methods to minimize impacts on system performance. MTI has a client base that includes customers from the United States, Canada, United Kingdom, Finland, Sweden, Hungary, Poland, Germany, Indonesia, Japan, Brazil, South Africa, India, South Korea, and Australia. Further information can be obtained from MTI's website at www.microbeam.com.

10. VALUE TO NORTH DAKOTA

A major challenge facing North Dakota lignite-fired utilities is managing highly variable lignite properties. This project will develop data and tools to identify cost-effective measures to decrease NOx emissions, slag freezing, ash deposition, and particulate collection and handling problems as a function of system operation conditions and lignite blends.

11. MANAGEMENT

The project management structure is illustrated in Figure 9. The overall project management will be the responsibility of Dr. Steve Benson. Dr. Benson will coordinate work with project sponsors to review progress.

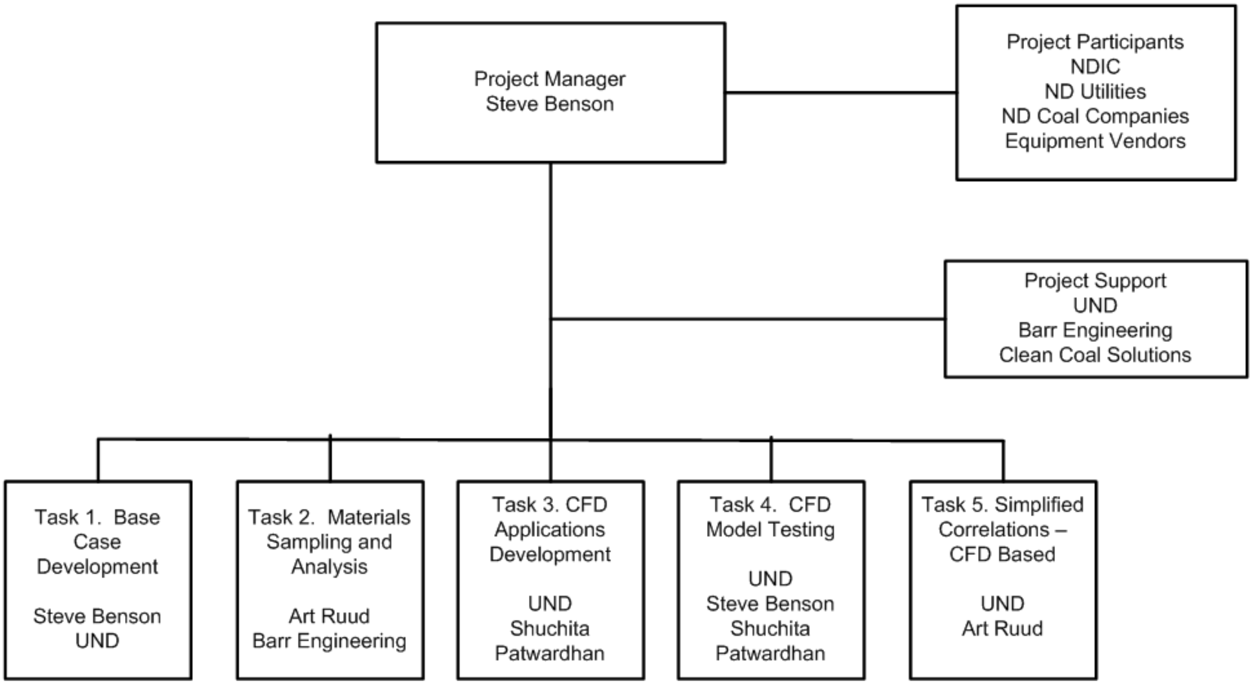


Figure 9. Project Organizational Chart.

Dr. Steve Benson will be the project manager and will be responsible for the coordination of efforts associated with testing and the development of the predictive methods. Dr. Benson currently is President of MTI. Dr. Benson has over 25 years of professional experience in the behavior of fuel impurities in combustion and gasification systems that include the following areas: high-temperature reaction mechanisms, coal-ash slagging and fouling, inorganic constituents in coals, scanning electron microscopy analysis, and fundamentals of coal combustion. Dr. Benson has extensive experience in managing complex multidisciplinary projects for federal and state departments and agencies such as the U.S. Department of Energy and the Environmental Protection Agency. He has managed numerous projects for industry alone and for industry and government co-funded programs. Dr. Benson is a member of several professional organizations and has written or co-written over 220 publications.

Mr. Arthur Ruud, Research Scientist at MTI, will be responsible for the coordination of testing and characterization of coal, slag and other materials. Mr. Ruud has a M.S. in Chemistry from the University of North Dakota, and nearly 30 years of experience in the coal combustion and analytical chemistry fields. He has a strong background in experimental design and system design and construction. Mr. Ruud has extensive experience in advanced analytical methods of analysis used to measure the form and abundance of ash-forming components in fuels and the chemical and physical properties of ash-related materials, metals, and refractories. Mr. Ruud also has experience with standard ASTM methods for coal and fuel analyses, including all standard fuel analyses.

Ms. Shuchita Patwardhan, Research Engineer at MTI, has a BS degree in Chemical Engineering and an MS in Environmental Engineering. She conducted her MS work on the development of mercury control technologies. She is currently responsible for fuel, fireside deposits, refractories, metals and other related materials analysis using scanning electron microscopy and x-ray microanalysis. She is also responsible for the development of improved applications for the analysis of fuels and related materials from combustion and gasification systems.

UND and Barr Engineering qualifications are included in the appendix.

12. TIMETABLE

The work is anticipated to take two years to complete. The overall project schedule is shown in Table 1.

Table 1. Overall Project Schedule.

ID	Task Name	Start	Finish
1	Task 1. Base Case Development	1/5/2015	7/8/2015
2	Task 2. Materials Sampling and Analysis	2/3/2015	1/15/2016
3	Task 3. CFD Applications Development	7/13/2015	5/13/2016
4	Task 4. CFD Model Testing	7/1/2015	12/29/2016
5	Task 5. Simplified Correlationst	1/14/2016	1/11/2017

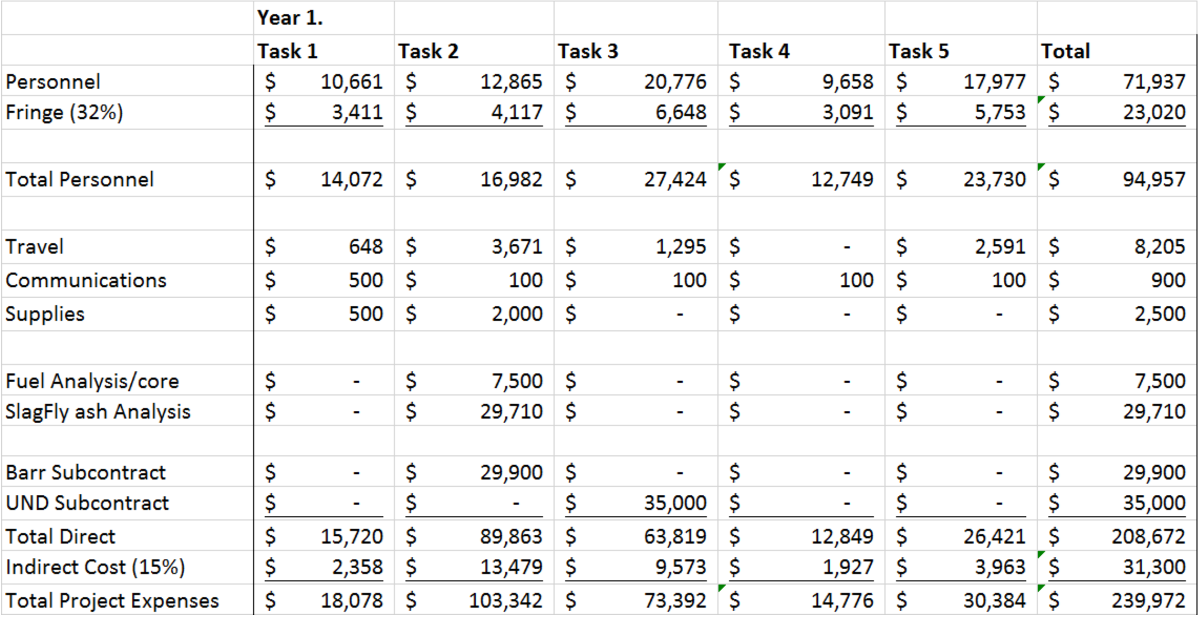
Deliverables resulting from the proposed work will include the following:

1. Database information on slag, partitioning, ash deposits and fly ash to be developed after the completion of Tasks 2.
2. CFD simplified measures or guidelines for managing slag flow.
3. Reports that include quarterly status reports, task reports and a final report.

13. BUDGET

The total project cost is $785,065 that includes $300,000 of in-kind cost share, $240,000 cash cost share from project sponsors currently being identified, and $245,065 from NDIC. The project budget is summarized in Tables 2 and 3. Table 4 is the overall two year budget. The cost share is summarized in Table 5.

Table 2. Project budget by year and task (UND and Barr Engineering subcontract budget is in the appendix).



	Year 1.					
	Task 1	**Task 2**	**Task 3**	**Task 4**	**Task 5**	**Total**
Personnel	$ 10,661	$ 12,865	$ 20,776	$ 9,658	$ 17,977	$ 71,937
Fringe (32%)	$ 3,411	$ 4,117	$ 6,648	$ 3,091	$ 5,753	$ 23,020
Total Personnel	$ 14,072	$ 16,982	$ 27,424	$ 12,749	$ 23,730	$ 94,957
Travel	$ 648	$ 3,671	$ 1,295	$ -	$ 2,591	$ 8,205
Communications	$ 500	$ 100	$ 100	$ 100	$ 100	$ 900
Supplies	$ 500	$ 2,000	$ -	$ -	$ -	$ 2,500
Fuel Analysis/core	$ -	$ 7,500	$ -	$ -	$ -	$ 7,500
SlagFly ash Analysis	$ -	$ 29,710	$ -	$ -	$ -	$ 29,710
Barr Subcontract	$ -	$ 29,900	$ -	$ -	$ -	$ 29,900
UND Subcontract	$ -	$ -	$ 35,000	$ -	$ -	$ 35,000
Total Direct	$ 15,720	$ 89,863	$ 63,819	$ 12,849	$ 26,421	$ 208,672
Indirect Cost (15%)	$ 2,358	$ 13,479	$ 9,573	$ 1,927	$ 3,963	$ 31,300
Total Project Expenses	$ 18,078	$ 103,342	$ 73,392	$ 14,776	$ 30,384	$ 239,972

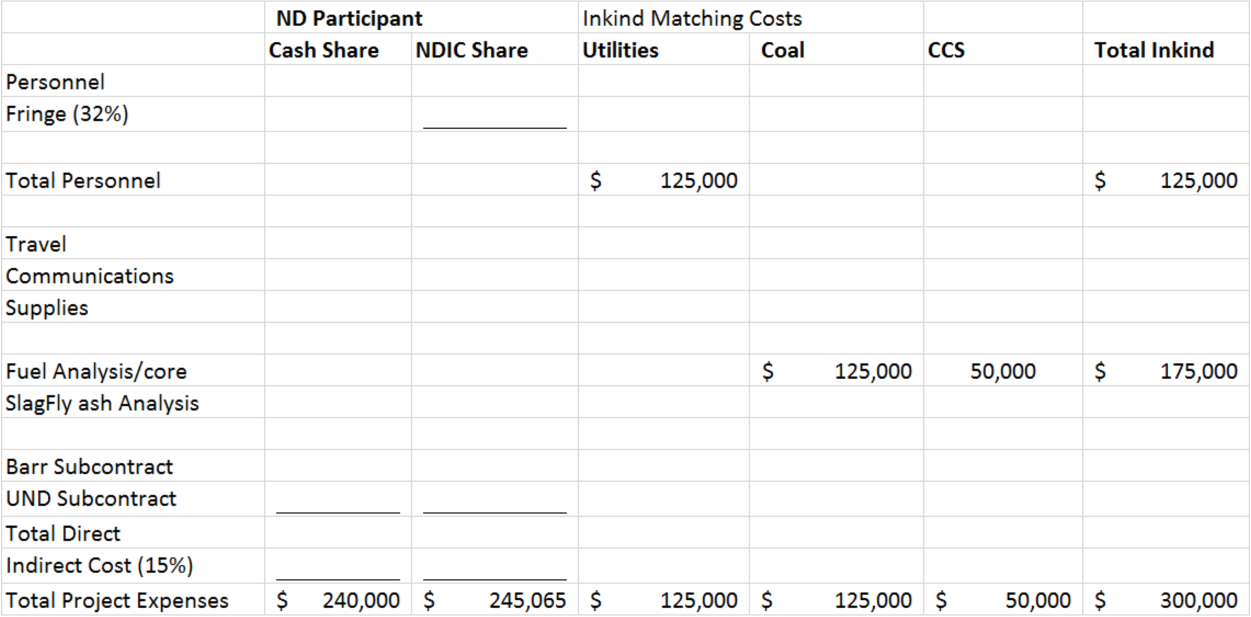
Table 3. Project budget by year and task (continued)

	Year 2.					
	Task 1	**Task 2**	**Task 3**	**Task 4**	**Task 5**	**Total Yr 2**
Personnel	$ 10,661	$ 12,865	$ 20,776	$ 9,658	$ 17,977	$ 71,937
Fringe (32%)	$ 3,411	$ 4,117	$ 6,648	$ 3,091	$ 5,753	$ 23,020
Total Personnel	$ 14,072	$ 16,982	$ 27,424	$ 12,749	$ 23,730	$ 94,957
Travel	$ 648	$ 3,671	$ -	$ 1,295	$ 1,943	$ 7,557
Communications	$ 500	$ 500	$ -	$ 500	$ 500	$ 2,000
Supplies	$ 500	$ 2,000	$ -	$ 2,000	$ 2,000	$ 6,500
Fuel Analysis/core	$ -	$ 7,500	$ -	$ -	$ -	$ 7,500
SlagFly ash Analysis	$ -	$ 29,710	$ -	$ -	$ -	$ 29,710
Barr Subcontract	$ -	$ 29,900	$ -	$ -	$ -	$ 29,900
UND Subcontract	$ -	$ -	$ 35,000	$ -	$ -	$ 35,000
Total Direct	$ 15,720	$ 90,263	$ 62,424	$ 16,544	$ 28,173	$ 213,124
Indirect Cost (15%)	$ 2,358	$ 13,539	$ 9,364	$ 2,482	$ 4,226	$ 31,969
Total Project Expenses	$ 18,078	$ 103,802	$ 71,788	$ 19,026	$ 32,399	$ 245,093

Table 4. Total two year budget.

	Total Year 1 and 2					
	Task 1	**Task 2**	**Task 3**	**Task 4**	**Task 5**	**Total Project**
Personnel	$ 21,322	$ 25,730	$ 41,552	$ 19,316	$ 35,954	$ 143,874
Fringe (32%)	$ 6,822	$ 8,234	$ 13,296	$ 6,182	$ 11,506	$ 46,040
Total Personnel	$ 28,144	$ 33,964	$ 54,848	$ 25,498	$ 47,460	$ 189,914
Travel	$ 1,296	$ 7,342	$ 1,295	$ 1,295	$ 4,534	$ 15,762
Communications	$ 1,000	$ 600	$ 100	$ 600	$ 600	$ 2,900
Supplies	$ 1,000	$ 4,000	$ -	$ 2,000	$ 2,000	$ 9,000
Fuel Analysis/core	$ -	$ 15,000	$ -	$ -	$ -	$ 15,000
SlagFly ash Analysis	$ -	$ 59,420	$ -	$ -	$ -	$ 59,420
Barr Subcontract	$ -	$ 59,800	$ -	$ -	$ -	$ 59,800
UND Subcontract	$ -	$ -	$ 70,000	$ -	$ -	$ 70,000
Total Direct	$ 31,440	$ 180,126	$ 126,243	$ 29,393	$ 54,594	$ 421,796
Indirect Cost (15%)	$ 4,716	$ 27,018	$ 18,937	$ 4,409	$ 8,189	$ 63,269
Total Project Expenses	$ 36,156	$ 207,144	$ 145,180	$ 33,802	$ 62,783	$ 485,065

Table 5. Budget Cost Share Summary.



	ND Participant		Inkind Matching Costs			
	Cash Share	**NDIC Share**	**Utilities**	**Coal**	**CCS**	**Total Inkind**
Personnel						
Fringe (32%)						
Total Personnel			$ 125,000			$ 125,000
Travel						
Communications						
Supplies						
Fuel Analysis/core				$ 125,000	50,000	$ 175,000
SlagFly ash Analysis						
Barr Subcontract						
UND Subcontract						
Total Direct						
Indirect Cost (15%)						
Total Project Expenses	$ 240,000	$ 245,065	$ 125,000	$ 125,000	$ 50,000	$ 300,000

14. MATCHING FUNDS

The total project cost is $785,065. The cost share contributions are summarized in Table 5. Letters of support for the project will be provided before the project is initiated.

15. Tax Liability

The applicant does not have an outstanding tax liability owed to the state of ND or any of its political subdivisions.

16. Confidential Information

No confidential information is included in the proposal.

17. APPENDICES

UNIVERSITY OF UND NORTH DAKOTA

DEPARTMENT OF CHEMICAL ENGINEERING
HARRINGTON HALL ROOM 323
241 CENTENNIAL DRIVE – STOP 7101
GRAND FORKS, NORTH DAKOTA 58202-7101
PHONE (701) 777-6699 FAX (701) 777-3773
Gautham.krishnamoorthy@engr.und.edu

CFD Modeling of Slag Flow Behavior in Combustion and Gasification Systems

Gautham Krishnamoorthy, University of North Dakota, Grand Forks, ND

Introduction

The aim of this write-up is to provide an overview of the computational fluid dynamics (CFD) modeling capabilities at the University of North Dakota (UND) that can assist operators of slagging combustion and gasification systems towards addressing various operational issues such as: poor slag flow, maintaining protective slag layers on refractory or membrane walls, ash/char retention in slag, and slag crystallization. A brief description of each capability/task, approximate task duration and associated costs on a per-plant basis are also described.

Description of Capabilities

1: Geometry Model Building and Meshing (Duration: 2 weeks; Cost: $ 2,500)

CAD files/drawings of the combustor or gasification system will be utilized to create a 3D geometric representation of the system geometry which will then be meshed to an adequate resolution. This will enable accurate predictions of the particle tracks, combustion behavior and temperature inside the gasifier or combustor. An example is given for the cyclone barrel (cf. Figure 1).

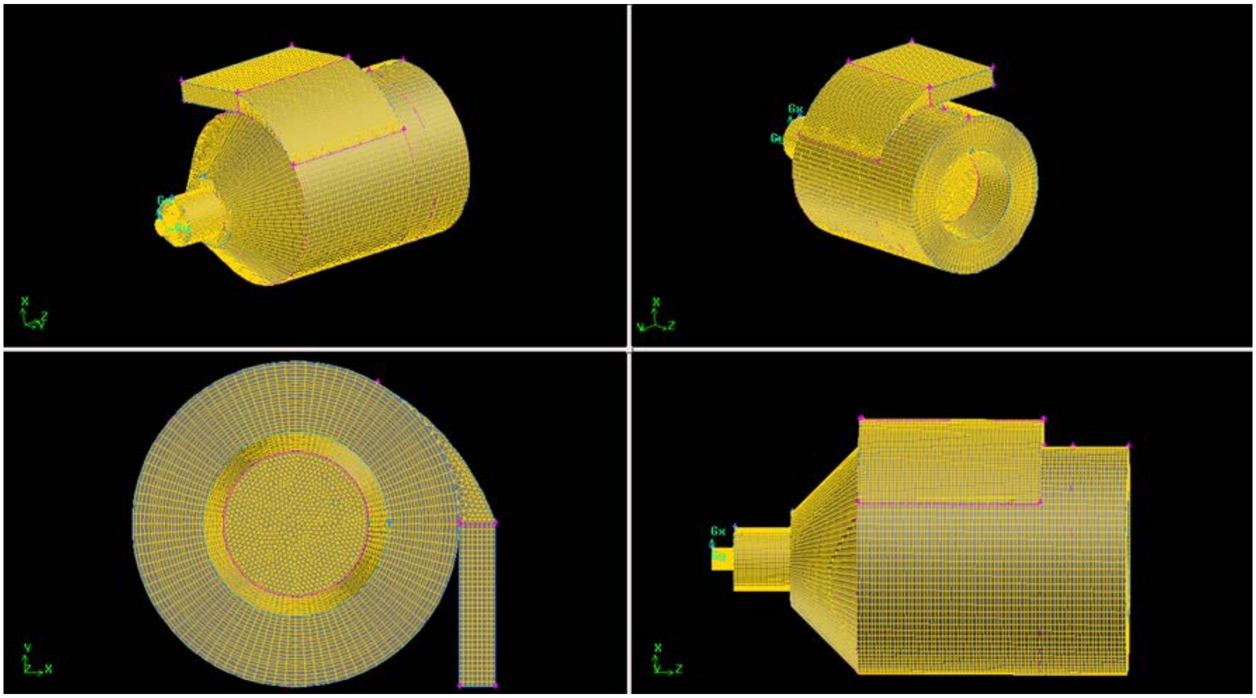


Figure 1: Geometry of a cyclone barrel simulated at UND

2: Full Scale Boiler Model Building and Meshing (Duration: 4 weeks; Cost: $ 5,000)

In combustion systems studies that are interested in assessing the effectiveness of NOx control strategies: over-fire air, re-burning, air-staging or SNCR methodologies towards NOx control, examining the flame impingement patterns, boiler fouling and heat transfer characteristics in front-wall fired furnaces, or estimating CO emissions and un-burnt carbon (UBC), will require comprehensive simulations of the entire boiler geometries. CAD files/drawings of the boiler will be utilized to create a 3D geometric representation of the boiler geometry which will then be meshed to an adequate resolution. This will enable accurate predictions of the particle tracks and their residence times across different temperature zones within the boiler. The project objectives might dictate carrying out high-fidelity simulations of the cyclone barrel first (capability 1) and then interpolating the results to the full scale boiler model.

3: Combustion/gasification Modeling inside each Cyclone Barrel (Duration: 2 weeks; Cost: $ 2,500)

CFD modeling of the combustion/gasification phenomena will be undertaken utilizing the commercial CFD software ANSYS FLUENT employing an Euler-Lagrangian approach. The continuum phase will be modeled in an Eulerian framework whereas the dispersed combustion particles will be modeled in a Lagrangian frame of reference. Models for fuel devolatilization, gas-phase chemistry, turbulence and radiative heat transfer will be appropriately chosen to accurately represent the combustion phenomenon (cf. Figure 2).

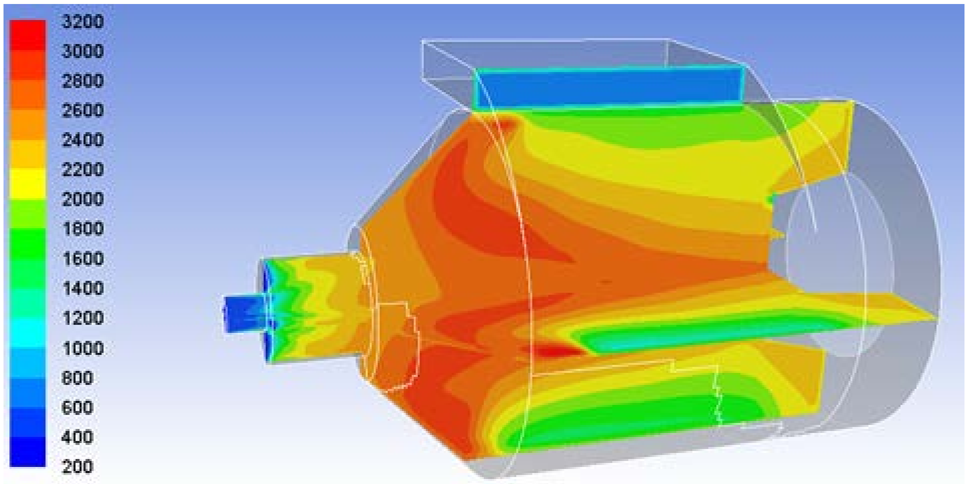


Figure 2: Temperature contours (in F) within a cyclone barrel simulated at UND

<u>4: Combustion Modeling inside the Boiler (Duration: 4 weeks; Cost: $ 5,000)</u>

CFD modeling of the combustion phenomena will be undertaken utilizing the commercial CFD software ANSYS FLUENT employing an Euler-Lagrangian approach. The continuum phase will be modeled in an Eulerian framework whereas the dispersed combustion particles will be modeled in a Lagrangian frame of reference. Models for fuel devolatilization, gas-phase chemistry, turbulence and radiative heat transfer will be appropriately chosen to accurately represent the combustion phenomenon (cf. Figure 3).

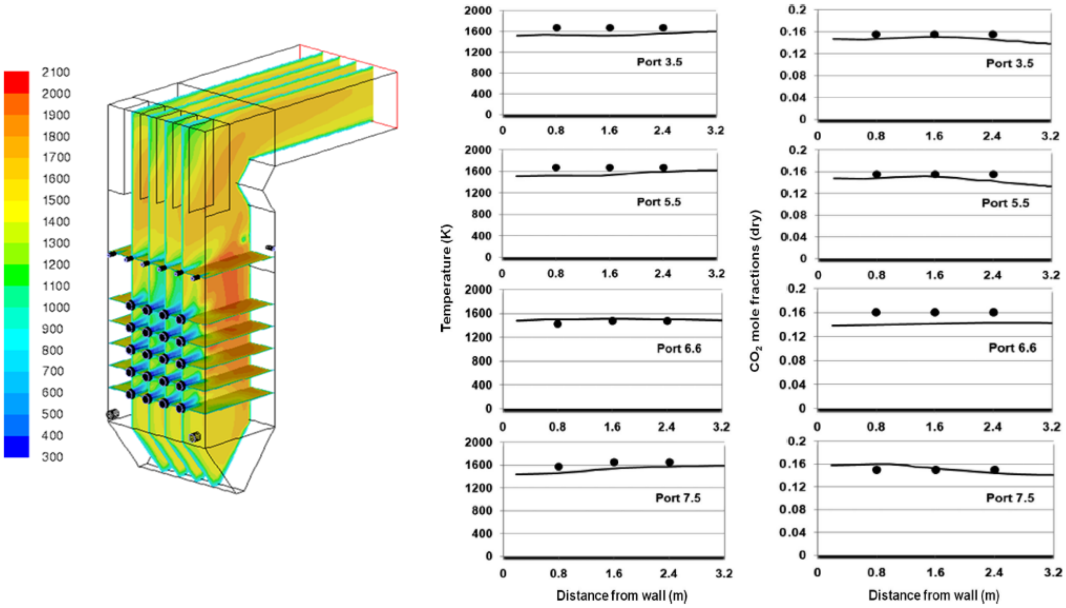


Figure 3: Temperature contours (in K) within a front wall fired furnace simulated at UND including comparisons between experimental measurements (dots) and simulations (solid lines) [1, 2].

Additional modules have been developed to accurately characterize radiative heat transfer in oxy-firing scenarios (cf. Figure 4).

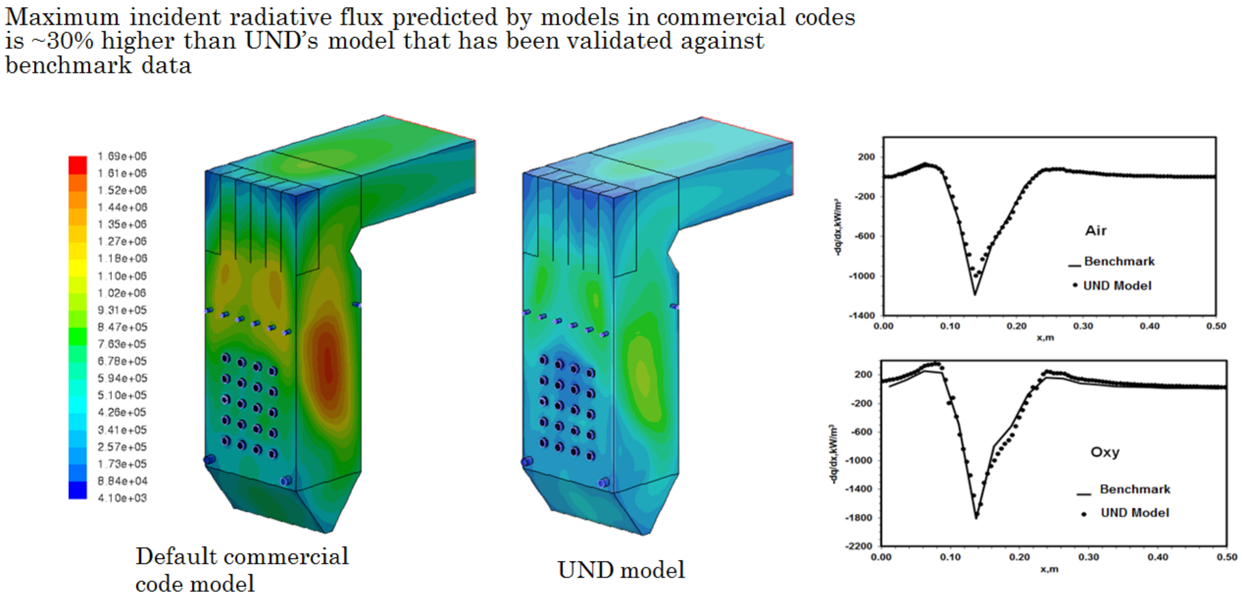


Figure 4: Contours of incident radiative flux (in W/m^2) along the walls of a front-wall fired boiler. Default models for gas radiative properties in commercial codes can predict 30% higher fluxes than UND's radiative property models that have been validated against benchmark data[3].

5: Sensitivity Analysis, running additional simulations at different operating conditions (Duration: 2 weeks/boundary condition; Cost: $ 1,250/run for each operation/fuel type; 4 weeks/boundary condition; Cost: $ 2,500/run for each boiler simulation)

To investigate the impact of changes to the operating conditions and fuel variability on the fly-ash to bottom ash distributions, CO, NOx emissions and UBC, additional CFD simulations corresponding to those conditions will be run to generate new particle tracks and the post-processing using the slag model will be repeated.

6: 3D Slag Model Development and Refinement (Duration: 8 weeks; Cost: $ 10,000)

The 3D slag flow behavior inside each system will be predicted employing a unique coupling between the Lagrangian particle-tracking method and a Volume-of-Fluid (VOF) modeling capability that tracks the interface between the slag layer and the combustion/gasification gases.

The slag model will be based on a particle capture criteria for the discrete phase where the *wall is assumed to be sticky* when the refractory wall inner surface temperature is above the ash temperature of critical viscosity (which will be estimated employing empirical correlations developed by Microbeam or those that are available in the literature). Correspondingly, the *particle will be assumed to be sticky* when the particle temperature is above the ash temperature of critical viscosity and the particle conversion is above a critical particle conversion. *If one of the two is non-sticky* the particle will be assumed to be trapped if the Weber number (the ratio of the kinetic energy and the interfacial surface tension energy) is smaller than unity or another pre-defined number. A combination of empirical correlations from the literature and models from Microbeam, Inc. will be employed to determine the important slag properties like the critical viscosity and surface tension that are needed to estimate the Weber number. Once the 3D mass flux profiles of the sticking particles are estimated at the walls, the slag model will be coupled with the VOF to estimate the transient evolution of the slag layer thickness along the walls. The model will be employed in a post-processing manner with the CFD simulations (cf. Figure 5).

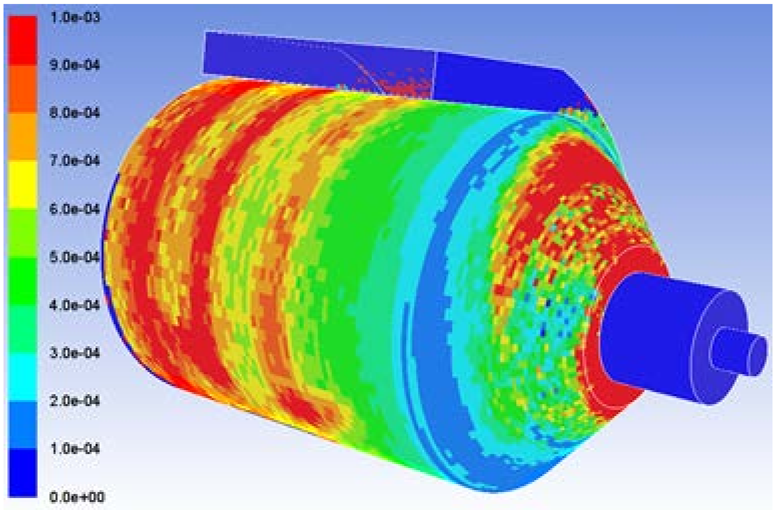


Figure 5: UND's slag model predictions of the average particle diameter of the depositing particles onto the slag layer within a cyclone barrel

7: Modeling of Inorganic Transformation Mechanisms (Duration: 8 - 16 weeks; Cost: $ 10,000 - $20,000)

Our current capabilities include quantifying the sub-micron component of the vaporized ash resulting from the volatilized/vaporized inorganic components. The coal particle tracks resulting from the CFD simulation in conjunction with equilibrium thermodynamic relationships are employed in a post-processing manner to quantify the fraction of ash vaporized. This capability can be enhanced by employing a population balance modeling approach to predict the evolving size distributions of the aerosol particles as a result of nucleation and coagulation mechanisms.

References

1. Gautham Krishnamoorthy, Anura Perera, Muhammad Sami, Stefano Orsino, Mehrdad Shahnam and David E. Huckaby, “Radiation Modelling in Oxy-Fuel Combustion Scenarios,” International Journal of Computational Fluid Dynamics, vol. 24, Nos. 3-4, pp. 69-82, 2010.
2. Pravin Nakod, Gautham Krishnamoorthy, Muhammad Sami and Stefano Orsino, A Comparative Evaluation of Gray and Non-Gray Radiation Modeling Strategies in Oxy-Coal Combustion Simulations, Applied Thermal Engineering, vol. 54, pp. 422-432, 2013.
3. Gautham Krishnamoorthy, “A New Weighted-Sum-of-Gray-Gases Model for Oxy-Combustion Scenarios,” International Journal of Energy Research, vol. 37, pp. 1752-1763, 2013.

Gautham Krishnamoorthy

Assistant Professor of Chemical Engineering

Professional Preparation

Bangalore University, INDIA	Chemical Engineering	B.E. ChE	1998
University of Utah	Chemical Engineering	M.S. ChE	2002
University of Utah	Chemical Engineering	Ph.D. ChE	2005

Appointments

Ann and Norman Hoffman Assistant Professor of National Defense/Energetics
University of North Dakota, Grand Forks, ND 08/2011 - current
Assistant Professor (non-tenure track),
University of North Dakota, Grand Forks, ND 11/2009 - 08/2011
Consulting Engineer,
ANSYS Inc., Lebanon, NH 07/2005 - 10/2009

Specialty Fields: Computational fluid dynamics; Combustion Modeling; Radiative transfer;

Five Publications Related to the Proposed Research:

1. Pravin Nakod, Gautham Krishnamoorthy, Muhammad Sami and Stefano Orsino, A Comparative Evaluation of Gray and Non-Gray Radiation Modeling Strategies in Oxy-Coal Combustion Simulations, Applied Thermal Engineering, vol. 54, pp. 422-432, 2013.
2. David W. James, Gautham Krishnamoorthy, Steven A. Benson and Wayne S. Seames "Modeling Trace Element Partitioning During Coal Combustion" Fuel Processing Technology, vol. 126, pp. 284 – 297, 2014.
3. Zachary Wheaton, David Stroh, Gautham Krishnamoorthy, Muhammad Sami, Stefano Orsino and Pravin Nakod, "A Comparative Study of Gray and Non-Gray Methods of Computing Gas Absorption Coefficients and its Effect on the Numerical Predictions of Oxy-Fuel Combustion," Industrial Combustion – Journal of the IFRF, Article Number 201302, July 2013, ISSN 2075-3071.
4. Gautham Krishnamoorthy, "A New Weighted-Sum-of-Gray-Gases Model for CO2-H2O gas mixtures," International Communications in Heat and Mass Transfer, vol. 37, pp. 1182-1186, 2010.
5. Gautham Krishnamoorthy, Anura Perera, Muhammad Sami, Stefano Orsino, Mehrdad Shahnam and David E. Huckaby, "Radiation Modelling in Oxy-Fuel Combustion Scenarios," International Journal of Computational Fluid Dynamics, vol. 24, Nos. 3-4, pp. 69-82, 2010.

Other Recent Publications (16 total peer-reviewed)

1. Hassan Abdul Sater, Gautham Krishnamoorthy, An Assessment of Radiation Modeling Strategies in Simulations of Laminar to Transitional, Oxy-Methane, Diffusion Flames Applied Thermal Engineering , vol. 61, pp. 507-518, 2013.
2. Zachary Wheaton and Gautham Krishnamoorthy, Modeling Radiative Transfer in Photobioreactors for Algal growth," Computers and Electronics in Agriculture, vol. 87, pp. 64-73, 2012.
3. Gautham Krishnamoorthy and Megan Jimenez, "A New Radiative Property Model for H2O Vapor in Hydrogen Combustion Scenarios," International Journal of Energy Research, vol. 36, pp. 789 – 797, 2012.
4. Gautham Krishnamoorthy, "A Comparison of Gray and Non-Gray Modeling Approaches to Radiative Transfer in Pool Fire Simulations," Journal of Hazardous Materials, vol. 182, pp. 570-580, 2010.
5. Gautham Krishnamoorthy and John M. Veranth, "Computational Modeling of CO/CO2 Ratio Inside Single Char Particles during Pulverized Coal Combustion," Energy & Fuels, vol. 17, pp. 1367-1371, 2003.

Synergistic Activities:

1. Outstanding Professor of the Year (Student's Choice Award for Teaching), School of Engineering and Mines, University of North Dakota, Grand Forks ND (2012)
2. Graduate Program Director: Chemical Engineering/Environmental Engineering/Sustainable Energy Engineering Graduate Programs (8/2012 – current)
3. Journal Reviewer: Bioresource Technology. Chemical Engineering Communications, Chemical Engineering Science, Energy and Fuels, Fuel, Fuel Processing Technology, Int. J. of Heat and Mass Transfer, International Journal of Hydrogen Energy, Journal of Hazardous Materials, Journal of Powder Technology, Journal of Thermal Sciences, Numerical Heat Transfer Part B, Recent Patents on Engineering, The Canadian Journal of Chemical Engineering
4. Proposal Reviewer: ND-NASA EPSCoR

Collaborators:

Stefano Orsino, Muhammad Sami, Pravin Nakod – ANSYS Inc.
Frank Bowman, Michael Mann, Steve Benson, Wayne Seames, Yun Ji, Brian Tande – University of North Dakota

Graduate Advisor: Philip J. Smith, University of Utah

Graduate Students (5 - past 5 years):

M.S. Thesis Advisees: Hassan Abdul Sater (August 2014), Hardy DeLong (expected 2014)

PhD Dissertation Advisees: David James (August 2013), Md. Ashiqur Rahman (expected 2015), Lucky Nteke Mulenga (expected 2016)

Number of Undergraduate Students Advised (past 5 years): 12

resourceful. naturally.
engineering and environmental consultants
BARR

September 19, 2014

Mr. Steve Benson
Microbeam technologies, Inc.
4200 James Ray Drive, Ste. 191
Grand Forks, ND 58203

Re: Stack test proposal for particulate matter testing for LEC tools project at Leland Olds and Coyote Station

Dear Mr. Benson:

Barr Engineering Co. (Barr) is pleased to provide the following cost estimate for stack testing services. It is our understanding that engineering testing will be performed on inlets to the ESP at Leland Olds Power Plant and Coyote Stations in ND. The stack testing work is being undertaken in support of a research project led by you.

Scope of Work

Services requested include the performance of engineering stack tests for particulate matter and providing the products of the field work for inclusion in your client reports. We understand that Barr will provide the personnel and gear to extract the samples from the sources using your particle sizing equipment for collection. You will retain the samples for subsequent analysis.

As directed, Barr has organized this proposal to provide the cost for each pre-test site visit and the cost for each one week test mobilization

Samples of stack emissions will be collected by the following EPA reference test methods found in 40 CFR Part 60, Appendix A, adapted as necessary for this project:

At Each Emission Source

• Test Port Location	EPA Method 1	(once per location
• Airflow Rate	EPA Method 2	(1 with each Method 29 run)
• Gas Composition & Molecular Weight	EPA Method 3	(1 with each Method 29 run)
• Gas Moisture Content	EPA Method 4	(1 with each Method 29 run)
• Particulate Matter	EPA Method 5	(4 test runs per day, 60 minutes per run, adjusted as necessary for these ESP inlet sources)

Project Team

The Barr project team is presented in the following table. The cost assumes a two-person field crew for particulate matter sample collection. Barr reserves the right to substitute available staff as necessary to meet our commitments at the time of the testing. Barr's stack test team includes sixteen staff with well over 200 years of combined testing experience. Over the past twenty-three years, we have successfully hired and retained highly experienced stack test team and project leaders while adding exceptional junior talent to provide appropriate balance to our project costs.

Team Member (1)	**Project Role**	**Stack Testing Experience, yrs.**
Tim Russell	Project Principal	28
Ben Wiltse	Project Manager	7
Dan Koschak	Senior Air Quality Technician	18
David Stroh	Air Quality Specialist	2

Schedule

As discussed with you, the field work is anticipated to begin in second quarter 2015. It is assumed that a pre-test site visit will be conducted once at each plant in advance of project mobilization. It is further assumed that sample collection will occur in one-week mobilizations as shown below.

Sunday	**Monday**	**Tuesday**	**Wednesday**	**Thursday**	**Friday**
Travel	Setup and Preliminary Measurements	Test Fuel Condition 1 **0700-1700**	Test Fuel Condition 2 **0700-1700**	Test Fuel Condition 3 **0700-1700**	Tear Down and Return Travel

Electronic copies of all field test data and test run summaries tables will be provided to you within 20 calendar days of the final test date of each one-week mobilization. Barr will work closely with you to provide the work product that will support your analysis and production of deliverables to your client(s).

Cost Estimate

The compensation is based on the entire Scope of Work, Schedule and Service Assumptions. The standby labor rate defined below will be applied as described in our Service Assumptions section.

Pre-test site visit (per occurrence)	**$5,000**
Particulate testing as shown in above schedule (per week)	**$24,900**

Two- person test team standby labor rate, $215/hr

Barr does not charge a fixed fee for test postponement or cancellation, we only require reimbursement for actual time and expense incurred as described in our Service Assumptions below. Barr meets our client's project schedule needs by billing at standard hourly rates for overtime and weekend hours (we do not have special weekend or overtime rates).

Barr will bill these services at 4-week intervals (thirteen invoicing periods per year). Payment terms are net 30 days, with a 1.5 percent monthly charge (18% annual interest) applied to unpaid invoices greater than 30 days old.

Service Assumptions

1. A plant or Microbeam representative familiar with the requested testing objectives, the test locations, available electrical service, and access to the facility will be available during the first day that the Barr test team is onsite to coordinate an efficient mobilization at the facility and will be in attendance during each test day to coordinate process operations with the Barr test team.

2. Reasonable access to each test location will be provided by each facility. If necessary, each facility will provide lift, scaffold, or other appropriate equipment that meets applicable OSHA standards, and trained lift equipment operators to access test locations that do not have permanent ladders and/or test platforms. Barr test crews include personnel trained as competent persons under 29 CFR Part 1926 – OSHA Standards for Scaffolds Used in the Construction Industry. The lift, scaffold, or other equipment must be in place, or made available on the day prior to the scheduled stack test to facilitate equipment setup and preliminary stack measurements. Barr will charge the standby labor rates provided in the attached cost table for delays caused by the unavailability of lift equipment and/or equipment operators.

3. Acceptable test ports will be provided by each facility as determined during the pre-test site visit. Generally, acceptable test ports are two or four 4-inch ports at 90 degrees on circular ducts, and a minimum of four 4-inch ports on rectangular ducts with adequate clearance for the sample train. Each test port should have a lifting lug, eyebolt, or padeye, located no less than 42 inches directly above each test port. Each test port must be opened, cleaned, with the cap left hand-tight no later than the day prior to each scheduled stack test.

4. We understand that inlet testing will be conducted at a single point, determined by traversing the duct during preliminary measurements.

5. Each facility will provide two 20A (110V) power circuits within 50 ft. of each location where the testing equipment is setup. The power circuits must be available upon arrival of the Barr test team

at the site to support the deployment of the test equipment. In the absence of the prescribed availability of these circuits, Barr will charge the test team standby rate provided in the cost section above.

6. Each process will be operating by 7:00 A.M. on each scheduled test day and will maintain the conditions appropriate for the emissions test for the entire test period defined in the project schedule.
7. Each facility will have responsibility for operating the process during each test to satisfy project objectives.
8. The work will be conducted under the Barr Standard Terms and Conditions for Professional Services provided as an attachment to this proposal.

If you have any questions regarding this quotation please call Tim Russell at 952-832-2630 or email trussell@barr.com. Microbeam may accept this proposal by signing below and returning to Barr along with a purchase order. Please refer to the proposal title and date, and address your response to Tim Russell.

Thank you for the opportunity to propose on this stack testing work.

Sincerely,

Tim Russell
Vice President

Attachment: Barr Standard Terms and Conditions for Professional Services

ACCEPTED BY____

PRINT NAME____

TITLE____

DATE____