Energy & Environmental Research Center
15 North 23rd Street, Stop 9018 • Grand Forks, ND 58202-9018 • P. 701.777.5000 • F. 701.777.5181
www.undeerc.org

September 30, 2019

Ms. Karlene Fine
North Dakota Industrial Commission
ATTN: Lignite Research Program
State Capitol – 14th Floor
600 East Boulevard Avenue, Department 405
Bismarck, ND 58505-0840

Dear Ms. Fine:

Subject: EERC Proposal No. 2020-0044 Entitled "Wastewater Recycling Using a Hygroscopic Cooling System"

The Energy & Environmental Research Center (EERC) is requesting cost-share funding from the Lignite Research, Development and Marketing Program for the subject project, which has been awarded by the U.S. Department of Energy to develop technology for existing coal-fired power plants that increases their water use efficiency and reduces their sensitivity to liquid effluent regulatory changes.

Enclosed please find an original and one copy of the subject proposal along with a check for $100. The EERC, a research organization within the University of North Dakota, an institution of higher education within the state of North Dakota, is not a taxable entity; therefore, it has no tax liability.

This transmittal letter represents a binding commitment by the EERC to complete the project described in this proposal. If you have any questions, please contact me by telephone at (701) 777-5083, by fax at (701) 777-5181, or by e-mail at cmartin@undeerc.org.

Sincerely,

Christopher L. Martin
Senior Research Engineer
Advanced Thermal Systems

Charles D. Gorecki, CEO
Energy & Environmental Research Center

CLM/rlo

Enclosures

Lignite Research, Development and Marketing Program

North Dakota Industrial Commission

Application

Project Title: Wastewater Recycling Using a Hygroscopic Cooling System

Applicant: University of North Dakota Energy & Environmental Research Center

Principal Investigator: Christopher L. Martin

Date of Application: September 30, 2019

Amount of Request: $100,000

Total Amount of Proposed Project: $820,675

Duration of Project: 3 years

Point of Contact (POC): Christopher L. Martin

POC Telephone: (701) 777-5083

POC E-Mail: cmartin@undeerc.org

POC Address: 15 North 23rd Street, Stop 9018
Grand Forks, ND 58202-9018

TABLE OF CONTENTS

ABSTRACT

The objective of this project is to test the feasibility of using the Energy & Environmental Research Center's (EERC's) hygroscopic cooling technology to eliminate power plant wastewater by recycling the water fraction to augment the plant's cooling load and collecting the remainder as a solid by-product for reuse or disposal. Hygroscopic cooling has been developed at the EERC under previous U.S. Department of Energy (DOE)-sponsored projects and is currently being demonstrated for air conditioner chiller cooling under a separate project. Key benefits of this approach at a coal-fired power plant are to improve the plant's overall water use efficiency while allowing the plant to more cost-effectively conform to zero-liquid-discharge (ZLD) requirements. Combined, these benefits result in reduced operating costs and fewer requirements for regulatory approval.

Key outcomes of the project include the design parameters for a hygroscopic system tailored for a North Dakota power plant wastewater stream and an initial techno-economic analysis of the concept based on measured performance. If the feasibility of this recycling concept can be shown, the primary beneficiaries would be existing power plant operators that would like to streamline their approach to effluent discharge by eliminating it as a regulatory concern.

The project team consists of the EERC, Baltimore Aircoil Company (BAC), and Great River Energy (GRE). Technical activities will be conducted by both the EERC and BAC, with BAC providing a cooling tower adapted specifically for hygroscopic operation. Testing will focus on wastewater streams at GRE's Coal Creek Station, and GRE will provide assistance for data collection, installation of a pilot system, and the engineering evaluation of its performance. While GRE is the partnering utility, the need for wastewater disposal alternatives is not unique, and the technology would be applicable to all North Dakota power plants. The specific benefit of Lignite Research Council (LRC) participation is that the evaluation testing will be performed at a lignite-fired plant under North Dakota weather conditions.

The project duration is 3 years, with two 18-month budget periods. The total project cost is $820,675, with $100,000 cash requested from the Lignite Research, Development and Marketing Program to be matched with $655,675 cash from DOE and $65,000 of in-kind equipment and services from BAC.

PROJECT SUMMARY

The objective of this project is to test the feasibility of using the Energy & Environmental Research Center's (EERC's) hygroscopic cooling technology to eliminate power plant wastewater by recycling the water fraction to augment the plant's cooling load and collecting the remainder as a solid by-product for reuse or disposal. Hygroscopic cooling has been developed at the EERC under previous U.S. Department of Energy (DOE)-sponsored projects and is currently being demonstrated for air conditioner chiller cooling under a separate project. Key benefits of this approach at a coal-fired power plant are to improve the plant's overall water use efficiency while allowing the plant to more cost-effectively conform to zero-liquid-discharge (ZLD) requirements. Combined, these benefits result in reduced operating costs and fewer requirements for regulatory approval.

Water is an essential resource for power production. In North Dakota, access to water is generally not an issue for the state's existing power plants. However, all of these plants need to regularly address the costs of water utilization and wastewater disposal. Water itself may be free or cost very little, however, expense is incurred to transport, treat, and ultimately dispose of it. In addition to cost, wastewater disposal involves some degree of regulatory approval from obtaining a National Pollution Discharge Elimination System (NPDES) permit for discharge to the environment or maintaining compliance for ZLD options such as an evaporation pond or injection well. Both disposal approaches are used in North Dakota, with two plants being designated ZLD facilities (Coal Creek and Antelope Valley). Discharge permits are affected by U.S. Environmental Protection Agency (EPA) rule making and are currently under revision.[1] ZLD facilities are less impacted by effluent regulations but must maintain sufficient disposal capacity within prescribed operating limits or else seek an exception.

EPA, in a 2015 review of power plant wastewater treatment technologies,[2] identified ZLD with water recycling as a preferred approach since it eliminated the need for a discharge permit and insulated operators from future guideline changes. The recycled water also cut operating costs by displacing the equivalent freshwater withdrawal. Despite these benefits, EPA judged that this option would be too costly for widespread implementation using existing technology.[2] Hygroscopic wastewater recycling appears to

compare favorably to conventional ZLD and even to EPA's best available technology economically achievable (BAT) for disposing of flue gas desulfurization (FGD) wastewater. If confirmed through this project, hygroscopic wastewater recycling could be an adaptable add-on system for North Dakota plants to either expand water disposal capacity or deal with specific wastewater streams that are difficult to permit, e.g., FGD scrubber blowdown.

This project is being conducted with cooperation from Great River Energy (GRE) and Baltimore Aircoil Company (BAC), a potential commercialization partner. The scope of work consists of determining optimal design parameters from laboratory studies of actual wastewater streams, fabrication of a small pilot system, and field testing at a North Dakota power plant to measure performance and inform a summary economic analysis. The pilot system is planned to be tested at GRE's Coal Creek Station; however, the need for wastewater disposal is not unique to GRE's operations, and the technology would be equally applicable to all North Dakota lignite power plants. As evidence, the project has received letters of support from other North Dakota plant operators including Basin Electric Power Cooperative and Minnkota Power Cooperative, in addition to GRE. All letters of support and commitment are included in Appendix C. The specific benefit of Lignite Research Council (LRC) participation is that the evaluation testing will be performed at a lignite-fired plant under North Dakota weather conditions and will therefore be directly comparable for other members of the Council.

PROJECT DESCRIPTION

Hygroscopic Cooling Description

The proposed wastewater-recycling concept is based on hygroscopic cooling, which is a water-saving cooling tower technology that uses a hygroscopic liquid desiccant instead of pure water as the working fluid in a cooling tower. The technology was originally devised as a novel way to increase the proportion of sensible (dry) heat transfer versus evaporative heat transfer that normally dominates heat rejection in a cooling tower. Water savings result when the ambient dry bulb temperature is below the tower's set point temperature and the desiccant working fluid can restrict evaporation to increase the proportion of sensible cooling. This trend is shown in Figure 1. Under favorable ambient conditions, such a tower can operate with no net water use, although it is generally more cost-effective to use this technology for water use optimization rather than elimination.

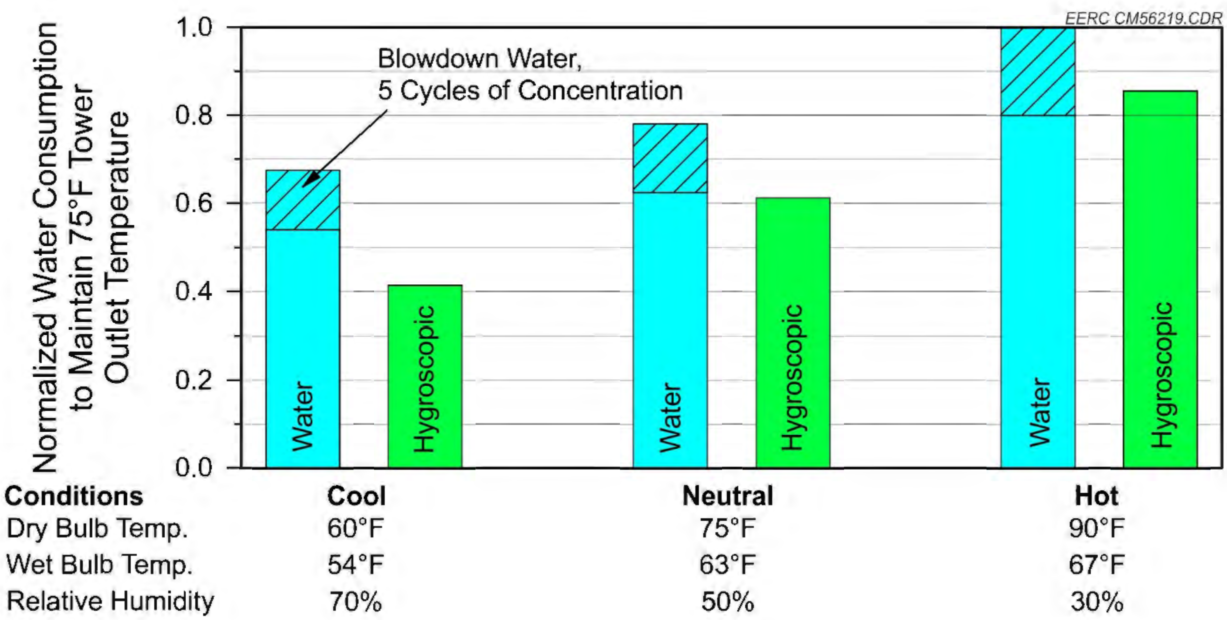

Figure 1. Trends of water savings with hygroscopic cooling. Hygroscopic cooling performance matches that of the conventional water cooling tower for the three scenarios. Water is saved by increasing sensible heat transfer when temperatures are sufficiently cool, but blowdown water is always saved.

Another key water-saving feature of hygroscopic cooling, and one that is central to this work, is that it does not rely on a blowdown stream for dissolved solids control. Instead of a blowdown stream, hygroscopic cooling takes advantage of desiccant properties to force the precipitation and direct separation of excess dissolved solids. When makeup water is added to a hygroscopic cooling tower, a supersaturated mixture is formed because of the low solubility that dissolved minerals have in the desiccant. Hygroscopic cooling capitalizes on this effect by regulating the mixing and residence time of makeup water addition in order to force the precipitation of dissolved substances in a controlled manner.

The process is somewhat similar to conventional lime softening, where hydrated lime ($Ca[OH]_2$) addition to hard water induces common ion effects and pH change that reduces the solubility of dissolved minerals, forcing them to precipitate.[3] The difference is that with hygroscopic cooling, creating a low-solubility transition does not consume a reagent as in lime softening; instead, the mechanism that causes low solubility, i.e., the concentrated desiccant solution, is continually regenerated as the water fraction of the working fluid is evaporated from the desiccant for cooling.

In addition to the potential for reduced water consumption, hygroscopic cooling can also alleviate some of the burdens associated with conventional water-cooling towers. For instance, the preferred desiccant working fluid, an aqueous solution of calcium chloride ($CaCl_2$), can have a substantially lower freezing point below that of pure water which adds a level of inherent freeze protection. At an optimal concentration, the solution's freezing point can approach −50°C, making it virtually freeze-proof even in North Dakota.

The concentrated desiccant also inhibits the growth of microbes that enter the tower from the airstream. While it is not considered a biocide, concentrated $CaCl_2$ (greater than 10% $CaCl_2$ by mass) effectively prevents the growth of microbes by lowering the water activity of the working fluid, much like the conditions found in preserved foods.[4] This characteristic of the working fluid prevents a hygroscopic tower from becoming a breeding ground for potentially harmful microbes—without ongoing biocide application.

Power Plant Wastewater Recycling

The primary driver for hygroscopic cooling development has thus far been water savings. However, this project aims to explore the ZLD aspect of its operation to increase the water use efficiency of coal-fired power plants and to eliminate water quality impacts associated with wastewater discharge. The overall concept is diagrammed in Figure 2, which shows a hygroscopic cooling circuit taking a slipstream of the condenser cooling water flow from a power plant. By cooling the slipstream, the hygroscopic system augments the plant's primary cooling system. However, instead of using freshwater for makeup, the hygroscopic system recycles wastewater from various streams at the plant, potentially including any or all of the following: blowdown from the existing cooling towers, blowdown from a wet desulfurization scrubber, or the rejected concentrate from the plant's demineralized water production system. The overall result is that freshwater makeup to the plant's primary cooling tower is reduced, and liquid effluent

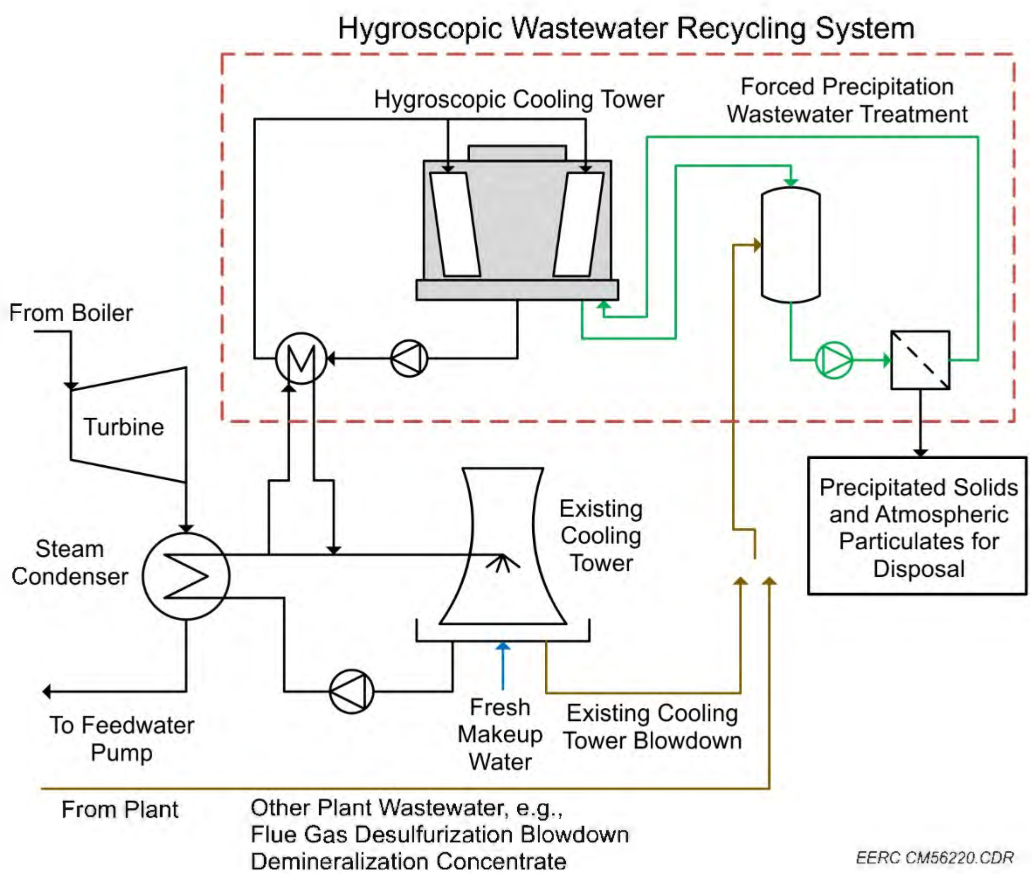

Figure 2. High-level schematic of a hygroscopic wastewater-recycling system applied at a full-scale thermoelectric power plant.

discharges are eliminated and replaced by a solid by-product that can likely go to the plant's ash disposal landfill or perhaps be recycled.

The proposed concept does not involve the complete replacement or reengineering of an existing plant's cooling system. Instead, the added hygroscopic system is largely self-contained, and there is significant flexibility in where and how it connects to the existing infrastructure. Because it is envisioned as an add-on system, the technology can be added to a plant in proportion to the need and/or optimized to generate the most favorable payback for a given site's conditions.

Technical Rationale

The underlying reason that makeup water can be completely evaporated in a hygroscopic cooling tower but not in a conventional water tower lies with the forced precipitation mechanism of dissolved mineral control. Because of the evaporation of water that takes place in any cooling tower, dissolved substances in the makeup water become more concentrated over time and there is eventually a risk of precipitation when their concentration exceeds the solubility limit for the given conditions (i.e., temperature, pH, species mix, etc.). In a conventional water-cooling tower, the only significant solubility gradient corresponds to temperature change, either across a heat exchanger or on the tower's wetted fill structure. These are clearly undesirable locations for scale to form, and instead, a blowdown stream is used to remove dissolved minerals and keep the entire system in a subsaturated condition.

In the hygroscopic tower, a strong change in dissolved mineral solubility is encountered when makeup water is mixed with the desiccant working fluid during operation. As shown in Figure 3, common dissolved minerals are much less soluble in concentrated desiccant versus water (i.e., 0% desiccant in Figure 3); therefore, it is possible to create a supersaturated mixture from makeup water addition. This supersaturated condition creates a driving gradient for excess dissolved minerals to precipitate and be removed from the system. In comparison, this elimination mechanism does not exist with a conventional water-cooling tower. In that case, mixing makeup water with nearly saturated water from the conventional tower does not result in a supersaturated mixture; at most, the new mixture remains near saturation and no gradient is created to precipitate minerals.

As shown in Figure 3, highly soluble species such as sodium chloride (NaCl) undergo a more gradual drop in solubility compared to the other sparingly soluble species. Nonetheless, they too can be forced from solution using the same mechanism once their solubility limit is reached. In fact, this mechanism is used commercially to increase the purity of $CaCl_2$ brine that is produced from naturally occurring sources.[5]

Creating the solubility gradient is only one part of maintaining a material balance with hygroscopic cooling; the other is actually getting precipitation to occur in a location and form where it does not interrupt flow and can be removed on an ongoing basis. Therefore, in addition to controlling the makeup mixing parameters to reach supersaturated conditions, the design and operation of the precipitation circuit are also key aspects of hygroscopic cooling technology that will be evaluated under this project.

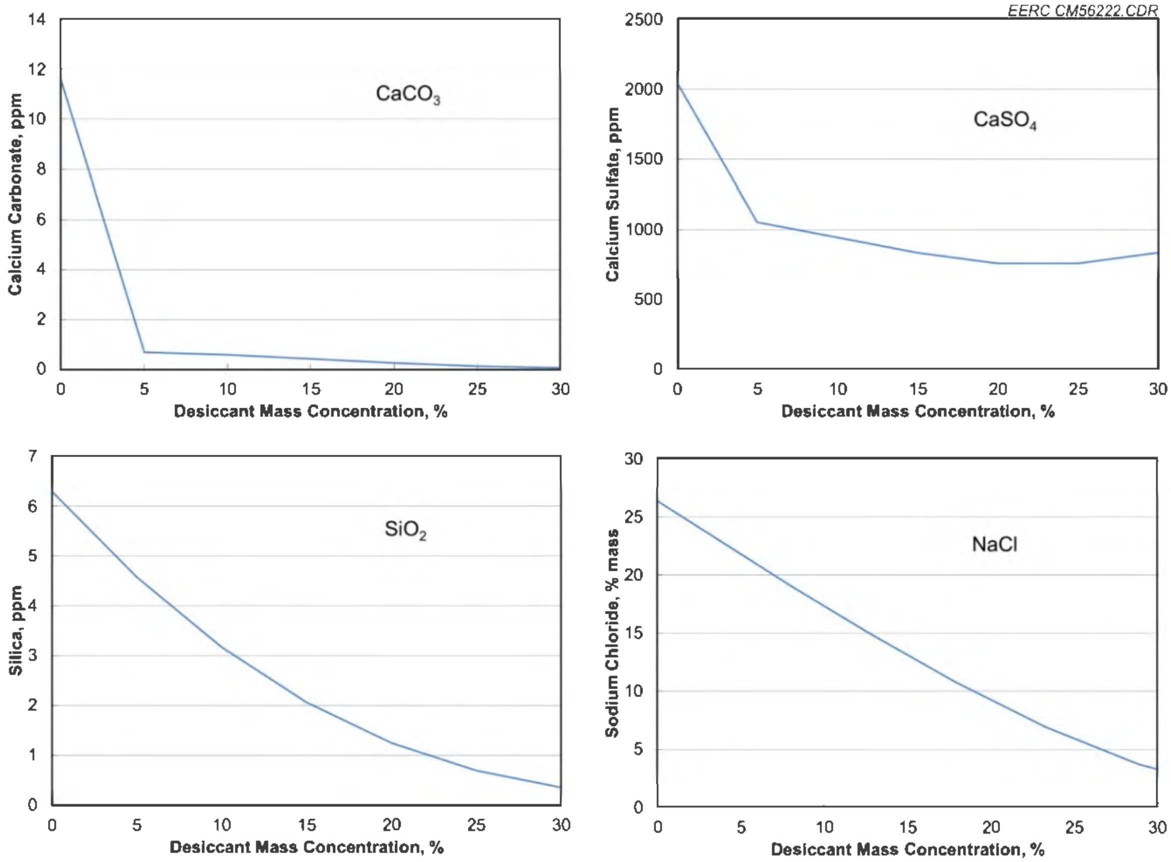

Figure 3. Calculated maximum solubility values for common dissolved species with increasing $CaCl_2$ desiccant concentration. These estimates were prepared using PHREEQC Interactive software (Version 3.310.12220) from the U.S. Geological Survey.

Objectives

In order to evaluate the feasibility of using hygroscopic cooling to recycle power plant wastewater, the following specific project objectives have been identified:

- Survey the wastewater streams produced at the partnering facility, and identify their representative characteristics; determine the optimal parameters for their use by a hygroscopic cooling system.
- Analyze the solid by-products produced by the hygroscopic system, and determine appropriate disposal or reuse options.
- Evaluate the environmental impacts of the process by determining the fate of bulk components and trace constituents of concern.

- Prepare a techno-economic analysis for the concept, and compare it to conventional means of ZLD wastewater treatment.

Methodology

To accomplish the objectives of the project, five tasks have been outlined. Aside from Task 1.0, which is Project Management and Planning, the remaining tasks are structured in a logical progression from analytic data collection, to laboratory evaluation of fundamental interactions, to the development and testing of a small pilot system, and finally ending with a techno-economic analysis (TEA). More detailed descriptions of each task are provided below:

- Task 1.0 – Project Management and Planning. This task is dedicated to project management and maintaining an active dialogue with the North Dakota Industrial Commission (NDIC) and DOE regarding project activities.
- Task 2.0 – Evaluation of Wastewater–Working Fluid Interactions. The objective of this task is to review the makeup mixing process and identify optimal conditions to achieve the desired precipitation and separation of wastewater contaminants. Key steps will be to survey wastewater streams at the partnering power plant, collect samples, and analyze them in the laboratory to estimate their potential treatability with the proposed concept. Following the survey, at least one target wastewater stream will be selected for laboratory batch mixing experiments to evaluate the parameters that affect precipitation and separation of the dissolved contaminants. The objective of these tests is to identify optimal parameter ranges for subsequent small pilot system design. A preliminary assessment of the by-products will also be performed to determine whether they have hazardous characteristics that could affect their reuse or disposal.
- Task 3.0 – Small Pilot Cooling System Design and Fabrication. The design parameters generated under Task 2.0 will be used to inform the design of a small pilot system capable of the following functions: evaporation of the water fraction of a real wastewater feed, sustainable

forced precipitation of dissolved contaminants in the wastewater, and recovery of the solid by-products. Design and fabrication tasks will be divided among the EERC and BAC; it is anticipated that BAC will provide a cooling tower subsystem based on an existing product offering but modified for hygroscopic cooling operation. The EERC will focus on the makeup water treatment subsystem and will also integrate the entire small pilot system for testing. Throughput of the small pilot system is anticipated to be in the range of 0.5 to 2 gpm of wastewater flow. This rate is consistent with previous demonstration units built and operated by the EERC.

- Task 4.0 – Wastewater Testing. The small pilot system will be used to evaluate the elimination of wastewater obtained from a host site power plant. Heat source temperatures will be consistent with those typical of the plant's condenser cooling water circuit. Preferably, testing will be conducted at the host site facility by transporting the small pilot system to the power plant. However, if it is not possible to temporarily site the small pilot within the time frame of the project, plant wastewater will instead be transported to the EERC for testing. Test duration will be sufficient to determine a heat and material balance for the wastewater-recycling process and to produce a sufficient quantity of by-product materials for subsequent analysis. The by-product material will be evaluated for potentially hazardous species, including the Resource Conservation and Recovery Act (RCRA) elements to determine disposal options. The material's reuse potential will also be considered. Testing the small pilot system with a real plant wastewater stream under actual outdoor ambient conditions will raise the technology readiness level (TRL) of the concept from 3 to 5.
- Task 5.0 – Techno-Economic Analysis. A summary TEA will be conducted based on findings from the small pilot system design and testing results. Estimates will be made for equipment capital, plant integration, and system operating costs. Cost or revenue associated with the by-product material will be evaluated as well as changes to other plant expenses, e.g., from a reduction in freshwater acquisition and treatment. Results from the analysis will be summarized

into installed capital and operating costs that can be directly compared to industry literature on ZLD technology.

Anticipated Results

This project promotes the goals of reducing water usage at coal-fired power plants and mitigating their impact on water quality by recycling wastewater for cooling. If successful, the technology under development could be a near-term solution to assist power plants, given that demonstrations of it for air conditioning use are currently under way.[6]

Key results from the project include the design parameters for a hygroscopic system tailored for a power plant wastewater stream and an initial techno-economic analysis of the concept based on measured performance that can be used to compare to other ZLD options. If the feasibility of this recycling concept can be shown, the primary beneficiaries would be existing power plant operators that would like to streamline their approach to liquid effluent discharge by eliminating it as a regulatory concern.

Facilities and Resources

The project team consists of the EERC, DOE, BAC, and GRE. Each organization will contribute the use of relevant facilities and resources to the project. Facility highlights include the following.

EERC. The EERC maintains 254,000 square feet of offices, technology demonstration facilities, and laboratories and currently employs more than 220 scientists, engineers, and support staff. The EERC's Analytical Research Laboratory is quality-trained in the methods for evaluating wastewater samples and those that support the sampling effort during wastewater testing. The EERC also has an in-house welding and machine shop for fabricating pilot equipment and has on-staff instrument technicians to support test campaigns immediately if problems arise.

BAC. As part of its commercial operation, BAC maintains facilities for fabricating and testing cooling tower product innovations, and these facilities will be leveraged to support this project. BAC test facilities meet requirements of the Cooling Technology Institute, the industry's governing body for certifying commercial and industrial evaporative cooling equipment.

GRE. GRE operates Coal Creek Station and Spiritwood Station in North Dakota. Coal Creek has a total generation capacity of more than 1100 MW, and Spiritwood has the capacity to generate up to 99 MW. Both plants supply process steam and other services to adjacent ethanol refineries; and both use beneficiated North Dakota lignite fuel. Coal Creek has been identified as the preferred location for this project's field testing; the plant has candidate wastewater streams including FGD scrubber blowdown and blowdown from closed-loop cooling towers. GRE's contribution to the project will be to adapt facilities at Coal Creek to connect the pilot system and supply it with thermal energy from the condenser cooling circuit and makeup water from a relevant blowdown stream.

As for key personnel, Christopher Martin, Ph.D., a Senior Research Engineer at the EERC, will serve as the project Principal Investigator (PI) and will be directly responsible for the scope of work assigned to the EERC. Yohann Rousselet, Ph.D., the Manager of Emerging Technology Partnerships at BAC, will lead the engineering, design, and fabrication efforts assigned to BAC. Resumes are provided in Appendix A.

As demonstrated in the proposal budget, project PI Dr. Martin will average 33.6% effort over the 3-year duration of the project. Similarly, facilities at the EERC will be made available as needed to the project for pilot equipment fabrication, shakedown testing, and wastewater testing, if required. BAC personnel, including Dr. Rousselet, and the facilities required for cooling tower development and shakedown testing are also committed to the project, as outlined in the provided letter of support in Appendix C. Power plant sample collection and support for pilot system testing will be provided through a working relationship with GRE documented in the letter of support, also in Appendix C.

Immediate Environmental and Economic Impacts

Each phase of the project, including laboratory data generation, design and fabrication of a pilot system, and field testing, will be handled in an environmentally responsible manner. For example, laboratory facilities at both the EERC and BAC are practiced in appropriate handling and disposal techniques for potentially hazardous emissions and by-products. Likewise, field testing will comply with applicable environmental regulations. The solid waste material produced during field testing will be evaluated for hazardous substances, and it will be disposed of accordingly based on its determined classification. After testing, pilot equipment will be removed from the demonstration site and returned to the EERC, leaving no permanent impact on host site operations.

The project's field testing has also been structured to minimize economic impacts to host site operations. Key to this is the relatively small scale of the pilot unit to be tested and the fact that it will be largely isolated from other plant operations. Outside of pilot system installation, EERC personnel will be primarily responsible for monitoring unit operation and performing system maintenance. This arrangement will avoid extended negative economic impacts for the host facility.

Ultimate Technological and Economic Impacts

The ultimate impact of this project will be to introduce a new technology for treating power plant wastewater at lower cost and with reduced permitting requirements compared to existing options. As a result, this technology could make it less costly for plants to comply with revised effluent limitation guidelines or to maintain their ZLD status. These issues complicate the continued operation of legacy facilities such as the power plants in North Dakota, and finding efficient technological solutions can aid in keeping them competitive.

Power plants that rely on NPDES permitting for wastewater disposal face increasing regulation as environmental quality standards continue to evolve. In 2015, EPA revised the effluent limitations guidelines and standards for coal-fired power plants to specifically address the effluent from flue gas desulfurization systems.[1] While the final rule has been challenged and its implementation is delayed until at least fall 2020, the regulatory limits it sets are expected to eventually become mandated.

As part of its rule-making process, EPA conducted a thorough evaluation of power plant wastewater treatment technologies that could comply with the final rule.[2] This evaluation included approaches currently in full-scale use, those that have been evaluated with power plant wastewater but not demonstrated at full scale, and state-of-the-art ideas currently at the bench-scale stage. Based on technical and economic considerations, EPA selected the combination of chemical precipitation for metal control with biological treatment for soluble contaminate control as the BAT for disposing of FGD wastewater.[1] The average costs for EPA's BAT have been determined to be approximately $65,000 per gpm of wastewater throughput for capital costs and $8/kgal for operating costs.[2]

While sufficient to meet proposed effluent guidelines, the BAT selected by EPA for FGD wastewater disposal does not eliminate effluent discharge that could be challenged under future regulations. From this perspective, ZLD with water recycling was identified as a preferred approach, but it was judged to be too costly for widespread implementation by EPA.[2] In general, low-cost ZLD options require significant land area to site evaporation ponds or need suitable geology for subsurface injection, which greatly limits their applicability. Alternatively, less restrictive ZLD options that use brine concentration are not synergistic with plant operations, which makes them costly to install and operate and reduces their comparative return on investment. A high-level comparison between the proposed hygroscopic wastewater-recycling concept and existing ZLD options is presented in Table 1.

Table 1. Comparison of Hygroscopic Cooling for Wastewater Recycling with Other ZLD Options

	Disposal-Only ZLD	**Hygroscopic Wastewater Recycling (this project)**	**Thermomechanical ZLD**
Description	Includes options such as evaporation ponds and subsurface injection wells where wastewater is sent for on-site, long-term disposal.	Steam condenser waste heat is dissipated by a hygroscopic cooling system using wastewater for makeup; the water fraction is completely evaporated, leaving a solid by-product.	Input energy powers a series of concentration stages that culminates with a brine crystallizer or equivalent process to recover a solid by-product.
Water Recovery	No.	Indirectly, by displacing water otherwise needed for cooling.	Yes, typically high quality suitable for many purposes.
Indicative Operating Cost	Potentially low, but limited to suitable climates and/or subsurface geology.	$7.40/kgal[a]	$32.82/kgal[b]
Indicative Installed Capital Cost	Highly variable depending on land availability and/or subsurface conditions.	$51,000/gpm[c]	$110,000/gpm[b]

[a] Based on the parasitic energy cost needed to run a demonstration hygroscopic cooling tower and assuming a $0.0763/kWh electricity cost, which is applicable to the project's host power plant (North Dakota industrial average for 2017).[6,7]

[b] Reported costs for ZLD treatment resulting in a solid for disposal.[8]

[c] Based on the average equipment and installation costs for current demonstrations of hygroscopic cooling.[6]

When compared to the other ZLD options shown in Table 1, the hygroscopic cooling concept offers a unique combination of features. Thermomechanical ZLD can use many different configurations, but in all cases, a combination of high-quality thermal and mechanical energy inputs is needed to separate high-purity water from the wastewater and ultimately leave behind a solid by-product. At the other end of the ZLD spectrum are disposal-only options such as the use of an evaporation pond or injection well. Ponds require virtually no input energy to operate since they rely on solar and wind energy to concentrate the wastewater. However, as a result of being a passive process, no recyclable water is recovered. Likewise, injection wells can use relatively little energy after drilling, but no water is recovered.

The hygroscopic wastewater-recycling concept has characteristics that fall between these conventional options and, as such, is hypothesized to be a beneficial option for existing power plants by exceeding EPA's selected BAT. Hygroscopic cooling requires thermal energy input to drive wastewater evaporation, but the temperatures needed are entirely compatible with those of the steam condenser cooling circuit and can make effective use of this vast waste heat resource. The trade-off for using low-grade energy with the hygroscopic process is that purified water is not directly recovered, but instead, the water component of the wastewater is put to productive cooling use, thereby displacing higher-quality water for use elsewhere.

An advantage of hygroscopic wastewater recycling is its lower estimated operating and capital costs compared to thermomechanical ZLD in Table 1. With the thermomechanical approach, the energy used to drive the process includes high-quality steam and/or vapor compressor power, all of which must be included in the operating cost. With the hygroscopic approach, waste heat taken from the plant's condenser cooling circuit is essentially free except for the energy needed to circulate condenser cooling water through the hygroscopic recycling system. Capital costs for hygroscopic wastewater recycling are also estimated to be significantly below thermomechanical ZLD, given that the core of the system is based on cooling tower equipment. These devices can have a low cost versus heat load capability compared to an equivalently rated brine crystallizer. While the values in Table 1 are preliminary, characteristics of the hygroscopic approach are believed to be competitive with EPA's BAT while offering the operational benefits associated with a ZLD process.

Project Justification

In order to apply hygroscopic cooling for power plant wastewater consumption, the tolerance of this process for more complex water compositions needs to be evaluated. Unlike the relatively simple composition of potable water that the EERC has used for air-conditioning applications of hygroscopic cooling,[6] power plant wastewater will introduce other species that may complicate the material balance process. These added species may include increased chlorides and potentially other halogen ions; metals, including trace species that will need to be evaluated for hazardous concentrations; and various additives used in the plant's existing cooling system, including biocides and antiscalants. Whereas the objective of previous EERC studies of hygroscopic cooling has been to maximize water savings, the present project is needed to determine the optimal forced precipitation parameters for a more complex makeup water source.

STANDARDS OF SUCCESS

Success criteria consist of quantitative measures of the concept's operational and economic viability. Economic criteria include the estimated capital and operating costs for the hygroscopic cooling approach to wastewater elimination; these estimates will be compared to equivalent metrics of existing process options for wastewater treatment and ZLD. The process selected to evaluate success is EPA's BAT for treating FGD wastewater, which consists of chemical metal precipitation followed by biological treatment for soluble contaminate control.[1,2] This option, however, does not result in recycled water to the plant, nor does it eliminate effluent discharge that could be challenged under future regulations. ZLD with water recycling is a preferred approach, and hygroscopic cooling wastewater recycling will be considered successful if it can offer these advantages within the projected cost of the current BAT, which has been estimated to be approximately $65,000 per gpm of wastewater throughput for capital costs and $8/kgal for operating costs.[2]

BACKGROUND

Hygroscopic cooling derives from initial development projects sponsored by DOE, state research programs, and private industry.[9,10] In these original projects, the idea was to operate on a net-dry basis, but subsequent development identified hybrid operation as more economically favorable. This mode of operation, termed hygroscopic cooling, uses a mild desiccant working fluid (aqueous $CaCl_2$) with makeup water to virtually match wet cooling performance but optimize water use rather than target completely dry operation.

The water-saving aspects of hygroscopic cooling are currently being demonstrated under an Environmental Security Technology Certification Program (ESTCP) project entitled “Hygroscopic Cooling for Reduced HVAC Water Consumption.”[6] The ESTCP is funded by the U.S. Department of Defense (DoD) to field-test promising, precommercial energy- and water-saving technologies at DoD facilities. The hygroscopic demonstration project includes two host sites that have contrasting climates to evaluate the effect of ambient conditions on potential water savings.[6] While the climates vary from a hot, arid high desert to a moderate coastal location, both sites have relatively high costs for makeup water and blowdown disposal (combined values are in the range of $10 to $16 per kgal). This made them good candidates for the ESTCP demonstration. Photos of the demonstration equipment and further details of the ESTCP testing are provided in Figure 4.

The ESTCP demonstrations are intended to show the potential water savings that could be gained from using a hygroscopic cooling tower versus a conventional alternative while minimizing any impact to chiller efficiency from poor cooling tower performance. The demonstration towers have shown water savings from increased sensible heat transfer when outdoor conditions were suitable, but the most consistent source of water savings has been the elimination of the blowdown stream normally needed for dissolved solids management. The demonstration towers get makeup water from the same potable water supply that is used for the existing cooling towers, and the results thus far show that the mechanism of

EERC CM56221.CDR

Figure 4. ESTCP demonstration hygroscopic cooling systems, Fort Irwin, California (left) and Seaside, California (right). The Fort Irwin demonstration began July 2018 and Seaside started March 2019. Both demonstrations will run through the 2019 cooling season.

forced precipitation is suitable for maintaining the material balance of common dissolved minerals found in tap water, i.e., calcium carbonate ($CaCO_3$), calcium sulfate ($CaSO_4$), and silicon dioxide (SiO_2).

QUALIFICATIONS

The project team consists of the EERC, DOE, BAC, and GRE. Technical activities will be conducted by both the EERC and BAC, with the duties being split as previously described according to areas of expertise. GRE will provide the end user perspective and will support testing by allowing power plant access to collect samples and making modifications at Coal Creek Station to connect the pilot system.

The EERC specializes in research, development, demonstration, and commercialization of promising technologies and has led the development of hygroscopic cooling technology utilizing in-house fabrication and test facilities as well as coordinating and conducting field evaluations.

BAC is a market leader for packaged cooling tower systems and will contribute expertise relating to cooling tower design, evaluation, and manufacturing cost development. BAC does not produce field-erected towers typical of coal-fired power plants; however, the proposed concept is based on self-contained, modular equipment, and the commercial units produced by BAC are a highly relevant platform.

GRE is a wholesale electric power cooperative based in Minnesota and operates two coal-fired assets in North Dakota: Coal Creek Station and Spiritwood Station. Both North Dakota facilities operate with beneficiated lignite produced via the Dryfining™ process, an innovative waste heat-recycling application. Wastewater streams from one or both sites will be included in the initial Task 2.0 survey. Under Task 4.0, Wastewater Testing, GRE will assist the team in deciding the best location for pilot system testing and will make on-site modifications to install the system and connect it to the necessary plant infrastructure.

Key project personnel include the EERC's Dr. Christopher Martin, the project PI, and Dr. Yohann Rousselet, the Manager of Emerging Technology Partnerships at BAC. Resumes for both Dr. Martin and Dr. Rousselet are included in Appendix A. Dr. Martin is a Senior Research Engineer at the EERC and is the inventor of the desiccant-based cooling concept and has been involved in the EERC's past development projects. Key relevant experience includes the ESTCP demonstration project mentioned previously.[4] Under that project, two hygroscopic units of similar size to the proposed small pilot were fabricated and have been installed at two separate field sites for yearlong demonstrations. Lessons learned from that experience will aid the planning and execution of the current project.

Dr. Rousselet will lead the engineering, design, and fabrication efforts assigned to BAC. He has been a key leader in developing and evaluating new technologies and product concepts that transferred successfully into product launches, most recently Nexus and Polairis. His succinct technology analyses, as well as cross-functional teamwork, have afforded BAC with excellent decisions for vetting successful technologies. Dr. Rousselet will leverage BAC's know-how, resources, and deep network of external partners to enable the team to design, manufacture, and test a prototype according to the highest standard of the industry.

VALUE TO NORTH DAKOTA

The key value offered by this project is furthering a technology option that can be considered for use by North Dakota lignite power plants. All five of North Dakota's major lignite-fired facilities, shown in Table 2, produce wastewater from wet scrubbing processes and/or closed-loop cooling towers. Two of

Table 2. Wastewater Source Information at North Dakota Lignite Power Plants*

Plant	ZLD Facility	Potential for FGD Blowdown	Potential for Cooling Water Blowdown
Coal Creek Station	Yes	Yes, from wet lime scrubber	Yes, from closed-loop cooling towers
Milton R. Young Station	No	Yes, from wet limestone and fly ash scrubber	No, once-through cooling from Lake Nelson used
Leland Olds Station	No	Yes, from wet limestone scrubber	No, once-through cooling from Missouri River used
Antelope Valley Station	Yes	No, dry scrubber used	Yes, from closed-loop cooling towers
Coyote Station	No	No, dry scrubber used	Yes, from closed-loop cooling towers

* Lewis & Clark Station and R.M. Heskett Station have scheduled closure dates and were therefore not included in this comparison.

these facilities are designated ZLD, while the others hold a NPDES permit for industrial wastewater discharge. Both plant categories could benefit from lower-cost ZLD water recycling. As evidence, the project has received letters of support from North Dakota plant operators, including Basin Electric Power Cooperative and Minnkota Power Cooperative, in addition to the partnering operator GRE. All letters of support and commitment are included in Appendix C.

For those plants holding a NPDES discharge permit, EPA is currently reviewing effluent limitation guidelines for steam power stations, and the requirements of the final rule are far from certain, given the abrupt actions by recent administrations. Revision of this rule was initiated to specifically address the changes to power plant effluent brought about by increased use of FGD scrubbers. The earliest compliance time frame for the revised rule is fall 2020, at which time preliminary data from this project will be available for affected North Dakota plants to evaluate hygroscopic wastewater treatment as a compliance option.

Plants already designated ZLD may not be subject to changes in the effluent limitation guidelines, but instead they must ensure sufficient disposal capacity at all times, even during times of net water retention. These conditions might arise during periods of high water use, e.g., from cooling in summer, or during periods of poor natural evaporation from retention ponds. These situations could involve expansion of evaporation ponds or increased injection rates for disposal wells, both of which incur cost and require some degree of regulatory approval. Here again, hygroscopic cooling may provide these plants a favorable alternative that preserves the capacity of current ZLD options.

The other aspect of hygroscopic treatment is its synergistic reuse of wastewater for cooling. With this approach, a plant is in essence adding cooling capacity that does not increase its overall water consumption. This added capacity could supplement marginal cooling capability in summer to help maintain electric power production.

Other potential North Dakota beneficiaries could include lignite-based industrial facilities such as the Great Plains Synfuels Plant, Spiritwood Industrial Park, and Blue Flint Ethanol facility collocated at Coal Creek Station. These facilities also use cooling towers and may also benefit from improved water use efficiency and alternative methods for blowdown disposal.

Commercially, the project will generate data essential to future hygroscopic cooling system designers, and it will introduce a potential manufacturer of these systems, BAC, to this potential market segment. Hygroscopic cooling technology is not yet commercially available, and field tests like this are essential to gaining not only end user acceptance, but also interest from a partner that has the capability to manufacture products and provide them to utility customers.

Ultimately, the technology resulting from this project could give power plant operators an additional choice regarding wastewater treatment. While the technology will be applicable to coal plants in other regions, the added value to North Dakota is that this testing will be conducted at a lignite-fired facility under North Dakota weather conditions. This makes the findings more easily transferrable to North Dakota plants versus other parts of the country.

MANAGEMENT

The EERC will be the lead organization for this effort, and there will be a single PI, Dr. Christopher Martin of the EERC. The technical scope of work is divided among the EERC and BAC. Dr. Yohann Rousselet will lead the effort by BAC which will consist of in-kind contributions, including providing technical input to the wastewater survey of Task 2.0, designing and fabricating the cooling tower subsystem in Task 3.0, providing technical insight for Task 4.0 testing, and developing costing guidance for the techno-economic analysis of Task 5.0. GRE will identify on-site contacts for collecting information about candidate wastewaters and will support the installation and operation of field test equipment. An organizational chart for the project team is provided in Figure 5.

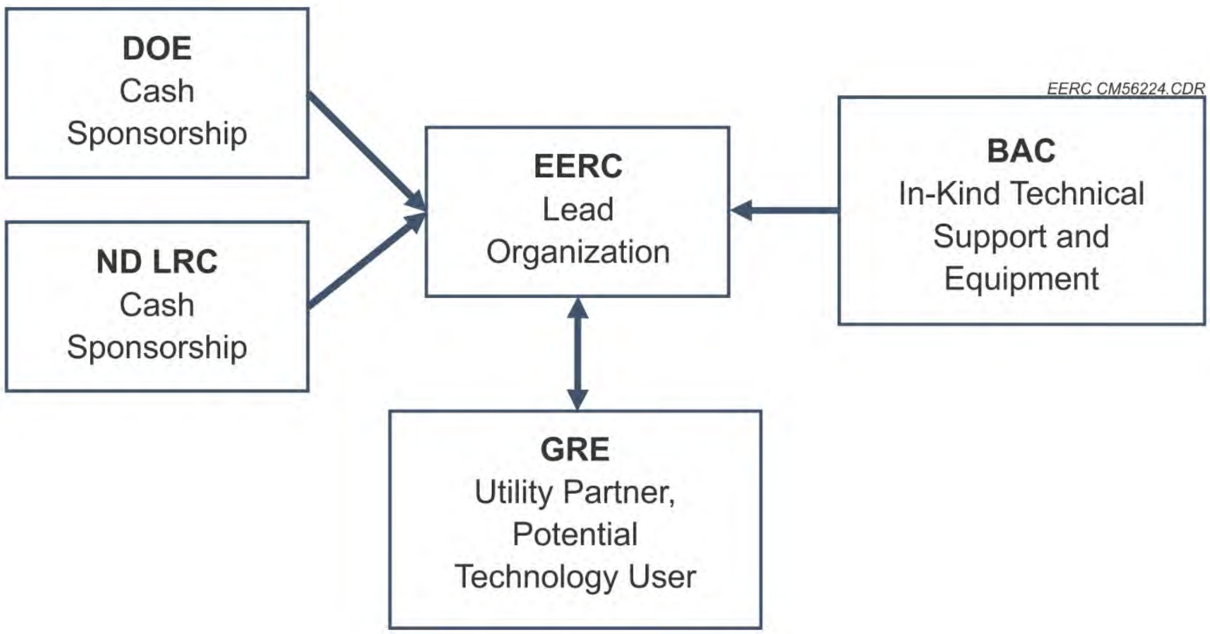

Figure 5. Organizational chart for the project team.

Communication among the team members will be maintained several ways. Regular quarterly reporting and update briefings will be the primary method to keep DOE and the North Dakota LRC apprised of the project's status. The technical team of the EERC and BAC will hold regular, biweekly conference calls to discuss ongoing project activities, while periodic discussions via WebEx and face-to-face meetings will be scheduled between the EERC, BAC, and GRE at critical project junctures to review progress and plan future activities.

In terms of risk management, the key risk identified for this project concerns the location and method of conducting wastewater testing under Task 4.0. The preferred plan is to temporarily site the small pilot system at one of GRE's plants in North Dakota for testing since that option has the advantage of using waste heat from the plant rather than needing to purchase high-quality steam at another location.

However, the EERC regularly conducts field testing, and this experience highlights the many ways such plans can be interrupted. Given the project's relatively short window to accomplish wastewater testing, the team has decided to include a more certain contingency plan from the start, i.e., site the small pilot system at the EERC and transport wastewater from one of GRE's plants to conduct the campaign.

Technical risks associated with wastewater recycling using hygroscopic cooling are considered to be manageable since the concept is an adaptation of similar technology being demonstrated under the ESTCP.[6]

Discussion of evaluation points that will be used to evaluate project progress is included under the Timetable section.

TIMETABLE

The project duration is planned for 3 years, with two 18-month budget periods. Figure 6 shows the schedule for all five tasks and the milestones associated with evaluating project progress. A go/no-go decision point is included at the end of Budget Period 1 to allow the project to be assessed before conducting wastewater testing. Milestone accomplishments lie on the critical path for the project, and it is required that they be successfully achieved in order to meet the project's overall objective. A schedule of the project's milestones is provided in Table 3.

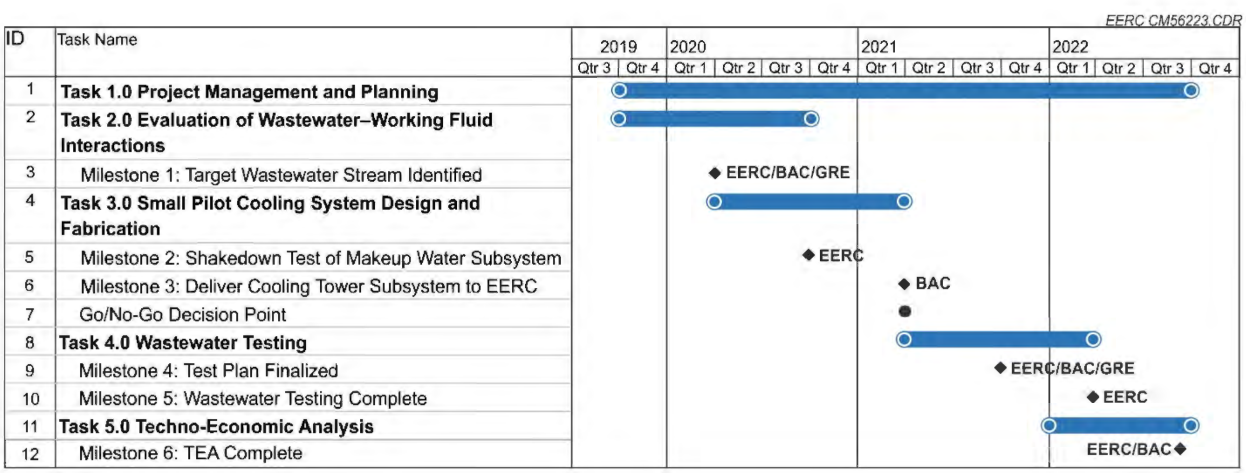

Figure 6. Project schedule.

Table 3. Schedule of Project Milestones

Task	Milestone Title and Description	Planned Completion Date	Verification Method
2.0	Milestone 1: Target Wastewater Stream Identified	6 months after project start	Cooling tower subsystem design criteria transmitted to BAC
3.0	Milestone 2: Shakedown Test of Makeup Water Subsystem	12 months after project start	Shakedown testing complete for makeup water subsystem
3.0	Milestone 3: Deliver Cooling Tower Subsystem to EERC	18 months after project start	Cooling tower subsystem delivered to EERC
4.0	Milestone 4: Test Plan Finalized	24 months after project start	Test plan in place; testing can proceed
4.0	Milestone 5: Wastewater Testing Complete	30 months after project start	Preliminary observations reported in next quarterly report
5.0	Milestone 6: TEA Complete	36 months after project start	TEA included in final report

Milestone 1 marks the beginning of design and fabrication of the small pilot system by clearly identifying the specific power plant and wastewater stream that will be used for the design basis. All team members will provide input to the decision process, and various factors will be considered, including the technical feasibility of consuming the water using hygroscopic cooling and the larger relevance of the water source, including its payback potential. Design and fabrication of the small pilot system under Task 3.0 is divided between the two key subsystems: the cooling tower subsystem and the makeup water subsystem. BAC will take charge of the former, and the EERC will complete the latter. Each organization is assigned a milestone corresponding to when the respective subsystems are ready to be combined for testing under Task 4.0. In preparation for this testing, the team will jointly decide on the most feasible approach to conduct the tests, either by temporarily siting the small pilot unit at a host site facility or by transporting wastewater back to the EERC. Finalizing this test plan will satisfy Milestone 4 and lead directly into the test campaign, which when completed (Milestone 5) will generate the data necessary to complete the techno-economic analysis (Milestone 6).

Project reporting to NDIC will include an interim report and a final report. The interim report will be submitted at the conclusion of Budget Period 1, or 18 months after project start, and the final report will be delivered at the conclusion of the project. Special reports will be prepared if warranted by project developments.

BUDGET

The estimated initial cost for the proposed effort is $820,675 as shown in Table 1. DOE has already confirmed $655,675 of funding, as the EERC and DOE are currently in final negotiations. $100,000 of cost share is requested from the NDIC Lignite Research, Development and Marketing Program (LRDMP). In-kind cost share will be provided by BAC in the amount of $65,000. Letters of commitment for in-kind providers can be found in Appendix C. Budget notes can be found in Appendix D.

Table 1. Budget Breakdown

Project Associated Expense	NDIC LRDMP Share (Cash)	Cost Share (Cash & In-Kind)	Total Project
Labor	$ 66,327	$ 320,268	$ 386,595
Travel	$ -	$ 14,074	$ 14,074
Equipment > $5000	$ -	$ 55,000	$ 55,000
Supplies	$ -	$ 6,660	$ 6,660
Communications	$ -	$ 830	$ 830
Printing & Duplicating	$ 7	$ 734	$ 741
Laboratory Fees & Services			
Analytical Research Lab	$ -	$ 38,155	$ 38,155
Particulate Analysis Lab	$ -	$ 2,858	$ 2,858
Graphics Services	$ -	$ 714	$ 714
Shop & Operations	$ -	$ 7,465	$ 7,465
Engineering Services Fee	$ 111	$ 1,361	$ 1,472
Freight	$ -	$ 6,000	$ 6,000
Total Direct Costs	$ 66,445	$ 454,119	$ 520,564
Facilities & Administration	$ 33,555	$ 201,556	$ 235,111
Total Cash Requested	**$ 100,000**	**$ 655,675**	**$ 755,675**
In-Kind Cost Share			
Baltimore Aircoil Co.	$ -	$ 65,000	$ 65,000
TOTAL PROJECT COSTS	**$ 100,000**	**$ 720,675**	**$ 820,675**

*Additional cash and/or in-kind contributions from industry are anticipated and will be reported to NDIC as received.

The budget includes equipment consisting of the pilot hygroscopic wastewater-recycling system, which will be used to evaluate the concept and advance the TRL of the technology from 3 to 5. This equipment will be designed and fabricated under the project through a partnership between the EERC and BAC. In the budget, this equipment is divided into two subsystems, the makeup water and precipitation subsystem that will be produced by the EERC and the cooling tower subsystem provided by BAC.

In the event of partial funding, it will not be possible to meet all of the project's objectives. The project team would adapt to partial funding by engaging tasks in a sequential manner rather than the proposed time line where certain tasks are active simultaneously. This would have the effect of lengthening the time needed to complete all project objectives, and some tasks might not be completed at all if full funding were not made available.

MATCHING FUNDS

Cash matching funds will be provided by DOE in the amount of $655,675. The contract for these funds is currently being negotiated between the EERC and DOE. A copy of the final agreement will be provided to NDIC after award for confirmation.

In-kind contributions to the project totaling $65,000 will be provided by BAC. The primary contribution includes services and materials to design and fabricate a cooling tower customized for hygroscopic cooling operation valued at $52,877. The remaining $12,123 is derived from personnel costs associated with Tasks 2.0, 4.0, and 5.0 for BAC to provide the following nonequipment assistance to the project. Task 2.0 BAC will advise the EERC on equipment impacts during wastewater evaluation. Task 4.0: BAC will assist with setup and monitoring of the cooling tower subsystem. Task 5.0: BAC will contribute production cost data to the analysis and review the final life cycle cost analysis.

Contributions from GRE to the project will be in-kind in nature and will ultimately depend on the specific needs of the project. The initial evaluation of wastewater will focus on blowdown streams at GRE's lignite-fueled facilities, and the preferred site for field testing is Coal Creek Station. Preliminary planning for this option has identified the following items as potential in-kind contributions: installing a concrete foundation for outdoor components of the pilot system, repurposing and reconfiguring an existing structure to house the indoor components, extending the necessary plumbing and electrical services, and providing services to initially place the equipment and remove it at the test's conclusion. In addition, it is expected that the techno-economic analysis will require support from the plant's laboratory and engineering staff. GRE will contribute costs associated with hosting the field testing to the project and will not receive reimbursement from either NDIC or DOE funds.

TAX LIABILITY

The EERC, a research organization within the University of North Dakota, an institution of higher education within the state of North Dakota, is not a taxable entity; therefore, the EERC has no tax liability.

CONFIDENTIAL INFORMATION

This application does not contain confidential information.

APPENDIX A

RESUMES OF KEY PERSONNEL

DR. CHRISTOPHER L. MARTIN
Senior Research Engineer, Advanced Thermal Systems
Energy & Environmental Research Center (EERC), University of North Dakota (UND)
15 North 23rd Street, Stop 9018, Grand Forks, North Dakota 58202-9018 USA
701.777.5083 (phone), 701.777.5181 (fax), cmartin@undeerc.org

Education and Training
Ph.D., Mechanical Engineering, University of Florida, Gainesville, FL, 2004.
M.S., Mechanical Engineering, University of Florida, Gainesville, FL, 2000.
B.S., Mechanical Engineering, University of North Carolina, Charlotte, North Carolina, 1998.

Research and Professional Experience
2005–Present: Senior Research Engineer, Advanced Thermal Systems, EERC, UND. Dr. Martin's responsibilities include assisting with current projects in environmentally compatible power generation, contributing to research proposals, and developing new project areas for the EERC. Notable project areas include the following:

- **Water-saving cooling technology for power plants.** The focus of these projects was a technology conceived by Dr. Martin to improve the efficiency and cost-effectiveness of dry cooling for power plants. This development effort has earned phases of state, federal and commercial support.
- **Gasification technology for nontraditional fuels.** Dr. Martin devised and evaluated gasification-based systems to recover energy from industrial and commercial solid waste streams. These efforts also include a system for high-efficiency waste processing at remote military forward operating bases.
- **Air emissions control at coal-fired utilities.** Dr. Martin managed a portfolio of emission control research projects by serving as a program area manager for the EERC's Center for Air Toxic Metals® program. He also evaluated novel emissions control technologies using laboratory, pilot plant, and field demonstrations.

Dr. Martin's principal areas of expertise include thermal energy conversion, utilization, and system analysis; mitigation of environmental effects from power generation including the prevention of air emissions from combustion and gasification systems, and the minimization of water use during energy conversion processes.

2002–2005: Research Assistant, Solar Energy and Energy Conversion Laboratory, University of Florida. Dr. Martin researched the conversion of low-temperature thermal energy resources using advanced thermodynamic cycles.

2001–2002: Teaching Assistant, Control Systems Laboratory, University of Florida. Dr. Martin taught lecture and laboratory components for an undergraduate control systems laboratory.

2000–2001: Design Engineer, Manufacturing Laboratories, Inc., Gainesville, Florida. Dr. Martin aided the design, manufacture, and assembly of a precision machine tool.

1998–2000: Research Assistant, Machine Tool Research Center, University of Florida. Dr. Martin conducted applied research in the areas of machine tool dynamics and cutting tool testing.

Publications

Martin, C.L. Heat Dissipation Systems with Hygroscopic Working Fluid. U.S. Patent 10,260,761, April 16, 2019.

Martin, C.L.; Zhuang, Y. Water-Saving Liquid-Gas Conditioning System. U.S. Patent 8,628,603, January 14, 2014.

Martin, C.L.; Folkedahl, B.C.; Dunham, D.J.; Kay, J.P. Application of Liquid Desiccant Dehumidification to Amine-Based Carbon Capture Systems. *Int. J. Greenhouse Gas Control* **2016,** *54*, 557–565.

Zhuang, Y.; Martin, C.L.; Pavlish, J.H.; Botha, F. Cobenefit of SO_3 Reduction on Mercury Capture with Activated Carbon in Coal Flue Gas. *Fuel* **2011,** *90*, 2998–3006.

Pavlish, J.H.; Thompson, J.S.; Martin, C.L.; Hamre, L.L.; Wiemuth, R.; Pletcher, S. Fabric Filter Bag Investigation Following Field Testing of Sorbent Injection for Mercury Control at TXU's Big Brown Station. In *Air Quality VI: Mercury, Trace, Elements, SO_3, Particulate Matter, and Greenhouse Gases*, Special Issue of *Fuel Process. Technol.* **2009**, *90* (11), 1333–1338.

DR. YOHANN ROUSSELET
Manager, Emerging Technology Partnerships
Baltimore Aircoil Company | Manufacturing
Phone: (410) 799-6352 | E-mail: yrousselet@baltimoreaircoil.com

Education and Training
Ph.D. and M.S., UCLA, Mechanical Engineering (concentration: Heat and Mass Transfer), 2014.
M.S., Energy and Environmental Engineering, INSA Lyon (Lyon, France), 2010.
B.S., Thermal Science and Energy Engineering, Université Joseph Fourier (Grenoble, France), 2007.

Research and Professional Experience
2019–Present: Manager, Emerging Technology Partnerships, Baltimore Aircoil Company. Build, manage, and execute a portfolio of internal and external technology research and development activities; manage allocated budget and team; responsible for project budgeting, planning and resource allocation.

2015–2019: Senior Research and Development Engineer, Baltimore Aircoil Company. Provide technical expertise to the Technology and Innovation team; Identify new technology opportunities; Lead and execute technology exploration and qualification towards product implementation.

2014–2015: Research and Development Engineer, Baltimore Aircoil Company. Responsible for discovering, exploring and qualifying new technologies that meet customers' needs as well as developing new technologies that will increase profitability and create new revenue streams for the organization.

2010–2014: Graduate Student Researcher UCLA Boiling Heat Transfer Laboratory. Studied the effects of inertia and gravity on bubble dynamics during flow nucleate boiling, with a focus on the use of flow nucleate boiling in space energy applications (NASA-funded project).

2013–2013: Thermal Engineering Consultant, Scope Products, Inc. Developed a MATLAB/Simulink computer program to simulate the air and bread moisture contents and temperature for an industrial process of rotary drying of bakery by-products.

2010–2010: Staff Research Associate, UCLA Boiling Heat Transfer Laboratory. Investigated the enhancement the natural convection and pool boiling heat transfer processes of carbon dioxide at near-critical pressures (NSF funded project).

2009–2009: Energy Engineering Intern COFELY INEO - GDF SUEZ/SUEZ GROUP, Annecy, France. Performed the energy analysis of the hospital buildings (including the HVAC+R equipment) and assisted the HVACR department director of the Annecy Regional Hospital.

2007: Research Assistant, LEGI & LEPMI research laboratories, Grenoble, France. Evaluated the performance of an ultrasonically enhanced shell and tube heat exchanger.

Relevant Publications
Y. Rousselet, V.K. Dhir, "Numerical modeling of a co-current cascading rotary dryer," Food and Bioproducts Processing 99 (2016) 166-178.

Y. Rousselet, G.R. Warrier, V.K. Dhir, "Experimental Study of Bubble Dynamics during Nucleate Flow Boiling on Horizontal and Vertical Surfaces," J. of Enhanced Heat Transfer 21 (4-5) (2014) 259-282.

Y. Rousselet, G.R. Warrier, V.K. Dhir, "Subcooled pool film boiling heat transfer from small horizontal cylinders at near-critical pressures," Int. J. Heat Mass Transfer 72 (2014) 531-543.

Y. Rousselet, G.R. Warrier, V.K. Dhir, "Natural convection from horizontal cylinders at near-critical pressures: Part 1 – Experimental study," J. Heat Transfer 135 (2) (2012) 022501.

G.R. Warrier, Y. Rousselet, V.K. Dhir, "Natural convection from horizontal cylinders at near-critical pressures: Part 2 – Numerical simulations," J. Heat Transfer 135 (2) (2012) 022502.

N. Gondrexon, Y. Rousselet, M. Legay, P. Boldo, S. Le Person, A. Bontemps, "Intensification of heat transfer process: Improvement of shell-and-tube heat exchanger performances by means of ultrasound," Chemical Engineering and Processing: Process Intensification, 49 (9) (2010) 936-942.

.

APPENDIX B

REFERENCES

REFERENCES

1. Effluent Limitations Guidelines and Standards for the Steam Electric Power Generating Point Source Category. *Code of Federal Regulations*, Part 423, Title 40, 2015.

2. U.S. Environmental Protection Agency. *Technical Development Document for the Effluent Limitations Guidelines and Standards for the Steam Electric Power Generating Point Source Category*; Report EPA-821-R-15-007; U.S. Environmental Protection Agency: Washington, DC, Sept 2015.

3. Nalco Water. *Nalco Water Handbook*, 4th ed.; McGraw-Hill Education: New York, 2018.

4. Cebrian, G.; Arroyo, C.; Manas, P.; Condon, S. Bacterial Maximum Non-Inhibitory and Minimum Inhibitory Concentrations of Different Water Activity Depressing Solutes. *International Journal of Food Microbiology* **2014**, *188*, 67–74.

5. Natural Brine Process, Tetra Chemicals. www.tetrachemicalseurope.com/index.asp?page_ID=529 (accessed May 2019).

6. Hygroscopic Cooling Tower for Reduced HVAC Water Consumption, Environmental Security Technology Certification Program. www.serdp-estcp.org/Program-Areas/Installation-Energy-and-Water/Water-Conservation/EW-201723 (accessed May 2019).

7. Electricity, Detailed State Data, U.S. Energy Information Administration. www.eia.gov/electricity/data/state/ (accessed May 2019).

8. Marlett, M. A Cost Comparison of ZLD and Biological Treatment for FGD Wastewater. *Power Engineering* 2018. www.power-eng.com/articles/2018/07/a-cost-comparison-of-zld-and-biological-treatment-for-fgd-wastewater.html (accessed May 2019).

9. Advanced Research Projects Agency—Energy. Novel Dry Cooling Technology for Power Plants, Project Overview. http://arpa-e.energy.gov/?q=slick-sheet-project/water-efficient-power-generation (accessed May 2019).

10. Martin, C.; Pavlish, J. *Subtask 5.10 – Testing of an Advanced Dry Cooling Technology for Power Plants*; Report 2013-EERC-09-09; Energy & Environmental Research Center: Grand Forks, ND, Sept 2013.

APPENDIX C

LETTERS OF SUPPORT

GREAT RIVER ENERGY™

2875 Third Street SW
Underwood, North Dakota 58576
701-442-3211
greatriverenergy.com

May 13, 2019

Christopher Martin, Ph.D.
Senior Research Engineer
Energy & Environmental Research Center
University of North Dakota
15 North 23rd Street, Stop 9018
Grand Forks, ND 58202-9018

Dear Dr. Martin:

Subject: EERC Crosscutting Program Proposal "Wastewater Recycling Using a Hygroscopic Cooling System"

I am writing to express my support for the Energy & Environmental Research Center's effort to secure funding from the U.S. Department of Energy for the subject project. The technology under investigation by the EERC has the potential to improve water use efficiency at existing coal-fired power plants while eliminating liquid wastewater discharge to the environment. If shown to be viable, such an innovation would be highly relevant to the electric generation industry.

Great River Energy is a wholesale power cooperative and is committed to conserving resources through environmental stewardship, pollution prevention, waste minimization, recycling and reuse. As such, I am pleased to have Great River Energy take part in the subject project and help further the development of innovative, water-saving technology.

Great River Energy operates two coal-fired power plants in North Dakota, Coal Creek Station and Spiritwood Station. If the project is awarded by the Department of Energy, Great River Energy will allow supervised access to these facilities to gather representative wastewater samples for evaluation. Plant personnel will also work with the EERC to evaluate options for testing the technology, which could include bringing a small pilot system to either Coal Creek or Spiritwood Stations.

I look forward to learning more about the EERC's wastewater recycling project, and I hope it is favorably reviewed by the Department of Energy.

Sincerely,

John Bauer

John Bauer, Director of ND Generation
Great River Energy

BALTIMORE AIRCOIL COMPANY

7600 Dorsey Run Road Jessup, MD 20794 › tel 410.799.6200 › fax 410.799.6416 › www.BaltimoreAircoil.com

May 15, 2019

Christopher Martin, Ph.D.
Senior Research Engineer
Energy & Environmental Research Center
University of North Dakota
15 North 23rd Street, Stop 9018
Grand Forks, ND 58202-9018

Subject: EERC Crosscutting Program Proposal "Wastewater Recycling Using a Hygroscopic Cooling System"

Dear Dr. Martin:

I am writing to express the support of Baltimore Aircoil Company for the Energy & Environmental Research Center's effort to secure funding from the U.S. Department of Energy for the subject project. The technology under investigation by the EERC has the potential to improve water use efficiency at existing coal-fired power plants while eliminating liquid wastewater discharge to the environment. If shown to be viable, such an innovation would be relevant to the electric generation industry and, I believe, to the evaporative heat rejection community more generally.

Baltimore Aircoil Company is recognized as the world's largest manufacturer of evaporative heat rejection and thermal storage equipment. BAC products are supplied to the commercial, industrial, refrigeration, process and power markets to meet a variety of heat transfer applications. BAC's manufacturing and testing expertise are well aligned with the needs of this project and I am pleased to offer our support to this effort.

BAC will provide the engineering support necessary to develop a cooling tower suitable for the hygroscopic wastewater recycling system that will be tested during the project. BAC personnel will also participate in regular project update meetings, in-person review meetings with the Department of Energy, and provide input to the final techno-economic analysis of the concept. BAC estimates the fair market value of these goods and services will amount to a minimum value of $65,000.00, and will provide supporting documentation to demonstrate the actual costs incurred during the project.

I look forward to working with the EERC on this innovative project and I hope it is favorably reviewed by the Department of Energy.

Sincerely,

M.Tenbrock

Michael Tenbrock
Global Director, Technology Research and Development
Baltimore Aircoil Company

September 25, 2019

Christopher Martin, Ph.D.
Senior Research Engineer
Energy & Environmental Research Center
University of North Dakota
15 North 23rd Street, Stop 9018
Grand Forks, ND 58202-9018

Dear Dr. Martin:

Subject: EERC Proposal to the Lignite Research Program Entitled "Wastewater Recycling Using a Hygroscopic Cooling System"

I am writing to express my support for the Energy & Environmental Research Center's effort to secure matching funds from the North Dakota Industrial Commission's Lignite Research Program for the subject project. The technology under investigation by the EERC has the potential to improve water use efficiency at existing lignite-fueled facilities while eliminating liquid wastewater discharge. If shown to be viable, such an innovation could be highly relevant to North Dakota's lignite energy sector.

The technology under investigation by the EERC differs from existing methods of wastewater disposal in that it may require fewer permitting approvals and could be complimentary to plant operations by increasing the plant's heat rejection capacity. If successful, such a technology may benefit existing lignite facilities as they prepare for the future.

Given the practical nature of this project and its potential applicability to lignite-fueled facilities in North Dakota's climate, Basin is supportive of the project and recommends favorable consideration by the Lignite Research Council.

I look forward to seeing the developments from the EERC's wastewater recycling project.

Sincerely,

Gavin McCollam, Vice President
Engineering and Construction

cc: Joshua Stanislowski
Benjamin Hertz
James Sheldon

Minnkota Power COOPERATIVE
A Touchstone Energy® Cooperative

5301 32nd Avenue South
Grand Forks, ND 58201

Phone 701.795.4000
www.minnkota.com

September 30, 2019

Christopher Martin, Ph.D.
Senior Research Engineer
Energy & Environmental Research Center
University of North Dakota
15 North 23rd Street, Stop 9018
Grand Forks, ND 58202-9018

Subject: Energy & Environmental Research Center (EERC) Proposal to the Lignite Research Program Entitled "Wastewater Recycling Using a Hydroscopic Cooling System"

Dear Dr. Martin:

Minnkota Power Cooperative, Inc. (Minnkota) is pleased to provide support for the EERC's effort to secure matching funds from the North Dakota Industrial Commission's Lignite Research Program for the research program entitled "Wastewater Recycling using a Hydroscopic Cooling System". This technology, under investigation by the EERC, has the potential to improve water use efficiency at existing lignite-fueled facilities while eliminating liquid wastewater discharge to the environment. If shown to be viable, such an innovation could be highly relevant to North Dakota's lignite energy sector.

Minnkota is a not-for-profit electric generation and transmission cooperative headquartered in Grand Forks, ND. Formed in 1940, Minnkota provides wholesale electric energy to 11 member-owner distribution cooperatives located in eastern North Dakota and northwestern Minnesota. The primary source of electric generation for the Minnkota member-owners is the Milton R. Young Station (MRYS), a two-unit, lignite coal-fired power plant located near the town of Center, ND. Technologies that can economically minimize wastewater discharge would be transformational for Minnkota, both from a water balance standpoint and from a good steward of the environment standpoint.

As such, Minnkota is supportive of the EERC's efforts to develop wastewater recycling technology that might be helpful to increase the competitive position of these plants. The technology under investigation by the EERC differs from existing methods of wastewater treatment in that it may require fewer permitting approvals and could be complimentary to plant operations by increasing the plant's heat rejection capacity.

Given the practical nature of this project and its applicability to lignite-fueled facilities in North Dakota's climate, Minnkota is supportive of the project and recommends favorable consideration by the Lignite Research Council.

We look forward to seeing the developments from the EERC's wastewater recycling project. If you have any questions or require additional information, please contact me at 701-794-7234 or at gpfau@minnkota.com.

Sincerely,

Gerry Pfau
Sr. Manager of Project Development

Cc: Dan Laudal
Craig Bleth
Tim Hagerott
Andy Freidt
Dylan Wolf

APPENDIX D

BUDGET NOTES

BUDGET NOTES

ENERGY & ENVIRONMENTAL RESEARCH CENTER (EERC)

BACKGROUND

The EERC is an independently organized multidisciplinary research center within the University of North Dakota (UND). The EERC is funded through federal and nonfederal grants, contracts, and other agreements. Although the EERC is not affiliated with any one academic department, university faculty may participate in a project, depending on the scope of work and expertise required to perform the project.

INTELLECTUAL PROPERTY

The applicable federal intellectual property (IP) regulations will govern any resulting research agreement(s). In the event that IP with the potential to generate revenue to which the EERC is entitled is developed under this project, such IP, including rights, title, interest, and obligations, may be transferred to the EERC Foundation, a separate legal entity.

BUDGET INFORMATION

The proposed work will be done on a cost-reimbursable basis. The distribution of costs between budget categories (labor, travel, supplies, equipment, etc.) and among funding sources of the same scope of work is for planning purposes only. The project manager may incur and allocate allowable project costs among the funding sources for this scope of work in accordance with Office of Management and Budget (OMB) Uniform Guidance 2 CFR 200.

Escalation of labor and EERC recharge center rates is incorporated into the budget when a project's duration extends beyond the university's current fiscal year (July 1 – June 30). Escalation is calculated by prorating an average annual increase over the anticipated life of the project.

The cost of this project is based on a specific start date indicated at the top of the EERC budget. Any delay in the start of this project may result in a budget increase. Budget category descriptions presented below are for informational purposes; some categories may not appear in the budget.

Salaries: Salary estimates are based on the scope of work and prior experience on projects of similar scope. The labor rate used for specifically identified personnel is the current hourly rate for that individual. The labor category rate is the average rate of a personnel group with similar job descriptions. Salary costs incurred are based on direct hourly effort on the project. Faculty who work on this project may be paid an amount over the normal base salary, creating an overload which is subject to limitation in accordance with university policy. As noted in the UND EERC Cost Accounting Standards Board Disclosure Statement, administrative salary and support costs which can be specifically identified to the project are direct-charged and not charged as facilities and administrative (F&A) costs. Costs for general support services such as contracts and IP, accounting, human resources, procurement, and clerical support of these functions are charged as F&A costs.

Fringe Benefits: Fringe benefits consist of two components which are budgeted as a percentage of direct labor. The first component is a fixed percentage approved annually by the UND cognizant audit agency, the Department of Health and Human Services. This portion of the rate covers vacation, holiday, and sick leave (VSL) and is applied to direct labor for permanent staff eligible for VSL benefits. Only the actual approved rate will be charged to the project. The second component is estimated on the basis of historical data and is charged as actual expenses for items such as health, life, and unemployment insurance; social security; worker's compensation; and UND retirement contributions.

Travel: Travel may include site visits, fieldwork, meetings, and conferences. Travel costs are estimated and paid in accordance with OMB Uniform Guidance 2 CFR 200, Section 474, and UND travel policies, which can be found at http://und.edu/finance-operations (Policies & Procedures, A–Z Policy Index, Travel). Daily meal rates are based on U.S. General Services Administration (GSA) rates unless further limited by UND travel policies; other estimates such as airfare, lodging, ground transportation, and miscellaneous costs are based on a combination of historical costs and current market prices. Miscellaneous travel costs may include parking fees, Internet charges, long-distance phone, copies, faxes, shipping, and postage.

Equipment: The EERC will fabricate the makeup water subsystem, which will be used to evaluate the elimination of wastewater obtained from a host site power plant. The estimated cost for this fabrication is $55,000.

Supplies: Supplies include items and materials that are necessary for the research project and can be directly identified to the project. Supply and material estimates are based on prior experience with similar projects. Examples of supply items are chemicals, gases, glassware, nuts, bolts, piping, data storage, paper, memory, software, toner cartridges, maps, sample containers, minor equipment (value less than $5000), signage, safety items, subscriptions, books, and reference materials. General purpose office supplies (pencils, pens, paper clips, staples, Post-it notes, etc.) are included in the F&A cost.

Subcontracts: Not applicable.

Professional Fees: Not applicable.

Communications: Telephone, cell phone, and fax line charges are included in the F&A cost; however, direct project costs may include line charges at remote locations, long-distance telephone charges, postage, and other data or document transportation costs that can be directly identified to a project. Estimated costs are based on prior experience with similar projects.

Printing and Duplicating: Page rates are established annually by the university's duplicating center. Printing and duplicating costs are allocated to the appropriate funding source. Estimated costs are based on prior experience with similar projects.

Food: Expenditures for project partner meetings where the primary purpose is dissemination of technical information may include the cost of food. The project will not be charged for any costs exceeding the applicable GSA meal rate. EERC employees in attendance will not receive per diem reimbursement for meals that are paid by project funds. The estimated cost is based on the number and location of project partner meetings.

Professional Development: Fees are for memberships in technical areas directly related to work on this project. Technical journals and newsletters received as a result of a membership are used throughout the development and execution of the project by the research team.

Operating Fees: Operating fees generally include EERC recharge centers, outside laboratories, and freight.

EERC recharge center rates are established annually and approved by the university.

Laboratory and analytical recharge fees are charged on a per-sample, hourly, or daily rate. Additionally, laboratory analyses may be performed outside the university when necessary. The estimated cost is based on the test protocol required for the scope of work.

Graphics recharge fees are based on an hourly rate for production of such items as report figures, posters, and/or images for presentations, maps, schematics, Web site design, brochures, and photographs. The estimated cost is based on prior experience with similar projects.

Shop and operations recharge fees cover specific expenses related to the pilot plant and the required expertise of individuals who perform related activities. Fees may be incurred in the pilot plant, at remote locations, or in EERC laboratories whenever these particular skills are required. The rate includes such items as specialized safety training, personal safety items, fall protection harnesses and respirators, CPR certification, annual physicals, protective clothing/eyewear, research by-product disposal, equipment repairs, equipment safety inspections, and labor to direct these activities. The estimated cost is based on the number of hours budgeted for this group of individuals.

Engineering services recharge fees cover specific expenses related to retaining qualified and certified design and engineering personnel. The rate includes training to enhance skill sets and maintain certifications using Webinars and workshops. The rate also includes specialized safety training and related physicals. The estimated cost is based on the number of hours budgeted for this group of individuals.

Software solutions services recharge fees are for development of customized Web sites and interfaces, software applications development, data and financial management systems for comprehensive reporting and predictive analysis tools, and custom integration with existing systems. The estimated cost is based on prior experience with similar projects.

Freight expenditures generally occur for outgoing items and field sample shipments.

Facilities and Administrative Cost: The F&A rate proposed herein is approved by the U.S. Department of Health and Human Services and is applied to modified total direct costs (MTDC). MTDC is defined as total direct costs less individual capital expenditures, such as equipment or software costing $5000 or more with a useful life of greater than 1 year, as well as sub awards in excess of the first $25,000 for each award.

Cost Share: DOE will provide $655,675 of cash for the current scope. In-kind cost share will be provided in the form of design and fabrication of the cooling tower subsystem, with $65,000 provided by Baltimore Aircoil Co.