CROSSCUTTING RESEARCH

# WATER MANAGEMENT PROJECT PORTFOLIO 2019

U.S. DEPARTMENT OF ENERGY

NATIONAL ENERGY TECHNOLOGY LABORATORY

## DISCLAIMER

# CONTENTS

# INTRODUCTION

The Crosscutting Research Program advances and accelerates promising fossil energy technology by serving as a bridge between basic and applied research. The program intersects the core capabilities of the National Energy Technology Laboratory (NETL) and combines researchers' expertise to address the nation's energy priorities. Its primary agenda is to serve as a space which matures and enables commercialization of novel technologies to enhance new and existing coal-fired power plants and reduce water consumption. As the research matures it benefits other Department of Energy (DOE) Office of Fossil Energy (FE) program areas such as those under Advanced Energy Systems. Due to the broad applicability of the Crosscutting portfolio, technologies tend to generate spillover benefits in other sectors, including gas-based power generation, oil and gas infrastructure, and aviation (both commercial and military).

On behalf of FE, NETL facilitates crosscutting research and development (R&D) through collaboration with other government agencies, world-renowned national labs, start-up and established businesses and academic institutions. Through collaboration, the program advances capabilities that accelerate progress toward enabling the next generation of fossil energy. These efforts address both known existing challenges to the coal fleet as well as developing key technologies to benefit the future of coal power. Enhancements to the fleet include improvements to plant efficiency, advancements addressing the challenges of load following and cyber intrusions, and developments in affordable, scalable technical solutions. The program invests in these enhancements to secure flexible, reliable coal power for future generations.

The Crosscutting Research Program sponsors two of the longest-running university training programs, preparing the next generation of scientists and engineers to meet future energy challenges. These are the University Coal Research (UCR) program and the Historically Black Colleges and Universities and Other Minority-Serving Institutions (HBCU-OMI) program. By training at the university level with students excited about technologies on the horizon, several key technology trends will become embedded in coal plants of the future including: advanced manufacturing, cybersecurity, smart data analytics and high-performance computing.

The activities within the five primary research areas target enhanced fossil energy systems with the goal of creating transformational technology, improving plant efficiency, reducing water consumption and reducing costs. To generate transformational technology, the program connects water, sensors, computational simulation, workforce development and materials under a single umbrella.

In combination these investments in innovation, informed by private sector stakeholders, enable more comprehensive risk assessment and techno-economic analysis, increase the resiliency of our Nation's fossil energy infrastructure and enable the adoption of cutting-edge data technologies for plant owners and operators.

The Crosscutting Research portfolio of programs fosters the development of innovative power systems by conducting research in the following key technology areas:

**Sensors and Controls** provides pivotal insights into optimizing plant performance, reliability and availability while utilizing and furthering technological megatrends such as advanced manufacturing processes and Industry 4.0 principles.

Sensor research is investigating a range of advanced manufacturing techniques to determine the feasibility of embedding sensors, capable of operation in extreme environments and outfitted with condition-based monitoring algorithms, into turbine blades, boiler walls, piping, and tubing to predict component failure, anticipate maintenance needs and reduce plant downtime.

Controls research is advancing the accuracy of artificial and distributed intelligence systems for process control, automation, and fault detection. The ability to monitor key plant parameters and align results in real-time with self-organizing information networks will enable decision-makers to improve the operational efficiency during challenging transient conditions, increase plant availability and dispatch, tighten cybersecurity and environmental control, and improve plant revenue profiles.

This program is exploring advances within, and the integration of technologies across, three primary platforms: Advanced Sensors, Distributed Intelligent Controls, and Cybersecurity.

**High Performance Materials** focuses on material discovery and development that will lower the cost and improve the performance of fossil-based power-generation systems.

Materials of interest are those that enable components and equipment to perform in the high-temperature, high-pressure, corrosive environments of an advanced energy system with specific emphasis on durability, availability and cost both within and across each of four primary platforms: Computational Materials Design, Advanced Structural Materials, Functional Materials for Process Performance, and Advanced Manufacturing.

**Modeling, Simulation and Analysis** applies simulation and modeling capabilities to the full range of maturities and technologies essential to plant operation, from fundamental energy science in reactive and multiphase flows to full-scale virtual and interactive plant performance.

This program supports the development and application of new and innovative physics- and chemistry-based models and computational tools at multiple scales (atomistic, device, process, grid, and market) and investigates the potential positive impact these tools may have in overcoming complexities that confound today's experimental scientists and influencing the discovery of a new generation of advanced fossil-fuel technologies.

Analysis and visualization tools are manipulated to gain scientific insights into complex, noisy, high-dimensional, and high-volume datasets. The information generated is then collected, processed and used to inform research that combines theory, computational modeling, advanced optimization, experiments, and industrial input with a focus in three main platforms: Multiphase Flow Science, Advanced Process Simulation, and Innovative Concept Analysis.

**Water Management** aims to reduce the amount of freshwater used by fossil-fueled power plants and to minimize the potential impacts of plant operations on water quality.

The vision for this program is to develop a 21st century America that can count on our Nation's abundant, sustainable fossil energy and water resources to achieve the flexibility, efficiency, reliability, and environmental quality essential to our continued economic health and national security.

Thermoelectric power generation accounts for more than 40 percent of freshwater withdrawals (143 billion gallons of water per day) and more than 3 percent of freshwater consumption (4 billion gallons per day) in the United States. As the cost associated with water consumption increases, so will the cost of water treatment, recovery, and reuse.

The Water Management Program addresses the competing needs for water consumption through research in three dynamic platforms: Increasing Water Efficiency and Reuse, Treatment of Alternative Sources of Water, and Energy Water Analysis.

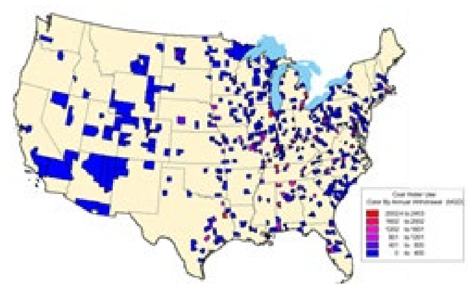
# WATER MANAGEMENT

This Project Portfolio report showcases 24 Water Management projects within the Crosscutting Research Program. Each project page clearly describes the technology, project goals, and anticipated overall benefits.

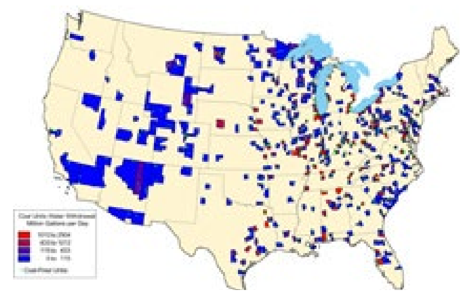
Water is a vital resource that is inextricably linked to our quality of life. The role water plays in generating power is well documented and national efforts are underway to minimize water demands.

The Crosscutting Research Program has supported water research over the past decade. The current goal is to identify a range of projects which will develop technologies to optimize and/or reduce freshwater use for energy processes by improving waste heat recovery, developing alternative heat transfer technologies, and utilizing alternative sources of water (e.g., treated effluent streams). Acquisition of these research projects is based on a comprehensive, multipronged R&D approach with a portfolio of technologies on multiple paths to enhance the probability of success of research efforts that are operating at the boundaries of current scientific understanding. The R&D covers a wide range, integrating advances and lessons learned from fundamental research, technology development, and large-scale testing. The success of this effort will enable cost-effective implementation of technologies throughout the power generation sector. These projects are being developed on three- to five-year timelines.

The Water Management Research and Development project portfolio is categorized into three core technologies:



**U.S. Water Withdrawal Coal Fired Units – County Level.**



**U.S. Water Consumption Coal Fired Units – County Level.**

### Increasing Water Efficiency and Reuse

There is an inextricable link between water and energy; it is increasingly important to use water effectively through the power generation sector. This area aims to advance concepts for both new and existing plants to minimize water intake and use. Examining plant cycles and testing new efficient processes not only can reduce water intake, but also can lower overall operating costs.

### Treating Alternative Sources of Water

Identifying and treating alternative sources of water (such as brackish water) and effluent streams, offers opportunities for scientists to address energy-water system challenges. This area focuses on furthering technology to utilize alternative water sources that span multiple facets of R&D including considerations of capital costs, operating costs, and system integration.

### Energy Water Analysis

The complex relationship between energy and water is constantly developing. The multiple components that impact the system can be modeled and analyzed to better inform decision-makers and scientists alike. This area helps prioritize research objectives through analyses of the behavior of the water-energy system.

# INCREASING WATER EFFICIENCY AND REUSE

# A Novel Steam Condenser with Loop Thermosyphons and Film-Forming Agents for Improved Heat Transfer Efficiency and Durability

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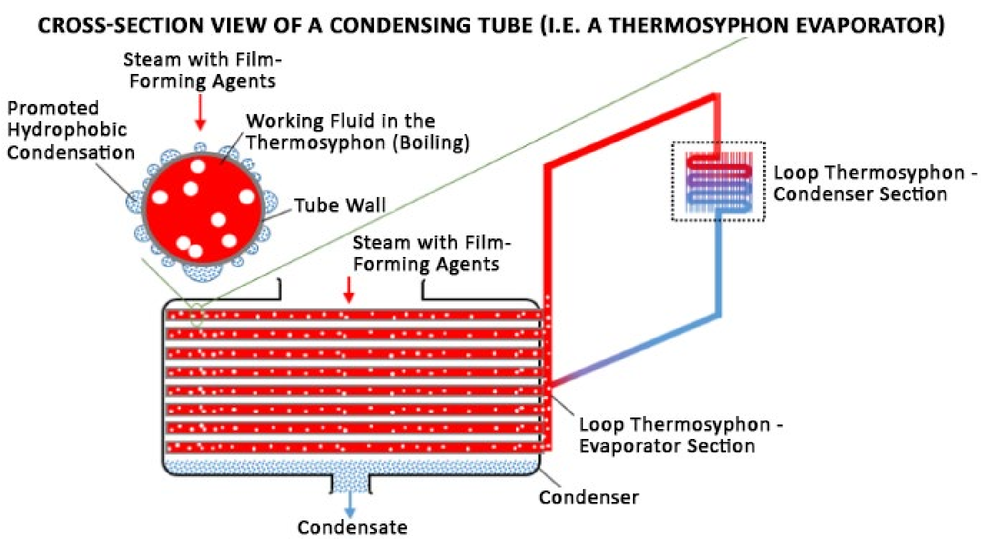
| **Performer** | **Advanced Cooling Technologies, Inc.** |
| **Award Number** | FE0031657 |
| **Project Duration** | 10/1/2018 – 9/30/2021 |
| **Total Project Value** | $ 937,498 |
| **Technology Area** | Plant Optimization Technologies |

This project will develop a novel steam condenser to enhance heat transfer performance and increase the overall efficiency of coal-fired power plants. The loop thermosyphon uses a low boiling point refrigerant fluid to cool the steam through evaporation. The evaporated refrigerant is then passively transported to a cooling source. A film-forming agent will be injected into the steam and be deposited on the condensing surface, i.e., the outside surface of the evaporator section of the proposed thermosyphon. Such film-forming chemicals have been developed by General Electric and have demonstrated their capability to enhance the durability of the tubes because of improved corrosion resistance. The resultant films also make the surface hydrophobic, changing the condensation from filmwise to dropwise and removing its thermal resistance. Improved corrosion resistance will allow the use of low-cost tubing and structural materials such as carbon-steel.

Benefits of the proposed loop thermosyphon/film-forming agent-based steam condenser include (1) passive and effective transport of the heat out of the process steam without auxiliary pumping system or electricity consumption, leading to a one percent increase in overall plant electrical conversion efficiency; (2) closed cooling loop system will require no maintenance or cleaning because it uses a refrigerant, thereby reducing downtime and maintenance costs; (3) strong enhancement of condensation heat transfer on the steam side (through dropwise condensation) and avoidance of issues related to mineral deposit, resulting in a 50 percent decrease in thermal resistance, and (4) enhancement of the durability of the condensing tubes due to the corrosion-inhibiting features of filming agents. Operating costs will be lower due to the absence of cooling water pump failures, water treatment chemicals, and maintenance required for a long-life loop thermosyphon tube.




Proposed steam condenser coupled with a loop thermosyphon and film-forming agent.

# Application of Heat Transfer Enhancement (HTE) System for Improved Efficiency of Power Plant Condensers

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| **Performer** | **Interphase Materials, Inc.** |
| **Award Number** | FE0031561 |
| **Project Duration** | 2/1/2018 – 1/31/2020 |
| **Total Project Value** | $ 961,915 |
| **Technology Area** | Plant Optimization Technologies |

NETL is partnering with Interphase Materials, Inc. to determine the condenser efficiency improvements as well as the reduction of continuous-feed water treatment that coal-fired plants could realize by utilizing Interphase's heat transfer enhancement technology (HTE system). Previous lab-scale work has demonstrated that the HTE system can inhibit biofouling, microbiologically induced corrosion, and scale buildup as well as improve the baseline heat transfer efficiency of cooling systems in laboratory scale testing. By applying the HTE system first to field test rigs at the Longview site and subsequently to the condenser at the Longview plant, Interphase and Longview will collect field data on the HTE system's potential to increase heat transfer efficiency in the condenser cooling systems of coal-fired power plants.

If the anti-biofouling and heat transfer enhancement properties of the HTE system are shown to be effective on in-service power plant condensers, there is an opportunity to lower the heat rate of the existing U.S. coal power generating fleet. Fouling prevention could result in a reduction of water treatment chemical volumes, which would help power plants meet requirements of the Environmental Protection Agency Clean Water Act. Reducing fouling will also reduce cleaning frequency and maintenance costs, increase hardware lifecycles, and help power plants maintain efficient long-term operation.

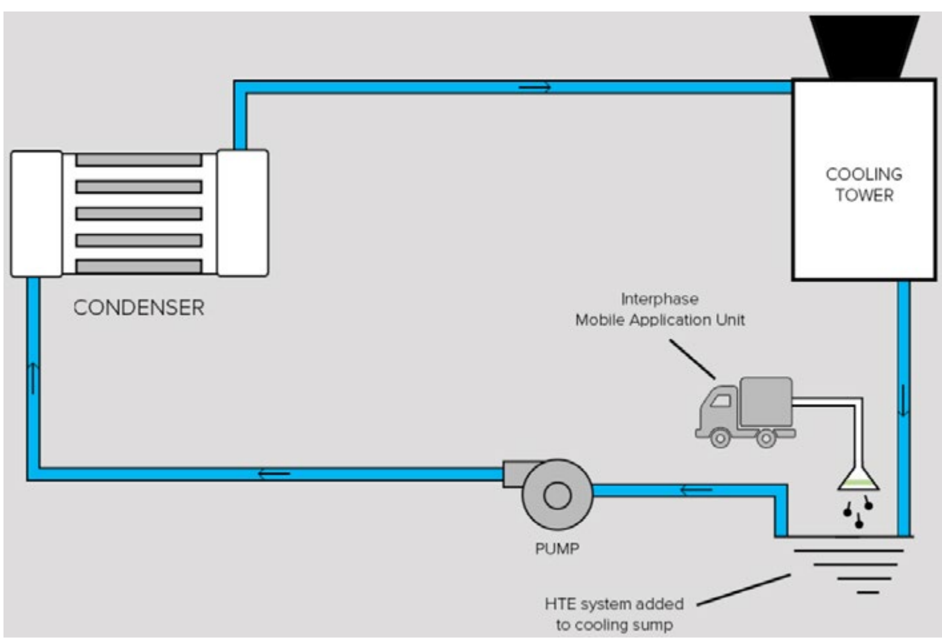


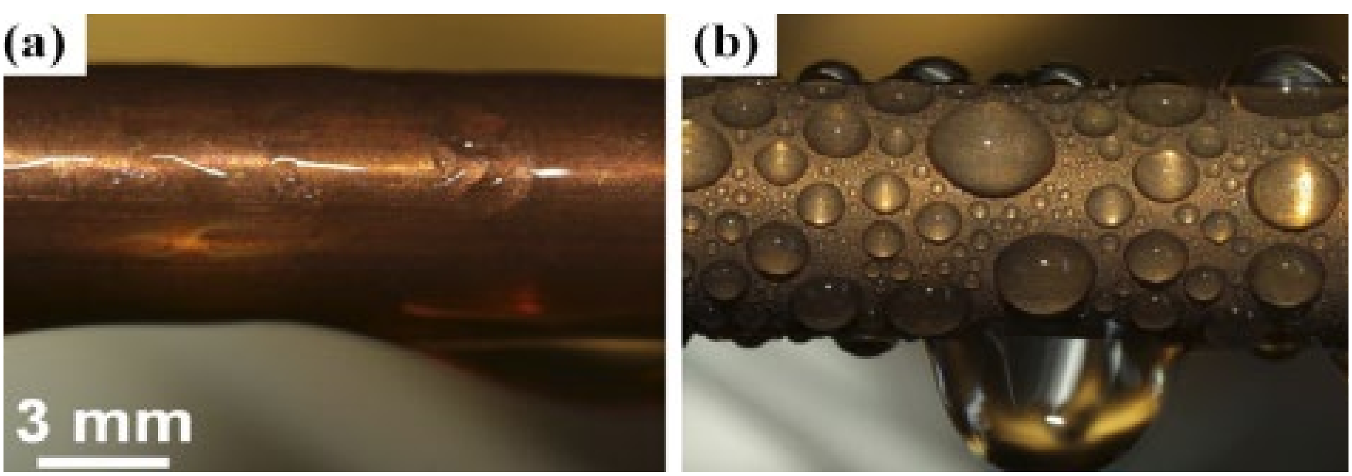

**Diagram of HTE application to Longview cooling system.**

# Capillary-Driven Condensation for Heat Transfer Enhancement in Steam Power Plants

| Performer | Massachusetts Institute of Technology |
|---|---|
| Award Number | FE0031677 |
| Project Duration | 10/1/2018 – 9/30/2021 |
| Total Project Value | $ 937,989 |
| Technology Area | Plant Optimization Technologies |

The Massachusetts Institute of Technology (MIT) will develop a robust new approach to enhance condensation heat transfer for steam power plants via capillary-driven condensation. To achieve this goal, MIT will (1) develop porous membranes and wicking structures for capillary-driven condensation, design and develop various wicking structures and porous hydrophobic membranes to reduce the thermal resistance and enhance capillary driven flow; (2) experimentally investigate capillary-driven condensation on flat and tube substrates, experimentally characterize the condensation heat transfer performance, and compare it with traditional film-wise condensation on various samples; (3) optimize the capillary-driven condensation structure with model development, develop a physics-based model to predict and optimize condensation heat transfer, and experimentally validate the results; (4) incorporate capillary-driven condensation structures to demonstrate scaled-up proof-of-concept operation, and (5) with HTRI support, perform experiments on tube bundles under relevant industrial conditions.

If successful, this approach will significantly improve power production while decreasing the amount of water needed for condensation in thermoelectric power plants. Also, a new robust condenser design for steam power plants with greater than five times enhancement in heat transfer coefficients compared to conventional film-wise condensation will be demonstrated. Due to the improved heat transfer coefficient of condensation, the steam condensation temperature and the turbine back-pressure can be reduced by up to 4 degrees Celsius and 0.7 kilopascals, respectively. Consequently, the overall heat rate of a typical power plant can be expected to be reduced by 1.5 percent, leading to an additional 13.80 megawatts (MW) of generated power from a 950 MW plant, and commensurate savings in water withdrawal and usage.




**(a) Filmwise condensation of water on a bare copper condenser tube and (b) dropwise condensation of water on a copper tube functionalized with a monolayer hydrophobic coating.**

# Enhancing Steam-Side Heat Transfer via Microdroplet Ejection using Inorganic Coatings

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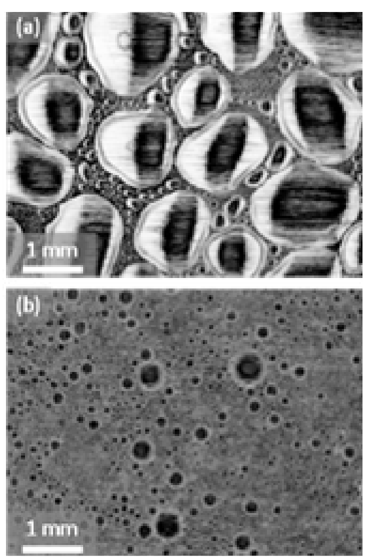
| **Performer** | **Nelumbo, Inc.** |
| **Award Number** | FE0031675 |
| **Project Duration** | 10/1/2018 – 9/30/2021 |
| **Total Project Value** | $ 704,747 |
| **Technology Area** | Plant Optimization Technologies |

The objective of this project is to develop and test droplet rejection coatings [previously optimized for aluminum (Al) and copper (Cu)] on stainless steel and Cu- nickel (Ni) alloys commonly found in coal power plant steam condensers. Specific tasks include (1) modifying the specific process and chemistries of the coating to steam condenser-relevant materials, (2) testing the heat transfer and durability coatings under a variety of conditions on a laboratory-scale test condenser, and (3) using a combination of microdroplet surface dynamics models and empirical results to develop a macroscale model to deduce the effect of droplet rejection surface treatments on condenser performance at full scale and across a variety of operating conditions. The project will adapt processes and compositions of Nelumbo coatings currently used in air conditioning and refrigeration on materials used in steam condensers. Nelumbo will focus on two alloys—stainless steel 304 and $Cu_{90}Ni_{10}$—due to their widespread use.

The results obtained from this project will adapt droplet ejection coatings to a shell-side heat exchanger under steam condenser conditions. Improved performance will be validated in the laboratory and additional data regarding tube-side potential application for these materials will be generated. Completion of test articles of the coated material under standardized tests for anti-fouling and anti-corrosion will be used to verify coating reliability and durability in a steam condenser environment. Additional benefits include reduced water usage in a once-through steam condenser by up to 39 percent, saving 78,000 gallons per minute and up to $6 million per year in operating a 500 MW turbine.




**Condensation on (a) uncoated and (b) coated surface with Nelumbo coating.**

# Novel Patterned Surfaces for Improved Condenser Performance in Power Plants

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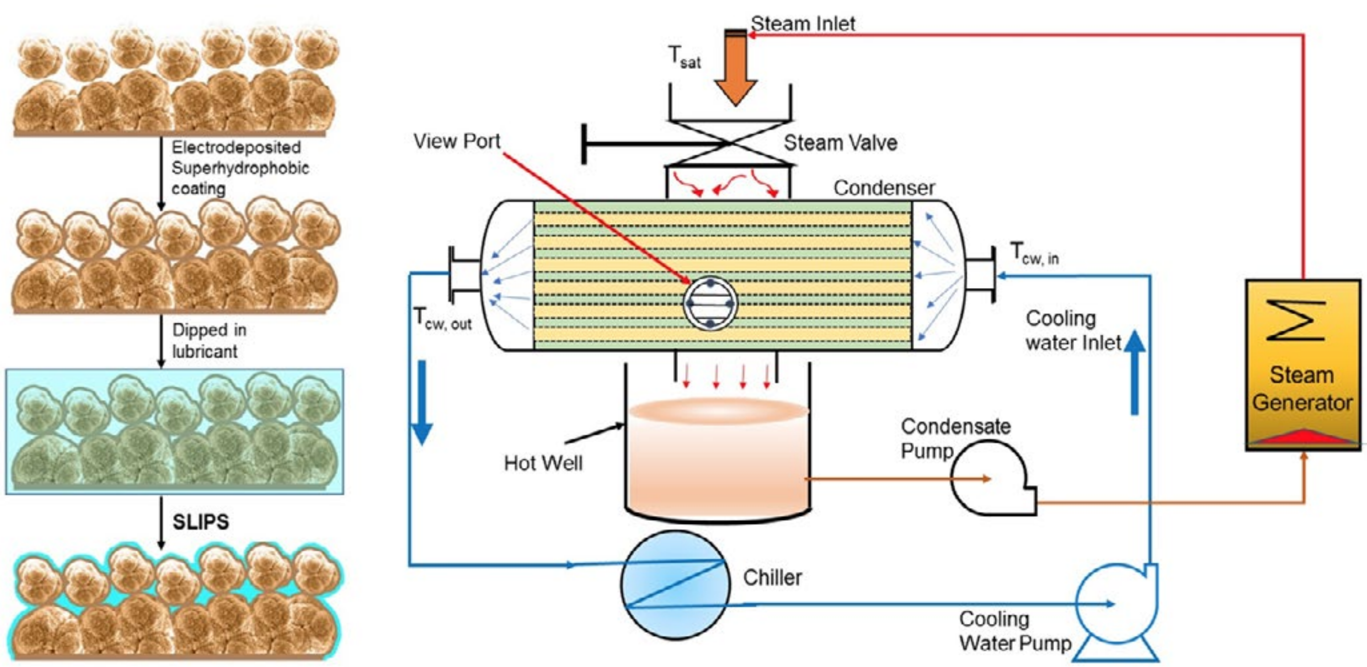
| **Performer** | **Virginia Polytechnic Institute and State University** |
| **Award Number** | FE0031556 |
| **Project Duration** | 12/15/2017 – 12/14/2020 |
| **Total Project Value** | $ 938,470 |
| **Technology Area** | Plant Optimization Technologies |

NETL is partnering with Virginia Polytechnic Institute and State University to improve thermoelectric power plant performance through engineered superhydrophobic/ slippery liquid infused porous surfaces (SLIPS) for condenser tube designs fabricated by a patented two-step electrodeposition technique. Electrodeposition is a widely-used industrial process that is applicable to a variety of shapes, materials, and sizes. The project will demonstrate and characterize a variety of SLIPS coatings based on copper, nickel, copper/ nickel, zinc, tungstite, and other materials commonly used on condenser tube surfaces—namely, copper, copper/ nickel, stainless steel, and titanium alloys—through a facile and cost-effective electrodeposition process. The goal is to demonstrate overall condenser heat exchanger effectiveness that is at least 50 percent higher than that of current systems while reducing condenser pressure and improving power plant efficiency.

The research conducted will broaden both fundamental and applied scientific knowledge in the field of transport phenomena using SLIPS surfaces and the robust, scalable fabrication process of the structures. Project success could advance novel, industrially scalable, and low-cost fabrication of durable SLIPS coatings that will lead to improved plant efficiency and performance, and thereby to reduced carbon dioxide emissions.




**Proposed SLIPS coating to enhance heat transfer and reduce drag on condenser surfaces.**

# TREATING ALTERNATIVE SOURCES OF WATER

# Demonstrations of Holistic, Lower Cost/Energy Effluent Water Management Approaches for Coal-Fired Energy

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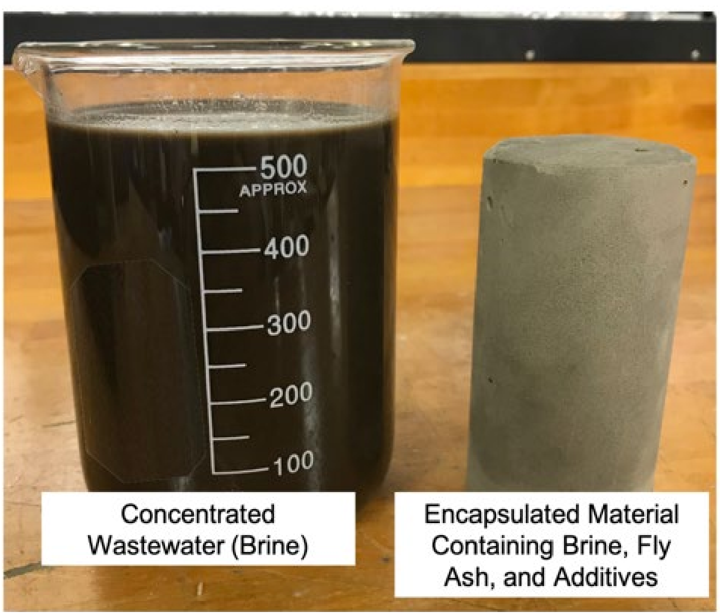
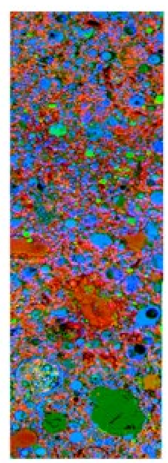
| **Performer** | **Electric Power Research Institute, Inc.** |
| **Award Number** | FE0031678 |
| **Project Duration** | 10/1/2018 – 9/30/2020 |
| **Total Project Value** | $ 922,989 |
| **Collaborators** | Golder Associates, Inc.; Saltworks Environmental USA, Inc. |
| **Technology Area** | Plant Optimization Technologies |

The objective of this project is to evaluate a set of effluent water management technologies and strategies that yield lower-cost clean water and reduced energy consumption compared to conventional systems used in coal-fired energy plants, and additionally generate salts and solids byproducts that can be reused or disposed as non-hazardous waste materials in landfills. The approach is holistic, addressing both water treatment and byproducts. The goals of the project are to (1) develop and use a statistical-based water mass balance model to identify opportunities for reducing water consumption and meeting discharge treatment requirements; (2) demonstrate at pilot scale a potentially highly effective, lower-cost energy technology for treating flue gas desulfurization (FGD) discharges at the Water Research Center (WRC); and (3) develop and test the encapsulation for safe disposal of solid byproducts of the wastewater treatment process that have no productive use.

The benefit of this project will be demonstration at pilot scale of a flue gas desulfurization discharge treatment system for significant cost/energy savings, along with approaches to make unusable byproducts safer and cheaper to dispose as non-hazardous materials. The software models and associated guidelines developed in the project will help energy plants see wastewater treatment and byproduct encapsulation as components of a holistic approach to water management.



Scanning Electron Microscope Image of a Sample from the Encapsulated Material

Concentrated wastewater combined with fly ash and additives to form an encapsulated material.

# Flue-Gas Desulfurization Effluent Management Using an Innovative Low-Energy Biosorption Treatment System to Remove Key Contaminants

| Performer | ES Engineering Services, LLC |
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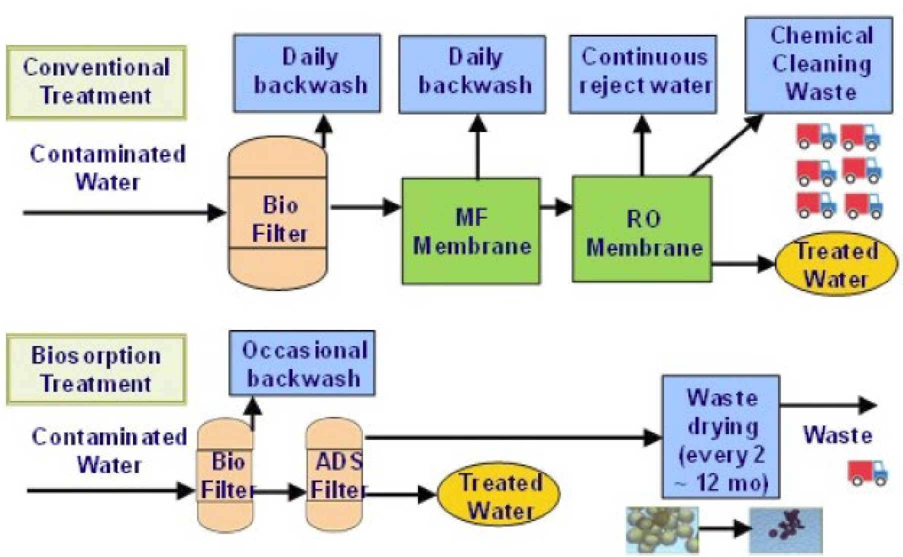
| Award Number | FE0031676 |
| Project Duration | 10/1/2018 – 3/31/2021 |
| Total Project Value | $ 941,206 |
| Technology Area | Plant Optimization Technologies |

The goal of this project is to demonstrate an innovative, energy-efficient water treatment system for FGD wastewater treatment to meet the Effluent Limitations Guidelines and Standards for the Steam Electric Power Generating Point Source Category (ELGs). The proposed treatment system uses hybrid biosorption, which is an adsorption process enhanced by biological activity to remove selenium, arsenic, nitrate, and potentially other contaminants from FGD wastewater. The objectives are to (1) evaluate a biosorption treatment system at the Water Research Center at Plant Bowen; (2) demonstrate both energy and water savings associated with the proposed innovative water treatment process; (3) using available published data, compare energy and water savings with alternative technologies that are typically used to remove the target contaminants, and (4) provide long-term management of the FGD wastewater challenge that plagues coal-fired power plants by offering a low-energy, high water-efficiency water treatment system that also significantly decreases waste byproducts by utilizing available waste heat.

Treating FGD effluents at the point of generation can provide clean water source for potential beneficial on-site reuse at power generating facilities. The energy-efficient water treatment system proposed in this project will help reduce energy demand associated with water treatment in power generating facilities, but can also be used in the industrial, agricultural, and municipal sectors.




Comparison of conventional process and proposed treatment system.

# Co-Generation Wastewater Treatment at Coal-Fired Energy Plants

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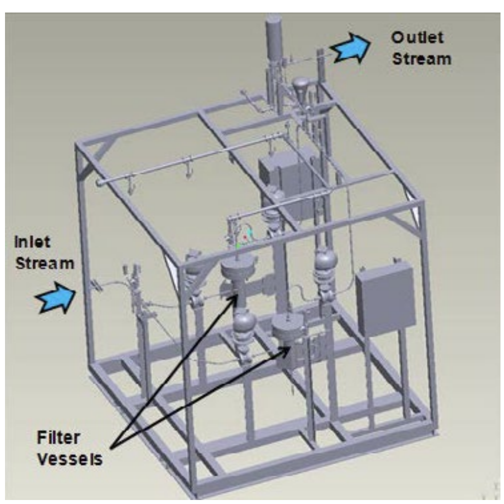
| **Performer** | **Gas Technology Institute** |
| **Award Number** | FE0031669 |
| **Project Duration** | 10/1/2018 – 9/30/2020 |
| **Total Project Value** | $ 936,000 |
| **Technology Area** | Plant Optimization Technologies |

The objective of this project is to show that Gas Technology Institute's FGD wastewater clean-up technology is effective at removing critical pollutants of concern (CPoC), can operate at low cost, offset some treatment costs, and is compact for retrofit applications. This technology uses Direct Contact Steam Generation (DCSG), a process developed for oil sands production over the last eight years. It is proposed to apply the DCSG technology for water cleanup, specifically for the FGD wastewater treatment at coal-fired energy plants, while co-generating power to offset treatment costs. The goal is to meet or exceed the CPoC emission requirements in the near future and to reuse the water in this effluent stream. This process was successfully demonstrated for oil sands produced water, and extending this technology for FGD wastewater holds great promise.

The FGD wastewater is vaporized in a DCSG unit (primarily burning natural gas) to produce steam. The gaseous steam is filtered to remove pollutants captured as solids. The CPoC are captured in a dry filter cake and disposed of in an appropriate landfill (an alternative approach that will be evaluated is to clean saturated steam in a steam separator and send the concentrated brine to a disposal well). The clean steam stream is then expanded through a turbine to co-generate power and offset the operating and capital recovery costs. Treated steam is cooled via incoming wastewater or a cooling tower to produce treated water (quantity depends on system configuration). The treated water will be released or re-used within the power generation facility to reduce freshwater requirements.

Successful development and application of this technology will result in improved wastewater management and reuse and a lower cost of electricity. The incumbent technology, physical-chemical and biological treatment systems, provides no offsetting revenue stream and adds significant costs to the overall process.




**Subscale (1/4 MWth) surface steam generator (produced water testing) skid.**

# Water Treatment and Water-Vapor Recovery Using Advanced Thermally Robust Membranes Power Production

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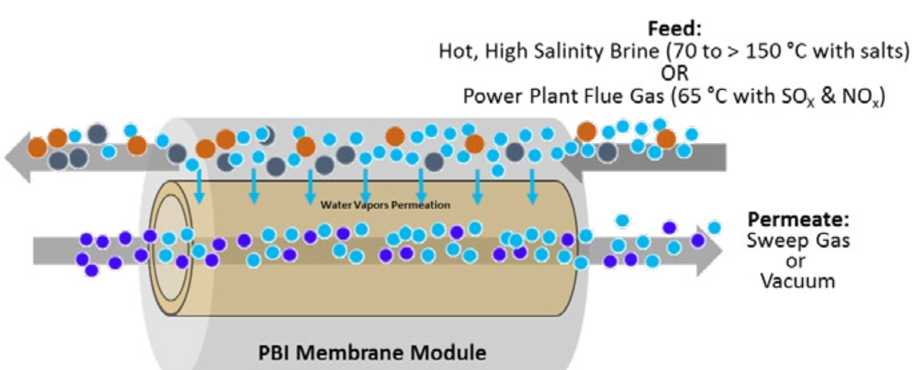
| **Performer** | **Los Alamos National Laboratory** |
| **Award Number** | FWP-FE-844-17-FY17 |
| **Project Duration** | 9/25/2017 – 3/31/2019 |
| **Total Project Value** | $ 400,000 |
| **Technology Area** | Plant Optimization Technologies |

Growing water and energy needs mandate implementation of technologies promoting water recovery and/or use of alternative water resources to provide clean water for power plant operations while reducing their reliance on fresh water. Water vapor capture from flue gas and non-conventional water resource utilization including extracted high-salinity brine treatment and use provide a path forward to meet the water needs of the power production industry. The focus of this effort is to develop a thermally robust membrane separation technology for use in challenging corrosive flue gas and high-salinity brine environments for clean water production. Polybenzimidazole (PBI)-based membranes are excellent candidates for these extreme environment water separations owing to their high water vapor transport characteristics and demonstrated thermo-chemical durability. Los Alamos National Laboratory has developed a suite of PBI materials and membrane platforms that have proven exceptional for harsh environment elevated temperature separations, e.g., carbon dioxide capture in pre-combustion syngas environments. The focus of this effort is to gather PBI membrane performance data and demonstrate durability at process-relevant operating conditions for flue gas dehydration (65 degrees Celsius [°C] in presence of sulfur oxides and nitrogen oxides) and high-salinity extracted water treatment (50,000 to 300,000 mg/L total dissolved solids and up to 200 °C).

Efficient process integration enabled by a thermo-chemically robust membrane technology will create increased power production opportunities by co-utilization of heat and water derived from hot power plant waste streams and high-salinity extracted waters. The focus of this effort is to gather the experimental data (e.g., water vapor permeability, thermo-chemical stability, water vapor selectivity) required to fully understand PBI membrane utilization potential for (1) high-salinity brine separations and (2) water vapor recovery from flue gas. The measured performance will provide the critical data required to facilitate future process design efforts toward optimum integration of a PBI membrane separation technology for water treatment and/or water vapor capture applications.




**Conceptual membrane process for high salinity brine treatment or flue gas dehydration leveraging highly selective water vapor permeation in polybenzimidazole (PBI) materials.**

# Wireless Networked Sensors in Water for Heavy Metal Detection

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| **Performer** | **NanoSonic, Inc.** |
| **Award Number** | SC0013811 |
| **Project Duration** | 6/8/2015 – 7/31/2019 |
| **Total Project Value** | $ 1,150,000 |
| **Technology Area** | Plant Optimization Technologies |

NanoSonic, Inc. will develop wireless sensors for use in analyzing heavy metal chemistry for power generation facilities and, more broadly, for commercial use. The company will develop wireless networked sensors using conformal nanomembrane-based chemical field effect transistors (ChemFETs) to detect heavy metals in water. NanoSonic will fabricate prototype nanomembrane ChemFET sensor elements, design and synthesize chemical-specific ionophores for selectively detecting targeted heavy metal elements, and demonstrate the performance of prototype sensor devices. NanoSonic will work with a local environmental monitoring company to explore field use requirements and to produce a wireless sensor network for in-situ environmental monitoring.

Project success will enable efficient monitoring of heavy metals in water for environmental surveillance, location of pollution sources using analysis from concentration gradients, and detection and mapping of chemical concentrations that are potentially harmful to people and/or destructive to agriculture.

Wireless sensor node.

Wireless sensor probe.

# Water Management for Power Systems: Guiding R&D for Treatment of Coal Power Plant Effluent Streams – Task 2

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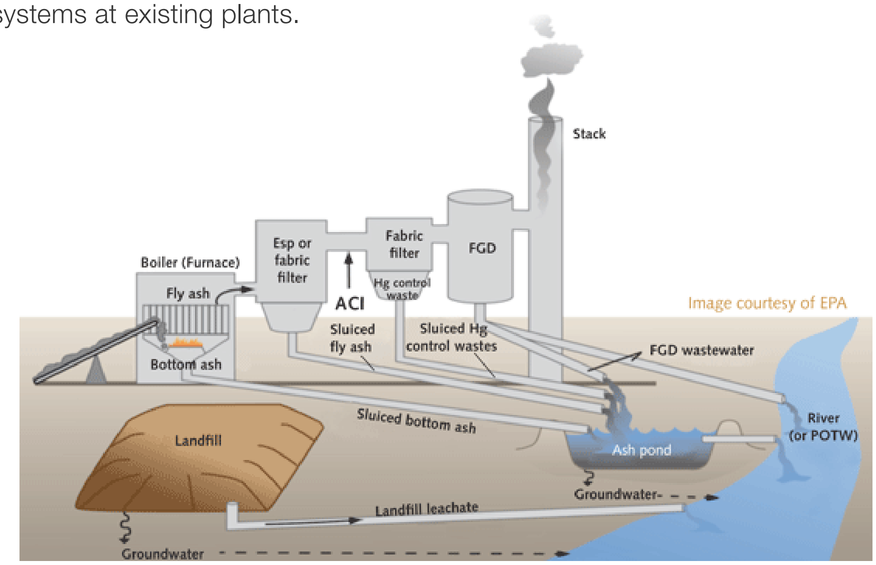
|---|---|
| **Performer** | **National Energy Technology Laboratory** |
| **Award Number** | FWP-1022428 Task 2 |
| **Project Duration** | 4/1/2018 – 3/31/2019 |
| **Total Project Value** | $ 820,000 |
| **Technology Area** | Plant Optimization Technologies |

The objective of this effort is to (1) evaluate effluent water-related issues at both existing and new coal power plants and (2) use the results obtained from techno-economic studies to help guide research in this area. Treatment of effluent streams at coal-fired power plants is currently attracting significant inquiry and interest due to recent Environmental Protection Agency (EPA) regulations. Because discharge requirements for new and existing coal plants are different, treatment approaches of their effluent streams will be different. This task will explore how the zero-liquid discharge (ZLD) systems required of new coal plants may change as a function of certain constituents in the coal, such as chlorine. Likewise, it is not clear if the wastewater/effluent treatment technology of choice for existing coal plants is applicable to coal plants burning low-rank coals (such as subbituminous or lignite) or how the technology will be required to perform. This task will also explore those issues as they relate to wastewater treatment systems at existing plants.

Technical information obtained from this task will identify water related research and development needs and provide management knowledge of current/future regulations and possible technologies to meet these regulations. The benefit to existing coal units will be greater knowledge of how heavy metals are divided amongst the various effluent streams and how this information could inform the EPA's anticipated revision of the wet flue gas desulfurization wastewater portion of the effluent limitation guideline rule. In addition, the ZLD technologies that are being evaluated for new coal power plants may eventually be required for existing units, since environmental standards typically only become more stringent over time. Understanding current and future water issues related to power plants is critical to inform program direction, goals, and research.



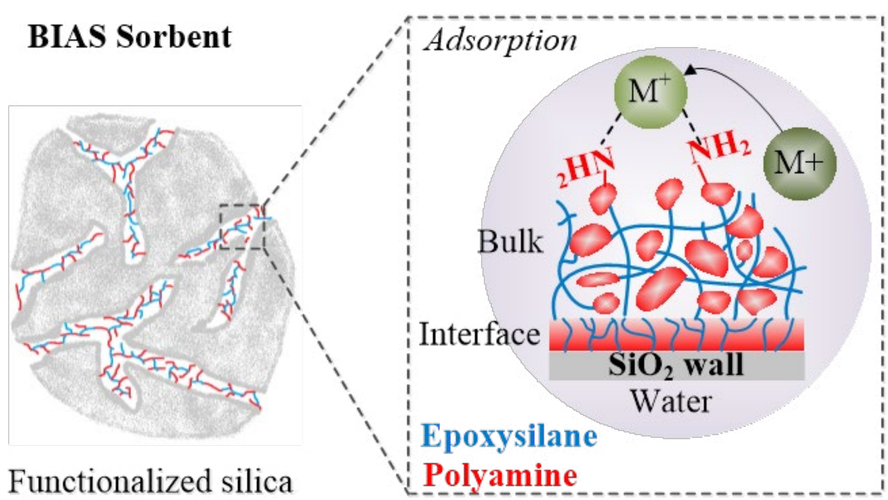

Coal-fired power plant.

# Water Management for Power Systems: Selective Removal of Heavy Metals from Effluent Streams – Task 3

| Performer | National Energy Technology Laboratory |
|---|---|
| Award Number | FWP-1022428 Task 3 |
| Project Duration | 1/1/2017 – 3/31/2019 |
| Total Project Value | $ 1,130,000 |
| Technology Area | Plant Optimization Technologies |

The objective of this effort is to develop basic immobilized amine sorbent (BIAS) materials for the selective removal of heavy metals from industrial effluent, with focus on those effluent streams that are generated during coal combustion. Previous work on related BIAS sorbents shows that it is feasible to capture metals from complex mixtures with selectivity using this technology. Challenges with the flue gas desulfurization (FGD) system are centered upon the chemical form in which the metals persist in the FGD water, as opposed to feed sources that have been studied. NETL will expand on previous work to develop a sorbent material that can reduce both the regulated oxy-anionic heavy metals as well as the regulated cationic metals to, at a minimum, the permissible discharge levels by using a flow-based treatment method. The effort will include fabrication of stabilized amine co-polymers on high surface area silica particles, screening for metal uptake, capacity testing, and treatment of authentic coal effluent water samples. In all phases of the work, detailed characterization of the BIAS materials, the feed solutions, and eluent solutions will be conducted. The target material will be designed to support effluent water treatment in a flow-through application with a low pressure drop across the sorbent bed. For this task, FGD water will be used as a target matrix for evaluating sorbent performance.

The technology developed in this project has the potential to reduce the cost of treating FGD or other effluent treatments by 50 percent compared to commercially-available zero liquid discharge or chemical/biological treatment options.




New research into novel chemical treatment options.

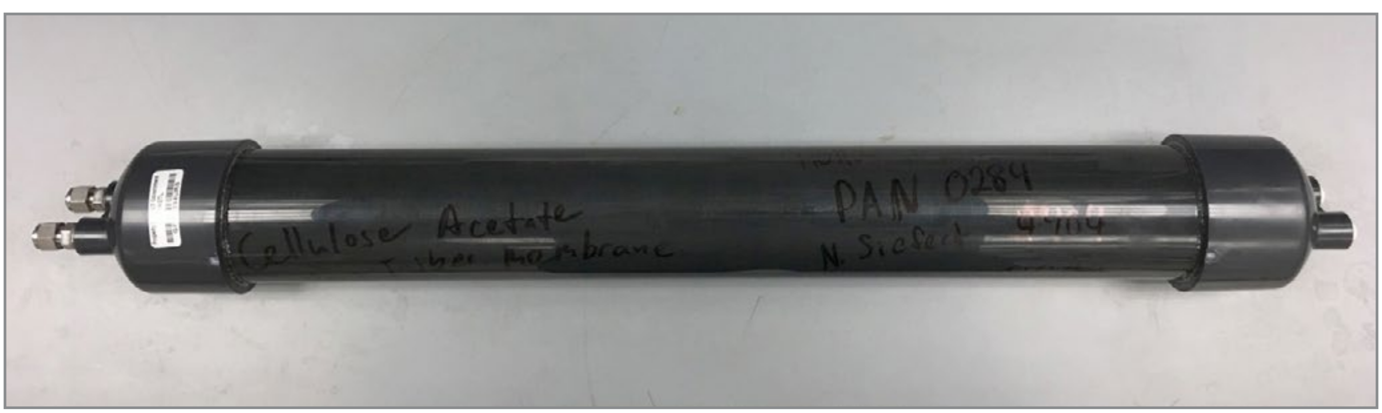
# Water Management for Power Systems: Concentrating Wastewater Effluent Streams – Task 4

| | |
|---|---|
| **Performer** | **National Energy Technology Laboratory** |
| **Award Number** | FWP-1022428 Task 4 |
| **Project Duration** | 4/1/2018 – 3/31/2019 |
| **Total Project Value** | $ 278,000 |
| **Technology Area** | Plant Optimization Technologies |

The objective of this research is to experimentally demonstrate and numerically simulate a novel membrane process for concentrating effluent streams. Effluent waste streams from coal power plants contain heavy metal contaminants and hence cannot be discharged to local waterways and treatment of these effluent streams is currently very expensive. While there are cost-effective treatment processes for low salinity water, such as reverse osmosis, this process ends up generating a medium salinity brine that must be further concentrated. The Environmental Protection Agency estimates that the compliance costs are $480 million for the Final Rule limiting effluent streams at coal power plants, with estimated benefits of between $451 and $566 million. Hence, to increase net benefits, it is crucial to develop innovative technologies that can lower the cost of treating these heavy metal effluent streams at coal power plants.

One option for treating these effluent streams is called zero liquid discharge (ZLD), which effectively concentrates the dissolved ionic species while separating out fresh water. Currently, ZLD is an expensive option for treating these effluent streams because of the high energy and capital cost associated with the brine concentration step in the ZLD process. As such, this task will demonstrate advanced technologies that can concentrate effluent streams to high concentrate while reducing energy consumption.

This brine concentration research has the potential to reduce capital cost and electricity consumption for treating and concentrating high salinity brines generated at coal-fired power plants by at least 50 percent compared to commercially-available, non-membrane technologies, such as mechanical vapor recompression.



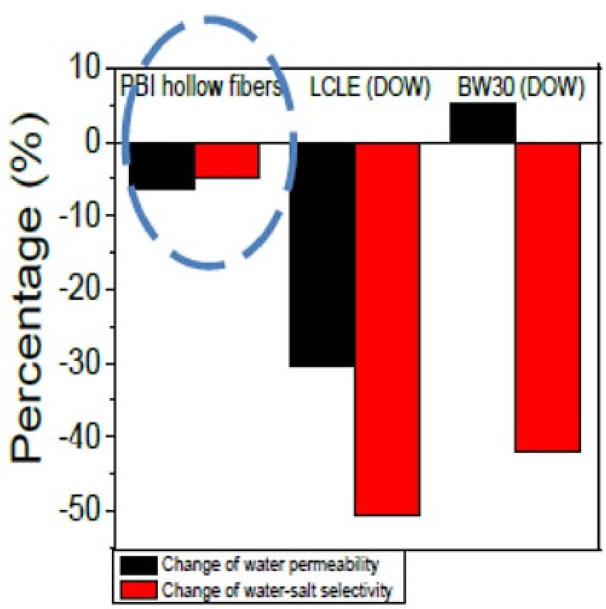

**Hollow fiber membranes for scale-up testing of osmotically assisted reverse osmosis process.**

# Development of a High Efficient Membrane-Based Wastewater Management System for Thermal Power Plants

| | |
|---|---|
| **Performer** | **SRI International** |
| **Award Number** | FE0031552 |
| **Project Duration** | 12/19/2017 – 6/18/2020 |
| **Total Project Value** | $ 799,949 |
| **Technology Area** | Plant Optimization Technologies |

The main goal of the proposed research is to develop innovative effluent water management practices at coal- fired energy plants. In particular, researchers plan to use SRI-based polybenzimidazole (PBI) hollow-fiber membrane (HFM) technology to remove selenium from flue gas desulfurization (FGD) wastewater below the effluent discharge limits (less than 5 parts per billion). The PBI membranes are resistant to fouling and can be operated under environments that are substantially harsher than those tolerated by commercially available membranes. The fouling resistance of the PBI-HFM based separation system under simulated FGD water discharge conditions will be tested.

The technology developed will allow the removal of toxic material in the FGD blowdown and other wastewater from the plant and provide an opportunity to develop methods for reducing water use within the plant and thereby reducing freshwater withdrawals. Success of this project will result in development of a power plant effluent control system that can remove the hazardous compounds and also recover and reuse the water to reduce freshwater withdrawal. In addition, energy use in effluent control systems in thermal power stations will be greatly reduced.




**Demonstration of chlorine stability of PBI HFM compared to commercial membranes.**

# Continuous Water Quality Sensing for Flue Gas Desulfurization Wastewater

| | |
|---|---|
| **Performer** | **University of Alabama at Birmingham** |
| **Award Number** | FE0027778 |
| **Project Duration** | 8/1/2016 – 3/31/2019 |
| **Total Project Value** | $ 439,986 |
| **Collaborator** | Southern Research |
| **Technology Area** | University Training and Research |

The overall goal of this project is to develop an integrated water sensor package for continuous water quality monitoring of flue gas desulfurization (FGD) wastewaters to include concentration measurements of multiple contaminants (e.g., trace metals: selenium, arsenic, and mercury) and measurement of common water quality indicators (e.g., pH, total dissolved solids).

The proof-of-concept prototype will successfully demonstrate the key features of the technology through on-site processing of FGD wastewater including reliable in-field automated operation for extended periods (e.g., one week); accurate trace metal detection using a proprietary FGD sample preparation technique; low cost, small footprint detection with a commercial off-the-shelf (COTS) voltammetry device, parts per trillion (ppt) limit of detection/qualification; continuous monitoring with high sampling frequency (i.e., more than one measurement per hour for trace metals); integration of COTS water quality indicators (e.g., pH, total dissolved solids); and wireless transmission of measurements to an on-site control room.

The project comprises three phases: Phase I, Development of Sample Preparation Batch Process; Phase II, Design and Development of Continuous Sample Preparation Prototype; and Phase III, Demonstration Unit Integration and Field Testing. The resulting demonstration unit will be used for extended in-field testing at a coal-fired power plant at a partner's site and will be validated for accuracy and reliability through comparison with the gold-standard analysis method provided by onsite inductively coupled plasma mass spectrometry analysis.

Anticipated project benefits include (1) the ability to monitor and detect contaminant concentration levels in FGD wastewater discharge in coal-fired power plants; (2) a reduction in recurring operating and off-site laboratory analysis costs by minimizing required FGD wastewater treatment reagents and equipment; and (3) closed-loop control of contaminant concentrations in effluent discharge resulting in a high level of confidence of compliance with EPA discharge guidelines.

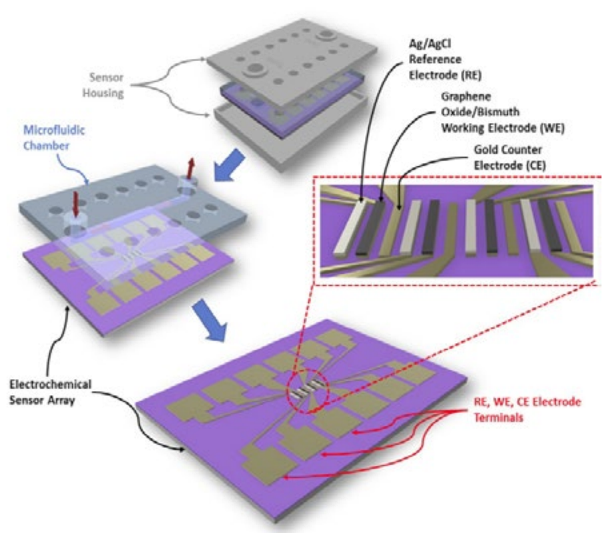
**Multi-phase approach.**

# Applying Anodic Stripping Voltammetry to Complex Wastewater Streams for Rapid Metal Detection

| | |
|---|---|
| **Performer** | **University of California Los Angeles** |
| **Award Number** | FE0030456 |
| **Project Duration** | 8/1/2017 – 7/31/2020 |
| **Total Project Value** | $ 400,000 |
| **Collaborator** | University of California at Riverside |
| **Technology Area** | University Training and Research |

This project's objective is to develop a lab-on-a-chip (LOC) electrochemical sensor capable of accurately measuring heavy metal concentrations, including lead (Pb), cadmium (Cd), and arsenic (As), in complex aqueous streams such as municipal wastewater. The sensor technology relies on anodic stripping voltammetry (ASV), which has been demonstrated to detect extremely low (sub parts-per-million) concentrations of these metals. The technology will be capable of autonomously conducting metal measurements and report the findings remotely via cellular technology. Furthermore, using open-source hardware and software tools, the project team will construct sensor technology that operates with minimal human intervention and is capable of autonomously performing all of the pre-treatment steps needed to perform metal measurement activities. To accomplish this objective, the project team will concentrate on characterizing metal speciation in wastewater, develop appropriate pre-treatment methods that will allow analysis of this complex matrix on an LOC device, fabricate a range of electrodes specifically tailored to enhance the detection of the target metals, and, finally, construct and test an autonomous LOC device that incorporates the pre-treatment steps and specialized electrodes for the detection of heavy metals in wastewater.

All pre-treatment steps will be integrated into the fully automated LOC device, which will conduct the metal analysis without the need for human intervention beyond periodically re-filling reagent reservoirs. Current heavy metal measuring methods are time-consuming and rely on grab sampling and expensive analytical instruments. Thus, the proposed technology would decrease costs and increase the frequency of measurements, enabling heavy metal contamination to be detected in near real-time.



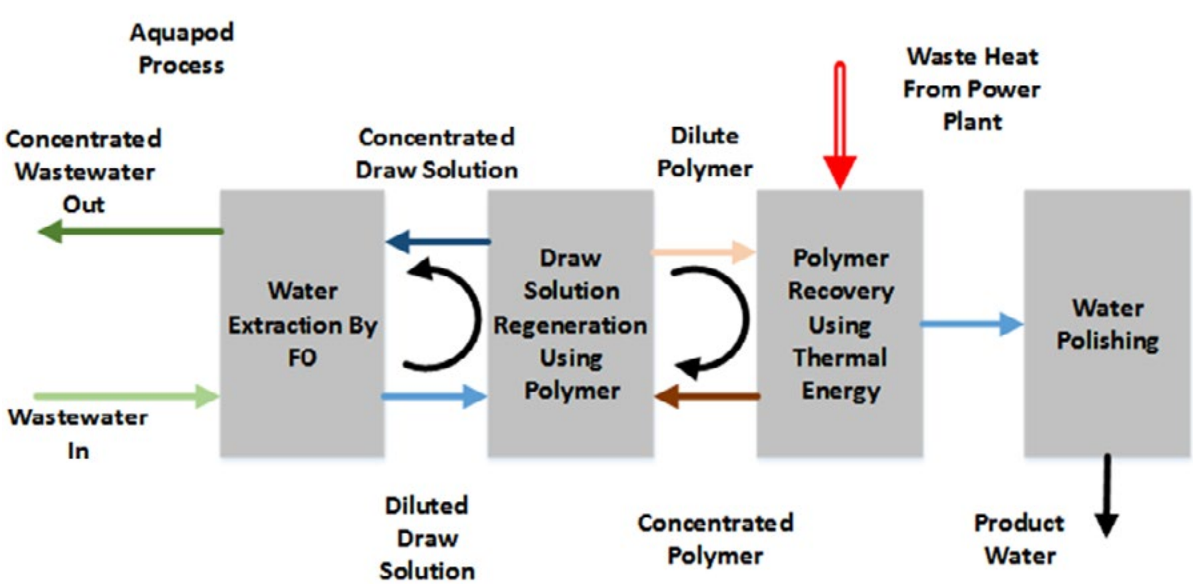

**Schematic of electrochemical sensor arrays microanalyzer system.**

# Energy Efficient Waste Heat Coupled Forward Osmosis for Effluent Water Management at Coal-Fired Power Plants

| | |
|---|---|
| **Performer** | **University of Illinois at Urbana-Champaign** |
| **Award Number** | FE0031551 |
| **Project Duration** | 12/19/2017 – 12/31/2020 |
| **Total Project Value** | $ 929,617 |
| **Technology Area** | Plant Optimization Technologies |

This project will evaluate a transformational low energy (less than 200 kilojoules/kilogram water) waste heat coupled forward osmosis (FO) based water treatment system (the Aquapod©), adapted to meet the complex and unique environment of a power plant, to manage effluents, meet cooling water demands and achieve water conservation. The target is to enable recovery of at least 50 percent of the water from highly degraded water sources without extensive pretreatment in a cost effective manner.

The use of the Aquapod© FO process can double to quadruple the amount of water recovery from power plant effluents per unit of input energy compared to the current state of the art. It is also an intrinsically safe process, unlike the current state of the art, which utilizes gaseous ammonia. Project outcomes will enable the early-stage evaluation of a transformational water treatment system adapted to the power plant environment. A partner utility is engaged early in the technology development to assure that results would be applicable to large-scale coal-fired power plants.



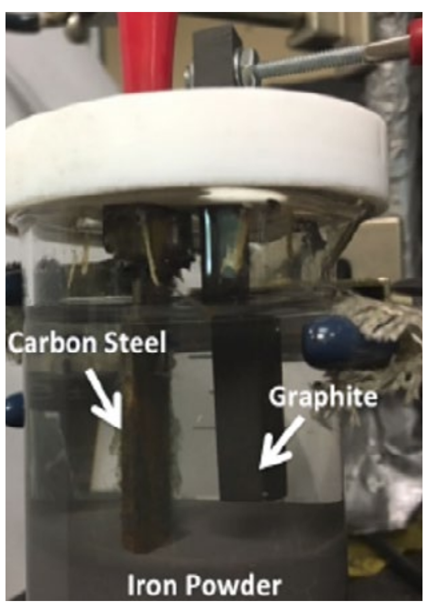

The process utilized by the University of Illinois.

# Intensified Flue Gas Desulfurization Water Treatment for Reuse, Solidification, and Discharge

| Performer | University of Kentucky Research Foundation |
|---|---|
| Award Number | FE0031555 |
| Project Duration | 1/22/2018 – 1/21/2020 |
| Total Project Value | $ 928,666 |
| Collaborators | Southern Research Institute; Trimeric Corporation |
| Technology Area | Plant Optimization Technologies |

This project will develop a process that is able to treat for reuse wastewater resulting from wet flue-gas desulfurization (FGD) scrubbing systems, leading to significant reductions in footprint and chemical consumption compared to the state-of-the-art water treatment technologies. To achieve this goal, the project will (1) evaluate the effectiveness of electrocoagulation with air-dissolved flotation in removing regulated species through design, construction, and testing of a one liter per hour sub-pilot unit, (2) examine a nanofiltration unit to achieve greater than 80 percent monovalent salt rejection, (3) conduct long-term operation of membrane-based filtration for FGD wastewater aimed at determining performance degradation, e.g., membrane fouling, (4) determine a practical salt concentration for solidification resulting in an acceptable leachate, and (5) apply continuous capacitive deionization as a polishing step to remove any remaining government-regulated species below the effluent limitation guidelines requirements for recycling or discharge.

Wastewater treatment is one of the most important and challenging environmental issues associated with coal-based power generation. Compared to existing state-of- the-art biological treatment methods based on several physical/chemical steps, the proposed process will result in a reduction in the footprint of a physical/chemical treatment process and withdrawals of fresh water at power generation plants.



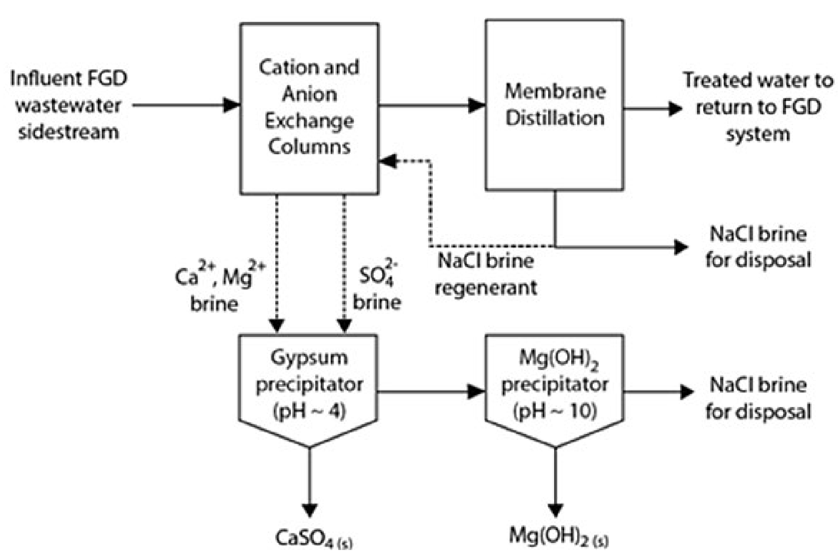

A lab-scale setup for electro-coagulation studies.

# Flue Gas Desulfurization Wastewater Treatment, Reuse and Recovery

| | |
|---|---|
| **Performer** | **University of New Mexico** |
| **Award Number** | FE0030584 |
| **Project Duration** | 8/1/2017 – 7/31/2019 |
| **Total Project Value** | $ 249,536 |
| **Technology Area** | Plant Optimization Technologies |

The objective of the proposed research is to develop a computer model of both the unit processes and overall treatment system. Model development will be supported by laboratory research addressing (1) the ability to concentrate divalent ions from high-salinity flue gas desulfurization (FGD) wastewater of varying chemistry, and (2) the ability to precipitate gypsum and magnesium hydroxide from concentrated ion-exchange brines. The model will calculate process performance, mass and liquid flow rates, and heat requirements; it will be used to evaluate the technical feasibility of a full-scale treatment process. The technology developed in this study will be relevant to utilities considering zero liquid discharge of FGD wastewaters. The project objectives will be achieved through a combined laboratory and modeling effort to develop a novel treatment process for FGD wastewater. Lab studies will be conducted to investigate divalent ion removal and precipitation of gypsum and magnesium hydroxide from brine solutions. The process model will enable performance to be predicted and optimized by calculating flow, mass, and energy balances.

This study will result in a new treatment process to recover water, commodities, and trace contaminants from FGD wastewater. The proposed treatment process will reduce water use by the FGD process, recycle treated wastewater, and use waste heat to improve process performance based on research at minority-serving institutions.




Process description.

# Developing Cost-Effective Biological Removal Technology for Selenium and Nitrate from Flue Gas Desulfurization Wastewater from Existing Power Generating Facility

| | |
|---|---|
| **Performer** | **West Virginia State University** |
| **Award Number** | FE0027893 |
| **Project Duration** | 10/1/2016 – 9/30/2019 |
| **Total Project Value** | $ 249,999 |
| **Technology Area** | Plant Optimization Technologies |

The overall goal of this project is to explore a variety of genomic, biochemical, genetic, and molecular approaches to understanding the molecular basis of selenium and nitrate sensing, uptake, and sequestration by algae and plants from flue gas desulfurization (FGD) wastewater. The ultimate objective of this project is to apply the knowledge gained to develop a cost-effective biological treatment to help reduce these compounds in FGD wastewater, reduce power plant use of freshwater, and increase biomass/crop production.

The work will focus on the following technical objectives: (1) investigate changes in transcripts and metabolism in algae and plants in response to FGD wastewater and (2) explore biotechnological strategies to increase sequestration of selenium and nitrates in biomass for agricultural productivity.

The project will develop transcriptomic and metabolomic data for basic and applied water research relating to algae, duckweeds, and mutants/transgenic plants derived using Arabidopsis transfer-DNA (T-DNA). Anticipated project benefits include maximizing sequestration of selenium and nitrates in biomass for FGD wastewater remediation, reduction of power plant use of freshwater resources, and enhanced agricultural production.

**Candidate genes in model system.**

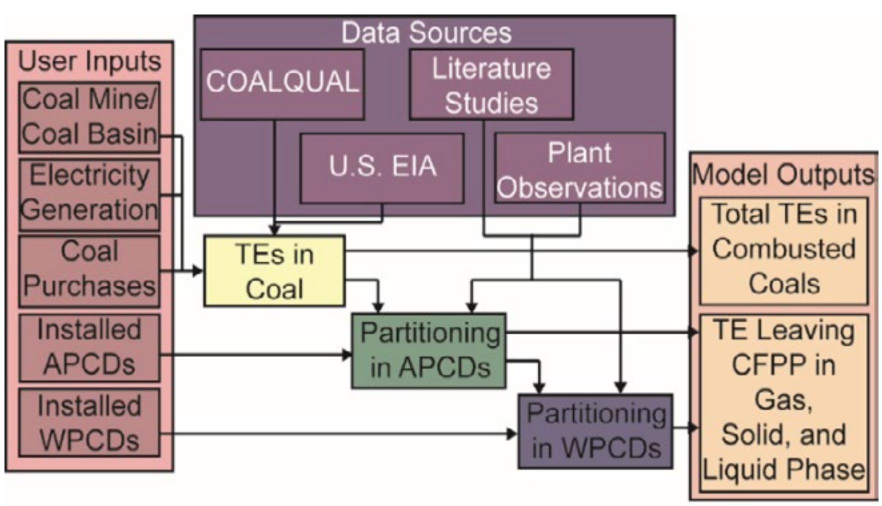
# ENERGY WATER ANALYSIS

# Trace Element Sampling and Partitioning Modeling to Estimate Wastewater Composition and Treatment Efficacy at Coal Generators

| | |
|---|---|
| **Performer** | **Carnegie Mellon University** |
| **Award Number** | FE0031646 |
| **Project Duration** | 9/10/2018 – 9/9/2021 |
| **Total Project Value** | $ 400,000 |
| **Technology Area** | University Training and Research |

Carnegie Mellon University researchers will sample pulverized-coal-fired power plants (CFPPs) owned and operated by Louisville Gas & Electricity–Kentucky Utilities (LGE-KU) to build a predictive model that will enable utility decision makers, academic researchers, and policymakers to simulate trace element (TE) emissions from CFPPs. Samples taken during baseload and cycling conditions will be used to develop and validate an open-source, easy-to-implement trace element partitioning model using publicly available datasets, literature studies of trace element partitioning, and sampling data from LGE-KU CFPPs to estimate trace element partitioning in air pollution control devices (APCDs) between the gas, liquid, and solid phases exiting boilers and flue gas treatment trains. The project team will use estimates of the liquid phase trace element concentration in flue gas desulfurization (FGD) wastewater to estimate trace element behavior in water pollution control devices (WPCDs) and evaluate treated wastewater effluent concentrations for compliance with the Effluent Limitations Guidelines and Standards for the Steam Electric Power Generating Point Source Category (ELGs). The team will then develop cost estimates of established and emerging wastewater treatment trains to identify the most cost-effective approaches to comply with the ELGs.

It is anticipated that this project will create an open-source predictive model of trace element partitioning to solid, liquid, and gas phases at CFPPs, establish a range of FGD wastewater chemistries for existing and new CFPPs, model costs for biological and emerging selenium removal technologies, and quantify the impact of non-steady state operation on trace element partitioning.



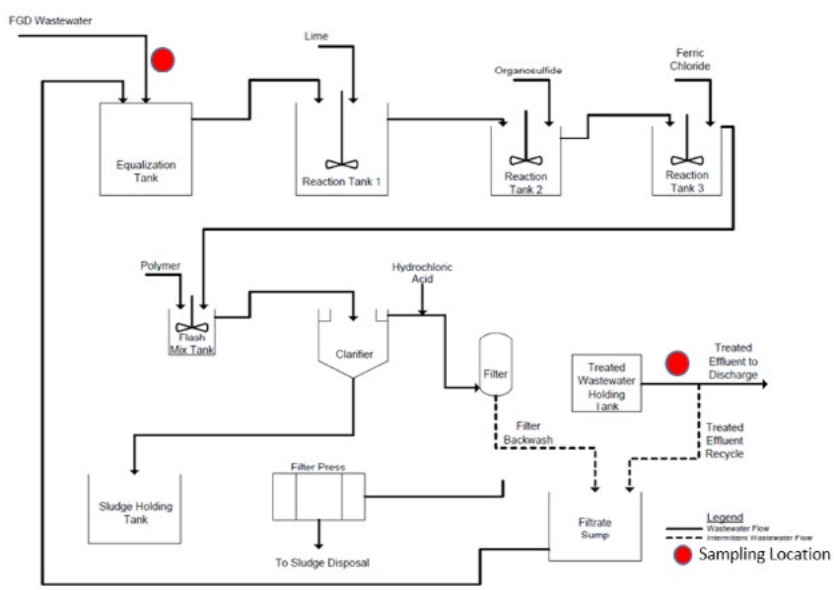

**Framework for the Trace Element Partitioning Model.**

# Coal-Fired Power Plant Configuration and Operation Impact on Plant Effluent Contaminants and Conditions

| | |
|---|---|
| **Performer** | **Lehigh University** |
| **Award Number** | FE0031654 |
| **Project Duration** | 9/1/2018 – 8/31/2020 |
| **Total Project Value** | $ 400,000 |
| **Technology Area** | University Training and Research |

Lehigh University, working with Western Kentucky University, will characterize coal contaminants in power plant wastewater as a function of coal type, plant type, plant operational profile, environmental controls, water treatment technology, and effluent species. Multiple utility companies will provide access to their coal-fired power plants and in-kind support for testing and data and sample collection from flue gas desulfurization wastewater discharge and treated water tank discharge effluent streams. Effluent samples will be analyzed for mercury, arsenic, selenium, nitrate/nitrite, and bromide. Coal sample analyses will include proximate analysis (moisture, volatile matter, ash and fixed carbon); ultimate analysis (carbon, hydrogen, nitrogen, sulfur, ash, and oxygen); trace elemental analysis (mercury, arsenic, and selenium); and anions analysis (bromide, nitrate + nitrite).

The results of the analyses obtained from this project will trace effluent conditions as a function of coal type, unit configuration, unit operation profile, and environmental control strategy, and will describe levels of uncertainty of the analysis. These results will provide feedback information about the impact of fuel type on effluents and help future decisions on wastewater compliance. Participation of students will encourage new research ideas and provide valuable training opportunities for future U.S. scientists and engineers.



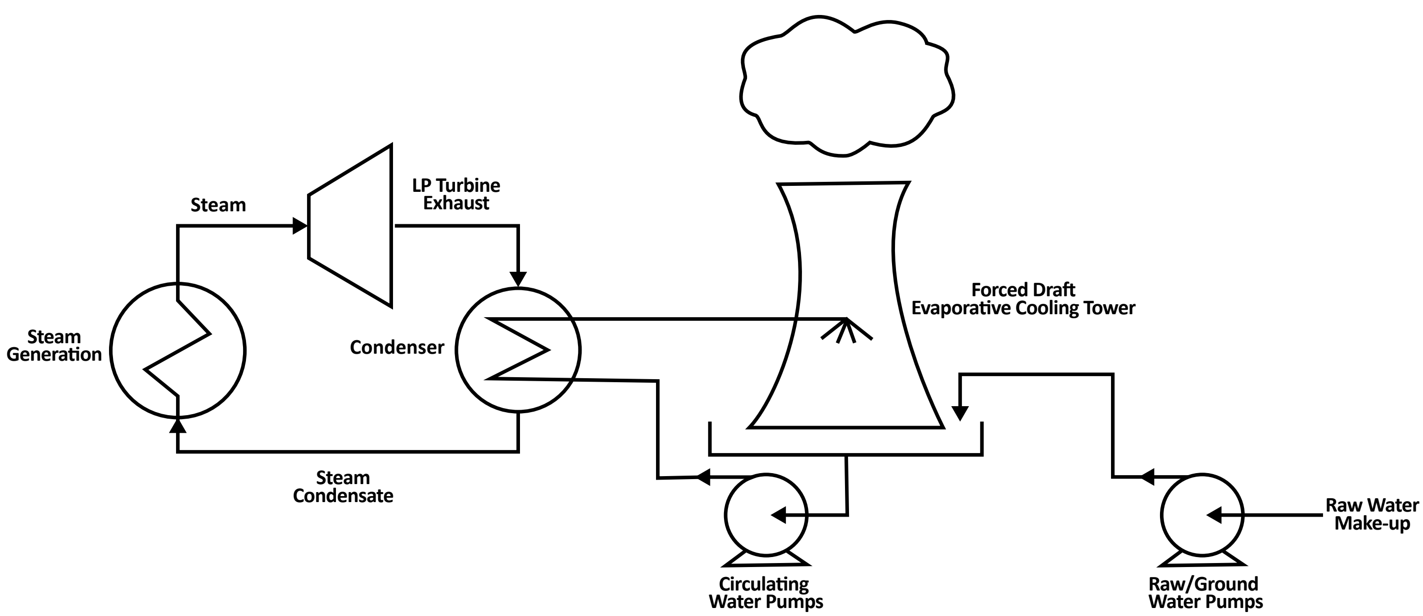

Sampling locations for waste-water chemical precipitation system.

# Water Management for Power Systems: Impact of Water Use of Power Systems – Task 5

| | |
|---|---|
| **Performer** | **National Energy Technology Laboratory** |
| **Award Number** | FWP-1022428 Task 5 |
| **Project Duration** | 4/1/2018 – 3/31/2019 |
| **Total Project Value** | $ 240,000 |
| **Technology Area** | Plant Optimization Technologies |

The interface of energy and water, or the water-energy nexus, can be defined as the many relationships between energy and water that are necessary to ensure an adequate supply of both resources for every purpose. Understanding the intertwining nature of water-energy interactions is the key to determining how to make the most efficient use of these critical resources, both for short-term economic benefit and for longer-term societal and environmental sustainability. A summary comparison of water and energy issues shows a striking correspondence between issues on the water side and issues on the energy side. The immediacy of these issues lends urgency to the effort to understand and manage the water-energy nexus. The objective of this task is to obtain and investigate current water data on individual plant- and fleet-wide water use, water stresses due to power generation, and how water stresses impact power plant operations.

Models and software developed under this task will provide information on the impacts of water use by power plants that can be used by existing coal power plants to make investment decisions on when and what type of equipment to purchase to reduce water consumption. Understanding the impact of water use on power generating systems is critical to guide program direction, goals, and research.



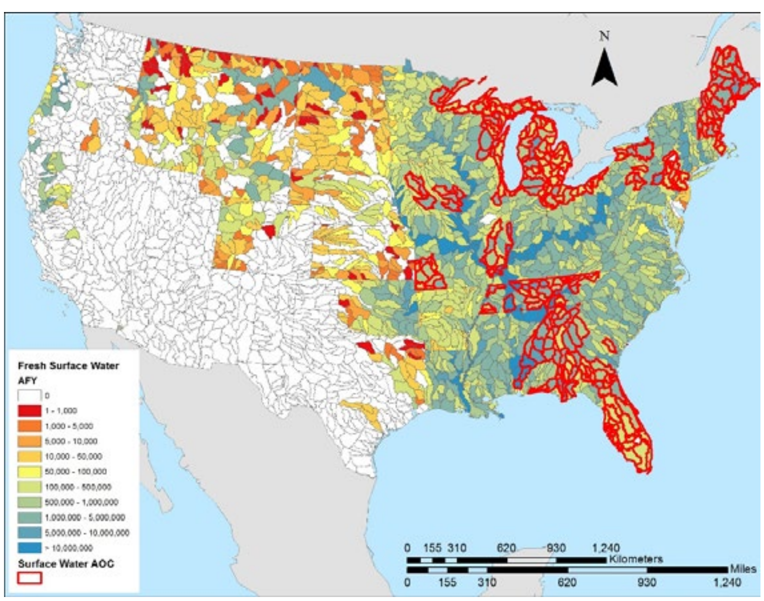

**Flow of water in a power plant.**

# Water Atlas Extension

| | |
|---|---|
| **Performer** | **Sandia National Laboratories** |
| **Award Number** | FWP-18-021409 |
| **Project Duration** | 10/1/2018 – 9/30/2019 |
| **Total Project Value** | $ 700,000 |
| **Technology Area** | Plant Optimization Technologies |

A water database, called the Water Atlas, has been previously developed by Sandia to support energy sector planning. The Water Atlas includes estimates of water availability at the watershed level (8-digit Hydraulic Unit Code [HUC], which corresponds to roughly 2250 watersheds) for the lower 48 states of the United States. These metrics have been developed for five sources of water including fresh surface water and groundwater, appropriated water, municipal wastewater, and shallow brackish groundwater. The compiled set of water availability data is unique in that it considers multiple sources of water; accommodates institutional controls placed on water use; is accompanied by cost estimates to access, treat, and convey each unique source of water; and is compared to projected future growth in consumptive water use to 2030. This current scope of work addresses efforts to extend the Water Atlas in three important ways. First, the database will be extended to include water data for Alaska and Hawaii. Second, the Water Atlas will be extended to include data on power plant water ownership; particularly, details on where each power plant gets its water and any potential constraints on water deliveries in times of drought. Finally, the database will be extended by adding a metadata layer that contains specifics concerning the origins of the water availability, cost, and future use data (including past and present data entries).

The Water Atlas provides two broad benefits to the electric power industry. First, the compiled water availability/cost data provide a basis for determining where limited water supply could impact siting decisions for new thermal generation. Second, this database helps better understand the physical and regulatory risks posed to thermal power plant operations by extremes in source water supply and quality.




**Fresh surface water availability mapped by 8-digit HUC watershed for the contiguous United States.**

# ABBREVIATIONS

Al......aluminum

APCD ...... air pollution control device

As...... arsenic

ASV ......anodic stripping voltammetry

BIAS...... basic immobilized amine sorbent

Cd ...... cadmium

CFPP...... coal-fired power plant

ChemFET ......chemical field effect transistor

$CO_2$ ......carbon dioxide

COTS ...... commercial off-the-shelf

CPoC ...... critical pollutants of concern

Cu ...... copper

DCSG......direct contact steam generation

ELGs ...... Effluent Limitations Guidelines and Standards for the Steam Electric Power Generating Point Source Category

EPA ......Environmental Protection Agency

FE...... Office of Fossil Energy

FGD...... flue gas desulfurization

FO ......forward osmosis

GTI ......Gas Technology Institute

HBCU......Historically Black Colleges and Universities

HFM ...... hollow-fiber membrane

HTE...... heat transfer enhancement

HTRI......Heat Transfer Research, Inc.

HUC ......Hydraulic Unit Code

LGE-KU .... Louisville Gas & Electricity – Kentucky Utilities

LOC......lab-on-a-chip

MIT......Massachusetts Institute of Technology

MF......microfiltration

MW ...... megawatts

NETL......National Energy Technology Laboratory

Ni ......nickel

NOX ......nitrogen oxides

OMI ...... Other Minority Institutions

Pb ......lead

PBI ......polybenzimidazole

pH ...... potential of hydrogen

ppt ......parts per trillion

R&D...... research and development

RO...... reverse osmosis

SLIPS ...... superhydrophobic/slippery liquid infused porous surfaces

SOX...... sulfur oxides

T-DNA ...... transfer-deoxyribonucleic acid

TDS ......total dissolved solids

TE ...... trace element

U.S. ......United States

UCR ......University Coal Research

USGS ......United States Geological Survey

WPCD ...... water pollution control device

WRC ......Water Research Center

ZLD ...... zero-liquid discharge

# NOTES

# NOTES

# NOTES

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https://netl.doe.gov/coal/water-management

https://netl.doe.gov/coal/crosscutting

https://energy.gov/fe/plant-optimization-technologies

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U.S. DEPARTMENT OF ENERGY

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