Application of pulse spark discharges for scale prevention and continuous filtration methods in coal-fired power plant

Oct. 1, 2008 – Sept. 30, 2011

U.S. DEPARTMENT OF ENERGY
National Energy Technology Laboratory

Drexel University
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Background

Thermoelectric generation accounted for 39% (136 billion gallons per day) of all freshwater withdrawals in 2000.

→ Why so high?

High concentration of mineral ions in the circulating cooling water due to evaporation of pure water evaporates

→Mineral fouling problem, reducing condenser capacity

To maintain a desired calcium level in the cooling water,

→ cycle of concentration, COC = 3.5

→ continuously blowdown with fresh makeup water

Three reactions leading to mineral fouling

Reaction 1: dissociation of bicarbonate ions into hydroxyl ions and carbon dioxide

$$HCO_3^- \, (aq) \leftrightarrow + OH^- \, (aq) + CO_2(g)\uparrow$$

Reaction 2: hydroxyl ions produced further react with existing bicarbonate ions, producing carbonate ions and water

$$HCO_3^- \, (aq) + OH^- \, (aq) \leftrightarrow CO_3^{2-} \, (aq) + H_20 \, (l)$$

Reaction 3: reaction between calcium and carbonate ions, resulting in the precipitation and crystallization of calcium carbonate particles

$$Ca^{2+} \, (aq) + CO_3^{2-} \, (aq) \leftrightarrow CaCO_3 \, (s) \downarrow$$

Rationale

COC → Calcium level in cooling water → Condenser tube fouling

An innovative water treatment technology
utilizing spark discharges in water for scale prevention.

The key issue:
How to precipitate and remove dissolved calcium ions in cooling water
so that the COC can be increased and at the same time calcium carbonate scales can be avoided.

Objectives

To reduce the amount of fresh water needed to achieve power plant cooling by preventing the buildup of mineral scale on condenser tubes, thereby increasing the Cycle of Concentration (COC) in the cooling water system from the present operational value of 3.5 to at least 8.

New scale-prevention technology
→ Use electrical pulse spark discharges to precipitate dissolved mineral ions
→ Remove them using a self-cleaning filter from cooling water.

Specific objectives of the proposed work

1. Determine whether the spark discharge can promote the precipitation of mineral ions in cooling water.

2. Determine whether the proposed technology can increase the COC through a continuous precipitation of calcium ions and removal of the precipitated salts with a self-cleaning filter.

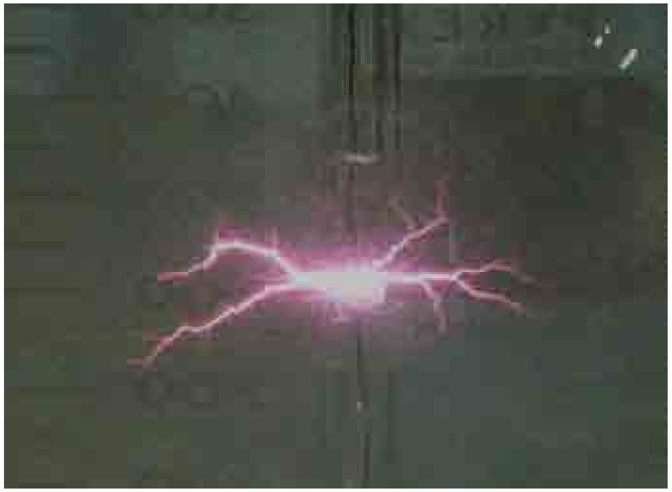
3. Demonstrate that mineral scale on condenser tubes can be prevented or minimized if a COC of 8 or almost zero blowdown can be achieved via the proposed spark discharge technology.

TASKS TO BE PERFORMED

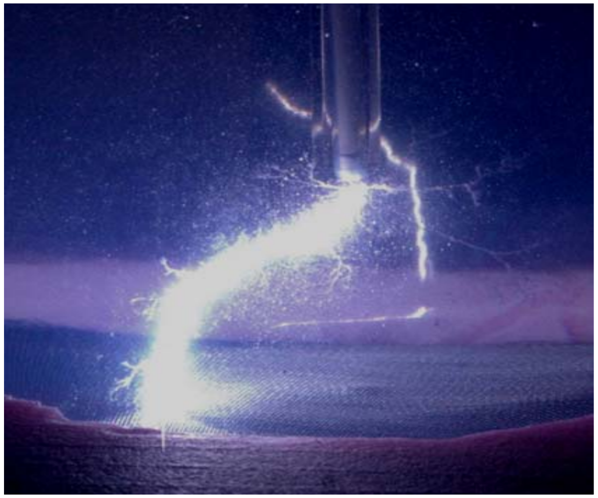
Task 1 – Precipitation of dissolved calcium ions using spark discharge

Task 1 attempts to maintain the desired calcium ion concentration (~ 400 mg/L) in circulating cooling water by precipitating dissolved calcium ions with spark discharges instead of via local heating or blowdown.

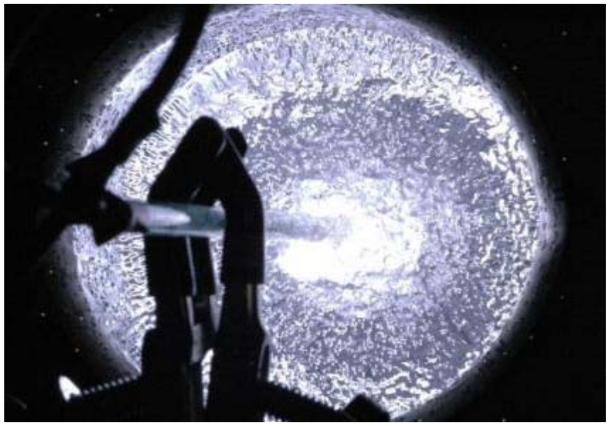
Plasma Discharges in Water
(Drexel University)



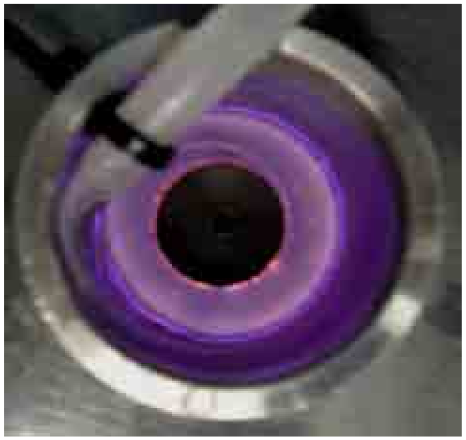
Pulsed Corona in water



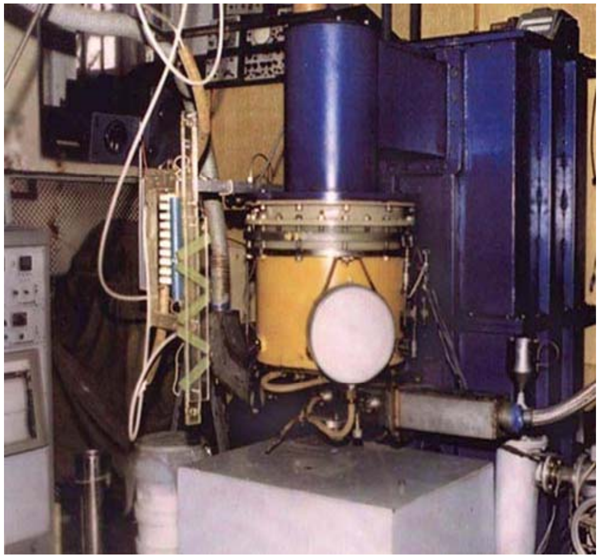
Spark Discharge in water



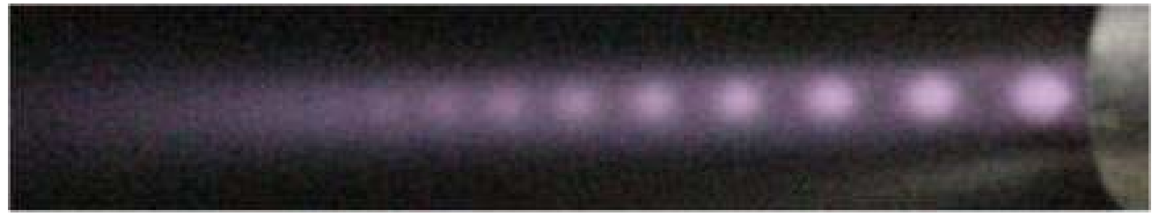
Spark Discharge in water



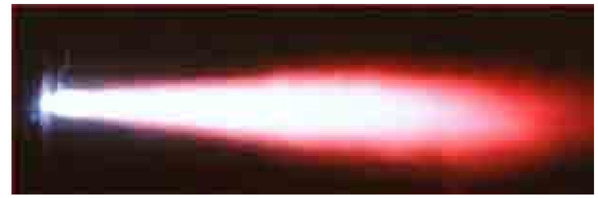
Gliding Arc in water



Electron Beam



SuperSonic flame plasma

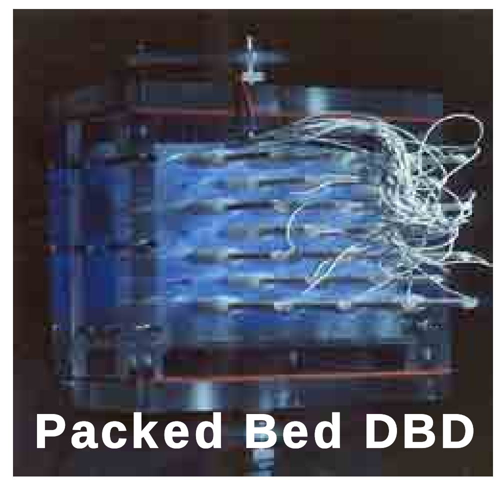


Plasma Torch

Gliding Arc

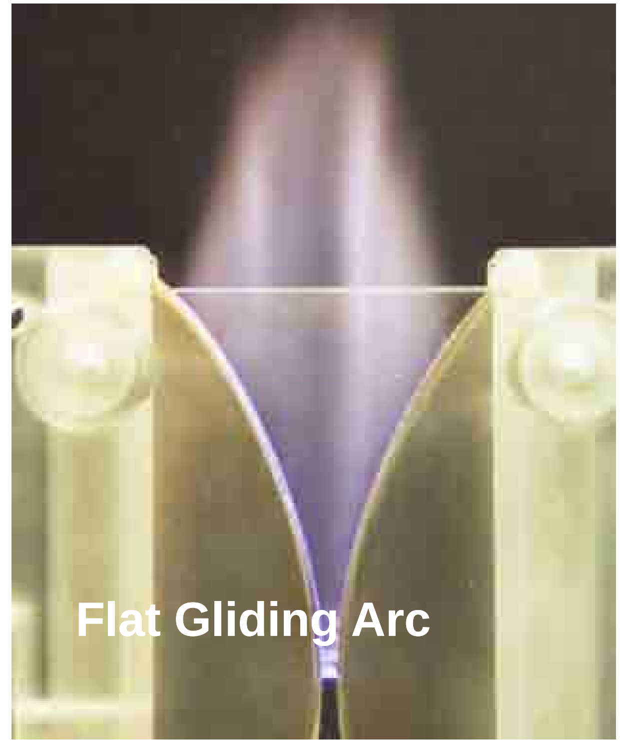
Micro-discharge

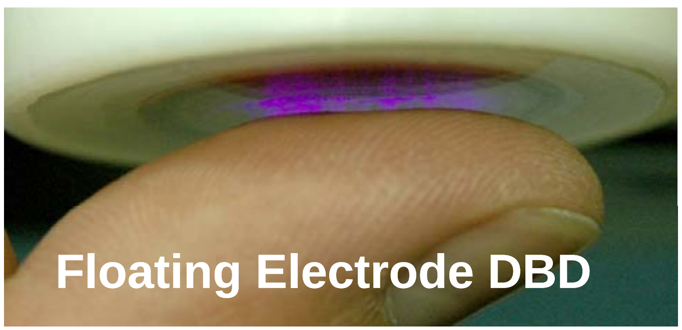
10kW Pulsed Corona

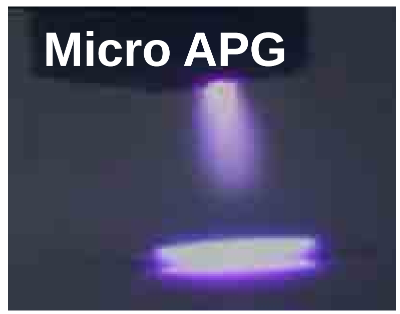


Packed Bed DBD

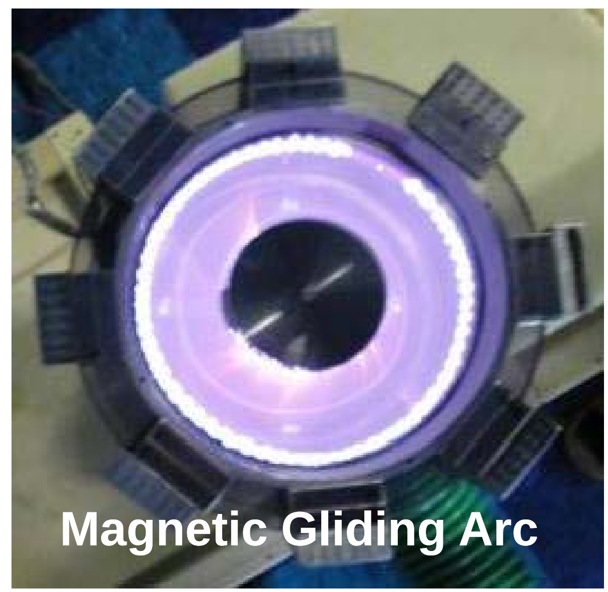

Pulsed Corona


Flat Gliding Arc


Floating Electrode DBD


Micro APG


Dielectric Barrier Discharge


Magnetic Gliding Arc

Task 1 – Precipitation of Dissolved Calcium Ions using Spark Discharge

Subtask 1.1 Modeling of Ca^{2+} precipitation process using water-related variables

The objective of this subtask is to investigate whether different cooling water conditions alter the Ca^{2+} precipitation efficiency of the spark discharges through computer modeling of the precipitation process.

Subtask 1.2 Parametric study of Ca^{2+} precipitation process using power-related variables

The objective of this subtask is to investigate whether different spark configurations alter the Ca^{2+} precipitation efficiency of the spark discharges.

Subtask 1.3 Optimization of electrode configuration for most efficient spark discharges

The objective of this subtask is to investigate the effects of electrode materials and geometry on the Ca^{2+} precipitation efficiency.

SUCCESS CRITERIA AND DECISION POINTS

Criteria for success for Task 1

The success of Task 1 study will be judged if the proposed spark discharge technology can reduce the concentration of calcium ions by more than 50% for different levels of hardness of cooling water. The actual hardness of recirculating cooling water can be as high as 400 ppm. If we can reduce the hardness of the cooling water by at least 50% for the maximum hardness case, we should consider Task 1 study successful.

TASKS TO BE PERFORMED

Task 2 – Validation experiments to increase COC

Task 2 will include building a laboratory cooling tower (Figure 2), where pure water continuously evaporates as heat is added through a small heat exchanger. In the laboratory tower, the water lost by evaporation, wind, and blowdown is automatically replaced by makeup water whose flow rate is controlled by a floating valve located at the tower sump. The cooling tower will have an automatic blowdown capability with a solenoid valve which is turned on-off by a preset conductivity meter. The laboratory tower will simulate a typical cooling tower operation using the tap water supplied by the City of Philadelphia as makeup water.

Task 2 – Validation Experiments to Increase COC

Subtask 2.1 Tests with COC of 4

The objective of this subtask is to investigate whether the proposed spark discharge system can increase the COC, starting at a COC of approximately 4.

Subtask 2.2 – Tests with COC of 6

Subtask 2.3 Tests with COC of 8

Subtask 2.4 Tests with zero blowdown

Subtask 2.5 Tests with bulk heating for COC of 4

Task 2 – Validation Experiments to Increase COC

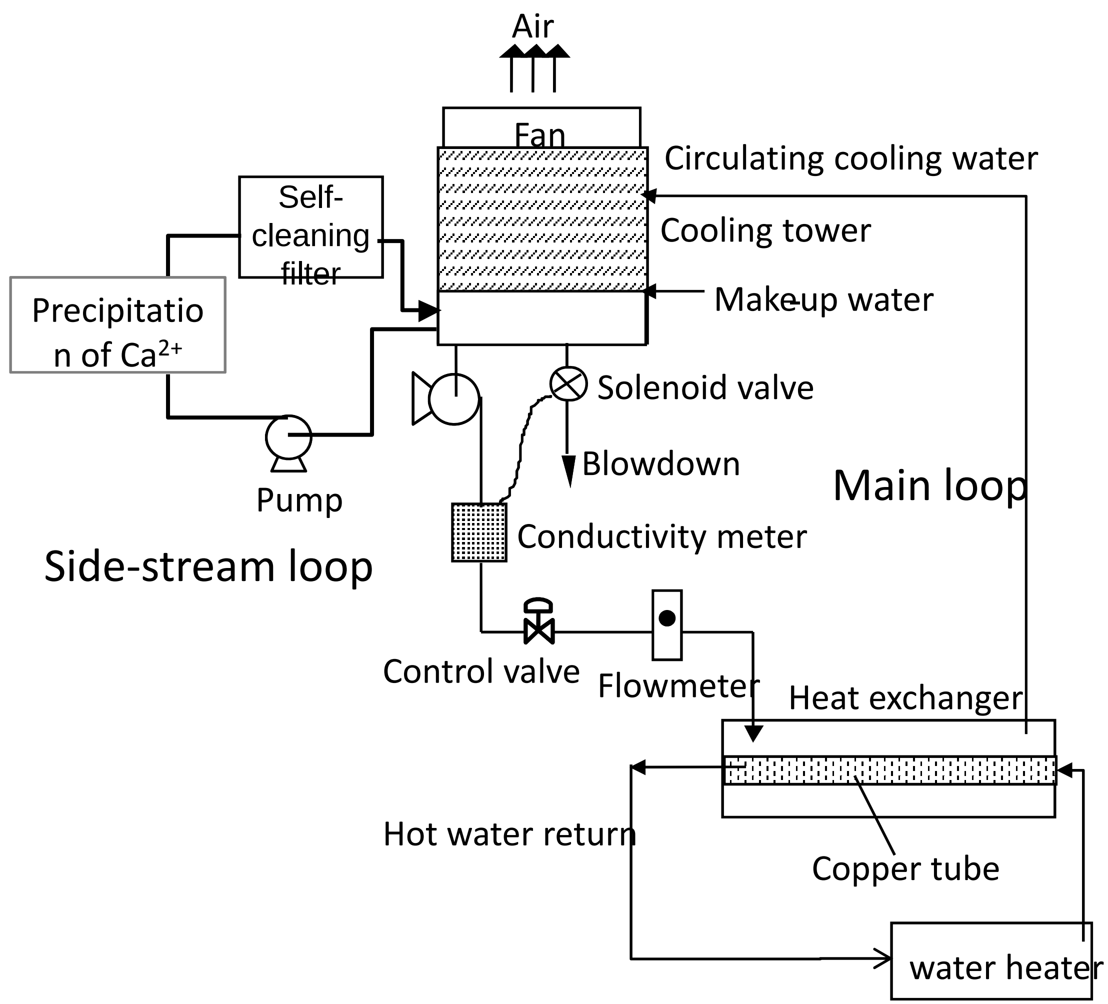


Figure 2 - Schematic diagram of a laboratory cooling tower test facility for the proposed study

Task 2 – Validation Experiments to Increase COC (Sample Water Data)

	Makeup	Baseline (Day 11)	PWT-S (Day 12)
Total alkalinity (ppm)	120	260	240
Chloride (ppm)	125	1,240	1,320
Total hardness (ppm)	190	1,720	1,680
Calcium (ppm)	170	1,360	1,240
Magnesium (ppm)	20	360	440
pH	6.8	6.9	7.2
Conductivity (micromho/cm)	445	4,600	4,550

Table 1 – Previous water analysis conducted at Drexel University

SUCCESS CRITERIA AND DECISION POINTS

Criteria for success for Task 2

The success of Task 2 study will be judged if the proposed spark discharge technology at least doubles the COC of the present practice. In other words, if the spark discharge technology can provide a steady operation of cooling tower operation at a COC of 8 over at least one week at the laboratory cooling tower system, we should consider Task 2 successful.

TASKS TO BE PERFORMED

Task 3 – Validation experiments for scale prevention (Year 3)

The objective of Task 3 is to investigate whether the proposed spark discharge technology can prevent or minimize scale deposits on the condenser tubes. A series of heat transfer fouling tests will be conducted using a condenser heat exchanger in the laboratory cooling tower. The fouling resistance will be experimentally determined by measuring the inlet and outlet temperatures at both cooling-water side and hot-fluid side. The fouling resistance obtained with the proposed scale-prevention technology will be compared with the no-treatment case as well as the scale-free case.

Task 3 – Validation experiments for scale prevention (Year 3)

Subtask 3.1 Tests with COC of 4

This task will deliver fouling test data, in terms of fouling resistance over time, for the baseline (no treatment) case, and for the proposed spark discharge technology conducted under the identical conditions as the baseline test.

Subtask 3.2 – Tests with COC of 6

Subtask 3.3 Tests with COC of 8

Subtask 3.4 Tests with zero blowdown

Task 3 – Validation experiments for scale prevention (Year 3)

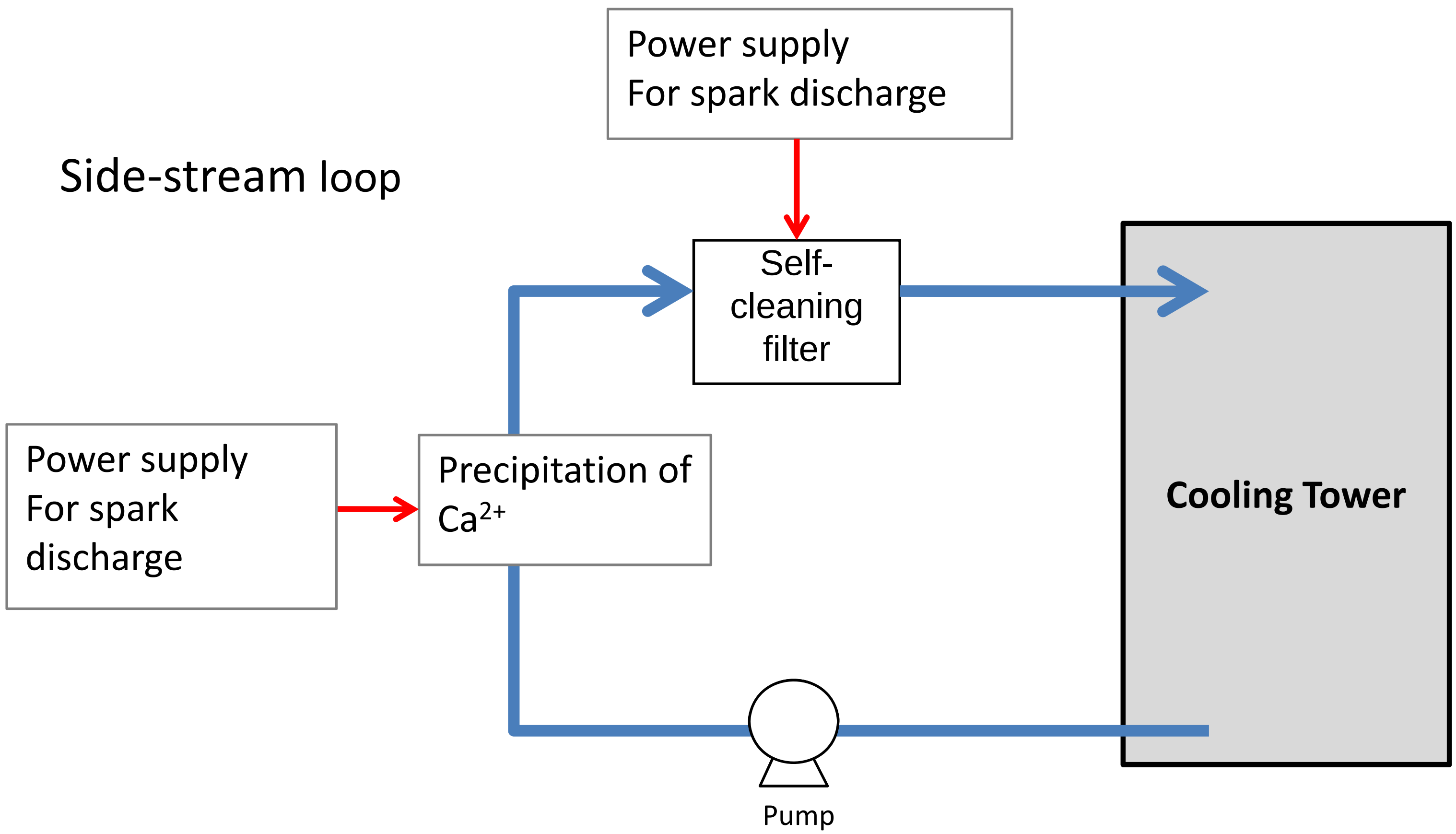


Figure 4 - Schematic diagram of the side-stream loop in a laboratory cooling tower test facility for the proposed study

Task 3 – Validation experiments for scale prevention (Year 3)

COC (Hardness)

- COC = 4
- COC = 6
- COC = 8
- No Blowdown

Spark discharge for Precipitation of Ca^{2+} Variables

- Frequency and strength of spark discharge
- Electrode geometry, material
- Flow velocity around electrode

Self-cleaning filter Variables

- Frequency and strength of spark discharges

Figure 5 - Block diagram of parameters that may affect the outcome of fouling tests

Task 3 – Validation experiments for scale prevention (Sample Fouling Data)

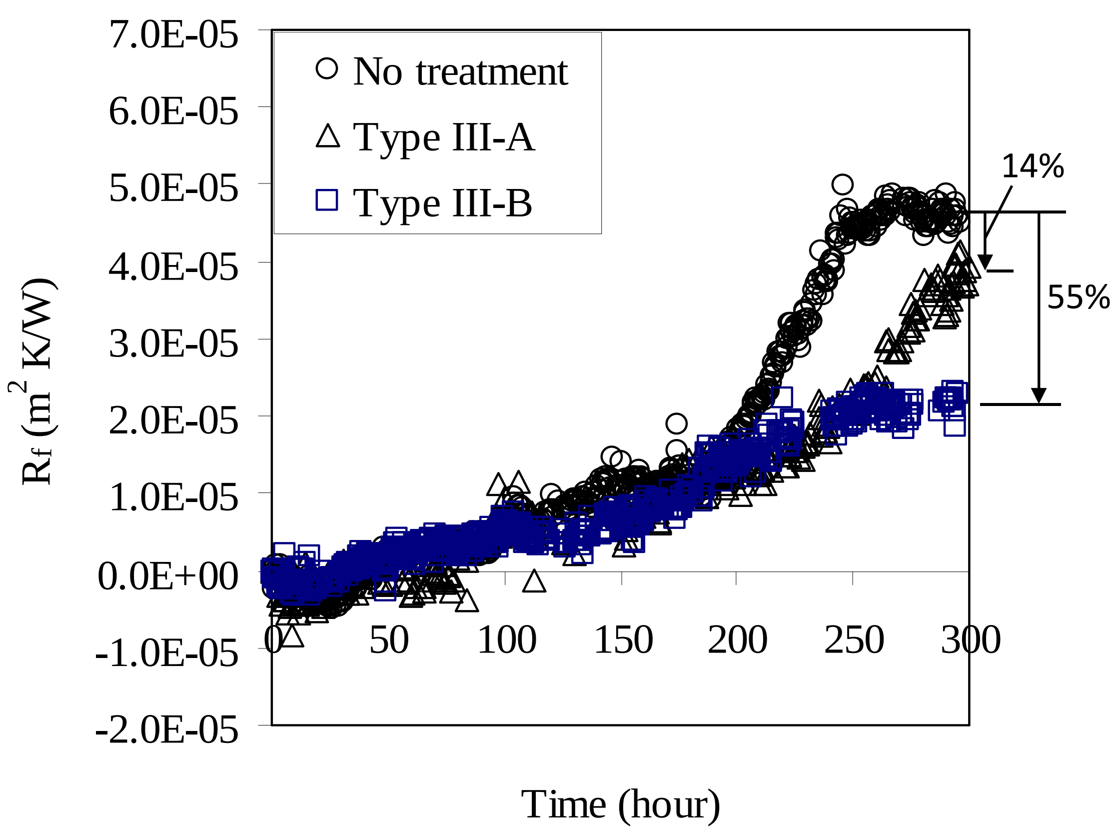
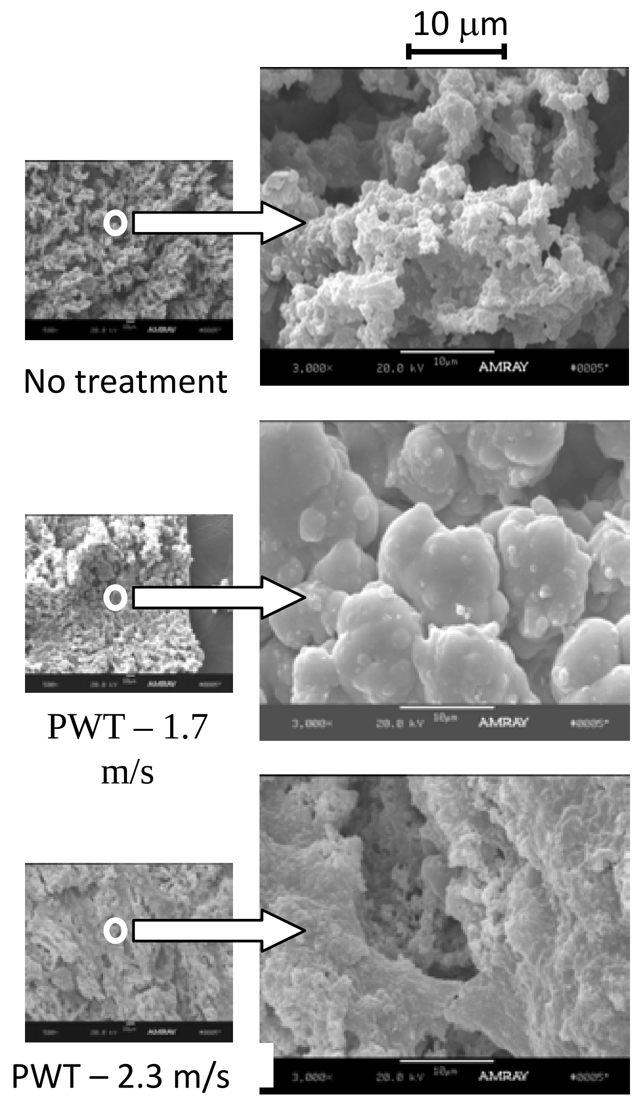
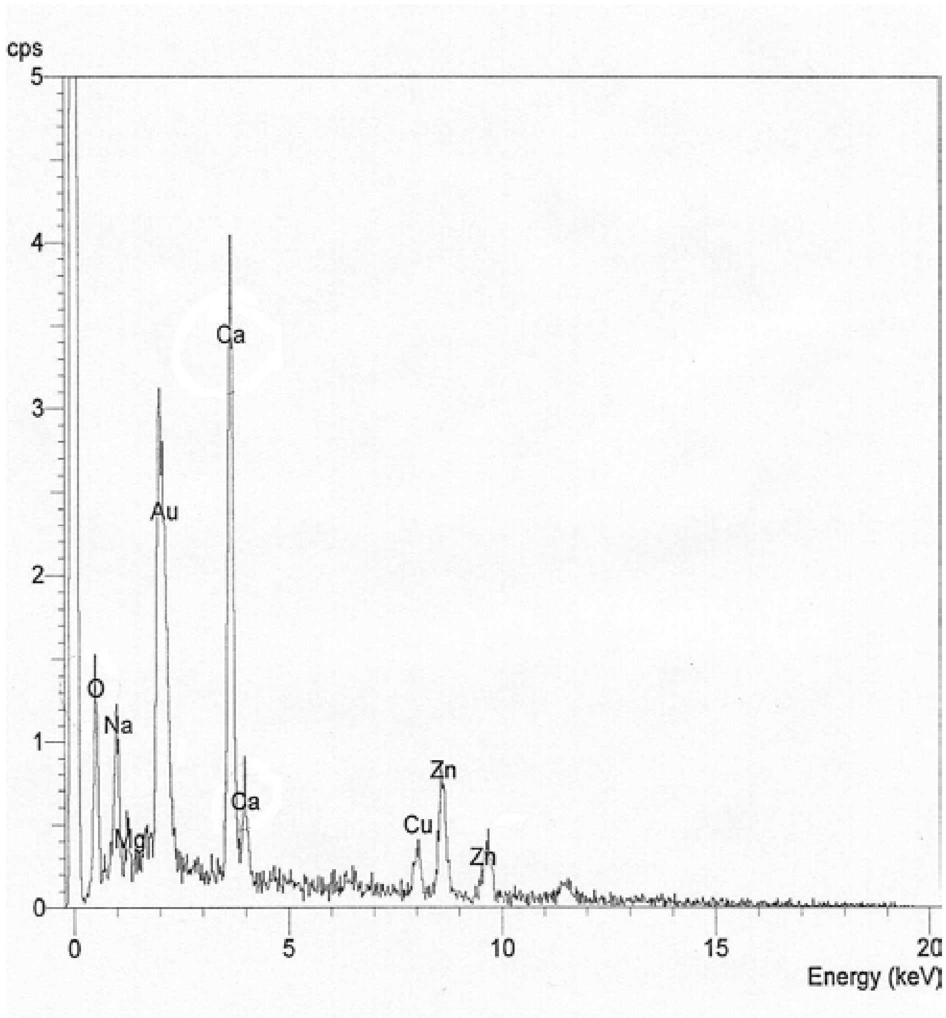


Figure 6 - Previous fouling test results obtained at Drexel University using two different types of permanent magnets [18]. R_f = fouling resistance; Zero fouling resistance means a perfectly maintained condenser tube.

Example of SEM photographs of CaCO3 Deposits on Condenser Tubes (Sample data from previous study)



Example of Energy Dispersive Spectrum (EDS) of CaCO3 Deposits on Condenser Tubes (X-ray diffraction)



SUCCESS CRITERIA AND DECISION POINTS

Criteria for success for fouling test

The success of the proposed fouling test will be judged if the proposed spark discharge technology can reduce the fouling resistance by at least 90% compared to those obtained from the baseline test for COC = 4. For higher COC cases (i.e., COC = 6 and 8, and no blowdown case), the improvement may be less than 90%, but still greater than 75%.

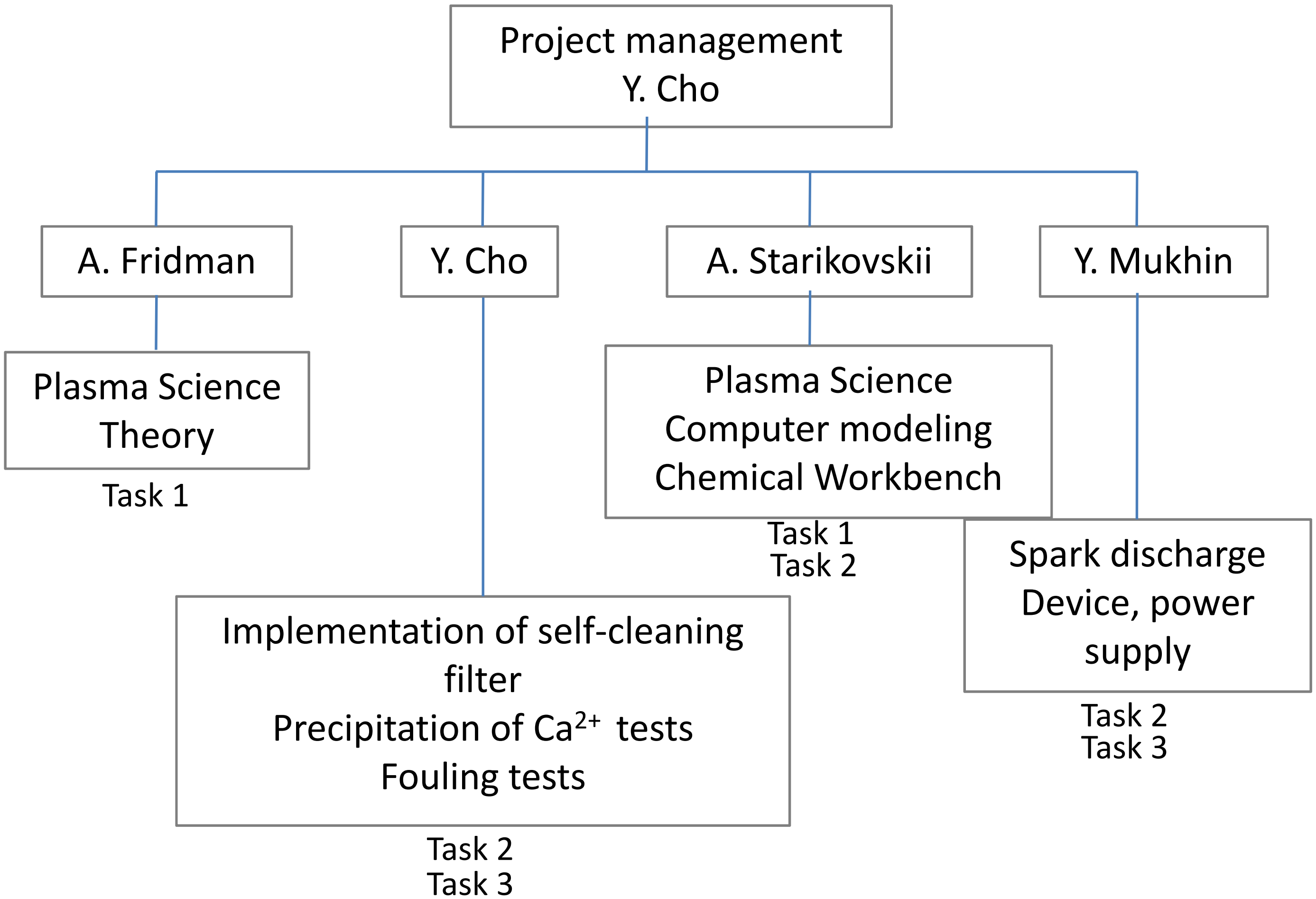
DELIVERABLES - Expected Results

If the excess calcium ions in cooling water can be successfully precipitated and removed, condenser-tube fouling can be prevented and the COC can be doubled at the same time. This accomplishes one of the major DOE goals of reducing/minimizing freshwater withdrawal in thermoelectric power plants.

The proposed study will begin with basic scientific research to better understand the mechanism of pulse spark discharges in water and conclude with a series of validation experiments to simulate scale build-up using hard water in a laboratory cooling tower equipped with the pulse spark discharge treatment system.

At the completion of the proposed work, a new prototype hardware using pulse spark discharges will be available for scale-up with validating test results. It will be a true mechanical water softener, which continuously converts hard water to soft water with a very little energy consumption.

Task 4 – Project Management, Planning, and Reporting



Risk Management

Under a previous DOE NETL project (DE-FC26-06NT42724), Drexel has successfully demonstrated that pulse spark discharges could be produced directly in water using 40,000 V at a frequency of 1-10 Hz with a pulse duration of 10-50 nanoseconds.

Scale-up from a small laboratory size to a large cooling tower application.
→ Two electrodes to produce spark discharges in water at Drexel lab.
→ In a large power plant, we need 1,000 or more electrodes.

Risk Management - Energy Requirement

The power of the spark discharge is approximately 2 J/pulse and about 10-20 pulses are needed for a volume of 0.5-L water for an effective removal of impurities from the filter membrane.

Hence, approximately 80 J/L of electric energy were consumed in laboratory tests.

The proposed spark discharge requires only 5 KW of electrical energy to treat water at a flow rate of 1,000 gpm.

The power needed to treat the cooling water in the 1000-MW power plant will be 200 KW, which is only 0.02% of the full capacity of 1000 MW.

Risk Management - Energy Requirement

Plasma Discharge in Water Comparison Chart

	Gliding Arc Discharge	**Pulsed Spark Discharge (Drexel)**	**Pulsed Corona Discharge (Max)**
Energy per Liter for 1 log reduction in E. Coli (J/L)	860	77	150000
Power requirement for household water consumption at 6 gpm (kW)	0.326	0.029	56.8
Power requirement for village water consumption at 1000 gpm (kW)	54.3	4.9	9463.5
Efficiency of power supply required	Excellent	Excellent	Poor
Maximum Water throughput based on Maximum power (gpm)	95	2058	0.03
Central lethal biological agent of discharge	UV and Chemical Radicals	UV	Chemical Radicals (OH, H_3O+, H_2O_2)

Risk Management

Risk: The pulse spark discharge system may fail to achieve the desired amount of calcium ion precipitation.

Mitigation/Management Approach: If this happens, the cause of the failure may be most likely due to the high electrical conductivity of circulating water in cooling tower system. In order to mitigate this risk, the cause of the failure will be investigated by reducing the electrical conductivity of water to see if the failure disappears. After this confirmation, the energy level of spark pulse will be increased so that a sufficient spark discharge can take place in water. This may require a significant improvement in the design of the power supply. It is believed that Drexel University has enough in-house expertise to handle the new design of the power supply.

Risk Management

Risk: The pulse spark discharge system may not achieve a significant increase in the COC when integrated with the laboratory-scale cooing tower.

Mitigation/Management Approach: Previously it was demonstrated at Drexel University with a relatively clean filter that the COC could be significantly increased with a combined use of physical water treatment and a filtration. However, in the present study, the failure of not being able to increase the COC to a level of 8 can occur. This may happen mostly likely due to the poor performance of a self-cleaning filtration system. If this failure occurs, an attempt will be made to improve the performance of the self-cleaning filter by adding additional electrodes to improve the self-cleaning performance.

Risk Management

Risk: The pulse spark discharge system may fail to achieve a significant reduction in fouling resistance when tested with the laboratory-scale cooling tower.

Mitigation/Management Approach:

If this happens, the causes of the failure can be multivariable,

1. the poor performance of the calcium precipitation process,
2. the poor performance of the self-cleaning filter,
3. the performance degradation of the spark-discharge system which utilizes a sharp tip electrode, and
4. too small flow velocity at the heat exchanger such that the deposition rate of calcium salt is much greater than the removal rate.

MILESTONE LOG

Milestone Title	Planned Completion Date	Milestone Verification Method
Task 1 – Precipitation of dissolved calcium ions using spark discharge (Year 1) (Oct. 1, 2008 – Sept. 31, 2009)	**Year 1**	
Subtask 1.1 Parametric study of Ca^{2+} precipitation process in water side		
Subtask 1.2 Parametric study of Ca^{2+} precipitation process in power supply side	Jun. 31, 09	
Subtask 1.3 Optimization of electrode configuration for most efficient spark discharges	Sept. 31, 09	
Task 2 – Continuous removal of precipitated calcium particles (Year 2) (Oct. 1, 2009 – Sept. 31, 2010)	**Year 2**	
Subtask 2.1 Tests with COC of 4		
Subtask 2.2 Tests with COC of 6		
Subtask 2.3 Tests with COC of 8	Jun. 31, 10	
Subtask 2.4 Tests with zero blowdown	Sept. 31, 10	
Subtask 2.5 Tests with bulk heating at COC of 4	Sept. 31, 10	
Task 3 – Validation experiments for scale prevention (Year 3) (Oct. 1, 2010 – Sept. 31, 2011)	**Year 3**	
Subtask 3.1 Tests with COC of 4		
Subtask 3.2 Tests with COC of 6		
Subtask 3.3 Tests with COC of 8	Jun. 31, 11	
Subtask 3.4 Tests with zero blowdown	Sept. 31, 11	

PROJECT TIMELINE

	Year 1				Year 2				Year 3			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Task 1 – Precipitation of dissolved calcium ions using spark discharge												
Subtask 1.1 Modeling of Ca^{2+} precipitation process	↔	↔										
Subtask 1.2 Parametric study of Ca^{2+} precipitation process in power supply side		↔										
Subtask 1.3 Optimization of electrode configuration for most efficient spark discharges			↔	↔								
Task 2 – Validation experiments to increase COC (Year 2)												
Subtask 2.1 Tests with COC of 4					↔							
Subtask 2.2 Tests with COC of 6						↔						
Subtask 2.3 Tests with COC of 8							↔					
Subtask 2.4 Tests with zero blowdown								↔				
Subtask 2.5 Tests with bulk heating for COC of 4								↔				
Task 3 – Validation experiments for scale prevention (Year 3)												
Subtask 3.1 Tests with COC of 4									↔			
Subtask 3.2 Tests with COC of 6										↔		
Subtask 3.3 Tests with COC of 8											↔	
Subtask 3.4 Tests with zero blowdown												↔
Task 4 – Project Management, Planning, and Reporting	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔