DISCLAIMER

This project was conducted with financial assistance from a grant from the Metropolitan Water District of Southern California (Metropolitan), the U.S. Bureau of Reclamation, the Environmental Protection Agency, the Central Arizona Project, the Southern Nevada Water Authority, the Southern California Gas Company, and the Western Resource Advocates through Metropolitan's Innovative Conservation Program (ICP). The ICP provides funding for research to help document water savings and reliability of innovative water savings devices, technologies, and strategies. The findings of this project, summarized in this report, are solely from the project proponent.

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California State University, Long Beach
Final Report
Metropolitan Water District – Innovative Conservation Program
Agreement number: ICP167252

Title: Effective Water Reuse in Cooling Tower Systems

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Summary

In this project, experimental investigation of cooling tower wastewater treatment by ion exchange process to enable its reuse in cooling towers was performed. The research team from California State University, Long Beach (CSULB) was collaborating with ABR Process Development to design a zero-liquid discharge (ZLD) cooling tower system. This treatment system employed ion exchange system to purify and recycle the cooling tower wastewater produced in the CSULB cooling tower plants. The raw water sample was collected directly from CSULB cooling tower blowdown and analyzed before and after treatment. The cost analysis on water savings from cooled water reuse was also performed. The project was initiated in January 2017 shortly after the contract between the Metropolitan Water District of Southern California and the California State University, Long Beach was signed.

Deliverables of the project

1. Supplemental literature review and sample analysis: The project team performed a focused literature review on potential cooling tower water reuse techniques including electrodialysis process which is the core principle of the water treatment technology that we proposed. Also, the samples were collected directly from blow-down (discharge) of the CSULB Central Heating and Cooling Plant and tested in IIRMES laboratory, CSULB for ionic composition analysis.

2. Test kit acquisition and set-up: The test cell unit was assembled and positioned in the Environmental Engineering Laboratory, CSULB.

3. Bench-scale operation: The project team performed an ion exchange electrodialysis process using bench-scale test cell.

4. Effluent analysis and evaluation: Treated effluent was analyzed for the total reduced level of dissolved solids, trace metals and anions at the IIRMES laboratory, CSULB and evaluated its reusability in the cooling system.

5. Saving analysis: The project team performed a comprehensive cost analysis on water savings from cooled water reuse.

1. Project background and objectives

Nowadays, water shortage has become a key issue in California. California communities, farms, businesses, and natural ecosystems depend upon adequate and reliable supplies of clean water. Water scarcity in California requires extensive wastewater reuse and intensive surface and groundwater reserve management. One of the promising ways to increase available water supply beyond hydrological cycle is to develop engineering strategies for sustainable and energy-efficient technologies. Therefore, it is critical that all water consuming systems strategically optimize their use of resource and thus increase available water supply. Methods to conserve and secure water include the development of on-site recycling/reclamation technologies, which will increase wastewater reuse and bring considerable savings in freshwater consumption.

One of the major water consumers in many industry, government and school buildings is a cooling tower. Given the ever-increasing urgency in water conservation of California, a more efficient cooling system technology is highly desirable. However, California's drought conditions and increasing water usage have combined to decrease the availability and increase the cost of the good quality, low hardness water preferred for cooling tower makeup use. At the same time, stricter environmental restrictions on effluent discharge have resulted in increased fees for disposal of cooling tower blowdown to the sewers. In addition, the concerns of scale, corrosion, deposition, and biological fouling have increased the difficulty and costs associated with cooling tower water system.

In this project, the advanced zero liquid discharge (ZLD) wastewater treatment technology was proposed for potential water savings in cooling tower system. The proposed study was conducted on the cooling tower (Carrier centrifugal chillers) at the Central Heating and Cooling Plant at CSULB. The tower has a fresh water source provided by the Long Beach Water Department and is recirculating the cooling tower make-up of 6.6 million gallons per year (MGPY). Current operation of CSULB cooling tower has blowdown of 1.5 MGPY, which implies that the evaporative loss of make-up at 5.1 MGPY. As water evaporates during the operation, the solids (salts) that are dissolved in the recirculation water accumulate over time, which becomes a main contributor to corrosion, scale, and biofilm formation in the tower facility.

Salt removal from the recirculation water by means of ion exchange electrodialysis (IX-ED) process is an effective method to resolve such problem. The research team from CSULB collaborated with ABR Process Development to design a lab-scale ZLD system for cooling tower plant. The proposed treatment system employed ion exchange system to purify and recycle virtually all the cooling tower wastewater produced (i.e., blowdown). Specifically, the engineered system strategy is an IX-ED based electrochemical cell & system for removal of the remaining alkali hydroxides. In addition to ED deionization, waste hydrogen and chlorine gas generated from the process is fully regenerated as usable acid in a separate acid recovery cell. The treatment of cooling tower blowdown waste from the existing plant using such technology is a direct mean of saving incoming fresh water as well as offering reliable strategy for increasing water reuse efficiency.

1.1. Literature review

The shortage of freshwater supply has become a serious problem due to increase in global population and environment problem. Currently, 1.6 billion people live in regions with absolute water scarcity, which is anticipated to be spread to two-third of the world's population by 2025 [1]. Cooling towers are one of the biggest water consumers in industrial, government, and school buildings. A typical cooling tower will flush over 3.9 million gallons of water down the drain each year [2].

Instead of receiving the fresh water after each cycle, the discharge water (blowdown) can be recycled through the process of desalination using electrodialysis. Undergoing this process will lead to the separation of the dissolved salts from salty feed water and produces reusable fresh water. The obtained water can be reused in the cooling system. The main objective of this study is to use blowdown water from the cooling towers of CSULB as a feed for electrodialysis treatment and recirculate the resultant water back to the cooling system.

Table 1. Ionic compositions of cooling towers in Dow Beneluex, the Netherland

Item	Tower 1	Tower 2
Cl^- (mg/L)	549	487
NO_3^- (mg/L)	88	93
SO_4^{2-} (mg/L)	1109	1056
Na^+ (mg/L)	332	408
Ca^{2+} (mg/L)	437	351
Mg^{2+} (mg/L)	61	49
K^+ (mg/L)	81	59
TOC (mg/L)	53	-
Conductivity (Ms/cm)	3.94	4.6
pH	7.5-8	6.5

There have been various studies reported for the treatment of the cooling tower blowdown water. Most widely applied and commercially proven desalination technologies fall into two categories: thermal (evaporative) methods and membrane-based methods. However, the membrane-based methods are often considered as less energy intensive and thus cost-effective compared to thermal methods [3]. In this literature review, we will only be focusing on the membrane-based processes. Membrane based processes include reverse osmosis (RO), membrane distillation (MD), electrodialysis (ED), and membrane capacitive deionization (MCDI). Koeman-Stein *et al*. used membrane distillation method for desalination of industrial cooling tower blowdown water [4]. In this study, the cooling tower blowdown water was obtained from two different cooling towers in Dow Beneluex, the Netherland. The Table 1 shows the ionic composition of blowdown of two cooling towers that the study benchmarked. The experiment was performed using direct contact MD setup with a membrane area of 429 cm^2. Two different type of membranes were used: polytetrafluorethylene (PTEE) and polyethylene (PE). The total salt retention was greater than 99% and individual ion concentration in permeate was less than detection limit. The cooling tower blowdown from tower 1 and tower 2 were concentrated by a factor of 5.25 and 5.3, respectively using PTFE membrane, which resulted the water recovery of 81%. PE membrane on the other hand achieved a water recovery of 90% for tower 1 with a concentration factor of 9.6. Therefore, the water recovery was ranged at 81-90% for cooling tower blowdown using MD method, which was achieved over a long period. For the cooling towers at Dow Benelux where the blowdown is approximately 1 Mm^3/year, the application of MD technique is estimated to save up to 800,000 m^3/year on make-up water.

In our project, the ED concept was employed for the treatment of cooled water. ED is often considered as much more flexible in terms of tunability (i.e., the ability to change input and output in the context of desalination) compared to RO [5]. Unlike RO being dependent on high pressure for treatment, ED operates under low pressure with lower lifecycle cost (10% lower than RO). Although these processes have their own benefits, the performance can further be enhanced by combining such individual processes as integrated system to promote synergistic impact. Abdel-Aal *et al*. used Red Sea as a feed solution to reduce the total dissolved salts level using the combined system of ED and RO [6]. The total dissolved salts of the Red Sea usually reach at 45,000 ppm with a salinity of 40%. The raw seawater was first treated by ED process alone at applied voltage of 12-18 V. As seen in Table 2, the chemical analysis results for ED-produced effluent exhibited that 95 % reduction of total dissolved salts was achieved, which decreased the level down to 2177 ppm with salinity of 3.8 %. The ED-treated seawater then entered the RO system to complete the ED/RO integrated system. After carrying out the combined experiment, the results revealed that the total dissolved salts and salinity further decreased and achieved nearly 100% removal and recovery efficiency with significant reduction in major ionic concentrations. In addition, the result also implies that ED alone is the most significant in removing unwanted salts as an individual process.

Table 2. Chemical analysis of the Red Sea desalination using ED and ED/RO combined system.

Item	Red Seawater	ED produced	ED/RO produced	Overall recovery ratio (%)
Total Dissolved Salts (ppm)	42,070	2177	243	99.4
Cl^- (ppm)	23,607	1367	108	99.5
SO_4^- (ppm)	1260	10	2.3	99.8
Salinity (%)	40.6	3.8	0	100
Conductivity (Ms/cm)	60.3	6.89	0.465	-

Our preliminary model calculation also estimated that wastewater savings can reach up to 99.7% and total dissolved solids could be reduced up to 67.6% with the ED system we proposed to design. Regarding wastewater reclamation and savings, using the ABR ED cell is also expected to be more efficient than other membrane methods such as membrane capacitive deionization (MCDI). The ED and MCDI cell, while similar, has several key differences. The MCDI technology consists of two porous carbon electrodes separated from each other by a spacer. On top of each electrode, corresponding ion exchange membranes are placed, and the electrodes are connected to current collectors. These current collectors serve as electrical conductors to facilitate the charge transport into and out of the electrodes. Similar to ED process, the ion exchange membrane plays an important role in MCDI process to achieve better salt removal from the feed water, but the main driver for this technique is the charged electrodes where the electro-adsorption of ionic species occur [7]. Limpt and Wal performed a study of MCDI on two cooling tower sites to remove the salts from the cooling tower recirculation water [8]. The aim of this study was to achieve larger fraction of the recirculation water, which expects to reduce the amount of discharge from the cooling system. Two cooling tower sites were evaluated for different period considering the quality of influent water (i.e., site 1 for 10 months and site 2 for 4 months) and achieved chemical savings of up to 85%, wastewater savings up to 48% and water savings up to 28% (Table 3).

Table 3. Total savings and energy use for the two cooling tower sites using MCDI

	Site 1	**Site 2**
Chemical savings	78 %	85 %
Water savings	28 %	12 %
Waste water savings	48 %	32 %
Energy use		
kWh m^{-3} purified water	0.234	0.105
kJ g^{-1} TDS reduction	2.6	2.2

There has also been a study reported to investigate the effect of key factors on ED separation of salt ions from artificial seawater. In this study, the effect of operating conditions (temperature, concentration, flow rate and voltage) on performance of an ED cell was studied [9]. Specifically, this study evaluated the effects of 4 different operating conditions at 3 varied levels: temperature (25, 40, 55°C), voltage (5, 7, 9 V), flow-rate (0.07, 0.13, 0.22 mL/s) and feed concentration (10,000, 20,000, 40,000 ppm). The ED cell used was packed with a pair of ion exchange membranes and pair of platinum electrodes. Each anion- and cation exchange membranes (Ionics incorporated) used in experiment had an effective membrane area of 60 × 65 mm^2 and possesses high ion exchange capacity of 2.4-2.8 meq/g dry membrane. It was found that all the controlled factors had significant effect on the performance of desalination to a certain extent. The highest percentage of desalination was achieved with the lowest feed concentration (10,000 mg/L) and flow rate (0.07 mL/s) levels at the highest voltage (9V) and temperature (55 °C) levels. The results showed that the feed concentration is the most influential factor on ED performance compared to other factors as its contribution percentage was calculated to be 82.4%.

As discussed in this literature review, the performance potential of ED-based technique has already been proved through many research studies and practical applications especially in seawater desalination. However, the application of ED technique in cooled water (blowdown) treatment is still rare. Our proposed study will focus on demonstrating the application of ABR ED cell at CSULB campus cooling tower site to investigate a potential ZLD and recycle system.

1.2. CSULB cooling tower blowdown analysis

The IIRMES laboratory has tested the sample of raw blowdown wasted at the Central Heating and Cooling Plant at CSULB. The blowdown water was tested for concentrations of ionic constituents to ensure that the right measures could be taken when ED treatment begins with ABR bench test kit. The sample was tested for numerous ions, but the highest concentrations of those respective ions are listed on Table 4.

The Table 4 illustrates that Na^+, Ca^{2+}, and Cl^- are among the most abundant of ions. As expected amongst cations, Na^+ ions have highest concentration of 262.8 mg/L and amongst anions, SO_4^{2-} and Cl^- are in high concentrations of 469.2 mg/L and 205.3 mg/L, respectively. The concentration of total dissolved solids (TDS) is 1330 mg/L. The high concentrations of Ca^{2+} are to be expected due the fact that wastewater typically has more concentrated Ca^{2+} content. This will need to be a focus when treatment begins to prevent scaling in the system. The TDS will also need to be addressed to avoid corrosion. Many other ionic constituents were also detected from the sample of cooling tower blowdown, but the amount of those ions was insignificant. Those ions measured in microscale include strontium, iron, titanium, and barium with concentrations of 1085.3, 634.3, 248.5, and 114.2 μg/L, respectively. Moreover, the concentrations of those ions are expected to further decrease after treatment under ED process, and may be considered as negligible or not detectable.

Table 4. Analysis results of CSULB cooling tower blowdown

Ionic constituents	**Concentration (mg/L)**
Calcium, Ca^{2+}	125.9
Magnesium, Mg^{2+}	12.5
Potassium, K^{+}	8.1
Sodium, Na^{+}	262.8
Sulfate, SO_4^{2-}	469.2
Chloride, Cl^{-}	205.3
Bromide, Br^{-}	43.1
Total Dissolved Solids	1330

2. Experimental methods

A bench-scale electrochemical cell was assembled to treat the blowdown waste from the cooling towers of CSULB and regenerate the acid used during the operation. As seen in Figure 2, the ED cell in the electrochemical setup is composed of 2 chambers, which consists of cation exchange membrane (CEM), anion exchange membrane (AEM), and spacers. The setup includes 3 tanks (8 L each) for catholyte, anolyte, and brine. The anolyte tank is filled with 3.8 liters (1 gallon) of 20 g/L HCl. The brine tank is filled with 5.67 liters of the cooling tower blowdown water. The catholyte tank is filled with 5.67 liters (1.5 gallons) of 40 g/L NaOH and is only used for the 2-chambered cell. These tanks are all connected to the magnetic pumps (MD-10L-220 Iwaki Co. Ltd). Each tank has its own flowmeter (F-400 Blue-White Industries Ltd) to measure and control the flow of the respective fluids. The flow rate of all tanks is fixed at 1000 mL/min. The rectifier (HSC-3402 Manson) is used to apply current to the ED cell. The red and black wire from the rectifier were connected to the anode and cathode respectively. The sample was also treated using 1-chambered cell (with only AEM in stack) to do a comparison with a 2-chambered cell.

For the 1-chambered cell, 3 samples were tested, and the applied current was kept constant at 3.0 A throughout the experiment. For the 2-chambered cell, 4 samples were tested. The first three samples underwent a constant current of 3.0 A, and the last sample was treated with a current of 3.5 A. A drastic increase of the voltage level is one of the indicators of salt separation from the brine. The desalted effluents were sampled every 30 minutes from the sampling tubes. The scope of this study includes TDS reduction at least up to the level of tap (fresh) water that is normally supplied in CSULB cooling tower plants, so it can be recirculated and reused in the cooling systems at CSULB. The TDS of the treated effluent was measured first at the site using a TDS meter (TDS Testr-11+) to check the progress. The pH was also checked using HACH sension 378. Note that the tap water in Long Beach area maintains the TDS level at 230 ppm (Long Beach Water Department).

The glass U-tube used in the setup is crucial for the formation of HCl gas. Generally, hydrogen gas combines with chlorine gas to form HCl gas at around 500 F. The glass U-tube is filled with activated carbons to catalyze the process; thus, the reaction takes place immediately in the U-tube at a lower temperature of 350 F. The heating tape (AWH-051-020D HTS-Amptek) is wrapped around the tube and helps to control the temperature at 350 F using a thermostat (PCT-10002 Tempco). Two traps in the bench-scale setup (Figure 2) are used to collect the portion of regenerated HCl. Trap 1 is filled with deionized water initially. Electro-absorption then takes place in the trap leading to conversion of gas to liquid form of HCl. Trap 2 is filled with 40 g/L NaOH to neutralize excess HCl gas. The whole setup is kept under vacuum condition. Venturimeter is used to maintain the flow of gas throughout the setup.

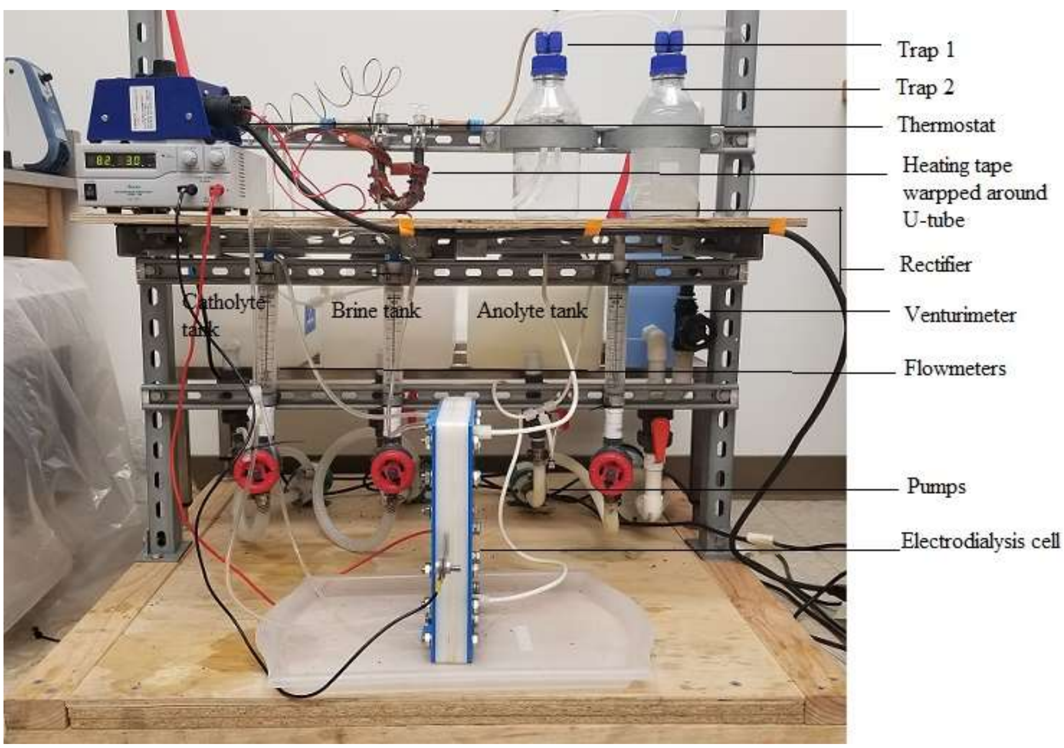

Figure 2. Bench scale test kit setup

3. Results and discussion

Each sample was treated for 270 minutes to maintain uniformity. The treated samples were analyzed in the IIRMES lab using SM 2540 C for TDS measurement and EPA 300.0 for concentrations and compositions of ionic constituents. The results obtained from the lab are displayed in figures below: the results of treated blowdown using 1-chambered cell and 2-chambered cell in Figure 3 and Figure 4, respectively. Note that the initial TDS for 3 samples used in 1-chambered cell experiment was 1330 mg/L and 4 samples used in 2-chambered cell experiment was 1280 mg/L. As seen in Figure 4, the blowdown samples treated using 2-chambered cell achieved significantly lower levels of TDS, which indicates that the additional cation exchange membrane in 2-chambered cell enhances the isolation of ionic constituents more effectively, resulting lower compositions of dissolved ions present in effluent water. As seen in Figure 3, the use of 1-chambered cell achieved an average reduction of 16.5-47.9% (lowest at 692 mg/L), but the samples treated with the 2-chambered cell reduced the TDS further down, below 230 mg/L, which is the standard level that the Long Beach Water Department complies for potable water. The TDS concentrations in samples 1, 2, 3, and 4 were reduced 91.3%, 84.6%, 83.7%, and 93.4%, respectively (Figure 4). A probable reason that the reduction in sample #4 is greater than the others is because a stronger current (i.e., 3.5 A) exerted to the cell allowed the enhanced ion transport across the membrane, whereas other 3 samples were treated under less current (i.e., 3.0 A).

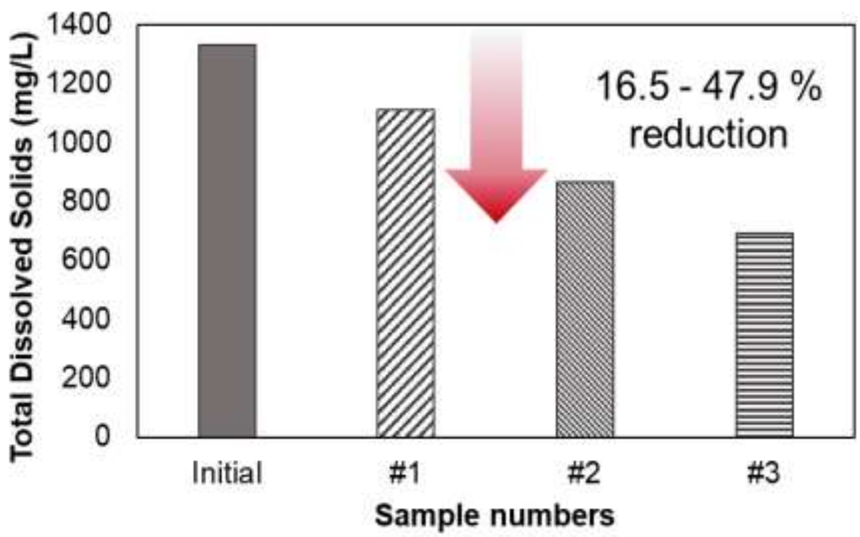

Figure 3. The total dissolved solids (TDS) concentrations using 1-chambered cell.

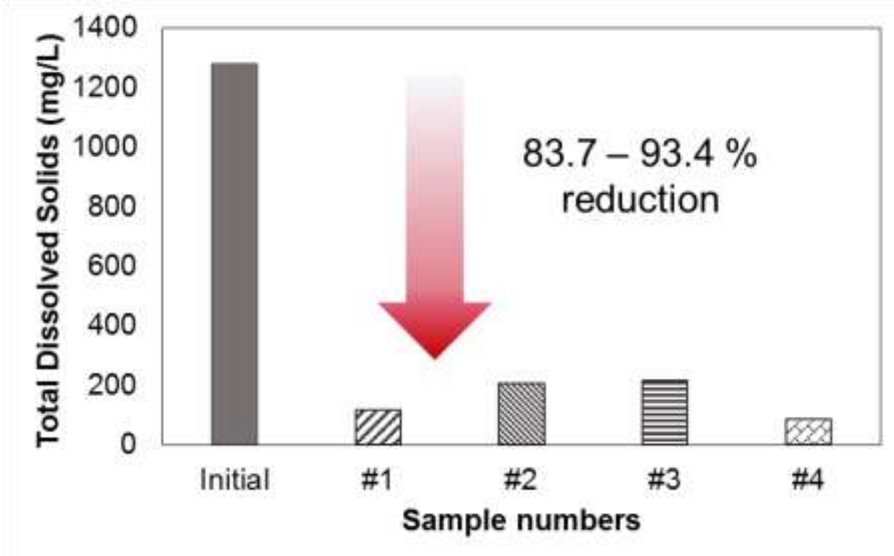

Figure 4. The total dissolved solids (TDS) concentrations using 2-chambered cell. Note that sample #4 was treated under a current of 3.5A and other 3 samples (#1-3) under 3.0A with the total operation time of 270 minutes each.

Table 5 shows the effluent concentrations of major ionic species in 4 samples treated using 2-chambered cell. The ions listed in Table 5 are the major ions, which contribute most to the TDS reduction in the experiment. Although the concentrations of many other ionic constituents that are not presented in the table were also significantly reduced, those ions were neglected owing to its minor effect on TDS result. An example of ions that were not fully removed from the operation includes dissolved orthophosphate as phosphorus, iron, nitrate, and tin. Despite these ions being detected at only small amount, they had the highest remaining concentrations. Using sample #4 as an example, the resultant TDS exhibited 93.4 % reduction with the final TDS of 88 ppm. Of that 88 ppm (equivalent to 88 mg/L), dissolved orthophosphate as phosphorus, iron, nitrate, and tin had concentrations of 497, 236.9, 150, and 42.9 μg/L respectively. Note that the pH was ranged around 6.2-6.4 for all samples treated using 2-chambered cell after 270 minutes of operation, but also observed the further decrease of pH when operating longer period. This implies that there exists an optimized time of cooling tower blowdown treatment in 2-chambered ED system. Below is the breakdown of reductions of individual ions compared to those in the original sample. The treatment was successful in reducing the concentrations of the major ionic constituents. As shown in Table 5, sulfate, sodium, chloride, and calcium were the major ions that contribute to its most salinity, but also experienced a significant reduction of concentrations after treatment. Specifically, sulfate was reduced over 96% for each sample. In addition, the average removal rate of chloride for all samples was found to be 91.9%. The average removal of calcium and sodium were 95.7% and 93.8% respectively. Also, we observed that the removal rate of monovalent ions was greater than those of multivalent ions in some of the samples.

Table 5. Effluent analysis of major ionic constituents after using 2-chambered cell

Ions	Initial (mg/L)	# 1		# 2		# 3		# 4	
		Final (mg/L)	Reduction (%)	Final (mg/L)	Reduction (%)	Final (mg/L)	Reduction (%)	Final (mg/L)	Reduction (%)
Ca^{2+}	125.9	0	100	10.4	91.74	11.4	90.95	0	100
Mg^{2+}	12.5	0	100	2.6	79.2	2.8	77.6	0	100
K^{+}	8.1	0	100	0	100	0	100	0	100
Na^{+}	262.8	0	100	31	88.2	37.5	85.73	0	100
Br^{-}	43.35	0.332	99.23	1.12	97.42	2.65	93.89	2.02	95.4
Cl^{-}	205.32	9.89	95.18	22.4	89.1	29.1	85.83	5.3	97.4
F^{-}	8.1	0	100	0.47	94.2	0.68	91.6	0.68	91.6
SO_4^{2-}	469.05	14.6	96.89	14.6	96.9	18.8	96.0	16.4	96.5

The secondary aspect of this project is to recover the HCl acids that is used as an anolyte for ED operation. The waste acid can be regenerated based on two processes: electro-hydrolysis and electro-absorption. Electro-hydrolysis is a process of separating the water molecules to hydrogen gas and oxygen gas upon application of DC voltage through electrodes. Ideally, the potential difference of 1.23 V is required to allow the process to release hydrogen and oxygen atoms. Following reactions takes place at cathode and anode, respectively,

$$\text{Cathode (reduction): } 2H_2O_{(l)} + 2e^- \rightarrow H_{2\,(g)} + 2OH^-_{(aq)}$$

$$\text{Anode (oxidation): } 4OH^-_{(aq)} \rightarrow O_{2(g)} + 2H_2O_{(l)} + 4e^-$$

$$\text{Overall reaction: } 2H_2O_{(l)} \rightarrow 2H_{2(g)} + O_{2(g)}$$

Similarly, chlorine gas will also be produced at the anode as the brine (blowdown) contains significant amount of sodium chloride salt. The chlorine and hydrogen gas then undergo electro-absorption process to form HCl gas, which will dissolve in the water to convert to the liquid form of HCl acid. In this study, the initial concentration of the HCl acid was measured to be 1.08 mol/L. The HCl anolyte used in all ED operations was expected to be regenerated with each new sample. A simple titration method was used to check the concentration of regenerated acids that we obtained throughout the operation. After performing titration, the concentration of the HCl was found out to be 1.42 mol/L. The results confirmed that the spent acid was successfully regenerated to a more concentrated level of new acids.

4. Saving analysis

Successful treatment and recycling of the cooling tower blowdown allows considerable amount of water savings, which in turn translates into cost savings. There are 3 major savings in this project: savings from wastewater recycling, sewer charges and spent acid recovery. We were successful in bringing the TDS levels down from 1330 mg/L to below 230 mg/L, which complies with the standard level of tap water supplied by Long Beach water department. Based on experimental demonstration, virtually all blowdown water can be recycled to the cooling tower system, thus the system eliminates the need for new freshwater supply from the water department. The Long Beach Water Department charges about $2.97 for 100 ft^3 of freshwater and $0.40 for 100 ft^3 of the sewer discharge to the city. As of now, no credits for the portion of evaporation losses is taken into consideration when estimating the water cost, so the total amount of metered water supply is fully counted as the total amount of discharge that drains into the sewer. The annual balance of CSULB cooling tower water is given as below,

- Cooling Tower make-up = 46,773,208.72 L/year
- Current annual cooling tower make up costs = $48,806.91
- Cooling tower blowdown = 10,362,564.76 L/year
- Current annual cooling tower blowdown costs = $48,806.91
- Cooling tower blowdown cost should be = $1450.86 (with evaporative credit)
- Evaporative losses = 36,410,643.96 L/year

Since the wastewater can be treated and recycled back to the cooling system, the water savings can be estimated at 10,362,564.76 L/year, which then translates to the annual cost savings of $10,813.13. As we assumed that there will be zero discharge from the cooling tower, the savings can further increase at $1450.88 per year.

The additional savings can be achieved from the regeneration of acid used during the ED operation. The successful recovery of waste acid with a concentration of 1.42 mol/L leads to further savings of $720. Therefore, the total estimated annual savings grow up to $12,984.01. All the parameters considered in the calculations are listed in Table 6.

Table 6. Parameters for the Payback and Life cycle cost analyses

Parameters	
Cost of the setup	$17,820
Equipment life	10 years
Rate of return	6% (assumed)
Maintenance cost per year	$600
Salary of operators per year	$8,100
Potential water savings per year	10,362,564.76 L/year
Amount of money saved by recycling per year	$12,263
Acid regeneration per year	$720

Ownership cost depends on various parameters such as purchased price, salvage value, equipment life, interest rates, taxes and licensing, insurance, storage cost, etc. In our case, since the equipment was purchased by CSULB through MWD-ICP project, only parameters that will affect the ownership cost are the (1) price of the bench-scale system, (2) equipment life, and (3) rate of return expected by the university (i.e., CSULB). The bench-scale ED system was purchased at $17,820. This cost includes the purchase of all components required for the operation. Rate of return is the gain or loss on an investment over a specified period, expressed as a percentage of the investment. In this calculation, it is assumed 6% over 10 years of the equipment life.

In this project, the operation cost is the amount of electricity used for the treatment. Based on the calculations, the entire setup consumes about 10.87 kWh for each operation cycle. The average electricity rate for 1kwh in Long Beach (commercial) is 11.81 cents. Therefore, the total cost of energy consumed for each cycle is estimated at $1.3. Assuming our bench-scale setup will be used to handle all the CSULB blowdown water for an entire year (10,362,564.76 L/year), the total cost of electricity will be $711,750. However, this parameter will not be considered in our calculations since the ED setup is only designed for a laboratory-scale operation, which is not capable of handling such large quantities of water. In addition, the operation time (which equivalents to electricity use) for the treatment is partly dependent upon effective area of the membranes used in the cell. Thus, adjusting the scale of the system (e.g., doubling the size of the ion exchange membranes) may reduce the operation time as well as electricity cost. Moreover, the maintenance cost comprises of membrane purchase costs only as there are no moving parts in the setup.

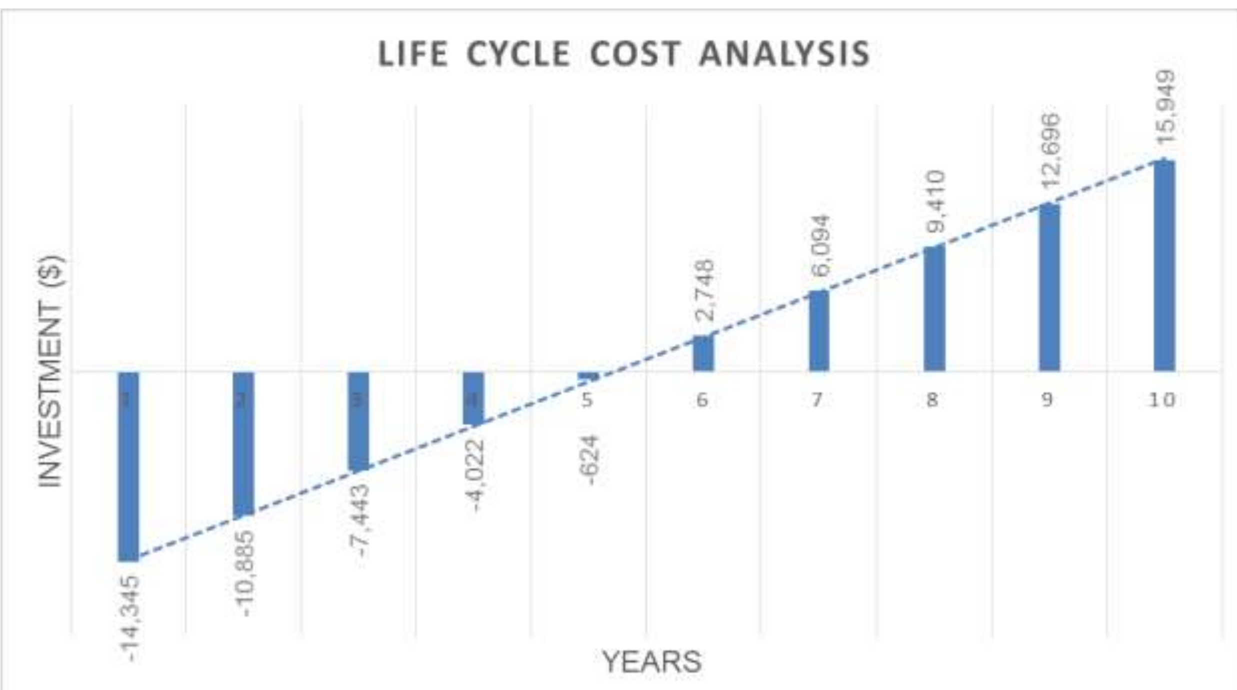

Figure 5. Life cycle cost analysis

Payback period analysis

Payback period refers to the period required to recoup the funds expended in an investment, or to reach the break-even point. The analysis only considers the initial investment cost and recurring savings in the calculation. It is not considering the cost of maintenance, financing, and any other interactions with other systems. Payback is given by following formula

Payback = Initial investment / (Total saving – Expenditure)

After inputting all the data in an analytical program, it was calculated that the return on investment will occur after 4.16 years or 50 months.

Life cycle cost analysis

Life cycle cost analysis (LCCA) is a data driven tool that provides a detailed account of the total costs of a project over its expected life. Use of LCCA has been much more prolific in the private sector as there is a need to defend the financial investment needs and decisions with an analytical tool. LCCA takes the initial costs, equipment life, savings, maintenance, and rate of return expected by investors into account for the calculations. It is assumed that there will be a 2% escalation in maintenance cost per year and 3% increase in savings annually. For this project, a 6% rate of return is assumed for the investors. Based on our calculations, it is found that the investors will start to gain a profit by 6^{th} year. By end of its equipment life (approximately 10 years), the investors would make a profit of $15949.48.

5. Conclusion

The research team of CSULB were successful in the treatment of cooling tower blowdown water to such levels that it can be reused in the cooling tower system. The team also compared the effectiveness of 1-chambered and 2-chambered cell in reducing the TDS under the same operational conditions. It was found that the 1-chambered cell was successful in reducing TDS level from 1330 mg/L to 889 mg/L (average) i.e. 33.2% reduction of TDS level. On the other hand, the 2-chambered cell was more effective in reducing the TDS level down to 156 mg/L (average) i.e. 88.3% reduction in TDS level. It is evident that the 2-chambered cell is more than twice as efficient as 1-chambered cell. It is possible to decrease the TDS level even more by extending the operation time, but it also leads to the reduction of pH, which may have corrosive effects in cooling system because of its acidic conditions. The secondary objective of this project was to regenerate acids that was used as an anolyte. The team was successful in recovering 1.42 mol/L of HCl acid via electro-hydrolysis and electro-absorption processes.

The combination of wastewater (cooling tower blowdown) recycling and spent acid recovery potentially results significant portion water and cost savings. The incoming fresh water for the cooling towers of CSULB is currently supplied by the Long Beach Water Department, which typically maintains the standard level of TDS at around 230 mg/L. As demonstrated in this project, the TDS level of the treated blowdown was low enough to be recycled back in the cooling system. If this recycle system is properly deployed at the plant site, it will potentially reduce or even eliminate the need of receiving fresh water for cooling operations. This benefit translates to the direct savings of $12,263 per year. Additional savings may occur from the regeneration of HCl acid, which leads to further savings of $720 annually. Therefore, the total annual saving estimates can be totaled at $12,983.

The team also performed the payback analysis based on the experimental setup to determine the time taken by the investor to recoup the investment. It was found that the total compensation could be made within 4.16 years. To defend the need for financial investment, the team also conducted the Life cycle cost analysis (LCCA). The LCCA analysis showed that the investors will foresee a profit from 6th year of initial operation. A profit will increase up to $15,499.48 by end of the projected life span of equipment setup (i.e., 10 years). Overall, our total estimated water savings could reach 10,362,564.76 L/year and expect to gain a significant fraction of financial profit at the end of the equipment life.

Appendix

Figure A1. Setup under construction

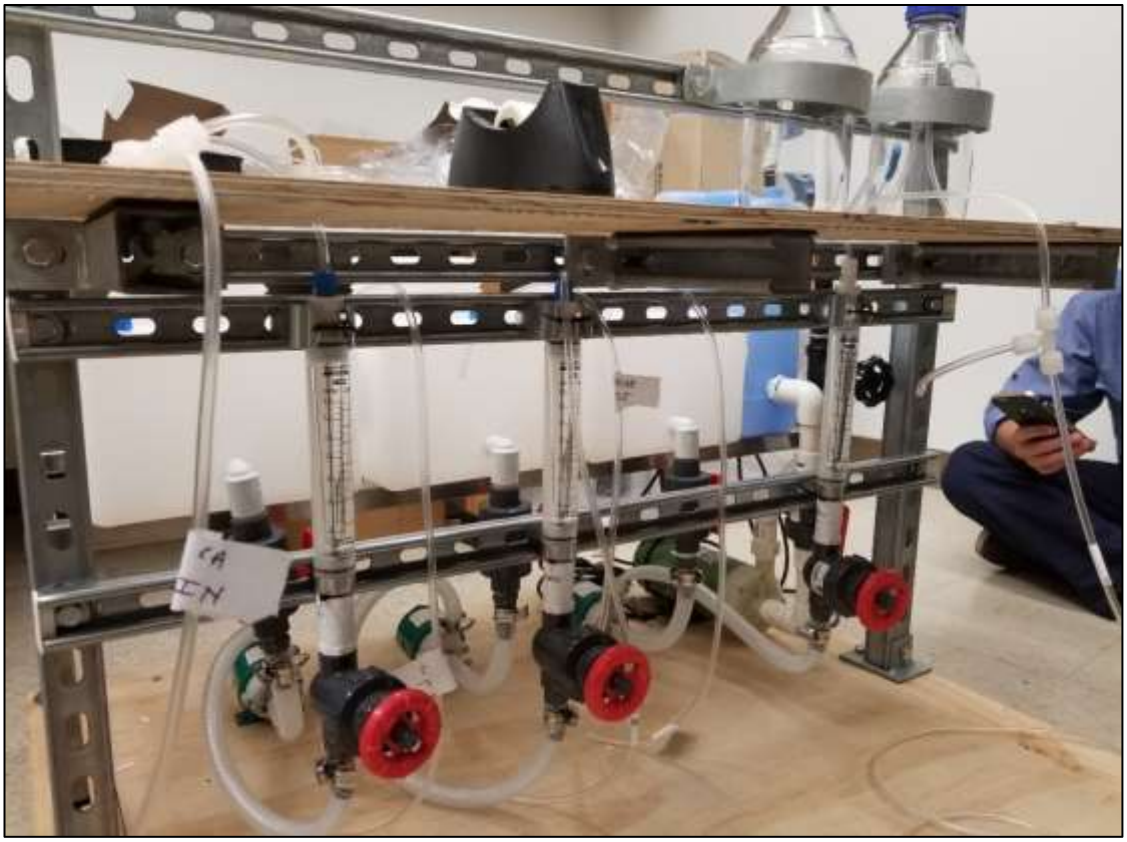

Figure A2. Setup under construction

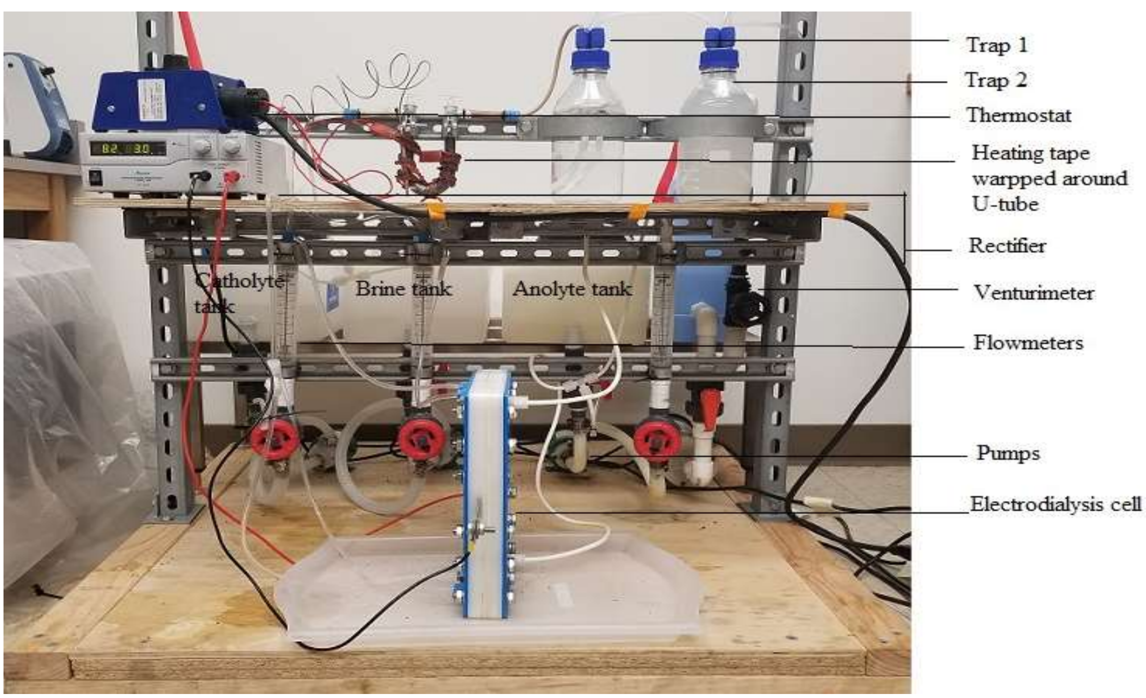

Figure A3. Complete bench-scale setup

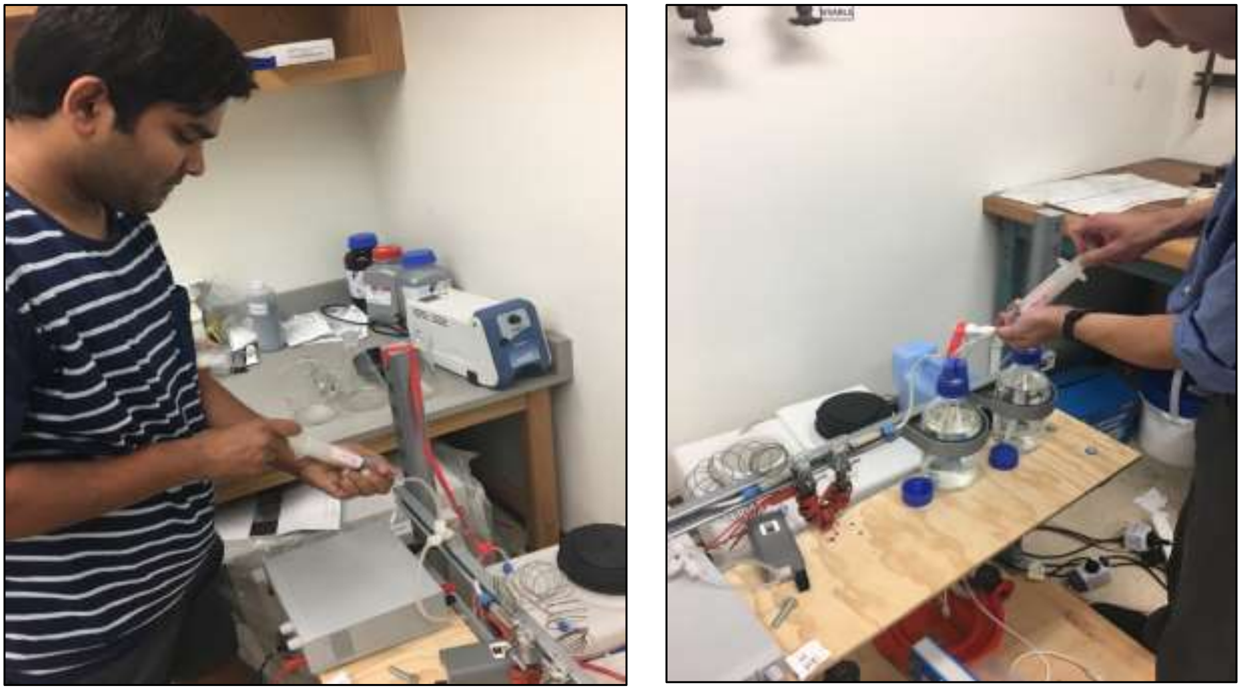

Figure A4. Collecting samples

Figure A5. Portable TDS measurement and pH testing

California State University, Long Beach, 1250 Bellflower Blvd., Long Beach, CA 90840 (562-985-2469)

Trace Metals

ANALYTICAL REPORT

Analyte	Fraction	Result	MDL	RL	Units	Batch	Prepared	Analyzed	Method	QA Code
15774-R1 Cooling TowerBlown Down					Freshwater	Sampled:			Received: 07-Mar-17	
Aluminum (Al)	Total	59.6	5	10	µg/L	TM-03-093	3/7/2017	3/15/2017	EPA 200.8m	
Antimony (Sb)	Total	0.5	0.1	0.5	µg/L	TM-03-093	3/7/2017	3/15/2017	EPA 200.8m	
Arsenic (As)	Total	2	0.2	0.5	µg/L	TM-03-093	3/7/2017	3/15/2017	EPA 200.8m	
Barium (Ba)	Total	114.2	0.2	0.5	µg/L	TM-03-093	3/7/2017	3/15/2017	EPA 200.8m	
Beryllium (Be)	Total	ND	0.2	0.5	µg/L	TM-03-093	3/7/2017	3/15/2017	EPA 200.8m	
Cadmium (Cd)	Total	0.2	0.2	0.4	µg/L	TM-03-093	3/7/2017	3/15/2017	EPA 200.8m	J
Calcium (Ca)	Total	125.9	0.05	0.1	mg/L	TM-03-093	3/7/2017	3/15/2017	EPA 200.8m	
Chromium (Cr)	Total	0.7	0.1	0.5	µg/L	TM-03-093	3/7/2017	3/15/2017	EPA 200.8m	
Cobalt (Co)	Total	0.2	0.1	0.5	µg/L	TM-03-093	3/7/2017	3/15/2017	EPA 200.8m	J
Copper (Cu)	Total	224	0.4	0.8	µg/L	TM-03-093	3/7/2017	3/15/2017	EPA 200.8m	
Iron (Fe)	Total	634.3	5	10	µg/L	TM-03-093	3/7/2017	3/15/2017	EPA 200.8m	
Lead (Pb)	Total	0.3	0.05	0.1	µg/L	TM-03-093	3/7/2017	3/15/2017	EPA 200.8m	
Magnesium (Mg)	Total	12.5	0.05	0.1	mg/L	TM-03-093	3/7/2017	3/15/2017	EPA 200.8m	
Manganese (Mn)	Total	9.7	0.2	0.5	µg/L	TM-03-093	3/7/2017	3/15/2017	EPA 200.8m	
Nickel (Ni)	Total	4	0.2	0.5	µg/L	TM-03-093	3/7/2017	3/15/2017	EPA 200.8m	
Potassium (K)	Total	8.1	1	3	mg/L	TM-03-093	3/7/2017	3/15/2017	EPA 200.8m	
Selenium (Se)	Total	0.6	0.2	0.5	µg/L	TM-03-093	3/7/2017	3/15/2017	EPA 200.8m	
Silver (Ag)	Total	ND	0.5	1	µg/L	TM-03-093	3/7/2017	3/15/2017	EPA 200.8m	
Sodium (Na)	Total	262.8	1	3	mg/L	TM-03-093	3/7/2017	3/15/2017	EPA 200.8m	
Strontium (Sr)	Total	1085.3	0.1	0.5	µg/L	TM-03-093	3/7/2017	3/15/2017	EPA 200.8m	
Thallium (Tl)	Total	ND	0.1	0.5	µg/L	TM-03-093	3/7/2017	3/15/2017	EPA 200.8m	
Tin (Sn)	Total	0.1	0.1	0.5	µg/L	TM-03-093	3/7/2017	3/15/2017	EPA 200.8m	J
Titanium (Ti)	Total	248.5	0.2	0.5	µg/L	TM-03-093	3/7/2017	3/15/2017	EPA 200.8m	
Vanadium (V)	Total	2.1	0.2	0.5	µg/L	TM-03-093	3/7/2017	3/15/2017	EPA 200.8m	
Zinc (Zn)	Total	85.6	0.1	0.5	µg/L	TM-03-093	3/7/2017	3/15/2017	EPA 200.8m	

142-17-01 Cooling Tower

Figure A6. Trace metal analysis for cooling tower blowdown

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Conventionals ANALYTICAL REPORT

ANALYTE	FRACTION	RESULT	MDL	RL	UNITS	QA CODE
Sample ID: 44205-R1	Cooling Tower	Matrix: Freshwater		Sampled: 07-Mar-17		Received: 23-Mar-17
	Method: SM 2540 C	Batch ID: C-29129		Prepared: 23-Mar-17		Analyzed: 23-Mar-17
Total Dissolved Solids	NA	1330	0.1	2	mg/L	H
	Method: EPA 300.0	Batch ID: C-31078		Prepared: 23-Mar-17		Analyzed: 23-Mar-17
Chloride	NA	205.2	0.01	0.05	mg/L	
Dissolved Orthophosphate as P	NA	1.533	0.0022	0.01	mg/L	H
Fluoride	NA	2.96	0.01	0.05	mg/L	
Nitrate as N	NA	8.07	0.01	0.05	mg/L	H
Sulfate	NA	469.2	0.01	0.05	mg/L	
	Method: SM 4500-NO2 B	Batch ID: C-31078		Prepared: 23-Mar-17		Analyzed: 23-Mar-17
Nitrite as N	NA	0.05	0.01	0.02	mg/L	H
	Method: EPA 300.0	Batch ID: C-31079		Prepared: 24-Mar-17		Analyzed: 24-Mar-17
Bromide	NA	43.41	0.001	0.005	mg/L	

Figure A7. Total dissolved solids and anion analysis for cooling tower blowdown

California State University, Long Beach, 1250 Bellflower Blvd., Long Beach, CA 90840 (562-985-2469)

Trace Metals

ANALYTICAL REPORT

Analyte	Fraction	Result	MDL	RL	Units	Batch	Prepared	Analyzed	Method	QA Code
16513-R1 Sample 1					**Freshwater**	**Sampled: 10/5/2017**			**Received: 11-Oct-17**	
Aluminum (Al)	Total	10.4	5	10	µg/L	TM-03-113	11/6/2017	11/6/2017	EPA 200.8m	
Antimony (Sb)	Total	0.4	0.1	0.5	µg/L	TM-03-113	11/6/2017	11/6/2017	EPA 200.8m	J
Arsenic (As)	Total	3.3	0.2	0.5	µg/L	TM-03-113	11/6/2017	11/6/2017	EPA 200.8m	
Barium (Ba)	Total	92	0.2	0.5	µg/L	TM-03-113	11/6/2017	11/6/2017	EPA 200.8m	
Beryllium (Be)	Total	ND	0.2	0.5	µg/L	TM-03-113	11/6/2017	11/6/2017	EPA 200.8m	
Cadmium (Cd)	Total	0.2	0.2	0.4	µg/L	TM-03-113	11/6/2017	11/6/2017	EPA 200.8m	J
Calcium (Ca)	Total	89.1	0.05	0.1	mg/L	TM-03-113	11/6/2017	11/6/2017	EPA 200.8m	
Chromium (Cr)	Total	0.8	0.1	0.5	µg/L	TM-03-113	11/6/2017	11/6/2017	EPA 200.8m	
Cobalt (Co)	Total	0.2	0.1	0.5	µg/L	TM-03-113	11/6/2017	11/6/2017	EPA 200.8m	J
Copper (Cu)	Total	85	0.4	0.8	µg/L	TM-03-113	11/6/2017	11/6/2017	EPA 200.8m	
Iron (Fe)	Total	430.2	5	10	µg/L	TM-03-113	11/6/2017	11/6/2017	EPA 200.8m	
Lead (Pb)	Total	1	0.05	0.1	µg/L	TM-03-113	11/6/2017	11/6/2017	EPA 200.8m	
Magnesium (Mg)	Total	19.4	0.05	0.1	mg/L	TM-03-113	11/6/2017	11/6/2017	EPA 200.8m	
Manganese (Mn)	Total	1.2	0.2	0.5	µg/L	TM-03-113	11/6/2017	11/6/2017	EPA 200.8m	
Molybdenum (Mo)	Total	23.4	0.2	0.5	µg/L	TM-03-113	11/6/2017	11/6/2017	EPA 200.8m	
Nickel (Ni)	Total	6.5	0.2	0.5	µg/L	TM-03-113	11/6/2017	11/6/2017	EPA 200.8m	
Potassium (K)	Total	8.9	1	3	mg/L	TM-03-113	11/6/2017	11/6/2017	EPA 200.8m	
Selenium (Se)	Total	1.1	0.2	0.5	µg/L	TM-03-113	11/6/2017	11/6/2017	EPA 200.8m	
Silver (Ag)	Total	ND	0.5	1	µg/L	TM-03-113	11/6/2017	11/6/2017	EPA 200.8m	
Sodium (Na)	Total	282	1	3	mg/L	TM-03-113	11/6/2017	11/6/2017	EPA 200.8m	
Strontium (Sr)	Total	834.5	0.1	0.5	µg/L	TM-03-113	11/6/2017	11/6/2017	EPA 200.8m	
Thallium (Tl)	Total	ND	0.1	0.5	µg/L	TM-03-113	11/6/2017	11/6/2017	EPA 200.8m	
Tin (Sn)	Total	0.3	0.1	0.5	µg/L	TM-03-113	11/6/2017	11/6/2017	EPA 200.8m	J
Titanium (Ti)	Total	2.1	0.2	0.5	µg/L	TM-03-113	11/6/2017	11/6/2017	EPA 200.8m	
Vanadium (V)	Total	4.6	0.2	0.5	µg/L	TM-03-113	11/6/2017	11/6/2017	EPA 200.8m	

107-17-02 Cooling Tower

Figure A8. Trace metal analysis for sample #1 from 1-chambered cell

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Conventionals — ANALYTICAL REPORT

ANALYTE	FRACTION	RESULT	MDL	RL	UNITS	QA CODE
Sample ID: 49091-R1	**Sample 1**	**Matrix: Freshwater**		**Sampled: 05-Oct-17**		**Received: 13-Oct-17**
	Method: SM 2540 C	Batch ID: C-33051		Prepared: 13-Oct-17		Analyzed: 27-Oct-17
Total Dissolved Solids	NA	1110	0.1	2	mg/L	H
	Method: EPA 300.0	Batch ID: C-34072		Prepared: 13-Oct-17		Analyzed: 13-Oct-17
Dissolved Orthophosphate as P	NA	0.634	0.002	0.005	mg/L	H
Fluoride	NA	3.03	0.01	0.05	mg/L	
Nitrate as N	NA	4.32	0.01	0.05	mg/L	H
Nitrite as N	NA	0.06	0.01	0.03	mg/L	H
	Method: EPA 300.0	Batch ID: C-34078		Prepared: 30-Oct-17		Analyzed: 30-Oct-17
Bromide	NA	9.07	0.001	0.005	mg/L	
Chloride	NA	238	0.01	0.05	mg/L	
Sulfate	NA	120	0.01	0.05	mg/L	

Figure A9. Total dissolved solids and anion analysis for sample #1 from 1-chambered cell

California State University, Long Beach, 1250 Bellflower Blvd., Long Beach, CA 90840 (562-985-2469)

Trace Metals

ANALYTICAL REPORT

Analyte	Fraction	Result	MDL	RL	Units	Batch	Prepared	Analyzed	Method	QA Code
Zinc (Zn)	Total	67.19	0.1	0.5	µg/L	TM-03-113	11/6/2017	11/6/2017	EPA 200.8m	
16514-R1	**Sample 2**				**Freshwater**	**Sampled: 10/5/2017**			**Received: 11-Oct-17**	
Aluminum (Al)	Total	7.6	5	10	µg/L	TM-03-113	11/6/2017	11/6/2017	EPA 200.8m	J
Antimony (Sb)	Total	0.3	0.1	0.5	µg/L	TM-03-113	11/6/2017	11/6/2017	EPA 200.8m	J
Arsenic (As)	Total	2.4	0.2	0.5	µg/L	TM-03-113	11/6/2017	11/6/2017	EPA 200.8m	
Barium (Ba)	Total	29.4	0.2	0.5	µg/L	TM-03-113	11/6/2017	11/6/2017	EPA 200.8m	
Beryllium (Be)	Total	ND	0.2	0.5	µg/L	TM-03-113	11/6/2017	11/6/2017	EPA 200.8m	
Cadmium (Cd)	Total	ND	0.2	0.4	µg/L	TM-03-113	11/6/2017	11/6/2017	EPA 200.8m	
Calcium (Ca)	Total	24.2	0.05	0.1	mg/L	TM-03-113	11/6/2017	11/6/2017	EPA 200.8m	
Chromium (Cr)	Total	1.4	0.1	0.5	µg/L	TM-03-113	11/6/2017	11/6/2017	EPA 200.8m	
Cobalt (Co)	Total	0.1	0.1	0.5	µg/L	TM-03-113	11/6/2017	11/6/2017	EPA 200.8m	J
Copper (Cu)	Total	30	0.4	0.8	µg/L	TM-03-113	11/6/2017	11/6/2017	EPA 200.8m	
Iron (Fe)	Total	135.5	5	10	µg/L	TM-03-113	11/6/2017	11/6/2017	EPA 200.8m	
Lead (Pb)	Total	3.6	0.05	0.1	µg/L	TM-03-113	11/6/2017	11/6/2017	EPA 200.8m	
Magnesium (Mg)	Total	11.3	0.05	0.1	mg/L	TM-03-113	11/6/2017	11/6/2017	EPA 200.8m	
Manganese (Mn)	Total	0.4	0.2	0.5	µg/L	TM-03-113	11/6/2017	11/6/2017	EPA 200.8m	J
Molybdenum (Mo)	Total	7.5	0.2	0.5	µg/L	TM-03-113	11/6/2017	11/6/2017	EPA 200.8m	
Nickel (Ni)	Total	3.7	0.2	0.5	µg/L	TM-03-113	11/6/2017	11/6/2017	EPA 200.8m	
Potassium (K)	Total	7.7	1	3	mg/L	TM-03-113	11/6/2017	11/6/2017	EPA 200.8m	
Selenium (Se)	Total	0.5	0.2	0.5	µg/L	TM-03-113	11/6/2017	11/6/2017	EPA 200.8m	
Silver (Ag)	Total	ND	0.5	1	µg/L	TM-03-113	11/6/2017	11/6/2017	EPA 200.8m	
Sodium (Na)	Total	255.5	1	3	mg/L	TM-03-113	11/6/2017	11/6/2017	EPA 200.8m	
Strontium (Sr)	Total	346.7	0.1	0.5	µg/L	TM-03-113	11/6/2017	11/6/2017	EPA 200.8m	
Thallium (Tl)	Total	ND	0.1	0.5	µg/L	TM-03-113	11/6/2017	11/6/2017	EPA 200.8m	
Tin (Sn)	Total	122.9	0.1	0.5	µg/L	TM-03-113	11/6/2017	11/6/2017	EPA 200.8m	
Titanium (Ti)	Total	1.5	0.2	0.5	µg/L	TM-03-113	11/6/2017	11/6/2017	EPA 200.8m	

107-17-02 Cooling Tower

Figure A10. Trace metal analysis for sample #2 from 1-chambered cell

Sample ID: 49092-R1	**Sample 2**	**Matrix: Freshwater**		**Sampled: 05-Oct-17**		**Received: 13-Oct-17**
	Method: SM 2540 C	Batch ID: C-33051		Prepared: 13-Oct-17		Analyzed: 27-Oct-17
Total Dissolved Solids	NA	866	0.1	2	mg/L	H
	Method: EPA 300.0	Batch ID: C-34072		Prepared: 13-Oct-17		Analyzed: 13-Oct-17
Dissolved Orthophosphate as P	NA	0.763	0.002	0.005	mg/L	H
Fluoride	NA	1.56	0.01	0.05	mg/L	
Nitrate as N	NA	0.06	0.01	0.05	mg/L	H
Nitrite as N	NA	ND	0.01	0.03	mg/L	H
	Method: EPA 300.0	Batch ID: C-34078		Prepared: 30-Oct-17		Analyzed: 30-Oct-17
Bromide	NA	1.56	0.001	0.005	mg/L	
Chloride	NA	144	0.01	0.05	mg/L	
Sulfate	NA	22.7	0.01	0.05	mg/L	

Figure A11. Total dissolved solids and anion analysis for sample #2 from 1-chambered cell

16515-R1	Sample 3				Freshwater	Sampled: 10/5/2017			Received: 11-Oct-17	
Aluminum (Al)	Total	53.8	5	10	µg/L	TM-03-113	11/6/2017	11/6/2017	EPA 200.8m	
Antimony (Sb)	Total	0.2	0.1	0.5	µg/L	TM-03-113	11/6/2017	11/6/2017	EPA 200.8m	J
Arsenic (As)	Total	1.8	0.2	0.5	µg/L	TM-03-113	11/6/2017	11/6/2017	EPA 200.8m	
Barium (Ba)	Total	50.4	0.2	0.5	µg/L	TM-03-113	11/6/2017	11/6/2017	EPA 200.8m	
Beryllium (Be)	Total	ND	0.2	0.5	µg/L	TM-03-113	11/6/2017	11/6/2017	EPA 200.8m	
Cadmium (Cd)	Total	ND	0.2	0.4	µg/L	TM-03-113	11/6/2017	11/6/2017	EPA 200.8m	
Calcium (Ca)	Total	16.1	0.05	0.1	mg/L	TM-03-113	11/6/2017	11/6/2017	EPA 200.8m	
Chromium (Cr)	Total	11.8	0.1	0.5	µg/L	TM-03-113	11/6/2017	11/6/2017	EPA 200.8m	
Cobalt (Co)	Total	0.4	0.1	0.5	µg/L	TM-03-113	11/6/2017	11/6/2017	EPA 200.8m	J
Copper (Cu)	Total	94	0.4	0.8	µg/L	TM-03-113	11/6/2017	11/6/2017	EPA 200.8m	
Iron (Fe)	Total	340.7	5	10	µg/L	TM-03-113	11/6/2017	11/6/2017	EPA 200.8m	
Lead (Pb)	Total	41.2	0.05	0.1	µg/L	TM-03-113	11/6/2017	11/6/2017	EPA 200.8m	
Magnesium (Mg)	Total	3.8	0.05	0.1	mg/L	TM-03-113	11/6/2017	11/6/2017	EPA 200.8m	
Manganese (Mn)	Total	10.9	0.2	0.5	µg/L	TM-03-113	11/6/2017	11/6/2017	EPA 200.8m	
Molybdenum (Mo)	Total	1.1	0.2	0.5	µg/L	TM-03-113	11/6/2017	11/6/2017	EPA 200.8m	
Nickel (Ni)	Total	12.1	0.2	0.5	µg/L	TM-03-113	11/6/2017	11/6/2017	EPA 200.8m	
Potassium (K)	Total	10.9	1	3	mg/L	TM-03-113	11/6/2017	11/6/2017	EPA 200.8m	
Selenium (Se)	Total	0.5	0.2	0.5	µg/L	TM-03-113	11/6/2017	11/6/2017	EPA 200.8m	
Silver (Ag)	Total	ND	0.5	1	µg/L	TM-03-113	11/6/2017	11/6/2017	EPA 200.8m	
Sodium (Na)	Total	382.9	1	3	mg/L	TM-03-113	11/6/2017	11/6/2017	EPA 200.8m	
Strontium (Sr)	Total	501.9	0.1	0.5	µg/L	TM-03-113	11/6/2017	11/6/2017	EPA 200.8m	
Thallium (Tl)	Total	ND	0.1	0.5	µg/L	TM-03-113	11/6/2017	11/6/2017	EPA 200.8m	
Tin (Sn)	Total	410.5	0.1	0.5	µg/L	TM-03-113	11/6/2017	11/6/2017	EPA 200.8m	

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Figure A12. Trace metal analysis for sample #3 from 1-chambered cell

Sample ID: 49093-R1	Sample 3	Matrix: Freshwater		Sampled: 05-Oct-17		Received: 13-Oct-17
	Method: SM 2540 C	Batch ID: C-33051		Prepared: 13-Oct-17		Analyzed: 27-Oct-17
Total Dissolved Solids	NA	692	0.1	2	mg/L	H
	Method: EPA 300.0	Batch ID: C-34072		Prepared: 13-Oct-17		Analyzed: 13-Oct-17
Dissolved Orthophosphate as P	NA	0.237	0.002	0.005	mg/L	H
Fluoride	NA	0.39	0.01	0.05	mg/L	

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Conventionals **ANALYTICAL REPORT**

ANALYTE	FRACTION	RESULT	MDL	RL	UNITS	QA CODE
Nitrate as N	NA	0.07	0.01	0.05	mg/L	H
Nitrite as N	NA	0.09	0.01	0.03	mg/L	H
	Method: EPA 300.0	Batch ID: C-34078		Prepared: 30-Oct-17		Analyzed: 30-Oct-17
Bromide	NA	1.31	0.001	0.005	mg/L	
Chloride	NA	24.9	0.01	0.05	mg/L	
Sulfate	NA	2.33	0.01	0.05	mg/L	

Figure A13. Total dissolved solids and anion analysis for sample #3 from 1-chambered cell

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California State University, Long Beach, 1250 Bellflower Blvd., Long Beach, CA 90840 (562-985-2469)

Trace Metals

ANALYTICAL REPORT

Analyte	Fraction	Result	MDL	RL	Units	Batch	Prepared	Analyzed	Method	QA Code
16527-R1 **Sample A**					**Freshwater**	**Sampled: 10/20/2017**			**Received: 17-Nov-17**	
Aluminum (Al)	Total	62.1	5	10	µg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	
Antimony (Sb)	Total	ND	0.1	0.5	µg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	
Arsenic (As)	Total	0.5	0.2	0.5	µg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	
Barium (Ba)	Total	2.3	0.2	0.5	µg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	
Beryllium (Be)	Total	ND	0.2	0.5	µg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	
Cadmium (Cd)	Total	ND	0.2	0.4	µg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	
Calcium (Ca)	Total	ND	0.05	0.1	mg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	
Chromium (Cr)	Total	1.3	0.1	0.5	µg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	
Cobalt (Co)	Total	0.1	0.1	0.5	µg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	J
Copper (Cu)	Total	33	0.4	0.8	µg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	
Iron (Fe)	Total	75.5	5	10	µg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	
Lead (Pb)	Total	2	0.05	0.1	µg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	
Magnesium (Mg)	Total	ND	0.05	0.1	mg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	
Manganese (Mn)	Total	3.5	0.2	0.5	µg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	
Molybdenum (Mo)	Total	1	0.2	0.5	µg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	
Nickel (Ni)	Total	0.9	0.2	0.5	µg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	
Potassium (K)	Total	ND	1	3	mg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	
Selenium (Se)	Total	ND	0.2	0.5	µg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	
Silver (Ag)	Total	ND	0.5	1	µg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	
Sodium (Na)	Total	ND	1	3	mg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	
Strontium (Sr)	Total	2.8	0.1	0.5	µg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	
Thallium (Tl)	Total	ND	0.1	0.5	µg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	
Tin (Sn)	Total	215.4	0.1	0.5	µg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	
Titanium (Ti)	Total	2.4	0.2	0.5	µg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	
Vanadium (V)	Total	0.6	0.2	0.5	µg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	

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Figure A14. Trace metal analysis for sample #1 from 2-chambered cell

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Conventionals ANALYTICAL REPORT

ANALYTE	FRACTION	RESULT	MDL	RL	UNITS	QA CODE
Sample ID: 51992-R1	**Sample A**	**Matrix: Freshwater**		**Sampled: 20-Oct-17**		**Received: 05-Dec-17**
	Method: SM 2540 C	Batch ID: C-33064		Prepared: 20-Dec-17		Analyzed: 20-Dec-17
Total Dissolved Solids	NA	116	0.1	2	mg/L	H
	Method: EPA 300.0	Batch ID: C-34099		Prepared: 20-Dec-17		Analyzed: 20-Dec-17
Dissolved Orthophosphate as P	NA	0.471	0.002	0.005	mg/L	H
Fluoride	NA	ND	0.01	0.05	mg/L	H
Nitrate as N	NA	0.12	0.01	0.05	mg/L	H
Nitrite as N	NA	ND	0.01	0.03	mg/L	H
	Method: EPA 300.0	Batch ID: C-34104		Prepared: 20-Dec-17		Analyzed: 10-Jan-18
Bromide	NA	0.332	0.001	0.005	mg/L	H
Chloride	NA	9.89	0.01	0.05	mg/L	H
Sulfate	NA	14.6	0.01	0.05	mg/L	H

Figure A15. Total dissolved solids and anion analysis for sample #1 from 2-chambered cell

INSTITUTE FOR INTEGRATED RESEARCH IN MATERIALS, ENVIRONMENTS & SOCIETY

California State University, Long Beach, 1250 Bellflower Blvd., Long Beach, CA 90840 (562-985-2469)

Trace Metals

ANALYTICAL REPORT

Analyte	Fraction	Result	MDL	RL	Units	Batch	Prepared	Analyzed	Method	QA Code
Zinc (Zn)	Total	25.3	0.1	0.5	µg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	
16528-R1	**Sample B**				**Freshwater**	**Sampled: 10/26/2017**			**Received: 17-Nov-17**	
Aluminum (Al)	Total	14.3	5	10	µg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	
Antimony (Sb)	Total	ND	0.1	0.5	µg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	
Arsenic (As)	Total	1.2	0.2	0.5	µg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	
Barium (Ba)	Total	10.2	0.2	0.5	µg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	
Beryllium (Be)	Total	ND	0.2	0.5	µg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	
Cadmium (Cd)	Total	ND	0.2	0.4	µg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	
Calcium (Ca)	Total	10.4	0.05	0.1	mg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	
Chromium (Cr)	Total	1.4	0.1	0.5	µg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	
Cobalt (Co)	Total	0.1	0.1	0.5	µg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	J
Copper (Cu)	Total	31	0.4	0.8	µg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	
Iron (Fe)	Total	37.5	5	10	µg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	
Lead (Pb)	Total	8	0.05	0.1	µg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	
Magnesium (Mg)	Total	2.6	0.05	0.1	mg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	
Manganese (Mn)	Total	1.1	0.2	0.5	µg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	
Molybdenum (Mo)	Total	4.5	0.2	0.5	µg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	
Nickel (Ni)	Total	3.3	0.2	0.5	µg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	
Potassium (K)	Total	ND	1	3	mg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	
Selenium (Se)	Total	ND	0.2	0.5	µg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	
Silver (Ag)	Total	ND	0.5	1	µg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	
Sodium (Na)	Total	31	1	3	mg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	
Strontium (Sr)	Total	98.7	0.1	0.5	µg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	
Thallium (Tl)	Total	ND	0.1	0.5	µg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	
Tin (Sn)	Total	336.4	0.1	0.5	µg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	
Titanium (Ti)	Total	1.1	0.2	0.5	µg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	

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Figure A16. Trace metal analysis for sample #2 from 2-chambered cell

Sample ID: 51993-R1	Sample B	Matrix: Freshwater		Sampled: 26-Oct-17		Received: 05-Dec-17
	Method: SM 2540 C	Batch ID: C-33064		Prepared: 20-Dec-17		Analyzed: 20-Dec-17
Total Dissolved Solids	NA	205	0.1	2	mg/L	H
	Method: EPA 300.0	Batch ID: C-34099		Prepared: 20-Dec-17		Analyzed: 20-Dec-17
Dissolved Orthophosphate as P	NA	0.358	0.002	0.005	mg/L	H
Fluoride	NA	0.47	0.01	0.05	mg/L	H
Nitrate as N	NA	0.06	0.01	0.05	mg/L	H
Nitrite as N	NA	ND	0.01	0.03	mg/L	H
	Method: EPA 300.0	Batch ID: C-34104		Prepared: 20-Dec-17		Analyzed: 10-Jan-18
Bromide	NA	1.12	0.001	0.005	mg/L	H
Chloride	NA	22.4	0.01	0.05	mg/L	H
Sulfate	NA	14.6	0.01	0.05	mg/L	H

Figure A17. Total dissolved solids and anion analysis for sample #2 from 2-chambered cell

16529-R1	Sample C				Freshwater	Sampled:			Received: 17-Nov-17	
Aluminum (Al)	Total	375.5	5	10	µg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	
Antimony (Sb)	Total	ND	0.1	0.5	µg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	
Arsenic (As)	Total	1.2	0.2	0.5	µg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	
Barium (Ba)	Total	15.4	0.2	0.5	µg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	
Beryllium (Be)	Total	ND	0.2	0.5	µg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	
Cadmium (Cd)	Total	ND	0.2	0.4	µg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	
Calcium (Ca)	Total	11.4	0.05	0.1	mg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	
Chromium (Cr)	Total	21.3	0.1	0.5	µg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	
Cobalt (Co)	Total	0.3	0.1	0.5	µg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	J
Copper (Cu)	Total	70	0.4	0.8	µg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	
Iron (Fe)	Total	282.3	5	10	µg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	
Lead (Pb)	Total	1.8	0.05	0.1	µg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	
Magnesium (Mg)	Total	2.8	0.05	0.1	mg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	
Manganese (Mn)	Total	6.9	0.2	0.5	µg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	
Molybdenum (Mo)	Total	7.1	0.2	0.5	µg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	
Nickel (Ni)	Total	11.3	0.2	0.5	µg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	
Potassium (K)	Total	ND	1	3	mg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	
Selenium (Se)	Total	ND	0.2	0.5	µg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	
Silver (Ag)	Total	ND	0.5	1	µg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	
Sodium (Na)	Total	37.5	1	3	mg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	
Strontium (Sr)	Total	109.7	0.1	0.5	µg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	
Thallium (Tl)	Total	ND	0.1	0.5	µg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	
Tin (Sn)	Total	106.4	0.1	0.5	µg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	

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Figure A18. Trace metal analysis for sample #3 from 2-chambered cell

Sample ID: 51994-R1	Sample C	Matrix: Freshwater		Sampled:		Received: 05-Dec-17
	Method: SM 2540 C	Batch ID: C-33064		Prepared: 20-Dec-17		Analyzed: 20-Dec-17
Total Dissolved Solids	NA	216	0.1	2	mg/L	
	Method: EPA 300.0	Batch ID: C-34099		Prepared: 20-Dec-17		Analyzed: 20-Dec-17
Dissolved Orthophosphate as P	NA	0.756	0.002	0.005	mg/L	
Fluoride	NA	0.68	0.01	0.05	mg/L	

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Conventionals ANALYTICAL REPORT

ANALYTE	FRACTION	RESULT	MDL	RL	UNITS	QA CODE
Nitrate as N	NA	0.06	0.01	0.05	mg/L	
Nitrite as N	NA	ND	0.01	0.03	mg/L	
	Method: EPA 300.0	Batch ID: C-34104		Prepared: 20-Dec-17		Analyzed: 10-Jan-18
Bromide	NA	2.65	0.001	0.005	mg/L	
Chloride	NA	29.1	0.01	0.05	mg/L	
Sulfate	NA	18.8	0.01	0.05	mg/L	

Figure A19. Total dissolved solids and anion analysis for sample #3 from 2-chambered cell

16530-R1	Sample D				Freshwater	Sampled: 11/9/2017			Received: 17-Nov-17	
Aluminum (Al)	Total	24.1	5	10	µg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	
Antimony (Sb)	Total	ND	0.1	0.5	µg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	
Arsenic (As)	Total	1.1	0.2	0.5	µg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	
Barium (Ba)	Total	2.7	0.2	0.5	µg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	
Beryllium (Be)	Total	ND	0.2	0.5	µg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	
Cadmium (Cd)	Total	ND	0.2	0.4	µg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	
Calcium (Ca)	Total	ND	0.05	0.1	mg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	
Chromium (Cr)	Total	22.7	0.1	0.5	µg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	
Cobalt (Co)	Total	0.2	0.1	0.5	µg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	J
Copper (Cu)	Total	19	0.4	0.8	µg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	
Iron (Fe)	Total	236.9	5	10	µg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	
Lead (Pb)	Total	0.6	0.05	0.1	µg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	
Magnesium (Mg)	Total	ND	0.05	0.1	mg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	
Manganese (Mn)	Total	3.9	0.2	0.5	µg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	
Molybdenum (Mo)	Total	10.5	0.2	0.5	µg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	
Nickel (Ni)	Total	5.6	0.2	0.5	µg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	
Potassium (K)	Total	ND	1	3	mg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	
Selenium (Se)	Total	ND	0.2	0.5	µg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	
Silver (Ag)	Total	ND	0.5	1	µg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	
Sodium (Na)	Total	ND	1	3	mg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	
Strontium (Sr)	Total	6.3	0.1	0.5	µg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	
Thallium (Tl)	Total	ND	0.1	0.5	µg/L	TM-03-117	12/14/2017	12/14/2017	EPA 200.8m	
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Figure A20. Trace metal analysis for sample #4 from 2-chambered cell

Sample ID: 51995-R1	Sample D	Matrix: Freshwater		Sampled: 09-Nov-17		Received: 05-Dec-17
	Method: SM 2540 C	Batch ID: C-33064		Prepared: 20-Dec-17		Analyzed: 20-Dec-17
Total Dissolved Solids	NA	88	0.1	2	mg/L	H
	Method: EPA 300.0	Batch ID: C-34099		Prepared: 20-Dec-17		Analyzed: 20-Dec-17
Dissolved Orthophosphate as P	NA	0.479	0.002	0.005	mg/L	H
Fluoride	NA	0.68	0.01	0.05	mg/L	H
Nitrate as N	NA	0.15	0.01	0.05	mg/L	H
Nitrite as N	NA	ND	0.01	0.03	mg/L	H
	Method: EPA 300.0	Batch ID: C-34104		Prepared: 20-Dec-17		Analyzed: 10-Jan-18
Bromide	NA	2.02	0.001	0.005	mg/L	H
Chloride	NA	5.3	0.01	0.05	mg/L	H
Sulfate	NA	16.4	0.01	0.05	mg/L	H

Figure A21. Total dissolved solids and anion analysis for sample #4 from 2-chambered cell

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