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FINAL PROJECT REPORT

Assessing Particulate Emissions from Power Plant Cooling Towers

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PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division supports energy research and development programs to spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution and transportation.

In 2012, the Electric Program Investment Charge (EPIC) was established by the California Public Utilities Commission to fund public investments in research to create and advance new energy solutions, foster regional innovation and bring ideas from the lab to the marketplace. The CEC and the state's three largest investor-owned utilities—Pacific Gas and Electric Company, San Diego Gas & Electric Company and Southern California Edison Company—were selected to administer the EPIC funds and advance novel technologies, tools, and strategies that provide benefits to their electric ratepayers.

The CEC is committed to ensuring public participation in its research and development programs that promote greater reliability, lower costs, and increase safety for the California electric ratepayer and include:

- Providing societal benefits.
- Reducing greenhouse gas emission in the electricity sector at the lowest possible cost.
- Supporting California's loading order to meet energy needs first with energy efficiency and demand response, next with renewable energy (distributed generation and utility scale), and finally with clean, conventional electricity supply.
- Supporting low-emission vehicles and transportation.
- Providing economic development.
- Using ratepayer funds efficiently.

Assessing Particulate Emissions from Power Plant Cooling Towers is the final report for the "Assessing Cooling Tower $PM_{2.5}$ and PM_{10} Emissions Using Advanced Instrumentation, Plume Transects, and Plume Modeling" (Contract Number: EPC-16-040) conducted by the University of California, Davis and University of California, Santa Cruz campuses. The information from this project contributes to the Energy Research and Development Division's EPIC Program.

For more information about the Energy Research and Development Division, please visit the CEC's research website (www.energy.ca.gov/research/) or contact the CEC at ERDD@energy.ca.gov.

ABSTRACT

Cooling towers from power plants and other applications use valuable fresh water to dissipate waste heat. Simultaneously, these cooling towers can emit particulates into the atmosphere, potentially worsening ambient air quality. The details of these emissions are poorly known and usually calculated based on estimates published decades ago. This study measured particulate matter emissions from cooling towers at two power plants located in California, one using brackish water and the other using fresh water. The results showed that (1) using brackish or fresh water does not influence particulate matter emissions from cooling towers, (2) cooling towers scrub nearly all the particulate matter between 2.5 and 10 microns from the air that enters the cooling tower, resulting in negative emissions, and (3) in regions of California with elevated particulate matter concentrations, cooling towers may scrub more particulate matter from the air than they emit.

Keywords: Particulate matter, PM_{10}, $PM_{2.5}$, emissions, scrubbing, cooling towers

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EXECUTIVE SUMMARY

Introduction

Cooling towers are used in a wide range of industrial applications to dissipate waste heat to the environment. In a wet cooling tower, sprayed warm water comes into contact with ambient air passing through the cooling tower, causing evaporative cooling of the water. While a vast majority of this spray water is recycled within the cooling tower system, a small fraction of the recirculating water escapes from the top of the cooling tower as *spray drift*.

After exiting the cooling tower, the water from these spray drift droplets evaporates leaving behind any material dissolved in the spray drift water. These remnants form particulate matter (PM), a mixture of minute solid particles and liquid droplets, between 10 microns (PM_{10}) and 2.5 ($PM_{2.5}$) microns in diameter. This particulate matter can cause serious health risks to sensitive groups by being inhaled and entering the lungs and is regulated both by the federal government and the State of California.

Because of the increased value of fresh water, cooling tower manufacturers have perfected drift eliminators that drastically reduce the amount of spray drift. Unfortunately, measurements of spray drift from cooling with modern drift eliminators has not been performed for decades. In addition, it may be possible to use brackish water instead of fresh water in cooling towers, reducing the burden on California's valuable fresh water supplies, but the brackish water may increase the emission of PM.

This project answered the following questions:

- Are particulate matter emissions greater if brackish water is used in cooling towers compared to fresh water?
- What are the emissions of particulate matter from cooling towers?
- If the dissolved solids concentration in recirculating water is higher, will that reduce the PM_{10} emissions from cooling towers?

Answering these questions could:

- Help the United States Environmental Protection Agency (EPA) reformulate the EPA AP-42 publication which provides guidance on estimating drift emissions based on measurements performed in the 1980s and 1990s to better reflect cooling tower performance.
- More accurately reflect actual emissions from cooling towers in both the PM_{10} and $PM_{2.5}$ size ranges.
- Reduce the required emission credits that power plants operators must purchase where regulations require PM from cooling towers be offset, due to more accurate measurement of emissions.

The information gained from this study will benefit the power plant operators, regulators and improve the health of California residents with reduced water use and less PM emissions.

Project Approach

The research team from the University of California – Davis and Santa Cruz campuses selected two power plants that used wet cooling towers; one using fresh water in their cooling towers while the other brackish water. To measure the range of total dissolved solids content in the recirculating cooling water, the project team built a frame for instruments and lifted it with a crane, suspending it over the cooling towers to measure the spray drift and collect PM on filters. The team used another set of instruments to measure the particulate matter concentrations in the air entering the cooling tower and analyzed the filters for mass and chemical composition.

The researchers developed a mathematical model to measure the PM entering and leaving a cooling tower that quantified the emissions from two sources: the spray drift and ambient air pollution drawn into the power plant.

Project Results

This project yielded three important results:

1) PM emissions did not depend on the type of cooling water, fresh or brackish, so brackish water instead of fresh water can be used without any additional particulate matter emissions.
2) Both cooling towers acted as scrubbers removing nearly 100 percent of the coarse PM from ambient air (particulates between 2.5 and 10 microns in size), so in effect they are negative emitters of coarse PM and should be counted against overall power plant PM emissions.
3) Both cooling towers also act as scrubbers of $PM_{2.5}$, but the fraction of $PM_{2.5}$ scrubbed was not as high as for the coarse fraction. The measurements were not able to accurately determine the $PM_{2.5}$ scrubbing efficiency, possibly because this efficiency depends on the size distribution of the $PM_{2.5}$. As a result, wet cooling towers may be either a positive or a negative emitter of $PM_{2.5}$, depending on the size distribution of the ambient $PM_{2.5}$, the concentration of $PM_{2.5}$ in the ambient air and possibly other factors. Additional measurements will be needed to quantify this effect more accurately.

The condition of the two cooling towers were quite different. The freshwater cooling tower was older and so did not have high efficiency spray drift eliminators. The brackish water cooling tower was relatively new and used high efficiency drift eliminators. Despite these differences, the measurements for coarse PM, showing that almost all were removed, were the same for both towers, so it is likely that generally wet cooling towers effectively scrub ambient coarse PM.

Fundamental calculations performed prior to the measurements demonstrated that emissions from wet cooling towers do not depend on the dissolved solids content of the recirculating water. This result was validated by the technical advisory committee (TAC).

Knowledge Transfer

The research team is sharing the results of this project with state agencies, academic researchers, electric utilities, and other relevant stakeholders through the project's TAC

members and interested industry and technical organizations. This information will also be sent to all relevant air quality districts to help guide their decision-making.

Three technical papers describing this work have been submitted to a peer-reviewed journal for publication including Atmospheric Measurement, Techniques and the journal of the Cooling Technology Institute. Finally, this work was presented at the Cooling Tower Institute Annual Conference in February 2022, which is the preeminent forum in the country for sharing information about cooling towers and their environmental effects.

Benefits to California

This project benefits California by removing one barrier for cooling tower operators to use brackish water instead of fresh water, since using brackish water will not increase the emissions of PM from cooling towers. If implemented, this will save on fresh water use in California.

The results from the project will inform the California Air Resources Board, Environmental Protection Agency and other decision makers that cooling towers are likely removing more course PM from the atmosphere than they emit and possibly also removing more $PM_{2.5}$ than they emit. This may reduce emissions charges from cooling towers at power plants, reducing cost to operators which they may pass down to ratepayers and decrease PM emissions, providing healthier air for Californians.

CHAPTER 1: Introduction

Cooling towers are used in a wide range of applications to dissipate waste heat to the environment. Wet cooling towers rely on the interaction between ambient air and cooling water to remove waste heat through evaporation. The interface between air and water results in some emission of liquid droplets, termed "spray drift." Drift emissions result in release of aerosolized materials, which may result in undesirable consequences in terms of respirable particle emissions, mineral deposition in nearby areas, and biological concerns such as the spread of legionella (Golay et al., 1986; Lucas et al., 2012; Mouchtouri et al., 2010). This study measured the particulate matter (PM) emissions from wet cooling towers. Such emissions were measured decades ago. Methods are now available for more accurately measuring both the droplet number and size distribution and the dried PM_{10} and $PM_{2.5}$ emissions (particulate matter of 10 and 2.5 microns in diameter, respectively). To use these methods, an instrument rack was built containing instrumentation for measuring the updraft velocity out of the cooling towers and their droplet size distribution and velocity. The instrument rack also contained driers that remove water from the air flow thereby drying the droplets to their aerosol size and composition for sampling by conventional PM instruments. Since California has high PM concentrations in many locations, ambient PM was also measured to differentiate how much of the emissions from the cooling towers is due to the cooling towers and how much is due to what is already in the ambient air. Using a mass balance model of the PM entering and leaving the cooling tower along with the data collected yielded the scrubbing efficiency of the towers for coarse PM (particles between 2.5 microns and 10 microns in size) and $PM_{2.5}$.

Since the instrumentation platform and techniques have not been developed or deployed in any prior study, Chapter 2 describes prior attempts to measure emissions from wet cooling towers along with the instrumentation deployed for this study.

Chapter 3 describes the droplet measurements which were performed using the same instrumentation used to measure the size distribution of droplets in fogs and clouds. Chapter 4 describes the dried particle measurements yielding scrubbing efficiencies and emissions factors for coarse PM and $PM_{2.5}$.

Chapter 5 describes the range of knowledge transfer activities employed during the study, Chapter 6 summarizes the major conclusions and Chapter 7 describes the benefits that the study provides to the taxpayers of California.

CHAPTER 2:
Instrument Description

Background

The United States Environmental Protection Agency (EPC) publication EPA AP-42 provides guidance on estimating drift emissions based on measurements performed in the 1980s and 1990s. AP-42 acknowledges a conservative calculation of emissions, and considers all emissions as PM_{10}, citing a lack of clear methodologies for accurately measuring both wet and dry tower emissions and characterizing the $PM_{2.5}$ fraction (EPA AP-42, 1995, p. 42).

A number of methods have previously been employed to more accurately characterize drift emissions. Comprehensive reviews of available characterization methods have found that while some methods do well in certain regards and under certain circumstances, no definitive method is suited to all ranges of conditions (Golay et al., 1986; Kinsey, 1991). Broadly, these methods may be categorized into those that measure elemental flux and those that measure droplet size distribution (Kinsey, 1991). Liquid water flux can be measured using thermodynamic methods employing calorimeters or heated psychrometers to measure total liquid water output. Several methods rely on collection of spray drift residue using impingers or cyclone separators to provide an insight into overall drift mass flux by comparing measured mineral flux against tower water composition. Drift emissions have also been characterized using addition of tracer chemical markers to the recirculating water reservoir and monitoring the tracer over time (Campbell, 1969; Lucas et al., 2012). Such methods allow determination of total drift while avoiding the issue of differentiating tower emissions from ambient particles. In general, mineral flux methods excel in high water emission conditions, but exhibit poor performance and higher uncertainty with the lower water emissions that are increasingly common with the use of modern drift eliminators (Golay et al., 1986). These methods have varying degrees of effectiveness depending on droplet size, require collection of significant material per sample, and do not preserve information on drift droplet size distribution, which is necessary to determine particle transport and deposition (Golay et al., 1986; Kinsey, 1991; Roffman and Van Vleck, 1974).

A second class of measurements characterize emissions by counting spray drift droplets and using water composition data to predict total drift emission as well as dried aerosol emission diameters. Sensitive paper methods to detect droplet impactions have been used for many years and have benefitted from advances in digital image processing to increase throughput (Ruiz et al., 2013), but require high sampling numbers to achieve sufficient statistics and are limited to short sampling times to prevent saturation of the sensitive surface. Sensitive surface methods also require droplet impaction to collect samples, necessitating disruption of the aerosol stream (Golay et al., 1986). Microphotography and laser scattering techniques have been used to determine droplet size distribution optically and have potential to provide time resolution but are subject to interference from droplet coincidence at high concentrations and have accuracy and droplet size limitations (Kinsey, 1991). In general, droplet counting methods excel in lower water loading scenarios (Golay et al., 1986). All counting methods require large amounts of data collection to achieve satisfactory statistics and may be prone to

error for droplet sizes that are not as abundant. While these techniques provide valuable information regarding droplet number concentration and size distribution, small errors in measurement of droplet diameter can result in large errors in calculation of total drift mass flux (Kinsey, 1991). Additionally, droplet-based methods are largely unable to distinguish between spray drift and condensation formed as saturated air exits the tower (Kinsey, 1991; Ruiz et al., 2013).

To directly measure cooling tower emissions, the research team constructed an instrument package and suspended it directly above active cooling towers. Direct measurement of tower emissions allows emission characterization and collection while minimizing the effect of dilution, the difficulties with plume tracking and the need for data extrapolation. Two subsequent papers report the results of these measurement.

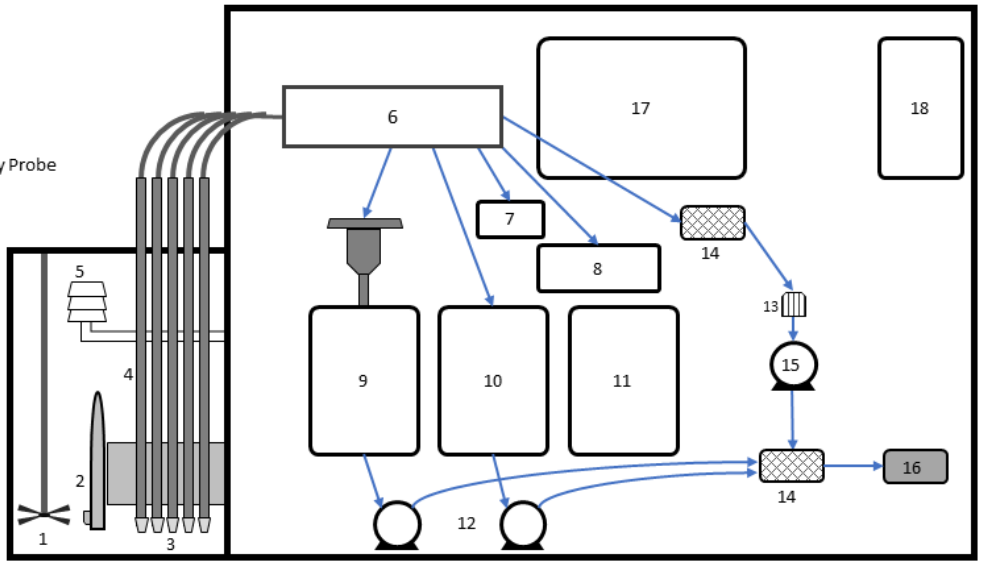
Instrumentation

Tower Sampling Instrumentation

A chassis was constructed of aluminum channel extrusion, built as an open frame to minimize disruption of air flow from the cooling tower exit. A sampling region at one end of the instrument chassis contains the aerosol sampling inlets, a phase Doppler interferometer (PDI), an updraft anemometer, and a temperature and humidity probe. Dried spray drift is sampled by drawing emissions through drying columns and subsequently distributing it to instrumentation for real-time size analysis as well as to filter-based PM samplers. Emissions are sampled by lifting the instrument package with a crane and suspending it about 1 meter over the top of the tower stack. Figure 1 shows the aerosol sampling train and sensors in the implementation used to characterize tower samples. Figure 2 shows the instrument package suspended above a cooling tower for sampling.

Figure 1: Sampling Instrumentation Package

1. Updraft Anemometer
2. Phase Doppler Interferometer
3. Inlet Nozzles
4. Nafion Dryers
5. Plume Temperature and Humidity Probe
6. Dried Aerosol Manifold
7. Aerodynamic Particle Sizer
8. Dusttrak
9. IMPROVE PM_{10} Sampler
10. IMPROVE $PM_{2.5}$ Sampler
11. IMPROVE Controller
12. IMPROVE Pumps
13. Dried Aerosol RH Probe
14. HEPA Filters
15. Flow Control Pump
16. Flow Meter
17. PDI Electronics
18. Electronics Enclosure



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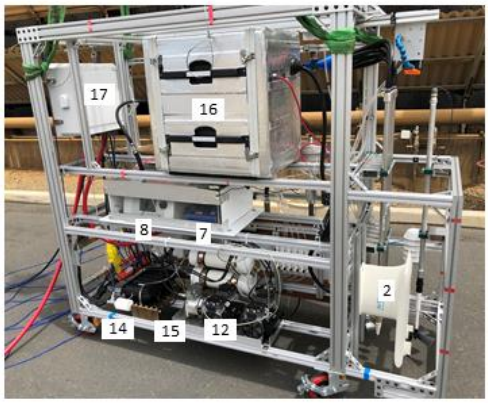

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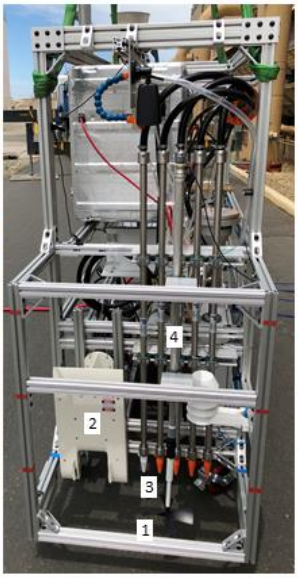

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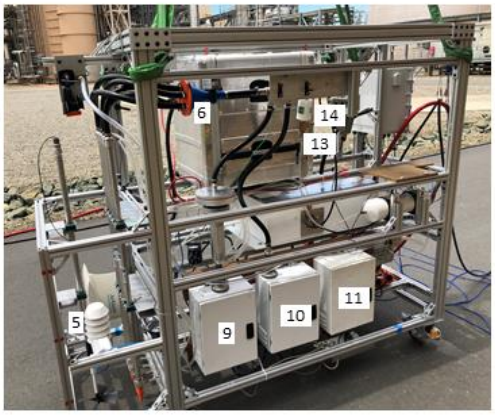


d.

Top figure (a) shows diagram; three photographs below show (b) right side, (c) sampling end, (d) left side

Source: Anthony Wexler

Figure 2: Instrument Package in Place Above a Cooling Tower

Source: Chris D. Wallis

Liquid Droplet Characterization

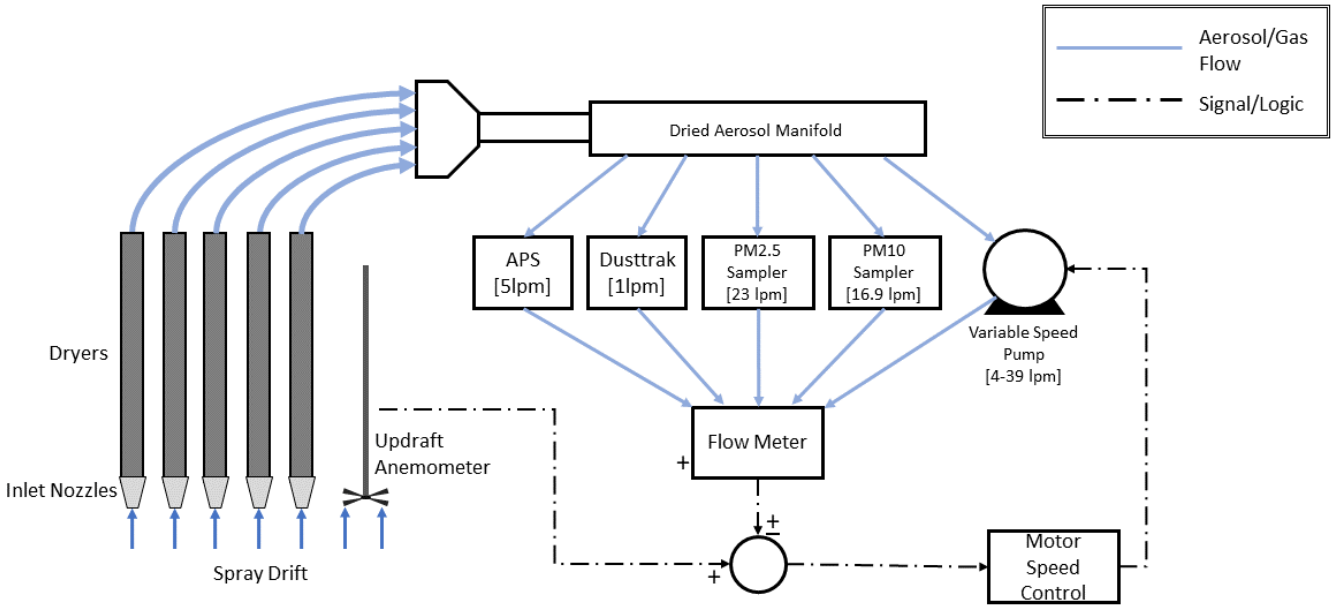
A PDI flight probe (Artium Technologies Inc, Sunnyvale, Ca) was mounted at the sampling end of the chassis to count and size liquid droplets emitted from the tower and phase which are used to precisely determine droplet velocity and diameter. This dual-range PDI measures drops in the range of 2 - 2000 micrometers (μm) (diameter) and provides droplet size and velocity (Bachalo 2000). To derive population-level statistics such as number concentration and liquid water content, the method described by (Chuang et al. 2008) was used. The PDI measurements are subject to several sources of uncertainty. The first is the uncertainty of the inferred diameter of any individual droplet, which is estimated from laboratory calibrations to be less than 1 micron.

The second is uncertainty in the probe volume, which determines the sampling rate of the instrument in units of volume of air per unit time. The uncertainty is estimated to be about 5 to 10 percent (Chuang et al. 2008 for details), with lower values at large drop sizes, and higher values at smaller drop sizes. The third is statistical counting uncertainty, which arises because the number of drops detected in any given time interval is subject to randomness. The magnitude of this uncertainty was estimated using the well-known formula: for n droplets counted, then the uncertainty in this count is $\sqrt{n}$. If the number of drops counted is more than 10^2, then the relative uncertainty is less than 10 percent. PDI electronics are housed in a protective enclosure covered in reflective material to reject solar heat. A low flow of spent sheath air from the drying system is used to remove moisture from the enclosure.

Dried Aerosol Characterization

Dried aerosol is isokinetically drawn through dryers and then distributed to various sampling instruments. Tower updraft velocity is monitored by a Model 21706T Updraft Propeller Anemometer (R.M. Young Company, TraverseCity, MI) mounted at the sampling end of the instrument at the same height as the PDI and dryer inlet nozzles. A variable speed oil-less piston pump (flow control pump) is used to control total instrument flow in order to maintain isokinetic sampling of the spray drift droplets into Nafion dryers. Total volume flow in the system is calculated by combining and filtering the exhaust of the three main pumps driving flow in the sampling system (IMPROVE $PM_{2.5}$, IMPROVE PM_{10}, and variable speed flow control pump) and measuring the combined volume flow using a mass flow meter (model 4100, TSI Incorporated, Shoreview, MN). Static values of 5 liters per minute (lpm) and 1 lpm respectively are added to account for the APS and Dusttrak flow rates. Volume flow rate is converted to inlet nozzle velocity based on the diameter of the inlet nozzles installed. The feedback loop for achieving isokinetic sampling is shown in Figure 3. An overpressure relief valve was included in the exhaust line to prevent accidental over pressurization of the flow meter.

Figure 3: Feedback Control for Isokinetic Sampling



Source: Anthony Wexler

A feedback algorithm was implemented using an on-board microcontroller to minimize error between calculated nozzle inlet velocity and measured updraft velocity by changing the speed of the flow control pump. Flow rates of between 50-85 lpm are achievable with this method. Installation of inlet nozzles of different diameters allows an adjustment to the range of inlet velocities that corresponded to this flow range (Table 1).

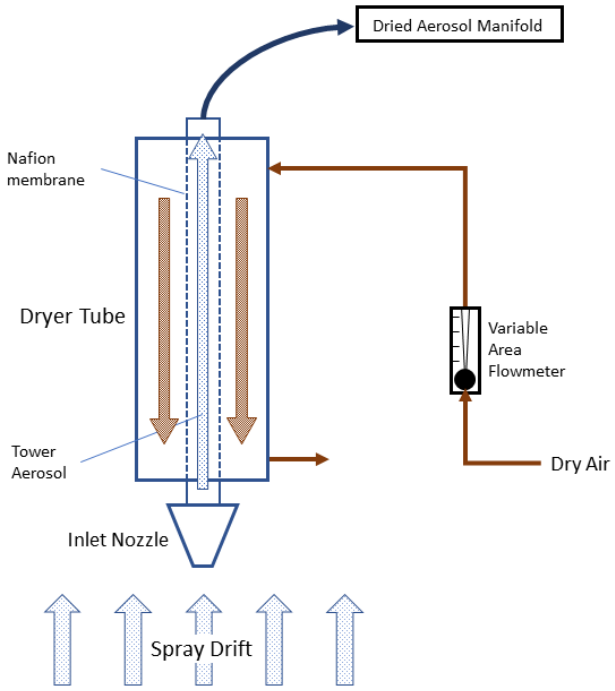
Table 1: Inlet Nozzle Diameters versus Nozzle Velocity Range

Nozzle Diameter, mm	Achievable Updraft Velocity, m/s
4.2	12.0 - 20.4
4.9	9.0 - 15.3
5.5	7.0 - 11.9
5.9	6.0 - 10.2
7.3	4.0 - 6.8

Source: Anthony Wexler

To characterize dry emissions while sampling at the tower exit, spray drift must be dried while preserving particle suspension. To emulate natural ambient drying, wet tower emissions are drawn in through a bank of Nafion tubing dryers model MD-700, Perma Pure, Toms River, NJ) located at the sampling end of the frame. Each dryer consists of a central tube conducting sample aerosol surrounded by a counter-flow of dry instrument-grade sheath air flowing at a minimum of twice the flow rate of the sample air. The two flows are separated by a Nafion membrane, allowing diffusion of water from the sample air into the sheath air without heating or diluting the aerosol sample. The bank of five 48-inch (122 cm) long dryers is operated in parallel to maintain an aerosol flow rate less than 16.7 lpm per dryer, which is the design maximum flow rate for the MD-700. Dry sheath air to each Nafion dryer is controlled using a variable area flowmeter. Figure 4 depicts a single MD-700 dryer configuration.

Figure 4: Configuration for Single MD-700 Dryer



Source: Anthony Wexler

Dry filtered air for the MD-700 sheath is generated on-site using an oil-less piston compressor (model 7HDD-57-M750X, Gast Manufacting, Inc, Benton Harbor, MI), an air-cooled aftercooler, and a refrigerated-type compressed air dryer (model Krad-15, Keltec Technolab, Twinsburg,

OH), generating approximately 170 lpm of 0.1 µm filtered air with a dew point of -16 °C. Figure 5 shows the dry air generation system. The air is then regulated to 10 psig (~70 kPa gauge) and supplied to the MD-700 driers on the aloft instrument via a 1-inch (25 mm) diameter 150 ft (46 m) umbilical hose. The hose is attached to the instrument chassis via a strain relief and is also strain relieved at the supply end near the dryer connection. The dry air is split into five separate flows for each of the Nafion dryer sheath air paths via a bank of variable area flowmeters.

Figure 5: Dry Air Generation Equipment Including Compressor, Aftercooler, Dryer, Regulator, and Umbilical Hose

Source: Anthony Wexler

Dried aerosol is then drawn to a manifold feeding a number of instruments. Grounded static dissipative tubing and lining are used to minimize particle loss due to accumulated surface charge. An aerodynamic particle sizer (APS) (Model 3321, TSI Incorporated, Shoreview, MN) is used forprimary dry aerosol size and number quantification. A DustTrak (Model 8533, TSI Incorporated, Shoreview, MN) provides auxiliary characterization of particle size and concentration. A water-tight enclosure protects both instruments from liquid damage. A low-power notebook computer is used to log data and remotely begin and end sampling for both instruments.

Dried aerosol samples are also collected from the manifold using a pair of Interagency Monitoring of Protected Visual Environments (IMPROVE) sampler modules. A $PM_{2.5}$ module collects sample at a rate of 23 lpm and a PM_{10} module with the sampling head modified for in-line flow collects sample at 16.9 lpm. Each sampler module contains four filter positions loaded with pre-weighed 25mm Polytetrafluoroethylene (PTFE) filters (Pall Teflo 3 µm, Pall Corporation, Port Washington, NY). Particulate matter gathered on these filters is subsequently analyzed gravimetrically and by X-ray fluorescence (XRF) to determine mass and elemental composition (IMPROVE 2017; 2020b; 2020a). An IMPROVE control module connected to both modules monitors sampling flow rates and is used to remotely start and stop the samplers over a cellular data connection.

Data Logging and Telemetry

Vital metrics are recorded using a custom electronics package based on a ruggedized version of an Arduino microcontroller (Rugged Mega, Rugged Circuits, MI) mounted on the aloft instrument. Updraft velocity, aerosol flow rate, dried aerosol temperature and humidity, and tower plume temperature and humidity are recorded to a local SD card and transmitted to a computer on the ground in real time. A 2.4 GHz Zigbee wireless connection is used to transmit data to a ground computer and to receive commands from the ground to start or stop sampling and adjust pump parameters. Custom code developed in LabView receives, parses, and logs data from the aloft instrument, and allows remote control of flow and sampling state.

A local positioning system (model MDEK1001, Decawave Limited) is used to assist with precise and repeatable positioning of the aloft instrument rack. Four fixed anchor nodes are placed on the top deck of the cooling tower. A fifth sensor is mounted to the sampling end of the instrument, and relayed position data via serial output. Scale markers were also painted on the instrument chassis at 12-inch intervals for visual reference relative to tower features. A wireless camera (Casacam VS1001) was installed above the sampling end of the instrument to provide a direct view of the sampler's position relative to the tower. Once the instrument is positioned in the desired location, two guy ropes are used to secure the instrument package to the tower structure to prevent unwanted motion due to air currents acting on the assembly. Once tethered, the instrument package is constrained to approximately 0.3 m of travel.

Tower plume temperature and humidity are continuously monitored by a probe mounted in the sampling end of the chassis (model HMS112, Vaisala Inc, Louisville, CO). Dried aerosol temperature and humidity is monitored by an additional probe (model 657C-1, Dwyer Instruments, Michigan City, IN) placed downstream of a high efficiency particulate air (HEPA) filter (model HC10-4N-PTF, Aerocolloid LLC, Minneapolis, MN) to protect the probe from contaminants. The humidity probe is positioned between the dry aerosol manifold and the flow control pump so that the probe does not affect aerosol being sampled by other instrumentation.

Environmental Considerations

The instrument package is required to operate in a variety of industrial environments, including electrically noisy environments, operation in heat and direct sunlight, and exposure to a constant upward flow of high humidity and water spray. To minimize potential impacts of electrical noise, analog sensor readings are transmitted as 4-20 mA current loop signals where possible. These signals are converted to digital and subsequently recorded by the microcontroller.

Sensitive instrumentation and electrical connections throughout the instrument package are housed in watertight enclosures. Where additional cooling is necessary, spent dry air from the Nafion dryer sheaths is directed to electrical enclosures to cool instrumentation before exhausting to the environment. Exhaust air from the motor control pump is expelled through a row of small air jets, positioned to deflect and remove droplets from the camera lens to maintain visibility. Instrumentation and connections that do not require additional cooling air are enclosed with desiccant packs as an additional precaution. Wireless temperature and humidity probes (Thermopro TP65) are placed in electronics enclosures to provide real time indication of equipment conditions to operators on the ground.

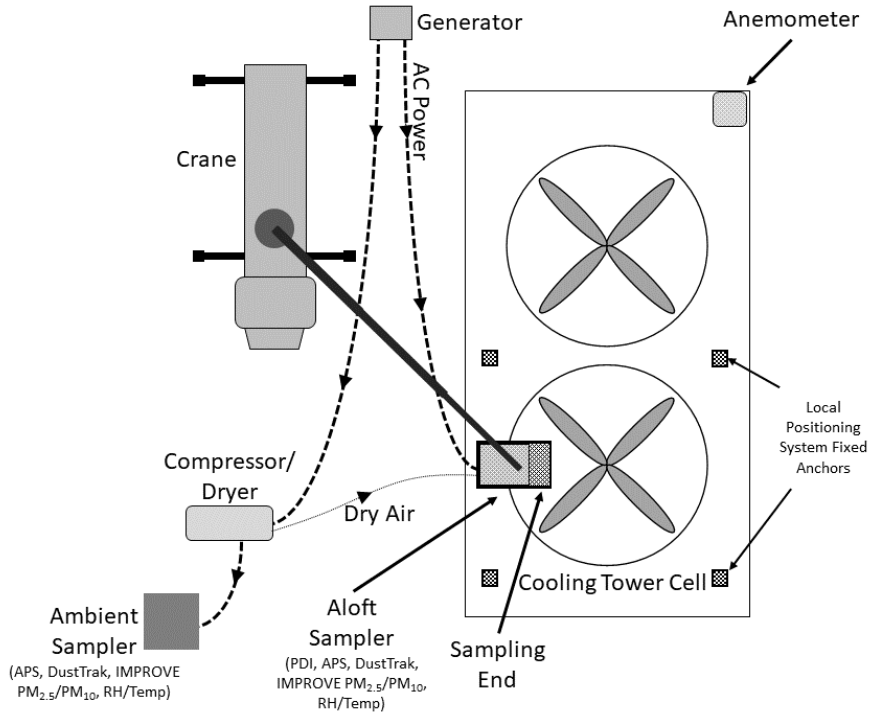
Ambient Sampling

To differentiate between spray-drift-based emissions and ambient aerosol passing through the tower, a parallel set of measurements are made adjacent to the tower. An instrument package including an APS, Dusttrak, IMPROVE $PM_{2.5}$ and PM_{10} samplers is operated concurrently with aloft sampling. Sampling inlets at the ambient sampling station are located at a height of 2 meters. Ambient temperature and humidity are continuously recorded using a model HL-1D data logger (Rotronic AG, Bassersdorf, Switzerland). Wind speed and direction near the tower are logged to a local SD card on a microcontroller attached to a battery-powered sonic anemometer (Model 81000, RM Young Company, Traverse City, MI).

Power

Power for operating ground and aloft instruments is generated on-site using a 1000 W propane-powered generator. A dual tank switching regulator allows the propane tanks to be exchanged without interrupting sampling. Generator exhaust is cooled via dilution with ambient air drawn in through an in-line blower (model FR110, Fantech, Lenexa, KS) and then HEPA filtered (model CFB-HP-6, HVACQuick, Medford, OR) prior to release to prevent contamination of sample aerosol at the site. A temperature probe is mounted in the dilute exhaust stream to ensure that exhaust gases do not damage the filter. The generator is positioned approximately 100 feet (30 m) from the ground sampling station and cooling cell, as shown in Figure 6. Power is delivered to the ground and aloft instruments via a 150 ft (46 m) supply umbilical, strain relieved near either end to the instrument chassis and to a stationary block near the generator.

Figure 6: Typical Deployment for Tower Sampling



Source: Anthony Wexler

Additional Considerations

Due to the nature of the sampling method, it is critical that no equipment or components could fall from the crane or instrument chassis due to the risk of damage to the plant facility. All equipment on the instrument platform is redundantly secured. Components that can potentially fall if one or two fasteners fail are secured with tether cables as an additional precaution.

The complete aloft instrument weighs approximately 800 lbs. It is fitted with shock-absorbing locking casters and can be moved on level ground by one or two people. All supplemental field equipment, including sampling equipment, compressors, dryers, generators, and exhaust filtration is mounted on carts or otherwise easily portable for field deployment.

Sampling Validation

Aloft and ground IMPROVE samplers and APSes were run in parallel in a collocated study within a well-mixed room to determine sampling differences. Gravimetric results are shown in Table 2. The discrepancy in collection of larger PM is presumed to be due to losses within the aloft sampling train.

Since APS instrument variability was observed with the entire aloft sampling train in place and with bare APS instruments placed side-by-side, collocated samples were also taken before and after every field sampling day. The two APS units were allowed to run with the aloft instrument placed on the ground near the ground sampling station. Data from the aloft APS were normalized to the ground APS for each site based on this collocation period. Normalization was applied for size ranges below 14 µm. Larger particles were likely lost to impaction on the way to the APS. In addition, aloft APS data were normalized to ground data to account for line losses leading to the aloft APS, which were characterized during the extended ground collocation test.

Table 2: Gravimetric Results from IMPROVE Sampler Collocation.

Test	PM2.5 [ug/m3]	PM10 [ug/m3]	Coarse (PM10 - PM2.5) [ug/m3]
Test 1: Aloft Instrument	8.93	11.41	2.48
Test 1: Ground Instrument	8.93	12.01	3.09
Test 2: Aloft Instrument	12.24	15.54	3.30
Test 2: Ground Instrument	12.22	16.14	3.92

Coarse PM is calculated as the difference between PM10 and PM2.5.

Source: Anthony Wexler

Discussion

- A number of previous methods have been used to characterize cooling tower emissions. Broadly, they are divided into methods that measure elemental flux and those that measure droplet size distribution (Kinsey 1991). Elemental flux methods include addition of unique chemical tracers to the water supply or collection of liquid emissions using devices such as heated impactors, impingers, or cyclone separators for collection

of drift droplets and subsequent extraction and analysis of mineral content (Kinsey 1991; Roffman and Van Vleck 1974). However, these methods have varying degrees of effectiveness depending on droplet size, require collection of significant material per sample, and do not preserve the ability to resolve tower emissions by size range (Kinsey 1991). Drift emissions have also been characterized using addition of tracer chemical markers to the recirculating water reservoir and monitoring the tracer over time (Campbell 1969; Lucas, Martinez, and Viedma 2012). This method allows determination of total drift while avoiding the issue of differentiating tower emissions from ambient particles but does not lend itself to further investigation of emitted particle size distribution.

- Characterization of the emitted liquid spray drift is often used in conjunction with water composition data to predict total drift emission as well as dried aerosol emission diameters. Sensitive paper methods to detect droplet impactions have been used for many years, but are labor intensive and have reduced sensitivity to smaller diameter drift droplets (Ruiz et al. 2013). Microphotography and laser scattering techniques determine droplet size distribution optically and have potential to provide time resolution but are subject to interference from droplet coincidence at high concentrations and are less sensitive to smaller droplets compared to PDI (Bachalo 2000; Kinsey 1991).

Direct sampling of tower emissions offers a number of advantages compared to other methods. Sampling directly above the tower allows measurements that reflect un-diluted emissions, in contrast to methods that sample further away and allow emissions to dry naturally. Rapid drying of spray drift mimics environmental drying while preserving dry aerosol size distribution, in contrast to bulk droplet collection methods such as heated glass bead sampling. This size preservation allows size-segregated sampling into coarse and fine ranges, as well as enabling more detailed size characterization using real-time instrumentation such as the APS. Specific instrumentation chosen for the instrument package, including the PDI and APS, allow high resolution size characterization compared to methods based on scattering, photography, or sensitive paper. The PDI operates with less than 10 percent relative uncertainty over a range of 2 µm to 2mm. The APS characterizes aerodynamic particle diameter over a range between 0.5 µm to 12 µm and provides much more detailed characterization than bulk collection methods. These instruments provide rapid characterization, requiring as little as five minutes of sampling at a single location above the tower to obtain an adequate sample size. Use of IMPROVE samplers for size-selected sample collection allows a distinction between coarse and fine particles when analyzing for total mass as well as composition. Longer sampling times are required when collecting filter samples to collect sufficient mass for analysis.

Conclusion

Spray drift emissions are difficult to accurately characterize for a number of reasons, and past attempts have not resulted in a definitive method. Direct sampling from the tower exit combined with rapid heatless drying enables representative sampling while preserving aerosol properties such as size distribution. Inclusion of modern instrumentation in the sampler package allows enhanced measurement precision compared to past techniques, and size-resolved collection of dried aerosol enables separate analysis of $PM_{2.5}$ and PM_{10} emissions

when using techniques such as XRF to determine composition. The instrumentation described is designed for characterization of wet cooling tower emissions, but is also suitable for measurement of droplet-, aerosol- or gas-based emissions from a variety of sources. The instrument rack configured with different instruments could, in general, be used to measure emissions from any stack.

CHAPTER 3:
Positive and Negative Emissions from Cooling Towers: Droplet Measurements

Introduction

A wet cooling tower is a specialized heat exchanger in which warm water comes into contact with air causing evaporative cooling of the water. Their primary function is to cool water used in industrial processes, power plants, and in heating, ventilation, and air conditioning systems. There are different cooling tower configurations depending on the application. In order to maximize the rate of evaporation, the water is dispersed into the air within the tower as a spray. Ideally, cooling tower emissions only comprise warmed, humidified air. However, a number of mechanisms lead to a small fraction of the spray droplets also being emitted from the tower, termed "spray drift." These drift droplets can impact local and regional air quality, and so the U.S. Environmental Protection Agency (EPA) recommends guidelines for calculating their emissions via AP-42 (EPA, 1995).

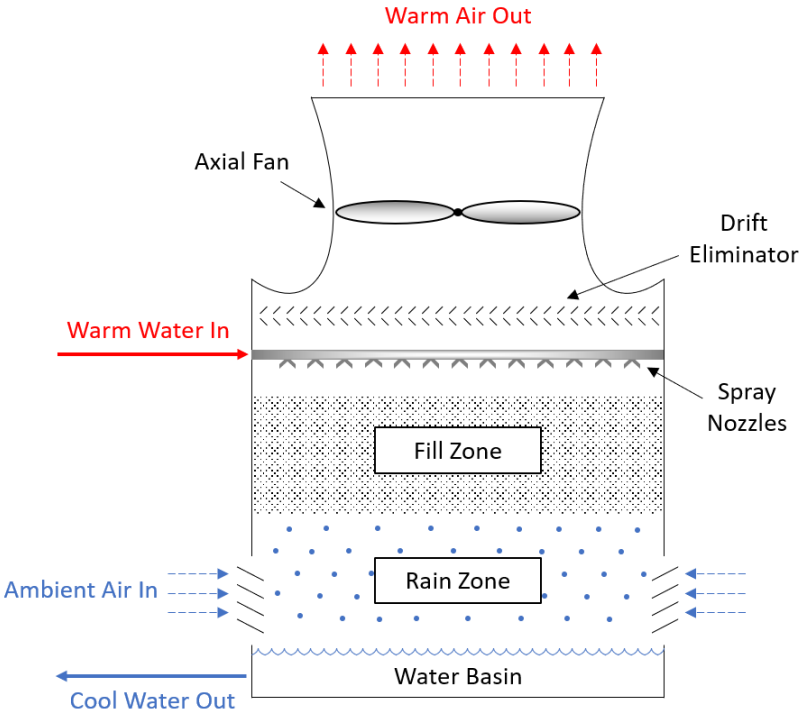
In this study, measurements are conducted only at induced-draft counterflow wet cooling towers (Figure 7), although this methodology could be applied to all types of wet cooling towers. An axial fan located at the top of the tower pulls ambient air into the tower through slots located near the bottom. The air then flows through the rain zone, the fill zone, and the spray zone. Warm water is pumped to the top of the tower and distributed by a system of spray nozzles to a lattice-structured fill material. The fill material increases the surface area of the water to allow for maximum contact with the passing air. The water then falls from the bottom of the fill zone into the rain zone and is deposited into a basin. When the water comes into contact with air in all three zones, there is mass and heat transfer which cools the water via evaporation, while warming and moistening the air. Approximately 10-20 percent of heat transfer takes place in the rain zone, while the remainder occurs in the fill zone (Kröger, 2004).

For small droplets, the updraft velocity may exceed the terminal settling velocity in which case these droplets will be entrained in the air stream and potentially exit the top of the tower as a drift droplet. To minimize this loss, drift eliminators between the axial fan and the spray nozzles reduce the number of droplets exiting the tower with the air stream. However, drift eliminators are not 100 percent effective and some droplets still exit the tower. Modern drift eliminators are rated to have an efficiency of 5×10^{-4} percent, defined as the percentage of circulating water which leaves the system as spray drift. Drift droplets typically evaporate upon leaving the tower and any impurities present in the droplets remain in the atmosphere as suspended PM.

Despite the small fraction of recirculating water that is lost as drift, PM emissions may be considerable, and cooling tower operators may need to purchase emission reduction credits to offset emissions. In the United States, the emission of PM less than or equal to 10 μm in diameter (PM_{10}) can be calculated using the methodology described by the EPA in AP-42 (EPA, 1995). This methodology does not distinguish between PM_{10} and $PM_{2.5}$ (the subset of

PM_{10} particles with a diameter less than or equal to 2.5 µm). This method of estimating PM_{10} emissions from cooling towers is considered "conservatively high" and is given the lowest level of acceptable confidence by the EPA (EPA, 1995). AP-42 assumes that all droplets evaporate before being deposited onto the ground and that all drift droplets, regardless of drift droplet size and total dissolved solids (TDS) concentration, produce particles that can be classified as PM_{10}. EPA (1995) also neglects the potential scrubbing effect of cooling towers, which is the process by which PM suspended in the ambient air passing through the tower is washed out in the rain and fill zones and thereby removed from the ambient air. PM emissions from wet cooling towers depend on the size distribution of drift droplets and the concentration of TDS in the water. Studies seeking to characterize the size distribution of drift droplets have found inconsistent results (Meroney, 2006), likely due to diversity in cooling tower design and/or uncertainty in measurement techniques. Large drift droplets with high TDS concentrations may produce particles with diameters greater than 10 µm upon evaporating and therefore do not qualify for emission regulation. Two previous studies (Reisman and Frisbie, 2002; Micheletti, 2006) conclude that EPA (1995) neglected to account for this effect, potentially overestimating PM_{10} emissions by 85 percent or more. In this study, the researchers seek to quantify PM_{10} and $PM_{2.5}$ emissions by collecting *in situ* measurements of drift droplets as they exit wet cooling towers using high-accuracy, modern instrumentation.

Figure 7: Schematic of Induced-Draft Counter Flow Cooling Tower



Source: Anthony Wexler

Warm water is pumped to the top of the tower and distributed into the fill zone by a system of spray nozzles. Ambient air is drawn through slots at the bottom of the tower by an axial fan located at the top. Water cools via evaporation through contact with the passing air as it trickles through the fill zone, falls through the rain zone, and is deposited into the water basin. Air exiting the top of the tower has accumulated heat and moisture through contact with the

passing water and has also entrained drift droplets. Drift eliminators are installed between the spray nozzles and axial fan to minimize the concentration of drift exiting the tower.

Methods

Instrumentation and Deployment

To directly measure PM emissions, the researchers constructed an instrument package designed to be lifted and held in place by crane just a few feet above a cooling tower. The instrumentation package is capable of sampling wet and dry emissions in the plume above the tower. Wallis et al. (2021a) describe in detail the entire instrument package. Described next are the specific aspects of this package most relevant to this study.

Wet emissions, that is, drift droplets, were sampled *in situ* using a PDI. This instrument relies on phase Doppler interferometry, a well-established technique which has been described in great detail in the literature (such as Bachalo 1980; Bachalo and Houser 1984; Davis and Schweiger 2002; Chuang et al. 2008) and used extensively in the spray sciences and cloud microphysics communities. A PDI measures the size and velocity of liquid water droplets between 0.5 and 2500 μm in diameter. Droplets passing through the instrument's detection region, consisting of two intersecting laser beams, act as a lens and project an image of the interference pattern produced by the two beams. A small droplet will act as a lens with large curvature and project a larger image than a large drop. Multiple detectors measure the phase shift of the projected image which has a linear relationship to droplet size. Droplet velocity is derived with high accuracy from the frequency of the scattered signal from any one of the detectors. For more information on how a PDI derives these values, see Chuang et al. (2008).

In addition to the direct drift droplet measurements by the PDI, air from the cooling tower plume was drawn isokinetically into drying tubes. The resulting dried PM were analyzed for their physical and chemical properties. The data and conclusions from these analyses are described in Chapter 4.

The described instrumentation package was installed above cooling towers located at two separate California power plants; "Tower 1," located in Northern California, and "Tower 2," located in Southern California. Table 3 provides a summary of some of the properties relevant to drift emissions for each tower. The described sampling unit was deployed above each tower at a height of ~1 meter above the tower exit. Results from a third cooling tower are described in part 2 to this paper, but a complete survey of this tower was not performed, and, thus, not used in the analysis here.

Particulate Matter Emissions Estimate

To estimate PM_{10} and $PM_{2.5}$ emissions from drift droplets at each tower, the research team (a) measure the drift droplet size distribution at various locations across the tower outlet; (b) convert the wet droplet size distribution to a dry PM emission rate at each location using the measured TDS concentration of the recirculating water along with the *in situ* measured air velocity; and (c) integrate PM emissions over all locations to generate total emissions rate from the tower. Characterization of recirculating tower water is critical to prediction of tower emissions. To determine the TDS concentration of recirculating water, the researchers collected samples of recirculating water from each tower for later chemical analysis. An

estimated 1-2 percent of recirculating water is lost to evaporation as it cycles through the tower and must be replenished with makeup water that is supplied by a variety of sources. This evaporation results in constantly increasing TDS concentration in the recirculating water since dissolved solids are not lost during evaporation and only a relatively small amount is lost in spray drift.

To manage TDS, towers must undergo blowdown, where recirculating water is purged and replaced with makeup water. High TDS may result in increased emissions as well as precipitation and buildup of minerals inside the tower.

Table 3: Summary of Cooling Tower Properties Relevant to Drift Emissions

	Tower 1	Tower 2
Construction date	2004	1957, updated 2006
Fan diameter	10 m (~32.8 ft)	4 m (~13.1 ft)
Nominal outlet diameter	11.5 m (~37.7 ft)	4 m (~13.1 ft)
Specified nominal air flow rate	746 m^3/s (1,580,000 acfm*)	217 m^3/s (460,000 acfm)
Measured air flow rate	429 m^3/s (910,000 acfm)	61 m^3/s (130,000 acfm)
Specified circulating water flow rate	9.27 m^3/s (147,000 gpm)	0.315 m^3/s (5,000 gpm)
Specified drift eliminator efficiency	5x10−4 %	0.2 %
Measured course water TDS	1230 ppm	433ppm

Source: Anthony Wexler ***Actual cubic foot per minute.**

To convert wet droplet sizes to dried particle sizes, the researchers make the following assumptions:

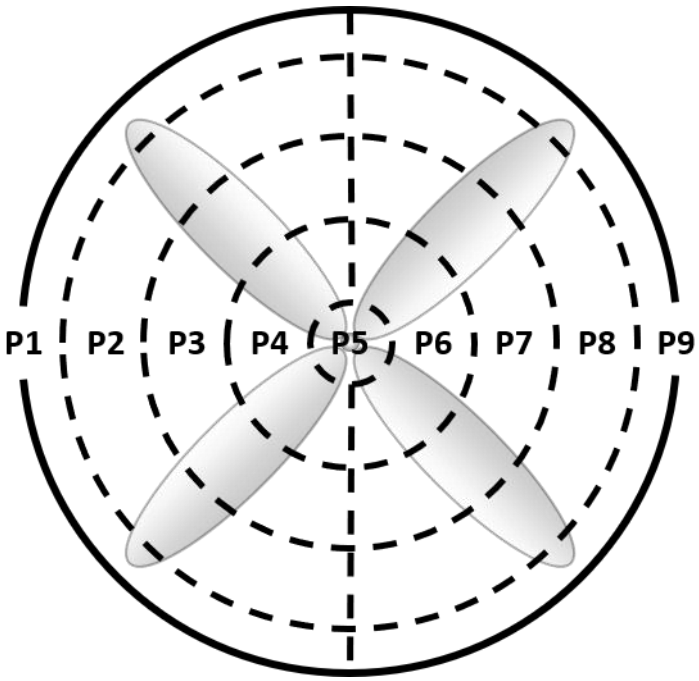
1. Drift droplets contain the same TDS concentration as source water.
2. Each drift droplet produces a single dry, spherical particle upon evaporating.
3. The density of the resultant dry particle is 2.6 g/ cm3, which was determined by averaging salt densities from the major anions and cations in the TDS analysis. The researchers estimate that this value is within ±0.2 g/ cm3.
4. Drift droplets evaporate entirely before leaving the facility fence line.

To generate a representative size distribution for the entire tower, the researchers sampled at positions transiting from one edge of the stack to the other, crossing over the center. Figure 8 shows an example of the positions sampled across the top of the tower. The research team assume that droplet measurements at each location are representative of half of the annulus in which that position is located or, in the case of the center position, the entire center circle. The team then generated a size distribution representative of emissions from the entire tower by averaging measurements at each position, weighting for both area and updraft velocity (V_{up}). V_{up} was determined by averaging the velocities of all droplets for

each position sampled. These estimates were also used to derive volumetric flow for the entire tower, again assuming V_{up} for each position is representative of half of the annulus in which that position is located. Because the estimate for V_{up} does not account for the terminal velocity of each droplet, true air speed is slightly underestimated. However, because the terminal velocity of each droplet is at least two orders of magnitude lower than the true air speed, the estimates are considered to be within 1 percent of the actual values.

For Tower 1, the research team sampled at nine positions, as shown in Figure 8, sampling at each position for 3 minutes. The researchers also sampled at two additional positions, slightly outside of the stack and equidistant from P1 and P9 but recorded no drift droplets in these positions. For Tower 2, the team employed a similar sampling technique as shown in Figure 8, but with seven positions instead of nine, due to the smaller size of the tower. Each position at Tower 2 was sampled for 5 min.

Figure 8: Birds-Eye View of Idealized Positions Sampled Over a Cooling Tower



Each position, denoted P1- P9, is assumed to represent the emissions for the area in which that position is bounded by dotted lines. A representative size distribution for the stack is determined by weighting measurements obtained at each position for both the areal coverage that they represent and updraft velocity in that area.

Source: Anthony Wexler

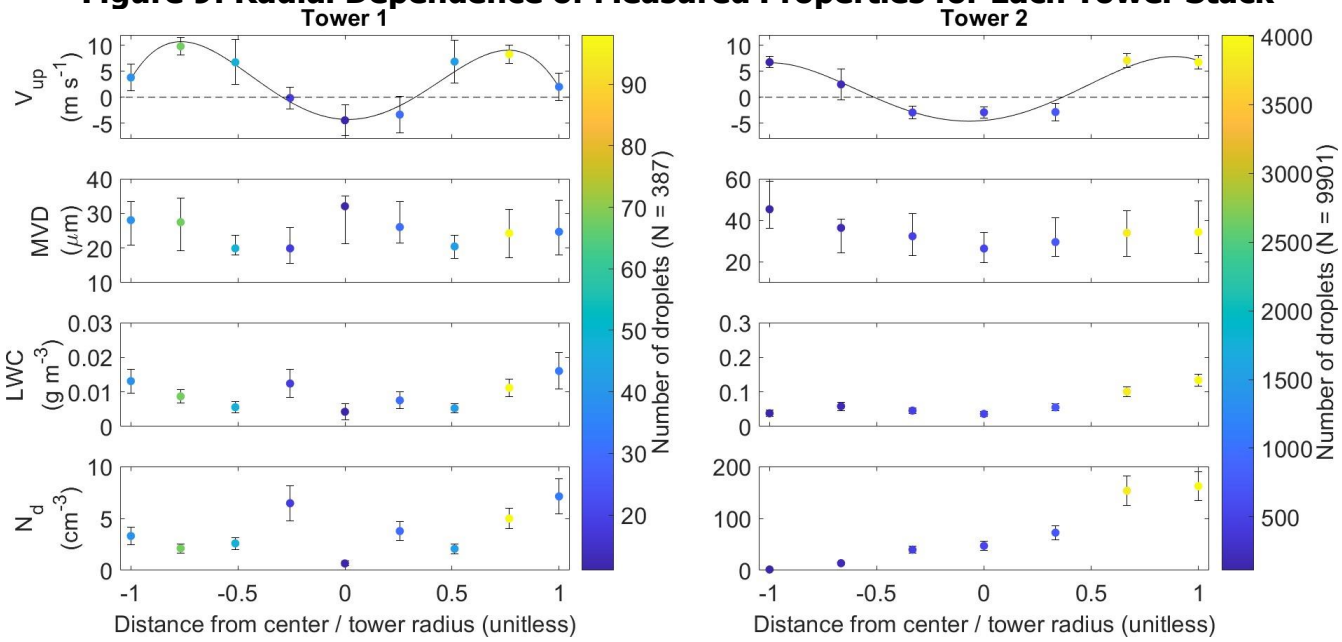
Results and Discussion

Radial Dependence of Properties

In collecting measurements during transits across each tower, the researchers observed a strong radial dependence on the drift droplet properties observed. Figure 9 shows how V_{up}, median volume diameter (MVD), liquid water content (LWC), and number concentration (N_d) varied radially across each tower. Tower radius was non-dimensionalized for better comparison between the two towers. Error bars in the first row represent ± one standard deviation in V_{up} and the solid black line represents a 4th-degree polynomial fit to the points.

Error bars in the second row represent the 25th and 75th percentiles of MVD at each position. Error bars in the third and fourth rows represent error in LWC and N_d, respectively, relating to Poisson counting uncertainty for each position. Color bars and corresponding-colored points represent the frequency of droplets encountered at each position, for each tower, with N total droplets observed at each tower.

Figure 9: Radial Dependence of Measured Properties for Each Tower Stack



Color bars and corresponding-colored points represent the number of drift droplets sampled in each position at each respective tower, with N total droplets sampled.

Source: Anthony Wexler

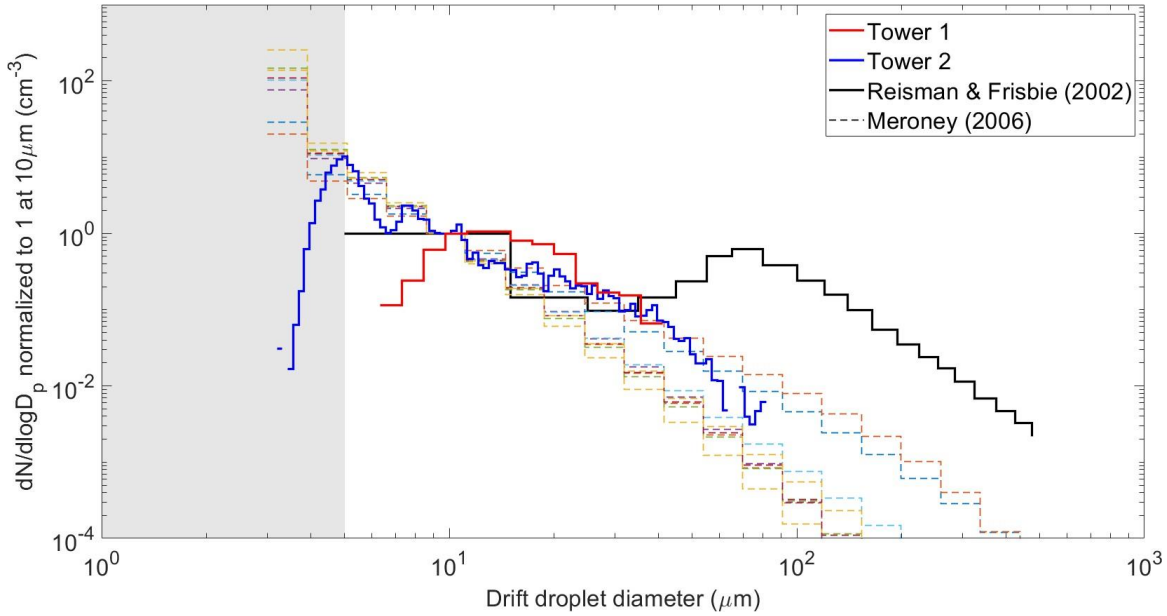
One feature in Figure 9 is that the updraft velocity at each tower becomes negative (that is, air flows downwards) near the center of the tower. This is not surprising given expected recirculation of air directly downstream of an axial fan hub, which then results in negative PM emissions towards the center of the tower, that is, particles enter rather than exit the tower. The research team also noticed an asymmetry in all other properties across the tower where one might expect symmetry in these properties. These asymmetries are attributed to environmental factors such as the ambient wind speed and direction that can influence the trajectory of the plume during sampling and/or the mixing of the plume with ambient air.

From a droplet emissions perspective, the two towers look very different from each other. Both the LWC and N_d are roughly an order of magnitude larger in the second tower compared to the first. This can likely be attributed to differences in tower design such as the type of drift eliminators installed, spray nozzle design, number and orientation of fan blades, fan speed, and water recirculation rate. Also, mineral buildup in the internal components of the tower can impact the size distribution of drift droplets and thus drift eliminator efficiency. Environmental factors such as relative humidity, wind speed, and wind direction may also impact these properties. Thus, the results of this study may not be generalizable to other cooling towers.

Drift Droplet Size Distribution

A representative size distribution of drift droplets was estimated for each tower from the measurements, and then compared to size distributions presented in previous studies (Figure 10). For better comparison, each distribution has been normalized by bin width and to a $dN/dlogD_p$ value of 1 at a droplet diameter of 10 µm. This normalization permits easier comparison of the shapes of the size distributions. The measurements for Towers 1 and 2 are presented with different size bin widths because the lower number of droplets measured in Tower 1 requires larger bins to have the same counting statistics. The gray area in the background of Figure 10 represents the size range in which assumptions inherent to the PDI begin to break down, thus, decreasing confidence in the measurements obtained. The size distribution representative of Tower 2 closely resembles certain ones described by Meroney (2006), while the distribution representative of Tower 1 does not resemble any previously reported distributions. The distribution reported by Reisman and Frisbie (2002) exhibits a second mode in the droplet size range of 70-80 µm, a feature not observed in any other distribution. This feature led Reisman and Frisbie (2002) to suggest that PM_{10} emissions could be decreased by increasing TDS concentrations in order to generate PM larger than 10 µm. This finding is not consistent with the measurements from this project. Meroney (2006) suggests that drift droplet size distributions may be bimodal, with the second peak occurring at larger droplet sizes, due to "inadequacies in design or subsequent maintenance of drift eliminators." The researchers do not see any evidence of bimodality in either of the towers surveyed.

Figure 10: Representative Size Distribution for Drift Droplets at Each Tower (Red and Blue Distributions) Compared to Size Distributions Reported in Previous Studies



Source: Anthony Wexler

Drift Eliminator Efficiency

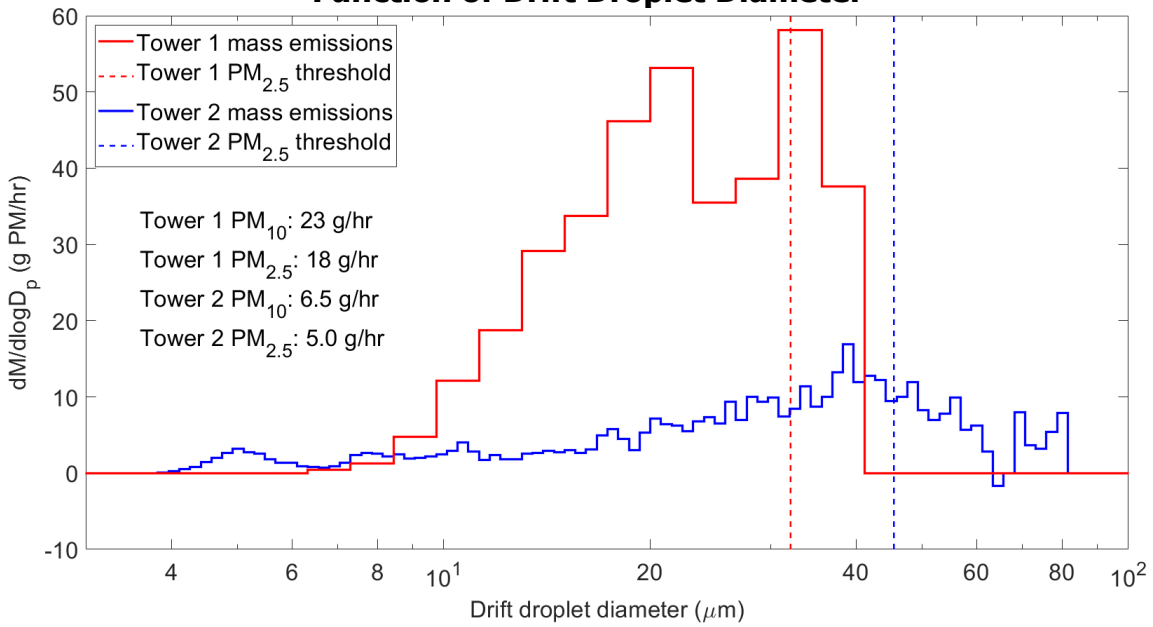
From these measurements, the drift eliminator efficiency of each tower and compare these values to manufacturer specifications can be computed. The team used the representative

size distributions derived by the measurements along with the water recirculation rate for each tower as reported in specifications sheets. For Tower 1, the measurements suggest a drift eliminator efficiency of ~5.6 × 10^{-5} percent, roughly an order of magnitude better than the reported nominal efficiency of 5 × 10^{-4} percent. For Tower 2, the research team estimates a drift eliminator efficiency of 1.3 × 10^{-3} percent, roughly two orders of magnitude better than the reported value of 0.2 percent. These findings suggest that the drift eliminators installed at each tower are much more efficient than manufacturers suggest. These calculations assume that the water recirculation rate is that from the tower specifications. If the actual flow rate is lower than specified, then the estimates of drift eliminator efficiency should be increased proportionally.

Particulate Matter Emissions from Drift

Using the derived size distributions along with measured TDS concentrations, the research team estimates PM_{10} and $PM_{2.5}$ emission rates for each tower (Figure 11).

Figure 11: Particulate Matter Emission Rate from Drift Droplets for Each Tower as a Function of Drift Droplet Diameter



Vertical dotted lines represent the threshold for drift droplets which would produce $PM_{2.5}$ upon evaporating based on measured TDS concentration at each respective tower. Total PM_{10} and $PM_{2.5}$ emission rates are summarized in text.

Source: Anthony Wexler

Vertical dotted lines represent the drift droplet size threshold in which droplets smaller than this value would produce $PM_{2.5}$ upon evaporating. All drift droplets produce PM_{10} upon evaporating, as the threshold for producing PM with a diameter greater than 10 µm is ~128 µm and ~182 µm for Towers 1 and 2, respectively, and no droplets greater than these sizes were observed. The measurements suggest that the large majority of drift droplets produce $PM_{2.5}$ upon evaporating, with 78 percent and 77 percent of the total PM_{10} emissions qualifying as $PM_{2.5}$ emissions for Towers 1 and 2, respectively. Assuming that the towers are operated continuously at the capacity measured, emissions of PM_{10} at Towers 1 and 2 are estimated as 23 and 6.5 g/hr, respectively, and emissions of $PM_{2.5}$ are 18 and 5.0 g/hr,

respectively. These emission rates are for a single cooling tower cell only, of which there often multiple at a facility. If emissions are normalized by the concentration of TDS in recirculating water, emissions for each of the two towers look remarkably similar. Towers 1 and 2 have emission rates of 0.019 and 0.015 grams of PM_{10} per hour per unit TDS, respectively. Because these two towers have major design and operational differences, more measurements are needed to determine if this similarity is meaningful or coincidental.

Currently the EPA AP-42 treats all cooling tower emissions as PM_{10}, but the measurements show that the majority of these emissions are $PM_{2.5}$ in size. This suggests that PM_{10} and $PM_{2.5}$ emissions should be considered when regulating cooling tower emissions.

A couple of assumptions are made in estimating these emissions. These calculations use the estimated dry particle density of 2.6 g/cm^3. Based on the species comprising TDS, this estimated density is likely to be within ±10 percent of the actual value. Also, EPA regulations specify that emissions are counted at the fence line and therefore any droplets that settle to the ground before reaching the boundary of the property are not considered emissions. From the measured drift droplet diameters, the maximum realistic settling velocities are a few centimeters per second. Given typical wind speeds and distances to the fence line, these drift droplets will fall at most a few meters before exiting the property, implying that almost all droplets should be considered emissions.

Comparing the PM_{10} emissions rate for each tower to that which would be calculated using methods outlined in EPA (1995), the researchers find that EPA (1995) overestimates the PM_{10} emissions rate by 89 percent for Tower 1 and 99 percent for Tower 2. In contrast to the findings of Reisman and Frisbie (2002) and Micheletti (2006), who argue that EPA (1995) overestimates emissions due to the assumption that all drift droplets produce PM_{10} upon evaporating, the researchers find that this overestimate is due to the discrepancy between the team's estimate of drift eliminator efficiency and the manufacturers' specifications.

Reisman and Frisbie (2002) suggests that increasing the TDS of recirculating water could result in PM emissions larger than 10 μm upon drift droplet evaporation, producing PM emissions that would not qualify as PM_{10}. TDS concentrations would need to increase ~4.7 fold and ~1.7 fold in each respective tower before even the largest droplets observed would produce particles larger than 10 μm. However, increasing TDS concentrations to these values would proportionally increase PM_{10} emissions for all other droplets. To ultimately decrease PM_{10} emissions, TDS concentrations would need to be increased to unreasonably high values ($\sim 10^3$ increase) so that the increase in PM_{10} due to higher TDS is offset by the decrease in PM_{10} due to particles exceeding this size range. Therefore, increasing TDS is not an effective strategy for decreasing PM_{10} emissions in either of the towers sampled.

Summary and Conclusions

This study reports particulate emissions from two cooling towers using measurements from a novel instrument package (Wallis et al., 2021a). The most relevant instrument for this study is the phase-Doppler interferometer (Chuang et al., 2008), which measures the ambient wet diameter of drift droplets, as well as their velocity. By locating the PDI at different positions across the cooling tower outlet, total tower drift emissions can be computed. There is strong radial dependence of spray drift droplet properties so it is important to sample at various places across the tower outlet for accurate emission estimates.

The researchers find that the measured drift droplet emissions for Tower 1 are roughly one order of magnitude lower than the drift eliminator specifications, while for Tower 2, this value is two orders of magnitude lower. Water TDS values are combined with the measured size distribution to estimate PM_{10} and $PM_{2.5}$ emissions (which, by definition, are dried particles), which for Tower 1 are 23 and 18 g/hr, respectively, while for Tower 2 are 6.5 and 5.0 g/hr, respectively. EPA AP-42 overestimates PM_{10} emissions for Tower 1 by 89 percent and Tower 2 by 99 percent. Cooling tower $PM_{2.5}$ emissions are not regulated, but the measurements made by this project suggest that they can be a large fraction of total particulate emissions, suggesting that regulation may be needed. Reisman and Frisbie (2002) have suggested that purposefully increasing TDS may result in particulate emissions larger than PM_{10}, and outside the regulated size range. The results from these two towers imply that this strategy would require $\sim 10^3$ increases in TDS which is unrealistic.

CHAPTER 4:
Positive and Negative Emissions from Cooling Towers: Particulate Matter

Background

Cooling towers are widely used in a variety of applications to remove large amounts of heat from industrial and commercial systems and dissipate it into the atmosphere. Wet cooling towers use recirculating water to draw waste heat and dissipate it to the environment through evaporation (Hollands 1974). An estimated two million cooling towers are in operation in the United States (Lowther 2017), in applications ranging from power generation to refrigeration to data centers. The interaction between cooling water and air required for evaporation in wet cooling towers results in emission of liquid spray drift droplets. These emissions are regulated by EPA AP-42, and are classified as PM_{10}. This determination and the corresponding calculation of emissions are based on decades-old measurements (Kinsey 1991). In this study, the researchers combine modern instrumentation with a direct sampling method to accurately measure wet and dry emissions from cooling towers, as well as to investigate potential scrubbing effects of towers on ambient particles.

Theory

Cooling Tower Operation

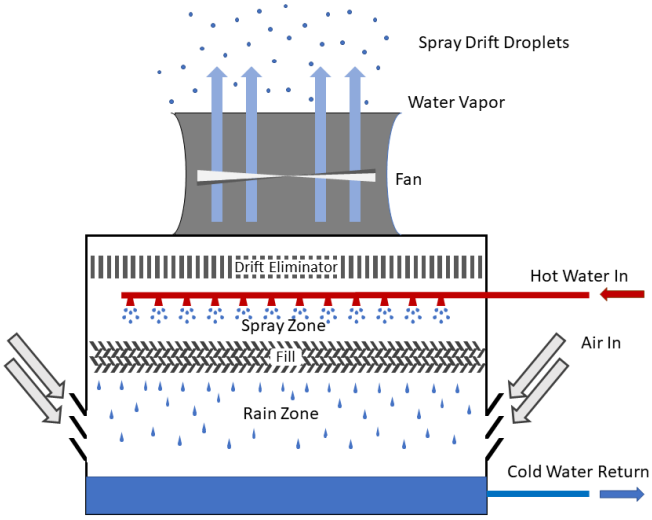
Mechanical draft wet cooling towers use evaporation of water to transfer heat to the environment. Waste heat is transferred from the primary process to recirculating water. The heated water is sprayed within the tower and subsequently enters a region of fill material designed to produce high surface area exposure to passing air (

Figure 12). Air is drawn into the tower and through the fill zone, and subsequently passes out of the tower outlet. Heat is transferred primarily through evaporation of water, taking advantage of latent heat of evaporation. The remaining cool water is then recirculated for reuse in the cooling system. In addition to the water vapor exiting the tower, a small fraction of the liquid spray become entrained in the air flow and escapes as spray drift. In modern cooling towers, drift eliminators of various designs are employed above the spray zone to reduce escape of liquid water droplets from the tower, which reduces emissions.

Emissions

Tower emissions occur as liquid spray drift droplets escape. After exiting the tower, liquid droplets eventually evaporate, resulting in particulate matter consisting of TDS in the recirculating water. These cooling tower emissions are regulated by EPA AP-42, which assumes that the dissolved solids form PM_{10}, while acknowledging that this assumption is likely conservative. AP-42 was last updated in 1991, and the conservative emission estimate reflects that EPA found no single measurement method to be wholly satisfactory and definitive at the time (Kinsey 1991).

Figure 12: Mechanical Draft Cooling Tower Operation



Source: Anthony Wexler

Aerosol emissions measured after drying consist of dried spray drift emissions as described above as well as ambient PM that has entered and subsequently exited the tower. Because ambient PM concentrations may be significant in comparison to tower-generated emissions, it is critical to characterize background aerosol to fully understand the contribution of spray drift to the tower effluent. In addition, spray droplets within the tower have potential to scrub ambient particles from the air.

Drift droplets exiting the tower ultimately evaporate in the environment leaving impurities from the water. Analysis of recirculating water TDS and composition is critical to prediction of tower emissions (Leandro et al. Submitted). Characterization of tower emissions requires analysis of both liquid droplet emission and eventual dried aerosol. Numerous studies have sought to characterize one or both aspects of tower emissions. Broadly, they are divided into attempts to characterize droplet emissions, and attempts to characterize mineral emissions. Droplet characterization often uses optical techniques including photography, light scattering, and chemically reactive paper which indicates droplet impacts with color changes (Roffman and Van Vleck 1974; Kinsey 1991; N. C. Chen and Hanna 1978; Golay, Glantschnig, and Best 1986). These techniques vary in accuracy, which suffers for smaller particles. Previous efforts to characterize dried aerosol largely center around measurement of total mineral mass flux. As such, detailed information regarding dry particle size distributions may be lost as particles are collected in bulk or are size selected while wet.

Methods

To accurately measure emissions from cooling towers, the researchers opted to directly characterize both liquid drift droplets and ultimately dry aerosol emissions at the exit of each tower. An instrument package was assembled and suspended by a crane directly above a series of active cooling towers to perform real-time characterization and to collect size-segregated samples for additional analysis. Dry emissions were obtained by rapidly drying droplets emitted from the tower prior to sampling and characterization. Simultaneous sampling

was performed at a nearby location to characterize ambient aerosol to differentiate it from tower emissions. Instrumentation is detailed in a companion paper (Wallis et al. Submitted).

Instrumentation

In brief, an open frame chassis was equipped with instrumentation including a PDI, IMPROVE $PM_{2.5}$ and PM_{10} samplers, a TSI Dusttrak, and a TSI APS. The sampling end of the instrument was positioned approximately 1 meter above the tower mouth unless otherwise noted. The PDI characterized spray drift droplets in situ as they exited the tower. Simultaneously, wet tower emissions were isokinetically drawn into a bank of Nafion diffusion dryers (Model MD700, Perma Pure, Toms River, NJ), where the droplets were rapidly dried. The dried aerosol cores were then characterized using the TSI APS and Dusttrak, as well as collected by IMPROVE $PM_{2.5}$ and PM_{10} samplers on PTFE filters for subsequent gravimetric and XRF spectrometry (Solomon et al. 2014; Hyslop et al. 2018; Indresand et al. 2013). Sampling was controlled remotely, and vital statistics including temperature, humidity, updraft velocity, and flow rates were recorded using a custom electronics package and transmitted to a ground station in real-time. A second sampling package, also composed of IMPROVE samplers, a Dusttrak, an APS, and temperature and humidity probes, was deployed on the ground near the tower entrance to characterize ambient air particle mass concentrations and compositions.

Instrumentation chosen for this study provides several advantages compared to previous tower characterizations. The PDI maintains a high level of accuracy and precision across its droplet detection size range of 2 μm to 2 mm. In contrast, methods based on photography, chemically reactive paper, and light scattering often suffer from low measurement accuracy, particularly when detecting smaller droplets (Golay, Glantschnig, and Best 1986; Kinsey 1991). Real-time particle drying on the instrument allows characterization of dried aerosol without dilution associated with sampling farther from the tower mouth, and, in contrast to bulk collection and analysis methods preserves the dried particle sizes. The TSI APS enables size characterization of dried aerosol on reasonable time scales and represents a significant advance in precision compared to bulk collection methods. Finally, IMPROVE PM samplers take advantage of the rapid on-board drying system to collect $PM_{2.5}$ and PM_{10} samples directly from the tower exit for gravimetric and elemental characterization.

Cooling Towers

For this study, three mechanical draft counter flow cooling towers were sampled. Towers 1 and 2 were the basis of the primary measurements for this study, and a consistent sampling regimen was used for these towers. Tower 3 was sampled chronologically earlier than Towers 1 and 2, and served partially as a test bed for equipment, methods, and sampling protocols. The sampling protocol for Tower 3 varied from the one used in the other towers and some data for Tower 3 is therefore not directly comparable. However, Tower 3 offers additional insight into some aspects of tower characterization due to the altered sampling protocol, as well as due to the operating parameters of the tower. Tower specifications are shown in

Table 4.

Table 4: Cooling Tower Specifications, If Available

	Tower 1	Tower 2	Tower 3
Manufacturer	Marley Cooling Tower Company	The Fluor Company	Composite Cooling Solutions
Model	W4119A-6.0-08	2FPA1144-1830BBLP	Phoenix FRP Counterflow 1FT-3024-75-P6
Construction Date	2004	1957	2012
Tower Type	Mechanical Draft Counterflow	Mechanical Draft Counterflow	Mechanical Draft Counterflow
Fill Type	PVC Film Fill Packs	Marley MX75 Crossflow	PVC, VOC-Pac 21
Drift Eliminator	PVC Cellular Packs	Not Available	PVC, CDE-150
Nominal Fan Diameter (ft) [m]	32.8 [10.0]	13.1 [4.0]	18 [5.5]
Nominal Water Flow Rate per Cell (gpm) [l/m]	18375 [69557]	5000 [18927]	4745 [17962]
Nominal Air Flow Rate (cfm) [m3/s]	1733146 [818]	460000 [217]	411425 [194]
Nominal Drift Loss (%)	0.0005	0.2	0.0051
Measured Drift Loss (%)	0.000054	0.0017	Not Available
Design Evaporation Loss (gpm) [l/m]	2513	Not Available	64.8
Sampling Height (m)	1	0.7	1.5
Supply Water Temperature (°C)	30.9 $\pm$ 0.9	29.7 $\pm$ 0.2	Not Available
Return Water Temperature (°C)	24.1 $\pm$ 0.5	23.0 $\pm$ 0.4	Not Available
Conductivity-based TDS (ppm)	1192	370	1334
Notes			Variable fan speed depending on load

Source: Anthony Wexler

Tower 1

Tower 1 is located at a power plant in northern California and is of recent construction. It was chosen due to the high TDS value of its circulating water. All measurements were taken from a

single cell located toward the center of an array of eight cells. A single set of filters was run for four consecutive days, from 2019/06/25 to 2019/06/28, totaling approximately 20 hours. Separate filters were used for transect sampling and abbreviated sampling at additional positions. Extended sampling for collection of $PM_{2.5}$ and PM_{10} filters was performed at approximately 3 meters from the center of the stack.

Tower 2

Tower 2 is located at a coastal power plant in southern CA. It was chosen due to the low TDS value in its circulating water. Two small, older-model cooling tower cells are used at this facility to dissipate bearing heat. Sampling was conducted on the eastern cell. A prevailing westerly wind blew from the ocean.

Sampling was performed over the course of two extended days on 2019/09/26 and 2019/09/27 from approximately 8am to 8pm. An ultrasonic anemometer (Model 81000, R.M. Young Company, Traverse City, Michigan) was deployed to the railing surrounding the top deck of the cooling tower to log ambient wind speed and direction at the cooling tower exit. Sampling for both days was collected for the same sampling position, resulting in approximately 24 hours of flow on a single set of filters.

Tower 3

Tower 3 is used to remove waste heat from a facility suppling chilled water to a university campus. It was used as a testbed for the instrument package and protocols. The tower was run on a feedback loop in which fan speed responded to recirculating water temperature, which in turn varied with demand for chilled water throughout the day. Sampling typically began in the late morning once chilled water was in demand and the tower was operating at higher capacity. Samples were collected at Tower 3 on May 14, 2019, May 17, 2019 and May 20, 2019, on days without rain. Days 2 and 3 followed periods of rain, likely resulting in decreased ambient particle concentrations noted in the sample data. Separate filters were used for sample collection on each of the three sampling days.

Sampling Location

After arriving at each sampling site, transverse sampling sweeps of the cooling cell were performed to establish position limits and characterize emissions across the cell using real-time drift droplet and dry aerosol instrumentation. The sampling end of the instrument was vertically located as close to the tower mouth as possible while maintaining a safe operating condition. Safe operating height varied between 0.7 – 1.5 meters above the edge of the tower fan stack. After surveying sampling sites across the full diameter of the cell, a sampling site located at approximately 2/3 of the tower radius from the tower center was chosen for extended sampling. Continuous sampling at a single location was necessary to collect sufficient sample for gravimetric and XRF analysis. This choice of location typically was near the peak particle count and avoided mixing from outside air at the edge of the tower and low velocity near the fan hub. A crane held the sampler in a stationary position, and two guide ropes attached the instrument to anchors on the tower structure for stability.

Sampling and Data Analysis Methods

IMPROVE Samplers

IMPROVE $PM_{2.5}$ and PM_{10} samplers were used to gather PM samples both above the tower and at a nearby ground location at each sampling site. The $PM_{2.5}$ and PM_{10} sampler types collected dry aerosol samples onto pre-weighed 25mm PTFE filters (Teflo 3 µm, Pall Corporation, Port Washington, NY) at flow rates of 23 lpm and 16.9 lpm, respectively (Solomon et al. 2014). The samples were subsequently analyzed at UC Davis. Samples were held in a temperature and humidity-controlled chamber for 24 hours before weighing (IMPROVE 2020b). After post-weighing, filters were analyzed using XRF by the IMPROVE program (IMPROVE 2018; 2017; 2020a) at UC Davis using a PANalytical Epsilon 5 (Malvern PANalytical, UK). This technique is capable of quantifying component concentrations for elements from sodium to lead. The XRF system is described in further detail by Indresand et al. 2013. PM Coarse (sizes between 2.5 and 10 µm) was determined by subtraction of $PM_{2.5}$ from PM_{10}.

Water Samples

Water samples were collected at each sampling site. The water was representative of the recirculating water in the cooling tower. Where possible, it was collected from the recirculating line. At Tower 2, no sampling tap was available on the recirculating water line, so samples were taken from the bearing cooling facility that supplied warm water to the cooling tower, and from the water returning from the tower to the collection pool. The samples were analyzed by Chemtreat (Ashland, VA) for pH, conductivity, and chemical composition including P-alkalinity, M-alkalinity, calcium hardness, magnesium hardness, iron, copper, zinc, sodium, potassium, chloride, sulfate, nitrate, ortho-phosphate, silica, and phosphonate. Where necessary, adjustments were made for mass completion to translate these measurements to the equivalent masses for the corresponding elements determined by XRF.

Aerodynamic Particle Size

Aerodynamic particle size data for dry aerosol were collected at 5-minute intervals, for 60 seconds, using two model 3321 APSs (TSI Inc, Shoreview, MN) located on the tower instrument package and on the ground sampling package. Data were analyzed as mass concentration assuming a density of 2.6 g/cm^3. A side-by-side comparison of the aloft and ground APS units, including the sampling train leading to the aloft APS, was performed at UC Davis to create a correction factor to account for particle line loss as well as instrument variability. At the beginning of each field sampling day, the aloft instrument was run outside of the plume near the ground instrument to generate collocated data to account for instrument drift over time.

Phase Doppler Interferometer

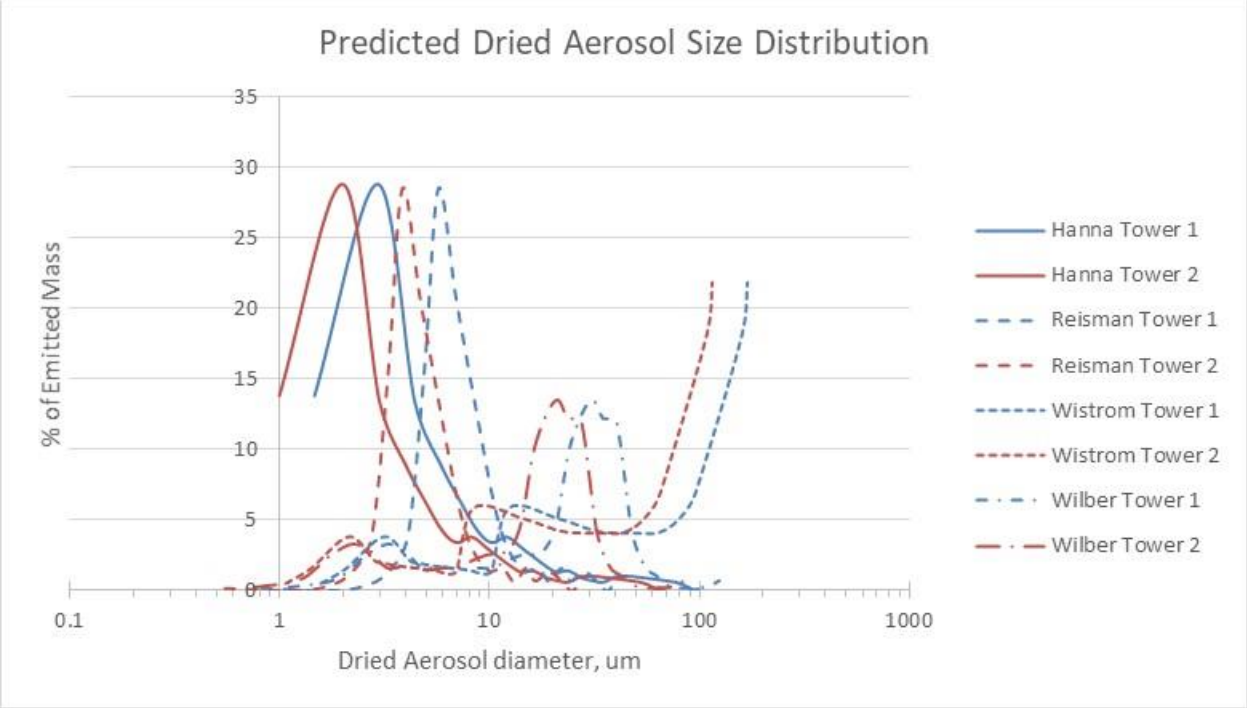
A PDI flight probe (Artium Technologies Inc, Sunnyvale, CA) was mounted to the sampling region of the instrument package to characterize liquid spray drift emitted from the tower. Two PDI channels were used to analyze droplets ranging from 2 µm to 2 mm in diameter. Detailed description is provided in a companion paper (Leandro et al. Submitted).

Results and Discussion

Modeling

Emissions were modeled using droplet size distributions from the literature (Hanna, Briggs, and Hosker Jr 1982; Reisman and Frisbie 2002; Wistrom and Ovard 1973; Wilber and Vercauteren 1986) in combination with analysis of recirculating water at each tower. Using the method proposed in AP-42, estimations of dried aerosol emission were performed for each tower using previously observed droplet distributions. Results for the two towers studied are shown in Figure 13.

Figure 13: Dried Aerosol Size Distribution Estimated for Towers 1 and 2 Using Characterizations from Literature



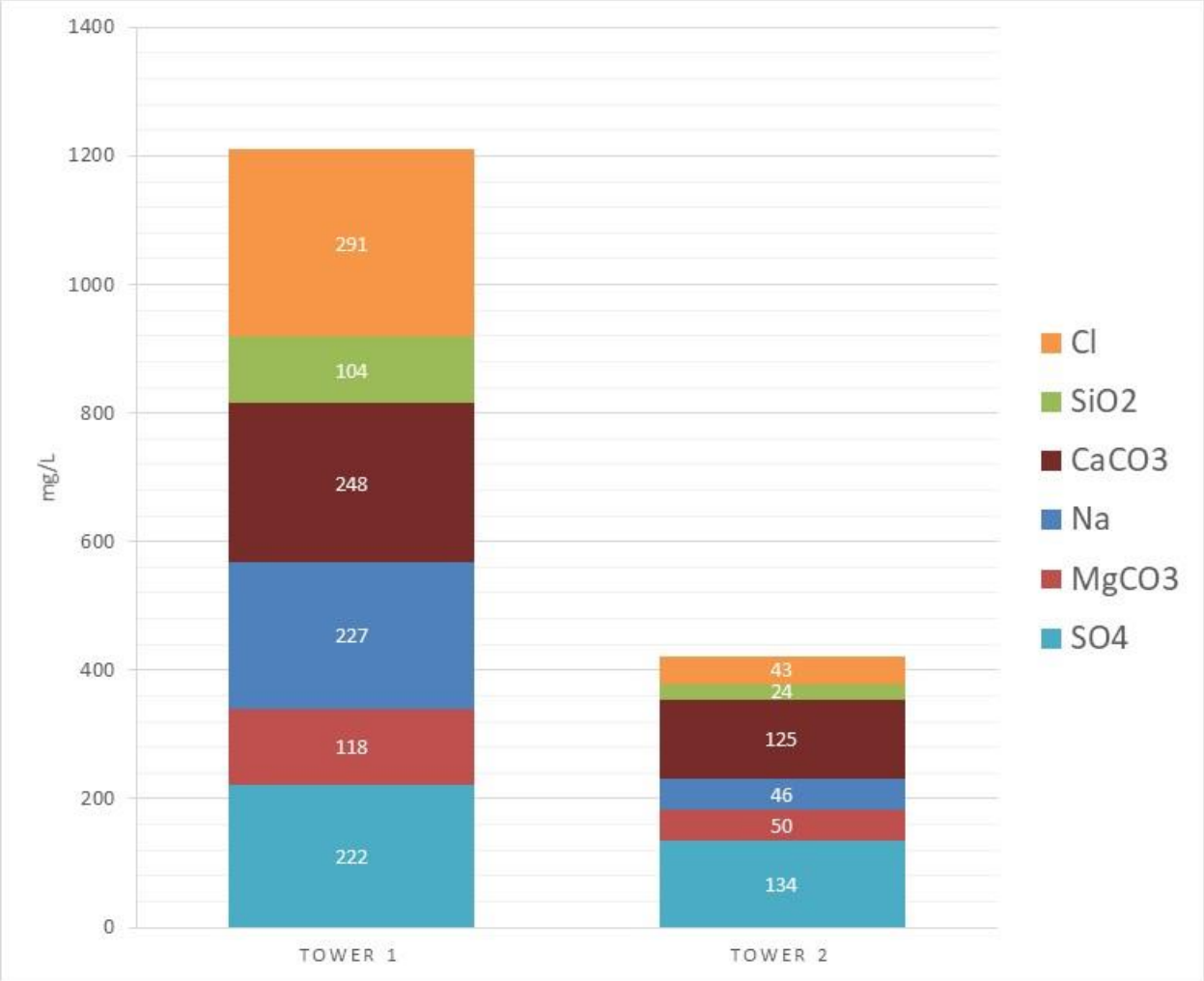
Source: Anthony Wexler

The wide range of dried particle sizes predicted for each tower stems from varying findings in previous studies of the droplet size distribution. Mass median diameter predictions for dried aerosol using Tower 1 water vary from as little as 4 μm to over 100 μm, depending on which drift droplet model is used. Drift droplet size distribution is a function of particular tower spray models, tower operating parameters such as air velocity and spray rate, physical tower design, drift eliminator design and effectiveness, and is also subject to measurement uncertainty (Kinsey 1991; N. C. Chen and Hanna 1978; Ruiz et al. 2013; Viljoen 2006).

Water Composition

Water composition and TDS is shown in Figure 14. The towers sampled represent TDS values ranging from approximately 400-1200 mg/L.

Figure 14: Tower Water Primary Components



Source: Anthony Wexler

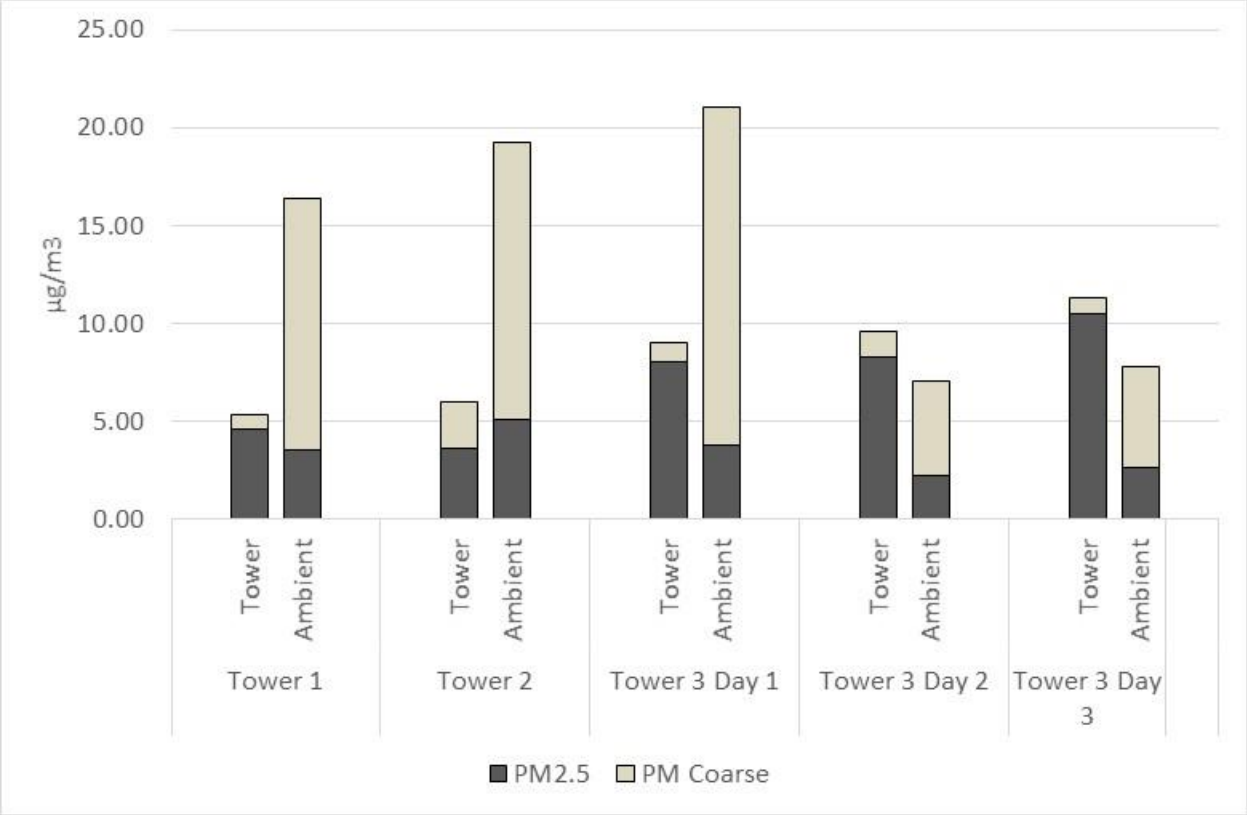
Mass

Mass concentration was obtained by gravimetric analysis of PTFE filters collected in aloft and ground IMPROVE $PM_{2.5}$ and PM_{10} samplers. Figure 15 and Table 5 compare coarse and fine mass data for each tower. Tower samples were collected on separate filters for each sampling day. Mass results from all towers show decreased coarse mass at the tower exit compared to corresponding ambient samples. Tower 3 had notably high ambient coarse mass on day 1. Days 2 and 3 followed a period of rain and had lower levels of coarse PM in comparison. Despite the change in background coarse PM, the coarse PM observed at the tower outlet remains fairly constant, suggesting that significant coarse particulate scrubbing is occurring and that much of the coarse PM observed at the tower exit originated from the spray drift.

Fine PM results for each tower vary compared to ambient. Tower 1 showed higher fine PM compared to ambient, while that for Tower 2 was lower. This is consistent with Tower 1's considerably higher TDS. In addition to having a low TDS, scrubbing of ambient $PM_{2.5}$ is necessary to achieve the lower-than-ambient result for Tower 2. Tower 3 consistently had high levels of fine PM and very little coarse PM above the tower stack. The measurements reported here sharply contrast those in prior work where $PM_{2.5}$ mass concentrations reported to be low

or insignificant (Kinsey 1991; Reisman and Frisbie 2002; Wilber and Vercauteren 1986; Wistrom and Ovard 1973).

Figure 15: Fine and Coarse Mass Concentration

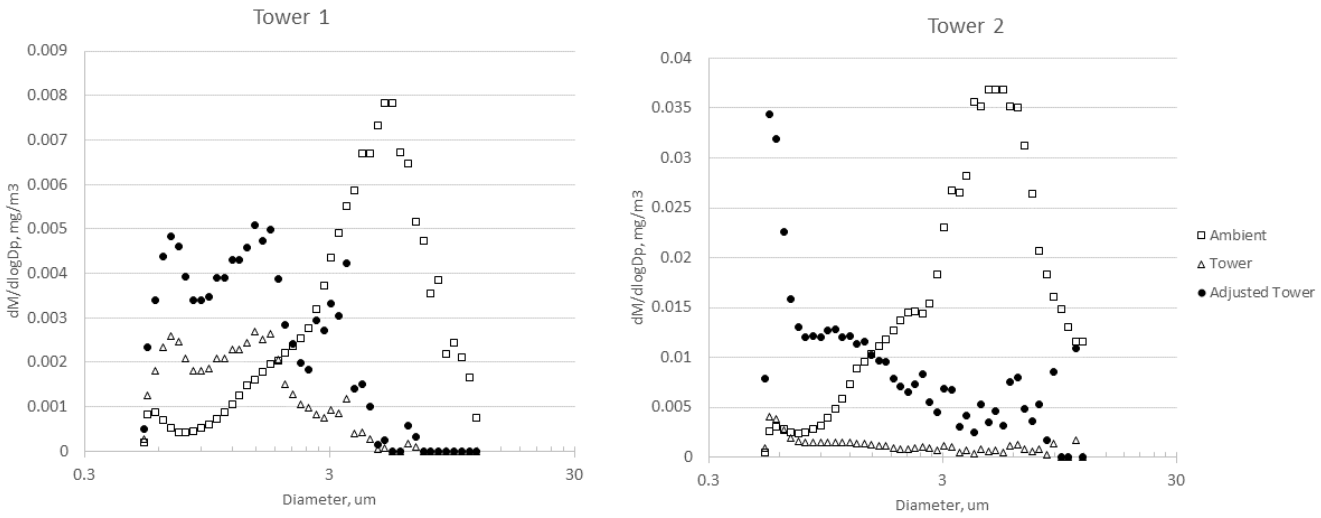


Source: Anthony Wexler

Size Distribution

Figure 16 shows particle size distributions measured on the ground and of dried PM from the tower exit. Aloft measurements are presented as corrected for instrument variation only (Tower) and with an additional correction for observed mass difference between PDI measurements and IMPROVE mass measurements for coarse and fine particles. This correction factor considers droplet losses when entering the nozzle due to lateral velocity and impaction. Tower 1 aloft PM had a mass median aerodynamic diameter (MMAD) of 1.2 µm, compared to 4.5 µm MMAD for the ambient air. Tower 1 had MMADs of 1.3 µm and 4.3 µm for tower sample and ambient sample, respectively. Both towers show a notably higher concentration of ambient PM at larger diameters. For Tower 2, emissions from the tower only exceed ambient for aerodynamic diameters below 0.6 µm. For Tower 1, tower emissions exceed ambient for aerodynamic diameters below 1.8 µm. This is consistent with gravimetric observations that both towers appear to be net scrubbers of coarse PM, and with the observation that Tower 1 had slightly higher than ambient fine PM while Tower 2 had slightly lower than ambient PM.

Figure 16: Aerodynamic Particle Sizer-Based Size Distribution



Adjusted concentrations include correction factor observed by comparing PDI and gravimetric results for $PM_{2.5}$ and PM Coarse.

Source: Anthony Wexler

Drift Droplets

Drift droplets escaping the tower were characterized in both the static sampling position during PM sample collection, as well as during transverse sweeps spanning the full tower diameter. A complete characterization of these findings is described in the companion paper (Leandro et al. Submitted). In the static sampling position, Tower 1 was observed to emit drift droplets ranging from 5.9 – 90.5 µm in diameter with a Sauter mean diameter of 23.0 µm, while Tower 2 emitted a great number of droplets ranging from 2.5-98.8 µm in diameter with a Sauter mean diameter of 28.1 µm. If drift droplets contain the same water chemistry as the recirculating water, nearly all droplets observed are predicted to form PM_{10} upon evaporation, and the large majority of these are predicted to form $PM_{2.5}$. Predicted coarse-to-fine mass ratios of 0.33 and 0.48 for Towers 1 and 2, respectively (Leandro et al. Submitted). This is again consistent with the general trend observed from gravimetric analysis. Drift droplet size distribution is expected to vary with each individual tower according to variables including tower design, drift eliminator design, air velocity, and nozzle type. Of the previous characterizations discussed in Section 5.1, the droplet distributions observed at Towers 1 and 2 align most closely with those by Chen and Hanna 1978 and Reisman and Frisbie 2002, and exhibit a much smaller size distribution than the characterizations of TP73-01 and TS86-01. High sensitivity of the PDI measurement to small size particles compared to other characterization methods may also contribute to this discrepancy.

Table 5: Particulate Matter Elemental Composition

		Tower 1				Tower 2			
	Concentration Uncertainty (ug/m3)	**Ambient PM_{10}**	**Ambient $PM_{2.5}$**	**Tower PM_{10}**	**Tower $PM_{2.5}$**	**Ambient PM_{10}**	**Ambient $PM_{2.5}$**	**Tower PM_{10}**	**Tower $PM_{2.5}$**
Na	Conc.	0.336	0.190	0.423	0.346	2.511	0.886	0.320	0.163
	Uncertainty	0.143	0.083	0.179	0.147	0.102	0.062	0.079	0.058
Mg	Conc.	0.131	0.025	0.052	0.036	0.309	0.078	0.092	0.033
	Uncertainty	0.029	0.006	0.012	0.009	0.028	0.020	0.028	0.020
Al	Conc.	0.648	0.046	0.153	0.040	0.252	0.024	0.969	0.014
	Uncertainty	0.072	0.006	0.016	0.004	0.012	0.008	0.024	0.008
Si	Conc.	1.709	0.106	0.163	0.089	0.656	0.053	0.075	0.041
	Uncertainty	0.129	0.008	0.012	0.007	0.013	0.005	0.006	0.005
P	Conc.	0.010	0.003	0.005	0.004	0.000	0.000	0.002	0.000
	Uncertainty	0.002	0.001	0.001	0.001	0.007	0.005	0.007	0.005
S	Conc.	0.335	0.308	0.325	0.315	0.600	0.460	0.377	0.346
	Uncertainty	0.026	0.024	0.026	0.025	0.020	0.015	0.020	0.015
Cl	Conc.	0.232	0.038	0.396	0.338	3.835	0.465	0.141	0.087
	Uncertainty	0.026	0.004	0.044	0.037	0.056	0.007	0.002	0.002
K	Conc.	0.165	0.026	0.034	0.027	0.181	0.039	0.023	0.021
	Uncertainty	0.014	0.003	0.003	0.003	0.003	0.002	0.002	0.001
Ca	Conc.	0.240	0.027	0.152	0.132	0.332	0.047	0.174	0.176
	Uncertainty	0.024	0.003	0.015	0.013	0.006	0.003	0.005	0.004
Fe	Conc.	0.533	0.040	0.060	0.036	0.245	0.026	0.033	0.023
	Uncertainty	0.045	0.004	0.006	0.004	0.009	0.003	0.005	0.003
Cu	Conc.	0.002	0.000	0.002	0.001	0.005	0.001	0.020	0.018
	Uncertainty	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
Zn	Conc.	0.009	0.001	0.001	0.001	0.008	0.001	0.003	0.003
	Uncertainty	0.001	0.000	0.000	0.000	0.002	0.001	0.002	0.001

Source: Anthony Wexler

Composition Analysis

XRF analysis of $PM_{2.5}$ and PM_{10} filters was used to determine elemental composition of aerosol gathered from each tower exit and from the surrounding environment. Twenty-four elements were analyzed. Elemental concentrations less than 5X uncertainty were removed from analysis. Table 5 shows the results of this analysis. Coarse PM values were calculated as the difference between these measurements.

To help quantify the relative contribution of tower water and ambient PM to tower emissions, the researcher team modeled the total tower emissions as the sum of ambient PM contribution (first term on the right-hand side) plus spray drift contribution (second term on the right-hand side):

$$C_i^X = (1 - \alpha_i)C_i^A + LC_i^W\eta \qquad (1)$$

where, for each element *i*, C_i^X is the concentration exiting the tower, C_i^A is the ambient concentration, α_i is the scrubbing efficiency, L is the liquid water content, C_i^W is the concentration of *i*th element in tower water which is assumed is the same as in the spray drift, and η is the nozzle sampling efficiency derived from comparison of aloft gravimetric results and PM emissions predicted from PDI measurements. Equation 1 applies for each element in the fine and coarse fractions and for total mass in these fractions.

All variables in Equation 1 were measured or deduced from measurements except the scrubbing efficiency. The scrubbing efficiency α was determined by minimizing the combined error between measured net emission and calculated net emission for each element for each tower and size range. Error was weighted as percent error as well as signal-to-uncertainty ratio for tower and ambient measurements for each element. The calculation was repeated using only mass to determine an α value in each size range. Scrubbing efficiency varies with dry particle size and will therefore vary by element depending on the prevailing particle size for each element in the aerosol entering the tower. Use of elemental data provides a wider data set with increased ability to differentiate ambient particles from those originating from tower spray, while use of overall gravimetric data provides higher measurement-to-uncertainty ratio for input parameters. Table 6 lists the scrubbing efficiency values.

Table 6: Scrubbing Efficiency Calculated Using Elemental Data and Mass Data

	α_{fine} [Elements]	α_{fine} [Mass]	α_{coarse} [Elements]	α_{coarse} Mass]
Tower 1	0.17	0.97	0.95	0.99
Tower 2	0.39	0.99	0.97	0.99

Source: Anthony Wexler

Scrubbing efficiency was consistently calculated to be above 90 percent for coarse particles at both towers using both elemental and mass data. Scrubbing efficiency for fine particles showed large uncertainty, ranging from 17-39 percent using elemental data, and as much as 99 percent using only mass data. Spray drift is estimated to contribute between 27-49 percent of the fine PM and 21-31 percent of the coarse PM sampled from above Tower 1, and less than 54 percent of the fine PM and 74-89 percent of the coarse PM at Tower 2. The initial estimates for η are made by assuming that PM above the tower is from spray drift, thereby

providing an upper bound for η. Varying values of η over a reasonable range provides a range of possible scrubbing efficiencies for each tower and PM size range resulting in fine particle scrubbing efficiency estimates between 7-35 percent for Tower 1 and less than 67 percent for Tower 2. Coarse particle scrubbing efficiency results remained more tightly bounded, ranging between 95-96 percent for Tower 1 and between 95-98 percent for Tower 2. Tower 2 experienced a persistent crosswind of similar magnitude to the updraft velocity, likely resulting in increased droplet loss at the nozzle inlets. Scrubbing efficiency calculation is expected to be more reliable for coarse particles since the range spans a more limited size range and so can be more accurately described by a single efficiency term. Fine particle scrubbing efficiency appears to be lower than coarse, but uncertainty is high for this size range, possibly because the different elements in ambient air have different size distributions leading to differences in their scrubbing efficiency. This trend of high scrubbing efficiency for coarse PM and reduced $PM_{2.5}$ scrubbing efficiency, as well as higher $PM_{2.5}$ scrubbing efficiency in Tower 2, is consistent with gravimetric results and APS data.

To determine whether these scrubbing efficiency values are consistent with impaction by droplets within the tower, scrubbing of ambient particles by droplets was estimated using a model based on nozzle spray characteristics described in previous reports. Scrubbing may also occur in the tower rain zone, below the fill, and in the fill itself. Droplets were modeled as between approximately 1-5 mm diameter based on a previous characterization of droplets in the spray zone and rain zone (Hollands 1974; Heidarinejad, Karami, and Delfani 2009; de Villiers and Kröger 1999; X. Chen, Sun, and Lyu 2019). Droplets were assumed to fall at terminal velocity relative to the upward velocity of the air being drawn through the tower and the ambient particles were assumed to have attained the upward velocity of the air. Considering the droplets as an impaction surface, a model can be made to predict removal efficiency of ambient particles as a function of droplet and particle diameter (Hinds 1999).

The likelihood of impaction between an ambient particle and a droplet is described by the Stokes number:

$$Stk = \frac{\tau V_{TS}}{d_d} \qquad (2)$$

where τ is the particle relaxation time, V_{TS} is the relative velocity between particle and droplet, equal to terminal settling velocity of droplet, and d_d is the characteristic length, in this case the droplet diameter.

For high Reynolds number, the terminal settling velocity of the droplet is given by

$$V_{TS} = \sqrt{\left(\frac{4\rho_d d_d g}{3C_D \rho_g}\right)} \qquad (3)$$

where ρ_d is the droplet density and ρ_g is the gas density. C_D is a discharge coefficient – for the range for Reynolds numbers in the set of conditions proposed, the discharge coefficient remains relatively constant at approximately 0.44.

For a dry particle, particle relaxation time τ is given by

$$\tau = \frac{\rho_p {d_p}^2 C_c}{18\eta} \qquad (4)$$

where ρ_p is the dry particle density, d_p is the particle diameter, C_C is the Cunningham Correction factor (equal to 1 for particles > 1 um), and η is the dynamic viscosity of air. Substituting for V_{TS} and τ from equations 2 and 3 into equation 4 gives

$$\frac{\rho_p {d_p}^2}{18\eta} = Stk\sqrt{\frac{3}{4}\frac{\rho_g}{\rho_d}\frac{C_D d_d}{g}} \qquad (5)$$

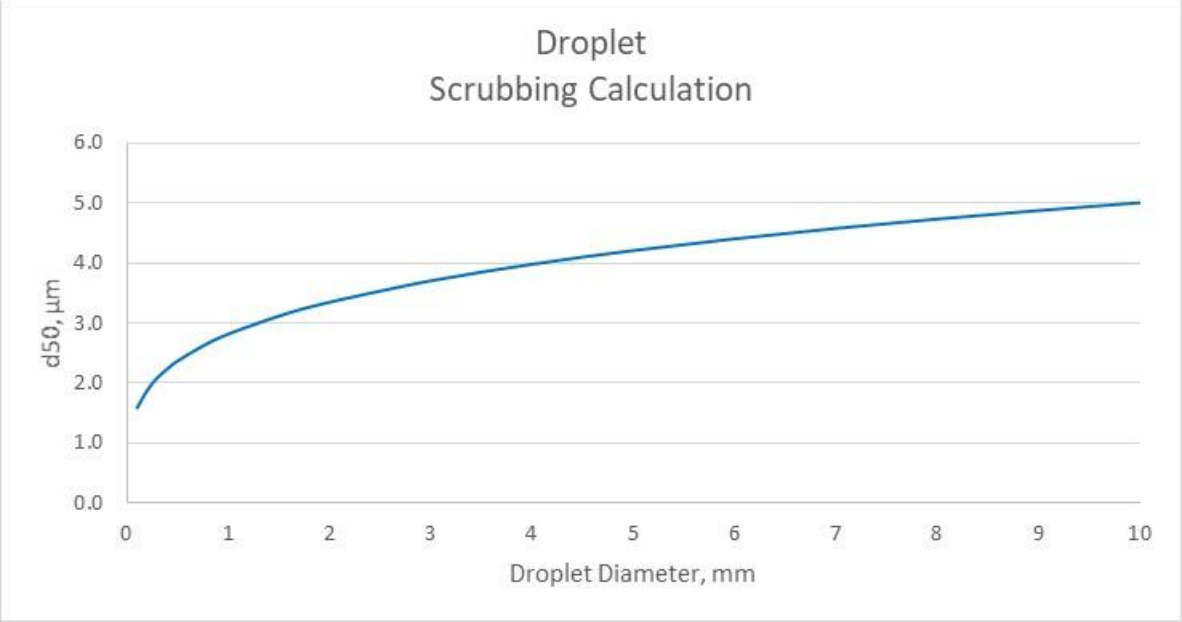
Rearranging, particle diameter can be expressed in terms of Stokes Number and other parameters as

$$d_p = 3\sqrt{Stk}\sqrt[4]{3\eta^2\frac{\rho_g}{{\rho_p}^2\rho_d}\frac{C_D d_{droplet}}{g}} \qquad (6)$$

50% probability of impaction (D_{50}) occurs at $\sqrt{Stk} = 0.49$.

Figure 17 shows calculated D_{50} for a range of droplet diameters. Larger droplet diameters result in increased D_{50}. The droplet diameter plays two roles: It determines the terminal settling velocity which tends to decrease the D_{50} and the characteristic dimension of the impaction surface, which tends to increase the D_{50} more than that of the velocity. D_{50} remains larger than $PM_{2.5}$ for nearly all droplet diameters, which is consistent with the findings from this project of high removal efficiency of coarse PM and lower removal efficiency for fine particles.

Figure 17: Scrubbing D50 Cut Point versus Droplet Diameter Assuming Impaction at Droplet Settling Velocity



Source: Anthony Wexler

Summary and Conclusion

Direct measurements of drift droplet size distribution, dried aerosol size distribution, and coarse and fine mass were made at active cooling towers and from the ambient air at each tower. High accuracy measurements of liquid drift droplets at old and new towers shows a

profile of droplets largely below 80 μm diameter, in contrast with a number of previous studies. Gravimetric and APS analysis of dried aerosol emissions further indicate a much higher fraction of $PM_{2.5}$ in dried emissions from these towers than that found in prior work, including EPA AP-42, which regulates wet cooling tower emissions. Furthermore, these analyses display a common trend of lower coarse PM mass in tower exhaust compared to the surrounding environment in the location studied, suggesting that significant scrubbing of ambient coarse particles occurs in the towers. The magnitude of this scrubbing effect for coarse and fine size ranges was quantified for different elements found in the towers sampled. Towers are found to have a high scrubbing efficiency on large ambient PM, and a diminished but significant scrubbing effect on fine PM.

CHAPTER 5:
Knowledge Transfer Activities

The technical advisory committee (TAC) met in April 2018. The TAC was composed of:

- Ben Kaldunski and Eladio Knipping, Electric Power Research Institute
- Michael DiFilippo, consultant. (author of CEC report 500-2005-170 and 500-2008-043)
- Richard Aull, Independent consultant
- Eric Poff, Sacramento Municipal Utility District
- Joe O'Hagan, CEC
- Gerry Bemis, CEC
- Wenjuh Qian, CEC
- Yu Hou, CEC

The research team plans to share the results from this project with state agencies, academic researchers, electric utilities, and other relevant stakeholders through the project's TAC members and the third parties listed above. This information will also be sent to all relevant air quality districts for their information.

The team also plans to summarize the results from this project in three journal articles: three papers have been submitted:

1. **An Instrument for Direct Measurement of Emissions: Cooling Tower Example**

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2. **Positive and Negative Emissions from Cooling Towers, Part 1: Droplet Measurements**

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3. Positive and Negative Emissions from Cooling Towers, Part 2: Particulate Matter

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The researchers also presented this work at the next Cooling Tower Institute annual conference in February 2022. The Cooling Technology Institute is the industry's forum for information on cooling systems for electric power generation.

CHAPTER 6: Conclusions

The measurements and modeling results led to a number of conclusions, namely:

(1) The use of brackish or fresh water does not influence emissions from cooling towers.

(2) Cooling towers scrub nearly all the coarse PM (the particulate matter between 2.5 and 10 µm) from the air that enters the cooling tower resulting in negative emissions.

(3) In regions of California with elevated PM_{10} and $PM_{2.5}$ concentrations, cooling towers may scrub more PM from the air than they emit.

(4) Additional measurements will be needed to quantify net emissions of $PM_{2.5}$ from cooling towers.

Conclusions 1 to 3 suggest that modifications to AP-42 are necessary. AP-42 assumes that spray drift emissions when dried result in PM10, whereas these measurements indicate that there is very little coarse PM (the PM between 10 um and 2.5 um) so that dried emissions are primarily $PM_{2.5}$.

Cooling towers are operated in a way that controls the TDS content of the recirculating water. This control is performed by measuring the TDS and when the TDS becomes too high, draining some of the water (called blowdown) and replacing it with source water, be it brackish or fresh. Since the operators of each cooling tower set the TDS desired, whether the source water is fresh or brackish does not influence the recirculating water TDS. The result is that fresh or brackish water can be used as a water source for wet cooling towers.

California has some of the highest PM concentrations in the country, especially in the South Coast Air Basin and the San Joaquin Valley. Ambient air drawn into cooling towers contains these high PM concentrations. The measurements conducted in this study indicate that nearly all of the coarse PM is scrubbed by the cooling towers measured so that operating cooling towers results in negative coarse PM emissions. These measurements are more ambiguous in relation to $PM_{2.5}$ so the researchers cannot conclude if or when cooling towers are a positive or negative emitter of $PM_{2.5}$.

Regarding conclusion 4, some of the uncertainty in $PM_{2.5}$ scrubbing efficiency is due to measurement artifacts. Turbulence at the tower exit and side winds may have impacted some of the larger particles in the surface of the drier nozzles. In future measurements, the researchers will use a cowling around the nozzle to straighten the flow before the nozzle to minimize this loss.

Another source of uncertainty is how $PM_{2.5}$ is scrubbed. The uncertainty for coarse PM was relatively low because the size distribution is narrow so one scrubbing efficiency value can describe the scrubbing, but $PM_{2.5}$ has a wide size distribution, so the scrubbing efficiency is likely to depend on particle size. Future measurements should use a multi-stage impactor to sample the dried PM and the ambient so that the size dependence of this scrubbing can be quantified.

CHAPTER 7:
Benefits to Ratepayers

This project benefits California ratepayers in two ways.

Generally, wet cooling tower operators in California use fresh water as the source of water for the tower. Due to periodic droughts in California, fresh water is a precious commodity. Calculations performed during this study, confirmed by the technical advisory committee, showed that using brackish water in cooling towers will not result in additional PM emissions. This removes one barrier to cooling tower operators using brackish water instead of fresh water, in that the use of brackish water will not increase the emissions of particulate matter from cooling towers. If implemented, this will save on fresh water use in California. This study did not quantify the number of cooling towers in California that use fresh water versus brackish water, but such a study could quantify the amount of fresh water saved if cooling towers switched to brackish water sources.

Informing the California Air Resources Board and the Environmental Protection Agency that cooling towers are likely removing more coarse PM from the atmosphere than they emit and that this is possibly also the case for $PM_{2.5}$. This may reduce emissions charges from cooling towers at power plants, reducing cost to operators which they may pass down to ratepayers. This study did not quantify how cooling tower operators calculate their emissions; that is, whether they are using AP-42 or an algorithm required by the local air district. This study did not quantify how much in emissions charges are paid by cooling tower operators in California. A study of this nature could quantify potential cost savings by using the algorithms recommended by this study instead of that recommended by AP-42.

GLOSSARY OR LIST OF ACRONYMS

Term	Definition
µm	Micrometers, microns
AP-42	Compilation of Air Pollutant Emissions Factors, published since 1972 as the primary compilation of EPA's emissions factor information
APS	Aerodynamic particle sizer
Coarse PM	Particulate Matter with a diameter between 2.5 and 10 microns
EPA	United States Environmental Protection Agency
HEPA	high efficiency particulate air
IMPROVE	Interagency Monitoring of Protected Visual Environments
LWC	Liquid water content
LPM	Liters per minute
PDI	Phase Doppler Interferometer
PM	Particulate Matter
PM_{10}	Particulate Matter with a diameter of 10 microns or less
$PM_{2.5}$	Particulate Matter with a diameter of 2.5 microns or less
PTFE	Polytetrafluoroethylene
MMAD	Mass median aerodynamic diameter
MVD	Median volume diameter
N_d	Number concentration
TDS	Total dissolved solids
V_{up}	Updraft velocity
XRF	X-Ray Fluorescence

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