Titre: Title:	A Mechanical and Economical Study on the Incorporation of Anti-Microbial Anodized Aluminum in Cooling Towers
Auteur: Author:	Alexis Nossovitch
Date:	2019
Type:	Mémoire ou thèse / Dissertation or Thesis
Référence: Citation:	Nossovitch, A. (2019). A Mechanical and Economical Study on the Incorporation of Anti-Microbial Anodized Aluminum in Cooling Towers [Mémoire de maîtrise, Polytechnique Montréal]. PolyPublie. https://publications.polymtl.ca/4043/

URL de PolyPublie: PolyPublie URL:	https://publications.polymtl.ca/4043/
Directeurs de recherche: Advisors:	Aurelian Vadean, & Myriam Brochu
Programme: Program:	Génie mécanique

POLYTECHNIQUE MONTRÉAL
affiliée à l'Université de Montréal

A Mechanical and Economical Study on The Incorporation of Anti-microbial Anodized Aluminum in Cooling Towers

ALEXIS NOSSOVITCH
Département de génie mécanique

Mémoire présenté en vue de l'obtention du diplôme de *Maîtrise en sciences appliquées*
Génie mécanique
Août 2019

POLYTECHNIQUE MONTRÉAL
affiliée à l'Université de Montréal

Ce mémoire intitulé :

A Mechanical and Economical Study on The Incorporation of Anti-microbial Anodized Aluminum in Cooling Towers

présenté par **Alexis NOSSOVITCH**
en vue de l'obtention du diplôme de *Maîtrise en sciences appliquées*
a été dûment accepté par le jury d'examen constitué de :

Sylvain TURENNE, président
Aurelian VADEAN, membre et directeur de recherche
Myriam BROCHU, membre et codirectrice de recherche
Olivier KERBAT, membre

ACKNOWLEDGEMENTS

I would like to begin by thanking my industrial partners: A3Surfaces, CoupeSag and PCP Aluminium for giving me this opportunity. In particular, Jean-Luc Bernier for proposing the project, his friendship and mentorship, which was a valuable part of my education and gave me a perspective on things you do not learn in school. Martin Lambert, Maxime Dumont and the A3Surfaces team for their knowledge, their time and making office space for me during my internship. Michel Lavoie for deciding to finance this work and allowing me to experience the aluminum industry in Saguenay through his different companies. I would also like to thank MITACS for financing such research projects. Aurelian Vadean and Myriam Brochu for their advice, their support and their flexibiliy concerning multiple changes in direction this research had. Paul Provencher, for the months he participated in the project and his recommendations. Michel Lareau and Yannick Decarie for letting me visit the towers at Polytechnique de Montreal and sharing information and usage data. Finally, I want to also thank the companies that allowed us to interview them on cooling tower maintenance and water treatments but decided to keep their identity confidential.

RÉSUMÉ

L'objectif de cette recherche a été de déterminer si l'aluminium anodisé impregné d'ammonium quaternaire et électrodéposé avec de l'argent pouvait être utilisé dans les tours de refroidissement pour aider à lutter contre l'encrassement biologique et le développement de bactéries tell que la *Legionella Pneumophila*. Cette thèse présente une campagne expérimentate qui a été menée sur le AAA (aluminium anodisé anti-microbien) ainsi qu'un cadre de design pour l'implémentation du AAA dans les tours de refroidissement focalisé sur la viabilité économique. Deux tours prototype ont été construites pour l'expérimentation: une des tours a été construite entièrement en AAA et l'autre en aluminium 5083 non-traité. Les tours ont fonctionnées avec de l'eau contaminée et des décomptes bactériens ont été pris (CFU/ml). Une campagne expérimentale a aussi été menée sur des échantillons de AAA pour établir si le AAA était en mesure de maintenir ses proprétés anti-microbiennes. La corrosion du AAA a aussi été évaluée en sous-traitant H20Biotech pour qu'ils placent des coupons de corrosion dans des bassins de tour de refroidissement. Ce travail présente un cadre économique qui présente l'ensemble des coûts liés à opérer une tour de refroidissement avec l'idée qu'une tour anti-microbienne doit apporter un avantage économique dans le long terme pour être acceptée par l'industrie. À travers ce cadre, des considérations de design clées pour l'implémentation du AAA sont mises en évidence. Il a été démontré dans cette étude que AAA tel que fabriqué n'est pas assez durable pour être utilisé dans les tours de refroidissement. La campagne expérimentale démontre une perte des propriétés biocides. Parcontre, la revue de littérature suggère qu'il y a plusieures avenues à explorer pour trouver le traitement adéquat car plusieures téchniques existent pour rendre l'aluminium hydrophobe et biocide. Le modèle économique suggère que le traitement adéquat pourrait être viable en réduisant l'encrassement et ainsi les coûts liés à l'éléctricité, l'eau, les produits chimiques et la maintenance.

ABSTRACT

Cooling towers are heat exchangers that achieve cooling by exchanging heat between water and air. They are typically located outdoors and are used around the world for any industrial process in which cooling is involved. They play essential roles in many manufacturing processes, in the food industry, power plants and air conditioning. Organic particles, non-organic particles and micro-organisms suspended in the air can accumulate in the tower and cause it to clog and lose efficiency. This fouling process hinders heat exchange and the formation of a biofilm in particular leads to the proliferation of dangerous bacteria such as *Legionella Pneumophila*, which can cause a potentially deadly form of pneumonia called legionnaires' disease.

In this context, the primary objective of this research is to determine if an anti-microbial anodized aluminum developed by A3Surfaces (AAA) can be successfully implemented to reduce biofilm development and microbial counts in cooling towers. The secondary objective is to establish design considerations and the economic viability of a cooling tower integrating AAA.

The antimicrobial efficacy of AAA is evaluated in two separate experiments. First, colony forming units (CFU) were repeatedly measured for experiments involving AAA samples placed in petri dishes with contaminated water. The antimicrobial durability of silver was evaluated for electroplated silver as opposed to samples dipped in a silver nitrate and quaternary ammonium solution prior to sealing. After being tested in a wet environment, they were tested again in a dry-environment and compared to brand new samples. It was shown that as currently fabricated, AAA samples lose their antimicrobial properties. Electroplating improved the biocide durability significantly but still showed a loss in efficacy.

Secondly, two identical prototype cooling towers were built and operated with contaminated water: one treated with AAA and one untreated. Bacterial counts (CFU/ml) for each tower were collected weekly. The entire water volume was replaced and the tower was cleaned with 70% isopropyl alcohol in between experiments. The AAA tower lost its capacity to reduce bacterial counts once the water volume was replaced in between runs.

Lastly, a framework for the design considerations and economical viability of an anti-microbial cooling tower is proposed here. The framework shows how according to the climate, intended use, electricity and water costs, a tower reducing bio-fouling in cooling systems could have economic benefits despite being more expensive. The economic framework shows that a small reduction in annual maintenance, chemical, water or electricity costs can quickly compensate a larger initial investment if we look at the costs over the entire lifespan of the cooling tower. This viability point depends on the intended use of the tower and climatic conditions.

Despite AAA not being durable enough as currently fabricated, the literature review suggests many avenues are left to explore to obtain an adequate biocide surface. The economic framework in this research suggests that such surface could potentially reduce the total costs and health risks related to operating a cooling tower.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS AND ABBREVIATIONS

AAA	Antimicrobial anodized aluminum
COC	Cycle of concentration
COP	Coefficient of performance
LF	Load factor
RT	Refrigeration tons
CFU	Colony forming units
OD	Optical density
TSA	Triptone soy agar
NFV	Net future value
ϵ_{tower}	Hypothetical annual savings coefficient for the tower purchase
ϵ_{op}	Hypothetical annual savings coefficient for electricity
ϵ_{maint}	Hypothetical annual savings coefficient for maintenance
ϵ_{chem}	Hypothetical annual savings coefficient for chemicals
ϵ_{w}	Hypothetical annual savings coefficient for water
C_{pa}	Heat capacity of dry air $\left(1.006\frac{kJ}{kgK}\right)$
C_{pv}	Heat capacity of water vapor $\left(1.84\frac{kJ}{kgK}\right)$
C_{w}	Heat capacity of water $\left(4.184\frac{kJ}{kgK}\right)$
i_{mw}	Enthalpy of water (kJ/kg)
i_{ma}	Enthalpy of dry air (kJ/kg)
i_{ma}	Enthalpy of air (with humidity w) (kJ/kg)
i_{we}	Enthalpy of evaporation of water vapor (2501kJ/kg)
i_{masw}	Enthalpy of saturated air at water temperature (kJ/kg)
R_{elec}	Electricity cost (\$/kWh)
R_{mu}	Make-up water cost (\$/m^3)
R_{bd}	Blow-down water cost (\$/m^3)
m_{a}	Water flow rate (kg/s)
m_{w}	Air flow rate (kg/s)
w	Humidity (kg/kg)
w_{sw}	Air humidity at saturation (kg/kg)
w_{makeup}	Make-up water rate (kg/kg)
$w_{blowdown}$	Blow-down water rate (kg/kg)
w_{drift}	Drift rate (kg/kg)
w_{evap}	Evaporation rate (kg/kg)

LIST OF APPENDICES

CHAPTER 1 INTRODUCTION

Cooling towers are one of the most efficient choices for heat dissipation and have industrial, commercial and residential applications. However, despite being a cost-effective choice for cooling, bio-fouling remains a serious health issue in need for better solutions. Biofilm adheres to cooling tower surfaces and is a suitable environment for bacteria to proliferate and reach dangerous concentrations. *Legionella Pneumophila* in particular thrives in cooling towers during the summer. Micro-droplets contaminated with *Legionella P.* escape cooling towers and can reach the lungs of individuals, leading to a dangerous respiratory infection called legionnaires' disease. Most outbreaks are not fatal but legionnaire's disease is dangerous and claims lives around the world. In 2019, 2 died in Evergem, Belgium from a contaminated tower (Johnston, 2019). In 2017, 6 died in Lisbon, Portugal (Khalip, 2017). In 2015 in Bronx 12 died from a contaminated tower (Chamberlain and al., 2017). In Quebec city in 2012, 14 people died from a contaminated tower (CBC, 2012). The list of incidents goes on.

As such, cooling tower owners are required to monitor bacterial counts to ensure the tower is kept clean. In Quebec, when the count is over 1×10^6 CFU/ml, the tower is required to shut down and a report is made to the *Régie du Bâtiment du Québec*. Since a lot of industrial processes depend on cooling towers, a shutdown can be very expensive for a business.

Besides being a breeding ground for *Legionella Pneumophila*, biofilm is one of the causes of fouling in cooling towers, which reduces efficacy. Fouling reduces the towers thermal performance and clogs the tower, increasing the costs related to electricity, maintenance, water and chemicals.

A handful of industries based in Saguenay, Quebec proposed an interesting alternative: making a cooling tower with anti-microbial surfaces. A3Surfaces has developed such a surface by impregnating the nanometric pores of anodized aluminum with silver and quaternary ammonium. They have already found many applications for this antimicrobial anodized aluminum (AAA) in dry environments such as hand rails, door knobs and other commonly touched components in public places, antiseptic hospital rooms and even cosmetics. However, the durability of AAA had not been properly evaluated for wet-environments such as cooling towers or water tanks.

CoupeSag, PCP Aluminum and A3Surfaces in partnership with MITACS have financed this project to determine if anti-microbial anodized aluminum can be a viable solution for cooling towers.

For such a solution to be viable, certain criteria need to be met: first, the antimicrobial surface must substantially reduce bio-film growth for the entire life-span of the tower, resisting aggressive water treatments used against corrosion, precipitation and microorganisms. Second, the tower must remain economical: incorporating the material must provide some sort of cost advantage in the future by reducing the chemical, maintenance and operation costs that result from fouling.

The first chapter of this thesis presents an overview of cooling tower parts, materials, design-variations, system variations and chemical treatments. The objective is to give the reader the necessary background information for the following chapters. This is followed by a literature review of antimicrobial coatings for anodized aluminum, the research objectives and methodology.

An entire chapter is then dedicated to the experimental campaign designed for this project. The first experiment is carried on two prototype cooling towers built from 5083 anodized aluminum, one being treated to be antimicrobial and the other one untreated. Bacteria were added to the prototype towers before allowing them to operate for periods of one week. CFU/ml (colony forming units per milliliter) were measured for 40 μl water samples on both towers over 3 runs. CFU's allow to estimate the amount of viable bacteria in a sample by spreading bacteria across the surface of a nutrient agar plate and incubating for a controlled amount of time before counting. The objective was to see if the surface would considerably affect bacterial levels in the water volume.

The second experiments are carried on antimicrobial anodized aluminum samples and silver electroplated samples. CFU counts were taken on samples exposed for 24 hours in a bacterial solution with an optical density $OD_{600} = 0.1$. Optical density indicates the absorbance of a sample measured at a wavelength of 600 nm, which is used to determine the concentration of bacteria in an aqueous solution. These samples were exposed to contaminated water repeatedly to establish if they would lose efficacy in what we will call "Rinse-cycle tests". New samples were then compared to the samples that had been rinsed in a "Dry test" where a bacterial solution is allowed to dry on the anodized aluminum samples before rubbing a wet Q-tip on the sample and spreading the Q-tip on agar for counting CFU's. These protocols were made in collaboration with Patrick Asselin Mullen, MS. in microbiology, who was hired by A3Surfaces for standardizing their protocols and for carrying the experiments in Chicoutimi, Quebec.

Corrosion results were also obtained by inserting samples in a cooling tower basin for a period of 65 days and measuring corrosion in *mpy* (mils per year), a unit of measurement equal to one thousandth of an inch of penetration in a surface. This is approximated by calculating the weight loss of a sample (the decrease in metal weight during the reference time period). These tests were carried by *H20Biotech*, a Montreal company that was subcontracted for this work.

Lastly, this work contains a design analysis for implementing such a biocide surface and an economic framework that was created to estimate the various costs of a cooling tower program. The design analysis begins with an axiomatic design framework in which the FR (functional requirements) of a cooling tower are linked to DP (design parameters) in order to see which DP are affected by the incorporation of a biocide surface. This lays the grounds for the subsequent economic framework whose objective is to determine under which conditions such a solution would be economically advantageous. The framework allows to approximate the total cost of a cooling tower program over its lifespan considering the load factor (LF), climatic conditions and utility rates. This allows to determine which savings the biocide surface must bring to be economically viable.

CHAPTER 2 BACKGROUND KNOWLEDGE ON COOLING TOWERS

2.1 Cooling tower design

A cooling tower is simply a device that maximizes the contact between water and air with the objective of exchanging heat between the two. It achieves this by distributing water over a corrugated heat exchange surface and circulating air with a fan. To understand how this works, the following diagram presents a standard cooling tower design for a small counter-flow induced-draft cooling tower. The model presented is model T-25 from *CTS - Cooling Tower Systems*. Different cooling towers will include extra components or have components placed differently as will be discussed further.

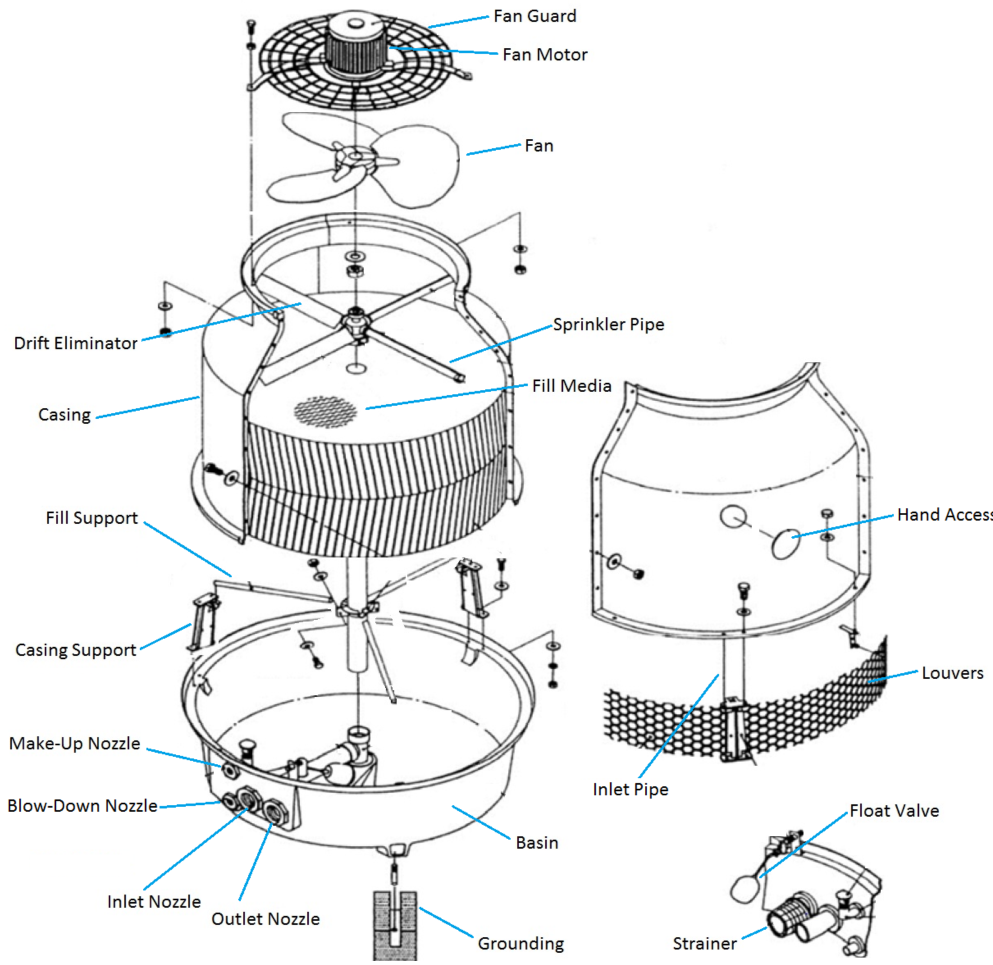


Figure 2.1 Cooling tower parts for tower T-25 from *Cooling Tower Systems*, a small counter-flow tower (*CTS*,2019)

The main components of a cooling tower are the following:

- **Fan**: A typical cooling tower has either a top or side-fan to generate air flow. These can be induction fans or forced draft fans. Large hyperbolic towers without fans that function with the stack effect also exist for industrial cooling with a high initial investment but low operation costs. The fan motor is usually electric and can require maintenance. The fan drive can be a belt-drive, gear-drive or direct-drive and usually is connected to a VFD (variable frequency drive) to adequately control fan speed. A fan guard typically prevents large objects from getting into the tower.
- **Basin**: The basin holds the bulk of the cooled water. It is also there where the blown-down outlet and make-up inlet are typically located. Cooled water from the basin is pumped out towards the heat-load. A grounding mechanism to anchor the tower usually connects to the basin.
- **Drift eliminator**: Drift eliminators prevent micro-droplets from escaping from the tower. They can vary in size and density.
- **Casing**: The casing is the main structure of the tower. A casing support connects the basin and the casing when they are independent structures. Typically towers have a casing access window. In medium and large towers, these are made large enough for a human to enter the tower for maintenance.
- **Louvers**: Louvers at the air inlets prevent objects from getting into the tower and occlude sunlight, which can promote algae and bacteria growth.
- **Fill media**: The fill is where the water is distributed for the heat and mass transfer to happen by maximizing the water-air contact in the tower. Fill can be more or less dense according to water-fouling tolerance. Sometimes splash-type bars are used instead of fill for low fouling applications.
- **Sprinkler or wet-deck**: The two most common water distribution systems are a wet-deck with holes or a sprinkler system. They aim at providing even distribution of water through the fill. Sprinkler pipes are also present for water distribution.
- **Blowdown nozzle**: The blowdown nozzle is where blow-down water (to be discussed) is evacuated to keep the concentration of solids in the tower in check.
- **Makeup nozzle**: The make-up nozzle is where make-up water (to be discussed) is added to compensate for evaporation, blow-down and drift. A float valve is commonly used to control the towers water level.

- **Inlet nozzle**: The inlet nozzle brings the warmed-water to the sprinklers. Inlet pipes typically go through outside or through the center of the tower.
- **Outlet nozzle**: The outlet nozzle receives the cooled-water from the tower basin and takes it to the heat load. A strainer used to prevent big objects from going to the pump.

2.2 Cooling tower materials

An overview of cooling tower materials is essential to assess the possibility of incorporating AAA. Cooling towers are very corrosive environments since naturally dissolved salts along with cooling tower chemicals often including chlorine are present in the water. As such the materials are chosen in consequence. The casing and base of the tower are typically made out of either galvanized steel, stainless steel (301L, 304, 306), fiber reinforced plastics (FRP) or other metal choices coated with polyurethane, PVC or epoxy compounds for corrosion resistance. Concrete basins are also common for large field erected towers. Cooling tower piping is typically made from either PVC, FRP or ABS. Fill media, drift-eliminators and louvers are usually made from PVC or ABS, although some high-temperature applications use stainless steel fills. The fan and pump components might have steel, cast iron, bronze, rubber, FRP, graphite components or other materials. Since heat-exchange happens between the air and the water, the fill media and drift eliminators would not exchange heat better if made from metal. They are made of PVC and ABS as corrugated plastic is cheap and easy to manufacture.

2.3 Types of cooling towers

A first essential division can be made between **closed-circuit cooling towers** and **open-circuit cooling towers**. An open-circuit cooling tower exposes the primary water directly to the atmosphere as shown in figure (2.2), where as a closed-circuit cooling tower uses a supplementary heat exchanger as shown in figure (2.3). In closed-circuit cooling towers, there are two volumes of circulating water that don't mix (ASH, 2016, pp. 40.2-40.7). An open-circuit cooling tower is fundamentally better at exchanging heat than a closed-circuit cooling tower since there is no intermediary heat exchanger. However, closed-circuit towers prevent the contamination of the primary water, allow cooling liquids other than water and allow the use of anti-freezing agents (ASH, 2016, pp. 40.4).

Cooling towers can also be divided into **dry cooling towers** and **wet cooling towers**. Dry cooling towers fall into the category of closed-circuit towers since the water is not exposed to the atmosphere. The difference as the name suggests is that the water is cooled with air only. Since the most classic cooling tower is the wet cooling tower and this is where the problem of bacteria occurs, only wet cooling towers will be discussed and presented.

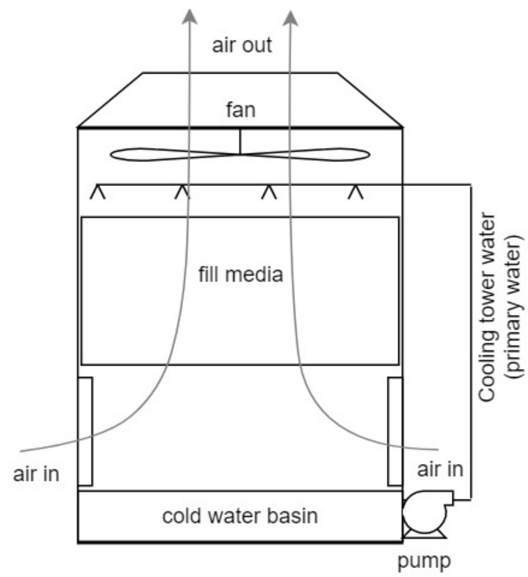


Figure 2.2 Open-circuit cooling tower schematic

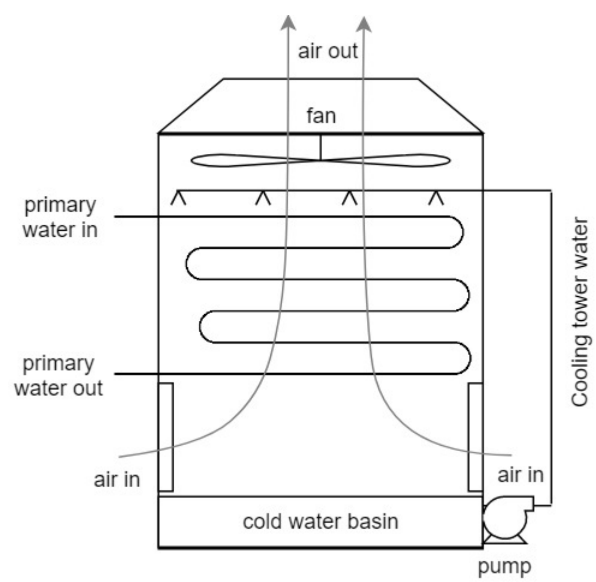


Figure 2.3 Closed-circuit cooling tower schematic

Another important distinction to make is between **counter-flow cooling towers** and **cross-flow cooling towers**. In a counter-flow configuration, air flows in the opposite direction as the water. In cross-flow configuration, water and air flow are perpendicular. Figure (2.4) shows an open-circuit cooling tower with a cross-flow configuration, as opposed to figures (2.2) & (2.3), that show counter-flow configurations.

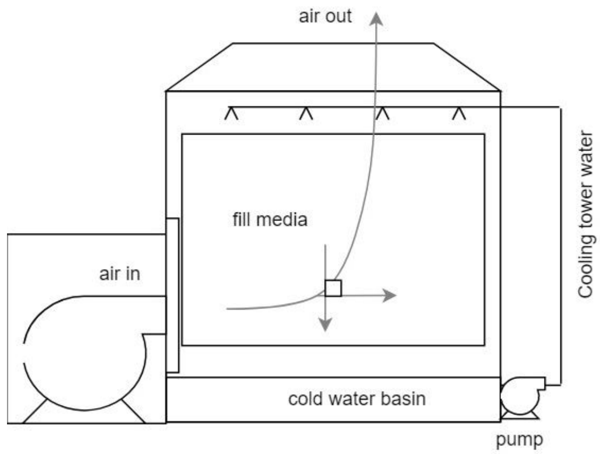


Figure 2.4 Cross-flow cooling tower schematic with water and air-flow perpendicular to eachother

Counter-flow cooling towers are generally more efficient heat exchangers per volume. In an ideal counter-flow configuration, water and air teperatures only vary vertically across the fill, which is not the case in cross-flow configurations. However, cross-flow towers have important advantages with respect to maintenance access since not all four sides of the tower have air inlets, allowing staircases or access doors to be build with more ease (SPX, 2016, pp. 2).

Another important division is between **induced-draft cooling towers** as opposed to **forced-draft cooling towers**: an induced-draft cooling tower has a fan at the at the top which pulls air up through the tower. This produces low entering and high exiting air velocities, reducing the possibility of recirculation in which discharged air flows back into the air intake.

A forced-draft tower has a blower-type fan at the intake. The result is high entering air velocities and low exiting air velocities. This configuration is more susceptible to recirculation. A forced-draft cooling tower will usually require more power than an equivalent induced-draft cooling tower. The principal advantage of a forced draft design is its ability to work with high static pressure. This allows more air-flow and therefore more heat exchange in a smaller volume when power is not the primary concern.

There are also **natural convection towers**, large often hyperbolic structures in which air flows naturally because of a differential in air density and the aspirating effect of water sprays (ASH, 2016, pp. 40.5). Figure (2.5) shows a counter-flow configuration with forced-draft while figure (2.6) shows a cross-flow induced-draft configuration. To contrast this, figures (2.2) & (2.3) are both induced-draft counter-flow towers and figure (2.4) shows a forced-draft cross-flow tower.

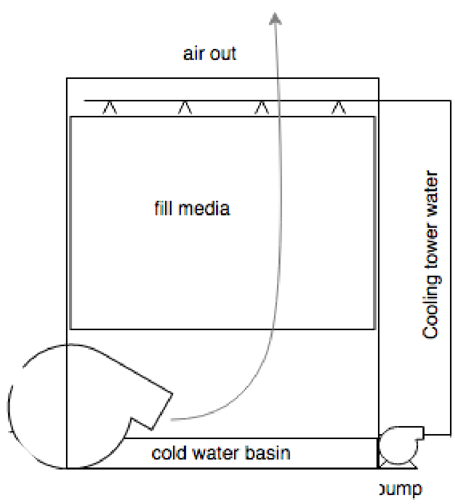


Figure 2.5 Forced-draft counter-flow cooling tower schematic

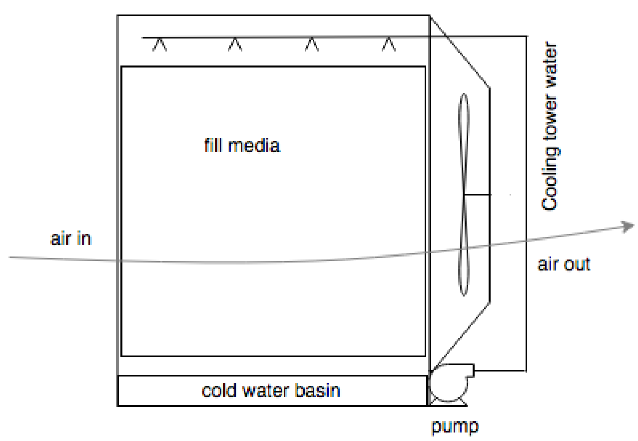


Figure 2.6 Induced-draft cross-flow cooling tower schematic

There are also **hybrid cooling towers** that have the capacity to change their operation mode according to the weather and water flow requirements. These have two closed loop heat exchangers for the primary water and can operate in wet or dry mode according to climate conditions.

Another common distinction is related to how the tower is built. Cooling towers can be **factory-assembled** cooling towers or **field-erected** cooling towers.

Factory-assembled cooling towers undergo a virtually complete assembly at their point of manufacture and are then transported in units that require very little assembly. **Field-erected** cooling towers are usually much larger constructions that require most of the construction activity to take place at the factory where they will be ultimately functioning (Hensley, 1985, pp. 12).

In short, the variety of cooling tower designs commercially available can be explained by the existence of different functional requirements and constraints such as climate, space, type of liquid to be cooled, water quality and heat load size. Cooling tower fouling is an issue in wet cooling towers whether open circuit, closed circuit, cross-flow, counter flow, forced or induced draft and it is the same heat exchange surfaces that are affected by biofilm and responsible for high bacterial counts in cooling towers.

2.3.1 Heat transfer in cooling towers

Heat transfer in cooling towers is complex as it involves mass and heat transfers in a air-vapor-water mixture through a very complex geometry. The thermal modeling methods used to this day are base on the Merkel model, which is presented in **Appendix A**. The Merkel model will be used in the economic framework to approximate how the load factor (LF) changes according to climatic considerations. The load factor is the percentage of cooling demand with respect to the maximum cooling capacity the tower can provide. Understanding in detail the Merkel model is not necessary to understand the conclusions drawn in this thesis.

2.3.2 Blowdown

A cooling tower looses about 1% to 2% of its design water-flow to evaporation. It is therefore necessary to continuously replace the evaporative loss. However, when the evaporative loss is replaced, then the dissolved solids that were in the evaporated water begin to build up in concentration in the circulating cooling water. The same way a soup left on the stove top for too long becomes thick, this process makes the water saturated which can cause problems with fouling. It is therefore necessary to continuously discharge some amount of the circulating water to prevent the concentration of dissolved solids to build up. This discharge is known as "blowdown" or "bleed-off". Figure (2.7) illustrates the water balance of a cooling tower.

The amount of "make-up" water to be added in order to keep the volume of water stable can be described by the following equation:

$$w_{make-up} = w_{evap} + w_{blowdown} + w_{drift} \tag{2.1}$$

where:

- w_{evap} = Evaporative water loss (usually around 1-2 % of the total design water-flow).
- $w_{blowdown}$ = Blowdown rate determined by the cycle of concentration (COC) to be discussed further.
- w_{drift} = Water loss to "drift" droplets escaping the tower, typicially in the order of 0.05 - 0.0005 % of design water-flow or 5% to 0.5% of w_{evap}.

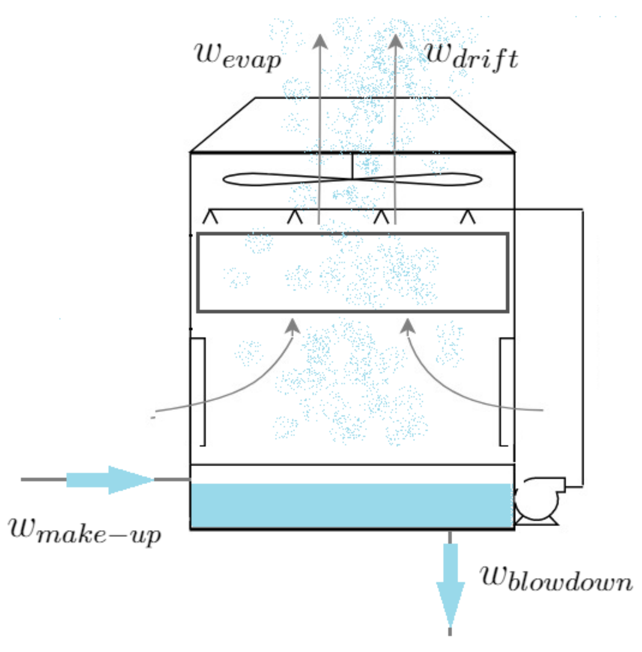


Figure 2.7 Water balance in a cooling tower illustrated

Usually from 65% to 90% of the cooling is accomplished through evaporative cooling (latent heat transfer as opposed to sensible heat transfer). Lets call this fraction f_{latent} (see **Appendix A** for details).

The water loss to evaporation can be estimated knowing h_{fg}, the latent heat of vaporisation of water which is ($2257\frac{kJ}{kg}$)

$$w_{evap} = \frac{Q_{rejected} \times f_{latent}}{h_{fg}} \tag{2.2}$$

Blowdown rates are set to control scaling, fouling, and corrosion by limiting the buildup of impurities in the circulating water. The amount of water in the blowdown is expressed in terms of the allowable cycles of concentration (COC):

$$w_{blowdown} = (\frac{1}{COC - 1}) \times w_{evap} \tag{2.3}$$

The value of COC can vary according to the tolerance to scale of the system and the quality of the make up water. The smaller the COC, the larger $w_{blowdown}$. Typical COC values (adimensional) for fresh water cooling towers are 3-8, but can be as low as 1.5 for salt-water systems. Usually manufacturers give an estimation of the amount of water loss to evaporation and drift in their specifications. The main value to influence the make-up water amount is the cycle of concentration (COC). The COC specifies how many times the fresh water is re-circulated, before it is blown-down from the cooling tower. The maximum concentration ratio at which a cooling tower can still properly operate will depend on the quality of the makeup water and the chosen chemical treatment program. The total dissolved solids (TDS), alkalinity, calcium hardness, silica and sulfate concentrations affect the water quality and determine the number of cycles that can be achieved without forming too many mineral deposits. As the number of cycles increases, the blow down is minimized but the concentrations of mineral salts in the system increases. The following table from the company CTS gives their recommended limits for different water parameters involved in fouling.

Table 2.1 Recommended water parameters from *CTS-Cooling Tower Systems*

Parameter	Make-up water	Circulating water
pH	6-8	6-8
Conductivity (mv/cm)	< 200	< 500
Total Hardness $CaCO_3$ (mg/L)	< 50	< 200
M Alkalinity $CaCO_3$ (mg/L)	< 50	< 100
Chlorine Ion Cl (mg/L)	< 50	< 200
Sulfuric Acid ion SO_4 (mg/L)	< 50	< 200
Silicic Acid Ion SiO_2 (mg/L)	< 30	< 50
Iron Fe (mg/L)	< 0.3	< 1

To sum things up, it is possible to estimate the amount of water the tower consumes according to the cycle of concentration chosen and the amount of heat rejected. The percentage of heat transfer accomplished by evaporative cooling (f_{latent}) is dependent on the climatic conditions but remains in all cases the dominant part of heat transfer because of waters high latent heat of vaporization. Being able to approximate the water consumption according to the heat load and the COC will be useful in estimating the costs of a cooling tower program. The COC chosen depends on the quality of the water where the tower is located and the choice of chemical treatment.

2.3.3 Cooling tower operation

It is not only cooling tower designs that vary greatly according the weather and intended use but also the choice of cooling system. Cooling towers are usually paired with a chiller that further cools the water via a vapor-compression cycle. A heat-exchanger is then used to transfer the heat from the load. A chiller is absolutely necessary for example in an air conditioning installation, to cool the water exiting the tower from say $24°C$ to $13°C$ to circulate it through an air-water heat exchanger and make cold air.

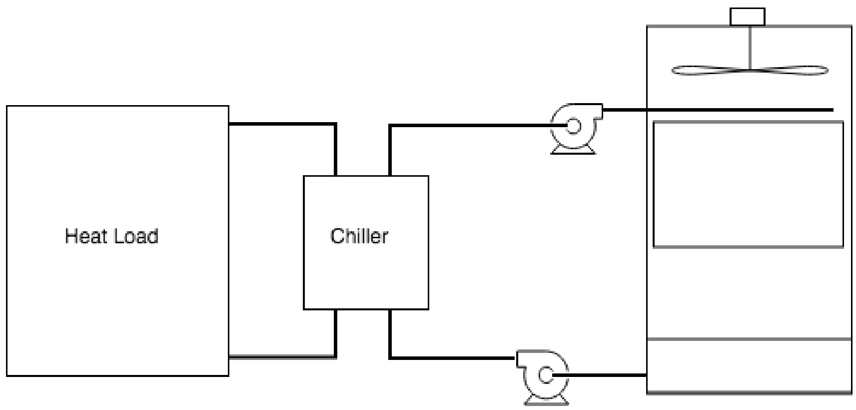


Figure 2.8 Cooling tower operating with a chiller

At optimal operating conditions, cooling towers can reach a COP (coefficient of performance) bigger than 20. Than means that for every Joule of energy in fan and pump power invested we can reject 20 Joules of energy in the form of heat. However, a cooling system with a chiller will have a much lower COP between 4.2 and 8.4 (Hasan, 2005, 25-27). For example, the company *Baltimore* states a typical performance of 0.2 kW/ton for cooling towers (COP = 17.58) while chillers usually are at 0.6-0.8 kW/ton (COP between 4.40-5.86). For this reason, when outside temperatures are cold enough, design variations attempt to bypass the chiller if further cooling is not required and take advantage of the cooling tower's higher COP. This is called "free-cooling".

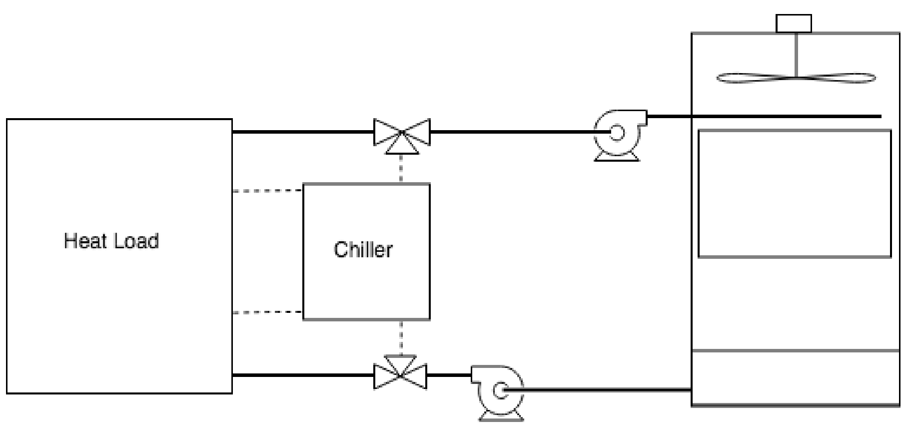


Figure 2.9 Tower with valves allowing a chiller bypass

If the necessary summer and winter cooling requirements are very different, it becomes impractical to operate a single cooling tower for both seasons. Acceptable water loading of cooling towers is limited by water/air ratio and nozzle size. A low-flow operating cooling tower tends to foul more easily and becomes inefficient. As such, many systems have multi-cell towers or several towers. A common variation for continental climates is to operate independent winter and summer towers.

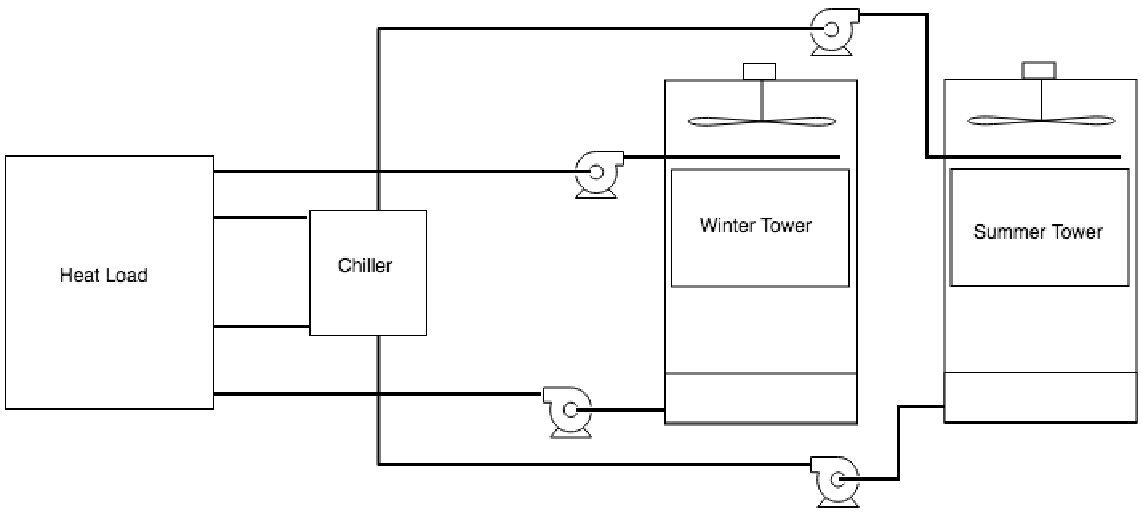


Figure 2.10 System with winter and summer towers

Without getting into all specific system variations, the general idea is that according to the industry and the climate, one can observe very different load factors (LF) and coefficients of performance (COP). For example, a cooling tower program for cooling computers in California will have a constant heat load (the heat from computers) and a relatively constant climate. The tower will be sized to operate at near full capacity (high LF) and if no chiller is needed, the COP will be very high, leading to low operating costs. In contrast, a cooling tower in Québec used for air-conditioning will operate 3 months a year and will have to be sized for the worse heat-waves (variable heat load). It will therefore have a low LF since it will be over-sized and a low COP since a chiller is indispensable for air-conditioning.

2.3.4 Fouling in cooling towers

Fouling can be biological or non-biological in nature although these two are often connected. Non-biological fouling can occur because of the dissolved solids precipitating or because of macro-sized solids that can clog the tower. Biological fouling refers to the adherence of biofilm to surfaces which creates high bacterial counts and clogs heat exchange surfaces. The following sections explain these phenomena and the strategies used to cope with them.

Water chemistry and dissolved solids

The chemical composition of water varies greatly according to the hydrological cycle and the geographical location on earth. Rivers, lakes, swamps, oceans and underground sources have different concentration of dissolved ions, dissolved gases, organic substances, micro-elements and pollutants.

The uptake of carbon dioxide (CO_2) from the atmosphere makes rain water contain dissolved carbonic acid (H_2CO_3), making it slightly acidic and helping it dissolve ions on the earths surface. As a result, many ions are present in water. The main anions contained in natural water are Cl^-, SO_4^{2-}, HCO^{3-} and CO_3^{2-} and the main cations are Na^+, Ca^{+2}, Mg^{+2} and K^+ (Nikanorov, 2009).

Metal cations with a valence of +2 or more have more difficulty staying dissolved in water that cations with a valence of +1 such as Na^+. For this reason, the common ions with a valence of one such as Na^+ and Cl^- generally do not cause any precipitation problems in cooling towers with fresh water supplies. However, salt water does increase the corrosion rate of metal in cooling towers and the cooling system.

Divalent ions deserve special attention since they are very important in scaling. The most abundant and important multivalent cation is usually Ca^{+2} by far, followed by Mg^{+2}. Calcium cations precipitate very easily with changes in temperature or pH, Ca^{+2} forming primarily calcium carbonate ($CaCO_3$) scale. At the same time, calcium carbonate is a spectacular buffer: meaning a substance that can resist changes in pH. When ($CaCO_3$) is added to water it separates into CO_3^{2-} and Ca^{2+}. The CO_3^{2-} combines with available H^+ in the water (effectively increasing the pH of the solution at first) forming HCO_3^-. It is HCO_3^- that has the buffering effect, controlling H^+ or OH^- concentrations with the following mecanism:

$$HCO_3^- + H^+ \rightarrow H_2CO_3 \tag{2.4}$$

If a base is added into the water:

$$HCO_3^- + OH^- \rightarrow CO_3^{2-} + H_2O \tag{2.5}$$

This way, $CaCO_3$ keeps aggressive and highly oxidizing H^+ and OH^- ions in check, making calcium carbonate great for reducing corrosion as it tends to keep the pH in control.

As discussed, one of the biggest concerns for plumbing, cooling towers, heat exchangers and other water system elements is precipitation. **Water hardness** is important in scaling and precipitation and thus essential to understand basic non-biological fouling and cooling tower water treatments. Water hardness is determined by the concentration of cations with a valence of 2 or more (since common cations with a valence of 1 tend to stay dissolved in the water) water is often referred to as **soft water** or **hard water**. General hardness is measured in equivalent g or mg of $CaCO_3$ per liter although other ions such as magnesium might contribute to it.

However, since calcium ions are often so dominant in water systems, water hardness is frequently identical in value to **carbonate hardness** measured in ppm of calcium carbonate ($CaCO_3$) or g or mg of $CaCO_3$ per liter.

To further add to the confusion, since calcium carbonate is the most important buffering agent, this is also confused with **alkalinity**. Total alkalinity is the buffering capacity of water, or its ability to resist change in pH. Since the most common and important buffering component is carbonate, total alkalinity is expressed as milligrams per liter (mg/L) or parts per million (ppm) of equivalent calcium carbonate ($CaCO_3$). This does not mean that calcium carbonate is the only thing contributing to alkalinity in any given scenario.

In short, calcium carbonate in water is a double-edged sword: high calcium carbonate concentrations make **hard water**, increasing the tendency for precipitation and making water more scale forming. Scale initiates a fouling process that reduces heat transfer and favors bio-film growth in towers. However, very low calcium carbonate concentrations make **soft water** allowing a very low pH and making conditions very corrosive for metals. There are more accurate ways of measuring the scale forming tendencies of water using indexes such as the Langelier Index (LI) and there is software specifically designed to tailor water treatments. These will not be presented but they are important in the water treatment industry.

Suspended solids

Although macro-fouling is just as important, it is much more easily summarized. Aside dissolved solids, suspended solids can be a problem in cooling towers. Pollen, dust and sand particles commonly end up in cooling towers. According to the cooling tower's design, larger things such as leaves or garbage can make their way in the tower.

Adequate chemistry control can only do so much for preventing non-biological fouling. As we will discuss, precipitation and corrosion control methods can help alot with dissolved solids. However, they can't stop macro-fouling. Interviewing two cooling tower maintenance companies from Montreal (that wish to keep their identity confidential) we learned that towers exposed to rough conditions can build up two inches of mud and sand in their basin. These situations cannot be rectified with adequate COC or water treatments. Design considerations must take this into account: strainers, louvers, fan access, the shape of the casing and the location of the tower must minimize the risk of big things getting stuck in the tower.

Biological fouling

The three microorganisms of concern in a cooling tower system are bacteria, algae, and fungi which enter the system by attachment to wind-blown dust. When the water trickles down the inside surface of the tower during normal operations it picks these dust particles out of the air and brings them into the water system. The main problem in cooling towers is the formation of **biofilm**. Biofilm is a consortium of microorganisms in which cells stick to each other and to a surface. Bacteria living in a biofilm tend to have significantly different properties from free-floating bacteria of the same species. This dense and protected environment allows highly resilient and adherent communities of microorganisms. In turn, biofilm is a breeding ground for dangerous bacteria like *Legionela Pneumophilia* which causes legionnaire's disease. The water treatment section presents different strategies for corrosion control, scaling control and bacterial control.

2.4 Water treatments

This section discusses the strategies used for preventing corrosion, scaling and biological growth in cooling towers. Unlike steel, which becomes practically immune to corrosion at high pH, aluminum is an amphoteric metal, meaning it can react and corrode at both acidic and alkaline conditions (Raymond M. Post, 2014, pp. 7). If the tower is made from AAA, a tailored water treatment would have to be created.

2.4.1 Corrosion and precipitation control

A very common treatment program in the 20th century that addressed both scaling and corrosion can be resumed in two main steps. The first step was adding sulfuric acid to maintain a pH within a range of approximately 6.5 to 7.0 in order to prevent water from forming scale, since adding an acid feed allows divalent ions to stay dissolved. This can be seen as manipulating the LI index into the non-scale forming range by modifying the pH. This does reduce precipitation greatly but makes the water more corrosive. It has long been known that if iron or steel are subjected to the action of chromic acid or soluble chromic salts, the metal is rendered passive, and the mechanism has been attributed to the deposition of a thin oxide film impervious to further attack (Roethell, 1931). Therefore, the next step was a feed of a chromate based salt such as sodium dichromate to the water. Chromium forms a surface layer on carbon steel and gives it stainless steel-like qualities (Buecker, November 2016).

However, chromate-based treatments can generate hexavalent chromium (Cr^{6+}), which is a proven carcinogen. As a result, despite being an excellent corrosion inhibitor, chromate based treatments are banned by most countries and should be avoided.

Acid feeds

Acid feeds are used to maintain ions dissolved and reduce precipitation. Sulfuric acid (H_2SO_4) is particularly great for controlling precipitation since it is cheap and it makes calcium ions form calcium sulfate, which is over 100 times more soluble than calcium carbonate.

However, sulfuric acid alone does not eliminate scaling and deposition in the long run and over feeding sulfuric acid corrodes the cooling tower, making ideal pitting sites for suspended solids and eventually microorganisms to accumulate. FRP's (fiberglass reinforced plastics) towers are popular since they are better structural materials for resisting sulfuric acid feeds than stainless or galvanized steel.

Solubilizers (precipitating inhibitors)

After chromate-based treatments, a large variety of **solubilizers**, also called **precipitating inhibitors** were introduced as alternatives. Solubilizing treatments allow water to remain stable when supersaturated with the scale-causing minerals. With solubilizers, instead of precipitating out of the solution and forming scale, the minerals stay in solution in the water. Solubilizers include polyacrylates(mainly acrylamide), organo-phosphorus and phosphonate based compounds.

Phosphate or phosphonate based water treatments became a popular replacement since they are both **solubilizers** and **passivating inhibitor** (which will be discussed later). Phosphonates and phosphates bond to calcium ions, magnesium ions and other metal ions preventing formation of insoluble precipitates, thus keeping them in solution (Nowack, 2003, pp. 2535-2536). There is a vast list of inorganic and organic phosphonates and various blends have been implemented and studied. Treatment methods employ a blend of organic and inorganic phosphates for primary scale and corrosion control, along with organic polymers that binds to calcium ions keeping them soluble for calcium phosphate scale control (Amjad, 1989, pp. 850).

Phosphates are also corrosion inhibitors for copper and steel. However, they have no beneficial effect on aluminum corrosion. HEDP (etidronic acid) , AMP (amino-methylene phosphonic acid) are very common phosphonates used. A problem with AMP is that it is broken down by chlorine, rendering it useless against scale when chlorine is added for biological control. HEDP is more popular because of its higher compatibility with chlorine. The main problem with phosphorus-based programs is they cause the eutrophication of bodies of water causing a boom in toxic algae and cyanobacteria. For this reason, their use is being heavily restricted around the world (Correll, 1998, pp. 261).

Crystal modifiers are another category that can be thought of as solubilizers, although the mechanism is different. These chemicals allow the scale to form but modify the crystalline structure of it, giving it the consistency of a sludge that will not adhere to surfaces well. Polymaleic acids and sulfonated polystyrenes are two common crystal modifiers that work best against calcium carbonate. The sludge deposits they create must be cleaned in the basin and are not compatible with some biocides.

Passivating inhibitors

Chromium is the perfect example of what we call a **passivating inhibitor**. Another used corrosion inhibitor is sodium molybdate, a salt containing molybdenum, which also helps create a protective layer on metals including steel, aluminum and copper (Vukasovich, 1977). It is similar in principle to chromate salts. Both can be categorized as **passivating inhibitors** but sodium molybdate is not as effective as chromium salts. Zinc is often added to the mix for its passivating properties. It is however not very effective on its own for corrosion protection. Azoles such as benzotriazole, benzimidazole and imidazole are organic compounds that have shown to have corrosion inhibiting properties for copper but also for steel (N.C. Subramanyam, 1985).

2.4.2 Biological control

Biocides are used in order to control microorganisms in cooling tower water. Biocides are usually divided into **oxidizing biocides** or **non-oxidizing biocides** depending on how they kill microorganisms. Biological fouling can influence scale and corrosion significantly, reducing the efficiency of corrosion and precipitation treatment programs. Biological films can consume certain inhibitors such as phosphates, phosphonates and azoles used in treatment programs (ASH, 2016, pp. 9).

Oxydizing biocides

Chlorine, bromine, and chlorine dioxide are commonly used oxidizing biocides. They are considered oxidizing agents because they accept electrons from other chemical compounds. The biocide gains an electron from the bacteria, and this electron loss essentially kills the bacteria. Chlorine (in the form of sodium hypochlorite or calcium hypochlorite) is an excellent biocide. However, it makes water much more corrosive and can be destroyed by other chemicals in the water-treatment program or it can destroy other water treatment chemicals itself. When chlorine is added in the form of sodium hypochlorite or calcium hypochlorite, it often binds and reacts with many other chemicals in the water, becoming less effective in killing viruses and other diseases. At high pH levels over 7.5, it breaks down to hypochlorite ions, a much less effective biocide.

Bromine (sodium bromide or BCDMH) and chlorine dioxide are other common oxydizing biocides. Bromine's advantage over chlorine is its ability to work at higher pH levels. However, it is less powerful and less cost-effective than chlorine salts. Chlorine dioxide is a toxic gas which easily mixes with water. It is perhaps the most powerful water sanitizing agent available. Chlorine dioxide does not bind and react with other water chemicals like chlorine salts. Chlorine dioxide is able to penetrate bio-film often removing it from the water system.

Non-oxydizing biocides

Oxydizing biocides are completely indifferent as to what they will oxidize or corrode. For this reason, there is a large list of non-oxydizing biocides that can be effectively used for bacterial control. However, no foolproof guide exists for the selection and application of biocides. Effective biocide programs are partially also the result of trial and error by individual field engineers. A common practice with biocide treatments is to alternate the use between different biocides in order to reduce the possibility of a microorganism developing an immunity to one biocide. Non-oxydizing biocides kill bacteria by a variety of different mechanisms. They each have their limitations in pH, toxicity, specific interactions with other chemicals present and limited efficacy on specific microorganisms.

Ozonation

There are several claims that ozonation can be used as a single chemical treatment for controlling scale, corrosion, and bacterial growth. Ozone is a form of oxygen with three oxygen molecules (O_3) that can be made by passing oxygen through a high voltage field. Without getting into the manufacturing details for ozone (Corona discharge method, UV lights, cold plasma), it is important to understand that it must be fabricated in-site from either ambient air or oxygen. The produced ozone (or ozone-air mixture) is bubbled in the water.

Several mechanisms are proposed to explain how ozone also reduces scale. Regardless of the mechanism, ozonation makes calcium carbonate precipitate into "sandy" easily filtered small grains in the basin instead of fouling exchange surfaces. For corrosion, ozone treatment results in the water having higher pH and alkalinity, which protects steel but not aluminum. Ozone treatments by far allow the highest cycle of concentration (10 COC or more) saving enormous amounts of water (Liou, 2009). The problem is many other cooling tower chemicals actually destroy ozone. The solubility of ozone and its half life time decrease with high temperatures. *Lenntech*, a company that offers ozone water treatments for cooling towers does not recommend ozone for temperatures over 45 C. Ozone is also not compatible with all materials: FRP's (fiber reinforced plastics) tend to have poor ozone compatibility and as mentioned aluminum can react and corrode at both acidic and alkaline conditions.

Water treatments summary

To conclude this section, it is important to tailor water treatment plans according to the local water quality and tower material used. Water treatment companies have elaborated complex recipes and methods for approximating scaling tendencies using software and through a trial and error basis. To incorporate anodized aluminum in a cooling tower, it is necessary to study the complex interactions between existing chemicals and aluminum. It is also important to consider how the added biocide components interact with the water in the tower. To name some potential issues, silver has the tendency to precipitate when combined with chloride and phosphate ions, some passivating inhibitors are not effective in protecting aluminum and ozone treatments are not compatible with aluminum. Water treatment programs must take into account water composition, pH, the metal or alloy to be protected, the biological inhibitors present, government regulations and the interaction between the different compounds they use. Due to the complexity of it all, companies have developed sophisticated treatment programs according to water characteristics. *French Creek Software* is a leader in this technology, and many of the major water treatment chemical vendors utilize the software for their programs (Buecker, November 2016). It is important to remember that biological and non-biological fouling are two linked phenomena and water treatment programs must consider this.

CHAPTER 3 LITERATURE REVIEW

The main objective of this research is to determine if silver deposited anodized aluminum impregnated with quaternary ammonium could be applied in cooling towers to help against bio-fouling and the health risks related to *Legionella Pneumophila* and other bacteria. As such, this literature review focuses on anti-microbial anodized aluminum surfaces. It first introduces the anti-microbial anodized aluminum patented by A3Surfaces and then goes over different methods mentioned in the litterature for rendering aluminum anti-microbial.

3.1 Antimicrobial anodized aluminum

Aluminium anodizing refers to conversion coating of the surface of aluminum and its alloys to porous aluminum oxide. This can be done for multiple reasons: increasing corrosion resistance, increasing abrasion resistance, increasing chemical resistance, improving decorative appearance, increasing paint adhesion, improving adhesive bonding, providing electrical insulation or permitting subsequent plating.

There are many processes and variations when it comes to anodization. Important parameters are alloy choice, acid choice, acid concentrations, anodization voltage, current densities, anodization temperature and anodization time to name a few. Anodic layer thickness can vary from under 1 micron to over 100 microns depending on the process.

A3Surfaces has patented a procedure for antimicrobial anodization. The methodology followed, and its possible variations are all presented in detail in their patent (Dumont et al., 2013). The invention relates to: **"A method for obtaining an antimicrobial metal product having an antimicrobial surface coating."**

Prior to its anodization, the aluminum is subjected to one or more pretreatment steps such as degreasing, electropolishing or etching according to procedures known in the art. "In one particular embodiment, the following steps are carried out: aluminum is degreased with acetone; etched with 10% weight/vol $NaOH$ for 2 min at 50- 60°C; neutralized in 35% vol/vol $HN0_3$ for 30 seconds at room temperature and submitted to a etching treatment for 10 min at 50-60°C with 33% v/v sulfuric acid" (Dumont et al., 2013).

Any suitable electrodeposition process may be used according to the invention. "In one particular embodiment, electrodeposition is carried out for about 30 seconds to about 10 minutes in an aqueous solution comprising about 1.5 % vol/vol sulfuric acid and about 5.1 g/L silver nitrate $AgN0_3$ at room temperature, Ac voltage 18 V." (Dumont et al., 2013)

The method may further comprise a sealing or clogging step which is carried out simultaneously or after the impregnation. "In particulars embodiments, the sealing is carried out by soaking in a solution or by exposing the porous layer to steam at ambient pressure or in an autoclave." (Dumont et al., 2013)

"The antimicrobial solution may further comprise a metallic salt such as $AgN0_3$, $Cu(N0_3)_2$, $Zn(N0_3)_2$, $Ni(N0_3)_2$ and mixtures thereof. The antimicrobial solution may also comprise additional antimicrobial agent(s) selected from antivirals, antibiotics, and antifungals." (Dumont et al., 2013)

The patent contains further details on the procedure. The specific protocol for obtaining the antimicrobial surface is confidential.

3.2 McGill study on AAA

A prior study on AAA was done by Amin Valiei, Mira Okshevsky, Nicholas Lin, and Nathalie Tufenkji at McGill university (Amin Valiei and Tufenkji, 2018). The study demonstrates the antimicrobial activity of AAA using both Gram-positive and Gram-negative bacteria in dry environments and for a 24 hour exposure in a wet environment. AAA samples 1 $cm \times 1$ cm not only did not develop biofilm when submerged in 2 ml of contaminated water but also sterilized the water volume. Understanding the underlying mechanism for wet environments can help us determine if this material is suitable for cooling towers. This study highly suggests that the mechanism by which this sterilization happens is diffusion:

"The fact that the bactericidal properties of the AAA material are caused solely by the presence of the impregnation solution, and not due to a mechano-bactericidal property of the nanostructured surface, can be confirmed from SEM analysis. Most recently, highly nanotextured topographies have been shown to kill attached bacteria. Specifically, physical bacterial interactions with nanostructures alone are capable of inducing cell death. Under the influence of such surfaces, bacterial cell morphology appears highly deformed, sunken into the surface, and leaking cytoplasmic material. However, no differences can be observed in the morphology of bacteria that are attached to control and A3S samples."

Part of our experimental campaign aims at determining how long this diffusion mechanism lasts. Tufenkji's team measured the MBC (minimum bactericidial concentration) necessary to kill 4 different lab strains of bacteria: *S. aureus, E. faecalis, E. coli, P. aeruginosa.* Knowing these concentrations and approximating the volume of the anodized pores per cm^2 from the litterature, it appears that this sterilizing effect could not last.

3.3 Electrodeposition & anti-microbial properties

Electrodeposition of silver or other elements in anodized aluminium pores for its anti-microbial properties has several mentions in the litterature. Electroplated anodized aluminium was shown to have bactericide properties with a kill efficacy from 96.6 % to 100 % for *Escherichia coli (E. coli), Pseudomonas aeruginosa (P. aeruginosa), Streptococcus faecalis (S. faecalis)* and *Staphylococcus aureus (S. aureus)* when conducting a dry-kill test (lawn method) counting CFU growth on agar after contact with the treated sample versus a control sample (Chi. et al., 2002, pp.162-165). Anti-microbial surfaces have also been created by depositing silver and titanium nanotubes into aluminium anodized with phosphoric, oxalic and tartaric acid. (Raad et al., 2018, pp.874-888). However, the anodic layers were around half a micron thick, which would not withstand a wet cooling tower environment.

Phophoric acid anodization, perfected by *Boeing* (*Boeing process*) is often recommended prior to electroplating for increased adhesion. However, the anodic layers obtained from phosphoric anodization are typically around 1 micron thick (Bjørgum and al., 2003). Chromic acid along with phosphoric acid is used in the aerospace industry prior to plating with chromium, cadmium or zinc-nickel electroless plating. The corrosion resistance is excellent relative to the thickness of the coating, which normally lies in the range of 2 to 5 μm but the process uses chromium which is contra-indicated from the health and environmental points of view since it is toxic and carcinogenic (Ferreira and Yasakau, 2012, 401-412).

Copper plating on alumina has also been shown to have anti-microbial properties. Vertically aligned nano-tubular Cu arrays (NT-Cu) fabricated via a template-based electrodeposition showed higher biological activity than electrodeposited Cu-foil (Razeeb, 2014, 60-63). The author suggests that the biocide effect is not solely due to the release of metal ions but to the capacity of nanoparticles to penetrate bacterial membranes. Antibacterial layers were prepared on the aluminum surface by anodizing pure Al and electrodepositing Cu in the pores of the anodic aluminum oxide membrane. The anodized aluminum was fabricated by a two-step anodization process in oxalic acid solution. The electrodeposition of Cu was conducted in a copper sulfate solution using alternating current (Zhang et al., 2014).

The mechanisms by which silver kills bacteria are not fully understood but it is believed that ionic silver ($Ag+$) enters cells and interact with multiple target sites (Russell and Hugo, 1994). This relates further to what is called the **oligodynamic effect**, which is the biocidal effect of metal ions, especially heavy metals, that occurs even in low concentrations. This antimicrobial effect is shown to different extents by ions of copper as well as mercury, iron, lead, zinc, bismuth, gold, and aluminum.

The presence of moisture is required for the penetration of ionic metals within bacteria. In the context of cooling towers, it is worth noting that silver has the tendency to precipitate when combined with chloride, sulphite and phosphate (Russell and Hugo, 1994). As discussed, chloride is abundant in cooling tower water and phosphates are commonly used in water treatment solutions as well.

Silver nanoparticles up to 80 nm have been shown to be able to penetrate bacterial cell membranes (Xu et al. 2004). In this case, the release of ionic silver from silver-nano particles (when it occurs) does not appear to be responsible for the observed bactericide properties (Maillard and Hartemann, 2012). Nanoparticles and nanowires are promising since they damage bacterial membranes and do not depend on the release of metal ions to kill bacteria.

Whether silver, copper or other biocide metals are incorporated, it is important to differentiate ion release based mechanisms from other nano-structured mechanisms. An ion-release mechanism must be very slow to withstand 25 years in a cooling tower environment. A surface with metallic nano-rods that can kill microorganisms with minimal release or loss of the biocide agent is perhaps more suitable for obtaining long term anti-bacterial properties. The other approach that is promising is the ability of hydrophobic surfaces to impede biofilm adhesion. The following section discusses strategies to render surfaces hydrophobic.

3.4 Anti-microbial properties dervied from nanostructure & hydrophobic elements

A surface is defined as superhydrophobic when it has a droplet contact angle greater than 150 ° and sliding angle smaller than 10 °.These surfaces are bioinspired from natural sources such as lotus leaves and butterfly wings. They can be explained by the presence of nanostructures. Despite having excellent properties (anti-bacterial, self-cleaning, anti-corrosive, anti-icing, etc.) superhydrophobic surfaces are often not industrially applicable because of a lack of mechanical stability.

A variety of methods for obtaining nanowires or nanostructred metal oxides exist: etching of aluminum oxide, sol-gel process and various types of chemical vapor deposition (VLS, VS, SLS). Nanowires have unique chemistry and physics and have potential applications in semiconductors, biology, optics, tragetted drug delivery, quantum computing and more. They also can add unique anti-microbial and hydrophobic properties to surfaces. This section will cover the mentions of hydrophobic aluminum surfaces specifically targeting the issue of bacteria and biofilm since covering all mentions of hydrophobic aluminum would be too large of a scope.

A combination of evaporative drying and etching have been used on anodized aluminum in order to obtain a "3D surface". Following this method, anodized aluminum is etched, which makes the pores grow in diameter until the surface has a disconnected nanopillared structure that can be shaped into sharp nano-rods of alumina using evaporative drying (Ferdi Hizala, 2014, pp.17-22). These sharp rods mechanically damage bacteria and reduce bacterial adhesion. The anodic thickness is said to be around 1.5 microns in thickness. A light uniform teflon coating under 10 nm thick renders the surface further hydrophobic, without removing the mechanical effect. The same teflon coated 3D structure was optimized and improved with the impregnation of perfluorinated oil (Ga-Hee et al., 2017, 359-363). There is no mention of the durability and mechanical stability of the surface. A similar 3D surface effect can be obtained by chemically modifying an anodized surface with myristic acid ($CH_3(CH_2)_{12}COOH$) for reducing corrosion and bacterial adhesion (Tao et al., 2010, 5281-5285). Again the subject of mechanical durability and stability seems to be avoided.

Super-hydrophobic surfaces with self-cleaning properties that claim to be mechanically stable have been created using etching with HNO_3 and HCl and impregnated with lauric acid ($C_{12}H_{24}O_2$) (Priya Varshney and Kumar, 2012). The mechanical stability is evaluated with a peeling test using adhesive tape 100 times.

Electrochemical precision etching to produce porous anodized aluminum oxide membranes with structurally well-defined surface nanopatterns was shown to effectively reduce biofilm growth (Mulansky, 2016). The article concludes that "Anti-adhesive and antimicrobial surfaces could potentially be very useful in preventing the bio-fouling of technical systems" but does not mention the thickness of the anodic layer obtained, mechanical stability or durability against corrosion. Bismuth ferrite nano-rods impregnated in aluminum oxide layers have also demonstrated hydrophobic and anti-microbial properties (Biswas and al., 2017). The thickness of the anodic layer or durability is not discussed. Zinc oxide in porous anodic alumina composite films have also shown hydrophobicity, dramatically restricting biofilm formation (X. and al, 2018). The films were prepared by two-step anodic oxidation and then the *ZnO/PAA* composite films were prepared by sol-gel method on their surface.

Polyaniline/chitosan/zinc stearate superhydrophobic coatings on aluminum with a nanosurface structure by polymerization of aniline and deposition of chitosan and zinc stearate coating have shown to have anti-biofilm properties (Mohan Raj and Raj, 2018) . Film thicknesses of up to 29.1 microns are mentioned along with adequate abrasion and corrosion resistance suitable for marine environments. They claim that "such an easy and low-cost method could be easily applied to large-scale productions of superhydrophobic anticorrosion aluminum alloy surfaces" with corrosion rates in as low as 0.14 mpy in a 3.5 % $NaCl$ solution.

Summary

Many interesting avenues for rendering surfaces anti-microbial exist but few seem to rigorously study the long-term durability of such a surface. An experimental campaign has yet to suggest that any of these anti-microbial surfaces are durable for a cooling tower environment, whether it is by surface-modification, electroplating or hydrophobic coating. Among the strategies for obtaining a biocide or anti-biofilm surface, those that render the surface hydrophobic or do not depend on a release based mechanism seem more promising for a long term application in a wet corrosive environment.

A durable surface capable of reducing the formation of biofilm or reducing bacterial counts in wet environments would potentially be applicable in cooling towers, water tanks, food production zones, marine environments and many other fields in which metal is in contact with water. As such, developing such a surface is of great interest and anodized aluminum being a resistant porous substrate is a good candidate.

Beyond the efficacy of such surface, design and cost considerations also play an important role since companies would not implement a solution that is not economically advantageous. It is in this context that I believe this work to be relevant as it aims not only at studying AAA and reviewing other biocide or hydrophobic methods but also at determining in which circumstances such a surface would be economically viable.

CHAPTER 4 OBJECTIVES & METHODOLOGY

Globally, the research question can be formulated as: can anti-microbial anodized aluminum (AAA) as developed by A3Surfaces be implemented to reduce microbial counts and biofilm development in cooling towers while remaining economically viable? However, an important nuance is that the study of economical viability is not restricted to AAA but to any surface that can effectively be biocide or prevent biofilm adhesion. As seen in the literature review, many avenues are left to explore and the economic framework applies to these surfaces as well. More specifically, the main research objectives and methodology can be broken down into groups as such:

4.1 Research objectives

[1] Can AAA can withstand a cooling tower environment while providing advantages in terms of bacterial control? Objective [1] can be broken down as such:

> **[1a]** Determine if the durability of AAA is sufficient to withstand a cooling tower environment.

> **[1b]** Determine if AAA surfaces in a simulated cooling tower environment reduce biofilm development and/or bacterial counts (CFU/ml) in the water volume.

[2] What are the design and economic implications of implementing AAA (or another biocide or anti-biofilm surface) in cooling towers assuming such a technology can be made durable and does reduce bacterial levels? Objective [2] can be broken down as such:

> **[2a]** Determine the design considerations of implementing AAA in a cooling tower.

> **[2b]** Establish the main parameters affecting the cost of a cooling **tower program**[1] and which advantages should AAA (or another biocide or anti-biofilm surface) bring to be economically viable?

[1]A cooling tower program specifically refers to all the costs associated to a cooling tower over its lifespan: electricity, water, maintenance, chemicals and the initial purchase of the tower itself.

4.2 Research methodology

[1] For objective [1], an experimental campaign was carried :

[**1a**] 32 samples were fabricated. These consisted of control samples, AAA samples and samples electroplated with silver. Two bacterial strains, *Pseudomonas Aeruginosa* and *Staphylococcus Aureus* were used in 2 different types of tests: a rinse-cycle test and a dry-kill test for which bacterial levels were measured in CFU/ml or CFU. These tests are described further and detailed in appendix B. A series of corrosion coupons were placed in cooling tower basins and corrosion was evaluated in *mpy* by subcontracting H20Biotech.

[**1b**] Two practically identical prototype cooling towers were built with one key difference: one was made with AAA and the other with untreated anodized aluminum 5083. The entire tower was made with aluminium as show in figure (5.1). These towers were contaminated with *Pseudomonas Aeruginosa* and *Staphylococcus Aureus* and they operated with a heat-source in a biological laboratory for several runs. Household bleach was used in between tests to sterilize the towers which were then rinsed. CFU/ml counts were taken for the water volume of the tower.

[2] For objective [2] the methodology can be broken down as such:

[**2a**] Axiomatic design was used to establish a basic design matrix for a cooling tower. This allows to see the key tower elements that play a role in bacterial development and other design considerations. It also helps to lay the grounds for the subsequent economic analysis.

[**2b**] Several sources were gathered to approximate the cost of cooling tower programs and the main key variables that influence cost were determined. A model was created that can evaluate which advantages an antimicrobial surface should bring in maintenance, chemical, water or operation costs to justify the extra initial investment.

CHAPTER 5 BACTERIAL COUNTS ON PROTOTYPE COOLING TOWERS AND ANTIMICROBIAL ANODIZED ALUMINIUM SAMPLES

The following section presents the experimental campaign carried on aluminum samples and the prototype towers along with the results obtained. The methodology is explained here, but the exact step by step protocols are written in Appendix B to lighten the reading.

5.1 Prototype cooling tower tests

Two prototype towers with identical experimental set-ups were built at A3Surfaces. The only difference is one tower was built in AAA (using alloy 5083) and the other one in hard anodized aluminum 5083 but untreated. A cocktail of bacteria, salt and peptone was carefully selected by Patrick Asselin-Mullen (M. A. Sc. Microbiology). These bacteria were added to kickstart the contamination of the towers. Each tower was operated 3 times, for a total of 6 runs. The parts of the experimental set up are presented in the following section.

Cooling tower test objectives

(1) Verify if CFU/ml counts in the water volume of the tower is lower for the AAA tower and if this remains true after several runs.

(2) Simulate a tower environment with realistic temperatures, chlorination, airflow and waterflow, where part of the water circulates out of the tower in an environment we can't control.

Prototype cooling towers test parts:

Figure (5.1) shows a schematic representation of the prototype. Other elements like tubing, wiring, pressure collars, screws and miscellaneous are not enumerated.

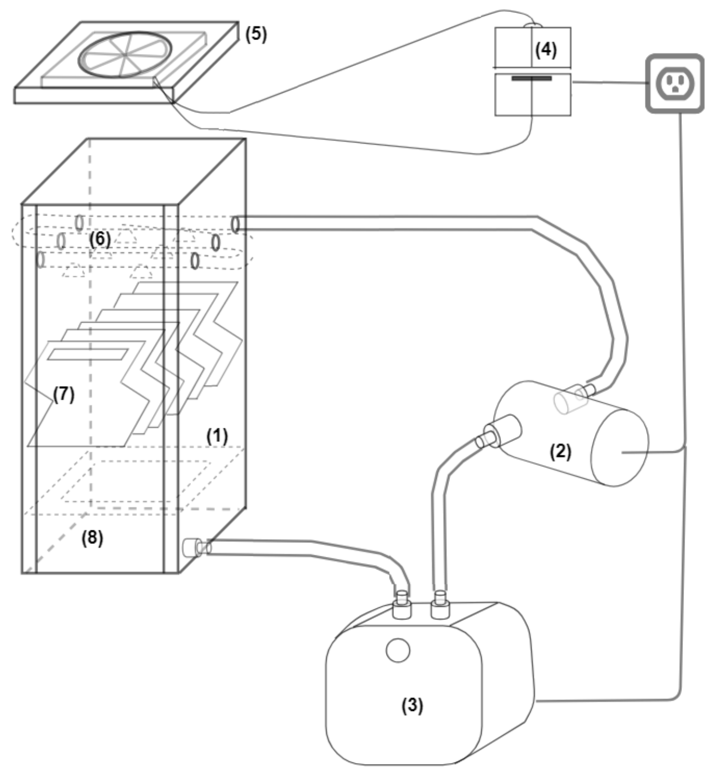


Figure 5.1 Experimental setup schematic: (1) Cooling tower casing (2) Master craft pump 062-3566-8 (3) Eccotemp EM-2.5 electric 2.5 gallon mini tank water heater (4) Motor master eliminator 12 V - 2A car battery charger (5) fan APEVIA - DF12025 (6) Water distribution system with 6 sprinklers (7) Cooling tower fill (8) Cooling tower basin

Figure 5.2 Picture of the experimental set up built in a biological laboratory at A3Surfaces

5.2 AAA sample tests

The objective of the experimental campaign carried on samples was to test the limits of AAA in wet-environments and study the effect of silver electrodeposition as opposed to the original AAA in which the aluminum is dipped in a silver nitrate solution before sealing. All the testing protocols are presented in Appendix B.

Table 5.1 Sample number and corresponding treatment

Sample number	Treatment
9,10,15,16,17,26	none. (control samples)
1, ... ,8 & 11, ... ,14	AAA (original treatment as in patent)
18,19,27,28	Electroplated with silver for 3 minutes.
20,21,29,30	Electroplated with silver for 10 minutes.
22,23,31,32	Electroplated with silver for 3 minutes and sealed as in AAA patent with a quaternary amonium solution.
24,25,33,34	Electroplated with silver for 10 minutes and sealed as in AAA patent with a quaternary amonium solution.

5.2.1 Rinse-cycle tests

The first study done at McGill demonstrated that AAA can sterilize a small water volume. With this in mind, the rinse-cycle test was design to test the limits of this sterilizing effect. The objective was to reach the exhaustion point of AAA and to compare how electroplated samples fare as opposed to the original AAA procedure. Figure (5.3) shows the steps of this procedure. The exact steps are in Appendix B.

5.2.2 Dry kill tests

The dry kill tests is based on the standard spread plate test for measuring CFU's. The objective was to verify how the prior exposure to a wet environment affects the antimicrobial qualities of AAA and electroplated samples once they are dry. Figure (5.4) shows the steps of this procedure. The exact steps are in Appendix B.

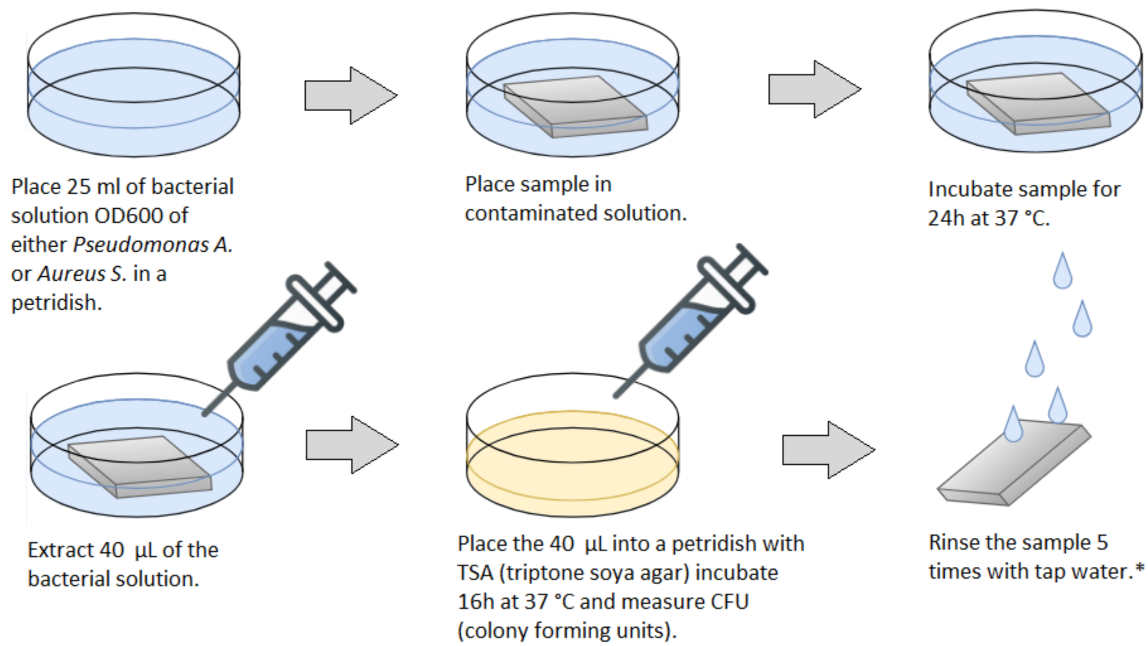


Figure 5.3 Schematic representation of the rinse-cycle test. (*) some samples were rinsed with isopropyl alcohol instead (protocol variation)

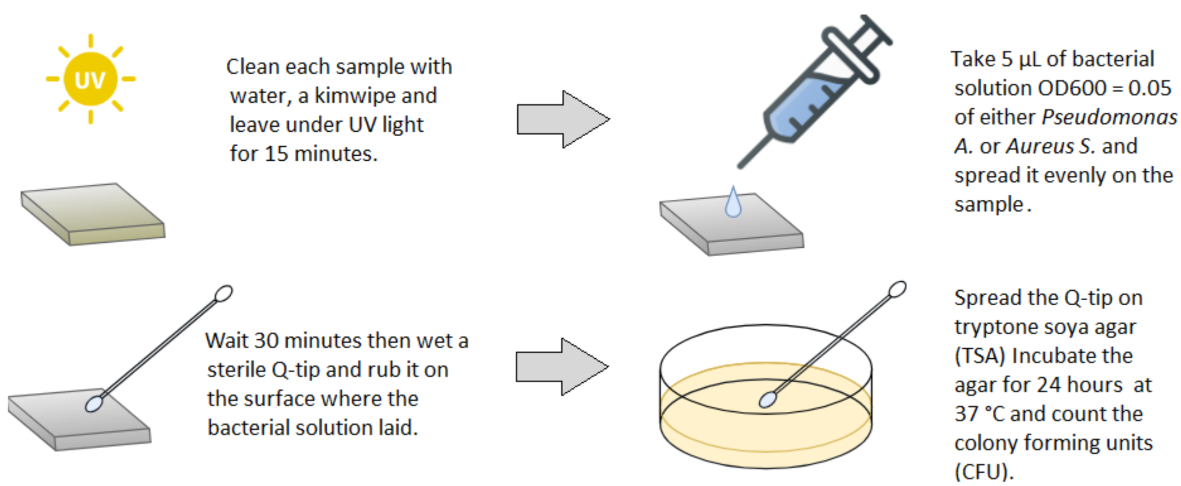


Figure 5.4 Schematic representation of the dry kill test

5.3 Cooling tower test results

The results obtained from the cooling tower tests clearly show that AAA impregnated with silver nitrate and quaternary ammonium without any electroplating quickly loses the capacity to reduce bacterial counts after the water volume is replaced. Figure (5.5) shows CFU/ml counts in the water volume for each run for both towers.

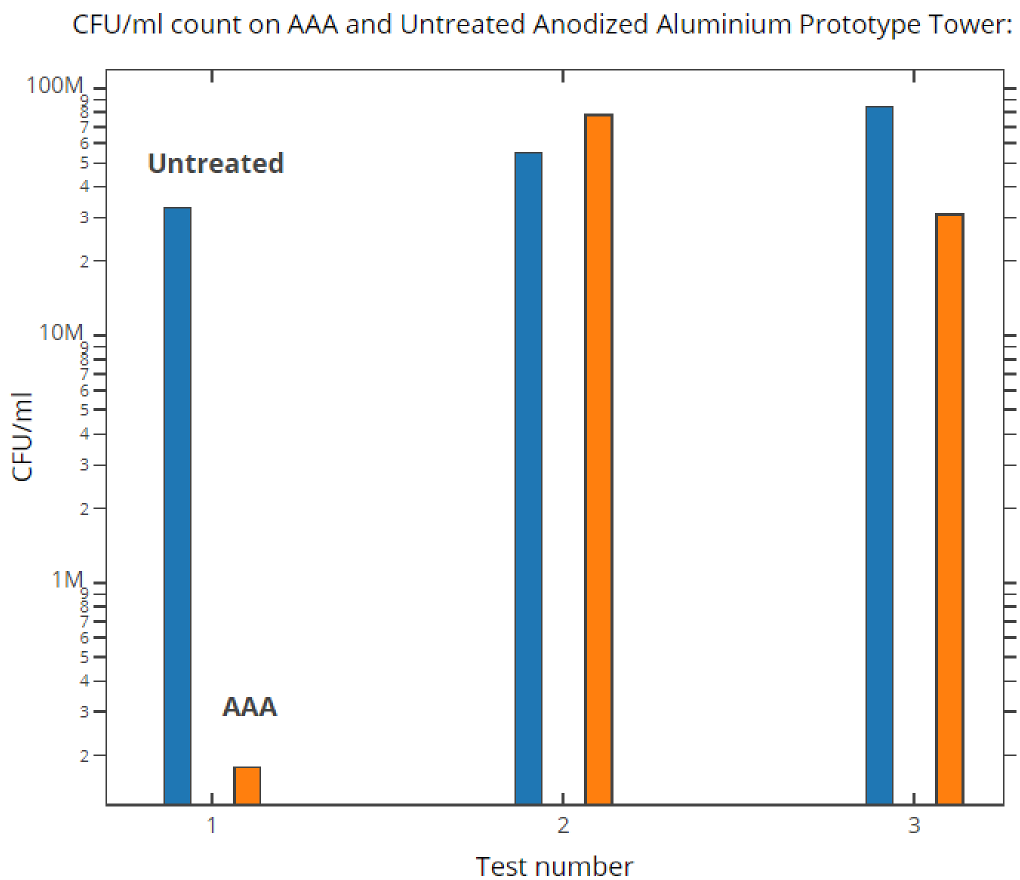


Figure 5.5 CFU/ml counts on the cooling tower water for the AAA tower and untreated tower for 3 runs. The anti-microbial performance of the two towers can be compared

The first run shows a much lower CFU/ml count for the AAA tower: $1.9 \times 10^5 CFU/ml$ as opposed to $3.3 \times \; 10^7 CFU/ml$. However, once the water is dumped out and a new run is started, we see both the untreated and AAA tower reach similar levels in the 10^7 CFU/ml range for the second and third runs.

A theory for this is that most of the biocide elements (silver nitrate and quaternary ammonium) diffused into the first water volume. This initially makes bacterial counts much lower acting much like a a standard water treatment where chemicals are added to the water. However, once that water is replaced, there was no evident advantage for the AAA tower. It can be hypothesized that bacteria are reproducing in the water volume regardless of the antimicrobial surfaces. However, the sample tests show that the samples that were not electroplated lose their biocide properties with prolonged exposure to a wet environment.

It is worth noting that sample testing showed that electroplated silver samples have a much greater durability in wet environments and the AAA protocol does include a variant in which silver is electroplated. These results are for AAA with silver nitrate and quaternary ammonium bath prior to sealing. The test could be repeated with an electroplated tower. However, I would suggest further testing on samples since running prototype towers can be expensive and the literature review shows other promising treatments that should be explored.

It is also important to note that chlorination might have had an effect on the durability. Chlorine interacts with silver ions forming silver chloride. It is possible that the chlorination accelerated the depletion of silver nitrate.

The reason prototype towers were built is because A3Surfaces had done prior experimental campaigns to verify if AAA resisted wet environments. Their results were positive but they did not have a clear and official protocol describing what they had done. This experimental campaign shows otherwise.

Considering the large array of techniques mentioned in the literature review, experimenting with these on samples until good results are achieved before moving to a prototype tower again is a better approach. The same prototype towers could be etched, re-anodized and used for future experiments if need be, once satisfactory sample results are obtained. A prototype tower is interesting since it gives a similar environment to a cooling tower, but it makes it more difficult to interpret the results due to the complexity of the experiment.

5.4 Sample test results

The following section presents the bacterial counts (CFU/ml) for the rinse-cycle test that was described in the chapter 5.

Rinse-cycle tests on original AAA samples

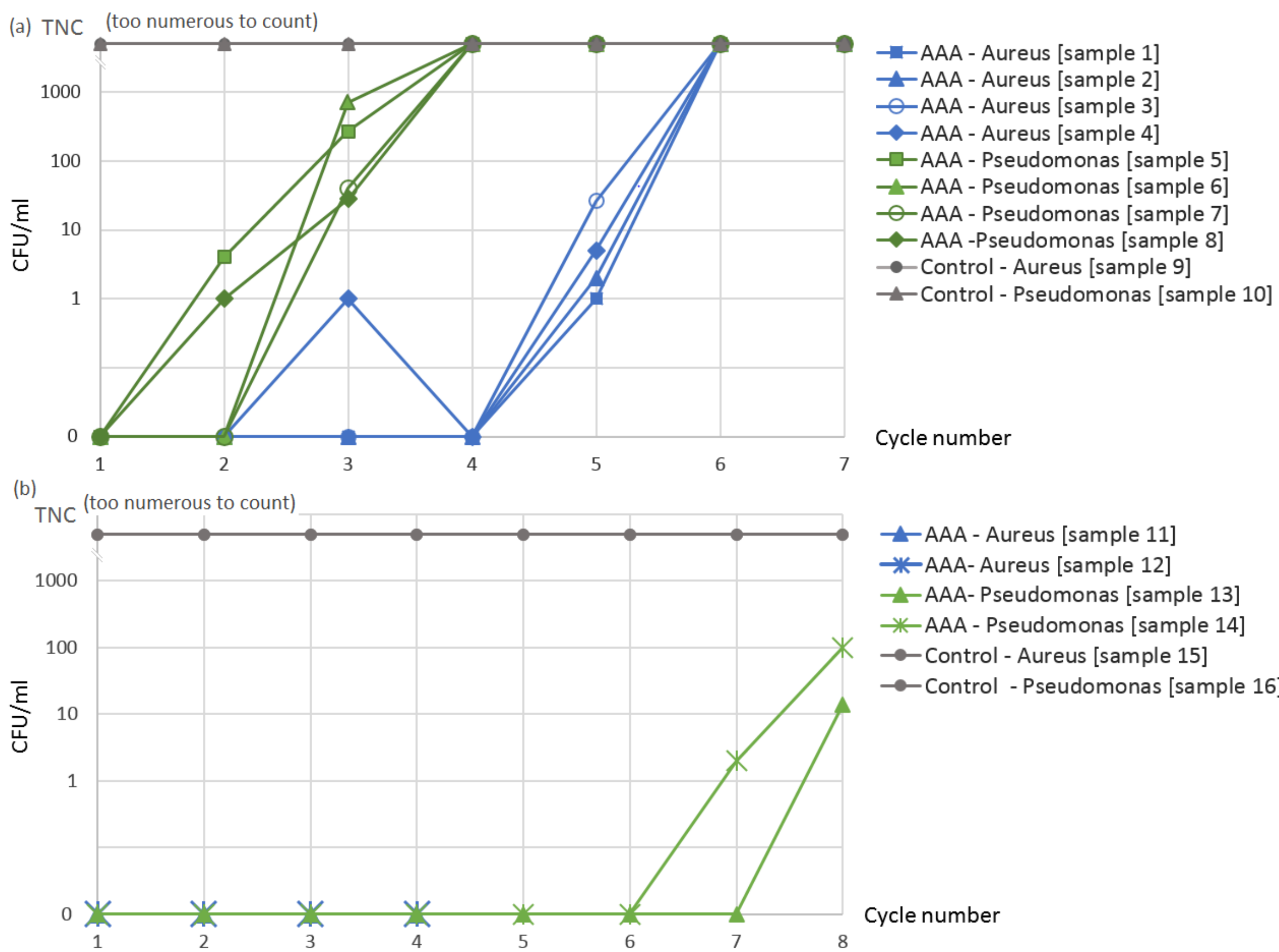


Figure 5.6 Graph (a) CFU/ml counts made on water contaminated with either *Staphylococcus Aureus* or *Pseudomonas Aeruginosa* (with a bacterial concentration measured at $OD_{600} = 0.1$) after a contact with AAA samples at 37 $°C$ for 16 hours following the wet-test protocol. Graph (b) same CFU/ml count but removing the isopropyl rinse from the wet protocol.

Rinse-cycle tests on electroplated samples (ED)

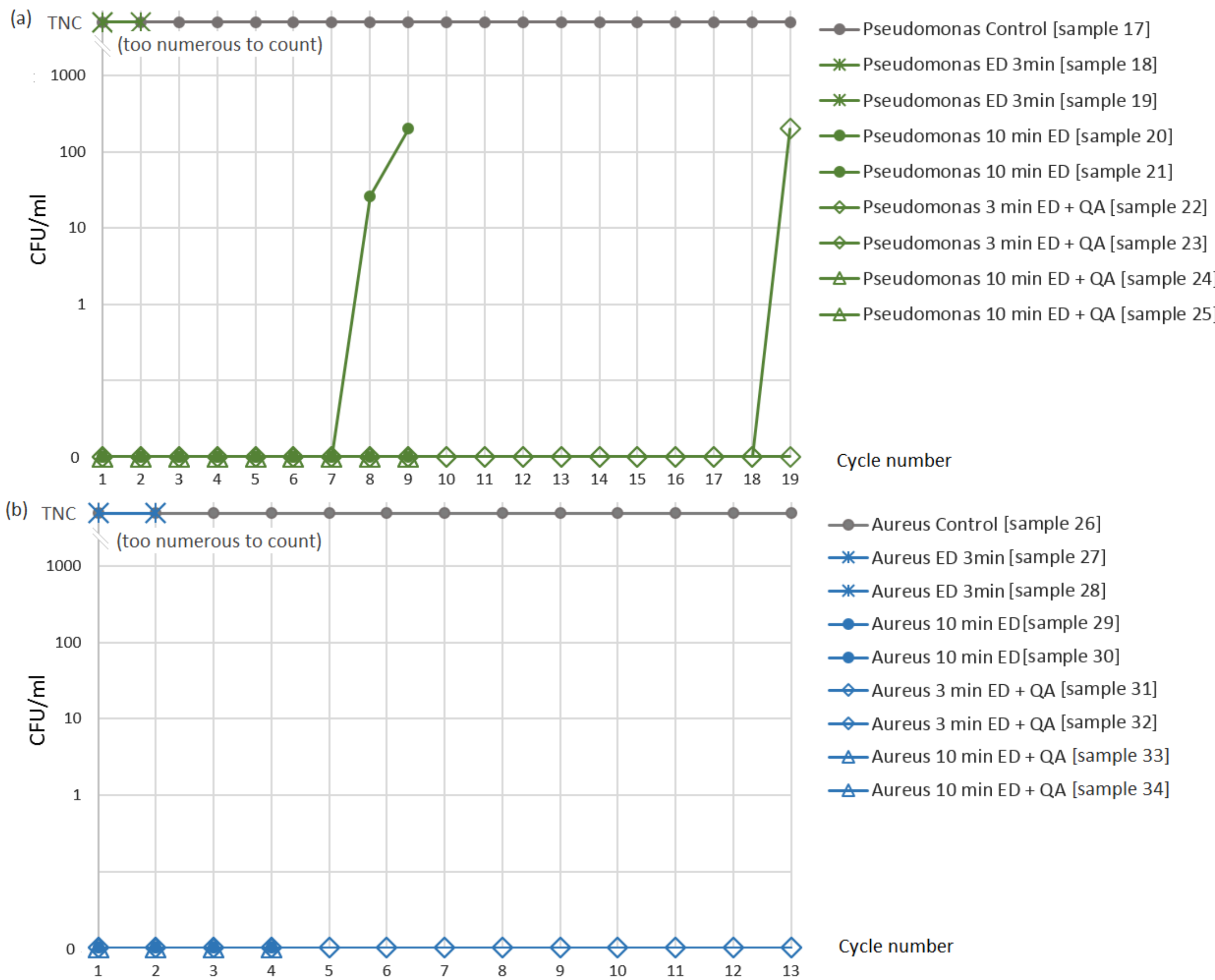


Figure 5.7 Graph (a) CFU/ml counts made on water contaminated with *Pseudomonas Aeruginosa* ($OD_{600} = 0.1$) after a contact with AAA samples at 37 °C for 16 hours following the wet-test protocol (without cleaning with isopropyl). Graph (b) CFU/ml counts made on water contaminated *Staphylococcus Aureus* (with a bacterial concentration measured at $OD_{600} = 0.1$) after a contact with AAA samples at 37 °C for 16 hours following the wet-test protocol (without cleaning with isopropyl).

The rinse cycle tests show that the sterilizing effect observed at McGill is short lived for original AAA samples. This further suggests that the biocide elements are depleted which implies that a diffusion of biocide elements is the primary mechanism by which AAA kills bacteria. Cleaning the samples with isopropyl alcohol has shown to further deplete the biocide elements.

An important finding is that electroplated samples show much greater durability in wet environments. 3 minutes and 10 minutes electrodeposition perform better than standard AAA in rinse cycle tests. The mechanisms by which silver kills cells are not entirely known but it is thought that the release of silver ions is the essential to silver's toxicity. This suggests that electroplating the samples results in higher concentrations of silver on the sample than simply doing a silver nitrate dip. Studying different methods of coating silver with slow release mechanisms could be an alternative worth exploring since very small concentrations of silver can kill bacteria. Another avenue would be experimenting with the incorporation of nanotubes or nanometric structures since they exhibit antimicrobial mechanisms other than diffusion.

It is worth noting that although *L. Pneumophila* and *P. Aeruginosa* are rapidly killed at a silver concentration of 0.1 mgL^1, they survive easily in amoeba when biofilm is present, showing that bacteria are less sensitive to silver in the presence of biofilm (Hwang, 2006). The question remains whether biofilm would form in the first place. This shows the difficulty of going from promising experiments to practical situations.

Exploring an antimicrobial surface with a different mechanism of action would perhaps be a better idea for cooling towers. As mentioned in the literature review, nanostructures alone have shown to exhibit bactericide and hydrophobic properties. A surface that can't form biofilm would help chemical treatments sterilize the water more efficiently, reduce maintenance and fouling.

Dry kill test before and after rinse-cycles

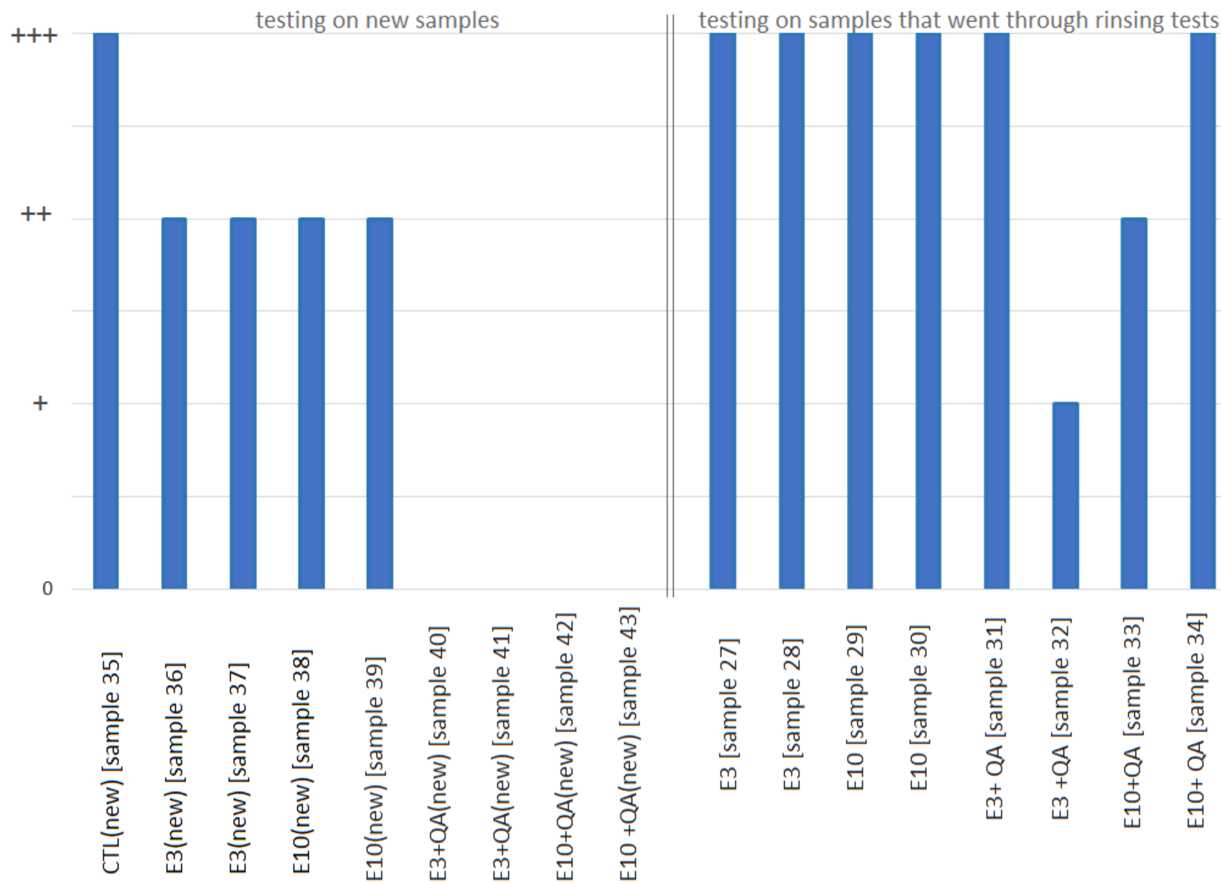


Figure 5.8 Qualitative bacterial growth observed on brand new samples compared to samples that went through several rinse-cycle tests. Four levels of visually observed bacteria are shown as (+++ = covered), (++ = significant) , (+ = present), (0 = none). The brand new samples are indicated in parenthesis (new).

The dry kill tests show that the samples that were repeatedly rinsed had lost their biocide properties when compared to brand new samples. It is important to notice that some of the electroplated samples that had not grown any bacteria after 18 rinse cycle tests developed bacteria after the dry kill test suggesting that the mechanism in a wet environment is different from a dry one. Since it is silver ions that kill bacteria, it could be that once the droplet already dried on the surface, silver ions can no longer diffuse to kill surviving bacteria. These are then free to reproduce once deposited on triptone soy agar (TSA).

5.4.1 Corrosion coupons submerged in cooling tower water results

Adequate corrosion resistance is fundametal for anodized aluminum to be able applicable in cooling towers. With this in mind *H20Biotech* was sub-contracted for a corrosion resistance evaluation of samples of AAA compared to other metals. In this particular study, 5083 anodized aluminium, copper, galvanized steel and carbon steel 1010 were submerged in a cooling tower basin for a period of 65 days and the corrosion was measured in mpy (by weight-loss method.)

It is worth metioning that the following corrosion tests do not adress the complex interactions that the chemicals used in this particular water treatment regimen could have had with the rate of corrosion overall, or the rate of corrosion of one metal with respect to the other. As discussed in chapter 1, water treatments involve increasingly complex recipes to prevent scaling and biofilm according to water quality and regulations. As such, this study cannot be regarded as providing an absolute guarantee that 5083 anodized aluminum is good for cooling tower environments. A more diligent study of the ideal water treatment for AAA should be carried. Precipitation is to be avoided at all costs to maintain the anti-microbial and anti bio-film properties of AAA. The document in appendix C by *H20Biotech* presents the corrosion results of their study.

Three different 5083 hard anodized aluminium samples with 95, 85 and 80 microns anodic layers presented corrosion rates of **0.5 mpy, 0.1 mpy** and **0.1 mpy** respectively. It is not clear why one of the samples showed more corrosion. What is important to notice is that this corrosion rate is lower than 1010 carbon steel and galvanized steel for the same environment. This suggests that corrosion will not be the primary concern here. Anodized aluminum can be made suitable for very corrosive marine environments. The issue to be analyzed is the cost as we will discuss further.

5.4.2 Experimental campaign summary

In short, AAA fabricated without electroplated silver was not durable in wet environments according to both the cooling tower prototype experiment and the experiments carried on samples. It was accidentally discovered that isopropyl alcohol accelerates the depletion process.

It was found that electroplating increased dramatically the biocide durability of the surface. Since there are no nanotubes formed by this electroplating procedure, the hypothesis is that the total amount of silver in the samples is much higher when they are electroplated and it is the diffusion of silver ions that keeps the surface biocide. This is reinforced by the fact that the dry-kill test shows bacteria growing on samples that were not depleted by the rinse test. Once the contaminated droplet dries, if some bacteria are still present, silver ions can no longer diffuse and these bacteria reproduce on TSA (triptone soy agar). However, depletion was also observed for electroplated surfaces and they cannot be used as such despite performing better.

The recommended approach for the future would be to test different bactericide and hydrophobic procedures described in the literature review and only proceed to testing on cooling towers once a sample shows durability in wet environments. Ideally, testing if biofilm grows after a longer time frame would be a better approach. At that point, the prototype towers can be etched, anodized and and re-used for testing.

CHAPTER 6 DESIGN & ECONOMIC VIABILITY FRAMEWORK FOR A NEW COOLING TOWER SOLUTION

Chapter 4 summarized the experimental campaign carried out on AAA to determine its suitability for cooling tower environments. The following section explores the design implications of adding a functional biocide surface to a cooling tower assuming such a surface exists and then presents an economic viability framework based on the cost of a cooling tower program.

6.1 General design matrix

Using the framework of axiomatic design, a cooling tower can be broken down into **FR** (functional requirements) that are each linked to their respective **DP** (design parameters). AAA is presented in a separate column to show which parameters it would influence. A small x indicates that AAA has an impact in these FR's without it being its primary role.

	DP0:	DP1: pump & piping	DP2: casing&basin	DP3: fill	DP4: drift eliminators	DP5: biocide treatment	DP6: make-up water system	DP7: Blowdown system	DP8: scale chemical treatment	DP9: Corrosion Inhibitors	DP10: fan	DP11: Modularity and access doors	DP : AAA
FR0: Cool Water with Air (by evaporative cooling)	O												
FR1: Circulate water		X											
FR2: Contain air&water			X										
FR3: Increase air / water contact				X									
FR4: Reduce water loss from drift					X								
FR5: Prevent bacterial growth			X	X	X	X							X
FR6: Compensate for water loss							X						
FR7: Prevent increase in concentration of minerals							X	X					
FR8: Prevent scale on surfaces						X	X	X	X				x
FR9: Prevent corrosion			X			X			X	X			x
FR10: Circulate air				X	X						X		
FR11: Allow easy maintenance		X	X	X	X		X	X			X	X	X

Figure 6.1 High level design matrix for a cooling tower showing dependencies. AAA is shown outside of the matrix to illustrate which FR's it impacts

This allows a neat visualization of the inter-dependencies of the main components of a cooling tower. By chosing any **FR**, we can look at which design components affect it.

Considerations when implementing AAA

AAA would be a **DP** that is expected to accomplish many roles: AAA is supposed to keep biofilm off surfaces, which is expected to reduce bio-fouling, which reduces chemical needs, increases performance and reduces electricity costs.

FR5: Prevent bacterial growth

The design matrix shows that 3 main physical components are linked to bacterial growth: the **DP2:basin&casing**, **DP3:fill** and **DP4:drift eliminator**. These are the main candidates for implementing AAA. Considering the complex geometry of fills and drift eliminators, AAA fills&drift-eliminators would be very expensive compared to ABS or PVC fills. Another important point is the manufacturing limitations related to making the fills out of anodized aluminum. These need to be explored since it is perhaps impossible to acheive the same geometries. The **DP5: biocide treatment** is also affected by AAA since chemical needs would be reduced by a material capable of staying biofilm free.

FR8 & FR9 : Scale and corrosion

Since water treatment considerations must be tailored according to the tower material both **DP8: scale chemical treatment** and **DP9: corrosion inhibitors** are linked to AAA. Aluminium is an amphoteric metal, meaning it corrodes at high and low pH. Alkaline-based treatment programs primarily relying on inorganic and organic phosphates may not be suited as well as ozonation which raises pH. A tailored water treatment for an anodized aluminium tower would need to be designed.

FR11: Allow easy maintenance

Maintenance access will not be simplified by AAA but an effective antimicrobial material would reduce biofilm formation and hence maintenance requirements. For this reason, low fouling improves tower performance, which reduces electricity costs. This is the best selling point for an efficient anti-fouling surface since these costs can be very high as we will see later.

Other design considerations

Closed-circuit cooling tower vs open-circuit cooling tower
A proper biocide surface has the potential not only to reduce biofilm development but to reduce total CFU/ml counts since biofilm is an essential development ground for microorganisms. A **closed-circuit cooling tower** would limit the exposure of the cooling tower water mainly to the tower itself. This is better suited for low bacterial levels compared to an open-circuit tower where the same water circulates through other components such as the chiller.

Side-filtration
If scale or particles deposit on AAA, it is unlikely that it will remain an effective biocide. Many towers include side-filtration systems where part of the water (or all) is filtered to remove dirt particles. A **filtration system** would be desirable or even necessary with an antimicrobial surface.

6.2 Economic framework

In order to study **cooling tower program costs** an economic framework was created where users can input relevant cooling tower variables for an installation and obtain a cooling tower program cost profile. This allows to see which costs are dominant according to location, usage, climate and utility prices. For each installation the viability point will be different, but we will see that the initial investment of the tower itself is often negligible compared to the total costs over the tower life span. This means that a decrease in fouling can quickly make a more expensive tower more economical in the long run. At the end of this section, some cost profiles will be presented for different HVAC cooling towers.

Lets first break down the costs of a cooling tower program in different categories:

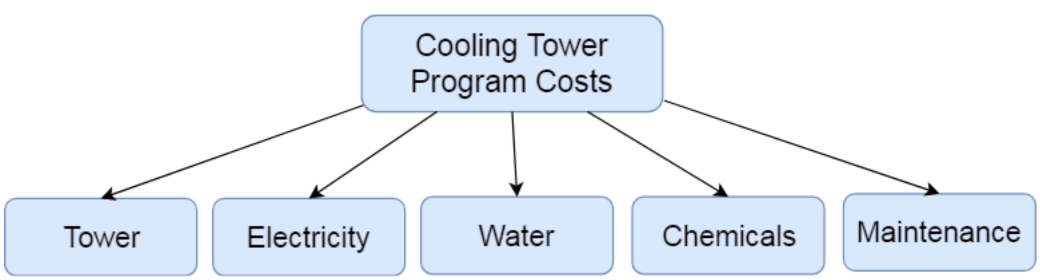


Figure 6.2 Cooling tower program costs, meaning all the costs associated with owning a cooling tower over its lifespan: tower purchase, electricity, water, chemicals and maintenance.

It is important to differentiate **variable costs** and **fixed costs**. We will only look at variable costs since it is not necessary to look at the costs that are not affected by the incorporation of a new anti-microbial anodized aluminum tower. Initial investment costs for a **cooling system** will typically also include installation, piping, pumps, chillers, valves, control units but these are not affected by the new technology and are considered fixed.

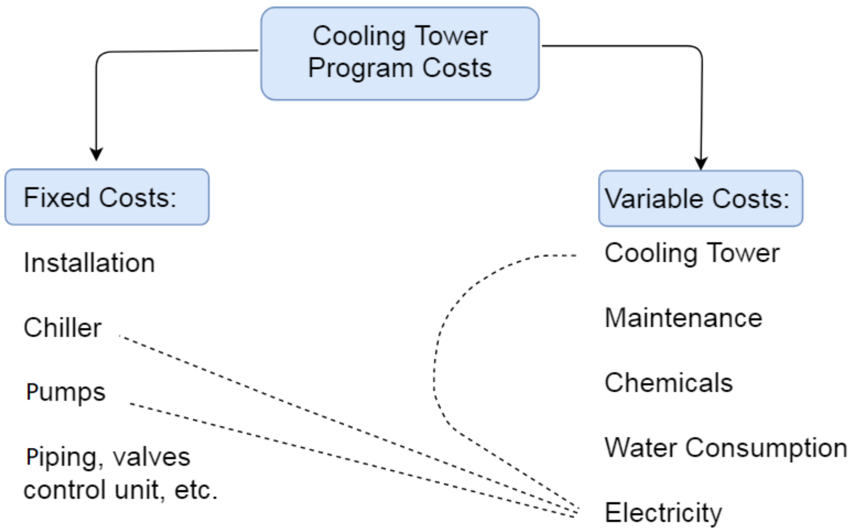


Figure 6.3 Fixed costs: costs not affected by implementing an anti-microbial surface in a cooling tower. Variable costs: costs affected by the implementation of an anti-microbial surface cooling tower. Dashed lines show dependencies of electric costs due to reduced fouling.

The idea is to first establish a **cost function** that estimates what a cooling tower program will cost throughout its lifespan. Then we can look at how much costs would need to be reduced to justify an anti-microbial tower. The costs were kept in US$ since more information is available and it is very easy to change to $CAD in the end. The following sections look at these costs individually.

The cost of a standard cooling tower program is considered a function of the following parameters.

$$C = f(\,RT,\; LF,\; COP,\; COC,\; t,\; R_{elec},\; R_{mu},\; R_{bd}\;, m)$$

These parameters are:

- RT: Cooling tonnage (refrigeration tons).
- LF: Load factor.
- COP: Coefficient of performance.
- t : Lifespan of the tower in years.
- COC: Cycle of concentration.
- R_{elec}: Cost of electricity (US$/kWh).
- R_{mu}: Cost of make up water ($US\$/m^3$).
- R_{bd}: Cost of water discharge ($US\$/m^3$).
- m: Number of months / year the tower is operational.

Cooling tower cost:

Several data points were used to obtain an approximation of the typical **cost of a cooling tower per cooling ton ($/RT)**. Using a MMSE (minimum mean square error) method, a first equation was obtained using 13 models from the *CTS - Cooling Tower Systems* 2018 catalog. A US dept of energy presents a graph with cooling tower prices per tower size (H.P. Loh; Jennifer Loyns; Charles W. White, January 2002). Extrapolating the curve from the data and adjusting for the inflation between 2002 and 2018 gave a second equation approximating the cost. Making the hypothesis of these sources being equally reliable we obtain the following equation:

$$C_{purchase} = 189.32(0.408RT^{0.8542} + RT^{0.744}) \tag{6.1}$$

- RT = Refrigeration tons.
- $C_{purchase}$ = US$.

Electricity cost:

The most straight forward method for evaluating operation costs is to look at evaluations of the COP (coefficient of performance) of cooling towers, and their LF (load factor). How to obtain these will be discussed further. With this information, the power in kW used by the tower can be calculated:

$$P_{in} = \frac{P_{out}LF}{COP} = \frac{RT[\frac{3.516kW}{ton}]LF}{COP} \tag{6.2}$$

- RT = Refrigeration tons ($\frac{3.516kW}{ton}$).
- LF = Load Factor.

- COP = Coefficient Of Performance.

The annual cost in

$$\$US$$

can be calculated with the electricity rate:

$$C_{power} = P_{in} R_e h_{yr} = \left[\frac{3.516kW}{RT}\right]\left[\frac{8760hr}{yr}\right]\left[\frac{RT\ LF\ R_e}{COP}\right] = 3.08 \times 10^4 \left[\frac{RT\ LF\ R_e}{COP}\right] \quad (6.3)$$

- R_e = Electricicty rate ($\frac{\$}{kWh}$).
- h_{yr} = Hours in a year (simply a conversion factor since the LF considers the actual amount of hours the tower operates.)

As such, the electricity cost over the lifespan of the tower is:

$$C_{power} = \sum_{n=0}^{t} 3.08 \times 10^4 \left[\frac{RT\ LF\ R_e}{COP}\right] \quad (6.4)$$

- t = Lifespan of the tower (typicall around 25 years).

Load Factor (LF) and Coefficient Of Performance (COP) :

The LF and COP for a specific cooling tower system depends on climate, intended use and installation type. In this particular analysis, we are looking at energy consumption at the level of the **tower, pump and chiller**. The reasoning behind this is that fouling affects the performance of all three in an open-circuit cooling tower and we want to look at all the affected costs (variable costs). The method used to estimate the load factor of a cooling tower according to hourly climate data for an HVAC tower paired with a chiller is presented in Appendix A.

The method employed uses hourly data for temperature, humidity and pressure. Using Merkel's model proved to be complicated for several reasons: first, the Merkel model will only allow us to calculate the % of the nominal airflow the tower requires to eliminate the heat load. However, in a cooling system the tower consumes much less energy than the chiller and even less than the pump. Second, the COP of the chiller does vary with the heat load but this depends on whether the tower and/or chiller have a VFD (variable frequency drive). This quickly became complicated so the approach taken was simplified. Appendix A goes through this method.

The coefficient of performance for the examples was chosen to be 5, which is a normal COP for a tower paired with an HVAC system.

The analysis was done using python programming language. Two scripts *ClimateAnalysis.py* and *LoadAnalysis.py* were created. They call functions from a third python script *CoolingTower.py* which defines a CoolingTower class that contains all the methods for calculating costs and cooling tower characteristics. The code is presented in Appendix A as well.

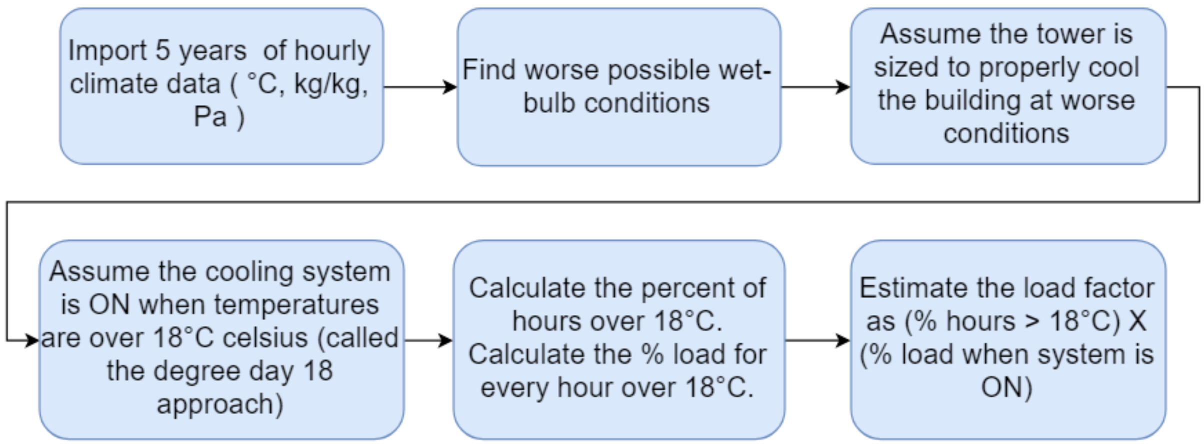


Figure 6.4 Diagram explaining the procedure used for obtaining an approximate load factor (LF) of an HVAC cooling tower and chiller installation according to climate data.

Water costs:

As seen in section (1.4.2) the amount of make-up water, blow-down water, drift and evaporation can be expressed as such:

$$w_{make-up} = w_{evap} + w_{blowdown} + w_{drift} \tag{6.5}$$

Knowing the amount of heat rejected ($Q_{rejected}$) by the tower and using the approximation that 80% of heat transfer is obtained through evaporative cooling we can approximate evaporation.

$$w_{evap} = \frac{Q_{rejected} \times f_{latent}}{h_{fg}} \tag{6.6}$$

The amount of blow-down amount can be written with the COC (cycle of concentration):

$$w_{blowdown} = (\frac{1}{COC-1})w_{evap} \tag{6.7}$$

Drift is typically negligible, in the order of 1 % of evaporation:

$$w_{drift} \approx 0.01 w_{evap} \tag{6.8}$$

- COC = Cycles Of Concentration.
- $f_{latent} \approx$ 0.7-0.9 percent of the cooling accomplished through evaporative cooling. we will use 0.8.
- h_{fg} latent heat of vaporisation of water ($2257\frac{kJ}{kg}$)
- $Q_{rejected} = RT3.516LF$ in kW is the heat-load of the tower.

Using equations (6.5) (6.6) and (6.7), w_{mu} and w_{bd} (short for $w_{make-up}$ and $w_{blowdown}$) in kg/s can be calculated the following way:

$$w_{mu} = \frac{RT\ LF\ f_{latent}}{h_{fg}}\left(1+\frac{1}{COC-1}\right) = 1.246\times10^{-3}\ RT\ LF\left(1+\frac{1}{COC-1}\right) \tag{6.9}$$

$$w_{bd} = \frac{RT\ LF\ f_{latent}}{h_{fg}}\left(\frac{1}{COC-1}\right) = 1.246\times10^{-3}\ RT\ LF\left(\frac{1}{COC-1}\right) \tag{6.10}$$

Knowing the costs of water purchase and the cost of water discharge in $\frac{\$}{m^3}$, we can calculate the annual water costs:

$$C_{mu} = w_{mu}\left[\frac{1m^3}{1000kg}\right][\frac{31536000s}{yr}]R_{mu} = 39.30\ RT\ LF\ R_{mu}\left(1+\frac{1}{COC-1}\right) \tag{6.11}$$

$$C_{bd} = w_{bd}\left[\frac{1m^3}{1000kg}\right][\frac{31536000s}{yr}]R_{bd} = 39.30\ RT\ LF\ R_{bd}\left(\frac{1}{COC-1}\right) \tag{6.12}$$

Chemical costs:

Getting an accurate comparison for different water treatment alternatives is extremely difficult for the following reasons:

- Different initial water conditions require different treatments.

- Make-up water costs vary greatly, giving either high *COC* (cycles of concentration) or low *COC* solutions an edge in a particular country or state.
- Most treatment products contain a mix of chemicals which are often secret formulas.
- Different tower designs & materials play a role in the *COC* and the choice of a water treatment.
- Different climate & usage change the annual ammount of hours a tower is operating.

The ASHRAE Green guide estimates 8$/RT/yr to 20$/RT/yr per refrigeration tonnage per year for cooling tower chemical costs as of 2006. Adjusted for inflation this gives 11.22$/RT/yr to 28.06 $/RT/yr, which averages to 19.64 $ /RT /yr. (ASHRAE, 2006, 191-193). LAKOS, a filtration systems company has an online cooling tower costs estimator to help companies calculate the potential earnings of adding a side-stream filtration system to a cooling tower. They use 1.2$/RT/month, which gives 14.4$/year if the tower operates 12 months a year. It is important to mention that the amount of months a tower operates a year is not equivalent to the load factor. In some climates, a tower can operate at low loads for many months. A value that considers the amount of months the tower operates is more desirable. It is important to understand that these estimates generalize the chemical costs without considering climate zones and water quality.

$$C_{Chemicals} = \sum_{n=0}^{t} 1.2\,[months]\,RT \tag{6.13}$$

Maintenance costs:

The US department of energy gives an example of a 400 RT cooling tower operated 3720 hours per year that costs 4320$ in maintenance.

$$C_{Maintenance} = \sum_{n=0}^{t} 11RT \tag{6.14}$$

Out of all the price estimates, maintenance is the most difficult one. Two companies in Montreal agreed to meet us and according ot them, cooling tower maintenance costs are usually between 1500 $CAD / year and 5000 $CAD / year for their clients. but that they can easily be up to 10 000 $CAD / year. However, they did not tell us what size tower these figures were for. The figure of 11 $ / ton / year is probably a low estimate, but we will work with this figure in this model.

Profiles for cooling towers:

To illustrate cooling tower program costs after 25 years, the model was applied for a hypothetical HVAC 400 ton cooling tower operating in 4 different cities: Miami, Chicago, Seattle and Jonesboro.

These cities were chosen as an example since they have very different climatic conditions, electricity costs and water costs. Also, actual consumption for 400 ton HVAC cooling towers is available for Miami and Chicago in an article by ASHRAE (Crowther and Furlong, 2004). This was used to compare the results.

Water costs were taken from the US department of energy (USDE, 2017). The electricity rates for different cities can be found in several online sources. Using the methodology for the LF described in Appendix A, an approximate load factor was calculated for these 4 cities. In the model, we assume the tower is turned on when outside temperatures are $> 18°C$ (DD_{18} Approach). Using the merkel model, the average % load relative to maximum load is calculated.

The true load factor for the 400 ton cooling towers in Miami, Chicago and Las Vegas was used to check the model's accuracy:

The values obtained from the ASHRAE article are: $LF_{Miami} = 0.2608$, $LF_{Chicago} = 0.0762$, $LF_{LasVegas} = 0.1570$.
The model we have created predicts: $LF_{Miami} = 0.301$**,** $LF_{Chicago} = 0.068$**,** $LF_{LasVegas} = 0.1470$**.**

Despite having simplified the problem a lot, this approach gives results not far from reality as seen prior. It is important to note that the load factor remains highly variable and case dependent. In any case, the economical model created and the method for the load factor are independent, meaning that the economic model can also be used approximating LF and COP from a different source or a hypothesis.

Figure 6.5 Approximate load factor (LF) for Miami, Chicago, Seattle and Jonesboro assuming an HVAC installation and utility costs (water & electricity) used for the model.

City	% hr $> 18°C$	Average % tower load when tower is ON	Calculated annual Load Factor (LF)	Electricity rate R_e (cents/kWh)	Make-up water rate R_{mu} ($\$/m^3$)	Blow-down water rate R_{bd} ($\$/m^3$)
Miami	0.706	0.43	0.303	11.90	1.11	2.06
Chicago	0.289	0.23	0.068	11.87	0.98	1.06
Seattle	0.1517	0.28	0.048	9.73	1.82	4.60
Jonesboro	0.456	0.55	0.251	9.30	0.33	0.42

The following bar diagrams finally present the 25 year cooling tower program costs predicted for these 4 cities. It illustrates how these values can vary for a tower of the same capacity (400 RT) according to climate and utility prices.

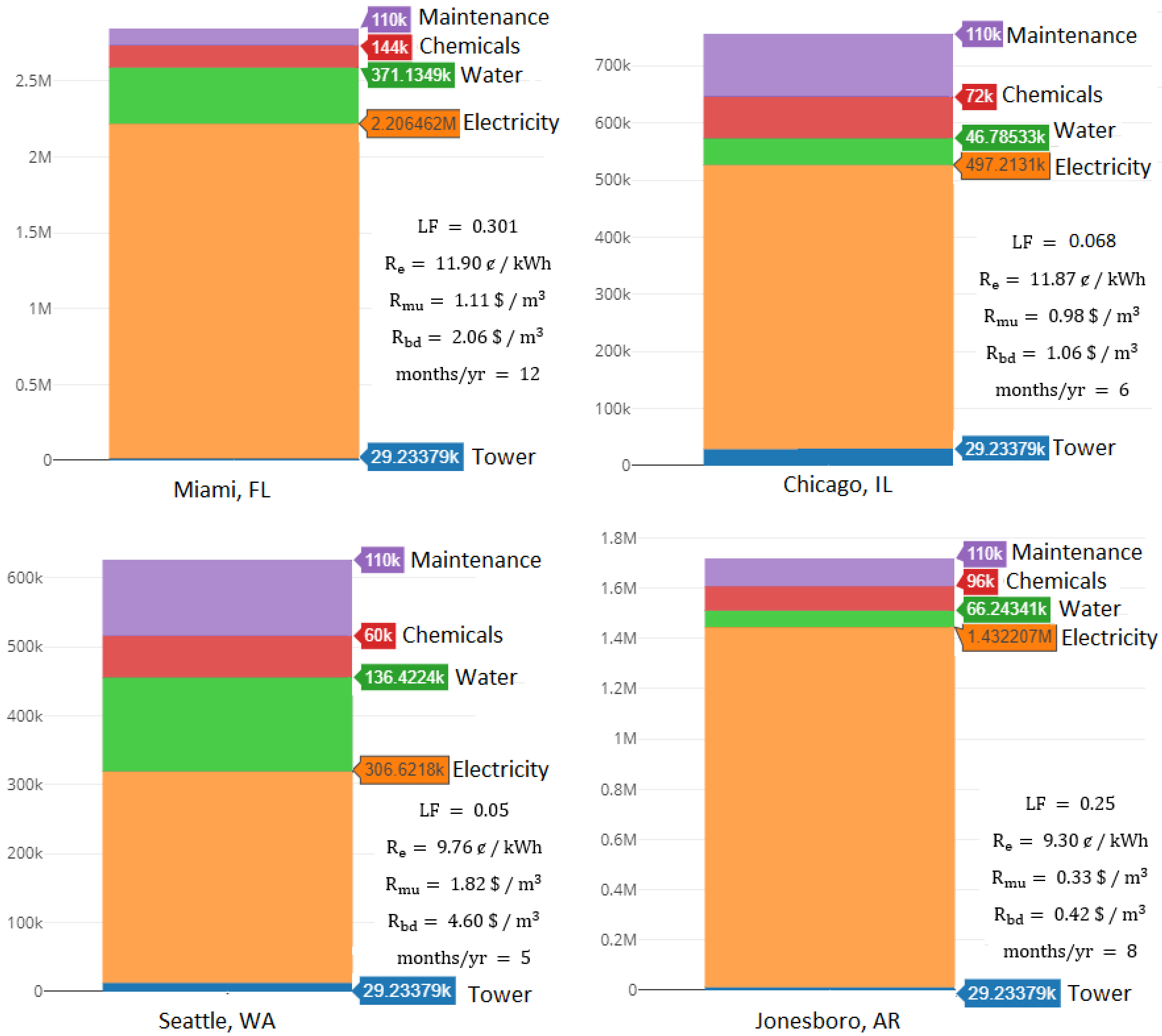


Figure 6.6 Cumulative predicted cost over 25 years for 400 ton HVAC cooling towers in 4 different cities in different states

Performance savings and net future value (NFV):

Once we have established the cost of a cooling tower program and its main parameters, the interesting thing is how these may be affected by a new technology such as a biocide tower. To visualize this, let the following factors represent hypothetical annual savings in maintenance, chemicals, water or operation costs: ϵ_{maint}, ϵ_{chem}, ϵ_{w}, ϵ_{op}
For example, if a certain solution reduces annual maintenance by 30 % , then $\epsilon_{maint} = 0.3$.

Net future value (NFV):

For any change in costs, we will apply a rate of interest and calculate the net future value.

$$C_{NFV} = C(1+i)^{(t-n)} \tag{6.15}$$

- t = Life-cycle in years of cooling tower program
- n = Current amount of years elapsed
- i = Interest (missed opportunity of investment and inflation)

Any savings or additional costs have to be compounded with an interest rate i. Any extra expense can be thought of as a missed or gained opportunity for the company to use that money elsewhere.

Performance savings

In order to visualize the importance of each parameter, the equations presented earlier for the tower, chemical, electricity, water and maintenance costs will be modified to incorporate the NFV.

If we modify the tower in a way that increases its initial cost by ϵ_{tower}, the NFV adjusted cost can be computed:

$$C_{purchase} = 189.32(0.408RT^{0.8542} + RT^{0.744})\left[1 + \epsilon_{tower}(1+i)^{t}\right] \tag{6.16}$$

If we modify the tower in a way that reduces annual electrical costs by a factor ϵ_{op}, the NFV adjusted cost can be computed:

$$C_{power} = \sum_{n=0}^{t} 3.08 \times 10^4 \Big[\frac{RT\ LF\ R_e}{COP}\Big] \Big[1 - \epsilon_{op}(1+i)^{(t-n)}\Big] \tag{6.17}$$

As such using the NFV approach a tower modification reducing water consumption by a factor ϵ_w can be taken into account:

$$C_{mu} = \sum_{n=0}^{t} 39.30\ RT\ LF\ R_{mu} \left(1 + \frac{1}{COC - 1}\right) \Big[(1 - \epsilon_w(1+i)^{t-n}\Big] \tag{6.18}$$

$$C_{bd} = \sum_{n=0}^{t} 39.30\ RT\ LF\ R_{bd} \left(\frac{1}{COC - 1}\right) \Big[(1 - \epsilon_w(1+i)^{t-n}\Big] \tag{6.19}$$

If a new tower has a reduced annual water and chemical usage of ϵ_w, the NFV adjusted chemical cost can be computed:

$$C_{Chemicals} = \sum_{n=0}^{t} 1.2RT[months] \Big[(1 - \epsilon_{chem}(1+i)^{t-n}\Big] \tag{6.20}$$

And for the maintenance costs:

$$C_{Maintenance} = \sum_{n=0}^{t} 11RT \Big[1 - \epsilon_{maint}(1+i)^{t-n}\Big] \tag{6.21}$$

With this model, we can now look at % of annual maintenance, electricity, water or chemical savings are needed to justify a bigger original investment in a cooling tower.

6.3 Comparing costs and finding viability points

Once that we have established the costs of a cooling tower program for its lifespan, lets pick Chicago as an example city and do some cost analysis to illustrate what the model allows. The first thing we need to do is pick some hypothetical savings. If a biocide tower was 75% more expensive, but with annual savings in operation, maintenance and water of 5% for each, would it be economically viable? To calculate this, we would chose: $\epsilon_{tower} = 0.75$, $\epsilon_{op} = 0.05$, $\epsilon_{maint} = 0.05$, $\epsilon_{chem} = \epsilon_w = 0.05$ and then we can calculate the original costs as opposed to the modified tower costs over the 25 year lifespan. The interest rate for this example was chosen to be 3 %.

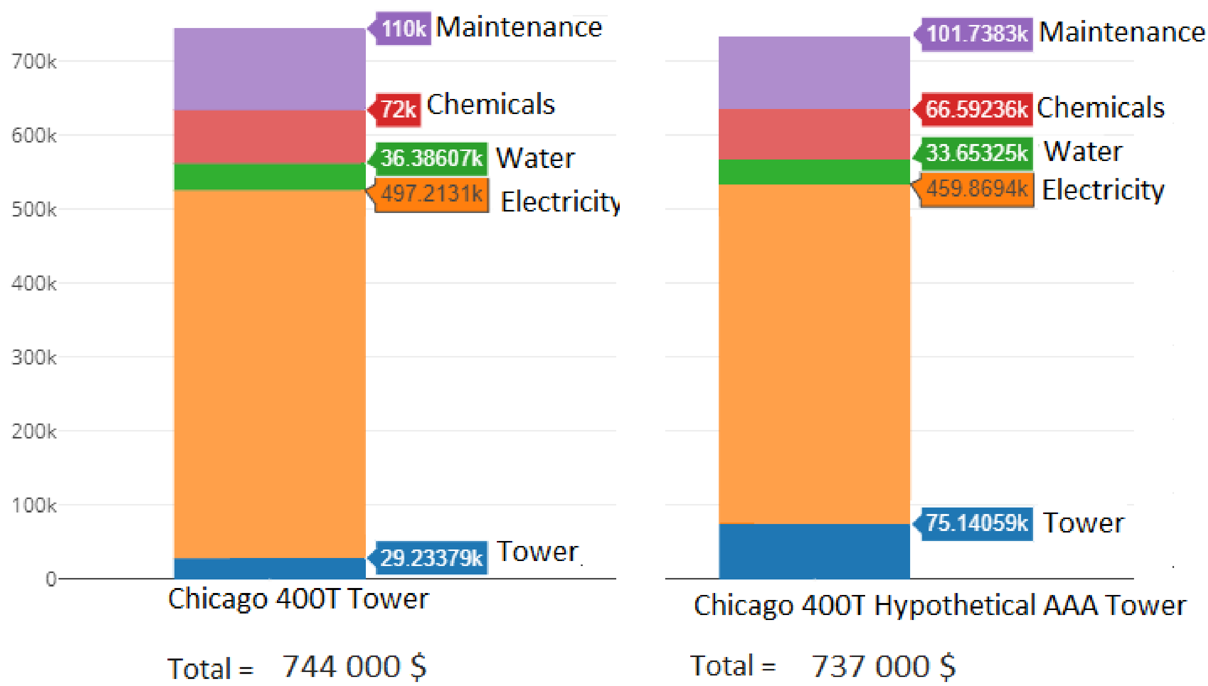


Figure 6.7 Predicted costs of a standard 400T HVAC cooling tower in Chicago compared to a hypothetical tower with 75% higher initial investment costs and 5% savings in electricity, water, chemicals and maintenance. The chosen interest rate for the future net value was 3%.

Figure 6.7 allows us to see that with Chicago's current costs and climate, a 3% interest rate, 5% annual savings in water, electricity and maintenance would justify a 75% bigger initial investment for the tower. This is only one specific scenario to illustrate what the model can do.

Instead of choosing values at random, it would be practical to see the set of values (viability points) that can justify a certain extra cost for our hypothetical tower. Figure (6.8) presents the viability points for a 400 ton HVAC tower in Chicago. For a cooling tower with an initial cost 75% higher, using an interest rate of 3%, these points represent the set of values that would compensate the higher initial investment.

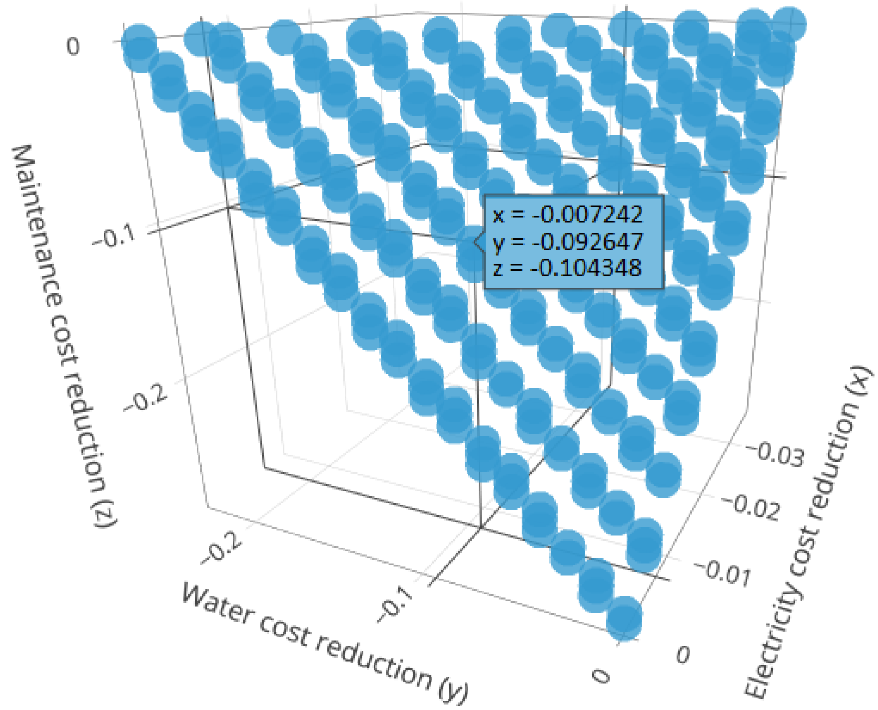


Figure 6.8 Viability points for a hypothetical AAA - 400 Ton HVAC Tower in Chicago with an initial cost 75% higher than a standard tower, using an interest rate of 3%, these points represent the set of values that would compensate the higher initial investment.

The example illustrated shows a coordinate (x,y,z) that can be interpreted the following way: at 0.72% lower annual operation costs, 9.2% lower annual water costs and 10.48% lower maintenance costs, a 400 RT cooling tower in Chicago with an initial cost 75% higher than a standard tower and using an interest rate of 3% would be economically viable.

Summary

The economic framework created allows a case by case analysis of economic viability that accounts for climate, water and electricity rates, and allows testing with different interest rates. It is intended to be a decision tool for determining whether a new technology is worth it. It can be applied to a new biocide tower or to other tower modifications. By inputting an approximate LF, COP, unit size, utility prices and interest rate it allows to compare a standard cooling tower program and an alternative cooling tower program. It shows that making a tower more expensive can be justified quickly if this modification brings annual savings in electricity, maintenance, chemicals and water.

CHAPTER 7 DISCUSSION

The primary reason why A3Surfaces, CoupeSag and PCP Aluminium financed this research was to determine if the anti-microbial anodized aluminum (AAA) they patented could be implemented to reduce microbial counts and biofilm development in cooling towers. As the research progressed, it became evident that the scope of this endeavour was larger than originally thought. This section discusses the limitations of this research.

The experiments carried on prototype cooling towers allowed us to see that AAA loses its capacity to impede bacterial development. However, the prototype tower experiments have several limitations:

First, if the bacterial counts would have been lower for the AAA prototype tower for several runs, it still would have not proven that AAA is suitable in the long run since cooling towers have a lifetime of approximately 25 years. It would have only been a promising result that could have justified a longer and more expensive experimental campaign. If *A3Surfaces* one day develops a method to make a surface that remains biocide for weeks without losing its efficacy, they would still need to show it can withstand many years in a corrosive environment while maintaining its properties.

Second, since we are cleaning the tower with isopropyl alcohol and sterilizing the water volume with bleach, it becomes difficult to know what was the leading cause of the depletion. Silver might be reacting with chlorine to make silver chloride and isopropyl alcohol was shown to accelerate the depletion process. The water treatment program needs to be tailored according to the surface chosen. In fact, this is already the case in the cooling tower industry: as we have seen in chapter two, stainless steel or FRP towers do not have the same tolerance to acid feeds or ozone. It would be easier to draw conclusions if the interaction with the chemicals added in the water and the development of bacteria were studied independently. A prototype cooling tower brings a more realistic environment but has the disadvantage of making the results harder to interpret. For this reason, testing on samples is more relevant at this research stage. The prototype towers should only be operated again if a more promising surface that shows good sample results is developed.

Lastly, as the research progressed it was found that more importance should have been given to biofilm development instead of bacterial counts (CFU/ml or CFU). Free floating bacteria in the water are rectified easily with water treatments but bacteria living in a biofilm tend to have significantly different properties. Surfaces are crucial proliferation grounds for bacteria. When biofilm is present in surfaces, *legionella pneumophila* counts in the water volume of the system are higher (Declerck, Priscilla, et al. 2009). As such, surfaces that do not allow biofilm adherence should naturally reduce CFU/ml in the entire volume of water. Free floating bacteria do not impede heat transfer but biofilm is intimately related to the fouling process that reduces heat exchange. Instead of measuring CFU/ml, perhaps the entire experiment should have focused on measuring biofilm. There are methods for measuring biofilm using a crystal violet dye. Crystal violet is absorbed by the bacteria in a biofilm. The biofilm can then be detached from the sample with acetic acid and quantified by a spectrometer in a brine solution (OD_{635}) thanks to the dye. The idea of doing biofilm tests was discussed with the team at A3Surfaces. However, since all experiments suggested that AAA as fabricated was being depleted of its biocide agents it was not necessary to spend money on biofilm tests at this point. The literature review shows that many avenues are left to explore for obtaining a surface that does not allow the adherence of biofilm. Once a more promising surface is found, future experimental campaigns should aim at measuring biofilm. In particular: how much biofilm forms, how fast does it form but also how easy it is to detach it.

There is a panoply of existing cooling tower design variations and each of them have a purpose. Climate, available space, noise limitations, heat load, cooling system design, water quality and maintenance access all play a role in deciding which design is best for any given application. The objective of using axiomatic design was to see if we could find design considerations that would need to be taken into account before implementing AAA or any other biocide surface. The reality is that regardless of whether the tower is cross-flow, counter flow, induced draft, forced draft, closed-loop, open-loop, factory assembled or field erected, it is approximately the same crucial surfaces that develop biofilm. Axiomatic design helped visualize which are the tower components that are affected by biofilm and led to other design recommendations: first, if scale or particles deposit on AAA, it is unlikely that it will remain an effective biocide. A filtration system would be desirable or even necessary with an antimicrobial surface. Second, a closed-circuit cooling tower would limit the exposure of the cooling tower water mainly to the tower itself. This would better suited for low bacterial levels compared to an open-circuit tower where the same water circulates through other components. Both these recommendations would need to be verified.

A design consideration that would need to be explored in more detail relates to the fabrication of AAA fills. Plastic fills are very easy to manufacture with a press in order to make different geometries. There are a variety of different geometries for fills. Some of them aim at minimizing fouling for locations with very hard water and some of them aim at optimizing heat exchange but are less resistant to fouling. The process for molding aluminium is different than plastic and anodization has its own set of manufacturing limitations. This subject needs to be explored further.

The economic framework approximates the costs of a cooling tower program and helps put things in perspective. It can be a useful tool for deciding whether to invest in cooling tower modifications such as biocide surfaces, hydrophobic surfaces or filtration systems. However, the model itself obviously has several limitations.

Accurately calculating the load factor and coefficient of performance of an installation is very difficult. It is better if a company uses figures from an existing installation. The climate is not the only thing to consider since the cooling system design, the quality of the chiller and tower, the level of fouling and whether variable frequency drives are used for the tower, pump and chiller all can change the performance. The numbers used for the maintenance costs are extremely variable since they depend on labor costs. Water and chemical costs are also very difficult to quantify since different initial water conditions require different water treatments, most treatment products contain a mix of chemicals which are often secret formulas and different tower designs and materials play a role in the COC and the choice of a water treatment.

Another aspect that the economic framework does not take into consideration is the cost of shutting down a cooling tower for maintenance reasons or for bacterial levels being too high. Since some industrial processes rely on cooling towers to operate, this shutdown can be very expensive. Considering cooling towers are used in so many different contexts, this cost is difficult to evaluate and individual companies are better placed to asses this risk.

CHAPTER 8 CONCLUSION

In conclusion, AAA is not suitable as fabricated for cooling tower environments since a loss in efficacy is observed both for the cooling tower experiment and for samples. The experiments carried on samples show a clear loss of the biocide properties. Electroplated samples improved biocide durability in a wet environment considerably and the fact that electroplated samples lose efficacy in the dry-test after the rinse cycle test supports the idea that the release of $Ag+$ ions is responsible for the longer lasting biocide effects of electroplated samples, since moisture is needed for the transfer of ionic silver to the surface.

the bacterial counts in the AAA prototype tower (CFU/ml) quickly reached similar levels as in the control protype tower which suggests that despite adequate corrosion resistance, AAA as fabricated does not reduce bacterial levels in the water volume of a cooling tower. It is important to mention that the results obtained do not represent the reality of a tower with a 25 year life span. A more diligent study on the effect an adequate biocide surface has should be made to take a serious look at the link between biofilm development and bacterial counts.

The literature review shows many promising avenues for biocide surfaces based on anodized aluminium left to explore. Anodized aluminium is a good candidate because its nano-pore structure can host metalic ions, biocide compounds or nano-wires. Nanostructured surfaces are an interesting alternative worth exploring since they may have biocide properties not based on a diffusion mechanism and can exhibit hydrophobic properties which reduce biofilm adherence. The suggested approach to find an adequate biocide surface would be to experiment with the techniques mentioned in the literature review and do extensive testing on samples placed in controlled environments and in cooling towers to determine if they develop biofilm and if they stay anti-microbial. The water treatment in place is an important factor to take into account since scale would most certainly render the surface useless.

Axiomatic design allows a neat visualization of what design parameters are affected by the inclusion of an antimicrobial surface. It helped establish an economic framework for the costs of a cooling tower program. According to this framework, a durable biocide material could justify a higher initial investment if such a material increased performance by reducing fouling, reduced maintenance, chemicals and water usage. This so called viability point depends on the usage of the tower, climate, electricity costs and water costs. When purchasing a cooling tower, it is important to look at the costs of the entire program over its lifespan since these are much larger than the initial cost of the cooling tower.

The other important element is adequate scale control. Fouling due to scaling will most likely cancel out any biocide properties. A proper study of the compatibility of a biocide anodized aluminum surface with the water treatment would be necessary. Phosphates and phosphonates do not protect aluminum from corrosion and are commonly used in water treatments. Chlorine interacts with silver ions forming silver chloride precipitates and ozone based treatments are not ideal for aluminum. A tower without adequate scale control would not benefit from biocide or hydrophobic surfaces. Two complementary design recommendations worth evaluating are the incorporation of a filtration system and a closed-loop system. A biocide surface might require being paired with a filtration system to keep this surface scale free and effectively biocide, and if the tower is intended to control bacteria on its own, a closed-loop system limiting the exposure of the water to non-biocide surfaces is ideal.

Future work

A biocide or hydrophobic surface capable of resisting wet environments would have potential applications in cooling towers, water tanks, food production zones, marine environments and a panoply of other fields in which metal is required to be in contact with water. As such, developing such a surface is of great interest and anodized aluminum, being a resistant porous substrate, is a great candidate. The development of such a surface could be economically beneficial for Canada, who has a significant aluminum industry.

An experimental campaign on different samples inspired by the literature review could determine if any of these treatments have the desired anti-biofilm properties. Hydrophobic and bactericide nanorods in an alumina substrate are promising since they do not rely on the diffusion of metallic ions. The incorporation of hydrophobic polymers or hydrocarbons is very interesting, but many of these works do not focus on durability and mechanical stability. A "tape peeling test" might be sufficient for some applications, but it is not sufficient for 25 years in a chlorinated cooling tower.

The work promoting the incorporation of polyaniline, chitosan and zinc stearate to create superhydrophobic coatings an anodized aluminium deserves attention in particular since it claims to have a hydrophobic surface with a film thickness of almost 30 microns, adequate abrasion and corrosion resistance for marine environments and low-cost of fabrication.

Understanding how anodization parameters such as acid choice, voltage, time and current density affect the pore size and adhesion of biocide and hydrophobic elements also deserves special attention. Another experimental campaign on prototype cooling towers is not recommended before finding the adequate treatment with samples. At this point, the prototype towers could be used but for a long term experiment.

A future experimental campaign should focus on biofilm in particular. Bacteria do not have the same properties when they live inside a biofilm and the focus should be on finding a surface that does not develop biofilm in the first place.

REFERENCES

ASHRAE Handbook - HVAC Systems and Equipment: Chapter 40. Books by ASHRAE, 2016.

SPX Cooling Technologies - Crossflow vs. Counterflow Cooling Towers, 2016.

N. L. Amin Valiei, Mira Okshevsky et N. Tufenkji, "Anodized aluminum with nanoholes impregnated with quaternary ammonium compounds can kill pathogenic bacteria within seconds of contact", *Applied Materials Interfaces*, pp. 41 207–41 214, 2018.

Z. Amjad, "Effect of precipitation inhibitors on calcium phosphate scale formation", *Canadian Journal of Chemistry*, pp. 850–856, 1989.

ASHRAE, *"The ASHRAE GreenGuide: The Design, Construction, and Operation of Sustainable Buildings"*, 2e éd. ASHRAE Press, 2006.

D. R. Baker et H. A. Shryock, *"A Comprehensive Approach to the Analysis of Cooling Tower Performance"*. Asme journal of heat transfer, Vol. 83, No. 3, 1961, pp. 339-350, 2016.

K. Biswas et al., "Enhanced polarization, magnetic response and pronounced antibacterial activity of bismuth ferrite nanorods", *Materials Chemistry and Physics*, vol. 195, pp. 207–212, 2017.

A. Bjørgum et al., "Anodising as pre-treatment for structural bonding", *International journal of ashesion and adhesives*, vol. 23, pp. 401–412, 2003.

B. Buecker, "New learner basics: Cooling tower water treatment", *POWER Engineering*, November 2016.

CBC. (2012) Quebec legionnaires' outbreak source found. En ligne: `https://www.cbc.ca/news/canada/montreal/quebec-legionnaires-outbreak-source-found-1.1208443`

A. Chamberlain et al., "The 2015 new york city legionnaires' disease outbreak: A case study on a history-making outbreak", *Journal of public health management and practice*, pp. 410–416, 2017.

G. Chi., Y. S.W, F. J, Z. W.G, et W. H.Z, “Antibacterial activity of anodized aluminum with deposited silver”, *Surface and Coatings Technology*, vol. 157, pp. 162–165, 2002.

D. L. Correll, “The role of phosphorus in the eutrophication of receiving waters: a review”, *Journal of environmental quality*, pp. 261–266, 1998.

H. Crowther et J. Furlong, “Optimizing chillers and towers”, *ASHRAE Journal*, 2004.

M. Dumont, J. Lambert, et al., “Anodized metal product with antimicrobial properties and method for producing the same”, 2013, (visited on 2019-06-27). En ligne: `https://patents.google.com/patent/WO2013155618A1/en`

S. J. C.-H. C. Ferdi Hizala, Natthakan Rungraengb, “Nano-engineered alumina surfaces for prevention of bacteria adhesions”, *Conference on Nano/Micro Engineered and Molecular Systems*, pp. 16–22, 2014.

M. Ferreira et K. Yasakau, “Self-healing nanocoatings for corrosion control”, *Corrosion Protection and Control Using Nanomaterials*, pp. 213–263, 2012.

B. Ga-Hee, L. Junghoon, C. Chang-Hwan, L. Yong, et J. Soojin, “Nano-patterned aluminum surface with oil-impregnation for improved antibacterial performance”, *ElSevier«: LWT - Food Science and Technology*, pp. 359–363, 2017.

A. A. Hasan, “Performance Analysis Of Heat Transfer Processes From Wet And Dry Surfaces: Cooling Towers And Heat Exchangers”, Mai 2005.

J. C. Hensley, *Cooling tower fundamentals*. Marley Cooling Tower Company, 1985.

I. H.P. Loh; Jennifer Loyns; Charles W. White, “Process equipment cost estimation final report”, no. DOE/NETL-2002/1169, p. 19, January 2002.

M. Hwang, “Effect of intracellular resuscitation of legionella pneumophila in acanthamoeba polyphage cells on the antimicrobial properties of silver and copper”, *PubMed*, 2006.

J. Johnston. (2019) Two new legionella victims reported in the canal area of ghent. (visited on 2019-05-22). En ligne: `http://brusselstimes.com/belgium/15734/two-new-legionella-victims-reported-in-the-canal-area-of-ghent-two-died-legionnaires`

A. Khalip. (2017) Death toll from legionnaires' disease in lisbon hospital up at four. (visited on 2019-05-22). En ligne: https://www.reuters.com/article/us-portugal-health-legionnaires/death-toll-from-legionnaires-disease-in-lisbon-hospital-up-at-four-idUSKBN1DA21V

H. T. Liou, "An on-site cooling tower treated by stand-alone low-concentration dissolved ozone", *Ozone: Science & Engineering*, vol. 31, no. 1, pp. 53–59, 2009, (visited on 2019-05-22). DOI: 10.1080/01919510802584470. En ligne: https://doi.org/10.1080/01919510802584470

J. Maillard et P. Hartemann, "Silver as an antimicrobial: Facts and gaps in knowledge", *Critical Reviews in Microbiology*, 2012.

R. Mohan Raj et V. Raj, "Fabrication of superhydrophobic coatings for combating bacterial colonization on al with relevance to marine and medical applications", *Journal of Coatings Technology and Research*, vol. 15, pp. 51–64, 2018.

S. e. a. Mulansky, "A modular flow cell system for studying biomimetic and bioinspired anti-adhesive and antimicrobial surfaces", *Heat Transfer Engineering*, pp. 1521–0537, 2016.

S. M. N.C. Subramanyam, "Azoles as corrosion inhibitors for mild steel in alkaline mine water." *Corrosion science [ISSN : 0010-938X]*, vol. 25, no. 3, pp. pp. 163 –169, 1985.

L. V. B. Nikanorov, A. M., *Water chemical composition of rivers, lakes and wetlands.*, série Types and properties of water, 2009, vol. 2.

B. Nowack, "Environmental chemistry of phosphonates." *Water research*, pp. 2533–2546., 2003.

S. S. M. Priya Varshney et A. Kumar, "Fabrication of mechanically stable superhydrophobic aluminium surface with excellent self-cleaning and anti-fogging properties", *Biomimetics*, pp. 1–12, 2012.

S. Raad, H. Anwar, A.-f. Ali, et H. Hamed Kadhim, "Enhanced antibacterial activity of anodic aluminum oxide membranes embedded with nano-silver-titanium dioxide", *Journal of Adhesion Science and Technology*, vol. 32, no. 8, pp. 874–888, 2018.

P. K. Raymond M. Post, Richard Tribble, "Development and application of phosphorus free cooling water technology." pp. pp. 1–11, 2014.

K. Razeeb, “Antimicrobial properties of vertically aligned nano-tubular copper”, *ElSevier: Materials Lettres*, vol. 128, pp. 60–63, 2014.

G. L. C. Roethell, B. E., “Prevention of corrosion of metals by sodium dichromate as affected by salt concentrations and temperature.” *Industrial & Engineering Chemistry*, vol. 23, no. 10, pp. 1084–1090., 1931.

A. Russell et W. Hugo, “Antimicrobial activity and action of silver.” *NCBI*, 1994.

L. Tao, D. Lihua, L. Tong, et Y. Yansheng, “Investigations on reducing microbiologically-influenced corrosion of aluminum by using super-hydrophobic surfaces”, *ElSevier: Electrochimica Acta*, no. 55, pp. 5281–5285, 2010.

USDE, “Water and wastewater annual price escalation rates for selected cities across the united states”, *Office of Energy Efficiency and renewable energy*, 2017.

Vukasovich, “Corrosion inhibition by sodium molybdate.” *Journal of the less-common metals [ISSN : 0022-5088]*, vol. 54, no. 2, pp. pp. 437 –448, 1977.

S. X. et al, “Preparation and antibiofilm properties of zinc oxide/porous anodic alumina composite films”, *Nanoscale Research Letters*, 2018.

Y. M. Zhang, Y. Hu, G. Q. Wang, Y. Gui, D. F. Wang, J. Q. Huang, et X. H. Jie, “Preparation and antimicrobial properties of surface antibacterial layer of aluminum”, dans *Materials and Processes Technologies V*, série Advanced Materials Research, vol. 941. Trans Tech Publications, 7 2014, pp. 1659–1663. DOI: 10.4028/www.scientific.net/AMR.941-944.1659

APPENDIX A Merkel model & load factor

A.1 The Merkel Model

The analysis of cooling tower performance was developpped by Merkel in 1925. The Merkel equations combine heat and mass transfer ingeniously by making two important approximations (Baker and Shryock, 2016, pp. 1).

To adequately present the model, lets begin by representing the water and air flow in a differential unit of cooling tower fill for a counter-flow tower. [1]

- m_a= Air flow $(\frac{kg}{s})$
- m_w= Water flow $\left(\frac{kg}{s}\right)$
- i_{ma}= Air enthalpy $\left(\frac{kJ}{kg}\right)$
- i_{mw}= Water enthalpy $\left(\frac{kJ}{kg}\right)$
- z= Height (m)

[1] The model applies also to cross-flow towers with the procedure being slightly different. This report only presents the counter-flow calculation which gives a solid understanding of the method.

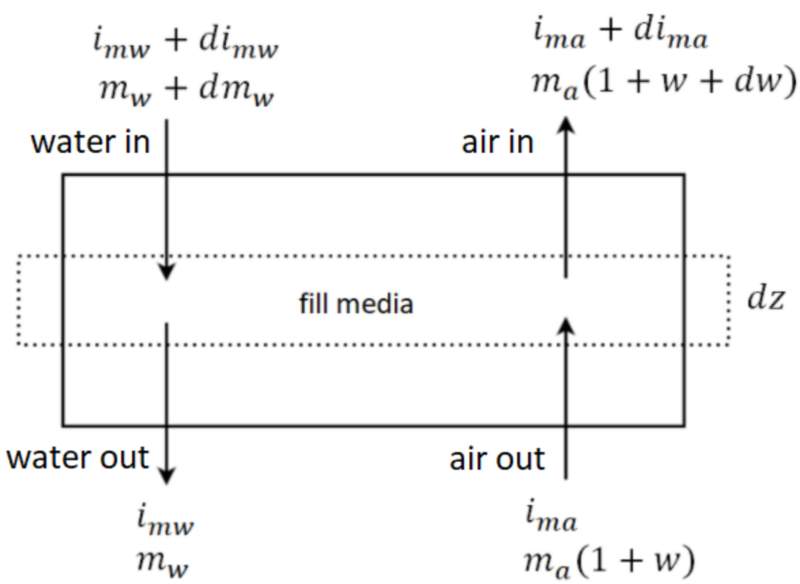


Figure A.1 Water-flow and air-flow in a differential unit of cooling tower fill

- w= Air humidity $\left(\frac{kg}{kg}\right)$

The first simplification Merkel made to his model is to ignore evaporation and assume the change in the mass of water is negligable: $dm_w \cong 0$.

The second assumption Merkel makes is that every surface of water in the tower is surrounded by a film of saturated air at water temperature. Figure (A.2) illustrates this idea.

The hypothesis is that the driving force of the heat exchange is proportional to the difference in enthalpy of the air with the enthalpy of the thin film of saturated air at water temperature. Mathematically this assumption can be written as:

$$di_{ma} = \frac{h_d a_{fill} A_{fr}}{m_a} \left(i_{masw} - i_{ma}\right) dz \tag{A.1}$$

Where:

- h_d = Mass transfer coefficient $\left(\frac{kg}{m^2 s}\right)$
- a_{fill} = Total area of the surfaces within the fill divided by the volume of the fill (m^{-1})
- A_{fr}= Frontal area of the fill (m^2)

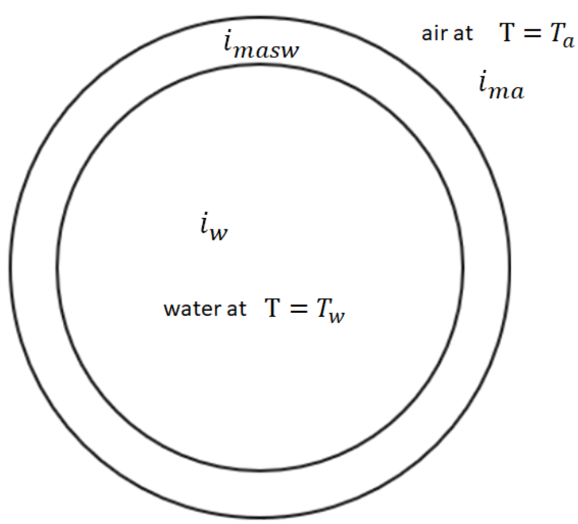


Figure A.2 Schematic of a water droplet surrounded by a thin film of saturated air at the same temperature as the droplet

Before developping Merkels model any further, it is important to understand the underlying enthalpy equations:

- $i_{ma} = i_a + wi_v$ (a)
- $i_a = C_{pa}T_a$ (b)
- $i_v = C_{pv}T_a + i_{we}$ (c)

Where:

- i_{ma}= Enthalpy of air (with humidity w) $\left(\frac{kJ}{kg}\right)$
- i_a= Enthalpy of dry air $\left(\frac{kJ}{kg}\right)$
- i_{we}= Enthalpy of evaporation of water vapor $\left(2501\frac{kJ}{kg}\right)$
- C_{pa}= Heat capacity of dry air $\left(1.006\frac{kJ}{KgK}\right)$
- C_{pv}= Heat capacity of water vapor $\left(1.84\frac{kJ}{KgK}\right)$
- i_{masw}= Enthalpy of saturated air at water temperature $\left(\frac{kJ}{kg}\right)$
- w= Air humidity $\left(\frac{kg}{kg}\right)$
- w_{sw}= Air humidity at saturation $\left(\frac{kg}{kg}\right)$ [2]

Inputing equation (a) and (b) in equation (c) we get:

$i_{ma} = C_{pa}T_a + w(C_{pv}T_a + i_{we})$

By Merkel's hypothesis, the enthalpy of the thin film of saturated air at water temperature is:

$i_{masw} = C_{pa}T_w + w_{sw}(C_{pv}T_w + i_{we})$

The energy transfered to the mass of air from the water is:

$$m_a di_{ma} = c_{pw}m_w dT_w$$

[2]the humidity of air at saturation must be obtained from a psychrometric table.

Note here that we work with the temperature of water but the enthalpy of air. This is where $dm_w \cong 0$, since the enthalpy of air considers humidity and the expression $c_{pw} m_w dT_w$ does not.

Which can be re-written as:

$mdT_w = \frac{m_a}{m_w}\frac{1}{c_{pw}} d_{ima}$

Using this relationship and equation (A.1) we can finally arrive to Merkel's equations of heat transfer in a cooling tower:

$$\frac{di_{ma}}{dz} = \frac{h_d a_{fill} A_{fr}}{m_a} (i_{masw} - i_{ma}) \tag{A.2}$$

$$\frac{dT_w}{dz} = \frac{m_a}{m_w}\frac{1}{c_{pw}}\frac{di_{ma}}{dz} \tag{A.3}$$

these two equations combined are used to determine the **required tower characteristic** TC. The tower characteristic is used to quantify "what is required" to achieve a targetted heat exchange.

$$m_w c_{pw} dT_w = m_a di_{ma} = h_d a_{fill} A_{fr} \; (i_{masw} - i_{ma}) \, dz \tag{A.4}$$

which can simply be re-written as:

$$\frac{h_d a_{filll} A_{fr} dz}{m_a} = \frac{di_{ma}}{(i_{masw} - i_{ma})} = \frac{m_w}{m_a}\frac{c_{pw} dT_w}{(i_{masw} - i_{ma})} \tag{A.5}$$

if we integrate this equation and isolate what we will call the tower characteristic TC=$\frac{h_d a_{filll} V}{m_w}$, we find mathematically there are different ways of calculating this quantity. We can theoretically integrate over the length z but we do not know how h_d behaves throughout the fill. Instead, what we will do is chose steps of water temperature since we know T_{wi} and T_{wo} for a functioning tower.

$$\begin{gathered} TC = \frac{h_d a_{filll} V}{m_w} = \frac{m_a}{m_w}\int_0^z \frac{h_d a_{filll} A_{fr}}{m_a} dz = \\ \frac{m_a}{m_w}\int_{i_{ma1}}^{i_{ma2}} \frac{di_{ma}}{(i_{masw} - i_{ma})} = \int_{T_{wi}}^{T_{wo}} \frac{c_{pw} dT_w}{(i_{masw} - i_{ma})} \end{gathered} \tag{A.6}$$

Let $NTU = \frac{c_{pw}\Delta T_w}{(i_{masw} - i_{ma})}$ be the "number of transfer units".

The Merkel model can only be used on an tower which has defined hot water in and cold water out temperatures, a defined water rate and for a chosen wet-bulb temperature to calculate the **required coefficient**. This coefficient can then be compared with the **available coefficient** that has to be obtained from an operational tower with empirical measures. In other words, the cooling performance of a cooling tower can only be accurately determined empirically by thermally testing the tower (Hensley, 1985, pp.97).

To fully grasp how this works, lets go through the example presented by ASHRAE's section on cooling towers (ASH, 2016, pp. 40.19-40.21).

Imagine air enters the base of a cooling counter-flow tower at $T_{ai} = 24°C$. Water leaves the base of the tower at $T_{wo} = 30°C$ and enters the top at $T_{wi} = 38°C$. The ratio of water-flow to air-flow is $\frac{m_w}{m_a} = 1.2$. Using a psychrometric table and having the humidity ($w = 0.0196\ \frac{kg}{kg}$), as well as the dry-bulb temperature, we can obtain that the wet-bulb temperature. We can then calculate at the base of the tower the enthalpy of the air.

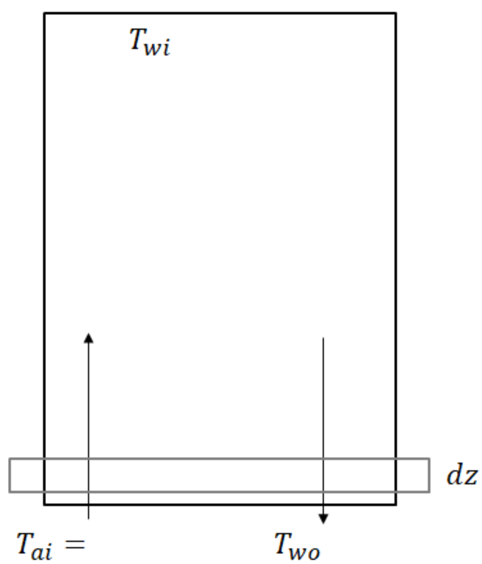


Figure A.3 schematic of the integration to obtain TC

$$\begin{aligned} i_{ma} = C_{pa}T_a + w(C_{pv}T_a + i_{we}) = (1.006)(24) \\ +(0.01964)((1.84)(24) + 2501) \\ = 72.40\frac{kJ}{kg} \end{aligned} \tag{A.7}$$

We can also calculate at the base of the tower the enthalpy of the thin film of saturated air at water temperature hypothesized by Merkel.

$$\begin{aligned} i_{masw} = C_{pa}T_w + w_{sw}(C_{pv}T_w + i_{we}) = (1.006)(30) \\ +(0.029)((1.84)(30) + 2501) \\ = 100\frac{kJ}{kg} \end{aligned} \tag{A.8}$$

The difference between these two enthalpies is what drives the mass and heat transfer.

$$(i_{masw} - i_{ma}) = 27.60\frac{kJ}{kg} \tag{A.9}$$

Lets calculate the NTU's. For this we need to chose an itteration step for the temperature. lets chose as done in ASHRAE a step of 0.5 degrees in water temperature.

$$NTU = \frac{(c_{pw}\Delta T_w)}{(i_{masw} - i_{ma})} = \frac{(4.18)(0.5)}{(100 - 72.4)} = 0.0755 \tag{A.10}$$

$$\begin{aligned} di_{ma} = \frac{m_w}{m_a}c_{pw}\Delta T_w \\ = (1.2)(4.18kJkg^{-1}K^{-1})(0.5K) = 2.508kJkg^{-1} \end{aligned} \tag{A.11}$$

So the new enthalpy of the air after a change of 0.5 degrees in water temperatre (note that the height change dz necessary is undefined here) can be calculated for the second itteration n=1:

$$i_{ma,(n=1)} = i_{ma,(n=0)} + di_{ma,(n=0)} \tag{A.12}$$

We can repeat this process until we reach the entering water temperature $T_{wi} = 38°C$.

Table (A.4) shows the calculation from ASHRAE done from $T_{wo} = 30°C$ to $T_{wi} = 38°$. The first column of NTU shows the value 0.0755 that we calculated. The sum of all NTU is TC. This number gives an idea of the difficulty of the task. if we look at the elements that compose the tower characteristic ($TC = \frac{h_d a_{fill} V}{m_w}$), we can interpet this quantity the following way: To cool water from 38°C to 30°C using air at 24°C with humidity $w = 0.0196 \frac{kg}{kg}$, we need this quantity to be 1.0764.

Water Temperature T_w °C	Enthalpy of Film i_{masw} kJ/kg	Enthalpy of Air i_{ma} kJ/kg	Enthalpy Difference $i_{masw} - i_{ma}$ kJ/kg	$\frac{1}{i_{masw} - i_{ma}}$	ΔT_w K	NTU = $\frac{c_p \Delta T_w}{i_{masw} - i_{ma}}$	ΣNTU	Cumulative Cooling Range, K
30	100.0	72.40	27.60	0.0362				
					0.5	0.0755	0.0755	0.5
30.5	102.7	74.91	27.79	0.0360				
					0.5	0.0749	0.1504	1
31	105.4	77.42	27.98	0.0357				
					0.5	0.0743	0.2247	1.5
31.5	108.2	79.92	28.28	0.0354				
					0.5	0.0735	0.2982	2
32	111.0	82.43	28.57	0.0350				
					0.5	0.0727	0.3709	2.5
32.5	113.9	84.94	28.96	0.0345				
					0.5	0.0716	0.4425	3
33	116.9	87.45	29.45	0.0334				
					1	0.1394	0.5819	4
34	123.0	92.46	30.54	0.0327				
					1	0.1337	0.7156	5
35	129.5	97.48	32.02	0.0312				
					1	0.1273	0.8429	6
36	136.2	102.50	33.70	0.0297				
					1	0.1204	0.9633	7
37	143.3	107.51	35.79	0.0279				
					1	0.1132	1.0764	8
38	150.7	112.53	38.17	0.0262				

Figure A.4 Example calculation for a cooling tower with a 0.5 degrees iterative step. the sum of NTU's is the total required tower characteristic to cool water from 38 °C to 30 °C with air at 24 °C and humidity $w = 0.0196 \frac{kg}{kg}$, air-flow to water-flow ratio of 1.2 .

The following python function calculates the required TC.

```
def get_TC_Merkel(T_ai,T_wi,T_wo,w,m_w,m_a):

    # Calculates the required Tower Characteristic using T_ai,T_wi,T_wo,w,m_w,m_a
            C_pa = 1.006 # kJ/kgK
            C_pv = 1.84 # kJ/kgK
            C_pw = 4.18 # kJ/kgK
            i_we = 2501 # kJ/kg
```

```
deltaT = 0.01

NTU = 0
i_ma = 0
i_masw = 0
w_sw = 0
T_a = T_ai
T_w = T_wo

i_ma = C_pa*T_a + w*(C_pv*T_a + i_we)

for n in range(round(  ( (T_wi - T_wo)/deltaT )+0.5)  ):

    w_sw = (2*10**-7)*(T_w**3) + (1*10**-5)*(T_w**2) + 0.0003*T_w + 0.0031
    i_masw = C_pa*T_w + w_sw*(C_pv*T_w + i_we)

    if i_masw <= i_ma:

        return None

        break

    NTU += C_pw*deltaT/ (float(Decimal(i_masw) - Decimal(i_ma)))
    i_ma += (m_w/m_a)*C_pw*deltaT
    T_w += deltaT
return NTU
```

Once a tower is built, we can empirically obtain the **avaiable coefficient** curve for different air rates by simply testing how the tower performs in different conditions. By comparing the required coefficient and the avaiable coefficient, we can determine if a cooling tower can achieve the desired cooling. The following equation is usually used to approximate how the available tower coefficient behaves with changing air and water flows:

$$TC_{available} = C(\frac{m_w}{m_a})^{-n} \tag{A.13}$$

where $n \approx 0.6$ and C must be found by looking at the specifications of the tower. If a tower's operation characteristics at a certain set of conditions are given, we know $TC_{available} = TC_{required}$ and we can find the constant C

```
def get_TC_available_Constant(T_ai,T_wi,T_wo,w,m_w,m_a):
# calculates the constant(TC_Cnst) in TC = KaV/L = TC_Cnst (L/G)^n
# using the design point of a cooling tower.
    NTU_req = CoolingTower.get_TC_Merkel(T_ai,T_wi,T_wo,w,m_w,m_a)

    n = -0.6

    TC_Cnst = NTU_req/ ((m_w/m_a)**n)

    return TC_Cnst

def get_TC_Available(TC_Cnst,m_w,m_a):

    # Calculates the available coefficient as a function of water flow and air flow
    # using TC = KaV/L = TC_Cnst (L/G)^n
    # Takes the constant calculated in
    #get_TC_available_Constant(T_ai,T_wi,T_wo,w,m_w,m_a).

    TC_available = TC_Cnst*(m_w/m_a)**(-0.6)

    return TC_available
```

When $TC_{available}$ is bigger or smaller than $TC_{required}$ the options we have are to increase air-flow or reduce water flow to obtain the desired water temperature. In many industrial processes, the water flow must be constant or only a small water flow change is allowed. For HVAC towers, some operate at constant water-flow in the chiller but in the ideal scenario both the tower and the chiller are operated in a way to minimize energy consumption. This can even be done custom for each building using machine learning techniques on prior data. It is important to notice that this equation does not account for temperature. In reality, although this curve is given by manufacturers in data sheets, a small correction factor for temperature does exist. What changes a lot based on temperature is the required coefficient to achieve the desired cooling and not the available coefficient. All these functions are placed in a python class called *CoolingTower*, in which different methods can be called that relate to cooling towers.

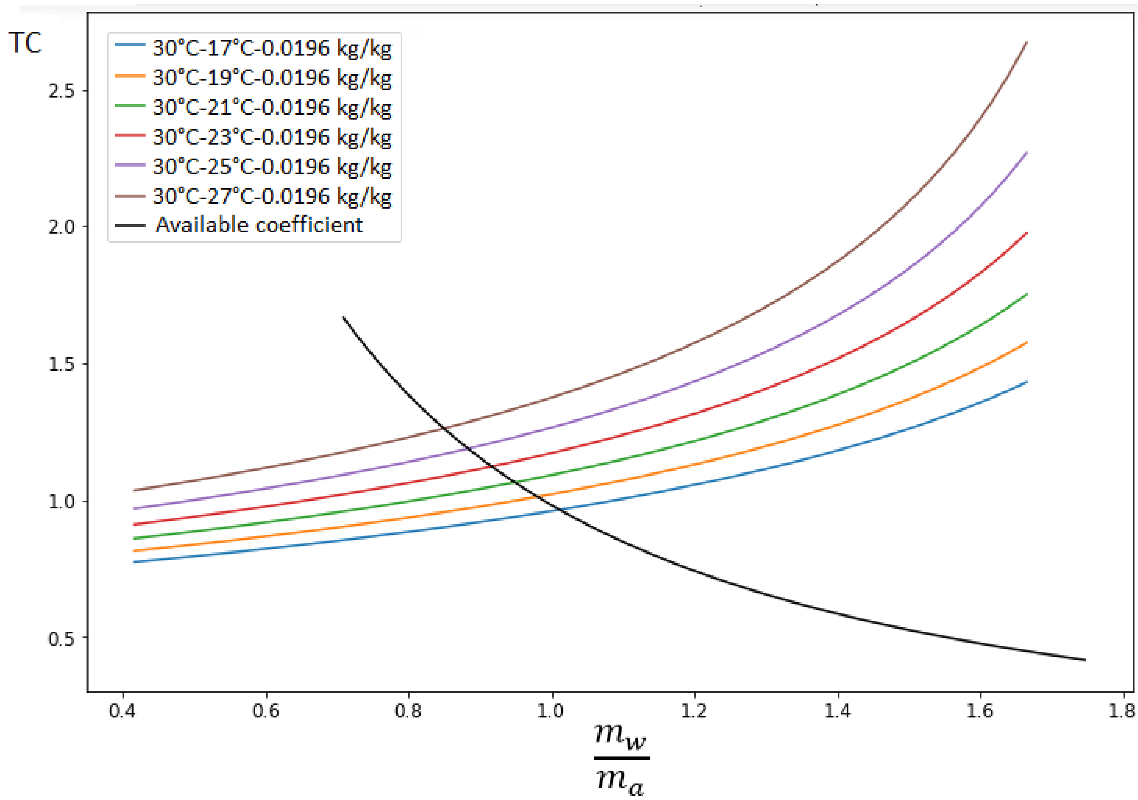


Figure A.5 Available coefficient (black) based on data from tower T-25 from *CTS - Cooling Tower Systems* plotted next to the required coefficient at different outside temperatures for water coming in at 38° and leaving the tower at 30° . Here n is hypothesized to be 0.6. When the required coefficient is above the available coefficient, the desired cooling will not be acheived and a new air-flow or water flow need to be found. If TC available is above TC required, the fan power can be diminished saving energy while still achieving the desired cooling. This optimal operation point can be found by iteration.

The book *Cooling Tower Fundamentals* ((Hensley, 1985, pp. 97) explains cooling tower performance testing in detail, highlighting that only an empirical test can properly determine the performance curves of a cooling tower.

A.2 Calculating the Load Factor (LF)

To approximate the LF from climatic conditions, hourly data for temperature, humidity pressure from 43 different cities for 5 years was obtained from Kaggle, an online community of data scientists and machine learners, owned by Google LLC. In this analysis, a main class called *CoolingTower* was created in Python which contains all the methods used. It will be given at the end of this Appendix.

First, the following code, called *ClimateAnalysis.py* imports the data for the desired city, cleans it and transforms it in the adequate units for treatment before outputting it all in one file with a .csv extension.

```
Created on Mon Mar  4 12:19:38 2019

@author: alexis

#This code imports hourly #temperature, humidity, and #pressure
#data obtained from csv's #from the internet from 43 #different cities,
#cleans NaNs by replacing #them with nearest available #data and
#converts them in the #adequate format (Celsius, #Pa, kg/kg) for treatment
#using the CoolingTower #class.

import math
import pandas

City = 'Montreal'

dataset = pandas.read_csv('temperature.csv')
dataset2 = pandas.read_csv('humidity.csv')
dataset3 = pandas.read_csv('pressure.csv')

City_Temperatures = dataset[ City ] - 273.15
City_Humidities = dataset2[ City ]
City_Pressures = dataset3[ City ]*100

City_Humidities_KgKg = City_Humidities*1.001

for n in range(len(City_Pressures)):

    if math.isnan(City_Pressures[n]) == True:

        m = 1

        while math.isnan(City_Pressures[n+m]) == True:
             m += 1

        City_Pressures[n] = City_Pressures[n+m]

for n in range(len(City_Humidities)):
```

```
    if math.isnan(City_Humidities[n]) == True:

        m = 1

        while math.isnan(City_Humidities[n+m]) == True:
             m += 1

        City_Humidities[n] = City_Humidities[n+m]
    City_Humidities_KgKg[n] = (City_Humidities[n]*3.802*
    \ math.exp( (17.67*City_Temperatures[n]/(City_Temperatures[n] + 243.51) ) )  / City_Pressures[n])
raw_data = {
        'City_Temp': City_Temperatures,
        'City_Pres': City_Pressures,
        'City_Humi': City_Humidities_KgKg }
df_a = pandas.DataFrame(raw_data, columns = ['City_Temp', 'City_Pres', 'City_Humi'])
df_a.to_csv(City +'_Temp_Pres_Hum.csv')
```

The second code *LoadAnalysis.py* first imports the file from *ClimateAnalysis.py*. It then allows chosing cooling tower by inputing its operation characteristics.

A degree-day 18 approach was used that estimates that a building needs cooling when outside temperatures surpass 18°C. Cooling towers are chosen so that under the worse possible summer conditions, the tower can still eliminate the maximum heat-load.

In the following code, tower $CTS-2100$ from *CTS- Cooling Tower Systems* was chosen as an example. This 125 cooling tons tower has a design operation point allowing 18.58 kg/s (296 GPM) of water to be cooled from 35°C to 29.44°C with an airflow of 14.16 kg/s (24500 CFM) with an outside wet bulb temperature of 23.89°C.

Looking at the highest wetbulb temperature on excel from the .csv file obtained with *ClimateAnalysis.py*, we can see the worse conditions for the chosen example city (Montreal) and check how much heat the $CTS-2100$ can eliminate in these conditions. Montreal's worse wet-bulb temperature is about the same as the 82°F in the CTS engineering brochure. This means it would cool approximately 228 gpm of water in these operating conditions from 98°F (36.6 celsius) to 88°F (31.1 celsius) which gives 94 cooling tons.

TOWER CAPACITIES													
HOT WATER	90 ° F	90 ° F	95 ° F	92 ° F	95 ° F	97 ° F	95 ° F	95 ° F	96 ° F	98 ° F	90 ° F	94 ° F	T MODEL
COLD WATER	80 ° F	80 ° F	85 ° F	82° F	85 ° F	87 ° F	85 ° F	85 ° F	86 ° F	88 ° F	83 ° F	85 ° F	
WET BULB	65 ° F	70 ° F	70 ° F	72 ° F	75 ° F	75 ° F	77 ° F	78 ° F	80 ° F	82 ° F	75 ° F	75 ° F	
	17	12	20	13	15	18	12	11	10	11	15	16	T-25
	27	20	32	21	23	29	20	18	16	17	25	26	T-28
	34	25	39	27	30	35	25	23	20	23	31	32	T-210
	51	37	60	40	44	54	37	33	31	33	46	48	T-215
	68	49	80	53	58	72	49	45	41	44	62	64	T-220
	85	62	97	66	73	90	62	56	52	56	77	79	T-225
	101	75	119	80	88	108	75	68	63	68	93	96	T-230
	134	100	156	106	118	142	101	92	85	91	124	128	T-240
	168	127	195	134	148	178	127	116	108	115	155	159	T-250
	201	150	224	160	177	211	151	138	128	137	185	191	T-260
	236	176	262	188	207	251	176	160	150	160	218	224	T-270
	268	203	308	215	237	253	203	185	173	184	248	256	T-280
	335	250	382	266	295	356	252	230	213	228	309	319	T-2100
GPM	420	316	480	235	369	446	316	289	270	289	388	400	T-2125
	504	383	574	405	446	534	383	353	328	350	466	479	T-2150
	588	441	676	471	518	611	444	407	377	404	541	558	T-2175
	669	509	774	542	592	712	512	469	440	469	621	640	T-2200
	757	559	885	595	656	803	559	503	468	503	696	717	T-2225
	838	625	970	666	737	889	630	574	533	569	772	798	T-2250
	1011	775	1175	800	883	1075	755	685	634	678	934	960	T-2300
	1176	889	1340	946	1036	1240	895	818	767	818	1087	1119	T-2350
	1349	1023	1540	1084	1190	1420	1023	930	871	932	1240	1278	T-2400
	1657	1301	1885	1377	1505	1763	1324	1226	1157	1233	1551	1604	T-2500
	2006	1526	2322	1625	1777	2137	1537	1406	1319	1406	1864	1919	T-2600
	2317	1819	2640	1928	2101	2469	1841	1700	1641	1711	2177	2242	T-2700
	2675	2035	3096	2166	2370	2849	2050	1875	1759	1875	2486	2559	T-2800
	3303	2616	3760	2762	3011	3300	2660	2484	2353	2499	3098	3201	T-3000

Figure A.6 *CTS- Cooling Tower Systems* Engineering brochure with T-2100 highlighted at highest wet-bulb conditions.

This means that if someone wanted to buy this tower for HVAC purposes for Montreal, a building system engineer should have calculated that the worse load conditions for the building in question is about 94 RT in summer so that the tower can adequately keep the building cool. If this procedure is followed, regardless of the size of tower, the load factor of the tower should be the same since the tower size will vary accordingly to the load of the building we intend to cool.

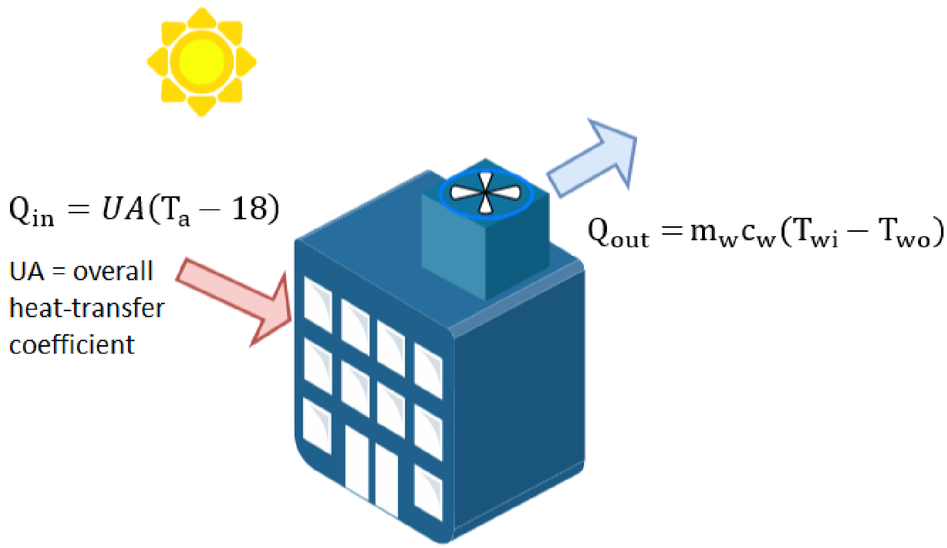


Figure A.7 Schematic of a buildings heat-balance simplified by the DD_{18} approach. For the building to maintain $21°C$, we approximate cooling must be turned on if the outside temperature is higher than $18°C$. It is equivalent to assuming that internal heat gains and solar gains are responsible for a ΔT of $3°C$ (from $18°C$ to $21°C$)

Considering figure (A.7), this means that for a record high temperature in Montreal of say $T_a = 36°C$:

$$Q_{in} = 94RT(\frac{3.516kW}{RT}) = 330.5kW$$

So the overall heat-transfer coefficient for a building in Montreal with this tower model, assuming this tower is chosen to eliminate this heat load:

$$UA = 330.5kW/(36°C - 18°C) = 18.36kW/°C$$

Since the heat-load in HVAC is proportional to the outside temperature, and $Q_{in} = Q_{out}$ we can approximate T_{wi}:

$$T_{wi} = T_{wo} + \frac{UA(T_a - 18)}{m_w c_w} \tag{A.14}$$

As mentioned, if we change the tower size to another tonnage, we would be using the tower for a larger building (bigger heat load) and the load factor does not change.

```
Created on Wed Mar 20 12:53:57 2019

@author: alexi
```

```
import CoolingTower
import math
import pandas
City = 'Montreal'

dataset = pandas.read_csv(City +'_Temp_Pres_Hum.csv')

#print(dataset)

T = dataset['City_Temp']
P = dataset['City_Pres']
w = dataset['City_Humi']

# CTS T-2100 Model (125RT)
T_wi = 35 #( 95F)    95 / 85 /  75 : 25C - 0.00805 kg/kg
T_wo = 29.44 #( 85F)   95 / 85 /  75 (29.44)
m_w = 18.58 #(125 RT - 296 gpm x 0.063kg/s/gpm)
m_a = 14.16 # (125 RT - 24500 CFM x 0.000578 kg/s/CFM)

TC_Cnst = CoolingTower.CoolingTower.get_TC_available_Constant(25,T_wi,29.44,0.0178,m_w,m_a)

TC_available = CoolingTower.CoolingTower.get_TC_Available(TC_Cnst,m_w,m_a)


for n in range(len(T)):

    T_w_in_tower[n] = 29.44 + 0.255*(T[n]-18)

    if T[n] >= 18:

        TC_r[n] = CoolingTower.CoolingTower.get_TC_Merkel(T[n],float(29.44 + \\
        0.292*(T[n]-18)),29.4,w[n],m_w,m_a)

        Airflow[n] = CoolingTower.CoolingTower.get_new_Airflow(TC_Cnst,T[n],T_wi,T_wo,w[n],m_w,m_a)

    else:

        TC_r[n] = 0

        Airflow[n] = 0

Airflow = pandas.DataFrame({'Airflow': Airflow})
TC_req = pandas.DataFrame({'TC_req': TC_r})
T_w_in_tower = pandas.DataFrame({'T_w_in_tower': T_w_in_tower})
```

```
print(TC_req)

raw_data2 = {
        'City_Temp': T,
        'City_Pres': P,
        'TC_required': TC_req,
        'City_Humi': w
        }

df_a = pandas.DataFrame(raw_data2, columns = ['City_Temp', 'City_Pres', 'TC_req','City_Humi' ])

df_a.to_csv(City +'_Temp_Pres_Hum_TCreq5.csv')

TC_req.to_csv(City + 'TC_req5.csv')
Airflow.to_csv(City + 'Airflow5.csv')
T_w_in_tower.to_csv(City + 'T_w_in_tower.csv')
```

This will give us *.csv* files which indicate **how many hours/year the cooling tower must be turned on**. Using equation (A.14) which assumes that while keeping a constant flow for the chiller, the temperature of the tower is proportional to heat load on the building. We can approximate the **% heat-load** of the building for every hour. We can also approximate the **% Airflow** of the tower relative nominal airflow.

The method chosen for estimating LF does not really use Merkel's model in the end but it uses cooling tower data to approximate the maximum heatload. The original idea was to use Merkel's model to obtain a new airflow relative to the nominal airflow and use affinity laws to calculate a relative fan power. However, the energy consumption for HVAC is primarily at the level of the chiller, so calculating the required fan power does not give us an idea of the % load of the system. This would be equivalent of having variable frequency drive (VFD) on the fan. Cooling tower installations optimize the fan and chiller consumption with VFD's which makes it impossible to calculate an accurate system LF from simply the cooling towers airflow without having more information about the system.

Considering that electricity costs are a combination of chiller, fan and cooling tower costs, it is difficult to estimate electric consumption adequately. The method chosen was to take the **% heat-load** of the tower for every hour with outside temperatures over $18°C$ and divide it by the total amount of hours. This approach gives a usable value for the annual load.

To see if this method gives decent approximations, I compared it with actual LF's for three identical HVAC 400T cooling towers in Chicago, Las Vegas and Miami. The actual annual load factors for these HVAC towers were LF = 0.0762 (Chicago), LF =0.157(Las Vegas), LF = 0.2608 (Miami) (Crowther and Furlong, 2004)

Using this model, the predictions were LF = 0.068 (Chicago), LF = 0.147 (Las Vegas) and LF = 0.303 (Miami)

This is the cooling tower class *CoolingTower.py* in which all relevant functions allowing calculations and chart plots were:

```
# Cooling Tower Economics:

import numpy as np
import matplotlib.pyplot as plt
import math
import pandas as pd
import plotly as py
import plotly.graph_objs as go
from decimal import Decimal
from mpl_toolkits import mplot3d
from IPython.display import display, Math, Latex

# for outputs using plotly interactive plots:
py.tools.set_credentials_file(username='alnos', api_key='qZPeIWMG2V6oTMhgRE4z')


class CoolingTower:

    def __init__(self,RT,LF,COP,COC,t,R_e,R_bd,R_mu,months):

    # Constructor for the class CoolingTower:
    # gives the object CoolingTower the following properties:
    # RT = Cooling capacity in Cooling Tons ; LF = load Factor ;
    # COP = coefficient of performance
    # t = expected life-span of tower ;
    # COC = cycle of concentration of tower ;
    # R_e = electricity cost $/kWh
    # R_bd = blowdown discharge costs $/m^3 (if applicable, or else = 0) ;
    # R_mu = make-up water costs $/m^3
    # (if applicable, or else = 0)

        self.RT = RT
        self.LF = LF
```

```
        self.COP = COP
        self.COC = COC
        self.t   = t
        self.R_e = R_e
        self.R_bd = R_bd
        self.R_mu = R_mu
        self.months = months

    def actualnetValue(self,e_eff,year,i):

    # Calculates actual net Value of money at the end of a towers
    # life-span "self.t" if that money was
    # spent at a specific "year = year" with interest rate = "i".

        return (1+e_eff*(1+i)**(self.t-year))


    def cooling_tower_program_Cost(self):

  # Calculates the effective cost of a cooling tower program using data found online.
    # The model gives a rough approximation,
  # to the best of my knowledge, of the costs
  # incurred over the life span "t.self" of the object in the class CoolingTower.
  # takes Tower purchase, electricity operation costs, maintenance costs, chemical costs
  # and water costs: meaning blow-down & make-up.
  # These can be presented in a bar graph using pandas.

        f_latent = 0.80
        h_fg = 2257 #kJ/kg
        C_tower = 189.32*(0.408*self.RT**0.8542 + self.RT**0.744)

        C_operation = 0
        C_water = 0
        C_chemical = 0
        C_maintenance = 0

        for year in range(self.t):

            C_operation += (3.516*self.RT*self.LF/ self.COP) * self.R_e * 8760

            C_water +=  31536*((3.516*self.RT*self.LF*f_latent*(1+ 1/(self.COC)+0.01))*self.R_mu/h_fg+

            C_chemical += 1.2*self.RT*self.months
```

```
        C_maintenance += 11*self.RT

    return  [C_tower, C_operation, C_water, C_chemical, C_maintenance]


def cooling_tower_program_cost_Change(self,i,e_tower,e_op,e_w,e_maint):

# Tweaks the method "cooling_tower_program_Cost(self)" By including 4 theoretical economy # paramete
#            [e_tower, e_op, e_w, e_maint]
#
# For example, if [e_tower = 0.75, e_op = -0.2 , e_w = -0.1 , e_maint = -0.3],

# it means that we have modified the tower
# such that its initial costs 75%, but 20% a year is saved in enegry consumption,
# 10% in water and 30% in maintenance costs.

# This function is used in "viabilityPoint(self,e_tower,dim)"
# to find the set of values [e_tower, e_op, e_w, e_maint] that
# make us break even and thus justify an initial investment.

    f_latent = 0.80
    h_fg = 2257 #kJ/kg

    C_tower_v = 189.32*(0.408*self.RT**0.8542 + \
    self.RT**0.744)*CoolingTower.actualnetValue(self,e_tower,0,i)

    C_operation_v = 0
    C_water_v = 0
    C_chemical_v = 0
    C_maintenance_v = 0

    for year in range(self.t):

        C_operation_v +=  (3.516*self.RT*self.LF self.COP) * self.R_e * 8760 *\
        CoolingTower.actualnetValue(self,e_op,year,i)

        C_water_v +=   31536*((3.516*self.RT* }self.LF*f_latent*(1 + \
        1/(self.COC)+0.01))*self.R_mu/h_fg + \
        (3.516*self.RT*self.LF*f_latent*(1/(self.COC)))*self.R_bd/h_fg) * \
        CoolingTower.actualnetValue(self,e_w,year,i)

        C_chemical_v += 1.2*self.RT*self.months  * CoolingTower.actualnetValue(self,e_w,year,i)

        C_maintenance_v += 11*self.RT * CoolingTower.actualnetValue(self,e_maint,year,i)
```

```
    return  [C_tower_v, C_operation_v, C_water_v, C_chemical_v, C_maintenance_v]

def viabilityPoint(self,i,e_tower,dim):

# for a given e_tower (a given extra initial cost of the tower once made in AAA, can be 0.5
#(50% more expensive) ,
# 2.1 (210% more expensive)) scans a set of values from 0 to -0.75 for e_op, e_w, e_maint
#with intervals defined by parameter
# "dim" (dim= 20 scans 20x20x20 = 8000 combinations)
# This function returns 3 vectors and a list of triplets.

    ViabilityPoints = []
    e_opX = []
    e_wY =[]
    e_maintZ = []

    for e_op in np.linspace(0,-0.85,dim):

        for e_w in np.linspace(0,-0.85,dim/2):

            for e_maint in np.linspace(0,-0.85,dim):

                if \
                round(sum(\
                 CoolingTower.cooling_tower_program_cost_Change(self,i,e_tower,e_op,e_w,e_maint))\
                 /3000) ==\
                 round(  sum( CoolingTower.cooling_tower_program_Cost(self) ) /3000):

                          ViabilityPoints.append([e_op,e_w,e_maint])

    for n in range(len(ViabilityPoints)):
           e_opX.append(ViabilityPoints[n][0])
        e_wY.append(ViabilityPoints[n][1])
        e_maintZ.append(ViabilityPoints[n][2])

    return e_opX, e_wY, e_maintZ, ViabilityPoints


def coolingtowerbarchartCompare(self,i,e_tower,e_op,e_w,e_maint):

# ['Tower', 'Operation', 'Water', 'Chemicals', 'Maintenance']
# Traces an interactive BarChart showing the prices of CoolingTower.self over its life-span,
#compared to the same tower parameters but
```

```
    #  modified in a way that increases the original investment by e_tower, yet decreases
    #other costs over its lifespan.

        trace2 = go.Bar(
      x=['Tower', 'AAAtower'],
      y=[CoolingTower.cooling_tower_program_Cost(self)[0],
         CoolingTower.cooling_tower_program_cost_Change(self,i,e_tower,e_op,e_w,e_maint)[0]],
      name='Tower', width = 0.3
)
        trace3 = go.Bar(
      x=['Tower', 'AAAtower'],
      y=[CoolingTower.cooling_tower_program_Cost(self)[1],
         CoolingTower.cooling_tower_program_cost_Change(self,i,e_tower,e_op,e_w,e_maint)[1]],
      name='Operation' , width = 0.3
)

        trace4 = go.Bar(
      x=['Tower', 'AAAtower'],
      y=[CoolingTower.cooling_tower_program_Cost(self)[2],
         CoolingTower.cooling_tower_program_cost_Change(self,i,e_tower,e_op,e_w,e_maint)[2]],
      name='Water', width = 0.3
)

        trace5 = go.Bar(
      x=['Tower', 'AAAtower'],
      y=[CoolingTower.cooling_tower_program_Cost(self)[3],
         CoolingTower.cooling_tower_program_cost_Change(self,i,e_tower,e_op,e_w,e_maint)[3]],
      name='Chemicals' , width = 0.3
)

        trace6 = go.Bar(
      x=['Tower', 'AAAtower'],
      y=[CoolingTower.cooling_tower_program_Cost(self)[4],
         CoolingTower.cooling_tower_program_cost_Change(self,i,e_tower,e_op,e_w,e_maint)[4]],
      name='Maintenance' , width = 0.3
)

        data = [trace2, trace3, trace4, trace5, trace6]
        layout = go.Layout(
        barmode='stack', title= 'Standard Tower Program vs AAA Tower Hypothetical Program'
             )


        fig = go.Figure(data=data, layout=layout)
```

```
        return py.plotly.iplot(fig, filename='stacked-bar')


    def coolingtowerbarChart(self):

    # ['Tower', 'Operation', 'Water', 'Chemicals', 'Maintenance']
    # Traces an interactive BarChart showing the prices of CoolingTower.self over its life-span.

        trace2 = go.Bar(
      x=['Tower'],
      y=[CoolingTower.cooling_tower_program_Cost(self)[0]],
      name='Tower', width = 0.25
)
        trace3 = go.Bar(
      x=['Tower'],
      y=[CoolingTower.cooling_tower_program_Cost(self)[1]],
      name='Operation' , width = 0.25
)

        trace4 = go.Bar(
      x=['Tower'],
      y=[CoolingTower.cooling_tower_program_Cost(self)[2]],
      name='Water', width = 0.25
)

        trace5 = go.Bar(
      x=['Tower'],
      y=[CoolingTower.cooling_tower_program_Cost(self)[3]],
      name='Chemicals' , width = 0.25
)

        trace6 = go.Bar(
      x=['Tower'],
      y=[CoolingTower.cooling_tower_program_Cost(self)[4]],
      name='Maintenance' , width = 0.25
)

        data = [trace2, trace3, trace4, trace5, trace6]
        layout = go.Layout(
        barmode='stack', title= 'Cooling Tower Program Costs over lifespan '
             )

        fig = go.Figure(data=data, layout=layout)
```

```
    return py.plotly.iplot(fig, filename='stacked-bar')

def get_TC_Merkel(T_ai,T_wi,T_wo,w,m_w,m_a):

# Calculates the required Tower Characteristic using T_ai,T_wi,T_wo,w,m_w,m_a

        C_pa = 1.006 # kJ/kgK
        C_pv = 1.84 # kJ/kgK
        C_pw = 4.18 # kJ/kgK
        i_we = 2501 # kJ/kg
        deltaT = 0.01

        NTU = 0
        i_ma = 0
        i_masw = 0
        w_sw = 0
        T_a = T_ai
        T_w = T_wo

        i_ma = C_pa*T_a + w*(C_pv*T_a + i_we)

        for n in range(round(  ( (T_wi - T_wo)/deltaT )+0.5)  ):

            w_sw = (2*10**-7)*(T_w**3) + (1*10**-5)*(T_w**2) + 0.0003*T_w + 0.0031

            i_masw = C_pa*T_w + w_sw*(C_pv*T_w + i_we)

            if i_masw <= i_ma:

                return None

                break

            NTU += C_pw*deltaT/ (float(Decimal(i_masw) - Decimal(i_ma)))
            i_ma += (m_w/m_a)*C_pw*deltaT

            T_w += deltaT
  return NTU

def get_TC_available_Constant(T_ai,T_wi,T_wo,w,m_w,m_a):

# calculates the constant(TC_Cnst) in TC = KaV/L =
#TC_Cnst (L/G)^n , using the design point of a cooling tower.
```

```
    NTU_req = CoolingTower.get_TC_Merkel(T_ai,T_wi,T_wo,w,m_w,m_a)

    n = -0.6

    TC_Cnst = NTU_req/ ((m_w/m_a)**n)


    return TC_Cnst

def get_TC_Available(TC_Cnst,m_w,m_a):

    # Calculates the available coefficient as a function of water flow and air flow using
    #TC = KaV/L = TC_Cnst (L/G)^n
    # Takes the constant calculated in get_TC_available_Constant(T_ai,T_wi,T_wo,w,m_w,m_a).

    TC_available = TC_Cnst*(m_w/m_a)**(-0.6)

    return TC_available

def get_new_Airflow(TC_Cnst,T_ai,T_wi,T_wo,w,m_w,m_a):

    # Calculates the airflow that would provide the required cooling in the current conditions
    #for the tower with TC_cnst
    # and fixed m_a = 100% of water flow.

    if CoolingTower.get_TC_Merkel(T_ai,T_wi,T_wo,w,m_w,m_a) == None:

        return None

    m_a_req = ( (TC_Cnst/CoolingTower.get_TC_Merkel(T_ai,T_wi,T_wo,w,m_w,m_a))*(m_w**-0.6) )\
    **(-1/0.6)

    #m_a_req = m_w*(TC_Cnst/CoolingTower.get_TC_Merkel(T_ai,T_wi,T_wo,w,m_w,m_a))**0.6

    m_a_percent = (m_a_req/m_a)

    return m_a_req, m_a_percent
```

APPENDIX B Experimental campaign protocols

Prototype cooling towers test protocol

The prototype should be installed as in figure (5.1).

- **(3.1a)** Before starting an experiment make sure to take a water sample to measure CFU levels in the tower from the prior experiment, sterilize the tower by adding a 1:49 ratio of household bleach. this is equivalent to approximately 300 ml of bleach for the whole 15 L. Let the tower operate 1 hour to purge the bacteria. The bleach can be added by unpluging the blue input on the water heater by first releasing the pressure collar (water will quickly drip down until you lift the tube higher than the sterilized tower water level) and using a funnel.
- **(3.1b)** Unplug the blue input on the water heater by first releasing the pressure collar (water will quickly drip down until you lift the tube higher than the sterilized tower water level). Grab a container and slowly empty the tower water into the sink. There should be a little under 2L of water draining from the tower.
- **(3.1c)** Unplug the red input on the water tank that goes to the pump and empty the 2.5L of water from the water tank. Rince the water tank, refill it with new clean water and set the tank at 35 degrees celcius. 3.1d Unplug the fan and the pump from the cooling tower and remove the cooling tower from the biological extraction hood (you will need two people to do so).
- **(3.1d)** Remove the sprinkler system and the cooling tower fill from the tower and use a sponge and 70% rubbing alcohol to clean the tower and remove any visible biofilm or dirt. The same individual should be cleaning the tower before every run to assure it is always cleaned in the same way.
- **(3.1e)** Once the tower, the fill and the sprinklers are clean, replace them in the tower
- **(3.1f)** Replace the tower into the biological hood. Inclining the tower too much will make the fill fall out of place. If this happens, it can be replaced from inside the hood although it is quite cumbersome to do so.
- **(3.1g)** Using a funnel connected to the tube that will later go to the heater, refill the tower with 1.85 L of water. At this point, the peptone, salt and bacterial cocktail can be added into the tower.
- **(3.1h)** Make sure water reaches the pump input hose. This should happen automatically if the pump is placed lower than the cooling tower. If it is not the case, moving the tubes can help the water reach the pump, or it might be necessary to add water.

Measuring make-up water necessary by evaporation

Originally an automatic make-up water system was put in place to automatically compensate for evaporation throught an aquarium valve with an inverted 4 L demineralized water bottle. However, the aquarium valve plastic connector became stripped easily and this unit made the whole prototype more cumbersome. For this reason, we have decided to evaluate loss to evaporation by running the system and verifying how much evaporated to then add that quantity manually.

- **(3.1i)** Fill the tower up by unplugging the blue input on the water heater by first releasing the pressure collar (water will quickly drip down until you lift the tube higher than the sterilized tower water level) and using a funnel to add 1.85 L of water.

- **(3.1j)** Let the tower operate 24 hours making sure the water heater is on at 35 degrees. After 24 hours of operating empty the tower as in **1.3b** and measure the amount of water emptied. There should be less than 1.85 L. This is the amount that evaporated. The make up water can be added directly from the top of the tower by unpluging the fan and removing the top.

Bacteria, nutrients and salts addition:

3 independent 4 ml solution one of *Staphylococcus Aureus* one of *Pseudomonas Aeruginosa* and on of *Enterobacter Cloacae* were prepared, measured with a spectrophotometer to obtain a OD_{600} equivalent to $1\times10^6 bactiera/ml$. These were allowed to stabilize at room temperature before being transfered together into 100 ml with a salt concentration of 0.5% and a peptone concentraion of 0.25%. before adding the 100ml bacterial cocktail, the tower operated 1 hour with 37.5 g peptone and 75 g NaCl for a total volume of 15 L to make sure the nutrients and salt were evenly distributed. The first run on the non-treated tower demonstrated that this methodolgy worked.

Micro-biological sample extraction and testing

A series of water samples can be directly extracted from the cooling tower input as in **1.3b** before adding bleach. CFU/ml counts are to be measured on this water sample.

Other considerations

The cleaning procedures were always carried out by the same individual - Patrick Asselin-Mullen, as to minimize any variable related to a different methodology between two individuals.

Rince-cycle test protocol:

- **(3.2.1a)** Take one of the samples (50mm x 25 mm x 2.5 mm with two 8mm x 6mm side protrusions as depicted in figure (B.1)) and place it in a petri dish (90 mm in diameter and 15 mm tall)
- **(3.2.1b)** Add 25 mL of bacterial solution (either *Staphylococcus aureus* or *Pseudomonas aeruginosa* according to the experiment) at bacterial concentration of $OD_{600} = 0.1$.
- **(3.2.1c)** Incubate for 24 hours at $37°C$.
- **(3.2.1d)**Take 40 μL of the bacterial solution in the petri dish and put it in or tryptone soya agar (TSA).
- **(3.2.1e)** Incubate the agar 16 hours at $37°C$.
- **(3.2.1f)** Rince 5 times the petri dish and the aluminium sample with tap water.
- **(3.2.1g)** Clean the sample with isopropanol 70%.

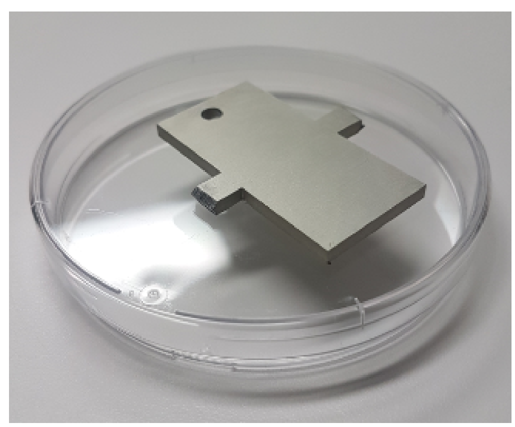


Figure B.1 Antimicrobial Anodized Aluminium (AAA) sample on top of a 90mm diameter petri dish for testing.

- **(3.2.1h)** Let the sample dry and restart the experiment.
- **(3.2.1i)** count the number of bacterial colonies (CFU) and measure the CFU/L using the adequate dilution

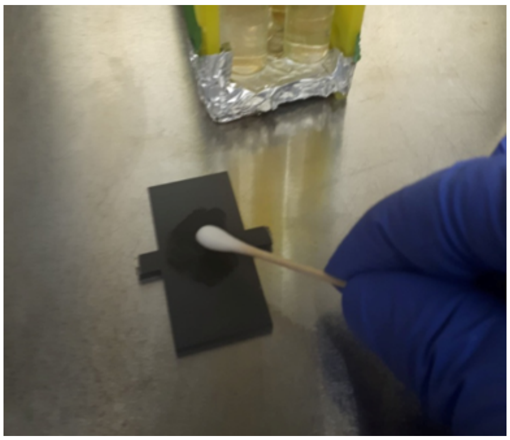


Figure B.2 Bacteria being collected from an AAA sample following th dry-kill test protocol.

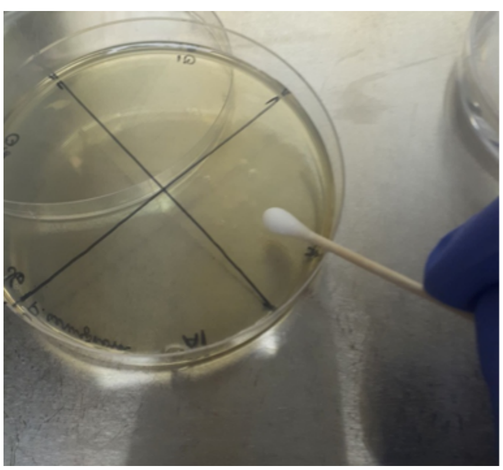


Figure B.3 Contaminated Q-tip being spread out on an Agar bed before incubation.

Dry-Tests protocole:

- **(3.2.3a)** Clean each sample with water, a kimwipe and leave under UV light for 15 minutes
- **(3.2.3b)** Take 5 μL of bacterial solution with an optical density of $OD_{600} = 0.05$ and spread it evenly on the sample. Let this solution dry on the sample.
- **(3.2.3c)** Once the drop dries, wait 30 minutes for the anti-microbial properties of the sample to take effect.
- **(3.2.3d)** Wet a sterile Q-tip and rub it on the surface where the bacterial solution laid.
- **(3.2.3e)** Spread the Q-tip on tryptone soya agar (TSA).
- **(3.2.3f)** Incubate the agar for 24 hours at 37 $°C$ and count the colony forming units.

Electroplating protocol:

- Rinse in water after last step of anodization. The anodization details prior to plating are confidential.
- Dip in $AgNO_3$ 5,1g/L, 1% H_2SO_4 electroplating bath for 1 minute, making sure the pieces are fully submerged and connected to a wire, as well as a cathode connected to a wire, then activate alternate current at 16V for X minutes (3 minutes or 10 minutes in the case of this study).
- Rinse with water.
- Submersion in sealing bath (Anodal MS-1 New Liquid, 2,5% v/v) at 80°C for 2 minutes.
- Rinse with water and let dry.

APPENDIX C H20 Biotech corrosion coupon results

H2O BIOTECH
406 Legendre Ouest
Montréal, QC, Canada, H2N 1H7

No de témoin	Type de métal	Date In	Date out	Poids initial gr	Surface total: Longeur cm	Surface total: Largeur cm	Surface total: Épaisseur cm	Surface total: Total cm2	Surface à éliminer - cm2, Diamètre des perforations: Troue 1	Surface à éliminer - cm2, Diamètre des perforations: Troue 2	Suface total des troues	Surface total cm2	Volume total cm3	Calcule du taux de corosion: Poids Fin gr	Calcule du taux de corosion: Temps Jour	Calcule du taux de corosion: Perte gr	TAUX DE CORROSION MPY
Témoins de corrosion par trempage																	
1	Acier Galvaniser	20-juin-17	24-août-17	4,136	6,297	1,361	0,089	1,604	0,488	0,000	0,510	1,094	0,745	4,107	65	0,029	**1,6**
2	Métal	20-juin-17	24-août-17	9,382	6,350	1,270	0,165	2,935	0,508	0,000	0,669	2,267	1,298	9,282	65	0,100	**2,4**
3	Cuivre	20-juin-17	24-août-17	12,568	7,623	1,207	0,165	3,312	0,648	0,000	0,995	2,317	1,464	12,541	65	0,027	**0,5**
4	AL anodisé 95un	20-juin-17	24-août-17	6,521	2,560	0,479	0,138	0,971	0,192	0,000	0,141	0,830	0,165	6,506	65	0,015	**0,5**
5	AL anodisé 85un	20-juin-17	24-août-17	6,472	2,556	0,479	0,130	0,914	0,192	0,000	0,136	0,777	0,155	6,469	65	0,003	**0,1**
6	AL anodisé 80un	20-juin-17	24-août-17	6,455	2,560	0,475	0,130	0,913	0,195	0,000	0,139	0,773	0,154	6,453	65	0,002	**0,1**
Témoins de corrosion par circulation																	
155167	1010 Carbon steel	21-juin-17	24-août-17	9,330	7,620	1,270	0,165	3,355	0,508	0,000	0,669	2,686	1,564	9,307	64	0,023	**0,5**
155166	1010 Carbon steel	21-juin-17	24-août-17	9,010	7,620	1,270	0,165	3,355	0,508	0,000	0,669	2,686	1,564	8,977	64	0,033	**0,8**

Cette étude fait suite a notre étude du mois d'avril la différence ici c'est que l'eau de la tour est traité avec des produits contre les précipitations et la formation de calcaire. Également des produits contre la prolifération bactérienne est utilisé dans cette tour d'eau. Le pH et la conductivité de l'eau étaient constant (pH 8.9 et 1,100 mmhos de conductivité. Les témoins de corrosions ont été installé dans le bassin de la tour d'eau (donc par méthode de trempage) pour 65 jours. A titre de comparaison nous avons installé des témoins de corrosion en acier noir en mode de recirculation afin de faire la comparaison entre les 2 méthode (statique, et circulation). À la lueur des résultats obtenues l'aluminium anodisé avec une épaisseur de 85 et 80 micron donnerait des résultats supérieur à l'acier galvanisé dans les mêmes conditions. Nous incluons avec ce rapport les photos de la tour d'eau ainsi que les résultats de conductivité d'eau d'appoint et d'injection de chlore 12% durant cette période.

Endroit ou les témoins ont été installés
Suspendu dans le bassin de la tour

H2O BIOTECH
406 Legendre Ouest
Montréal, QC, Canada, H2N 1H7

ÉTUDE COMPARATIVE DE CORROSION SUR L'ALUMINIUM DANS L'EAU D'UNE TOUR D'EAU
Sur différent types de métaux et d'aluminium anodisé de différente épaisseur

TÉMOINS DE CORROSION APRÈS UN NETTOYAGE

	Installé	Installé	Installé	Installé	Installé	Installé
Date in	20-juin-17	20-juin-17	20-juin-17	20-juin-17	20-juin-17	20-juin-17
Date out	24-août-17	24-août-17	24-août-17	24-août-17	24-août-17	24-août-17






No 1	No 2	No 3	No 4	No 5	No 6
Acier Galvanisé	Acier noir	Cuivre 1010	Aluminium 95 um	Aluminium 85 um	Aluminium 80 um
Corrosion apparente	Corrosion apprente	Corrosion sous contrôle	Corrosion faible	Corrosion faible	Corrosion faible
Taux de corrosion	Taux de corrosion	Taux de corrosion	Taux de corrosion	Taux de corrosion	Taux de corrosion
1,6 mpy	**2,4 mpy**	**0,5 mpy**	**0,5 mpy**	**0,1 mpy**	**0,1 mpy**

TÉMOINS DE CORROSION AVANT UN NETTOYAGE






No 1	No 2	No 3	No 4	No 5	No 6
Acier Galvanisé	Acier noir	Cuivre 1010	Aluminium 95 um	Aluminium 85 um	Aluminium 80 um
Corrosion apparente	Corrosion apprente	Corrosion sous contrôle	Corrosion faible	Corrosion faible	Corrosion faible
Taux de corrosion	Taux de corrosion	Taux de corrosion	Taux de corrosion	Taux de corrosion	Taux de corrosion
1,6 mpy	**2,4 mpy**	**0,5 mpy**	**0,5 mpy**	**0,1 mpy**	**0,1 mpy**

H2O BIOTECH
406 Legendre Ouest
Montréal, QC, Canada, H2N 1H7

ÉTUDE COMPARATIVE DE CORROSION SUR L'ALUMINIUM DANS L'EAU D'UNE TOUR D'EAU
Sur différent types de métaux et d'aluminium anodisé de différente épaisseur
EN MODE CIRCULATION À 4 PIEDS LINÉAIRE SECONDE

TÉMOINS DE CORROSION APRÈS UN NETTOYAGE

	Installé	Installé
Date in	20-juin-17	20-juin-17
Date out	24-août-17	24-août-17

No 2
Acier noir
Corrosion apprente
Taux de corrosion
0,5 mpy

No 2
Acier noir
Corrosion apprente
Taux de corrosion
0,8 mpy

TÉMOINS DE CORROSION AVANT UN NETTOYAGE

No 2
Acier noir
Corrosion apprente
Taux de corrosion
0,5 mpy

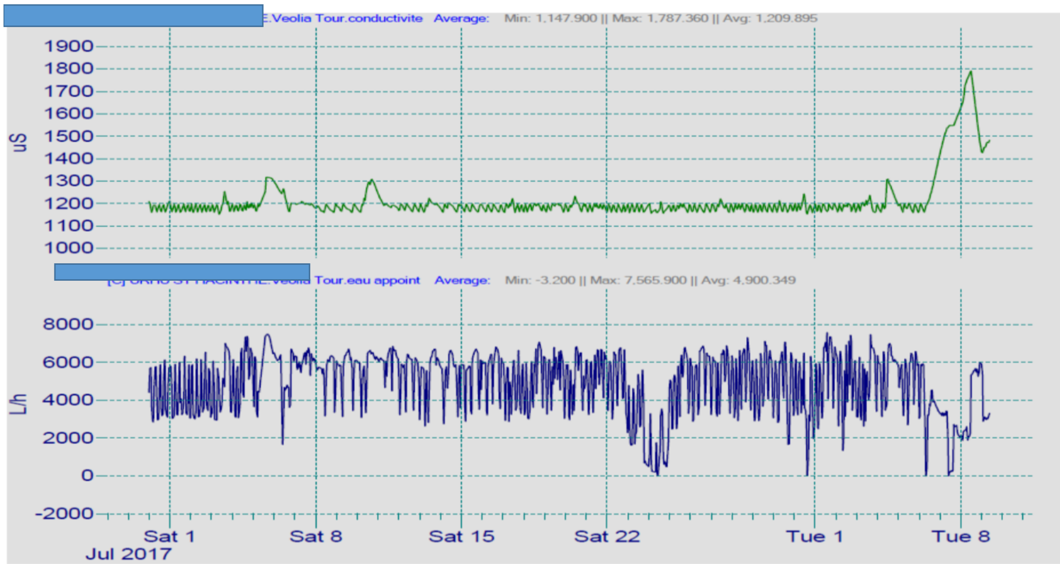
No 2
Acier noir
Corrosion apprente
Taux de corrosion
0,8 mpy

H2O BIOTECH
406 Legendre Ouest
Montréal, QC, Canada, H2N 1H7

ETUDE COMPARATIVE DE CORROSION SUR L'ALUMINIUM DANS L'EAU D'UNE TOUR D'EAU

Paramètre d'opération durant cette période

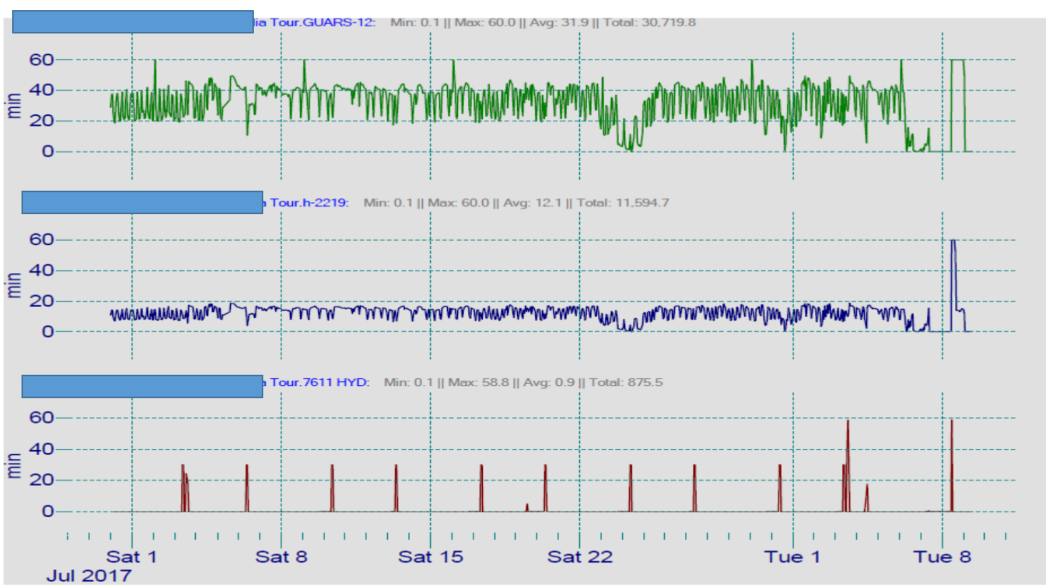
Conuctivité et eau d'appoint



Conductivité

d'appoint

Injection de chlore, d'inhibteur de calcaire et de biocide Hydrex 7611



Chlore

Inhibiteur

Biocide