BIOFOULING CONTROL IN HEAT EXCHANGERS USING HIGH VOLTAGE CAPACITANCE BASED TECHNOLOGY.

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ABSTRACT

Biofouling in industrial heat exchangers and piping systems is common in water from all sources. Problems generated by biofouling such as corrosion, sludge deposition and scale formation have a costly impact on industrial equipment and productivity.

The addition of chemical biocides is the most commonly used methodology to control bacteria levels in aqueous systems within acceptable parameters. Resistance of microbes to the chemicals used to control them is not uncommon, often requiring changes of biocide formulations as a program strategy to maintain control.

Bacteria are most vulnerable to biocides when they are in their planktonic form; however most bacteria live and reproduce in the protective barrier of the biofilm, allowing them to survive biocide attack. Biofilm deposits render many treatment programs inefficient and costly. High bacterial populations protected by biofilm continue to persist and provide the prime source of daughter cells for continued inoculation and new colony development.

This paper describes an electronic approach to biofouling control in industrial heat exchangers, focusing upon biofilm removal and the prevention of biofilm formation. The biostatic effect of High Voltage Capacitance Based (HVCB) technology does not kill microorganisms directly; rather it provides a deposit control program to disperse exopolysaccarides (EPS) and appears to inhibit the metabolism of bacteria. By dispersing existing biofilm deposits and preventing the further formation of additional EPS deposits, a control routine is established that sharply reduces microbiological populations.

In water systems made up of clean source water, HVCB technology maintains clean surfaces on pipes and heat exchangers and delivers extremely low bacteria counts without the use of added biocides. The powerful biodispersant action and increased permeability of deposits also enhances chemical programs where operating conditions warrant the continued use of biocides. Use of waste water as cooling system makeup becomes feasible with the addition of small amounts of biocide.

HVCB technology has demonstrated high level control of biofouling and scale in a wide range of industrial and domestic water systems. Data and observations from several HVCB treatment programs are presented in this paper.

Results reported from these applications correlate with existing theories on the mechanisms involved in biofilm formation. The examples described represent very difficult fouling challenges that could not be controlled by conventional means. In all locations biofilm is controlled, biocide consumption is significantly reduced or eliminated, and the biofouling and biocorrosion problems are eliminated.

From the data presented, conclusions are drawn that the application of HVCB treatment programs can be successful in interfering with the three recognized stages of biofilm formation in industrial heat exchangers and piping systems.

INTRODUCTION

Microorganisms such as bacteria, fungi, and other microbes have been studied for over a hundred years. Louis Pasteur was one of the first scientists to develop theories and concepts in microbiology that are still applied today. In 1683 the Dutch scientist Antony Van Leeuwenhoek wrote to the Royal Society about his observations on the plaque between his own teeth using one of his simple microscopes. In a study published in 1933 Henrici makes what some consider to be the first observation concerning biofilms: "..it is quite evident that for the most part water bacteria are not free floating organisms, but grow upon submerged surfaces".

Since the work by Henrici, considerable research has been performed to understand biofilms better. Biofilm structure, formation mechanisms, resistance to biocides, gene mutation, quorum signaling and sensing, and the role biofilms play in medical, dental and industrial challenges, have received increased attention.

With the advance of microscopy and new laboratory methodologies, biofilms may now be studied in great detail. Whereas early studies were limited to the use of simple microscopes, the development of scanning electron microscopes (SEM) opened a new window into the complex matrix structures formed by bacteria. However, the SEM technology had its drawbacks; preparation of the samples required dehydration which led to "..a deceivingly simplistic view of biofilms as cells piled atop one another.." (O'Toole et al. 2000 and Costerton et al. 1995).

Confocal laser scanning microscopy (CLSM) has allowed for the visual inspection of fully hydrated live biofilms, which opened a new perspective and understanding of how biofilm structures are viewed and studied (Lawrence et al. 1991, and Kuehn et al. 1998). Observations of in situ live biofilms using CLSM have revealed heterogeneous spatial structures consisting of clusters of bacteria as well as voids and channels (Kuehn et al. 1998).

Although we know more about biofilms today than when Henrici made his first observations, there is still much to be learned about them, their prevention and control.

For heat exchanger fouling mitigation, it appears that biofouling control presents a much greater challenge than mineral scaling and/or corrosion. The biofouling/ biocorrosion challenge is deepened by the vast number of variables involved with biofouling. The improved knowledge of the chemical reactions and physicochemical interactions that take place in mineral and biofilm deposition has furnished more insight into the complexities.

Traditional methods of microbiological research focused on studying single species in a controlled environment. These studies have yielded an abundance of knowledge regarding the complexities of biofilms, but have little in common with complex conditions present in the industrial setting. Sheikholeslami (1999) writes “Usually several types of fouling occur simultaneously, not in isolation.”

McCoy (1983) devotes a full chapter in his book to the microbiology of cooling systems, describing the currently accepted methods for biofouling control, monitoring and the chemicals most typically used for this purpose. There are numerous types of chemical biocides available in the market for use in control of biofouling. These biocides and biodispersants are formulated to disperse existing biofilms or to prevent waterborne microorganisms from attaching to a surface. The rationale behind the formulations is that bacteria are far more susceptible to a biocide when they are in their planktonic form than when they are in their sessile form protected by the biofilm (Chambless et al. 2005, Williams et al. 2005, O’Toole et al. 2000, McCoy 1983).

Biofilm formation is considered to be a three phase process. The first phase is referred to as the initiation, induction, adhesion or adsorption phase. Physicochemical interactions between organisms are believed to play a critical role in this phase. (O’Toole et al. 2000, Busscher et al. 1997, Weerkamp et al. 1988, Melo 1997). During this phase O’Toole et al. (2000) cite environmental conditions such as nutrient availability, as a cue taken by the bacteria to form a biofilm; and a transition in the organisms is mentioned that allows them to go from planktonic to sessile cells. Quorum signaling and sensing has recently been demonstrated to play a role in cell attachment and detachment from biofilms (Donlan 2002). Davies et al. (1998) showed that “two different cell-to-cell signaling systems in *P. aureginosa, lasR-lasI* and *rhlR-rhlI,* were involved in biofilm formation. At sufficient population densities, these signals reach concentrations required for activation of genes involved in biofilm differentiation.”

The second, or growth, phase of biofilm formation is controlled by environmental conditions. Growth of the biofilm during this phase is primarily driven from within the biofilm rather than by attachment of new cells from the bulk fluid. It is also during this phase that the production of EPS and the development of resistance to biocides takes place (O’Toole et al 2000). Mass transfer mechanisms also play an important role in the transport of nutrients into the EPS matrix (Melo 1997).

The third phase in biofilm formation is designated as the plateau, maintenance, or dissolution phase. During this phase the biofilm reaches equilibrium and the growth rate equals the detachment rate. Physical and environmental factors as well as hydrodynamic forces play critical roles during this phase. Factors known to have an impact on the thickness of the biofilm include temperature, pH, nutrient availability, and flow velocity (O’Toole et al. 2000, Tsai 2005, Costerton et al. 1995, Kuehn et al. 1998, Melo 1997). Cell detachment by quorum sensing is also considered to be a factor in this stage of biofilm formation (Donlan 2002).

The use of a technology defined as High Voltage Capacitance Based (HVCB) provides an effective means to prevent biofouling in cooling systems. Pitts (1992 and 1995) describes the effect of such technology on mineral deposits in mining applications and its potential application for HVAC cooling systems. A study prepared by the Department of Mechanical and Aerospace Engineering at Arizona State University under a grant from the U.S. Department of Energy describes the effects of HVCB technology when applied to a cooling system and provides a long term head-to-head comparison with a conventional chemical based water treatment program (Phelan et al. 1999). Other studies have evaluated the effect of HVCB technology in biofouling prevention for reverse osmosis (RO) systems (Romo et al. 1999, 2000 & 2002, Schrader 2006).

DESCRIPTION OF HVCB TECHNOLOGY

The behavior of colloidal particles and the interaction forces between particles and the wetted surfaces in which they are contained have been the subject of considerable study. In his two-part paper Riddick (June 26 and July 10, 1961) makes some observations about how the manipulation of the surface charge of colloidal particles could lead to an improvement in various water treatment processes.

The effect of opposing electrostatic repulsion forces – explained by the Derjaguin-Landau and Verwey-Overbeek (DLVO) theory- and Van der Waals attraction forces is considered to be a key determinant on the stability of colloidal particles dispersion.

Pitts (1992) describes dispersion effects achieved at a copper mine in Arizona. In his paper, Pitts evaluates an HVCB technology to prevent colloidal mineral and biological material from interrupting the operation of a solvent extraction electrowinning circuit. In his findings, Pitts shows that the application of the HVCB technology causes an increase in the zeta potential of the colloidal particles after being exposed to the HVCB system. He further makes two key observations from his experiments: the increased surface charge generated by the HVCB system is temporary and second, that the increase in zeta potential is a function of exposure time and field strength.

In his study, Pitts (1995) describes the principles of induced electrostatic dispersion in aqueous systems. The underlying principles involve capacitance, double layer, Gaussian surface charge, dielectric properties of colloids and ionic strength of solutions.

To produce electrostatic dispersion, a cylindrical capacitor is created by inserting an insulated and sealed electrode into a metal pipe or vessel (Figure 1).

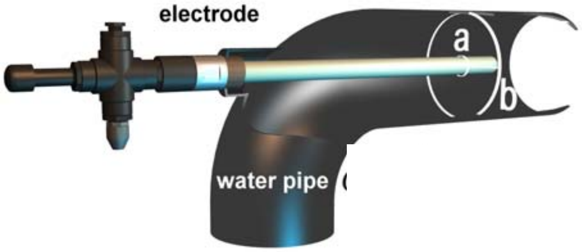

Figure 1: Illustration of the capacitor formed in a pipe by an HVCB System. Courtesy of Zeta Corporation.

The system functions by inducing a time transient alteration of the particle surface charge over the natural state. The effect is expressed on dielectric colloidal particles, as well as on the wetted surfaces of the pipe or vessel.

The conductive lining of the ceramic electrode used in commercial equipment serves as one plate of the capacitor. The dielectric strength of the vitrified ceramic prevents current flow to the other plate of the capacitor. The grounded plane of the capacitor is established by the metal of the pipe or vessel. A direct current power supply charges the capacitor system to a very high potential (normally 30 to 35 kV DC). The field strength between the plates of the cylindrical capacitor is a function of charge voltage, system dimensions, and the dielectric constant of the ceramic. Pitts (1995) established that at a sufficiently elevated voltage, the field strength across the liquid between the plates of the capacitor influences the Gaussian surface charge of the particle. The result is a significant increase in the surface charge of wetted surfaces and in prevention of agglomeration (flocculation) of particles, impeding adherence of these particles to the walls of their containment.

The effect of electrostatic particle dispersion that has been observed in colloidal particles (Fiabish et al. 1998, Hoek et al. 2003, and Riddick 1961) has been extrapolated and applied to microorganisms responsible for biofouling in different aqueous environments (Marshall et al 1994, Romo et al 2000, Schraeder 2005 & 2006, Sheikholeslami 1999). Beginning with the recognition of bacteria as a colloidal particle, associations may be made between prior research findings and field observations of applied HVCB technology. With this linkage established it becomes possible to explain and develop a rationale for biofouling control using HVCB technology that supports the observations and results obtained in the laboratory and field.

EFFECT OF HVCB TECHNOLOGY ON BIOFOULING: FORMULATION OF HYPOTHESES.

Phase I: Adhesion and Physicochemical Forces.

The importance that physicochemical forces such as DLVO and Van der Waals attraction play in the initial stage of biofilm formation is explained in several studies.

O’Toole et al. (2000) observe in their paper, “Early studies suggested that the overall hydrophobicity and/or surface charge of a bacterium could serve as a good predictor of the surfaces that an organism might colonize.”

Weerkamp et al. (1998) observe that “..successive steps in the adhesion process are thought to involve physicochemical interactions, such as long-range Van der Waals forces, intermediate-range electrostatic and short range polar and hydrophobic interactions”.

Busscher et al. (1997) refer to the “..adhesive interactions among colloidal particles –whether microorganisms or inert synthetic particles- and molecular entities are mediated by physicochemical interactions.”

Pitts (1992) described the effect of the direct application of an electrostatic field generated by an HVCB system on the zeta potential of a pregnant leach solution (PLS). In his study Pitts observes an increase in the value of the zeta potential from 35 (-mV) to 60 (-mV).

Schraeder (2006) shows in his work an immediate increase in the electrokinetic mobility of the colloidal matter in the effluent he worked with of -0.15 µm.cm/V.s to -0.4 µm.cm/V.s.

The findings of these two studies serve as evidence that HVCB has the capability of altering the surface charge of colloidal particles in a solution. Therefore, the first hypothesis to explain the biofouling prevention capabilities of HVCB technology could be stated as:

The alteration of the surface charge of bacteria or biofilm forming organisms in the water and the hydrophobicity of the wetted surfaces would produce the observed net effect wherein the initial phase of the biofilm forming process is prevented.

O'Toole (2000) mentions in his study that "Biofilm formation is thought to begin when bacteria sense environmental conditions that trigger the transition from pelagic life to life on a surface. This thought is further advanced by the recognition of "quorum sensing and signaling" in the early stage of biofilm formation. It is reasonable to conclude that the electrostatic field established by the HVCB technology might be perceived by bacteria as an adverse environmental condition, thereby preventing the conditions for colony expansion after a quorum of individual bacteria is present. An explanation is thus provided for field observations where surfaces are maintained free of biofilm. This rationale carries over into a discussion of how existing biofilms are removed from surfaces when a strong electrostatic field is present in the water flow.

Phase II: Growth

After the initial phase of adhesion, bacteria undergo further adaptation to the conditions in a biofilm. It is at this stage that the increased production of EPS is noted and it is also the time when resistance to biocides is developed (O'Toole 2000).

Chambless et al. (2006) have described four hypothetical mechanisms used by bacteria to generate their resistance to biocides. Among the mechanisms mentioned are poor biocide penetration into the biofilm (the EPS acting as a protective barrier); and the presence of phenotypic variants or persistent cells, indicating that bacteria have gone through changes that allow them to tolerate high dosages of biocides.

Another reason for bacteria in a biofilm to be more resistant to a biocide is the simple fact that the biocide would have to penetrate or destroy the entire layer of biofilm and still have sufficient residue to kill the organisms embedded within the EPS. Planktonic organisms have no protective barrier around them and are therefore far more susceptible to the effect of a toxin.

During this second stage, the growth of the biofilm is mainly due to the activity and reproduction of the organisms within the biofilm and not due to the adhesion of new organisms from the bulk fluid into the biofilm matrix (Tsai 2005). Mass transfer mechanisms play an important role in the transport of nutrients into the EPS matrix. As the biofilm mass increases, the metabolism in the deeper areas of the biofilm may be deprived of nutrient caused by an internal resistance to nutrient transport. Additionally, the organisms near the liquid interface may consume all of the nutrients before they reach the lower zones of the biofilm (Melo 1997).

Tsai (2005) and Melo (1997) report on the effect of flow velocity and its shear forces on the thickness of biofilm. In their findings there seem to be two contradictory results. Initially, as the flow velocity is increased, the thickness of the biofilm increases as well. This apparent conflict is resolved by understanding that the diffusion rate of nutrients through the biofilm is a more significant factor than the destructive shear force of the flow. As the flow velocity is further increased, the turbulent flow shear force overcomes the increased diffusivity of the nutrient supply and shear becomes the limiting factor determining the thickness of the biofilm.

Based on these observations, coupled with observations made on the mechanisms that control Phase I of biofilm formation, a hypothesis can be stated to explain the effect of the HVCB technology on existing biofilms:

By changing the zeta potential of bacteria and other colloidal particles through the application of HVCB technology, a change is also created in the surface tension or wetting effect of water. This increase in wetting effect would have a twofold effect on the biofilm: If biocides were present, increased wetting would enhance the transport of biocides deeper into the biofilm matrix thereby increasing their kill rate; and the increase in the wetting effect would cause the biofilm to super-hydrate, absorb more water, become flaccid and therefore be more susceptible to sloughing by shear forces generated under a turbulent flow regime.

Phase III: Detachment

After growth and development of the biofilm, the developmental cycle is completed when planktonic cells are shed from the biofilm into the water flow. This may be the result of insufficient nutrients, the direct release of daughter cells, alteration in cell or substratum properties, reversible adhesion, or shear forces (Costerton 1995, O'Toole et al. 2000, Marshall et al. 1994).

Considering the mechanisms involved in all three phases of biofilm formation, the effect of applied HVCB technology toward limiting biofouling can be explained by several theories. These theories include a series of physicochemical interactions, hydrophobicity effects, hydrodynamic forces, mass transfer phenomena and environmental signals. These influences apply to both planktonic and sessile bacteria, establishing a hostile environment in which the conditions do not favor the formation of a biofilm.

FIELD OBSERVATIONS ON BIOFOULING CONTROL USING HVCB TECHNOLOGY

The following examples serve as illustrations relative to the use of HVCB systems for deposit control in an array of industrial cooling applications. The systems used in all these cases were commercial Zeta Rod® systems manufactured by Zeta Corporation of Tucson, Arizona, USA.

Data collected, observations, and reports provided are the product of collaboration between the end users, independent researchers, and the authors of this paper. Some end users have provided data but request that their corporate identity not be published.

An objective approach is maintained in presentation of each of these cases and some cases have a greater amount of data than others. It is important to note that the conditions in each one of these locations, while being far from the conditions desired for a controlled experiment, do provide conditions representative of those found in industrial situations.

Removal of mature biofilm from evaporative cooling media.

Swelling and sloughing of biofilm was observed on an evaporative cooling wet wall in the greenhouse at the Biosphere 2 environmental research complex north of Tucson, Arizona. Biofilm deposits treated by the HVCB system were removed quickly and did not recur.

The evaporative cooling media pads (CELdek®) are made from a cellulose paper that is chemically treated to resist deterioration. The pads were approximately 5 years old and were considered to be fouled beyond recovery. Biofilm based deposition caused blockage of the air channels, limiting cooling efficiency (figure 2). In the extreme heat of the Arizona desert it was difficult to maintain the greenhouse set point temperatures, and energy consumption for cooling fan operation was extraordinarily high.

With constant aeration, laminar water flow over the pads, and nutrient availability made it an ideal environment for biofilms to grow without hydrodynamic forces as a limiting factor. Coupling these ideal conditions favoring biofilm formation, internal management policy did not allow for the use of any type of biocides.

The cooling system was operated with no bleed of the concentrated water and make up water was added to replace the water lost to evaporation. The system was purged after the cooling season and refilled with fresh water at the beginning of the next cooling season. The high concentration of mineral salts in the water exacerbated the scale formation. The resultant biofilm deposit was both thick and dense; and included mineral scaling, dust and pollen. Spraying with a garden hose would not remove it, and pressure washing was not an option since the pads would be damaged by the cutting force of the water jets.

The HVCB system was activated in the middle of May 1997, a few months into the cooling season. In the course of six weeks the biofilm deposits became moist, soft, and swollen. Some of the biofilm began to fall off under its own weight. The slow trickle of water onto the pads was meant only for wetting and did not have enough shear force to slough the biofilm. Greenhouse workers reported a dramatic change in the smell of the greenhouse, according to some “the strong swampy odor had disappeared”. At the end of the sixth week the pads were cleaned using a regular garden hose. The deposits, biofouling and mineral scale were easily removed (figure 3). Until the 2006 shut down of that section of the campus, the pads had remained clean for nine years with no new biofilm or mineral scale deposits.

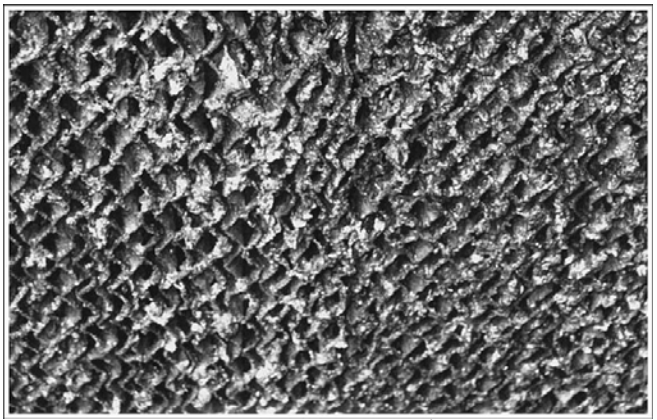

Figure 2: Internal face of CELdek® pad at Biosphere 2 campus analog greenhouses before the installation of HVCB system.

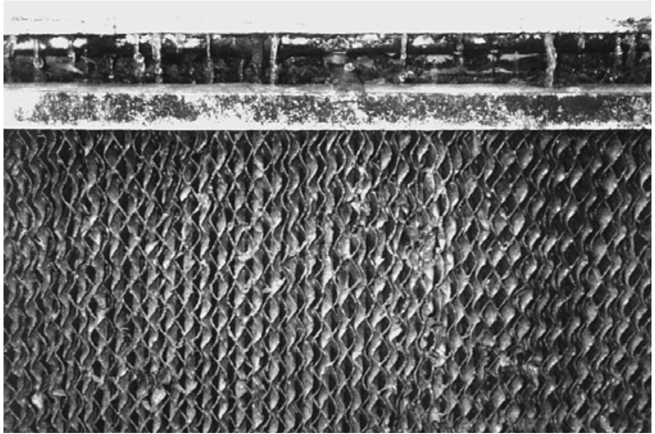

Figure 3: Internal face of CELdek® pad after six weeks of treatment with HVCB system after rinsing with a garden hose.

The dense biofilm, its hydration and resultant fluidity were readily recognizable. These physical effects very likely relate to a reduction in the surface tension of the water. Odor elimination signals a modification of metabolic activity with possible prevention of the bacteria from reproducing and forming new colonies.

These cumulative observations support the theories offered by Schrader (2006) in his doctoral thesis that " .. an increase of the electrostatic repulsion between the negatively charged membrane surface and negatively charged colloidal matter will decrease the possibility of sorption of organic molecules on the membrane." And "..surface charge of macromolecules has an effect on the properties of the fouling layer". In his earlier research Schrader (2005) showed that effluent colloidal matter with a high zeta potential formed less compact and more permeable fouling layers compared to effluent colloidal matter with neutral zeta potential.

Comparison study of biofouling, scale formation and corrosion in a condenser-cooling tower water system.

A study of HVCB technology was performed by the Department of Mechanical and Aerospace Engineering of Arizona State University (Phelan 1999) under a research grant from the United States Department of Energy. The objective was to compare the performance between a conventional chemical treatment program and a HVCB system. The nine month study compared the control of scale, biofouling, corrosion, and water conservation. Phelan (1999) predicated his work by saying that conventional chemical programs can be quite effective in controlling scaling, biofouling and corrosion, however, the use of chemicals is often "quite costly and not beneficial to the environment".

The trial was set in a semiconductor plant in Tempe, Arizona with two identical HVAC systems; each consisting of a cooling tower and a chiller rated at 4500 kW. Both towers and chillers were independent from each other and were located side by side. Both received make up water from the same source and were exposed to the same environmental conditions. The two chillers were set to run at the same load.

One of the systems received a complete chemical treatment program (control) that included corrosion inhibitor, an anti-scale formulation and a biocide (sodium hypochlorite). The test system was equipped only with a HVCB system and all chemical treatments were discontinued. The parameters monitored were:

- Scaling: monitored by wet surface observations and the coefficient of performance (COP) of the chillers.
- Biofouling: monitored by periodic incubated samples using paddle testers (HACH model 26108-10 for total aerobic bacteria, Yeast & Mold)
- Corrosion: monitored by installing and analyzing pre-weighed corrosion coupons for mild steel and copper.
- Water Conservation: monitored by metering the amount of water being added and bled by each system.

The results of the trial relative to scaling and corrosion showed no significant difference between the two treatment programs. Both programs met the set metrics with acceptable results. In water conservation, the HVCB treated system was able to run at higher cycles of concentration and therefore delivered greater water use efficiency.

In the bacteria control facet of the study the HVCB treated system constantly maintained lower bacteria counts than the chemically treated system (Table 1). The report concludes to this effect that: " The HVCB system proved successful in reducing the bacteria level in the chiller/cooling tower system and thus appears to be an effective means of bacteria and biofilm control".

Table 1: Pelagic Population Counts - HVCB Treated System vs. Chemical Treatment Program.

Time (days)	HVCB System (cfu/ml)	Chemical System (cfu/ml)
0	1×10^5	1×10^5
17	1×10^3	1×10^6
224	1×10^3	1×10^5
259	1×10^2	1×10^5

As evidenced by the data, the HVCB system maintained two to three orders of magnitude lower pelagic bacteria counts in a cooling water system without the use of biocides.

The lower bacteria counts in the HVCB system can be explained by factors described in several studies (McCoy 1983, Melo 1997, and Chambless et al. 2006). All of these authors write about the resistance of biofilm to biocides and how certain characteristics of the water, such as pH, can inhibit the efficiency of certain biocides; especially those that are chlorine based.

Costerton (1994) describes the biofilm matrix as an ion exchange resin to which waterborne particles and precipitated mineral salts can readily adhere. Biofilm thus provides an ideal substrate for scale formation. As seen in this test, the scale attachment characteristic of biofilms is observed within the fill of these cooling towers. Upon initiation of the trial, all cooling towers had a significant amount of scale deposition on the surfaces of the high density fill. As the trial progressed, the HVCB cooling tower began to shed large amounts of scale from within the tower fill. No similar effect was observed in the chemically treated tower. It is reasonable to assume that the exfoliation of scale from cooling tower fill was related to the previously mentioned hydration of aged biofilm. The low bacteria counts correlate with prior observations that bacterial activity and biofilm growth were inhibited by the application of the HVCB program.

The electrostatic field generated by the HVCB system disrupts the metabolic processes of sessile and planktonic bacteria alike and causes bacteria to detach from biofilms. Biofilm formation and the maintenance of that biofilm by viable colonies of bacteria is interrupted. As seen in the long demonstration period, low bacteria counts prevail in water systems without the use of chemical biocides.

Biofouling and biocorrosion control in a cooling tower water system, Camas, Washington, USA.

The central cooling plant of a semiconductor manufacturing facility in Camas, Washington contained eight 4600 kW chillers. Cooling of condenser water was done through a six cell cooling tower. The condenser water supply (CWS) and condenser water return (CWR) lines are 1050 mm carbon steel pipes going from the towers into the chiller room and back to the towers.

The limitations of the local water treatment plant forced the facility to reuse wafer processing rinse water as part of the make up to the cooling tower. The subsequent introduction of nutrients into the recirculating water system generated a massive bloom of bacteria and the formation of massive biofilm on all wetted surfaces of chillers and piping. Total Aerobic Bacteria (TAB) counts constantly exceeded $1x10^6$ colony forming units per milliliter (cfu/ml). Heavy biofilm deposits favored the abundance of a highly aggressive population of Iron Reducing Bacteria (IRB) and Sulfate Reducing Bacteria (SRB).

The treatment to the cooling system consisted of a continuous feed of sodium hydroxide to neutralize the acidity of the water, along with a private label corrosion inhibitor and a continuous feed of hydrogen peroxide as a biocide.

In spite of the treatment, bacteria counts were high and corrosion to the mild steel pipe, as measured by coupons and a corrator probe, indicated corrosion levels above 375 µm per year (acceptable corrosion rates for mild steel are below 125 µm per year). The biofilm deposit on the condenser tubes was so aggressive that each one of the condensers needed to be back flushed every 4 to 6 days. Despite the back flush of the condensers, approach temperatures could not be brought under 2.3 ºC and temperatures would increase to over 8.3 ºC by the time the next back flush operation was performed. When condensers were opened for inspections, plant operators reported the odor coming from the condensers as “too strong to withstand”.

An HVCB system of 12 electrodes was installed in two groups of six into the CWS and CWR pipes to accomplish a 90 day performance demonstration.

The feed of sodium hydroxide and hydrogen peroxide was stopped and a controlled program of sodium hypochlorite was initiated along with a regime of chemical dose reduction corresponding to the measured reduction of the pelagic bacteria count.

The graphs in Figure 4 show the decrease in the approach temperatures following the installation of the HVCB system. Within four weeks the approach temperatures were below 2.78ºC without the back flush routine. The graphs in Figure 5 show the reduction in total aerobic bacteria in cfu/ml and the reduction of total ATP in Relative Light Units (RLU).

The data produced from total aerobic bacteria counts and ATP counts show a steady decline in biological activity (Figure 5). The graph shows two events during which large amounts of biomass were sloughed off the piping system. The second spike in biological activity correlates to the change in biocide program.

As the level of biological activity declined, an increase in corrosion levels was noticed. This was associated with the constant feed of Hydrogen Peroxide –a strong oxidizing product- so the biocide program was switched to employ sodium hypochlorite, a less aggressive biocide.

The water from the cooling system was replaced after the large amount of biomass had sloughed from the system. After replenishing the system with fresh water (May 8, 2000), condenser approach temperatures remained at or below 1.6ºC and bacteria counts remained at or below $1x10^5$ cfu/ml. Because of the characteristics of the unique composition of the make up water at this location, the corrosion inhibitor is still being used. However, corrosion rates for mild steel are now under 0.025 mm per year. After the system was flushed, tests for SRB and IRB showed an absence of both types of bacteria. Currently operators report that there are no odors coming from the condensers when they are opened for their annual inspections.

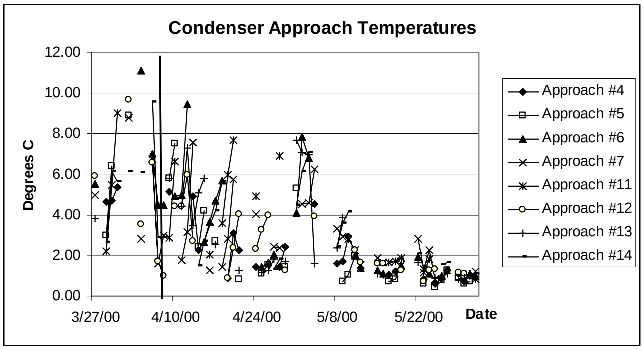

Figure 4: Condenser approach temperatures (ºC) in semiconductor facility, Camas WA.

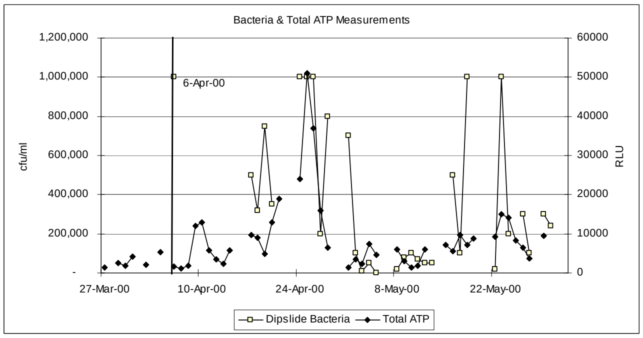

Figure 5: Total Aerobic Bacteria and total ATP in semiconductor plant in Camas WA.

The large amount of biofilm material sloughed from the piping and condensers was subsequently transported by flow to the cooling towers. So much residue collected in the tower basins that they were individually drained and cleaned by truck mounted sludge removal equipment.

Energy conservation analysis showed a decrease in the operating cost from $0.145 per kW down to $0.099 per kW. This reduction in cost was directly associated with improved heat transfer.

Update: In December of 2001 some of the facility engineers questioned the contribution of the HVCB to the performance of the cooling system. Believing that the improvement was related to the flushing of the system and the exchange of biocides, the HVCB system was turned off. Three weeks later biocide consumption had more than tripled, yet no chlorine residual could be measured. The HVCB system was returned to service and has since operated continuously.

The condensers have operated at design approach temperatures for seven years.

Biofouling control in a power utility steam plant piping system

Biofouling is a major concern in electric power generation facilities. The large volumes of water from rivers and lakes invite biofouling and biocorrosion of condenser cooling and auxiliary cooling systems.

Environmental regulation restricts the discharge of chlorine residuals and residuals of chlorinated compounds, limiting the application of historically successful treatment routines using chlorine or other biocidal chemicals.

In certain regions, both micro biofouling as well as macro biofouling are of primary concern. Several waterways in the United States have been invaded by the Zebra Mussel (*Dreissena polymorpha)*, a fresh water mollusk that was introduced by ballast water discharge of ships. In 2005, the research division of one of the largest electric power generation organizations in the U.S. began a research evaluation of HVCB technology with the objective of examining its potential as a control factor for biofouling and Zebra Mussel infestation. .

A large multiple-unit coal-fired station was chosen for the initial test installation. HVCB systems were installed in the piping of the auxiliary cooling water systems of two boilers, and two adjacent boilers were designated as control units. HVCB electrodes were placed into intake water strainers, and locally ahead of specific heat exchangers including oil, hydrogen, and boiler feed pump cooling. Each one of the four auxiliary cooling water systems of the test was equipped with carbon steel precision-machined coupons used for biofilm mass analysis.

The study began on April 24, 2005. During the study, coupons were removed and weighed after a 20 week exposure time to quantify the amount of total biomass deposited on the surface over the test period. Zebra Mussel Veliger/Larvae Plate counts were also performed to identify the larvae of mollusks and to count the number density with respect to the coupon area. Each coupon was measured 75mm x 25mm x 6.25mm for a total area of 5,000 mm^2. Table 2 presents the results of biomass accumulation in the coupons during the 20 week period between September 05, 2005 and February 05, 2006.

As seen from Table 2, a significantly lower amount of biomass was accumulated on the coupons installed in the treated lines. No activity related to Zebra Mussel accumulation was in evidence during this period and the Zebra Mussel study period was extended awaiting meaningful growth on control surfaces from which to draw conclusions.

The current study report sites in its conclusions:

- *"..a significant reduction in biofilm mass"*
- *"..potential Zebra Mussel as well as biofouling and biocorrosion control".*

Table 2: Biomass Accumulation On Carbon Steel Coupons At Power Plant River Water Trial (USA).

	Biomass weight (g)	
Sample Point	Treatment	Control
Strainer #2&3 -	0.6214	2.5715
Strainer #4 & 5	2.5931	6.2274
Boiler Feed Pumps 3A & B	0.1063	2.5715
Boiler Feed Pumps 9A & B	3.1553	9.258

Testing continues in the steam plant to complete the Zebra Mussel portion of the evaluation. The study is intended to run through two growth cycles of the mollusks. The research division of the power utility has decided to leave the coupons in place for a longer period of time to see if a difference may be observed in the accumulation of Zebra Mussels on the coupon surfaces. Results from the study will be published at a future date.

CONCLUSIONS

The examples presented provide reliable data which support the theory that High Voltage Capacitive Based systems can significantly reduce or eliminate biological deposits in cooling systems under several conditions ranging from mild to severely aggressive accumulation.

The detailed effect of HCVB technology on microorganisms and the fluid in which they exist is not fully revealed. However, observed results have a strong correlation with accepted theories explaining the three main phases of biofilm formation.

Conclusions from these studies may be listed as follows:

1. Application of HCVB technology alters the particle surface interaction forces that play a key role in the initial phase of biofilm formation. By changing surface charge densities, the physical forces relating to the change in bacteria from planktonic to sessile are interrupted.
2. The HVCB signal causes microorganisms to enter a stasis with reduced metabolic activity and reduced viability to form and maintain biofilm deposits.
3. The effect of HVCB reduces the surface tension of the fluid, enhances the transport of biocides into the biofilm matrix and enhances the efficiency of biocides.
4. The reduction in surface tension or hydrophobicity along with reduced metabolic activity contributes to increased hydration where biofilm deposits become flaccid and are subject to sloughing influenced by hydraulic forces.

Additional work is under way to more fully understand the capabilities of HVCB technology in removal and prevention of biofouling. Continuing studies include applications in reverse osmosis membrane fouling, metalworking fluids bio-stabilization, and continuing work in micro and macro biofouling and biocorrosion control.

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