

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.

This paper describes an electronic approach using High Voltage Capacitance Based technology (HVCB) to control biofouling in industrial heat exchangers, focusing upon biofilm removal and the prevention of biofilm formation.

Four different application case studies are presented in this paper in which the HVCB technology was used to control biofouling. The applications include an evaporative cooling wall in a greenhouse in Oracle, Arizona; a cooling tower-condenser application in Phoenix, Arizona (study performed by Arizona State University under a U.S. Department of Energy grant); a cooling tower system using reclaimed industrial waste water at a wafer facility in Camas, WA; and a piping system for a major utility plant (Tennessee Valley Authority – TVA) using river water.

All four locations showed a significant improvement in biofouling control when the HVCB system was applied. Depending on the conditions of the water at each location, biofouling was controlled, while achieving a complete elimination of biocides, or with a significant reduction in biocide feed.

From the data presented, 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

Fouling of industrial heat exchangers can be traced to two primary types of fouling: mineral fouling or scaling, and organic fouling or biofouling. The physical and chemical processes involved in mineral fouling and its control seem to be well understood, however, it appears that biofouling control presents a much greater challenge. 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-rhII*, 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

extracellular polymeric substances (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.

When a solution containing water, dissolved salts, and organic molecules is passed through a charged capacitor such as the one created by the HVCB system, numerous charge related effects take place. The HVCB technology creates an external non-uniform static electric field. This field causes polarization of almost every surface between solvent and dissolved or colloidal particles as long as the dielectric constants of the dissolved materials are different from the solvent. Polarized matter is accelerated in the electric field with a change in the arrangement of free ions around polarized matter as a result of a change in the hydrodynamic resistance in the fluid (Derjaguin et al 1980).

Apart from polarization and orientation of surfaces, two other important effects take place. Due to the distance between the charge centers of ion-pairs in macro-molecular structures, deformation, rotation and alignment will take place along the electric field line. At sufficient field strength structural-conformational changes can take place. It has been shown that collapsed charged polymers can be distorted due to induced motion of ions and alignment of fixed charge groups (Boroudjerdi et al. 2005). Secondly, an external electric field increases the dissociation of weak acids and base and promotes the separation of ion pairs into the corresponding free ions (Neumann 1986).

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.

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.

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).

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 resultant biofilm deposit was both thick and dense; and included mineral scaling, dust and pollen.

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).

The dense biofilm, its hydration and resultant fluidity were readily recognizable. 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.

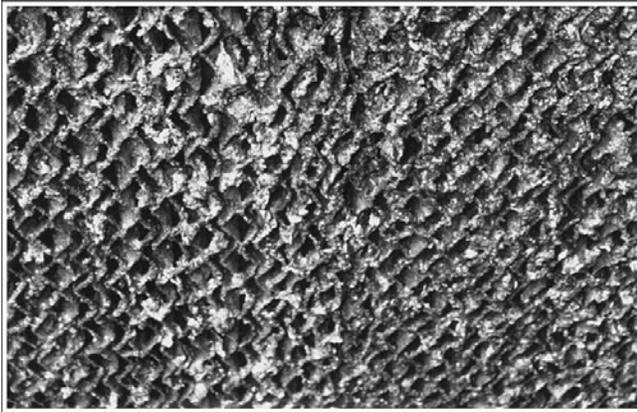


Figure 2: Internal face of CELdek® pad at Biosphere 2 campus analog greenhouses before the installation of HVCB system.

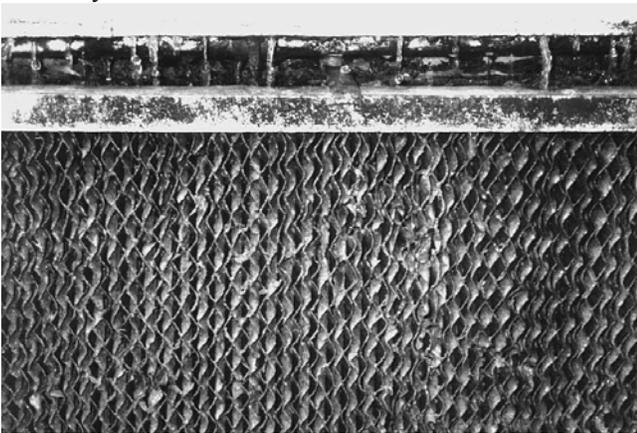


Figure 3: Internal face of CELdek® pad after six weeks of treatment with HVCB system after rinsing with a garden hose.

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.

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). HACH Dip slides were used during the test to measure the total aerobic bacteria counts. 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: Total Aerobic Bacteria 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 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.

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 contains eight 4600 kW chillers. Cooling of condenser water is 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.

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 °C and

temperatures would increase to over 8.3 °C 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.

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 2.78°C 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 1.6°C and bacteria counts remained at or below 1×10^5 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 25 μm 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.

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.

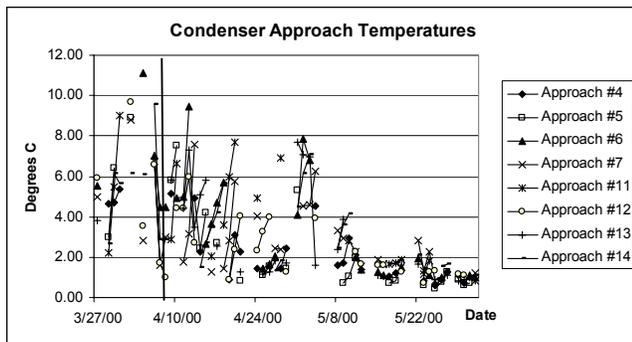


Figure 4: Condenser approach temperatures (°C) in semiconductor facility, Camas WA.

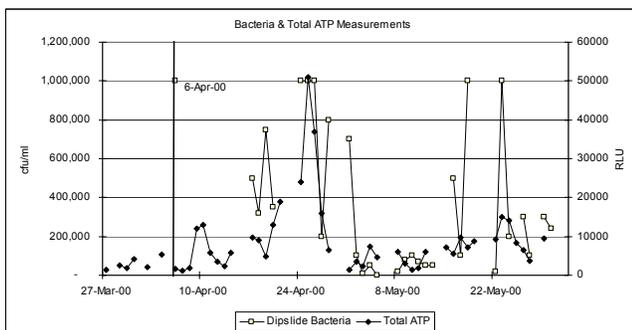


Figure 5: Total Aerobic Bacteria and total ATP in semiconductor plant in Camas WA.

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 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 mm². Table 2 presents the results of total biomass accumulation on 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).

Sample Point	Biomass weight (g)	
	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.

Additional work is under way to more fully understand the capabilities of HCVB 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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