Extremely Low Frequency Electromagnetism: An Effective Nonchemical Method for Control of Zebra Mussel Infestation

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Summary: The application of extremely low frequency (ELF) electromagnetic fields as an effective method for the control of zebra mussel (*Dreissena polymorpha*) infestation is described. Work focused on monitoring the survival of zebra mussels in which the water was irradiated by an ELF field. The efflux of Ca^{2+}, Mg^{2+} and other cations from zebra mussels exposed to ELF electromagnetism was used to gauge the efficacy of the method. Experiments examined the application of ELF electromagnetic fields under different environmental conditions: closed and flow-through systems. For a static systems, mortality of zebra mussels exposed to ELF EM irradiated water occurred as soon as 5 days. A four-fold increase in the dissolved calcium concentration in the bath water was observed. The rate of change in the calcium concentration points toward a process which affects the mussels' ability to assimilate calcium from water and also removes calcium from the shells and bodies of the zebra mussels. ELF EM is thought to increase the solubility of calcium carbonate by enhancing the ion-dipole bonding probability of water with dissolved salts. A qualitative model is presented to interpret experimental findings.

INTRODUCTION

Since introduction into the fresh waters of North America in ca. 1985, the zebra mussel has spread throughout the waterways of the northeast United States and now threatens to further extend its range to the inland rivers and lakes of the western states.[1,2] Zebra mussels can attach to variety of solid substrates and can foul water intake systems as a consequence. Water intake facilities are extremely vulnerable if they draw from water sources that are infested with *D. polymorpha.*[3,4]

Because of the impracticality of manual removal, chemical methods are commonly employed to control infestation. Chemical treatments largely involve strong oxidants such as chlorine, bromine, and ozone.[5] Chlorination is perhaps the most widely used chemical abatement strategy and although effective, chlorinated compounds are not without adverse repercussions.[6,7] For example, prolonged use and exposure to chlorine can damage a facility's infrastructure. Additionally, chlorine has been shown to be lethal to nontarget fish and invertebrates.[7] Bromine although often believed to be less toxic than chlorine has actually been shown to be more toxic to nontarget species.[7]

Because of environmental concerns particularly on native species, [5-7] discharge of toxic materials into the environment and requisite compliance with Federal and Local regulations remain a daunting problem regarding chemical control strategies. Chemical methods are subject to continued scrutiny and ecological concerns which further limit their use.[5, 8] Moreover, even after chemical treatments, zebra mussel colonization may reoccur and the treated area, pipeline, or intake system must be retreated.[3, 8-10] Ultimately, effective nonchemical strategies are needed to control zebra mussel infestations.

The zebra mussel is built for survival. In spite of several significant physiological shortcomings, the mussel flourishes in most fresh-water environments. *Dreissena polymorpha* have an inefficient digestive system and unlike other molluska, zebra mussels lack the ability to store essential minerals such as calcium.[11] The zebra mussel overcomes these shortcoming by its prolific ability to filter feed and thus continually assimilating nutrients. However, these shortcomings may indeed be the Achilles heal of the zebra mussel. *How so?* What if a control method that prevents the mussel from acquiring essential nutrients such as calcium could be developed? The mussels would not be able to grow or maintain normal life functions. Moreover, eggs and veligers would not be able to mature because they could not acquire the calcium needed to develop their shells: they would not be able to reach adulthood nor to reproduce.[12]

In this paper, we describe the results of the use of extremely low frequency (ELF) electromagnetism (EM) as a method for the control of zebra mussel infestation. ELF electromagnetism was considered as a viable control method for several reasons. First, this method is economical especially when measured against the cost and regulatory concerns of chemical treatments. Additionally, ELF sources can be permanently installed on commercial or municipal water-intake systems, requiring minimal maintenance once in operation. Additionally, ELF EM fields represent an environmentally-safe nonchemical method of control.

The application of electromagnetism on biological systems is a rapidly growing area of biophysics and bioengineering.[13-17] However, the use of ELF EM to control biofouling organisms such as *Dreissena* has not been explored. Furthermore, the biological effects of electromagnetic field are not well understood due the complexity and breadth of biosystems, environmental conditions and the diversity of electromagnetic permutations.[13, 16] The objective of this work is to determine the effects of extremely low frequency electromagnetism on zebra mussels, particularly on how ELF fields affect the calcium movement of the mussels, and to describe the underpinnings and origins of the effects.

Extremely low frequency electromagnetism refers to electromagnetic energy with frequencies $\nu < 300$ Hz and wavelengths $\lambda > 1 \times 10^6$ m. ELF is a nonionizing form of electromagnetism because of its relatively low energy and slowly time-varying field. For example, the energy output of ELF radiation is less than 1 μJ/mol which is considered too low to even induce localized temperature variations: the interaction of an imposed ELF signal is less than the Boltzmann thermal energy.[16]

The biological effects of ELF radiation are well documented.[13] ELF radiation lowers the energy barrier for cellular ion transport between the high-dielectric aqueous-phase and low-dielectric lipid-containing barriers.[15] Ostensibly, the activation energy associated with the interactions of polar and ionic substances and nonpolar lipophilic tissue are attenuated by ELF EM. This will influence the ion influx and efflux for biological systems. The bonding interactions of ions with cellular membranes and tissue which will consequently influence normal cellular function are also affected by ELF radiation. For example, ELF EM has been shown to affect ion binding to cellular-membrane macromolecules, to influence transmembrane ion transport and to alter membrane signaling events.[14] Although the initial physical mechanism of interaction of ELF radiation with living tissue is the induction of electrical currents, the triggering of biological effects by ELF fields involves subsequent electrochemical processes that influence cellular function.[14]

MATERIALS AND METHODS.

Animals. Zebra mussels were collected from Lake Michigan near Hammond, Indiana (August - September) or from the Huron River in Ann Arbor, Michigan (January). Animals were acclimated in lake water (LW) for at least three days before use in experiments. Mussels were stored in aerated lake water at 20 ± 2°C. The mussels obtained food from the lake water which was changed in the stock tank every 3-5 days. Zebra mussels survived 90+ days with less than 1% mortality in our laboratory. To avoid contamination of local water systems, all water samples and containers were treated with 1% bleach solutions for 24 hr before being discarded.

Ion Assays. Ion assays were performed by using a Perkin-Elmer 460 atomic absorption spectrophotometer (AAS). For optimal precision, an oxidant rich air/acetylene flame was used for all analyses.[18] For each assay, two 20 mL samples were taken from both the test and control tanks. Samples were filtered through a 0.45μ filter pad (Micron Separations) to remove undissolved solids. Accordingly, results reported herein represent the amount of dissolved substance and total mass loss resulting from exposure to ELF EM may actually be greater. All dilutions and sample preparations were made by using volumetric glassware; associated errors for sample preparation are less than 0.15 %. Samples were prepared to contain 5.0 % (v/v) HCl, and 0.25 % (w/v) lanthanum to optimize spectral sensitivity of the alkaline earth metals.[18] Primary standards were prepared according to literature procedures. All reagents used were analytical quality. Typically, 50 absorbance measurements were recorded for each sample and an average value (std. dev. < 0.5 %) was used to determine ion concentrations. Concentrations were derived from a 4-point Beer-Lambert calibration curve. Correlation coefficients (R) for calibrations are as follows: Ca^{2+}, R = 0.999; Mg^{2+}, R = 0.995; Na^{+}, R = 0.999; K^{+}, R = 0.995. Ion concentrations are accurate to within ± 2 ppm (95% confidence).

Closed-System Experiments. Lake water used for all closed (static) studies was untreated. In a typical experiment, two equal populations of mussels taken from the stock tank were placed in equivalent volumes (4 - 6 L) of lake water. Mussel densities ranged from 40-70 animals/L. A submersible pump and the ELF source were fitted to one tank (test sample; see Figure 1). Dissolved O_2

levels (Sentry) were maintained at greater than 7 ppm. The flow rate through the ELF source was ca. 4 L/min. Water samples were periodically taken and were prepared and assayed for dissolved ions as described earlier. The pH (Fisher Model S60008) ranged between 7.8 and 8.0 for both test and control samples; no significant deviation in pH between test and control samples was observed. Because the water of test and control was aerated, water loss due to evaporation could not be prevented. Final sample concentrations were corrected to account for concentration effects due to evaporation and sampling.

Flow-Through Studies. Nonchlorinated well water with a pH range of 7.0 to 7.5 was used. Dissolved oxygen levels were greater than 7 ppm. Water flowed through an in-line ELF EM source connected to the well-water supply and drained out through a screened pipe mounted in the tank. For the test study, ca. 2000 mussels were placed in a 50-gallon tank. Water flow was ca. 80-100 gallons/hr; the entire volume of water in the tank was replaced on average every 30 minutes. Controls were bathed in well water and were maintained under the same laboratory conditions. Water samples were taken every 7 days and assayed for calcium by AAS.

Nonliving Systems. Closed-system experiments on zebra mussel shells were conducted in municipal tap water ($[Ca^{2+}]$ = 11 ppm) and deionized water. Cleaned shells were stirred in deionized water for 24 hours to remove residual tissue. For each study, 193.00 grams of shells were dried, weighed and placed in 3.0 L of water. A pump circulated water through an ELF EM source for the test sample (Figure 1). The control was magnetically stirred to provide circulation equal to that of the test sample. Water samples were taken periodically during the course of each study. Water samples, prepared as described earlier, were assayed for calcium and magnesium. The pH (7.7 - 7.8) for the test and control systems varied insignificantly throughout the study. Gravimetric analysis of the shells was preformed according to standard procedures.[18]

Marble ($CaCO_3$) was thoroughly rinsed to remove dust and contaminants. Experiments were conducted in deionized water and municipal tap water. For each experiment, 530 g of marble chips were placed in 3.0 L of water. The experimental set-up was similar to that described for other closed-system studies (Figure 1). Samples periodically taken throughout the study were prepared and assayed as described above.

RESULTS AND DISCUSSION

Static Systems.

Studies were conducted on closed systems in which the bath water of a sample of ca. 200 - 400 animals in lake water[19, 20] (LW; from Lake Michigan in East Chicago, Indiana) was irradiated by an electromagnetic field. The experimental design for the static systems is shown in Figure 1. In these studies, 100% mortality occurred after 15 days depending on the volume of water and the number of animals. In one study, the calcium increased from 28 ppm (the natural Ca^{2+} concentration of the lake water) to 116 ppm. The controls exhibited a less significant [Ca^{2+}] change. Average results of several static studies are given in Figure 2. For the closed systems, ion concentrations in excess of LW result from a negative ion flux which stems from loss of calcium from the tissue and shell of the zebra mussels resulting in animal mortality.

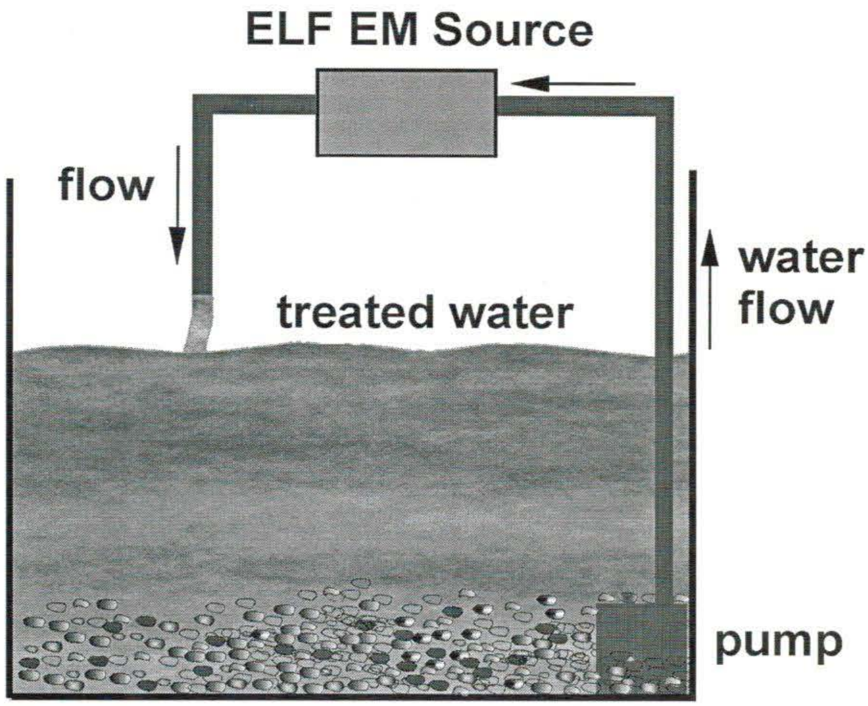

Figure 1. Side view of the experimental design for a closed system used to determine the effects of extremely low frequency electromagnetism on *Dreissena polymorpha.* Water pumped through the ELF EM source is irradiate. The mussels are continually bathed in the treated water.

Because of their ubiquity, concentrations of sodium, potassium and magnesium were also monitored. Magnesium (and the divalent cations Sr^{2+} and Ba^{2+}) present in the extrapallial fluid influence shell formation and integrity of the $CaCO_3$ crystal lattice.[21] To maintain normal physiological function, *Dreissena* may attempt to assimilate (influx) other divalent cations to balance the excessive calcium efflux. Alternatively, effluxes of Mg^{2+}, Sr^{2+} and Ba^{2+} and the alkali cations may be evident if ELF EM influences all ionic movement through body and mantle epithelium layers. Magnesium concentrations for test samples increased from 18 ppm to 22 ppm. The control [Mg^{2+}] did not change. Significant concentration changes of the alkali cations were not observed. Sodium and potassium concentrations were 7 - 8 ppm and 2 - 3 ppm, respectively, for both test and control samples and these values most likely reflect the natural abundance of the alkali cations in Lake Michigan.

Table 1 provides radius-charge (r/q) ratios and hydration numbers for some biochemically important ions. Ions with similar r/q values generally have associated biofunctions.[22] The r/q values of Sr^{2+} and Ba^{2+} are similar to Ca^{2+} and these ions may also be important in the maintenance and structure of the shell. Future work will explore divalent other cations and their relationship to calcium.

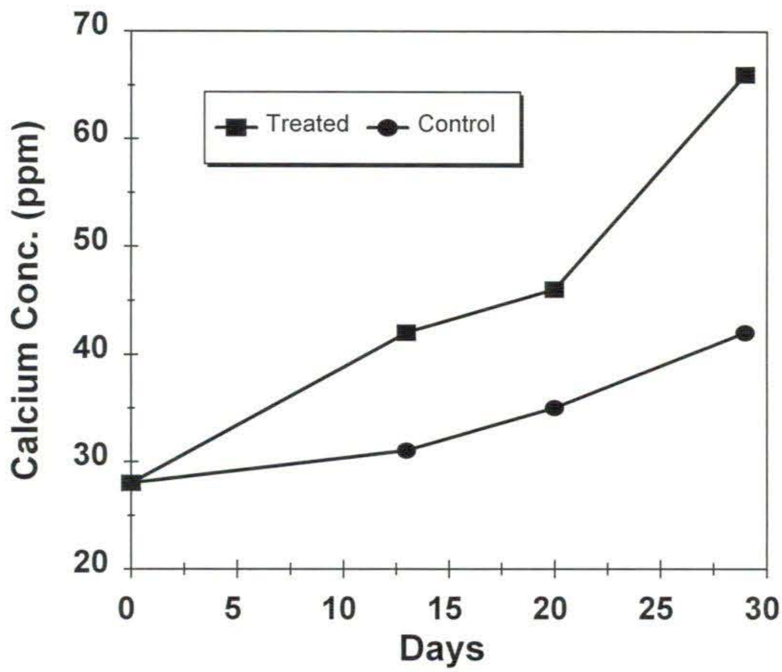

Figure 2. Calcium concentration versus time of exposure for static test and control studies. Data are average values from three different experiments. Calcium concentrations are accurate to within ± 1 ppm.

A detailed study of ion concentration versus exposure time was performed (Figure 3) which entailed using a larger mussel population to magnify concentration changes and more frequent sampling. The stress level of the animals was also closely monitored. The control population (Figure 3) showed the expected behavior for a closed system: mussels abstracted the calcium demonstrating normal development and maintenance and consequently dissolved calcium concentrations decreased.[19] An increase was observed after a minimum of 25 ppm was reached.

Table 1. Characteristics of Biochemically Important Alkali and Alkaline Metal Cations

Ion	radius (Å)	r/q[a]	Rel r/q[b]	O/q[c]	Hydration No.[d]
Na^+	0.99	0.99	1.98	12.31	13
K^+	1.38	1.38	2.76	22.23	7
Mg^{2+}	0.66	0.33	0.66	2.74	36
Ca^{2+}	1.00	0.50	1.00	6.16	29
Sr^{2+}	1.12	0.56	1.12	7.88	29
Ba^{2+}	1.34	0.67	1.34	1.28	28

[a]Ratio of ionic radius/charge (Å/elemental charge) for six-coordinate ions.[21] [b]Relative r/q ratio (Ca^{2+} = 1). [c]Ion surface area/charge ratio ($Å^2$/elemental charge). [d]Number of water molecules restrained by the cation (1st and 2nd solvent spheres) in dilute aqueous solution as measured from transference data.[23]

Calcium tolerances for *Dreissena polymorpha* are reported to be 25-26 ppm for maintenance and shell growth.[20] The test sample showed a marked increase in dissolved calcium levels. Lethal tolerance of 50% (LT_{50}) was observed at 13 days and over 90% mortality was observed after 21 days for a population of 420 adults in 6.0 L of LW. During the same period, [Mg^{2+}] increased from 16 to 20 ppm. Because of the mussel density (70 animal/L), the rate of calcium efflux was greater than previously observed (Figure 2). As the increased in dissolved calcium parallels mortality, it is clear that low frequency electromagnetism induces an negative response in the mussels as to inhibit calcium uptake and the triggered physiological reaction ultimately results in death.

Response to ELF EM exhibited by *Dreissena polymorpha* was, in general, manifested after 24 hr of exposure (Figure 3) even though the mussels were acclimated to lab conditions for several days prior to experiment. The degrees of stress were characterized by previously described criteria which include the width of the shell opening, the degree of which the siphons extend past the shell margin, and response to external stimuli.[19] After six days, the test mussels were moderately stressed: their siphons were completely retracted. The mussels never attached to the tank walls, another indication of environmental stress.[19] Up to the time of 100% mortality, the mussels were moderately to severely stressed and most animals responded only to direct prodding. The controls were generally unstressed manifested by fully extended siphons and siphon tentacles for nearly the duration of the studies.

The shells of the mussels exposed to ELF EM were very brittle and dull in appearance relative to the controls. The shells could easily be broken by hand indicating severe compromise of structural integrity. Shell wear was evident at the edges and the along the mid-dorsoventral axis where the shell is widest.[24] The periostracum was loosened inferring that the shell underneath the matrix had dissolved. A bleaching of the shells was also observed however the reasons for this behavior are not clear. Similar effects were not observed for the control samples: no loss of shell structural integrity was observed.

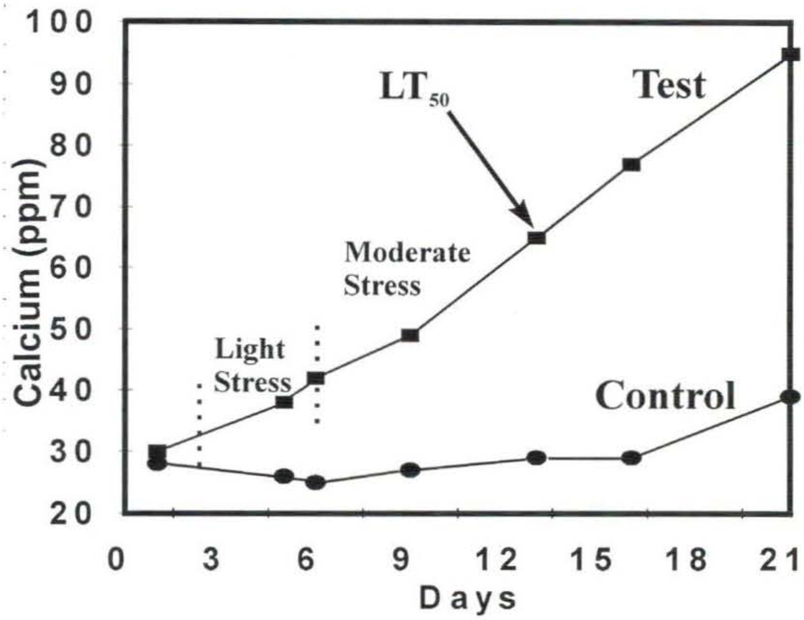

Figure 3. Change in dissolved calcium concentrations (ppm) over time for detailed static-system experiment. Environmental stress levels of zebra mussels bathed in irradiated water are indicated on graph. See text for details.

For *Dreissena,* exposure to ELF irradiated water has the effect of increasing the Ca^{2+} efflux (and to some extent Mg^{2+}) at a rate more rapid than ion influx as inferred from the sharp rise in dissolved calcium (Figures 2 and 3). These divalent cations are key to maintaining membrane permeability and integrity,[12] and a negative ion flux will have an adverse response on survival. During post-moult calcification in the crustacean *Callinectes sapidus*, a net influx of calcium exists; however, if the Ca^{2+}(aq) level drops below a threshold (ca. 100 ppm for *C. sapidus*), the ion flux reverses to a net calcium loss.[25] ELF radiation is envisaged to induced an analogous response in *Dreissena* by blocking Ca^{2+} influx channels. The large post-moult calcium demand of *C. sapidus* is met in part by high dissolved [Ca^{2+}]. Large calcium concentrations may be needed to overcome the effects of electromagnetism as discussed next.

Flow-Through Studies.

Results of our flow-through studies are to date still incomplete and we are presently conducting additional studies. Data support that ELF EM is effective for flow-through systems. In a preliminary study, after 28 days of exposure to ELF irradiated water, a sample of ca. 2000 mussels in a flow-through system showed significant stress and shell deterioration. Loss of shell integrity was evidenced in that periostracum of the mussels was loosened and the shells were very brittle. After 7 days of exposure the shells of the mussels were slightly closed and their siphons retracted indicating environmental stress; however the animals never did reach the stress levels observed in the static-system investigations. The mortality level of the test sample was negligible relative to the control.

We point to several factors which account for the relatively slow response, in particular the low mortality rate, exhibited in our preliminary flow-through experiment. i) The calcium content in well water used for the flow-through study was ca. four times larger than the lake water used in the closed systems. The mechanisms induced by extremely low frequency electromagnetism may still have been operative, but because of the relatively large calcium levels, the animals were capable of assimilating calcium. Perhaps concentration limitation exist for the ELF EM process. ii) The electrical current used may have been too low to accommodate the volume of the sample *and* the large calcium levels. However, ELF waves can be modulated to change their amplitude and frequency. The power output can be changed by varying the electrical current: an increase in current should increase the effectiveness of the ELF EM process. iii) A kinetic factor may exist. For example, calcium uptake may have been affected but the time frame of the experiment was too brief to observe significant impacts in mortality.

During the study, calcium concentrations were monitored. Although an increase in calcium was not expected as observed in the closed system, an increase was nevertheless observed (Table 2). The ratio of test/control concentrations was greater than unity which infers that some calcium loss occurred. The difference may result from the time lag in the flow-through study between water inflow and discharge. The water flow was 1.5 gallon /min, and for a 50-gallon tank, water will reside in the system for ~30 minutes before discharge. Thus, a slight increase above the normal calcium level of the well water for the test sample is not surprising. The concentration plateaus because the water in the system is being replaced achieving a dynamic equilibrium in Ca^{2+}.

Table 2. Calcium Concentrations (ppm) for a Flow-Through Experiment.

Days	Test	Control	Ratio[a]
1	120	120	1.00
7	126	117	1.11
14	131	112	1.16
21	119	116	1.03
28	115	98	1.17

[a]Ratio of Test/Control calcium concentrations.

Nonliving and Inorganic Systems: Shells, Marble and Other Materials.

The effects of ELF EM fields on solid mussel shells and crystalline calcite were undertaken to reveal the nature of ELF radiation on nonliving and purely inorganic substances and to illuminate whether the solubility of $CaCO_3$ is indeed enhanced in the treated water or if external stress and modified cellular activity is responsible for the large calcium efflux. In this way, differentiation between effects of ELF radiation of living mollusks and on their inorganic components, specifically the shells, could be established.

After 35 days in ELF EM irradiated water, the calcium concentration for shell samples varied insignificantly from the calcium levels of the controls regardless of water type. From studies in deionized water, the calcium concentration rose from 0 to 28 ppm for both test and control studies. This equates to dissolution of 84 mg of shell or only 0.044 % of the total mass of the shell samples. This observation points to two possible scenarios. First, the rate of ELF EM induced dissolution of $CaCO_3$ for a nonliving system may be slow such that the elapsed time was not sufficient to measure a discernible change in the calcium levels. Alternatively, ELF may have little effect on nonliving systems; however this is not true since similar systems are used to descale water intakes. Nevertheless, the results support the premise that ELF EM significantly affects physiological processes of the animals. It is also conceivable that ELF electromagnetism induces a response that actually promotes shell dissolution.

Gravimetric analysis of the shells was complicated by mass balance problems due to perhaps to incomplete ashing. Preliminary results for the test and control shell were similar: samples lost 45.5 ± 0.1 % of their mass during ashing and spectroscopic measurements indicate the shells contain 34.7 ± 3.3% calcium and 0.6 ± 0.1 % magnesium.

Qualitatively, the results of the studies of extremely low frequency electromagnetism on marble are not much different than those of the shells. Dissolved calcium levels were equivalent for test and control studies regardless of the water type. The extent of dissolution was much less than for the shells which is not unexpected since the shell is an amorphous form of $CaCO_3$,[19] while marble is crystalline calcite.[29] Only 0.014 % dissociation was measured both test and control marble samples in tap and deionized water after 35 days. It seems evident that ELF EM has little kinetic or thermodynamic effect on the dissolution of marble. Again this underscores a biophysical connection between ELF electromagnetic radiation and cation fluxes for zebra mussels.

Regarding other inorganic systems, in particular cement, ELF electromagnetism should have no effect on the dissolution of cement. Cement contains calcium aluminates and silicates (sands) which are extremely stable.[26, 27] The thermodynamic difficulty associated with dissociation of calcium aluminates and silicates are much greater than that of marble. Moreover, cements generally show outstanding resistance to sea water, brines, and mineral acids.[27]

Impacts of Acid-Base Chemistry.

Carbonate in the shell derives from the CO_2/HCO_3^- pool within the mantle.[21] Inward transport of calcium and bicarbonate must be electrically balance by an outward flow of H^+ (eq 1). Accordingly, pH variations may be manifested in the test samples and ELF fields may significantly affect acid-base chemistry associated with the mineral flux of zebra mussels.[13, 16, 17]

$$Ca^{2+} + HCO_3^- \longrightarrow CaCO_3 \tag{1}$$

The solubility of $CaCO_3$ is strongly pH dependent as shown in equations 2 and 3, for example. There exist numerous other acid-base equilibrium reactions that participate in the dissolution of $CaCO_3$.[27] From net equation 4, it is evident that the calcium concentration will increase with decreasing pH and this will have a negative impact on mollusks:[28] acid-base balance is critical for ion uptake.[25] Evidence of pH changes as a result of exposure of *D. polymorpha* to irradiated

$$CaCO_3 = Ca^{2+} + CO_3^{2-} \quad K_{eq} = 4.96 \times 10^{-9} \tag{2}$$

$$CO_3^{2-} + H_2O = OH^- + HCO_3^- \quad K_{eq} = 2.08 \times 10^{-4} \tag{3}$$

$$CaCO_3 + H_2O = Ca^{2+} + HCO_3^- + OH^- \quad K_{eq,\,net} = 1.03 \times 10^{-12} \tag{4}$$

water was monitored over time (until 100% mortality is observed) for a static system however, bulk changes were not observed an the pH remained fairly constant at 7.8 - 8.0 during all investigations. However, localized pH changes or pH changes in the blood may be occur and it is conceivable these pH changes also contribute to the calcium increase. For *Dreissena,* calcium loss may exceed ion influx when the pH level is ca. 6.9 or less.[12] Moreover, *Dreissena* are quite sensitive to acid-base variations relative to other mollusks[12] and large or anomalous variations in pH may indicate that electromagnetism alters the H-pump mechanism associated with calcium carbonate uptake.[21]

Qualitative Description of ELF Electromagnetism.

The experimental geometry (Figure 1) shows that the circulating water couples the zebra mussel population to the ELF cell. Thus, the question to be answered is: *what effect does the ELF EM have on the water and the ionic species dissolve therein?* The ELF source generates a rectified sinusoidal electric field when driven by a rectified AC signal. The low frequency of this signal (60 Hz) means that the water will react with a relative permittivity that is nearer in value to that which it experiences under electrostatic fields ($\varepsilon = 81$) rather than that for the other extreme of optical frequencies ($\varepsilon =$

1.8).[29] The calcium ion, hydrated by several layers of water, will polarize under such a slowly-varying field in what can be called a diffuse dipole.

These diffuse dipoles will interact with a dipole-dipole interactions which have the effect of increasing the calcium concentration in the outflow water of the ELF source. Although the concentration increase is transient, given the thermal motions inherent in water, any such local increase will increase the effective concentration gradient that pulls calcium away from the mussel population in another section of the system.

This mechanism, though conjectural, is in keeping with the experimental evidence. Increased calcium concentrations require an effective increase in the concentration gradient near the shells. Given that the ELF source is the only device linked to the mussels, it must be that ELF EM increases the calcium concentration in the water near the ELF source.

CONCLUSIONS

Experiments conducted in this investigation reveal that ELF electromagnetism induces a negative response in zebra mussels as to be fatal. Mussels in a closed system exhibit a marked loss in calcium which ultimately results in 100 % mortality. The origins for this behavior lie in the interactions of water and calcium in an electromagnetic field. Because the calcium demand of veligers is greater than that of the adults, the effect of ELF is expected to be even greater; veligers, unable to acquire calcium, will not be able to develop shells and to mature to adulthood. Preliminary data also demonstrate that ELF EM is effective on open and once-through systems.

The implications of this study strongly point toward the use of ELF EM as a viable nonchemical control method for zebra mussels in a variety of environments. Applications include supply intakes that draw from infested sources, processing lines, canal locks operating in infested and even rivers. Low frequency electromagnetism is envisioned to have applications wherever water flow exists.

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