

An Experiment in Preventing Zebra Mussel Settlement Using Electro-Expulsive Separation Technology

Nathan D. Mulherin and Andrew C. Miller

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ABSTRACT

The authors attempted to evaluate the effectiveness of an electromechanical method to prevent nuisance infestation by aquatic zebra mussels. A prototype “electro-expulsive separation” system was constructed, installed at a field site, and monitored during the 2002 summer and fall seasons. Data collected during the program were limited by system failures and an unexplained general lack of mussel infestation at the test site. However, such a system is highly efficient to operate, and may be effective in controlling mussel infestation. Data on system operational cost are presented, but additional testing is needed to verify system effectiveness. Because of lack of funding, follow-on work could not be conducted at this time.

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PREFACE

This report was prepared by Nathan D. Mulherin, Research Physical Scientist, U.S. Army Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire, and by Dr. Andrew C. Miller, Research Limnologist, U.S. Army Engineer Research and Development Center, Environmental Laboratory, Vicksburg, Mississippi.

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The authors are indebted to Dr. Steven Daly and Robert Haehnel for their timely technical reviews of this report. Lon Meixner, Lockmaster at Lock and Dam 4, provided the field site and allowed his staff to assist in the experimental setup and monitoring. James Noren, Hydrologist at the USACE–St. Paul District in Minneapolis, helped monitor and photodocument the experiment, and ensured the timely shipment of field samples. Roy Wiley and Michael Vasquez of Ice Management Systems, Inc., Temecula, California, designed, constructed, and installed the EESS at Lock and Dam 4. Robert Haehnel, Mechanical Engineer at CRREL, provided hardware, software, and crucial assistance for measuring the system's power consumption.

The Commander of the Engineer Research and Development Center is Colonel James R. Rowan, EN. The Director is Dr. James R. Houston.

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1 BACKGROUND

Dreissena polymorpha, or zebra mussels, are non-indigenous, biofouling bivalves of European origin that were introduced into North American waters from discharged ballast water or after dislodging from the hulls of transoceanic ships. They were first discovered in Lake St. Clair, on the U.S.–Canadian border near Detroit, Michigan, in the mid to late 1980s, and now, less than two decades later, proliferate in the fresh waters of at least 20 northern U.S. states and the Canadian Provinces of Ontario and Quebec. They multiply rapidly with water temperatures in the range of 57–61 °F (14–16 °C), and find optimal growing conditions (up to 50 mm [2 in.] in size) in waters ranging from 63 to 77 °F (17–25 °C). Their reproductive capacity, their altering effect on the ecosystem, and their negative economic impact are enormous. It is reported that a power plant in Michigan experienced colonization densities of 700,000 per m² (FCSC 2002). Their colonies can reduce by two-thirds the flow capacity of valves and intake pipes for water supply and treatment facilities and hydroelectric, nuclear power, and manufacturing plants. They are filter feeders, each adult capable of filtering a liter of water per day, in the process stripping as much as 80% of the zoo- and phytoplankton from the water they ingest. It is estimated that their population filters the entire volume of Lake Erie’s western basin every week (UWSGI 2001).

Other control techniques

Methods of zebra mussel control that have been attempted in the past with variable success (FCSC 2002) include

- Manual removal (pigging, high pressure wash)
- Filters, screens

- Dewatering/desiccation (freezing, heated air)
- Thermal (steam injection, hot water > 32 °C)
- Acoustical vibration
- Electrical current shocking
- Ultraviolet irradiation
- Coatings: toxic (copper, zinc) and non-toxic (silicone-based)
- Toxic constructed piping (copper, brass, galvanized metals)
- Oxidizing and non-oxidizing chemical molluscicides (chlorine, chlorine dioxide)
- CO₂ injection
- Anoxia/hypoxia
- Biological (predators, parasites, diseases)

Some of these methods are labor-intensive or produce short-lived results. Others create undesirable environmental conditions that preclude their use in certain situations. Our objective in the present work was to study the effectiveness of preventing zebra mussel attachment to the submerged portions of navigation and hydroelectric facilities using “electro-expulsive separation” (EES) technology. Its perceived advantages over current methods include 1) low operational cost, 2) localized, physical protection rather than more widely invasive chemical, biological, thermal, or electrical protection, and 3) labor-free, auto-operability.

EES is NASA-patented technology that was originally envisioned as a means for removing in-flight icing from aircraft (NASA 1998). Its simple, underlying principle lies in the repulsive force that is induced between magnetized conductors that have their poles aligned. In this case, the conductors are parallel strips of copper ribbon sandwiched between flexible membranes or sheet material. When electrically charged with a burst of current from a capacitor, the repelling force and its acceleration is proportional to the voltage difference between the sets of conductors. The capacitor allows the buildup and instantaneous discharge of an electromotive force that is transferred to the system’s outer sheet material. The acceleration of the induced pressure wave is capable of shattering ice (brittle at this rate of strain) that is frozen to the flexible outer material. The effectiveness of an EES prototype to remove ice buildup from a submersible panel was first demonstrated at ERDC-CRREL in September 2000 (Haehnel et al. 2002).

It is important to distinguish this type of electromechanical system from electrical shocking systems that are used for zebra mussel control. The EES system's surface flexural acceleration can be extremely high while keeping its extent of flexure (surface travel distance) relatively low, and still induce tremendous mechanical force into bonded ice or undesirable biotic colonies. Therefore, biotic species, which may be in close or physical contact but not actually bonded with an EES-protected surface, are unlikely to be affected by its action.

EES panels can be manufactured in a variety of shapes and sizes to accommodate a range of surfaces needing protection. Our lock wall application allowed us to use a simple, flat-panel configuration. The system was powered from a 120-VAC source and, according to the licensed manufacturer*, its capacitor charges to approximately 500 V and discharges to the panel in a 4-millisecond burst when activated. This results in a peak mechanical flexure of the panel's outer skin of approximately 3 mm, and produces an effective pressure of 60–80 psi. During our laboratory testing, we confirmed the manufacturer's claim that it was painless to touch while being fired, even though it is definitely startling due to its loud and sudden report.

The manufacturer states that the system is incapable of firing if water leaks into the panel and contacts both sets of copper conductors, due to the fact that a perfect ground becomes established, thereby containing the current within an isolated step-up transformer in the power supply box, which is atop the lock wall and above water, and eliminates current leakage into the surrounding water medium. The system is, therefore, safeguarded against accidental electrical shocking.

Its power consumption was said to be 600 W for each 15-sec charging peak, and 5 W-sec while in standby mode (while awaiting signal to fire). In our laboratory and field tests, we measured the system's power consumption using a recording wattmeter, and showed that our 1.27-m² panel used approximately 880 W (700 W/m²) during each 10-sec charging cycle prior to firing. Figure 1 shows the prototype panel with laboratory-grown ice, and then after having been fired only four times. Assuming that four bursts are needed to completely clear the panel of ice, the total energy required was 21 kJ/m² or 0.0058 kWh/m². This is an extremely cost-effective method of ice removal. That is, if the cost of power is \$0.10 per kilowatt hour, then a 1-m²-square panel could be fired 68 times, or totally cleared of ice 17 times, for a penny's worth of electricity. Even though this system is proven to remove ice for low operational cost, it is unknown how well it might prevent zebra mussel settlement.

*Ice Management Systems, Inc., Temecula, California.



a. Ice formed on the EES panel (black).



b. Panel clear of ice (except for the white patch of frost near left center) after only four firing cycles.

Figure 1. Laboratory EES ice removal experiment.

Based on successful results from our laboratory and field deicing experiments, we proposed that the EES mechanical shock wave may physically propel the mussel from the surface being protected, or that it may induce the mussel to find a more hospitable environment. Furthermore, we proposed that the technology might provide a safe, low-cost, low-maintenance, environmentally benign solution to prevent fouling and clogging by zebra mussels.

2 EXPERIMENTAL SETUP

Our experiment consisted of placing two test panels in the field at a location that experiences seasonal zebra mussel infestation. One was an EESS prototype panel with automatic firing capability (hereinafter referred to as “the live panel”). The second panel, a “control panel,” was similar in size, shape, and material construction, but without EES capability, thereby acting as an experimental control. The panels were monitored and photographed on a regular basis throughout the summer of 2002 to record whether the mussels had colonized them. If the bivalves attached to the control unit but not to the live panel, then we could assume that the electromechanical action was successful in preventing colonization. The site chosen for our field test was USACE Lock and Dam 4, located on the Mississippi River at Alma, Wisconsin, approximately 128 km (80 statute mi) south-east of Minneapolis, Minnesota (Fig. 2).

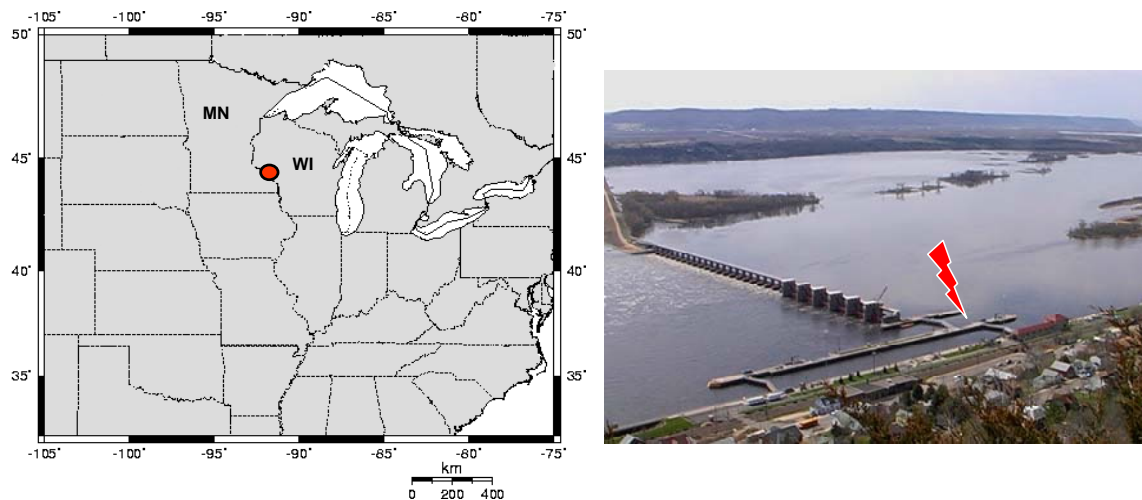


Figure 2. Site of zebra mussel control field experiment on the Mississippi River between Minnesota and Wisconsin (red circle on map), at U.S. Army Corps of Engineers Lock and Dam No. 4. Red arrow on photo shows field experiment location.

The live panel consisted of 0.515-in.-wide (13-mm) copper conductors sealed between two sheets of 0.125-in.-thick (3.2-mm) fiberglass, with another sheet of 0.6-in.-thick (1.5-mm) ultra-high-molecular-weight polyethylene (UHMWPE) adhered to the front surface. This composite sandwich was then bolted to a 1-in.-thick (25-mm) aluminum backing plate for stiffness and to ensure that the mechanical energy was directed preferentially toward the front surface. In total,

the live panel measured 3 ft (0.91 m) square and was 1.8 in. (45 mm) thick. It was sealed to prevent the energized ribbons from contacting the surrounding water. For added safety, electrical isolation was guaranteed through the use of a sensor that tripped a circuit-interrupt condition when moisture was detected inside the panel.

The control panel consisted of a single sheet of 0.125-in.-thick (3.2-mm) fiberglass, with another sheet of 0.6-in.-thick (1.5-mm) UHMWPE adhered to its front surface. This assembly also measured 3 ft square. Since it wasn't backed with aluminum, cylindrical steel weights were welded to a bar, which in turn was bolted to the bottom of the control panel to add mass and prevent it from swinging significantly as a result of water currents. Both the control and live panels were suspended vertically in the water alongside the lock wall beginning 14 June 2002. The top of each panel remained at a constant depth of 0.9 m (3 ft) below the water surface. The EES was initially set to fire on a half-hourly schedule. At approximately biweekly intervals, both panels were hoisted out of the water and checked qualitatively for mussel infestation, and photographed (Fig. 3). If inspection determined that mussels were accumulating, then the EES firing frequency was to be doubled. If there were fewer or the same number of mussels present, then the previous rate would be maintained unless and until subsequent inspection determined otherwise.



a. EES “live” panel raised out of water for first periodic inspection.

Figure 3. Panels being checked for mussel infestation.



b. EES “control” panel raised out of water for first periodic inspection.



c. Hoist used to raise and lower test panels. The large gray box and the small blue box at base of hoist are the EESS’s power supply and control boxes, respectively.

Figure 3 (cont’d). Panels being checked for mussel infestation.

To quantitatively document the mussel population at Lock 4, additional strings of PVC sampler plates were suspended in the water adjacent to the panels. It was hoped that the sampler plates would colonize with zebra mussels and provide background information on density and size demography of natural populations in the vicinity of the experiment. The samplers were constructed of two 0.25-in.-thick (7-mm) PVC plates measuring 6 in. (15 cm) on a side with a 0.6-in.- (15-mm-) diameter hole in the center of each. Two plates were positioned horizontally 2.4 in. (7 cm) apart on an eyebolt, and held in place with nuts and washers (Fig. 4). A rope was secured to the eyebolt with the other end attached to a metal railing post at the top of the lock wall. Plate samplers were centered approximately 4.5 ft (1.4 m) beneath the water surface for the summer. The field components were arranged on site as shown in Figure 5.



a. Assembling sets of small plates, one each of which was retrieved monthly and returned to the laboratory for sampling.

Figure 4. Plates used for mussel population sampling.



b. Set of small plates retrieved from the water, showing zebra mussels attached along the right-hand edge.

Figure 4 (cont'd). Plates used for mussel population sampling.



Figure 5. Experimental arrangement at Lock and Dam 4, showing relative positions of field components.

On 14 June 2002, six strings of substrate samplers were placed in the water adjacent to the live and control panels. Samplers were to be sequentially retrieved from the water and shipped back to Vicksburg for analysis throughout the summer. Depending on when the samplers were removed, they were to be in the water anywhere from three to six months. Every four weeks, two sets of samplers were removed from the water and disassembled; the two plates were each sealed in a plastic bag, and shipped to the laboratory in a cooler. There, the contents of each bag were preserved in 10% formalin for later analysis.

3 RESULTS

Field results: System operations and documentation of mussel settlement

The EES system (EESS) was non-operable for several periods during the 2002 season, making its effectiveness impossible to evaluate. The following timeline details the technical difficulties that we experienced and when they occurred.

- 24 Apr Arrived at Lock 4 to set up experiment. EESS not functioning so Ice Management Systems, Inc. (IMS) representative, R. Wiley, took controls and power supply back to California for repair. Found a charging component had loosened during initial shipping.
- ~16 May Unit was returned to Lock 25 and operated until EES panel was lowered into the water. Red warning light indicated moisture leakage into panel. Entire system was returned to IMS for repair. Diagnosis: leak detection logic was too sensitive and responded to mere elevated humidity.
- 11 Jun IMS representative traveled to Lock 4 and set up system to fire at four times per hour.
- 14 Jun N. Mulherin arrived at Lock 4, found EESS operating, and conducted force and power measurements. Estimated operational cost based on actual watt-meter measurements on site = \$0.014/day for charging + \$0.43/day for standby operation. Lowered live and control panels, and all strings of samples, into the water, and left EESS firing at two times per hour. Experiment begun.
- 24 Jun Lock personnel raise and photograph panels.
- 5 Jul J. Noren of USACE-St. Paul District found EESS operating, photographed panels, and shipped first set of samples to laboratory in Vicksburg for mussel population analysis.
- 22 Jul Lock personnel raised and photographed panels, and found the EESS not operating, having failed sometime between July 5 and July 22. Panels remained in water but power supply was shipped back to IMS. Diagnosis: charging circuitry and transformer was found damaged—possible lightning strike.

- 9 Aug Power supply returned and reinstalled at Lock 4. J. Noren arrived on site to photograph panels and shipped second set of samples to Vicksburg.
- 19 Aug Panels inspected by lock personnel, but not photographed, as they were found mussel-free. Power supply again found not operating, having failed sometime between August 9 and August 19. Power supply was returned to IMS.
- 10 Sep Power supply reinstalled at Lock 4. J. Noren arrived on site to ship third set of samples.
- 17 Oct J. Noren arrived on site to photograph panels.
- 21 Oct Panels taken out of water and experiment concluded for 2002.

Figure 6 summarizes the system's operational periods during 2002.

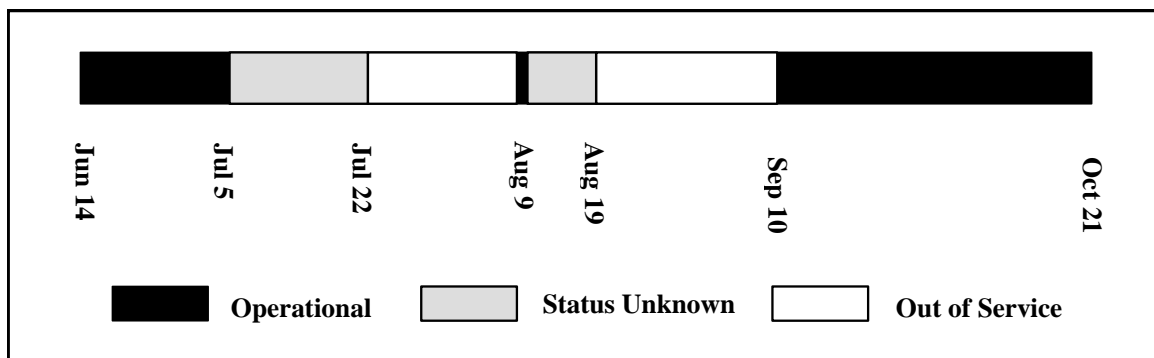


Figure 6. Timeline of EES system's periods of operation.

The dates when the panels were lifted from the water to document mussel settlement are listed below, along with brief observations made by on-site personnel at the time. In general, very few mussels settled onto either panel.

- 24 Jun Very few mussels found growing on aluminum back surface of live panel, none on the front surface, and none found on either front or back of control panel.
- 5 Jul A few more mussels found growing on the back surface and along the edges of the live panel. Few found growing on front and back of control panel.
- 22 Jul Seven large mussels and numerous small ones found growing on back of live panel, none found on the control panel.

9 Aug	None found on front of either the live or control panels, fewer than 20 found on each back surface of both panels.
19 Aug	None found on front of either the live or control panels.
10 Sep	None found except very few on back surface and along edges of the live panel. Most have disappeared since 9 August.
17 Oct	About 10 found growing on back of control panel and one found on the front surface. None found anywhere on the live panel.

Laboratory results: Mussel population analyses

Zebra mussels were scraped off the top and bottom of each sampler plate. Total shell length of each zebra mussel was measured with digital calipers, and the total number on the top and bottom of each plate was counted. A few zebra mussels were dislodged from the plates during shipment. It was assumed that they came from the top of the plate, since these typically had more mussels than the bottom of the plate.

None of the plates that were collected on 5 July supported live zebra mussels (Table 1). However, live specimens were found in August, September, and October. Total number of live zebra mussels on the plate samplers declined during the summer. This could be the result of natural mortality during the year, or natural variation in colonization rates among the samplers. Mean shell length (as well as minimum and maximum shell length) increased throughout the summer, as a result of growth of attached zebra mussels. Since minimum shell length increases throughout the summer, it is safe to assume that there was no additional settlement of immature zebra mussels after the early spring period.

Date	7/5/02	8/9/02	9/10/02	10/17/02
Count	0	67	51	44
Ave SL*, mm	N/D	8.65	12.98	13.53
Min SL*, mm	N/D	6.12	9.66	10.24
Max SL*, mm	N/D	11.72	15.95	17.67

* SL = Shell length

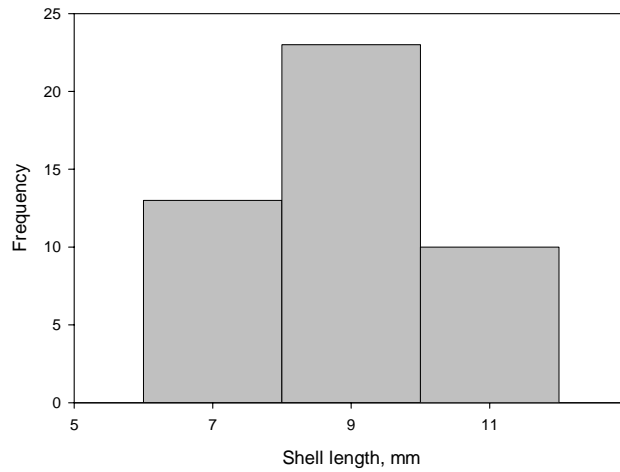
The majority of the zebra mussels colonized the top of the uppermost plate (Table 2). Since immature zebra mussels become negatively buoyant as they develop they are more likely to be abundant on the top plate. Density estimates on the top plate (as numbers per square meter) were very similar in August and September (approximately 2,300 individuals/m²). The estimated zebra mussel density declined slightly (1,946 individuals/m²) by mid October. This was likely the result of natural mortality, or of some of the live zebra mussels having fallen off the plates.

Table 2. Estimated population density (per m²) of *Dreissena polymorpha* on PVC plate samplers deployed in the upper Mississippi River, Lock and Dam 4, near Alma, Wisconsin, 2002.

Date	Plate	Top	Bottom
7/5/02	Top	0.0	0.0
7/5/02	Bottom	0.0	0.0
8/9/02	Top	2,398.2	45.2
8/9/02	Bottom	316.7	271.5
9/10/02	Top	2,307.7	0.0
9/10/02	Bottom	0.0	0.0
10/17/02	Top	1,945.7	45.2
10/17/02	Bottom	0.0	45.2

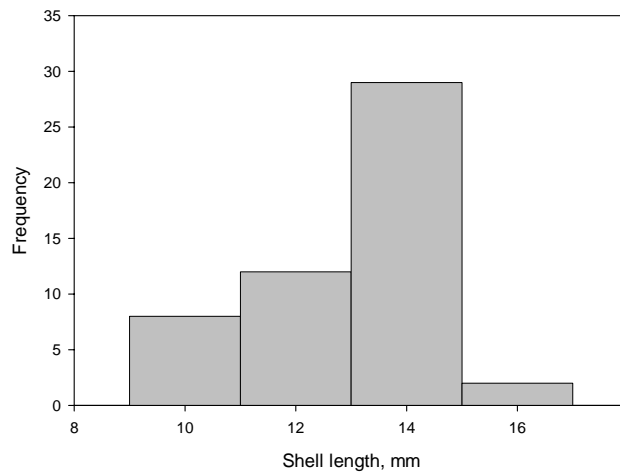
Length frequency histograms for zebra mussels in August, September, and October 2002 appear in Figures 7a–c, respectively. In August, the majority of the mussels were 9 mm long and none were longer than 11 mm. In September 2002 the majority were 14 mm long and the maximum size was 16 mm. Between 5 July and 9 August (35 days), zebra mussels grew an average of 11.72 mm (and possibly more, since they could have settled after 5 July). Between August and September and between September and October, zebra mussels grew an average of 4.33 and 0.55 mm, respectively. See Table 3 for estimated growth rates of the zebra mussels on plate samplers at Lock and Dam 4 during the 2002 season.

Dreissena polymorpha
Lock and Dam 4
09 August 2002



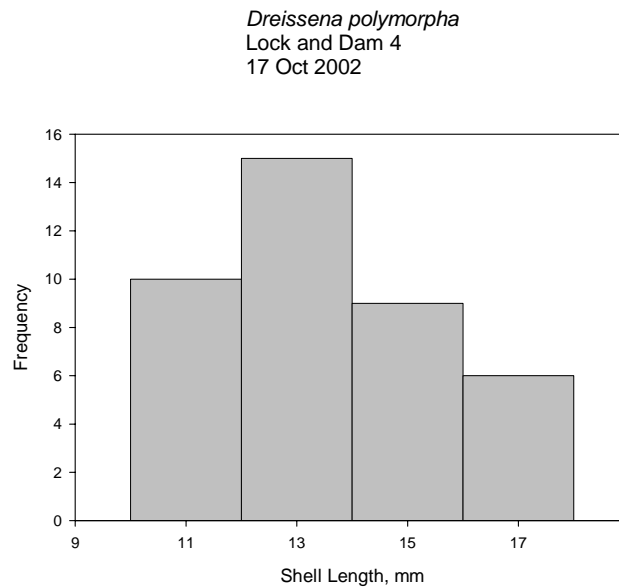
a. August 2002.

Dreissena polymorpha
Lock and Dam 4
10 Sept 2002



b. September 2002.

Figure 7. Length frequency histograms for zebra mussels collected from sampler plates at Lock 4.



c. October 2002.

Figure 7 (cont'd).

Table 3. Estimated rate of growth for zebra mussels at Lock and Dam 4, Upper Mississippi River, 2002.			
Date	Mean Shell Length	Days	mm/day
7/5/02	0		
8/9/02	8.65	35	0.25
9/10/02	12.98	32	0.14
10/17/02	13.53	37	0.01

4 DISCUSSION AND CONCLUSIONS

Equipment failures and an apparent lack of heavy mussel infestation at Lock 4 during the summer of 2002 prevented us from proving the success of EES protection from zebra mussel infestation. The leakage and electrical problems were eventually resolved, as the system operated normally for the last one and a half months of the season. With their normal duties, lock personnel could not be relied upon to closely monitor the system's operations. Although the power supply box was equipped with small lights to indicate whether or not the system was operational, they were not bright enough to see from the lock control room, especially during the daytime. Therefore, the experiment suffered when system failure went undetected for long periods of time. Though the problems now appear to be solved, a more positive method for detecting system failure should be addressed with, for example, higher-visibility warning lights and a protocol of more frequent personnel checks of their status.

Analysis of the sampler plates indicated that sufficient immature zebra mussels were present in the water to have colonized the EESS panel. Also, there were no apparent changes in water quality that prevented zebra mussel infestation during the summer and early fall. Still, only a small number of mussels attached to the backs of the live and control panels, and practically none attached to the front of either panel. The lack of definitive colonization of the live and control panels is not well understood at this time. Two possible explanations are that 1) these shellfish have an aversion to the materials we used in the construction of the panels, and 2) they prefer to settle in more-sheltered areas with lower-velocity water current.

The mussels that we did see attached preferentially to the aluminum backing plate of the live panel, to the steel bar that attached the cylindrical weights to the control panel, in the seam between the two sheets of UHMWPE covering the front of the control panel, and, to lesser extent, to the fiberglass rear of the control panel. This indicates that we should perhaps cover the front of these panels with a material that better promotes their attachment, such as a thin and flexible sheet of aluminum. Smooth surfaces may also inhibit settlement, and roughening of the test surfaces to encourage settlement could eliminate this possibility.

Locations with low-velocity water current appear to be more favorable for zebra mussel settlement. Figure 8 shows an infestation at Lock 4 during 2000. The darker, textured area covering the lower half of the gate (Fig. 8a) is a mass of zebra mussels. Note the heavy infestation in the ladder well (Fig. 8b) where ambient water currents are reduced, but not on the adjacent wall. Figure 4c also

supports this hypothesis. It shows the mussels preferred attachment between the plates. This hypothesis is supported by research. USACE (2002), citing a study by Claudi and Mackie (1994), states that the juvenile stage of the mussel will settle on internal piping and submerged surfaces where the flow velocity is less than 1.5 m/sec. While the water velocity in the vicinity of our panels was not measured, local turbulence, as stated earlier, required us to weight the control panel to prevent it from swinging in the current. To better promote zebra mussel colonization of the test panels in a future experiment, consideration should be made for reducing the ambient current velocity in the vicinity of the test panels. This might be accomplished, for example, by placing the panels in a more sheltered location, or by enclosing them in baffled stilling boxes that will allow water to freely circulate but at much lower velocity. We anticipate that, with implementation of these changes in our experimental equipment and protocol, and funding for another field season to collect data, our zebra mussel control concept can be proven.



a. Lower half of gate.

Figure 8. Lock and Dam 4 during January maintenance drawdown in 2001, showing heavy zebra mussel infestation. (Photos provided by L. Meixner.)



b. Recessed ladder well.

Figure 8 (cont'd). Lock and Dam 4 during January maintenance drawdown in 2001, showing heavy zebra mussel infestation. (Photos provided by L. Meixner.)

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