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US Army Corps of Engineers
Waterways Experiment Station

Zebra Mussel Research Program

Zebra Mussel (*Dreissena polymorpha*) Control Handbook for Facility Operators, First Edition

by Shawn F. Boelman, Frank M. Neilson,
Elba A. Dardeau, Jr., Thomas Cross

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Prepared for Headquarters, U.S. Army Corps of Engineers

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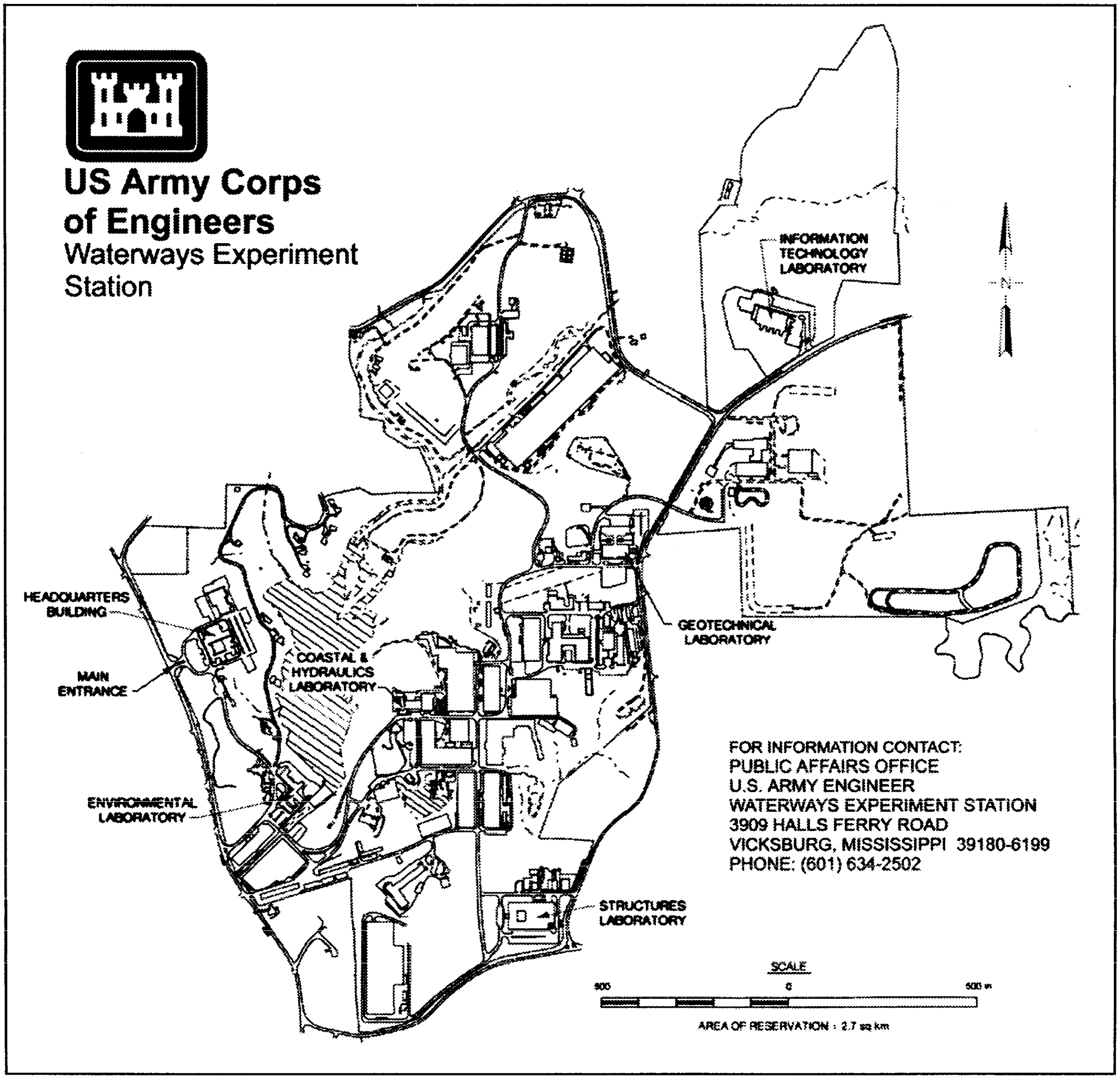

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Preface

The Nonindigenous Aquatic Nuisance Prevention and Control Act of 1990 specified that the Assistant Secretary of the Army, Civil Works, will develop a program of research and technology development for the environmentally sound control of zebra mussels (*Dreissena polymorpha*). As a result, the U.S. Army Engineer Waterways Experiment Station (WES) initiated the Zebra Mussel Research Program (ZMRP).

This report was compiled by Messrs. Shawn F. Boelman, Elba A. Dardeau, Jr., and Thomas Cross, Environmental Resources Engineering Branch (EREB), Environmental Engineering Division (EED), Environmental Laboratory (EL), WES, and by Dr. Frank M. Neilson, Spillways and Channels Branch, Hydraulic Structures Division, Coastal and Hydraulics Laboratory, WES. Information and reviews were received from the ZMRP/Working Group (WG). WG members are listed in Appendix A. Chairmen included Mr. Dardeau, Hydropower; Mr. Jerry Miller, Public Facilities; Dr. Neilson, Navigation; and Dr. J. Craig Fischenich, Floating Plant. U.S. Army Corps of Engineers technical advisors were Drs. Andrew C. Miller, Barry S. Payne, Henry E. Tatem, and Toy S. Poole, WES; and Mr. Tim Race, U.S. Army Corps of Engineers Construction Engineering Research Laboratories. Dr. Edwin A. Theriot, EL, was Program Manager, ZMRP.

This study was conducted as a milestone requirement of ZMRP Work Unit No. 32817, "Susceptibility of Public Facilities," with Mr. Dardeau, serving as Principal Investigator. During the conduct of this study, Mr. Thomas R. Patin was Chief, EREB; Mr. Norman R. Francingues was Chief, EED; and Dr. John Harrison was Director, EL.

Dr. Robert W. Whalin was Director of WES at the time of publication of this report. COL Bruce K. Howard, EN, was Commander.

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1 The Zebra Mussel [1]

Background

In 1988, a ship discharged its ballast water into Lake St. Clair, Michigan, releasing billions of organisms that it had taken on at a freshwater port in Europe. In the ballast were the larvae of a freshwater mollusc, the zebra mussel ***(Dreissena polymorpha).*** This small mussel is usually no more than 5 cm long with characteristic zebra-like stripes (Figure 1). The zebra mussel is native to the Caspian Sea and Ural River in Asia. In the nineteenth century, it spread west, and is now found in most of Europe, the western portion of Russia, neighboring former Soviet Union republics, and Turkey.

Figure 1. Zebra mussel (courtesy Great Lakes Sea Grant)

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[1] This chapter is largely extracted from the work by Miller, Payne, and McMahon (1992).

Reason for concern

The zebra mussel is a macrofouler. It quickly colonizes new areas and rapidly achieves high densities. Unlike native mussels that burrow in sand and gravel, zebra mussels spend their adult lives attached to hard substrate. Under natural conditions, they are found on rocks, logs, aquatic plants, shells of native mussels, and exoskeletons of crayfish. They can also attach to plastic, concrete, wood, fiberglass, iron surfaces (Figure 2), and surfaces covered with conventional paints.

Figure 2. Zebra mussel infestation (photographed by Peter Yates)

In 1988 and 1989, zebra mussels were first found in water intake pipes in industrial and municipal water plants in Lakes St. Clair, Erie, and Ontario. The Monroe water plant in Monroe, MI, had to temporarily suspend service when its main intake line became clogged with zebra mussels. Many power plants along Lake Erie now spend more than $250,000 each year on control. Infestations have caused temporary power outages and difficulties in obtaining water for cooling and waste removal. Within their range, they could render inoperable miter gates on locks, fire prevention systems that use raw water, reservoir release structures, navigation dams, pumping stations, water intake structures, dredges, and commercial and recreational vessels.

Materials and equipment such as small-diameter pipes, seals, valves, gears, air vents, weep holes, screens, trash racks, chains, pulleys, and wire ropes are vulnerable. When a thick layer of zebra mussels covers a metallic surface, it can cause anoxia and pH reduction, exacerbating corrosion rates. Estimates are that this species could cause 5 billion dollars in damage in the United States by the year 2000.

Spread of zebra mussels in this country

In the summer of 1994, 6 years after they were first found in Lake St. Clair, zebra mussels were collected in the Arkansas, Cumberland, Hudson, Illinois, Mississippi, Ohio, Susquehanna, and Tennessee rivers. Figure 3 shows December 1995 distributions in the United States and Canada. Within a relatively short time, this species has spread throughout the eastern United States and is spreading west. Zebra mussels have been transported westward in Louisiana via the Gulf Intercoastal Waterway and are now in the Atchafalaya Basin. They have also been found in Oklahoma on the Arkansas River. Lawrence (1995) discussed how these organisms have spread across the various river systems.

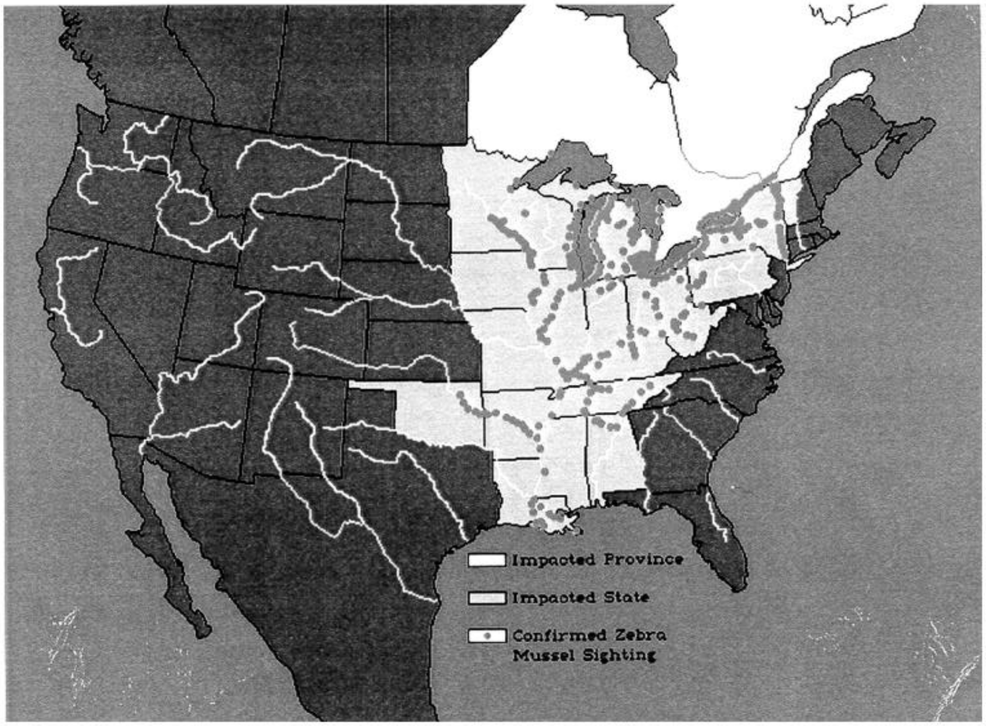

Figure 3. Locations of zebra mussels in the United States and Canada (December 1995)

Authority

The Corps' authority to study and develop control strategies for zebra mussels is based on the Nonindigenous Aquatic Nuisance Prevention and Control Act of 1990, Public Law 101-646 (Congressional Record-House, 27 October 1990). The legislation required that the Secretary of the Army develop a program of research and technology development for the environmentally sound control of zebra mussels at public facilities. Public facilities include not only locks, dams, and reservoirs, but also water pumping stations, water intakes, hydropower stations, and drainage structures. In October 1991, the U.S. Army Engineer Waterways Experiment Station (WES) initiated a research program to develop environmentally sound control strategies for zebra mussels.

Biology and Ecology of Zebra Mussels

Physical description

Zebra mussels are bivalve molluscs related to oysters, clams, and native freshwater mussels. They are also related to the exotic Asiatic clam (*Corbicula fluminea*), which is a biofouler in the central and southern United States. Zebra mussels can grow to 5 cm, although most specimens collected in this country have been less than 3.8 cm long. They have an elongated, somewhat pointed, thin shell usually with a zebra-like pattern of stripes. An individual mussel can attach to an object with up to 100 proteinaceous byssal threads that are secreted from a gland at the base of its muscular foot. These threads are extremely tenacious; an attempt to remove the animal by hand usually results in breaking the shell or damaging soft tissue. Native freshwater mussels and Asiatic clams have a single, thin byssal thread that is present only in the juvenile stage. The zebra mussel is the only bivalve in this country that retains these threads as an adult. The main reason zebra mussels cause problems in industrial and domestic water supplies is that large numbers of mussels attach themselves to hard surfaces within raw water systems by their byssal threads.

Densities

Zebra mussels often achieve high densities immediately after colonizing a new habitat. For example, biologists at Detroit Edison reported that zebra mussel densities on an intake screen climbed from 200 individuals/m^2 in 1988 to 700,000 individuals/m^2 in 1989. A car submerged for 8 months in Lake Erie was 90-percent covered with mussels at an average density of 45,000 individuals/m^2. As many as 10,000 zebra mussels have been counted on a single freshwater mussel. This ability to rapidly achieve high densities makes the zebra mussel a threat to industrial and domestic water supplies.

Within 10 or 20 years of colonization, densities of zebra mussels may decline as natural predators and diseases begin to act as control agents. In much of Europe, zebra mussel densities have declined from levels achieved within the first 10 to 15 years of introduction and are generally lower than those now being reported from the Great Lakes.

Feeding

Zebra mussels feed on suspended particles (unicellular algae, bacteria, and fine organic detritus) using a complex arrangement of cilia. Water enters the animal through an incurrent siphon and is carried over the gill where suspended particles are filtered by cilia and are sorted according to size. Accepted particles are combined with mucus and passed to the mouth. Rejected particles are combined with mucus and ejected as pseudofeces. Zebra mussels can effectively remove particles less than 1 μm in diameter, whereas most other bivalves cannot filter objects less than 3 μm. This enhanced filtration capability enables zebra mussels to feed on planktonic bacteria that are unavailable to native mussels.

This method of feeding is common in all freshwater and marine bivalves. An individual zebra mussel can filter up to 8.5 ℓ of water a day. Because of their mode of feeding and their ability to achieve high densities, zebra mussel filter feeding can increase water clarity locally. Phytoplankton, fine organic matter, and clay or silt particles are filtered out of the water and ingested or deposited as pseudofeces. Deposition of silt into zebra mussel feces and pseudofeces can greatly increase sedimentation rates in natural habitats and raw water systems. Zebra mussels are often used in Europe as water clarifiers at treatment plants.

Reproduction

Zebra mussels are dioecious (a population that consists of males and females). When water temperatures reach 11 or 12 °C, females release eggs. Females can reproduce when 12 to 18 months old (age at maturity decreases with growth rate; sexual maturity is at a shell length of 10 mm) and are capable of producing 40,000 eggs per season. Males release sperm directly into the water, and eggs are fertilized externally. The fertilized eggs hatch into a free swimming veliger larva that ranges in size from 0.04 to 0.07 mm. Because zebra mussels do not release sperm and eggs at the same time, spawning, once initiated, can occur over extended periods. In waters of the United States, veligers can be found from May to October. Native freshwater mussels reproduce at a specific time, usually in the spring and typically are not reproductive when older than 5 or 10 years.

Early development

Newly hatched zebra mussel veligers have a velum that supports a ring of cilia that are used for swimming and feeding. Larvae tend to swim up at night and move down during the day but are unable to swim horizontally toward specific objects. They colonize new areas by being carried passively on water currents. Veliger densities have been reported to range between 70 and 400,000 individuals/m^2.

The veliger feeds and grows in the plankton for about 10 to 14 days. Gradually the velum begins to decrease in size, and the veliger settles to the substratum gradually metamorphosing into a shelled juvenile. The newly settled mussel resembles an adult and is no more than 0.2 or 0.3 mm long; hence, it is easily overlooked. Settlement of immature mussels takes place in areas with velocities less than 1.5 to 2.0 m/s. However, once attached, zebra mussels can tolerate velocities greater than 2.0 m/s. Zebra mussels usually attach to surfaces that are covered with a film of algae or bacteria. This film can develop on a clean surface within a few days.

The ability of immature zebra mussels to remain suspended in the water column for up to 2 weeks allows them to be dispersed great distances in rivers. The immature stage of most native mussels are not free living but must spend a developmental period on the gills or fins of a specific species of fish.

Growth

Growth rate depends on water quality and temperature and can range from 1.0 to 1.6 cm/year. Maximum annual production reported for a zebra mussel population is 29.8 g of dry tissue/sq m/year. This rate of tissue accumulation is one of the highest recorded for freshwater or marine bivalves and emphasizes the ability of these animals to quickly develop large biomass.

Locomotion

After an immature mussel settles, it can remain attached to hard substrate for life. If conditions become unsuitable because of physical disturbance or poor water quality, zebra mussels can release from their byssal threads. Once detached from the substrate, single individuals can be carried passively to new structures where they can settle and secrete new byssal threads. Zebra mussels can also crawl by extending the foot tip, anchoring it to substrate with mucus, then contracting the muscles to pull the body forward. Small individuals are more mobile than large mussels.

The ability of zebra mussels to remain attached to boat hulls, woody vegetation, and debris is also responsible for their rapid dispersal. In addition, groups of byssal-attached mussels can break loose from dense mats and infest new areas.

Ecology

Zebra mussels are found in freshwater lakes, ponds, embayments, and rivers. If temperature and water quality are appropriate, they can tolerate velocities up to 2.0 m/s. They typically are found where water temperatures range from 0° to 25 °C. They have been collected in shallow waters (less than 1 m deep), but maximum abundance usually occurs at depths between 2 and 14 m. Zebra mussels are clean-water inhabitants and are usually found where dissolved oxygen is greater than 90-percent saturation. They are stressed in water with less than 40- to 50-percent saturation, and 100-percent mortality occurs in the absence of dissolved oxygen. Zebra mussels, like all bivalves, require calcium to construct their shell. They have not been found in water with less than 10 mg/ℓ dissolved calcium.

Natural predators

Zebra mussels are eaten by the freshwater drum, catfish, lake sturgeon, and most sunfishes. Even though zebra mussels are consumed by a certain fish and waterfowl, they will not likely be controlled by natural predation.

Environmental considerations

Filter feeding by zebra mussels could reduce plankton and decrease the food base for planktivorous fishes such as shad and shiners. By blanketing sediments, removing fine particulate matter, and depositing nutritious and nonnutritious particles as pseudofeces, zebra mussels could affect the density and biomass of native clams, immature insects, and other invertebrates. Large numbers of mussels could even cover spawning shoals used by riverine fishes.

Monitoring

Monitoring is a key component of preventive maintenance and control because it provides information on the presence of zebra mussels, their abundance in the water system, and the effectiveness of treatment programs. Zebra mussels are capable of rapid dispersal and growth rates. Therefore, cost-effective implementation of control strategies depends upon effective monitoring.

Preventive maintenance applications

The chance for zebra mussels to become established and abundant in specific areas can sometimes be inferred from geography, water quality, and temperature. Zebra mussels may never become established in some parts of the United States. For large areas of this country, their status cannot be readily predicted. Monitoring the dispersal and abundance patterns of the species may be prudent in these areas if periodic and unexpected loss of water supply cannot be tolerated.

Monitoring can be used to determine the time frame or urgency for treatment. It also provides feedback for treatment effectiveness and provides information to "fine tune" the treatment strategy needed for different facility operating conditions and seasons of the year.

Initial inspection

A thorough inspection of the water system at a facility should be undertaken prior to initiation of a monitoring and sampling program. Facility components susceptible to zebra mussel infestations are identified in subsequent chapters. The initial inspection is intended to determine existing infestation levels and map zebra mussel concentrations throughout the water system.

An underwater inspection by divers may initially be in order; however, dewatering or drydocking (in the case of floating plant) is preferable and can also be accomplished in conjunction with routine maintenance. Both types of inspection allow for the documentation of zebra mussel infestation levels. Professional divers are an important component of underwater inspection. Most commercial diving companies use underwater cameras for documenting conditions and work performance. Remotely operated underwater vehicles equipped with cameras can be used without divers. The larger commercial underwater inspection companies and some engineering companies supply these services.

Inspection of dewatered facilities and structures allows for a complete evaluation of zebra mussel infestations in conjunction with regular structural maintenance. Thorough cleaning and the addition, replacement, or repair of control mechanisms should be completed during dewatering. Recently settled mussels often are not apparent; however, they can be detected in the early stages in crevices or seams of concrete or steel structures when mussels are in the 1- to 4-mm size range.

Monitoring programs

Following the initial inspection, a long-term monitoring and control program can be designed and established to meet specific operating conditions at a facility. Such information is useful to evaluate current infestation reduction programs and the effectiveness of implemented zebra mussel controls. Scheduled maintenance and monitoring programs can be adjusted accordingly.

Sampling

Operators should monitor for immature zebra mussels to determine when control strategies should be initiated. There are usually two (although in some instances, there has been one) high-density peaks of immature zebra mussels each season. However, immature zebra mussels can be found in the water all year when temperatures are above 12 °C. Monitoring for immature zebra mussels is more difficult than for adults. This type of monitoring should be considered at pumping plants, especially where potable water supplies or electricity generation could be threatened. Monitoring to detect the presence of immature zebra mussels makes little sense at hydropower facilities where there is not a need to develop a strategy. Samplers constructed from polyvinyl chloride (PVC) plates (5 cm by 15 cm) suspended horizontally about 3 cm apart should be considered if information on density, growth, or time of settlement is required. However, these are unnecessary if only presence/absence information is required.

Presence/absence sampling for adults should be conducted to prepare for implementing strategies. The preferred substrates are PVC plates or pipes because they are lightweight, easy to obtain, inexpensive, and zebra mussels are easily seen or felt on their smooth surface. If PVC is unavailable, other appropriate substrates should be used to collect presence/absence information. Concrete blocks, ceramic tiles, or nylon sponges are also acceptable as monitoring substrate.

Conditions where zebra mussels are first found should be thoroughly documented, including water velocity, depth, and type of substrate on which the mussels are attached. Age can be estimated by measuring the length of 5 to 10 of the largest individuals. Shell length is measured along the flat portion of the shell with calipers or a small rule. Zebra mussels will grow less than 1 cm/year in most areas. Density can be estimated by making several counts of mussels in a unit area (1-m^2 sample size, if possible). Water temperature needs to be recorded and, if equipment is available, dissolved oxygen, pH, and total hardness.

Project personnel or divers can collect zebra mussels or other molluscs by hand. A simple procedure is to remove all shells and other material within a quadrat of a specific size and count the number of individuals in a unit area. Quadrats can be fabricated or purchased ready-made. Quadrats have been constructed from aluminum stock approximately 0.3 cm thick and 10 cm wide or from 2.5-cm-diam PVC pipe. The size of the quadrat square depends on the population densities of mussels. A 1-m square may be necessary to count reasonable numbers of mussels in areas of low density ($< 100/m^2$), whereas a 10-cm square may be sufficient in high-density areas. All shells and materials collected from within the quadrat should be placed in a single container. Material can be examined directly or screened through 0.6-cm and 1.3-cm mesh to facilitate sorting, which is the preferred method for estimating mussel density.

Disposal

Many of the suggested cleaning procedures require additional work of maintenance personnel. Potential users should investigate the success of suggested cleaning procedures and modify them if certain aspects are needless or burdensome.

Zebra mussels removed from a water body must be transported to a landfill or otherwise disposed. If mussels are dislodged from an underwater surface and not brought to the surface, they could be left to be removed by water currents, which is an advantage of underwater cleaning, use of antifouling coatings, and biocides.

Disposing of zebra mussels safely is sometimes difficult because of odor problems that may cause landfill operators to refuse such material and the remote potential for contamination by the zebra mussels. If screening procedures are not already in place, facility operators considering zebra mussel disposal should first consider conducting a toxicity characteristic leaching procedure test. This procedure tests for heavy metals and polychlorinated biphenyl. If the test is completed and results indicate low toxicity, zebra mussels can be safely deposited in a landfill. As part of the Corps' research, zebra mussels are being collected and analyzed for toxicants to provide baseline data on the existing contaminant levels that will guide site-specific strategies. Thus far, however, preliminary findings show no cause for concern with toxicity of zebra mussels.[1]

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[1] Personal Communication, 28 June 1995, Dr. Henry E. Tatem, zoologist, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

2 Control Methods

Zebra mussel control methods include both preventive and reactive strategies. Preventive control methods include repellent construction materials, antifouling coatings, chemical use, and thermal treatment. Reactive control methods are mechanical cleaning, high-pressure water jetting, carbon dioxide pellet blasting, freezing, and desiccation. Chemical and thermal treatments can be used as a reactive treatment to clean a system, then preventively as regular maintenance to prevent further fouling. These options, along with new designs, retrofit, and future control techniques are reviewed in this chapter. Selection of appropriate control methods should be based on environmental and economic factors, ease of application, and the nature of the application.

Preventive Control Methods

Repellent construction materials

Small-diameter pipes, fixtures, and components made of copper, brass, or galvanized steel are not susceptible to fouling. These materials should be considered for retrofit, maintenance, and construction.

Antifouling, foul-release, and thermal-spray coatings

Specialized coatings can be effective in controlling zebra mussels in raw water systems. Traditional antifouling coatings leach an aquatic toxin, typically cuprous oxide, into the water to repel fouling organisms, such as the zebra mussel. These products are effective for approximately 2 to 5 years. Foul-release coatings present a slippery surface that minimizes the adhesion of the zebra mussel. These products are considered to be more environmentally sound because they do not leach aquatic toxins. However, they are subject to abrasion; therefore, their use should be limited to areas that are not susceptible to damage caused by ice and debris. Thermal-spray coatings are metallic coatings, such as zinc, copper, and brass, that are applied by melting a wire feedstock and propelling the molten droplets in a stream of compressed air on the surface to be treated. These coatings repel zebra mussels through the slow dissolution of metal ions into the water. Zinc thermal spray also provides excellent corrosion resistance on steel surfaces. Copper and brass should never be applied directly to steel because the steel will corrode. Thermal spray coatings should not be used on nonferrous metal substrates. With proper surface preparation, they may be used on concrete. Thermal spray coatings are potentially the most durable and lasting zebra-mussel repellent coating.

The use of coatings as a control measure should be preceded by a complete understanding of recognized or predictable impact on the operation of the facility. Other control options should be considered as appropriate. Headquarters, U.S. Army Corps of Engineers (HQUSACE) (1993a,b,c) recommended two coating systems described below for the control of zebra mussels. Coating System A is for use on mild steel or concrete and can be expected to provide effective protection for 10 or more years. Coating System B is for use on mild steel and on some previously painted surfaces. System B should provide approximately 3 years protection.

a. *Coating System A.* This coating system consists of zinc thermal spray coating system number 3-Z, described in CWGS-05036, "Metallizing Hydraulic Structures" (HQUSACE 1993a). This specification contains all of the necessary guidance including surface preparation, coating application, and safety. The metallized coating should not be top-coated or sealed. The system may only be applied to blast-cleaned surfaces and is not appropriate for application over existing coatings.

b. *Coating System B.* This coating system consists of a base anticorrosive system and an antifouling topcoat. Coating system number 5-E-Z described in CWGS-09940 "Painting: Hydraulic Structures and Appurtenant Works" (HQUSACE 1993c), comprises the anticorrosive portion of the system. Military Specification MIL-P-15931F, "Paint, Antifouling, Vinyl, Type I, Class 2" (HQUSACE 1993b), is applied over the base anticorrosive system. MIL-P-15931 should be spray applied to a dry film thickness of between 3 and 5 mils. Surface preparation, application, and safety guidance for system 5-E-Z is detailed in CWGS-09940. The safety guidance in CWGS-09940 is also appropriate for the application of MIL-P-15931.

MIL-P-15931 may also be used over some existing coatings, including Systems 3, 3-A-Z, 4, and 5-A-Z, described in CWGS-09940, provided the receiving surface has been cleaned and is in good condition. Existing coating systems to be top-coated with MIL-P-15931 should be cleaned using high-pressure water at 10,350 kPa. Prior to top-coating, the cleaned surface should be dry and free of visible deposits that may interfere with intercoat adhesion.

Systems A and B described herein contain significant amounts of zinc and copper, respectively. Most States do not currently regulate the disposal of zinc and copper containing wastes; however, proposed legislation suggests that they may be more widely regulated at some future time. Disposal of regulated wastes can be expensive.

The effectiveness of these coating systems at preventing the attachment of zebra mussels is a direct result of the aquatic toxicity of copper and zinc. Systems A and B introduce measurable amounts of zinc and copper into the water that may affect nontarget organisms. The zinc and copper leach rates of these coatings have been measured in controlled laboratory experiments. The relatively low release rates and high dilution rates associated with their practical application suggest negligible or very low secondary effects on nontarget organisms. Cuprous oxide, the active constituent in System B, is subject to regulation under the Federal Insecticide, Fungicide, and Rodenticide Act, as amended. For additional information on this topic, refer to Zebra Mussel Research Technical Note ZMR-1-15 (Howe et al. 1994).

The paints in System B may be regulated in some locations based on their volatile organic compound (VOC) content. Regulations affecting shop and field application of these coatings may be different from VOC content restrictions for shop-applied coatings. The specifier should learn the air quality regulations in their area.

For additional information on conducting environmental assessments for zebra mussel control, see Tippett, Cathey, and Swor (1993). The Paint Technology Center, U.S. Army Construction Engineering Research Laboratories, 1-800-USACERL, extension 6769 or 7237, can provide additional information on the use of coatings to prevent zebra mussel fouling.

Chemicals

A number of chemicals have been tested with varying degrees of success and acceptability. Claudi and Mackie (1994) pointed out that the major advantage offered by most chemical treatments is that they can be engineered to protect almost the entire facility. The disadvantage rests in limiting the discharge of toxic materials to the environment and meeting environmental regulations.

Chemical treatment technologies are subjected to continued scrutiny, and environmental concerns may further limit their use. However, until suitable substitutes are found, facility managers will have to rely on chemicals as a component of their overall control strategy for problem infestations of zebra mussels. Many chemical treatments have been tested, but chlorination, specifically, sodium hypochlorite (NaOCl), seems to have the widest use and acceptance. Section IV (Mitigation) of the volume edited by Nalepa and Schloesser (1993) contains case studies dealing with successes and failures of various chemical applications to control zebra mussels.

Oxidizing chemicals. Of all the chemical methods tested thus far, chlorination seems to have almost universal acceptability in that it generally satisfies environmental concerns and is also affordable and reasonably easy to apply at most facilities. Change is on the horizon, however, and new control strategies are being proposed and tested in anticipation of more stringent environmental limitations. Chlorination forms trihalogenated methanes and other hydrocarbons that are carcinogenic. In 1993, Ontario Hydro gave its researchers 5 years to develop alternative control strategies that might replace chlorination. Even though this goal is being pursued, the Canadians believe that chlorination will always have to be a viable control option, especially with problem infestations that they have experienced on the Great Lakes and St. Lawrence River. There is also a trend in the United States toward tighter environmental restrictions regarding the use of chlorination. Like their counterparts in Canada, United States facility managers will need to have chlorination available to them for zebra mussel control, especially when operation is in jeopardy or efficiency is greatly reduced. Thus, guidelines are needed for the reasonable and prudent use of chlorination as a means of zebra mussel control at hydropower facilities.

Chlorination systems have gained wider acceptance than other treatment technologies, mainly because they effectively control zebra mussel infestations. McMahon, Ussery, and Clarke (1994) reviewed zebra mussel control methods and noted that "there is a large and varied body of literature from Europe and, more recently, from North America, describing the relative merits of chemical and nonchemical control technologies for zebra mussels." Their tables are useful for comparing the merits of individual control methods. The treatment methods listed with the oxidizing molluscicides compiled by McMahon, Ussery, and Clarke (1994) include chlorination, chlorine dioxide (ClO_2), and chloramines, with the latter being broadly classified as a reaction product of "chlorine with any compound containing the nitrogen atom with one or more hydrogen atoms attached (mostly inorganic nitrogen)" (Claudi and Mackie 1994). The literature clearly shows a variation in not only the methods of chlorine treatments but also the concentrations and duration of application and the lethality of these treatments. McMahon, Ussery, and Clarke (1994) report the following application and effect ranges for chlorine treatments (Table 1):

Table 1
Application and Effect Ranges for Chlorine Treatments (McMahon, Ussery, and Clarke 1994)

Treatment	Application	Effect
Chlorination (adults)	0.5 ppm for 7 days	75-percent kill
	0.3 ppm for 14 to 21 days	>95-percent kill
Chlorination (adults)	2 ppm continuous flow-through	90-percent kill
Chlorine dioxide	0.5 ppm for 24 hr	100-percent veliger kill
Chloramine	1.2 ppm for 24 hr	100-percent veliger kill

Hypochlorite reaction. Chlorine treatments have relied on the use of pressurized gas; liquid sodium hypochlorite is the chlorine source of choice because of safety concerns. Sodium hypochlorite, NaOCl, is considered a safe and versatile chlorinating liquid. Claudi and Mackie (1994) described the reaction that takes place when sodium hypochlorite is added to water, with hypochlorous acid (HOCl) formed as the oxidizing agent in this reaction. As a "weak" acid, hypochlorous acid tends to undergo partial dissociation, to produce a hydrogen ion (H^+) and a hypochlorite ion (OCl^-). Hypochlorous acid has more biocidal effect than the hypochlorite ion because of its ability to penetrate cell walls (White 1986). The FAC is the combined amount of HOCl and OCl^- in the water.

Chloramine. As indicated earlier, chloramines are produced in the reaction of free available chlorine with various forms of nitrogen-containing compounds occurring in the water such as ammonia, nitrites, nitrates, and amino acids. Chloramines are formed naturally when chlorine or sodium hypochlorite is added to raw water. The chloramines include monochloramine (NH_2Cl), dichloramine ($NHCl_2$), and trichloramine (NCl_3), together designated as TCC (Claudi and Mackie 1994). The more ammonium that is present, the higher the level of chloramines that are formed. Claudi and Mackie (1994) stated that chloramines are considered less powerful as oxidants than hypochlorous acid. At sites where the formation of trihalomethanes is a concern, the use of chloramines offers some advantages. Chloramine treatments are applied by coinjection of ammonium as either ammonium gas or ammonium hydroxide and sodium hypochlorite. Exact dosing requirements for effective zebra mussel control is unknown.

Chlorine dioxide. Chlorine dioxide (ClO_2) has been an effective disinfectant in the water industry for over 50 years (Claudi and Mackie 1994). Unlike the hypochlorite reaction, its by-products are primarily sodium chloride and sodium chlorite, and a chlorine dioxide reaction does not lead directly to the formation of trihalomethanes. Opinions differ as to its effectiveness in zebra mussel control. The use of chlorine dioxide may not offer significant advantages over sodium hypochlorite when cost and ease of use are considered. Chlorine dioxide must be manufactured onsite with the use of specialized equipment. Chlorine dioxide control methods may be beneficial if a chlorine dioxide system is already in place or the formation of trihalomethanes is a serious problem.

Factors influencing chlorine effectiveness. A number of raw water parameters influence the effectiveness of chlorine treatments. These factors include organic and inorganic compound concentrations, temperature, and pH (Claudi and Mackie 1994; Electric Power Research Institute (EPRI) 1992). The physical state of the zebra mussel and the extent of infestation will also influence the effectiveness of the chlorine treatment (Claudi and Mackie 1994).

Water chemistry has a very important impact on the toxicity of chlorination to zebra mussels. Claudi and Mackie (1994) stated that waters rich in organic and inorganic compounds have high chlorine demand, consuming larger amounts of chlorine residuals through oxidation-reduction reactions. The presence of reducing agents, such as S^{2-}, Fe^{2+}, Mn^{2+}, and NO^{2-}, accelerate the chlorine decomposition rate and should be taken into account to ensure expected zebra mussel mortality.

Water temperature affects both the dissociation of hypochlorous acid into the hydrogen and hypochlorite ions and the metabolic rate of zebra mussels. As water temperatures rise, the concentration of the more effective hypochlorous acid decreases as the concentration of the dissociated ions increase. Higher temperatures also seem to escalate the intake of chlorine compounds as the zebra mussel's metabolic rates increase. As a result, even though higher temperatures lower the toxicity of the chlorine, the increased uptake of chlorine compounds increases the overall chlorine effectiveness.

Water pH strongly influences the dissociation of hypochlorous acid into the hydrogen and hypochlorite ions. Claudi and Mackie (1994) presented a graph showing dissociation of hypochlorous acid versus pH, showing that when the pH of the chlorinated water is approximately 7.5, 50 percent of the chlorine concentration present will be undissociated hypochlorous acid and the remainder, the hypochlorite ion. A 100-percent hypochlorite ion concentration is attained at a water pH of 10. Conversely, at pH 5, 100 percent of the chlorine concentration will be the more effective undissociated hypochlorous acid.

Chloramine formation is pH-dependent; a lower pH will yield a higher concentration of dichloramines, whereas a higher pH will yield a higher concentration of monochloramines. Dichloramines are more potent disinfectants than monochloramines (Claudi and Mackie 1994). Maximum (100 percent) dichloramine concentrations occur at pH 4.5. At pH 8.5, 100-percent monochloramine concentrations exist.

Toxicity studies have shown that mature zebra mussels are slightly more resistant to chlorine than are various veliger stages (Claudi and Mackie 1994). Chlorine treatments are more effective at the end of a growing season due to the physiologically exhausted state of the mussel following the reproductive effort. There is an inverse relation between the population biomass and the treatment effectiveness. Larger populations, particularly individuals farther away from the surface layer, are less vulnerable than are single-layer colonies (Claudi and Mackie 1994). Thus, multiple applications or multiple treatment methods may be necessary in problem infestations.

Treatment strategies. The applied chemical treatment strategy is as important as the type of chemical used. There are five different chemical treatment strategies proposed by Claudi and Mackie (1994) for zebra mussel infestations: end-of-season, periodic, intermittent, continuous, and semicontinuous. A chemical zebra mussel control strategy may consist of a single treatment scenario or a combination of treatments used in concert. The treatments most applicable to a particular facility depend on the extent of zebra mussel infestation, the degree of permissible infestation, water quality, existing facility systems, economics, permit requirements, and environmental regulations. An effective chemical treatment design allows for flexibility in treatment applications in accordance with the entire zebra mussel control program for each facility.

End-of-season treatment. End-of-season treatment is generally a reactive strategy, acceptable in systems that can tolerate limited macrofouling. Limited macrofouling can be anticipated if chemical treatments are applied once during the year, usually after the spawning season or at the end of the growing season. Treatments after the spawning season increase chemical effectiveness and reduce required concentrations, as individuals are fatigued and weakened. Also, shells and soft tissue debris of young-of-the-year mussels more easily pass through facility systems.

Mitigation of established mussels by end-of-season treatments requires higher dosages of chemicals over an extended period of time (2 to 3 weeks) (Claudi and Mackie 1994). Chemical concentrations and exposure times are dependent on the chemical used, water quality, and health of the mussels. Defining absolute levels applicable to all locations at all times is very difficult. Byssal threads remaining after end-of-season treatment can promote the settlement of veligers, cause corrosion, and add surface friction.

Periodic treatment. Periodic chemical treatment, like end-of-season treatment, is usually a reactive treatment (usually conducted on a regular basis, such as every 2 months) designed to eliminate adults that have accumulated since the previous application. Again, limited infestations must be tolerable, but because treatments are more frequent, infestations will be proportionally smaller. The chemical concentration and exposure time should be comparable to end-of-season values, though the total removed biomass will be smaller.

Intermittent treatment. Intermittent chemical use is designed to prevent initial zebra mussel infestation at facilities that cannot tolerate macrofouling. Dosing at frequent intervals (e.g., 6, 12, 24 hr) destroys postveligers that have settled since the previous treatment. Postveligers are more susceptible to oxidizing chemicals than are adults; thus, the concentration of the chemical and exposure times will be considerably less than if adults were the target. Because postveligers with shells about 250 μm long can easily pass through the system, disposal and under-deposit corrosion is eliminated.

Semicontinuous treatment. Semicontinuous treatment is a preventive control method developed by Ontario Hydro. Because zebra mussels will stop filtering and close their shell when exposed to a toxic substance, the utility postulated that frequent on-off cycling of chlorine was more effective than continuous chemical treatments. Treatment schedules can be adjusted to 15 min on and 15 to 45 min off. Chlorination treatments consisting of 15 min on and 15 or 30 min off at the 0.5-mg/ℓ level have been as effective as continuous treatment (Claudi and Mackie 1994). Semicontinuous treatment is ideal for facilities where several discrete systems need to be treated and results in less chemical usage than continuous chlorination.

Continuous treatment. Continuous chemical treatment is designed for facilities that cannot tolerate any level of macrofouling. Low chemical concentrations, applied continuously, prevent any postveliger settlement and is stressful enough to either kill adult mussels or cause them to detach and move out of the system. Continuous treatment should be carried out for the entire zebra mussel breeding season.

Nontarget effects of chlorine. Chlorine, chloramines, and chlorine dioxide are nonselective and highly toxic to nontarget fish and invertebrates. Claudi and Mackie (1994) have provided detailed information on the impacts of chlorination on fishes, invertebrates, and phytoplankton, which can be consulted for guidance. Fish seem to be more negatively affected than are other aquatic organisms (Claudi and Mackie 1994), though literature related to the effects on other aquatic organisms (i.e., invertebrates and phytoplankton) is less abundant. Following chlorine treatment, phytoplankton populations may drastically decrease; however, their recovery is generally rapid.

Besides killing the nontarget organisms, sublethal life parameters of nontarget species that chlorine may affect include behavior, reproduction, growth, and mutagenesis. Claudi and Mackie (1994) stated that the most important aspect of behavior affected by chlorination is avoidance, and fishes have received more attention in the literature with regard to their avoidance of chlorine. Reproduction is a sensitive indicator of sublethal toxicity. Chlorination adversely affects the reproduction of certain nontarget aquatic organisms, and its presence inhibits the growth of both plant and animal species. Chlorine can also react with dissolved organic material to form chlorinated organics, some of which are suspected mutagens.

Dechlorination. Federal and State statutes regulate the concentrations of chlorine that can be released into the environment and require that water samples be analyzed accurately for the presence of free and residual chlorine. A major concern when using chlorine in fresh waters is that it will combine with various organic compounds to form trihalomethanes, which are considered carcinogenic. Stringent requirements are also placed on the level of total residual chlorine allowed in the discharge. Facilities unable to meet TRC water quality limits must dilute the discharge with raw water or neutralize the chlorine prior to release. Sodium sulfite (Na_2SO_3), sodium bisulfite ($NaHSO_3$), sodium metabisulfite ($Na_2S_2O_5$), or sulfur dioxide (SO_2) may be used. The most convenient chemical used to neutralize residual chlorine is sodium bisulfite (sometimes called "liquid sulfite"), with the dosage requirement being a concentration of 1.8 to 2.0 units of sodium bisulfite for each unit of TRC (Claudi and Mackie 1994). Sodium bisulfite can be fed directly into the discharge prior to reintroduction into the water body because the reaction of chlorine with sulfite is almost instantaneous.

Bromine. Several forms of bromine can be used as antifoulants, including activated bromine, sodium bromine, bromine chloride, and proprietary mixtures of bromine and chlorine or other chemicals (e.g., Acti-Brom by Nalco Chemical Company and BromiCide by Great Lakes Chemical Corporation).

Generally, the same precautions for chlorine apply to bromine (Claudi and Mackie 1994). Bromine in all forms has been shown as a more effective oxidizing agent than chlorine when water pH levels are greater then 8.0. Bromine ultimately forms Br^- in aquatic systems; however, the pathways are largely specific to environmental conditions. Furthermore, a single bromine atom may undergo a series of cyclic transformations. Hence, exact mechanisms and temporal relations are not well understood (EPRI 1993). The type of information available for treatment using chlorine is not readily available for bromine or bromine-based products. However, as a rough guide, the amount of total oxidant required would be the same with bromine and chlorine. Bromine has the reputation of being less toxic to nontarget species than chlorine. However, recent data suggest that the toxicity to nontarget species is in fact higher than that of chlorine (Howe et al. 1994).

Ozone. Ozone is a well-known bacterial agent, used in Europe to disinfect drinking water and industrial and municipal wastewater (EPRI 1993). Ozone also improves taste, odor, and color of drinking water and can be used to prevent biofouling. Ozone outperforms chlorine in terms of contact time at comparable residual levels. An Ontario Hydro unpublished report indicated that at 15 to 20 °C, a minimum of 5 hr contact time was required at 0.5 mg/ℓ for a 100-percent mortality of veligers and post-veligers in the water column.[1] Ozone residuals of 0.5 mg/ℓ or greater for 7 to 12 days will cause 100-percent mortality of adult zebra mussels. Time to death is inversely related to both on concentration and ambient temperature.

Ozone is highly explosive, especially when solutions are warmed. Commercial ozone is not available due to shipping problems, and ozone used in water treatment is always generated onsite (EPRI 1993). Ozone is a powerful natural oxidant in the atmosphere, not occurring naturally in surface waters. When released in natural waters, residual ozone concentrations quickly dissipate. Dissipation in raw water is so rapid that, if injected in pipe intakes or forebays, no ozone residual can be found in facility discharge.

Properties of ozone offer both advantages and disadvantages. Ozone treatments do not exhibit downstream environmental impacts, making it attractive for use in once-through systems. This characteristic, however, is undesirable when considering control of downstream zebra mussel settlement and growth. Maintaining sufficient residual ozone levels required to kill adult zebra mussels in an extensive piping system is very difficult and expensive, and multiple injection points would be required.

Potassium permanganate. Potassium permanganate ($KMnO_4$) is another oxidizing chemical commonly used in municipal facilities for water purification. It is widely used for oxidation of iron and manganese and for control of taste and odor problems. Cost and effectiveness have limited municipal use of

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[1] Lewis, D., Van Benschoten, J. E., and Jensen, J. N. (1993). "A study to determine effective ozone dose at various temperatures for inactivation of zebra mussels," unpublished report, Ontario Hydro, Toronto, Canada.

potassium permanganate to control zebra mussels. Unlike chlorine, potassium permanganate does not eliminate the mussels except at high, continuous dosage. The greatest advantage of potassium permanganate use is that it does not produce THMs. Some studies suggest that it can be used against adult zebra mussels, although it is less effective than chlorine (Klerks, Fraleigh, and Stevenson 1993; Claudi and Mackie 1994). In flow-through experiments using 1.0 and 2.5 mg/ℓ potassium permanganate, veliger densities in the outflows of treatment bioboxes were reduced 90 percent from inflow densities. At these concentrations, potassium permanganate also prevented settlement of zebra mussels in the test tanks. In static experiments, Klerks, Fraleigh, and Stevenson (1993) found 27-percent mortality in veligers exposed to 2.5 mg/ℓ of potassium permanganate for 3 hr. These results suggest that potassium permanganate may prevent settlement of zebra mussels, but it is not acutely toxic to the veligers.

Sodium chlorite. Sodium chlorite ($NaClO_2$) solutions appear to have numerous advantages over other chemicals. They have more environment-friendly characteristics, such as the nongeneration of undesired by-products common to the use of chlorine. Their use does not induce increased water oxidation/reduction potential and they are noncorrosive. These solutions are stable and easy to apply with the existing equipment in most industries that commonly use hypochlorite as a treatment. If the concentration and exposure time required for an efficient kill of the mussels could be lowered, there is a great potential for future use of sodium chlorite treatment (Dion, Richer, and Messer 1995).

Sodium chlorite is an oxidant. When dissolved in water, sodium chlorite produces the chlorite ion, ClO^{-2}. The other ingredients in solution set up an oscillation reaction that quickly converts ClO^{-2} to chlorine dioxide (ClO_2) and dichlorine dioxide (Cl_2O_2), which in turn, produces superoxide, O^{-2}, and up to 62 other intermediates. In the oscillation reactions, the intermediates have very short lifetimes that do not allow the formation of undesired by-products, without stopping their known biocidal activity.

For all mussel sizes, increases in treatment concentration above 80-ppm dilution offer no benefit. Even at the highest concentration tested, the time required for 50-percent sample mortality (LT_{50}) is over 10 days. A shock treatment is therefore not a good option for these chemicals.

Nonoxidizing chemicals. Nonoxidizing chemicals are effective in controlling zebra mussels because the organisms appear insensitive to such compounds. In the presence of oxidizing chemicals such as chlorine, zebra mussels will close their valves to avoid the chemical. When nonoxidizing compounds are applied, the valves remain open while water is actively filtered through their gills, exposing the tissues to the toxic actions of compounds even when the chemicals are present in surrounding waters in relatively high concentrations. The toxic actions of the nonoxidizing chemicals prevent the zebra mussel from maintaining its chemical balance, resulting in death.

A number of efficacious nonoxidizing chemicals have been developed to control zebra mussels in raw water systems. Very few of these chemicals have U.S. Environmental Protection Agency (EPA) registration for use in once-through cooling systems. Primarily, there is a concern with the persistence of these chemicals in the environment after discharge. Those that have been registered are used primarily for end-of-season or periodic treatments (Claudi and Mackie 1994).

Nonoxidizing molluscicides. Nonoxidizing molluscicides are one of the primary chemical treatment methods available to control zebra mussels. Nonoxidizing biocides are a group of proprietary chemicals that have been found effective in producing mortality in zebra mussels. Quaternary ammonium compounds are the most frequently used nonoxidizers. A number of chemical companies market these chemicals under various trade names such as Clam-Trol CT-1 (Betz Chemicals), H-130 (Calgon Corporation), Macro-Trol 7326 (Nalco), and poly-quaternary ammonium compound Bulab 6002 (Buckman Laboratories). More recently, a propriety variation of endothall has been tested against zebra mussels and found effective. This product is marketed by Elf Atochem and is being tested as TD 2335 (Claudi and Mackie 1994; Green 1995).

In addition, Mexel 432, a product marketed by RTK Technologies, Inc., of Baton Rouge, LA, has received EPA approval for use as a molluscicide. It is an aqueous dispersion of straight-chain aliphatic hydrocarbons with alcohol and amine functionality. It controls zebra mussels in three ways: (a) on clean surfaces, the film prevents settlement; (b) on infested surfaces, it attacks the byssal thread and inhibits formation of more byssal threads, causing many viable zebra mussels to detach; and (c) it forms a film on zebra mussels that remain in the system, causing lesions on the gill surfaces and, ultimately, death on the organism.

Mexel 432 biodegrades rapidly to harmless substances, necessitating daily dosage to sustain the film. Its half-life in river water is 22 hr at 19 °C. Biodegradation is accelerated by agitation and aeration. Mexel 432 decomposes immediately in the presence of oxidizing agents such as chlorine or ozone (Giamberini, Czembor, and Pihan 1995; Khalanski 1994; Van Donk 1995).

The success of a nonoxidizing zebra mussel control treatment is directly related to the time spent planning the treatment. Procedures should be in place prior to the treatment to overcome any obstacles that may prevent completion. Contingency planning, facility preparation, and accurate chemical application will ensure an effective treatment.

Treatment. Application of nonoxidizers in once-through systems typically consists of short periodic applications during the warmwater season. Depending on the chemical used, permit restrictions, and ambient water temperatures, significant mortality can occur in 4 to 24 hr (Claudi and Mackie 1994; Green 1995). Nonoxidizing treatments are used to cleanse the system of recently settled mussels. Mortality is reported at or near 100 percent (EPRI 1992). Such treatments are effective provided a regular program of periodic treatments is employed.

Because treatments are designed to cleanse the system of any settled zebra mussels, application of nonoxidizing molluscicides is heavily dependent on the history of the local mussel population. Frequency and timing of treatments are established based on the settlement history and veliger population dynamics. Therefore, thorough monitoring programs are essential. A complete veliger monitoring program along with accurate data relating to the lake or river temperature regime will result in an effective and economic treatment schedule.

Normally two or three applications a year have proved sufficient to kill all the mussels in a system. A treatment should, therefore, occur immediately after peak veliger activity and the beginning of settlement evidence. Normally this is approximately 4 to 6 weeks after the veliger peak (Green 1995). Timing a treatment in this manner allows the remaining shells to be flushed through the piping system without causing flow blockage in small pipes, valves, and screens. Scheduling a treatment at this time also ensures that the settled mussels are quite small. An early season treatment is also recommended to cleanse the system of any late season settlement and to prevent any translocaters from becoming established in the piping systems.

Because plant configurations and water volumes vary, several differing strategies can be employed for the application of nonoxidizing biocides. These methods include targeted treatments, entire system treatments, and recirculation treatments (Green 1995). Treatments are coordinated with veliger and mussel settlement data to minimize the frequency of applications.

Treatment of the entire system is recommended for facilities with relatively small water usage. To treat the entire system, the nonoxidizing chemical is added to either the forebay or injected into either the suction or discharge of system pump piping. Forebay addition is preferred. Addition into the forebays should be as far in advance of the pumps as possible to allow for proper mixing to occur and the forebays to be treated.

Targeted treatment should be used by facilities when only select components are fouled by zebra mussels. Facilities may have several raw water systems being fed by a single forebay or intake. Treating the entire system by injection at the intake may be cost prohibitive and environmentally damaging. Targeted treatments are used in the individual fouled systems. Thus, a smaller water volume and a lesser amount of nonoxidizing biocide will be required, multiple systems being supplied by a common forebay. Injection of the nonoxidizing biocide is made either directly in front of the smaller pumps or to the piping pump area.

Large-volume systems that can be isolated are ideal for recirculation type treatments. Recirculation also makes possible the eradication of mussels in the forebays. Once a particular system is isolated from external water contact, the nonoxidizing molluscicide can be added to the system (usually to the forebay) and the water recirculated for a predetermined length of treatment. After the desired time has elapsed, the forebay and discharge bay can be reconfigured and the water system flow paths returned to normal.

Detoxification. Effects of nonoxidizing molluscicides on nontarget species are a major concern. Nonoxidizing chemicals are normally added at dosages that are toxic to zebra mussels as well as other aquatic organisms. Consequently, detoxification is required to meet State and Federal discharge requirements. Bentonite clay, added to the plant discharge upstream of its entry into an aquatic ecosystem, is the standard detoxification agent (Claudi and Mackie 1994; Green 1995). Additional downstream sampling for chemical residuals is a normal permit requirement.

Potassium ions. A number of metallic salts have been tested for toxicity to zebra mussels. Of these, potassium (K^+) may have the greatest potential for use in on-line control of zebra mussel macrofouling. Normal concentrations are between 88 and 228 mg/ℓ, depending on the potassium compound used, permit restrictions, water quality, and ambient water temperature (Fisher 1991). In flow-through experiments, Fisher, Fisher, and Polizotto (1993) found 50 mg/ℓ of potassium chloride prevented settlement of zebra mussels in test chambers.

Potassium compounds are nontoxic to higher organisms, such as fish (Claudi and Mackie 1994). Unfortunately, many native freshwater mussels are even more sensitive to potassium salts than are zebra mussels (tolerance level of 4 to 7 mg/ℓ), making their use and approval for control of mussel fouling in once-through raw water systems unlikely. In closed-loop systems, however, these compounds can be an attractive, economic alternative.

Flocculation. Flocculation is used to remove unwanted suspended particles from drinking water supplies. This process causes small particles to agglomerate into larger particles or floc that is of sufficient size and density to settle. The agglomeration of fine suspended particles is a result of interparticle polymer bridging. Aluminum sulfate (alum) is the flocculent most frequently used in the drinking water industry. Alum will remove zebra mussel veligers by causing chemical toxicity in the mixing zone and by flocculation of both living and dead veligers in other areas. Studies by Mackie and Kilgour (1993) investigated the effect of alum on zebra mussel veligers. Mackie and Kilgour (1993) found that the alum concentrations used in most water treatment plants (i.e., 20 to 50 ppm) is not sufficient to kill zebra mussel veligers. Studies indicated that the lethal alum concentration for 50-percent mortality is near 126 ppm. Most veligers remain alive for at least 24 hr in the floc at concentrations below 100 ppm. The studies also indicated a pH below 5 caused by the addition of alum, especially in the area of alum addition (mixing zone), caused instantaneous kill of veligers. Mackie and Kilgour (1993) also found that the role of alum in removal of veligers appeared to be mainly a physical one, with the floc physically removing even living veligers. Prechlorination improves the efficacy of alum in removing veligers from raw water supplies. Flocculation may be an appropriate zebra mussel mitigation treatment for some drinking water plant intakes, provided that flocculation does not cause sediment formation problems in the intake (Claudi and Mackie 1994).

Thermal treatment

Thermal treatment is generally an accepted nonchemical mitigation technology to alleviate macrofouling of raw water system by invertebrates. For the zebra mussel and other macrofouling species, the upper lethal thermal limits on which thermal mitigation strategies are based have generally been determined as either the acute upper lethal temperatures or the chronic upper lethal temperatures (McMahon et al. 1995). The reduced thermal tolerance of zebra mussels relative to other North American biofouling species makes the mollusc more susceptible to thermal mitigation.

Thermal treatment is a cost-effective and efficient method for zebra mussel control. Most regulatory authorities regard heat treatment as a more environmentally safe and benign method than chemical treatment; however, restrictions on the discharge of heated water have to be taken into account. The zebra mussel is capable of extensive temperature acclimation, affecting both its acute and chronic lethal temperature limits. Thus, regardless of the thermal treatment strategy employed, a raw water system will need to be heated to higher temperatures to achieve 100-percent eradication of mussel infestations during summer months when source water temperatures are elevated than in winter months when source water temperatures decline. Initiating either chronic or acute thermal treatments during periods when water temperatures are below maximum summer levels may significantly reduce both the exposure time and treatment temperature required to achieve 100-percent kills of zebra mussels. Also important is the fact that smaller zebra mussels have greater thermal tolerance than larger mussels. Because of their higher thermal tolerance, infestations consisting primarily of smaller individuals (the usual case if a raw water system is subjected to annual or biannual mitigation treatments) will require higher treatment temperatures and/or longer exposure times to induce the desired mussel kill (McMahon et al. 1995).

Acute thermal treatment. Acute upper lethal temperatures are defined as the temperature at which death occurs when water temperature is raised at a specific rate. Heating of raw water systems to the acute lethal temperature of zebra mussels followed by rapid return to normal operating temperatures is a promising thermal mitigation technology for zebra mussel macrofouling (McMahon et al. 1995). Use of acute upper lethal temperature treatment to mitigate zebra mussel fouling is most applicable in raw water systems where lethal temperatures are difficult or inefficient to maintain for extended periods. In these systems, increasing water temperature to a level that induces an instantaneous 100-percent mussel mortality followed by return to normal operating temperatures is more practical. Acute thermal treatment, which does not require precise, long-term regulation of elevated temperatures, has been proposed for raw water systems where operation above normal water temperatures for prolonged periods reduces efficiency and increases component wear, making chronic thermal treatment of zebra mussels economically infeasible. Acute thermal mitigation may also be particularly applicable for use in off-line components such as intake embayments heated by steam injection of other means.

The acute upper lethal temperature of zebra mussels is affected by both the acclimation or ambient water temperature and the rate at which the temperature rises and induces instantaneous death. The temperature at which instantaneous death ensues increases with increased acclimation temperature and increased heating rate. McMahon et al. (1995) studied the relation of acclimation temperature and rate of temperature increase versus zebra mussel mortality. The time to achieve 100-percent sample mortality (SM_{100}) was recorded, and the time required for induction of 50-percent (LT_{50}) and near 100-percent mortality (LT_{100}), respectively, at a given test temperature, were estimated. McMahon et al. (1995) found a relation between intake water temperature and system heating rate to a suite of temperatures that would yield 100-percent instantaneous mortality (i.e., SM_{100}). Thus, the maximum temperature required for 100-percent mussel kill would be 41 °C if mussels were maximally acclimated to 25 °C and subjected to rapid heating rate of 1 °C/5 min. Figure 4 plots the time required for 100-percent sample mortality versus acclimation temperature for heating temperature of 35, 36, and 37 °C.

Chronic thermal treatment. Zebra mussel thermal mitigation strategies based on the chronic upper thermal limits of the organism involve continuous exposure to constant lethal temperatures for durations sufficient to achieve significant mortality. Chronic thermal treatment for mitigation of zebra mussel infestations is most applicable to industrial and steam-electric power station raw water systems that generate heated discharge water and are designed to recirculate or backwash heated effluent into their intakes to maintain operating temperatures at relatively constant, elevated, lethal levels for prolonged periods.

The exposure time of chronic thermal treatments is affected by both the acclimation water temperature and the treatment water temperature. The required exposure time increases as the acclimation temperature increases and treatment temperature decreases (McMahon and Ussery 1995). Mitigation treatment with temperatures greater than or equal to 34 °C could induce near 100-percent kills of zebra mussels infestations within 6 to 26 hr depending on the prior acclimation/operating temperature (McMahon and Ussery 1995). At treatment temperatures ranging from 34 to 37 °C, exposure times required for 100-percent kill of zebra mussel are short enough to be cost-effective; application temperatures are low enough to prevent major loss of production or excessive equipment wear and/or malfunction; and discharge temperatures are likely to be low enough to meet the discharge temperature restrictions of State and/or Federal regulatory agencies (EPRI 1992; Claudi and Mackie 1994).

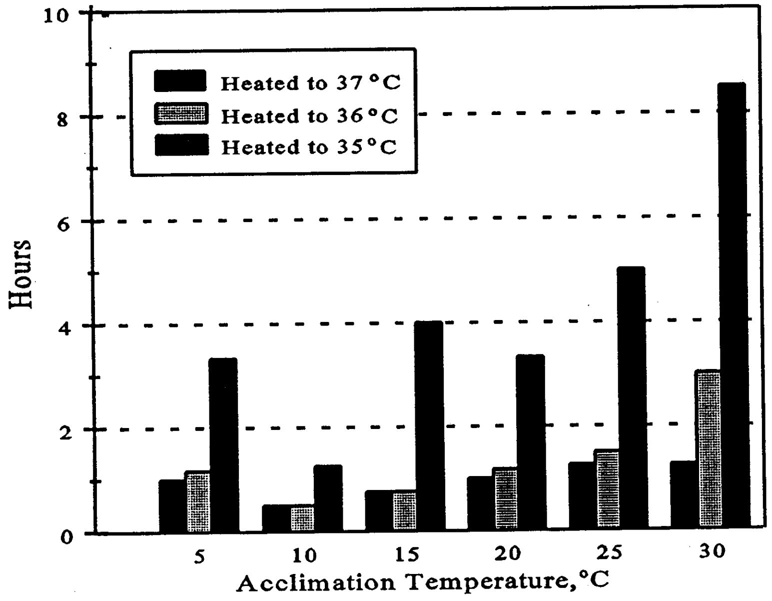

Figure 4. Time required for 100-percent zebra mussel mortality with respect to acclimation temperature (adapted from McMahon et al. 1995)

Mechanical filtration

Conventional water traveling screens, in-line debris filters, strainers, and ultrification can be effective for blocking adult mussels and shells. Typical screen mesh openings (3- to 10-mm) and filter or strainer opening size (3- to 5-mm) are too large to block mussel veligers; however, these screens and filters can be obtained in sizes suitable for the largest once-through circulating water systems down to small raw water makeup systems (EPRI 1992). Although screens and filters can control the carry-over and carry-through of translocators and shells from the intake to the downstream piping system, they cannot control the growth of mussels within the piping system. Ultrafiltration (40-μm) is a feasible zebra mussel veliger control technology for small-flow cooling water systems (Claudi and Mackie 1994; EPRI 1992; Smythe and Short 1995). Rigden (1993) reported on filters with 25- and 40-μm mesh screens. After testing in adverse conditions such as high turbidity, the filters successfully stopped all zebra mussel veligers using either of the screens. Other filtration tests (e.g., Dardeau and Bivens 1995; Smythe and Short 1995) are currently underway.

Traveling screens at raw water intakes are effective at blocking the passage of adult zebra mussels into raw water intakes. Traveling screens in either the through-flow or dual-flow configurations are typically located downstream from trash racks. Baskets with screen mesh are mounted on a vertically rotating chain and continuously screen the flowing intake water. Mesh openings are usually small enough to collect adult zebra mussels, though veligers are not blocked. As baskets travel along the rotation cycle, they are exposed to air and subjected to water jet cleaning. Debris and shells washed from the screen are carried off in discharge flow. This system allows for uninterrupted, unobstructed screening.

Because traveling screen mesh openings are too large to restrict the flow of mussel veligers, they do not prevent subsequent infestations within the piping systems. Traveling screens should, therefore, be used in conjunction with other control strategies for the protection of water intakes. In addition to the cyclic areal exposure and spray cleaning, screens can be kept unfouled by using nonmetallic, smooth screen baskets, or antifoulant-coated baskets. Water spray pressure should be in the 550-kPa range for effective cleaning (EPRI 1992).

Reactive Control Methods

Several reactive control methods have proved to be effective for zebra mussel control. Scraping, scrubbing, pigging, high-pressure water, and carbon dioxide pellet blasting are all procedures that will detach zebra mussels from affected components. Freezing, desiccation, and chemicals are not the only effective means of killing zebra mussels that also facilitate removal of dead organisms and shell material.

Mechanical cleaning

Mechanical removal of zebra mussels using wire brushes, scrapers, or other physical means is effective. However, manual means are generally less cost effective than the preventive type of control methodology because they must be repeated at regular intervals, and removal and disposal of zebra mussel shells need to be considered (Figure 5).

Pigging systems involve forcing plugs (pigs) through mussel-infested lines to scrape mussels from pipe walls, forcing them out in front of the advancing pig. Pigs can be forced through lines by gas or fluid pressures or by hauling on cable systems. For smaller intakes (< 60 cm), mechanical pigging operations may be the method of choice. Pigs are available in a wide variety of designs and are manufactured to clean pipes up to 180 cm in diameter. Generally, the piping will need some modifications to provide entrance and exit capabilities (Claudi and Mackie 1994).

High-pressure water jet cleaning

Water jets with pressures between 27,600 to 68,900 kPa are recommended for the removal of zebra mussels (Wong 1991). Precautions should be taken

Figure 5. Removal of zebra mussel shell debris by vacuum hose (photographed by Peter Yates)

to ensure correct operation of the equipment for safety purposes and to avoid removing material other than zebra mussels. The standoff distance (mussel-infested surface to tip of water jet nozzle) is important to the efficient operation of the water jet method. The greater the standoff distance, the less effective the cutting action of the water. Water jetting can be performed underwater. Figure 6 illustrates a typical water jetting operation.

Carbon dioxide pellet blast cleaning

Carbon dioxide pellet blasting is similar to sandblasting except that carbon dioxide pellets are used instead of sand. Carbon dioxide pellet blasting is preferred over conventional sandblasting, because sand removes only the zebra mussel outer shell exposing the soft inner tissues, which absorb the pressure. Unlike sandblasting, this method removes more organic material and is less likely to damage the surface. The method has been used extensively to remove organics from aircraft, producing no deterioration of surfaces. In confined areas where the removal of sand is a problem, no additional material must be removed since carbon dioxide pellets readily vaporize. Carbon dioxide pellet blasting cools the zebra mussels, making them brittle and more easily removed. When solid carbon dioxide is converted to gas, it penetrates voids and the area of zebra mussel attachment, lifting the organism off the surface.

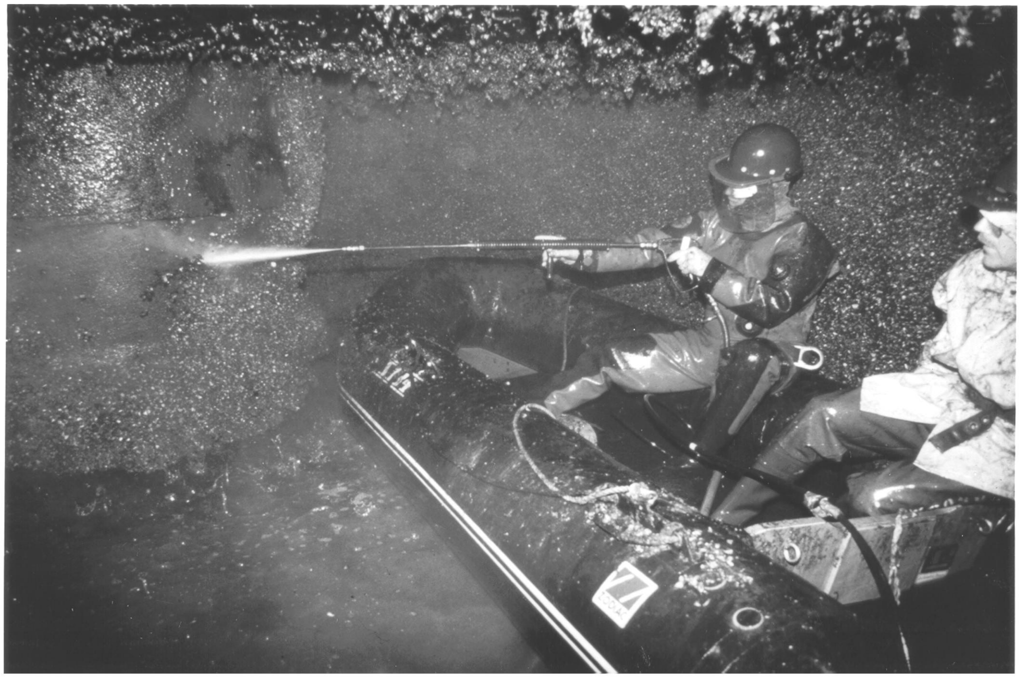

Figure 6. **Water jetting being used to clean pump room (photographed by Peter Yates)**

Freezing/desiccation

Water levels can be drawn down in impoundments to expose resident mussel infestations to air. Subsequent freezing during the winter or desiccation at high summer temperatures can be effective in killing a large proportion of the exposed population. The majority of the zebra mussel population could be exposed by lowering water levels since the mussels are usually restricted to shallow areas above the thermocline.

Zebra mussels can be effectively controlled by winter drawdown and exposure to subfreezing air temperatures (Payne 1992a). Clustered mussels are more tolerant of reduced air temperatures than are individual organisms. Exposure time for loo-percent mortality of individual mussels range from 15 hr at -1.5 °C to less than 2 hr at -10 °C. For clustered mussels, these times range from over 48 hr at - 1.5 °C to 2 hr at - 10 °C (Payne 1992a). Figure 7 illustrates exposure times required for loo-percent mussel mortality in air temperatures ranging from - 10 to 0 °C.

Zebra mussels can also be effectively controlled in the summer by desiccation, although exposure times are longer than in winter months. Temperature is positively related and humidity negatively related to zebra mussel mortality. To ensure loo-percent mortality, aerial exposure must last nearly a month at moderately low temperature (5 °C) and high humidity (95-percent) but only 2 days at moderately high temperature (25 °C) and extremely low

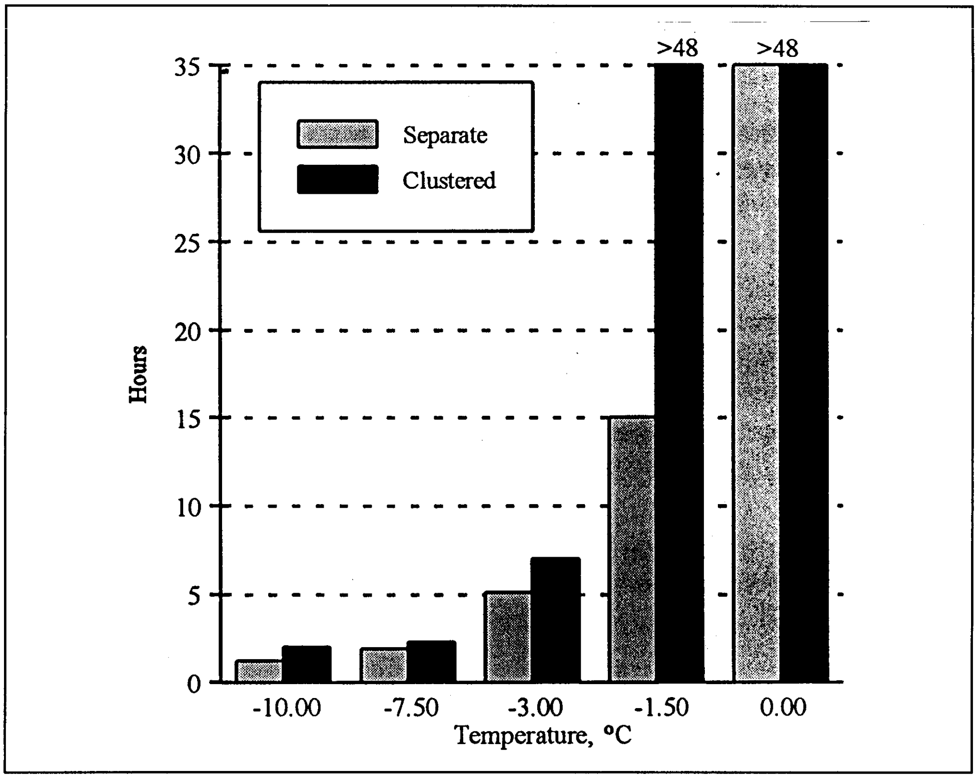

Figure 7. Freezing air exposure time required for 100-percent zebra mussel mortality (Payne 1992a)

humidity (5-percent). However, even at high humidity (95-percent), 100-percent mortality is expected in approximately 5 days at 25 °C (Payne 1992b).

Backwash of water supply piping

Properly located flushing valves and piping arrangements that allow on-line high-velocity (3 mps) backflushing of low-flow sections of pipe can be very effective in flushing zebra mussels (EPRI 1992). In areas of piping where on-line flushing is not feasible, flushing valves that allow flushing of sections of pipe during shutdown using an external source of water can also be used. The backwash cycle can be designed to engage automatically for several minutes prior to the system being activated.

Prospective Control Methods

Prospective control methods and new designs such as water intake retrofit, infiltration intakes, acoustics, electric fields, and ultraviolet light (UV light) can be engineered into existing or future facilities. These new designs may prevent future zebra mussel-related problems.

Water intake retrofit

Options other than completely draining all pipes in a raw water system include isolating and dewatering the intake only or providing an undesirable intake water environment when the system is out of use. Installation of a swivel joint on smaller diameter intakes permits the intake to be lifted out of the water (dewatered) when the pump is not in use. This design modification exposes the intake pipe to ambient aerial conditions and, subsequently, leaves residual water in the system stagnant. Other methods to produce undesirable water environments include the placement of a larger pipe over the intake and angled 90 deg downward to produce a still well effect or the lowering of a larger pipe sealed at the upper end to trap air over an intake facing upward, exposing the intake to the atmosphere. In any of these three cases, the intake pipes would have to be uncovered or returned to operating position before use.

Infiltration intakes

Infiltration intakes may be an effective control strategy for new intakes serving facilities such as small drinking water plants, where the total volume of water used is modest. Using naturally layered soils or constructed layers, infiltration intakes draw water through porous layers. Apart from construction impacts, infiltration intakes are considered environmentally benign. Several different infiltration intake designs exist, including sand-filtration methods and Ranney wells.

Filtration is used in water treatment for removing suspended solids and zebra mussel veligers by use of graded granular media. Common granular materials used for filter media are sand, anthracite coal, activated carbon, resin beads, and garnet. Coarse filter material for the removal of larger particles and debris make up the upstream or top layers. Subsequent layers are composed of finer media with higher specific gravities for the removal of finer particles.

Ranney wells intercept and collect groundwater derived principally from surface-water infiltration. Ranney wells are most suitable in areas having subsurface sand and gravel deposits that are hydraulically connected to surface sources such as rivers and lakes. Most designs consist of protected vertical conduit sunk to depths up to 60 m with horizontal perforated pipe extending radially. The filtering capabilities of the soil eliminate zebra mussel infestation.

Regional and local hydraulic/hydrologic conditions, the availability of space, and flow requirements must be addressed when considering infiltration systems. To obtain a large amount of filtered water, infiltration intakes of huge dimensions would have to be constructed. Initial costs, including feasibility studies, design, and implementation, are high. The feasibility study and design process consider variables such as raw water quality, proximity to sources of high turbidity, water volume, and pressure drops. Infiltration intakes are not maintenance free. Granular filters are generally backflushed with filtered water or periodically have the top layer, which captures all extraneous material, removed. For a general discussion of infiltration intakes and other types of filtration systems, see Smythe and Short (1995).

Acoustics

The use of sound energy (acoustics) is developing as a zebra mussel control strategy, though investigations of its effectiveness have been inconsistent and more research is needed to adequately develop this strategy. Acoustics has several potential advantages over other methods; it is less likely to kill nontargeted organisms, has no obvious residue effects, and equipment can be installed relatively easily (Kowalewski, Patrick, and Christie 1993). There are three major approaches to using acoustic energy:

a. *Cavitation.* The formation and collapse of microbubbles. Such bubble formation occurs at the rarefaction phase of pressure in a highly intensive ultrasonic wave or in high-velocity turbulent water flow.

b. *Sound treatment.* The use of waterborne acoustic energy (acoustic waves) having an intensity below the cavitation threshold. These include sound (20-Hz to 20-kHz) and ultrasound (above 20-kHz) waves. The sound waves having frequency below 1 kHz are called low-frequency sound.

c. *Vibration.* The use of solid-borne acoustic energy (vibration) in mechanical structures (pipes, walls, etc.).

Kowalewski, Patrick, and Christie (1993) conducted experiments on the effectiveness of using acoustic energy (3- to 18-kHz) as a potential control measure for zebra mussels. Experiments using solid-borne sound at sonic frequencies were effective in preventing attachment of juvenile mussels in a pipe section. In the 8- to 10-kHz range, with acceleration of vibration to about 150 m/sec^2, nearly 100-percent control (i.e., detachment) and 75- to 95-percent mortality was achieved. In the 10- to 12-kHz range, almost 100-percent unattachment and mortality occurred at vibration accelerations exceeding 200 m/sec^2. Although vibration amplitude needed for effectiveness appeared to increase with frequency, these were well within the permissible limits for normally operating equipment such as piping.

Donskoy and Ludyanski (1995) studied the effectiveness of low-frequency sound techniques to control zebra mussel fouling. Sound treatments were found to stress and immobilize the veligers, causing them to drop out of the water column. Treatments using a combination of sound energy and vibration exposure caused a higher rate of mortality than sound treatment alone. Veligers responded to sound energy by the loss of their free swimming ability and subsequent sinking to the bottom. The vibration energy traveling in the pipe mechanically dissipated the immobilized veligers. This control strategy was found to be most effective in low-frequency range (below 200 Hz). Low-frequency sound was also effective in limiting the settlement of translocators into the study volume.

From their research, the following results of acoustic techniques, applied frequencies, and mussel life stages can be inferred (Donskoy and Ludyanski 1995):

a. Ultrasonic cavitation at frequencies between 10 and 380 kHz have been shown to kill veliger, juvenile, and adult zebra mussels.

b. Sound treatments of low frequency (<500 Hz) have proved effective against zebra mussel veligers.

c. Vibration treatments are effective below 200 Hz and between 4 and 100 kHz against zebra mussel juveniles and below 200 Hz and between 10 and 100 kHz against zebra mussel veligers.

These results indicate that with further development, acoustic energy may be a practical mitigation strategy against mussel attachment in water handling facilities. There is a concern, however, about the destructive effect of vibration on structures, especially in the vicinity of the vibrator attachment. Further studies are necessary.

Electric fields

Electric methods have been tested and considered as possible proactive controls. Some research has been directed towards killing the mussels using electricity. Other research has attempted to find methods that do not necessarily kill mussels, but that will affect their behavior. These latter studies examined direct or alternating currents applied over a wide range of voltage intensities (e.g., pulse power and cathodic protection approaches). Although these studies produced inconsistent results, some were promising.

Smythe et al. (1995) stated that electric fields can stun postveligers and affect the settlement behavior of the zebra mussels. Peak pulse power direct current (DC) signals of 15.75 and 26.2 V/cm appeared to have had a reasonably large and significant effect on mussel settlement behavior with settlement reduction between 78 and 88 percent and 83 to 88 percent, respectively. Alternating current (AC) voltages higher than 39 V/cm produced reductions in settlement as high as 35 percent. Fears and Mackie (1995) tested the efficacy of systems that use low-voltage AC for preventing settlement and attachment by zebra mussels. They found that 3 V/cm with steel rods on both wood and concrete surfaces and with steel plate trash bars completely prevented settlement of both new recruits and translocators. Partial prevention of settlement at 2 V/cm with steel rods on both wood and concrete surfaces and steel plates was observed. In contrast, EPRI (1992) reported on previous studies indicating that to be effective, voltage should be in the 700- to 800-V/cm range. Lange et al. (1993) reported that field strengths of up to 17 V/cm with a corresponding veliger exposure time of 0.1 sec had little or no effect on zebra mussel attachment.

Investigations have focused on the prevention of colonization by young zebra mussels using a modified impressed current cathodic protection. Lewis and Pawson (1993) found that current densities of approximately 20, 40, and 50 mA/m^2 did not provide complete protection from zebra mussel settlement, though significant protection was accomplished at approximately 50 mA/m^2. Additional tests at higher electric current densities are being conducted.

Ultraviolet (UV) light

UV light (wavelengths between 40 and 4,000 Å) is a prospective zebra mussel control method. Chalker-Scott et al. (1993) found that both zebra mussel veligers and adults are sensitive to UV-B radiation (2,800-3,200 Å), provided that the radiation is applied constantly. EPRI (1992) reported that veliger mortality was 42 percent after 1 hr, 85 percent after 2 hr, and 100 percent after 4 hr exposure to UV-B radiation.

EPRI (1992) stated that large UV units are now available to treat flow rates of up to 2.5 m^3/sec. UV lamps can be installed in the intake bay or a pipe perpendicular to the flow or along sidewalls to control zebra mussels. Water with high suspended loads and high turbidity limit the depth at which light wavelengths can penetrate the water column, reducing the effectiveness of UV light. A possible impact, although no environmental impacts as predicted are expected from the UV treatment, is that nontarget species also may be killed. UV light is most applicable in medium-sized service water systems and other smaller raw water systems.

3 Hydropower Facility Components at Risk

Several components of a hydropower facility may be affected by zebra mussels. Figure 6 shows an infestation at the condenser cooling unit at the Detriot Edison Power Plant; there was a heavy zebra mussel infestation on all surfaces. Figure 8 is a closer view of this same infested surface. These components include trash racks, penstocks, turbine headcovers, imbedded piping, raw water cooling systems, instrumentation, gates, and fish ladders. The problems associated with each component are described below along with suggested control strategies.

Raw Water Systems

Raw water systems provide water for generator and turbine oil coolers, air coolers, turbine shaft seals, and fire protection. Because of the low flow rate and the fact that these systems may lie dormant for long periods of time, zebra mussel infestations can become a major problem. Adult mussels and shells can clog piping, valves, screens, and other components of raw water delivery systems, which could result in major problems, including complete shutdown. Suggested control methods include conversion of open raw water systems to closed systems to halt the introduction of veligers. Local municipal water supplies could be used as facility cooling water. Using air-cooled instead of water-cooled equipment within the system would also eliminate a source of infested water to the system. In addition, cleaning with hot water or steam, injection of chlorine at or near intake, or cleaning manually are all control strategies that could be applied.

Instrumentation

Instruments at a hydropower facility include head and tailwater gauges and other raw water contact devices. These instruments are small, sensitive devices that can easily become macrofouled by zebra mussels, causing

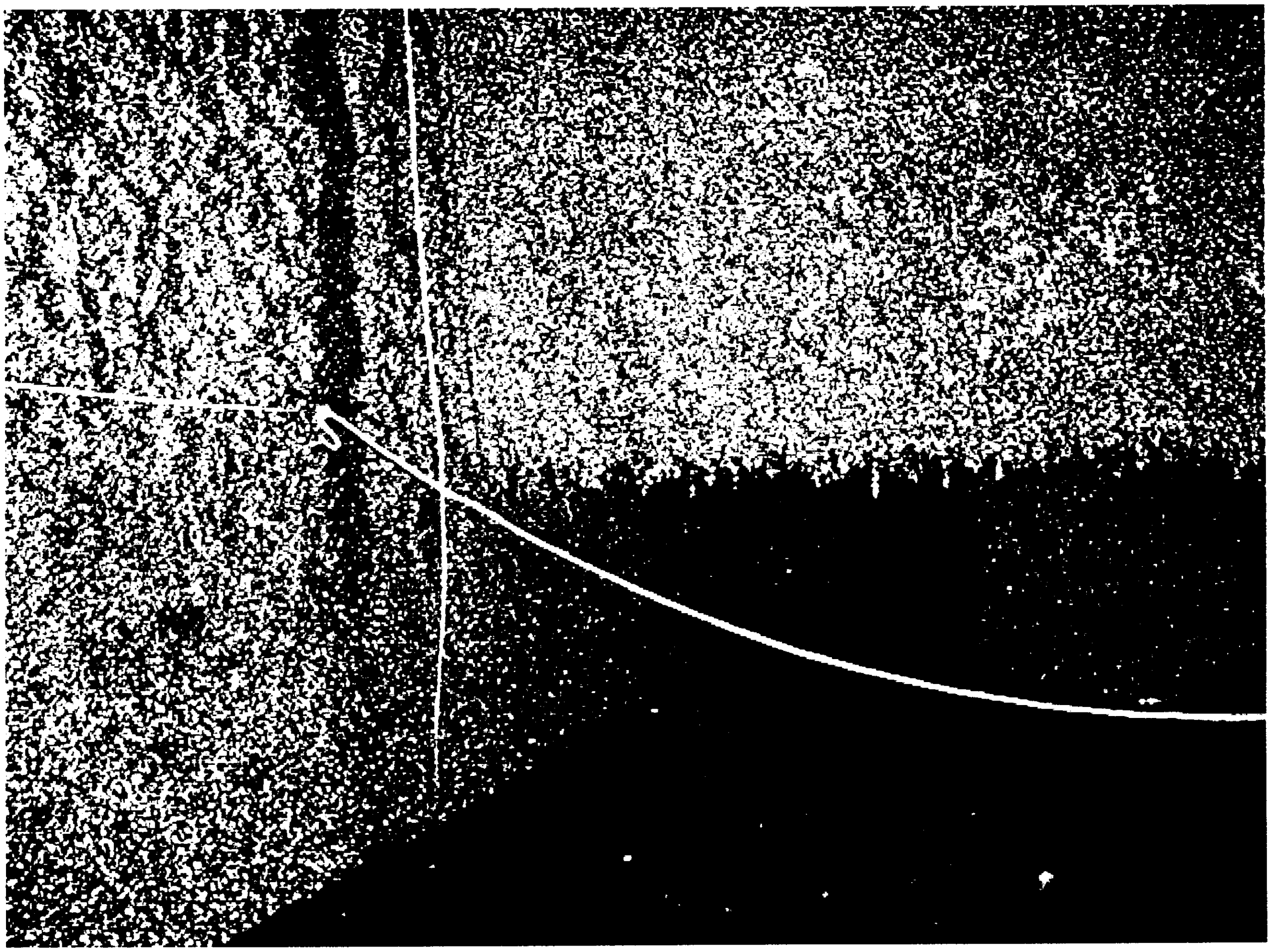

Figure 8. Closer view of the zebra mussel infestation that caused shutdown of the Detroit Edison power plant for cleaning (photographed by Peter Yates)

significant plant operational problems. Control strategies include hot water injections and chlorine injections on the instrument. In addition, application of heat tape to exposed pipes, replacement of contact instruments with non-contact instruments, and coating with antifouling compounds are other options.

Imbedded Piping

Imbedded piping located throughout the plant can easily become fouled by zebra mussels, causing blockage of flow and the prevention of system operation (Figure 2). In addition, the corrosion of metallic surfaces, poor joint sealing, erosion and abrasion of seals, increased maintenance, poor flow distribution, and increased loads on pumps are all problems associated with macrofouled imbedded piping. Fortunately, these are primarily internal systems and thermal treatment or chlorination treatment can be used to control fouling.

Turbine Headcovers

Turbine headcovers can easily become macrofouled by zebra mussels. Control strategies for turbine headcovers include hot water wash, antifouling coatings, chlorine wash, and manual cleaning.

Trash Racks

Trash racks are exposed to all organisms present in a stream or lake and are prone to biofouling by zebra mussels (Figure 9). Trash racks can be manually cleaned or coated with antifouling compounds.

Penstocks

Penstocks are normally equipped with a gate system and a surge tank. Flows are large with a major portion of the water supply flowing through the penstock system. Flow in penstocks is regulated by turbine operation and is nil when turbines are not in service. Control strategies include hot water wash, manual cleaning, antifoulant coatings, and desiccation.

Gates

Flap gates at the downstream end of pipes that discharge into streams, lakes, or other drainages are not only susceptible to infestation but are also often difficult to inspect. If a flap gate becomes fouled with zebra mussels and associated debris so that it does not close, floodwaters will enter protected areas at high river stages.

Facility operators should carefully inspect flap gates at least once a year when water temperature is greater than 12 °C. The inspection should include the outer portion of the gate, the hinges, and the downstream end of the pipe. If not observed in these areas, zebra mussels are unlikely to exist farther up the pipe. If the flap gate is underwater or in a difficult area to inspect, attach a section of PVC pipe or plate (an appropriate test substrate) and a concrete or ceramic tile to a nylon rope or cable in a protected area near the flap gate. Zebra mussels will attach to the test substrate, which can be easily pulled out of the water and inspected.

Zebra mussels can be removed from the flap gate and adjacent piping with a wire brush, high-pressure water, scrapers, or by other physical means.

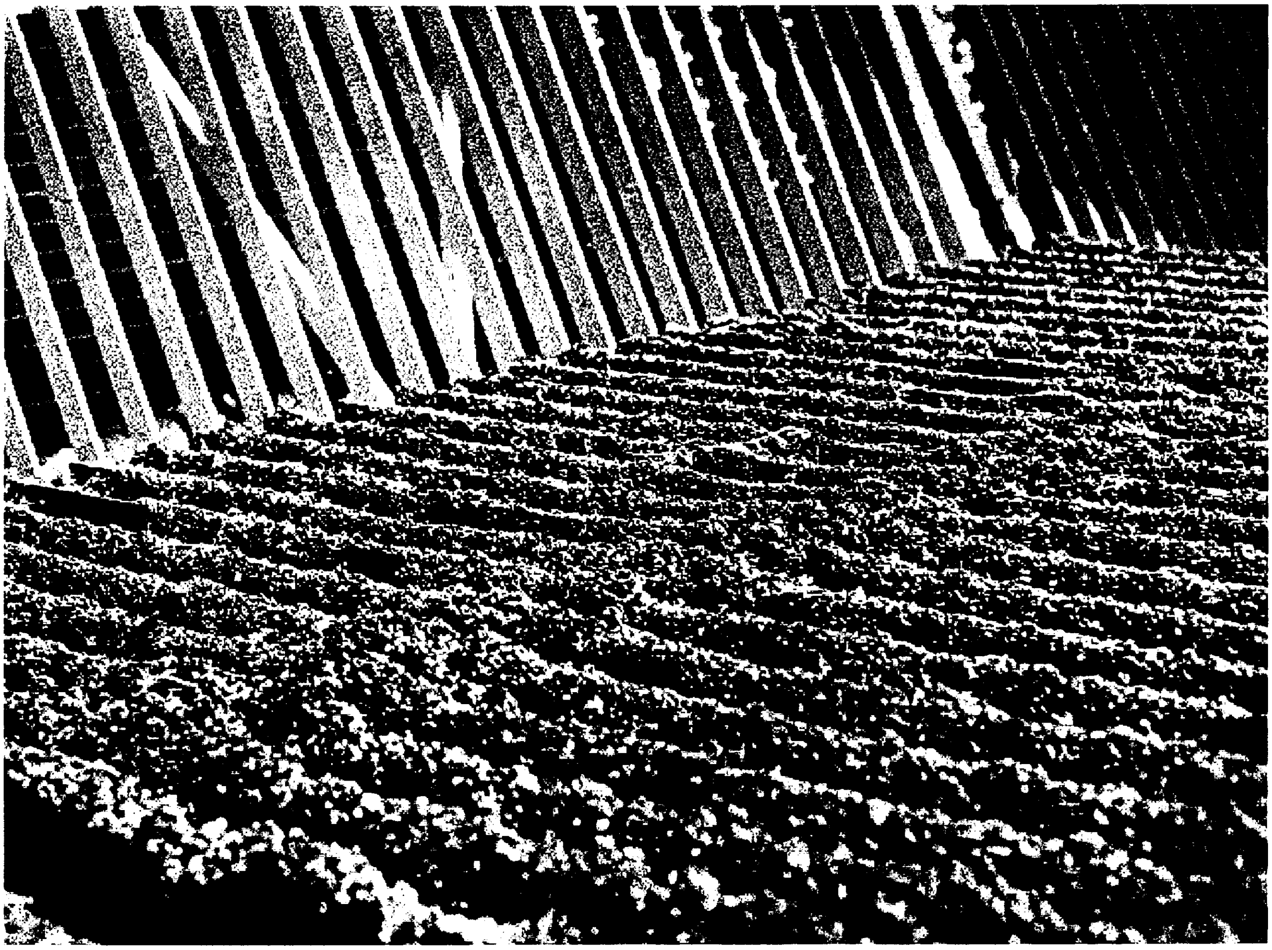

Figure 9. Trash rack covered with zebra mussels

Surfaces can be coated with nontoxic foul-release paint with a slick surface that zebra mussels do not remain attached to during high flow. Alternatively, toxic antifouling paints could be applied.

Water Supply Withdrawal

Various hydropower facilities supply water to the local area for municipal use, fish hatcheries, irrigation, and other requirements. These systems are just as susceptible to zebra mussel infestations as are hydropower facilities. Control strategies include parallel lines, desiccation, chlorination, and manual cleaning. The user should have a plan for potential zebra mussel infestations and be informed when zebra mussels have been detected at the source hydropower facility.

Applicable Control Methods

Applicable zebra mussel control methods include both preventive and reactive strategies. Preventive control methods include toxic construction materials, antifouling coatings, chemical treatments, thermal treatment, and mechanical filtration. Reactive control methods, those applied after infestations have been detected, consist of mechanical cleaning, high-pressure water jetting, carbon dioxide pellet blasting, freezing, and desiccation. Thermal treatment and chlorination use can be initially used as a reactive treatment to clean a system, then preventively as regular maintenance to prevent further fouling. These options, coupled with new designs, retrofit, and prospective control techniques are reviewed in this chapter. Table 2 lists the facility components most susceptible to zebra mussel infestations and applicable control strategies.

Reasons for acceptance or rejection of zebra mussel control methods are varied. Criteria for selecting an appropriate control method include environmental and economic concerns and ease of application. Multiple control strategies may apply to a given zebra mussel infestation, though the strategy of choice will be the most cost-effective, environmentally sound, and easy to apply.

Table 2
Control Strategies Appropriate for Hydropower Facilities

Component	Control Strategies
Raw Water Systems	*Preventive*
	Closed System - Designed to halt introduction of veligers.
	Noncontaminated Water Source - Use water from a source known to be free of zebra mussel adults and veligers (i.e., stored water, city water, well water).
	Equipment Modification - Use air-cooled equipment.
	Mechanical Filtration - A number of filter and strainer components are available for zebra mussel control.
	Chemical Treatment - There are a wide variety of chemical treatments using oxidizing and nonoxidizing chemicals, which vary in concentrations, durations, and lethality.
	Thermal Treatment - Raise the isolated volume of water to or above 38 °C for 1 hr (41 °C for southern region).
	Copper Piping - Retrofit piping systems with copper, copper alloys, or galvanized piping.
	Reactive
	Thermal Treatment - Raise the isolated volume of water to or above 38 °C for 1 hr (41 °C for southern region).
	Chemical Treatment - There are a wide variety of chemical treatments using oxidizing and nonoxidizing chemicals, which vary in concentrations, durations, and lethality.
	Component Replacement - Replace fouled component. Replacement of component should take zebra mussels toleration into consideration.
	Manual Cleaning - Use scrapers or pigs.
Instrumentation	*Preventive*
	Antifouling Coatings - Use Coating System A or B.
	Chemical Treatment - There are a wide variety of chemical treatments using oxidizing and nonoxidizing chemicals, which vary in concentrations, durations, and lethality.
	Reactive
	Chemical treatment - There are a wide variety of chemical treatments using oxidizing and nonoxidizing chemicals, which vary in concentrations, durations, and lethality.
	Mechanical Cleaning - Any method, such as scraping, high-pressure water jet cleaning with pressure between 27,600 and 68,900 kPa, or carbon dioxide pellet blasting.

(Sheet 1 of 3)

Table 2 (Continued)

Component	Control Strategies
Imbedded Piping	*Preventive*
	Chemical Treatment - There are a wide variety of chemical treatments using oxidizing and nonoxidizing chemicals, which vary in concentrations, durations, and lethality.
	Thermal Treatment - Raise the isolated volume of water to or above 38 °C for 1 hr.
	Reactive
	Chemical Treatment - There are a wide variety of chemical treatments using oxidizing and nonoxidizing chemicals, which vary in concentrations, durations, and lethality.
	Mechanical Cleaning - Any method, such as scraping, high-pressure water jet cleaning with pressure between 27,600 and 68,900 kPa, or carbon dioxide pellet blasting.
	Thermal Treatment - Raise the isolated volume of water to or above 38 °C for 1 hr (41 °C for southern region).
Turbine Headcover	*Preventive*
	Thermal Treatment - Raise the isolated volume of water to or above 38 °C for 1 hr.
	Antifouling Coatings - Use Coating System A or B.
	Chemical Treatment - There are a wide variety of chemical treatments using oxidizing and nonoxidizing chemicals, which vary in concentrations, durations, and lethality.
	Reactive
	Thermal Treatment - Raise the isolated volume of water to or above 38 °C for 1 hr.
	Chemical Treatment - There are a wide variety of chemical treatments using oxidizing and nonoxidizing chemicals, which vary in concentrations, durations, and lethality.
	Mechanical Cleaning - Any method, such as scraping, high-pressure water jet cleaning with pressure between 27,600 and 68,900 kPa, or carbon dioxide pellet blasting.
Trash Racks	*Preventive*
	Antifouling Coatings - Use Coating System A or B.
	Reactive
	Mechanical Cleaning - Any method, such as scraping, high-pressure water jet cleaning with pressure between 27,600 and 68,900 kPa, or carbon dioxide pellet blasting.
Penstocks	*Preventive*
	Antifouling Coatings - Use Coating System A or B.

(Sheet 2 of 3)

Table 2 (Concluded)

Component	**Control Strategies**
Penstocks (Continued)	*Reactive*
	Thermal Treatment - Raise the isolated volume of water to or above 38 °C for 1 hr.
	Desiccation - Aerial exposure of the organisms during a period of inactivity.
	Mechanical Cleaning - Any method, such as scraping, high-pressure water jet cleaning with pressure between 27,600 and 68,900 kPa, or carbon dioxide pellet blasting.
Gates	*Preventive*
	Antifouling Coatings - Use Coating System A or B.
	Reactive
	Mechanical Cleaning - Any method such as scraping, high-pressure water jet cleaning with pressure between 27,600 and 68,900 kPa, or carbon dioxide pellet blasting.
Water Supply Withdrawal	*Preventive*
	Parallel Lines - Allows system maintenance without shutdown.
	Chemical Treatment - There are a wide variety of chemical treatments using oxidizing and nonoxidizing chemicals, which vary in concentrations, durations, and lethality.
	Reactive
	Mechanical Cleaning - Any method such as scraping, high-pressure water jet cleaning with pressure between 27,600 and 68,900 kPa, or carbon dioxide pellet blasting.
	Chemical Treatment - There are a wide variety of chemical treatments using oxidizing and nonoxidizing chemicals, which vary in concentrations, durations, and lethality.
	Desiccation - Aerial exposure of the organisms during a period of inactivity.

(Sheet 3 of 3)

4 Public Facility Components at Risk

Public facilities susceptible to zebra mussels include water intakes, raw water systems, pumping stations, instrumentation, and reservoir level control structures. This chapter also details each component of concern and applicable zebra mussel control methods.

Water Intakes

Components of water intake facilities that could be infested with zebra mussels include the crib, intake pipe, and screens (McMahon, Ussery, and Clarke 1994). Figure 10 is a screen clogged with zebra mussels. Live mussels can cause flow reductions; however, the presence of zebra mussel shells (dead organisms) could also be a problem throughout the system. Impellers on trash pumps (which are used to remove flocculent material) can be damaged by shells. Some facilities that have not removed all dead organisms after reactive chemical or mechanical cleaning have been fouled a second time by the dead mussel shells.

Trash racks (Figure 9) and fish protection devices are also likely to be infested with zebra mussels. Designs that are most efficient for protecting fish or collecting trash are susceptible to heavy infestation. Less efficient designs or those that do not attract zebra mussels may be necessary in infested waters. These fish protection devices will have to be carefully evaluated to determine their vulnerability to zebra mussels.

A zebra mussel control method applicable to the crib is physical cleaning by divers. Chemicals are effective in disinfecting water intakes. If two intake pipes are present (i.e., a parallel system), one can be shut down, inspected, and cleaned if necessary. Low dissolved oxygen levels in an intake pipe idled for several weeks will kill zebra mussels. Small-diameter pipes have less water exchange than larger diameter pipes and should achieve low dissolved oxygen levels more quickly. Periodic cleaning of screens to remove zebra mussels is recommended. Screens or strainers at the end of a pipe can be

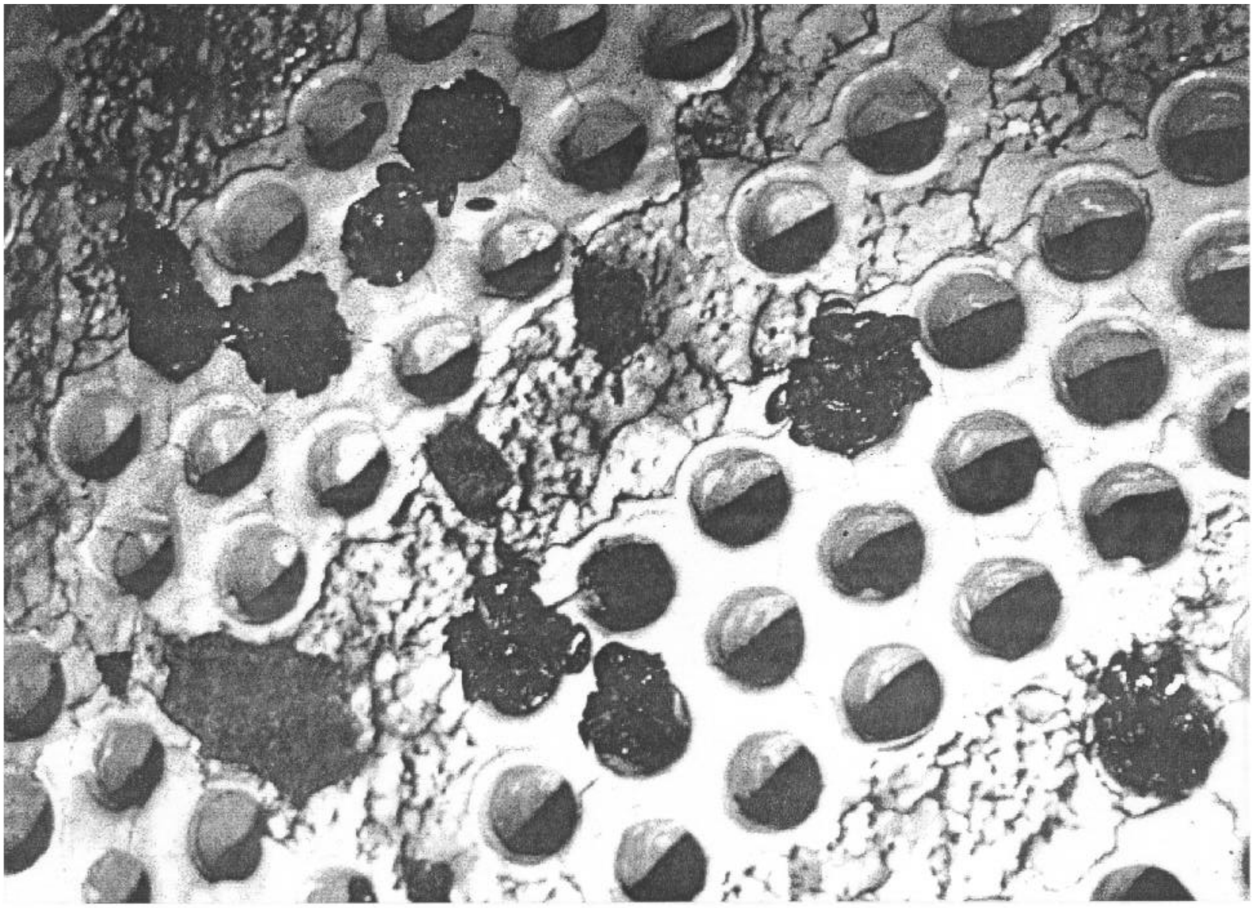

Figure 10. Screen clogged with zebra mussels

cleaned while in place, while some screens or strainers should be removed for additional cleaning. Modifying traveling screens to withstand higher loads of zebra mussels is a consideration. Trash pumps with stainless steel impellers, which are less prone to failure, should be installed if shell accumulation is expected. Antifouling coatings containing copper are effective but must be certified by the EPA as appropriate for a particular use.

Raw Water Systems

Raw water systems and components including cooling and fire prevention systems, piping (Figure 2), screens (Figure 10), and valves related to each are susceptible to zebra mussel infestations. These systems are particularly susceptible if they leak or are used periodically (once every several days or weeks) and, therefore, do not become stagnant. Zebra mussels can foul the intake screens, piping, valves, and joints of these systems, preventing normal operation and leading to equipment damage. Control methods applicable to raw water systems include the use of noncontaminated (commercial or ground well) water, regular backflushing or backflushing using water heated above 38 °C, storing lines in the dry during periods of nonuse, chemical treatment (e.g., chlorination), and minimizing leakage so that lines become anoxic.

Pumping Stations

Pumping stations and related elements (trash racks (Figure 9) or fixed screens, walls, de-icing systems, traveling screens, sluice gates, screen well, pump bell and sump, conduit, pump, and skimmer boom) are susceptible to zebra mussel fouling. Occlusion of pipes, unbalanced flow, excessive loading of components, accelerated corrosion, and poor sealing or closures of gates/valves are problems related to zebra mussel infestations.

Control strategies for pumping stations consist of any of the following: frequent use of valves or other movable devices, mechanical cleaning, selective use of chemical treatment, antifoulant coatings, biocides, backflushing, and thermal treatments. Another effective strategy is to use a chemical treatment at the beginning or upstream end of the intake pipe. Such an application would eliminate infestations at the beginning of the pipe because zebra mussels are usually more dense here than at the plant itself.

Instrumentation

Because of their small size and proximity to nutrient-rich, well-oxygenated, flowing waters, instrumentation devices such as gauging stations, transducers, and piezometers are susceptible to zebra mussel infestations. These measuring devices are installed along waterways to record surface water elevation, velocity, and flow. Infestation of the intake pipe between water source and measurement device leads to erroneous readings and incorrect conclusions regarding project conditions. The added weight of zebra mussels on gauge well floats leads to inaccurate recordings.

Personnel should inspect gauging station intakes, stilling wells, and floats carefully at least once a year when water temperature is greater than 12 °C. The outer portion of the intake should be examined. If infestations are not observed on the outer portion of the intake, zebra mussels are unlikely to exist farther up the chamber or within the still well. These interior areas are not generally suitable for zebra mussels because they are usually stagnant and lack sufficient levels of dissolved oxygen. Zebra mussels can be removed with a wire brush, high-pressure water, scrapers, or other physical means. Surfaces can be coated with antifoulants to control and prevent zebra mussel infestations. Doses of chlorine can effectively minimize infestations within the well and intake piping; however, coordination with local water quality regulators is necessary before use of chemicals.

Reservoir Level Control Structures

Flap gates and stop logs are water-level control or flood retardation structures susceptible to zebra mussel macrofouling. These infestations could lead to improper sealing of a flap gate or stop logs resulting in inoperable reservoir or drainage control. Control strategies relating to reservoir level control structures include mechanical cleaning, leaving one stop log in place permanently on the bottom (so grooves would not be fouled), and the use of antifouling coatings.

Applicable Control Methods

Applicable zebra mussel control methods include both preventive and reactive strategies. Preventive control methods include toxic construction materials, antifouling coatings, chemical treatments, thermal treatment, and mechanical filtration. Reactive control methods, those applied after infestations have been detected, consist of mechanical cleaning, high-pressure water jetting, carbon dioxide pellet blasting, freezing, and desiccation. Thermal treatment and chlorination use can be initially used as a reactive treatment to clean a system, then preventively as regular maintenance to prevent further fouling. These options, coupled with new designs, retrofit, and prospective control techniques, are reviewed in this chapter. Table 3 lists the facility components most susceptible to zebra mussel infestations and applicable control strategies.

Reasons for acceptance or rejection of zebra mussel control methods are varied. Criteria for selecting an appropriate control method include environmental and economic concerns and ease of application. Multiple control strategies may apply to a given zebra mussel infestation, and the chosen strategy or strategies should be the most cost-effective, environmentally sound, and easy to apply.

Table 3
Control Strategies Appropriate for Public Facilities

Component	Control Strategies
Water Intakes	*Preventive*
	Mechanical Filtration - A number of filter and strainer components are available for zebra mussel control.
	Antifouling Coatings - Use Coating System A or B.
	Chemical Treatment - There are a wide variety of chemical treatments using oxidizing and nonoxidizing chemicals, which vary in concentrations, durations, and lethality.
	Reactive
	Freezing/Desiccation - Aerial exposure during the winter months when temperatures are below freezing (0 °C) or during hot, dry summer months.
	Mechanical Cleaning - Any method, such as scraping, high-pressure water jet cleaning with pressure between 27,600 and 68,900 kPa, or carbon dioxide pellet blasting.
	Chemical Treatment - There are a wide variety of chemical treatments using oxidizing and nonoxidizing chemicals, which vary in concentrations, durations, and lethality.
Raw Water Systems	*Preventive*
	Mechanical Filtration - A number of filter and strainer components are available for zebra mussel control.
	Chemical Treatment - There are a wide variety of chemical treatments using oxidizing and nonoxidizing chemicals, which vary in concentrations, durations, and lethality.
	Thermal Treatment - Raise the isolated volume of water to or above 38 °C for 1 hr.
	Noncontaminated Water Source - Use water from a source known to be free of zebra mussel adults and veligers (i.e., stored water, city water, well water).
	Copper Piping - Retrofit piping systems with copper, copper alloys, or galvanized piping.
	Self-Cleaning Nozzles - Piping systems ending in restrictive nozzles or valves should be retrofitted with self-cleaning nozzles and copper or coating valves.
	Reactive
	Chemical Treatment - There are a wide variety of chemical treatments using oxidizing and nonoxidizing chemicals, which vary in concentrations, durations, and lethality.
	Periodic Operation - Water velocities in most piping systems are high enough that periodic operation will flush out mussels and shell debris.
	Component Replacement - Replace fouled component. Replacement of component should take zebra mussels into consideration.

(Continued)

Table 3 (Concluded)

Component	Control Strategies
Pumping Stations	*Preventive*
	Antifouling Coatings - Use Coating System A or B.
	Chemical Treatment - There are a wide variety of chemical treatments using oxidizing and nonoxidizing chemicals, which vary in concentrations, durations, and lethality.
	Thermal Treatment - Raise the isolated volume of water to or above 38 °C for 1 hr (41 °C for southern region).
	Frequent Use - When in use, water velocities are great enough to prevent settlement and infestation.
	Reactive
	Chemical Treatment - There are a wide variety of chemical treatments using oxidizing and nonoxidizing chemicals, which vary in concentrations, durations, and lethality.
	Mechanical Cleaning - Any method, such as scraping, high-pressure water jet cleaning with pressure between 27,600 and 68,900 kPa, or carbon dioxide pellet blasting.
	Component Replacement - Replace fouled component. Replacement of component should take zebra mussels into consideration.
Instrumentation	*Preventive*
	Antifouling Coatings - Use Coating System A or B.
	Chemical Treatment - There are a wide variety of chemical treatments using oxidizing and nonoxidizing chemicals, which vary in concentrations, durations, and lethality.
	Reactive
	Chemical Treatment - There are a wide variety of chemical treatments using oxidizing and nonoxidizing chemicals, which vary in concentrations, durations, and lethality.
	Mechanical Cleaning - Any method, such as scraping, high-pressure water jet cleaning with pressure between 27,600 and 68,900 kPa, or carbon dioxide pellet blasting.
Reservoir Level Control Structures	*Preventive*
	Antifouling Coatings - Use Coating System A or B.
	Permanent Log Placement - Leave the bottom log in place permanently to keep the grooves from becoming fouled and to maintain a complete seal.
	Reactive
	Mechanical Cleaning- Any method, such as scraping, high-pressure water jet cleaning with pressure between 27,600 and 68,900 kPa, or carbon dioxide pellet blasting.

5 Navigation Facility Components at Risk

Navigation facility components susceptible to zebra mussel infestation include measurement systems, raw water systems, chamber gates, spillway gates, culvert valves and racks, emergency closure and dewatering gates, concrete surfaces, and navigation aids. This chapter details each component of concern and applicable zebra mussel control methods.

The migration of zebra mussels from the Great Lakes is traceable from observations at projects on navigable streams. The Corps of Engineers operates nearly 250 lock and dam projects nationwide. A significant number of non-Corps projects are operated along the St. Lawrence Seaway, the New York Barge Canal, and various smaller facilities. Infestations at these projects have been an early indicator of operations and maintenance problems, as well as an information source regarding remediation.

Locks

The layout, mechanical systems, and operational procedures of lock and dam projects are diverse. Some differences are due to the historic development of lock design technology. Most differences, however, are due to project-by-project hydrologic constraints and commercial navigation needs. The following four examples of lock variations highlight differences in design and operation.

a. The high-lift lock shown in Figure 11 is located adjacent to flood control, river regulation, and hydropower structures as well as other salient features (e.g., fish passage facilities). The project accommodates a lift (the difference between extreme upper and lower pools) of 32 m. The gates used to close the chamber during filling and emptying are an upstream submersible tainter gate and an extremely high downstream miter gate. The chamber has clear dimensions of 26 m wide and 206 m long. Flow into and out of the lock chamber is through a complex hydraulic system that includes intakes with trash racks, culverts, valves, manifolds, ports, and baffles.

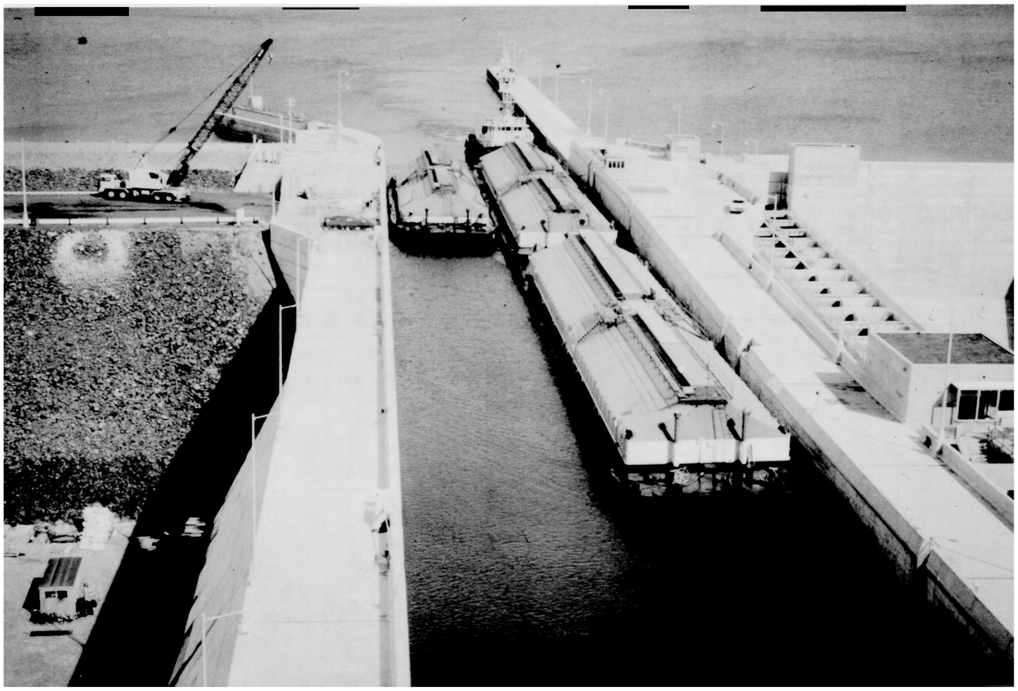

Figure 11. A tow entering the high-lift John Day Lock on the Columbia River from upstream

b. The high-lift (21 m) lock shown in Figure 12 is located in a channel that bypasses river regulation and flood control facilities. Miter gates are used upstream and downstream to close the chamber. The chamber has clear dimensions of 34 m wide and 183 m long. Flow into and out of the lock chamber is through a complex hydraulic system that includes intakes with trash racks, culverts, valves, manifolds, ports, and baffles.

c. The medium-lift (6 m) locks shown in Figure 13 accommodate a relatively large volume of commercial traffic. Thus, the project includes a large main lock (34 m by 366 m) and a smaller auxiliary lock (34 m by 183 m). The hydraulic system includes components similar to the first two examples, but is less complex and has lower flow velocities than the high-lift locks. In fact, many low to medium lift locks do not include manifold systems on the chamber floor. Instead, ports lead directly from the wall culverts into the chamber and are termed side port systems (large ports) or multiport systems (many small ports).

d. The low-lift lock shown in Figure 14 is a relatively low-cost lock that fills and empties using flow through the upstream and downstream gates (sector gates), respectively. The sector gates are structurally designed to operate under reverse as well as normal lift conditions and are therefore often, but not always, used in tidal areas.

Figure 12. Bay Springs Lock, Tennessee-Tombigbee Waterway, illustrates a high-lift lock that bypasses the river regulation and flood control facilities

Figure 13. Belleville Lock and Dam on the Ohio River illustrates a typical medium-lift navigation project

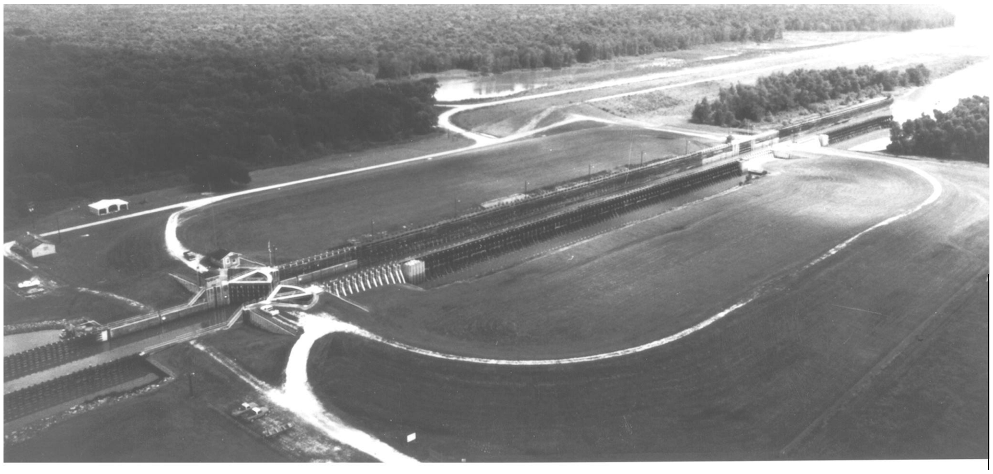

Figure 14. Vermilion, on the Gulf Intercoastal Waterway, Louisiana, is a low-lift navigation project

Zebra mussel infestation can interfere with operations at lock and dam projects in many ways. Clogging intake screens and roughening smaller flow passage surfaces (decreasing hydraulic efficiency) are examples. The large scale of navigation projects tends to preclude the physical clogging of most lock valves, gates, culverts, and other appurtenances. However, secondary problems dealing with paint, corrosion, instrumentation, cleaning, and disposal can be significant.

Measurement Systems

Because of their small size and proximity to nutrient-rich, well-oxygenated, flowing waters, measurement systems such as pressure transducers, piezometer lines, gauge wells, float and pulley devices, and mechanical sensors are susceptible to zebra mussel infestations. These small devices provide data (i.e., river stages, status of gates and valves, and lock-chamber water surface elevation) that are used to guide project operators and, for recent designs, to introduce some level of automation into the operation of navigation projects. Infestation of the intake pipe between water source and measurement devices leads to erroneous readings and incorrect conclusions regarding project conditions. No readings lead to nonoperable automated systems and lack of data for project control. Inaccurate recordings can result from the added weight of zebra mussels on gauge well floats.

Personnel should inspect pressure transducers, piezometer lines, gauge wells, float and pulley devices, and mechanical sensors carefully at least once a year when water temperature is greater then 12 °C. Occlusion of the intake pipe leading from water source to the chamber or still well is of concern. The wells are commonly on the order of 1 m in diameter with a 2- to 3-cm-diam PVC pipe leading to the river. Consequently, the conditions around the float and pipe make visual inspection nearly impossible.

To minimize infestations within the well and intake piping, chemical treatments can be effective as both preventive and reactive controls. Coordination with local water quality regulators is necessary before any use of chemicals as a treatment strategy. Component surfaces can also be coated with antifoulants to control and prevent zebra mussel infestations. Upon detection of an infestation, zebra mussels can be removed with a wire brush, high-pressure water, scrapers, or other physical means.

Raw Water Systems

Raw water systems and their components, including mechanical cooling systems, fire prevention systems, screens, and valves are susceptible to zebra mussel infestations. These systems are particularly susceptible if they leak or are used periodically (once every several days or weeks) and, therefore, do not become stagnant. Zebra mussels can foul the intake screens and piping of these systems, preventing normal operation and leading to equipment damage. Control methods applicable to raw water systems include the use of non-contaminated (commercial or ground well) water, regular backflushing or backflushing using water heated above 38 °C, storing lines in the dry during periods of nonuse, chemical treatment (e.g., chlorination), and minimizing leakage so that lines become anoxic.

Chamber Gates

Chamber gates include miter gates, submersible vertical lift (one to three segments) gates, sector gates, submersible tainter gates, vertical lift gates, and bubbler systems (used for ice and debris control). These gates have many locations that appear favorable for accumulation of zebra mussels. Concerns include corrosion, paint deterioration, and unbalanced or excessive loading. The horizontal seals at the sill and the vertical seals along the gate, if torn or otherwise unable to function properly, can also cause operational problems. The susceptibility of bubbler systems to zebra mussel infestations is unknown. Instrumentation bubblers commonly use some form of nitrogen gas as a drying agent and bubbler systems used for ice and debris control. The high-velocity air flow associated with bubblers is generally a hostile environment for zebra mussels. Project operators, however, should observe the effectiveness of their systems during the active season. Excessively low bubbling rates may mean the bubbler manifold is partially clogged. The manner in which the mussels affect cathodic protection systems is unknown and a potential concern for all large gates.

Locks located on streams that are prone to zebra mussel infestations should be exercised regularly to ensure that the recesses are kept clear of large accumulations of mussels. The gates should be cleaned and painted during normal dewaterings. Antifouling coatings may be economically justifiable. Lock operators should be aware of the possibility of changed mechanical loads. Whenever conditions, such as deflections of the gate leaf, indicate an unusual loading condition, visual inspection using divers may be warranted. Larger increased loadings, due to sediment being combined with mussel accumulations, may occur. There is not a great deal of overload capability designed into the operating machinery for these gates. Potential problems associated with miter gates, above, also apply to submersible lift gates. These gates can be raised, inspected, and cleaned if required. Holding the gates in the open position (air drying) will clear the gates of live mussels. The gates can be painted with an antifouling paint to reduce future infestations.

Spillway Gates

Spillway gates include tainter gates, vertical lift gates, wicket gates, and needles. Wicket type gates remain in a set position for several months and may be an ideal location for zebra mussel development. To maintain pool levels, the wickets are raised to form a dam. When open, the wickets lay on the bottom and, if not properly seated, can swing up and be damaged by prop wash. Other major concerns are encrustations of the eye-bolt, preventing raising, or that the tracks become clogged, causing misoperation. Zebra mussels adding extra weight during raising and causing blockage during closure are a less significant concern.

Detection generally requires that some substrate or structural element be inspected by a diver. These structures are not easily remedied if infestation is severe enough to cause problems. For example, two pieces of floating plant are needed to move a wicket. Experience information will be helpful, and communication between Districts and projects is encouraged.

Culvert Valves and Racks

Culvert valves and racks include navigation project components, such as tainter valves, butterfly valves, and vertical lift valves. High velocities and regular use inhibit attachment, so that these valves are considered unlikely to have problems with zebra mussel fouling. Added weight for operating machinery, improper sealing, seal deterioration, corrosion, and paint deterioration are potential (but unlikely) problems for these valves and racks.

Normal usage, or periodic operation for low-usage locks, should keep the sealing tracks clear. Valves can be cleaned on scheduled dewatering and rehabilitated. An upstream bulkhead must be installed before inspecting and cleaning. Therefore, early detection and careful observations of performance are needed. Once the bulkhead units are placed, the gate can be fully exposed to atmosphere, cleaned, and a protective coating applied, as required. High-pressure water and scraping may be needed. Seals and sealing surfaces can also be inspected and repaired. In periods of low flow, the gates can be operated regularly to clean the side and bottom sealing surfaces.

Racks with large bar spacings (commonly, 15 cm) that are regularly exposed to high-velocity flow, such as at lock culvert intakes, are unlikely to accumulate large numbers of zebra mussels. When accumulation does occur, then unbalanced flow, excessive loadings on the bars, corrosion, and slower operation may result. A program of gate exercise can be instituted for rarely used locks. In addition, antifouling coatings may be worthwhile for such components. Removable screens can be raised, cleaned, and replaced.

Emergency Closure and Dewatering Gates

Emergency closure and dewatering gates include vertical lift (one to two segments) gates, poiree gates, bulkheads, and stop logs. These gates have seams, edges, and other areas that are favorable sites for zebra mussel accumulation. Potential problems include corrosion, paint deterioration, and unbalanced or excessive loading. The seals at the sill and vertically along the gate, if torn or otherwise unable to function properly, can also cause operational problems. Larger increased loadings, due to inclusion of sediment in mussel accumulations, may occur. There is not a great deal of overload capability designed into the operating machinery for these gates. The manner in which the mussels affect cathodic protection systems is unknown and a potential concern for all large gates.

Detection through occasional inspection is suggested. The gates can be cleaned and painted during regular dewaterings. Antifouling coatings can be used if economically justifiable. Some gates can be raised, inspected, and cleaned if required. Holding the gates in the open position (air drying) will kill any live mussels. The gates at heavily infested locks should be exercised at regular intervals during low-usage periods to assist cleaning and clearing operations.

Concrete Surfaces

Concrete surfaces, such as chamber walls, culvert surfaces, bulkhead slots, and similar irregularities, are susceptible to zebra mussel infestations. Infestations of zebra mussels on concrete surfaces as thick as 10 cm have been observed. There is concern about concrete deterioration because of high ammonia levels produced by zebra mussels. However, the major known problems are associated with cleaning and disposing of very large quantities of odorous debris. The high velocities in the filling and emptying system probably preclude major infestation on the culvert boundaries; however, an increase in lock operation time could indicate infestations in these areas. Structural damage, at least in the short term, is expected to be limited to abrasion during cleaning operations. Long-term effects due to chemical actions, for example, have yet to be identified. Early monitoring of observations along the wall just below the waterline during low pool levels is recommended. An accumulation along the slots or sealing surfaces may cause closure problems. However, the expectation is that the weight of bulkheads is adequate to clear the slots and crush any mussel accumulation on the seals. New locks on the Ohio River are designed with low culverts so that air vents are not required. Older locks and high lift locks use air vents for the purpose of preventing cavitation downstream of culvert valves. In the unlikely event of total occlusion, cavitation damage might occur.

Periodic filling and emptying of low-usage locks will preclude significant attachments within intake manifold, culvert, chamber manifold, and outlet manifold. Cleaning is generally accomplished mechanically. Various mechanical cleaning procedures including scraping, high-pressure hosing (possibly barge mounted for near-surface cleaning), and scrubbers (barge mounted for deeper cleaning) are available. Dewatering is probably needed for complete zebra mussel removal. Dewatering during winter months or hot summer months resulting in freezing or desiccation is applicable. Use of an antifouling coating to prevent zebra mussel attachment is probably not cost efficient. For smaller flow passages, the suggested method is physical removal by some type of pigging arrangement. A modified chimney cleaner may be applicable to clean lock air vents if necessary.

Navigation Aids

Navigation aids such as mooring bitts, buoys, trash booms, and ladders are susceptible to zebra mussel infestations. Large accumulations of mussels have been observed on buoys, cables, and chains. The extra weight and drag force can cause these devices to sink. Clusters of mussels may prevent free movement of floating bitts. The mussels may attach to either the submerged bitt elements or to the slot below lower pool. Because no large buildup of mussels are expected for elevations between lower and upper pool, the ladders should not be a problem area.

Towboat operators generally report actual sinking of buoys. Project operators should regularly observe the conditions of trash booms and similar floating devices. Buoys can be periodically removed and dried to eliminate accumulations. In heavily infested areas, diver inspections of cables may be warranted. Mooring bitts usually can be raised, tied off, and dried, thereby permitting removal by hosing or scraping. The bitts may be a suitable environment for testing protective coatings. Some Corps of Engineers Districts already have heaters on floating devices to prevent zebra mussel attachment.

Applicable Control Methods

Applicable zebra mussel control methods include both preventive and reactive strategies. Preventive control methods include toxic construction materials, antifouling coatings, chemical treatments, thermal treatment, and mechanical filtration. Reactive control methods consist of mechanical cleaning, high-pressure water jetting, carbon dioxide pellet blasting, freezing, and desiccation. Thermal treatment and chlorination can be initially used as a reactive treatment to clean a system, then preventively as regular maintenance to prevent further fouling. These options, coupled with new designs, retrofit, and prospective control techniques, are reviewed in this chapter. Table 4 lists the navigation facility components most susceptible to zebra mussel infestations and applicable control strategies.

Reasons for acceptance or rejection of zebra mussel control methods are varied. Criteria for selecting an appropriate control method include environmental and economic concerns and ease of application. Multiple control strategies may apply to a given zebra mussel infestation, and the strategy or strategies chosen should be the most cost-effective, environmentally sound, and easy to apply.

Table 4
Control Strategies Appropriate for Navigation Facilities

Component	Control Strategies
Measurement Systems	*Preventive*
	Antifouling Coatings - Use Coating System A or B.
	Chemical Treatment - There are a wide variety of chemical treatments using oxidizing and nonoxidizing chemicals, which vary in concentrations, durations, and lethality.
	Toxic Construction Materials - Retrofit navigation aids with materials toxic to zebra mussels such as copper, copper alloys, or galvanized piping.
	Reactive
	Mechanical Cleaning - Any method, such as scraping, high-pressure water jet cleaning with pressure between 27,600 and 68,900 kPa, or carbon dioxide pellet blasting. Caution with regard to damaging sensitive instruments may require hands-on cleaning.
	Chemical Treatment - There are a wide variety of chemical treatments using oxidizing and nonoxidizing chemicals, which vary in concentrations, durations, and lethality.
Raw Water Systems	*Preventive*
	Mechanical Filtration - A number of filter and strainer components are available for zebra mussel control.
	Chemical Treatment - There are a wide variety of chemical treatments using oxidizing and nonoxidizing chemicals, which vary in concentrations, durations, and lethality.
	Thermal Treatment - Raise the isolated volume of water to or above 38 °C for 1 hr (41 °C for southern region)
	Noncontaminated Water Source - Use water from a source known to be free of zebra mussel adults and veligers (i.e., stored water, city water, well water).
	Copper Piping - Retrofit piping systems with copper, copper alloys, or galvanized piping.
	Self-Cleaning Nozzles - Piping systems ending in restrictive nozzles or valves should be retrofitted with self-cleaning nozzles and copper or coating valves.
	Reactive
	Chemical treatment - There are a wide variety of chemical treatments using oxidizing and nonoxidizing chemicals, which vary in concentrations, durations, and lethality.
	Periodic Operation - Water velocities in most piping systems are high enough that periodic operation will flush out mussels and shell debris.

(Sheet 1 of 3)

Table 4 (Continued)

Component	Control Strategies
Raw Water Systems (Continued)	*Reactive (Continued)*
	Component Replacement - Replace fouled component. Replacement of component should take zebra mussels into consideration.
Chamber Gates	*Preventive*
	Antifouling Coatings - Use Coating System A or B.
	Frequent Use - Gate movement and water velocities help prevent excessive settlement and infestation at locations that zebra mussel infestations might inhibit gate movement.
	Reactive
	Mechanical Cleaning - Any method, such as scraping, high-pressure water jet cleaning with pressure between 27,600 and 68,900 kPa, or carbon dioxide pellet blasting.
	Freezing/Desiccation - Aerial exposure during the winter months when temperatures are below freezing (0 °C) or during hot, dry summer months.
	Component Replacement - Replace fouled component. Replacement of component should take zebra mussel toleration into consideration.
Spillway Gates	*Preventive*
	Antifouling Coatings - Use Coating System A or B.
	Frequent Use - Gate movement and water velocities help prevent excessive settlement and infestation at locations that zebra mussel infestations might inhibit gate movement.
	Reactive
	Mechanical Cleaning - Any method, such as scraping, high-pressure water jet cleaning with pressure between 27,600 and 68,900 kPa, or carbon dioxide pellet blasting.
	Freezing/Desiccation - Aerial exposure during the winter months when temperatures are below freezing (0 °C) or during hot, dry summer months.
Culvert Valves and Racks	*Preventive*
	Antifouling Coatings - Use Coating System A or B.
	Frequent Use - Gate movement and water velocities help prevent excessive settlement and infestation at locations that zebra mussel infestations might inhibit gate movement.
	Reactive
	Mechanical Cleaning - Any method, such as scraping, high-pressure water jet cleaning with pressure between 27,600 and 68,900 kPa, or carbon dioxide pellet blasting.

(Sheet 2 of 3)

Table 4 (Concluded)

Component	Control Strategies
Emergency Closure and Dewatering Gates	*Preventive*
	Antifouling Coatings - Use Coating System A or B.
	Reactive
	Mechanical Cleaning - Any method, such as scraping, high-pressure water jet cleaning with pressure between 27,600 and 68,900 kPa, or carbon dioxide pellet blasting.
	Occasional Use - Gate movement and water velocities help prevent excessive settlement and infestation at locations that zebra mussel infestations might inhibit gate movement.
	Freezing/Desiccation - Aerial exposure during the winter months when temperatures are below freezing (0 °C) or during hot, dry summer months.
Concrete Surfaces	*Preventive*
	Antifouling Coatings - Apply toxic or nontoxic antifouling to concrete surface.
	Reactive
	Mechanical Cleaning - Any method such as scraping, high-pressure water jet cleaning with pressure between 27,600 and 68,900 kPa, or carbon dioxide pellet blasting.
	Freezing/Desiccation - Aerial exposure during the winter months when temperatures are below freezing (0 °C) or during hot, dry summer months.
Navigation Aids	*Preventive*
	Repellent Construction Materials - Retrofit navigation aids with materials toxic to zebra mussels such as copper, copper alloys, or galvanized piping.
	Antifouling Coatings - Apply toxic or nontoxic antifouling to navigation aid of concern.
	Reactive
	Mechanical Cleaning - Any method such as scraping, high-pressure water jet cleaning with pressure between 27,600 and 68,900 kPa, or carbon dioxide pellet blasting.
	Freezing/Desiccation - Aerial exposure during the winter months when temperatures are below freezing (0 °C) or during hot, dry summer months.

(Sheet 3 of 3)

6 Floating Plant Components at Risk

The floating plant encompasses vessels, dredges, and their associated components. Floating plant components susceptible to zebra mussels include the sea chests, keel coolers, piping systems, and hulls (Boelman and Fischenich 1995). Of these, sea chests and piping systems are considered to be the most susceptible to serious infestation. Zebra mussel problems related to the sea chest include clogging of the protective grate and the individual water intakes within the sea chest. Piping systems leading from the sea chest, particularly those that stand idle for long periods of time, are subject to clogging from zebra mussels in varying degrees. Shell debris can clog systems that terminate in nozzles. The flow of water available for engine cooling, fire protection, air conditioning, and refrigeration is significantly reduced when such an infestation occurs within the sea chest and/or piping system. The problems associated with each component and applicable zebra mussel control methods are discussed.

Sea Chest

The sea chest is a rectangular recess in the hull of a vessel that provides an intake reservoir from which piping systems draw raw water. Most sea chests are protected by removable gratings and contain baffle plates to dampen the effects of vessel speed or sea state. The intake size of sea chests vary from less than 10 cm^2 to several square meters.

The hard steel surfaces of the sea chest, protective grates, and baffles, combined with low water velocities created in this area, provide a suitable environment for zebra mussel attachment. Zebra mussel infestations have been found to clog the individual intakes and gates of the various water piping systems, decreasing the availability of water for onboard operations, which could result in damage to engines and other components that require water for cooling. Sea chests are, therefore, considered to be the most susceptible component to serious infestation.

Control strategies include coating all surfaces with an antifoulant such as copper-based epoxy paint or hot-dipped galvanized material. Periodic inspection and replacement of grates and screens also reduce the risk. Increasing the size of the sea chests 20 to 30 percent may delay the onset of serious problems that could force an engine shutdown. Thermal treatment is a highly effective strategy for the control of zebra mussels (McMahon et al. 1995). Thermal treatment may include retrofitting a closed loop system to recirculate the heated water to the sea chest or the addition of a second sea chest system, allowing engine cooling water to be discharged through the idle sea chest. Recirculation of engine cooling water as a thermal control strategy has proved extremely effective in controlling zebra mussels (Palermo 1992; U.S. Coast Guard 1994).

Keel Coolers

Keel coolers are systems of pipes or channels located on the hull surface. Engine cooling water is circulated and cooled by the water in which the vessel is floating. Channel-type coolers are half pipes welded to the hull and are usually located on the sides or on the afterrake of the stern. Recessed coolers are bundles of pipe, similar to a tube-type heat exchanger, located in recessed wells in the hull, usually in a protected area.

Keel coolers have a large surface area and are difficult to clean. Though no more susceptible than hulls (discussed below), the loss of efficiency of the coolers due to even "minimal" infestation could present a critical problem to the operation of the floating plant. Although no reports of major keel cooler infestation have been received, periodic inspection of these surfaces is recommended. Antifouling coating of the keel coolers and the adjacent surfaces is recommended in all cases.

Piping Systems

Various piping systems draw raw water from the sea chest or header piping. These systems provide water for engine cooling, fire protection, air conditioning, and refrigeration systems. Cooling water lines leading from the intakes usually have a valve located on the suction side or near the sea chest, which can be closed to allow for specific system alignment. Most of the piping systems leading from the sea chest are operated continuously at velocities in excess of those required for settling and attachment so only their system valves are subject to clogging. Some of these piping systems (e.g., fire fighting systems, air conditioning systems) stand idle for long periods of time, allowing an opportunity for zebra mussels to settle.

Although few reports of floating plant-based piping system clogging have been received, such instances have occurred at other facilities. The threat and seriousness of this type of infestation warrants the exercise of control strategies that include periodic operation of all systems, valves, and nozzles. In some cases, it may be prudent to replace standard piping with copper pipe and nozzles with self-cleaning nozzles.

Hulls

The added weight of zebra mussel infestations on ship hulls reduces cargo-carrying capacity, and the additional drag reduces fuel efficiency. Figure 15 illustrates a floating plant hull infested by zebra mussels. To date, zebra mussel infestations on hulls have not proved to be a serious problem. Vessels that operate in waters with ice flows are probably not at risk due to the abrasive action of the ice and its subsequent removal of zebra mussels. The primary means of controlling zebra mussels on hulls of vessels not operating during an ice season is periodic dry docking (4-year frequency), mechanical cleaning of the hull surface, and resurfacing with a copper- or zinc-based paint that provides the requisite protective coating to the hull for normal operations as well as antifouling benefits. Floating plant that routinely operate in waters with a salinity above 8 ppt will probably not experience zebra mussel infestations. As an end-of-year treatment, floating plant operators may schedule duty in brackish waters or waters of higher salinity.

Applicable Control Methods

Applicable floating plant zebra mussel control methods include both preventive and reactive strategies. Preventive control methods include antifouling coatings and thermal treatment. Reactive control methods consist of mechanical cleaning, high-pressure water jetting, carbon dioxide pellet blasting, freezing, and desiccation. Thermal treatment can be initially used as a reactive treatment to clean a system, then preventively as regular maintenance to prevent further fouling. These options, coupled with prospective control methods, new designs, and retrofit are reviewed in this chapter. Table 5 lists the components of floating plants most susceptible to zebra mussel infestations and applicable control strategies.

Reasons for acceptance or rejection of zebra mussel control methods are varied. Criteria for selecting appropriate control methods include environmental and economic concerns and ease of application. Multiple control strategies may apply to a given zebra mussel infestation, and the strategy or strategies chosen should be the most cost-effective, environmentally sound, and easy to apply.

Figure 15. Floating plant hull infested with zebra mussels (courtesy Great Lakes Sea Grant)

Table 5
Control Strategies Appropriate for Floating Plants

Component	Control Strategies
Sea Chests	*Preventive*
	Antifouling Coatings - Use combination of Coating Systems A, B, and C.
	Thermal Treatment - Recirculate engine cooling water bringing the sea chest water temperature to 38 °C or above for 1 hr (41 °C for southern region). Thermal treatment should be conducted at least every 30 to 45 days during the summer months (May through October).
	Reactive
	Mechanical Cleaning - Any method, such as scraping, high-pressure water jet cleaning with pressure between 27,600 and 68,900 kPa, or carbon dioxide pellet blasting.
	Freezing/Desiccation - Aerial exposure during the winter months when temperatures are below freezing (0 °C) or during hot, dry summer months.
Keel Coolers	*Preventive*
	Antifouling Coatings - Application of Coating System B.
	Reactive
	Mechanical Cleaning - Any method, such as scraping, high-pressure water jet cleaning with pressure between 27,600 and 68,900 kPa, or carbon dioxide pellet blasting.
	Component Replacement - Replace fouled component. Replacement of component should consider zebra mussel impacts.
Piping Systems	*Preventive*
	Periodic Operation - Water velocities in most piping systems are high enough that periodic operation will flush out mussels and shell debris.
	Toxic Construction Materials - Retrofit piping systems with copper, copper alloys, or galvanized piping.
	Self-Cleaning Nozzles - Piping systems ending in restrictive nozzles or valves should be retrofitted with self-cleaning nozzles and copper or coating valves.

(Continued)

Table 5 (Concluded)

Component	**Control Strategies**
Piping Systems (Continued)	*Reactive*
	Component Replacement - Replace fouled component. Replacement of component should consider zebra mussel impacts.
Hulls	*Preventive*
	Antifouling Coatings - Application of Coating System B.
	Reactive
	Mechanical Cleaning - Any method, such as scraping, high-pressure water jet cleaning with pressure between 27,600 and 68,900 kPa, or carbon dioxide pellet blasting.
	Freezing/Desiccation - Aerial exposure during the winter months when temperatures are below freezing (0 °C) or during hot, dry summer months.
	Ice Operation/Grounding - Abrasive action of operating during ice conditions or grounding removes zebra mussels.

7 Technology Transfer

In North America, zebra mussel information, including sightings, monitoring, environmental concerns, and control activities, is shared through both formal and informal networks. Informal networks are maintained by contacts with both Corps and non-Corps personnel through professional organizations and Government committees. Formal networks include both the Zebra Mussel Information Clearinghouse and the U.S. Army Corps of Engineers Zebra Mussel Research Program (ZMRP). The best information sharing has resulted from interdisciplinary cooperation involving (a) facility experts, (b) zebra mussel experts, and (c) control strategy experts.

Clearinghouse

Reports of zebra mussel sightings, substrate preferences, environmental concerns, control strategies, and other information related to zebra mussels is shared through the clearinghouse, which publishes *Dreissena!* Information received by the clearinghouse comes from Federal, State, and local agencies, academia, and the private sector. Facility managers are encouraged to use the services of the clearinghouse and to share information on these organisms.

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Zebra Mussel Research Program

Additional information on zebra mussels is available from technical notes and other documents resulting from the ZMRP. Management of the ZMRP resides at the U.S. Army Engineer Waterways Experiment Station (WES), with Dr. Edwin A. Theriot (601/634-2678) serving as Program Manager. Technical specialists at Corps Districts, Divisions, WES, the U.S. Army Construction Engineering Research Laboratories, and other agencies (e.g., Tennessee Valley Authority, U.S. Coast Guard) associated with the ZMRP are given in Appendix A. The four working groups and their chairs are as follows:

Power facilities - Mr. E. A. Dardeau, Jr, (601) 634-2278
Reservoirs, intakes, pumping plants, gauging stations, and drainage structures - Mr. Jerry Miller, (601) 634-3931
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8 Conclusions

Zebra mussels, first found in North American waters in 1988 at Lake St. Clair, Michigan, have since found their way into many midwestern, eastern, and southern streams and lakes. They are macrofoulers that quickly colonize new areas on many different types of natural and artificial substrates. The potential exists for these organisms to infest most freshwater lakes and rivers in the United States. Once established, the zebra mussel can achieve high densities, with adult mussels producing byssal threads to attach to any available hard substrate. The zebra mussel is a serious threat to public facilities, and the extent of future infestation is still unknown.

An effective, cost-efficient zebra mussel control program must consist of a thorough monitoring plan and implementation of applicable control methods relevant to the operating situation at hand. Monitoring is a key component of preventative maintenance and control because it provides information on the presence of zebra mussels, their abundance in the water system, and the effectiveness of treatment programs.

There are numerous zebra mussel control methods that can be separated into preventive and reactive measures. Preventive control strategies reduce the possibility of infestation occurrence. These methods include toxic construction materials, antifouling coatings, thermal treatment, mechanical filtration, and chemical treatment. Reactive control strategies are used after an infestation has been detected. Reactive methods include replacing fouled component, mechanical cleaning, high-pressure water jetting, carbon dioxide pellet blasting, chemical treatment, and freezing or desiccation.

As newer environmental restrictions are placed on their use, more environmentally benign techniques need to be investigated to determine their potential applicability at public facilities. Prospective treatments and retrofits such as component enlargement, self-cleaning nozzles, acoustics, electric fields, and UV light have demonstrated possible applications. Further testing and development are required in these fields to ensure zebra mussel control effectiveness and applicability to floating plant.

Information sharing should continue through both formal and informal networks, such as the Zebra Mussel Information Clearinghouse and the

ZMRP. New research areas should be identified and funded; however, full advantage should be taken of ongoing work in this country and elsewhere.

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Although much information exists on zebra mussels (*Dreissena polymorpha*), their biology, monitoring, and control methods, not all of this information is readily available in a form that is useful for operators of facilities susceptible to zebra mussel infestations. Thus, as part of the Congressional mandate to address zebra mussel control, the U.S. Army Corps of Engineers recognized that a concise set of guidelines was necessary. These guidelines are needed to identify facility components at risk and appropriate control measures. In this first edition of the control handbook, only those methods that were shown to be effective, environmentally acceptable, and economically justified were included. Besides an overview of zebra mussel biology, reasons for concern, and generalized control methods, the handbook contains sections specifically devoted to (a) hydropower facilities, (b) public facilities (i.e., water intakes, raw water systems, pumping plants, instrumentation, and reservoir level control structures), (c) navigation structures, and (d) floating plant. Preventive, reactive, and prospective control methods are discussed for each type of facility, with summary tables provided. Other methods not currently listed may be included in the final edition of the handbook that will be prepared at the culmination of the Zebra Mussel Research Program, provided they satisfy the required constraints.

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