IMPACT of EUROPEAN ZEBRA MUSSEL INFESTATION to the ELECTRIC POWER INDUSTRY

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ABSTRACT - Dreissena polymorpha, the European freshwater zebra mussel, was introduced to the Great Lakes in 1985. It is now found throughout Lakes St. Clair and Erie, in Green Bay, Lake Michigan and invaded western Lake Ontario by Fall 1989. As its planktonic "veliger" larva is dispersed on water currents and adults are transported by human and natural vectors, it is likely to spread throughout U.S. and southern Canadian freshwaters. When entrained on intake waters, veligers settle in raw water systems, growing to adults attached by byssal threads to hard surfaces. Mussel accumulations impede flow, and aggravate sedimentation and corrosion. Settlement occurs at flow velocities less than 1.5-2.0 m/sec. Mussels foul intake structures, low-flow piping, steam condensers, heat exchangers, fire protection systems, and cooling tower basins. Monitoring of source waters for mussels and veligers allows initiation of control measures before macrofouling occurs. Mussel fouling should be prevented as removal is difficult and expensive. Mitigation and control technologies include manual removal, robotic cleaning, water jetting, line pigging, acidic chemical cleaning, oxidizing and non-oxidizing molluscicides, shell strainers, exposure to high voltage electrical fields, and possibly thermal backwashing and sand-filtration. Controls generally need only be applied during spawning periods (> 14-16°C or 57-61°F) when veligers are present.

INTRODUCTION

The exotic freshwater bivalve, Dreissena polymorpha, the "zebra mussel" (Fig. 1) was released into Lake St. Clair/Detroit River in the Great Lakes in 1985 by the discharge of ship ballast water carried from a freshwater European port (1, 2). The mussel’s planktonic larval stage (the "veliger") has allowed it to spread rapidly downstream throughout the shallow near-shore waters of Lake Erie (2) (Fig. 2). Zebra mussels now extend into western Lake Ontario and have been recently reported in Lake Michigan, near Green Bay, Wisconsin (3) (Fig 2) and at Cornwall and several other sites on the St. Lawrence River.

This species was originally restricted to the Caspian Sea and Ural River, Asia. It spread through European freshwaters in the 19th century and now occurs throughout most of Europe and the western Soviet Union, south into Turkey (2) (Fig 3). Veliger larvae are entrained on intake waters and settle in low-flow areas of raw water systems where they attach to hard surfaces by proteinaceous threads called "byssal" threads. Once settled, they grow to sizes and accumulate in numbers that reduce or block flow (2, 3, 4, 5). Byssal threads are retained in adult mussels. Secreted from a gland at the base of the foot, they form a tough hold-fast from which mussels cannot be dislodged even under high flow velocities. As post-veligers can settle in massive numbers, dense mats of mussels many shells thick can rapidly develop in low-flow areas from which shells and clusters of shells can be released to foul downstream components such as heat exchangers (2, 3). Mats of mussels 4-12 in thick reduce maximum sustainable flow rates even in large diameter piping (4, 6). Recent utility experience in Lake Erie suggests that mussel mats may develop more rapidly than reported in Europe (3). In European hydroelectric stations, zebra mussels foul piping, walls of turbine-bearing chambers, cooling pipes of the mercury valves of generator ionic exciters, and intake trash racks and gates. In steam-electric power stations, they foul piping, small diameter components, intake structures, trash racks, and screening (2, 5, 7, 8 and references therein).

Power stations and municipal water treatment plants on Lake Erie already report zebra mussel infestations (9, 10). As Asian clam (Corbicula fluminea) macrofouling now costs the U.S. power industry over one billion dollars per year (11), advent of zebra mussels in North America can only increase the macrofouling costs experienced in the future.

In the past, EPRI has sponsored projects to review all macrofouling control technologies and to evaluate those that are most cost effective. EPRI report CS-3550 *Condenser Macrofouling Control Technologies* and CS-5271 *Guidelines on Macrofouling Control Technology* presented research results. To address the zebra mussel issue, EPRI initiated project 1689-24 to study the impact of zebra mussels to the electric power industry in December 1989. This paper is an excerpt from the EPRI project report entitled "The Zebra Mussel - U.S. Utility Implications." An EPRI inter-divisional task force and a utility advisory group planto conduct additional R & D work and to develop a monitoring and control guide.

This paper (1) reviews the general biology and ecology of zebra mussels, (2) provides a prospectus for the United States power industry regarding future mussel macrofouling and (3) outlines the technologies presently available for their mitigation and control.

Figure 1. The external anatomy of a zebra mussel. A. Lateral view of the left shell valve. Note the inhalant and exhalant siphons projecting from the posterior margins of the shell and byssal attachment threads. B. Dorsal view of the shell valves. Note hinge at anterior mid-line. C. Posterior view of the shell valves. Note the openings of the ventral inhalant and dorsal exhalent siphons in the dorsal-ventral mid-line and flattened ventral shell margins.

RELEVANT BIOLOGY

Zebra mussels rarely reach a shell length (SL) of greater than 5 cm. The anterior end of the shell is reduced, making it decidedly pointed (a shell shape characteristic of mussels). The posterior end is inflated with a rounded margin. The shell has no hinge teeth. It is the only North American freshwater bivalve of its size (3-5 cm) in which adults have a byssal thread hold-fast. Newly settled juveniles are 0.2-0.3 mm in length (2). The ventral shell margins are extremely flattened (Fig. 1). The external surface of the shell is generally light tan to dark brown with a series of dark, vertical color bands giving it its common name. Shell coloration and marking are variable, ranging from lightly colored shells without banding to darkly pigmented shells with banding obliterated.

Retention of a byssal thread hold-fast in adults (Fig. 1) sets zebra mussels apart from all other large North American freshwater bivalves. With it, they attach to and grow on the walls of piping, tube sheets, embayments and other raw water system components. Although settlement of the "post-veliger" occurs at flow rates < 1.5-2.0 m/sec (7, 8), once attached, individuals can tolerate much higher flow velocities. Thus, juveniles that become established during non-operational low-flow conditions (redundant systems, peaking units) will not be dislodged from them by higher flows when operating. Byssal attachment can be made to almost any firm material including metal, concrete, stone, wood, cloth, nylon, plastic, fiberglass, vinyl, glass and the shells of other bivalves (2, 12).

The sexes are separate. Sperm and eggs are released into the water for external fertilization. The embryo develops within the egg (required temperature is 12-24°C or 54-75°F) and hatches into the veliger larva (2). The planktonic veliger has a bivalved shell, a ciliated "velum" for swimming and feeding and a rudimentary foot (Fig. 4). It is 0.04-0.07 mm in diameter at hatching, reaching 0.18-0.29 mm before settlement as a "post-veliger" which then metamorphoses into a juvenile.

Zebra mussel reproductive seasons vary between habitats and with temperature. Females mature at an SL of 8-9 mm, usually in their second year of life. Spawning occurs above 14-16°C (57-61°F). Veliger development is optimal at 20-22°C (68-72°F). Post-veliger settlement is generally 8-10
zebra mussels rarely occur in shallow waters (< 1 m). Depth of maximum abundance varies between 2-14 m, but may be as great as 18 m (2). Mussels have been found below 18 m in Lake Erie (17). The depth of maximum abundance (≥2-14 m) corresponds roughly to that spanned by intake structures. Because intake structures provide an abundance of suitable substrata and ideal flow conditions, they can support the development of dense mussel populations.

Figure 3. Present distribution of zebra mussels in Europe (cross-hatched areas) and their original home range in the Caspian Sea (dark area).

days after hatching, but may take up to 16 days under suboptimal conditions. Spawning continues for 3-5 months, but may range from 2-8 months dependent on temperature and food availability. Thus, in North America, veligers may maximally occur in source waters from May-October (2).

Growth rates and life-span are also dependent on environmental conditions. The greatest growth rates occur in habitats with elevated temperatures and high food levels (i.e., suspended algae and bacteria) (13, 14). Growth rate decreases with increased water depth. It is stimulated at flows of 0.5-0.8 m/sec, but reduced in near-stagnant conditions or at flows greater than 1.5 m/sec (14). Slow growing mussels have maximal life-spans of 6-7 yr, while faster growing mussels live for only 4-5 yr (Fig. 5) (13, 14). Because of their high reproductive rates (30,000-40,000 eggs/female/year), zebra mussel populations can rapidly form mats of living mussels many shells thick in both natural habitats and raw water systems. Natural population densities of 5,000 -30,000 mussels/m² are not uncommon (2); 114,000 mussels/m² reported in a lagoon pond (15). Densities may be higher in raw water systems where flow, high food levels and abundance of hard substrata provide optimal conditions for settlement and growth. A density of 216,000 mussels/m² was reported on fishing net suspended in a hydroelectric plant intake (16). Densities of 700,000 individuals/m² occur in the intake canal of a power station drawing water from Lake Erie (3), suggesting that raw water systems may be particularly susceptible to zebra mussel fouling soon after invasion of source habitats. For example, a car submerged in Lake Erie for only eight months had 90% of its surfaces covered by zebra mussels at an average density of 45,000 mussels/m² (12), indicating very rapid colonization. Similar or higher colonization rates can occur in raw water systems (16).

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Figure 4. Anterior and lateral views of the planktonic "veliger" larva of zebra mussels (veliger size range is 0.04-0.29 mm).

Figure 5. Life span growth rates of zebra mussels in four European populations (20).

The natural habitats of zebra mussels are characterized by high levels of dissolved O₂ (> 90% of air saturation). It cannot tolerate O₂ concentrations below 40-50% of air saturation (18). Without O₂, 100% mortality occurs within 3-6 days. Intolerance of reduced O₂ restricts zebra mussels to shallow waters above the thermocline (thermal discontinuity layer) of lakes and excludes them from habitats chronically exposed to O₂ depletion.

Zebra mussels feed on suspended food particles (including unicellular algae, bacteria and fine, particulate organic detritus) filtered from water currents over the gills. In raw water systems, continual flow supplies mussels with both O₂ and suspended food, while eliminating predators, thus optimizing mussel growth and survival (2, 3). Flow also stimulates growth in natural populations (14). Conversely,
lack of O₂ and food prevent mussels from settling or surviving in stagnant or dead lines, if they remain truly stagnant.

**DISTRIBUTION IN NORTH AMERICA**

With a strong and expanding presence in the Great Lakes, zebra mussels are likely to spread throughout North America. Possible dispersal routes from the Great Lakes include: the Chicago Ship Canal from Lake Michigan into the Illinois River to the Mississippi River drainage; from the Niagara River through Tonawanda Creek into the western terminus of the Erie-Barge Canal in western New York; and from Lake Ontario through the Oswego River Canal in central New York into the Erie-Barge Canal. The Erie Barge Canal is connected to the Mohawk, Seneca and Hudson Rivers.

Besides dispersal on currents, veligers can be transported in the bilge water of pleasure craft, by fish stocking programs, and through canals. Adult mussels may disperse within drainage systems attached to boat hulls or other floating objects. They can be introduced to new drainage systems by the trailing of pleasure craft to which they are attached between launch sites [adults survive air exposure for at least 4 days (19)]. Mussels on aquatic vegetation can be transported by nesting water fowl. Mussels used as aquarium pets or fish bait will be readily dispersed.

Zebra mussels are relatively intolerant of elevated temperatures. Water temperatures above 26-27°C (79-81°F) prevent veliger development and settlement (20). Exposure to 32.5°C (90.5°F) for five hours is lethal (21). Thus, in North America, this species is unlikely to extend into the southern and southwestern United States where summer water temperatures approach 28-32°C (82-90°F) (Fig. 6). As this species tolerates 0°C (32°F) and initiates reproduction above 14-15°C (57-59°F) (2), it is likely to spread into cooler freshwaters as far north as southern Canada (Fig. 6), making power stations in much of North America susceptible to its macrofouling.

**CHARACTERISTICS OF ZEBRA MUSSEL MACROFOULING**

Zebra mussels invade power station raw water systems as veligers entrained on intake water. Densities of veligers in intake water can range from 70-400,000 veligers/m³ or 0.27-1,516 veligers/gal (2), leading to extremely high entrainment and fouling rates. Thus, very dense infestations of mussels can rapidly develop within raw water systems; up to 45,000 - 216,920 mussels/m² settling within a single spawning season (12, 16). Maximum veliger densities occur at depths of 3-7 m as they are usually restricted to warm, well oxygenated, surface waters above the thermocline. Power stations generally draw water from this depth range, assuring that large numbers of veligers will be entrained. Only those plants drawing water from below the thermocline will have low veliger entrainment rates.

![Figure 6. The hypothetical future distribution of zebra mussels in North America (cross hatched area). The dark areas represent the present distribution of this species in the Great Lakes and St. Lawrence River as of March 1990. The hypothetical future distribution of zebra mussels is based on a 14-16°C lower limit for spawning and a 26-27°C upper limit for development and settlement of the veliger (2).](image-url)

Settlement of the zebra mussel post-veliger does not occur at flows above 2 m/sec (2, 8) and is unlikely above 1.5 m/sec (2). Microbial films and surface corrosion increase the probability of settlement (7, 8) by locally reducing flow rates at the pipe surface, thus allowing post-veligers to settle and attach in piping with relatively high flow.

Mussel fouling of intake water structures will be associated with massive accumulations of individuals on embayment walls, stationary trash racks, pump intake housings and other exposed surfaces, reducing flow and increasing pressure differentials across them. Mussels may even attach to traveling screens. Mussels infesting embayment areas could grow to sizes or be sloughed off as clusters of individuals (bound together by byssus threads) that foul downstream components such as steam condensers, service water system heat exchangers or fire protection systems (3).

In condenser water systems (CWS), mussel infestations reduce pipe diameters and flow rates. They settle on the walls of the inlet water box and tube sheet, aggravating corrosion rates. Dislodged shells can enter condenser tubes and become lodged at slight constrictions, blocking flow; completely occluding the tube as other debris accumulate behind them, reducing heat exchanger efficiency and aggravating tube wall corrosion rates in low-flow areas downstream of blockage points. Increased flow velocity in unblocked tubes could increase tube wall erosion rates.
floors, limiting basin infestations to hard surfaces. Mussels will not settle in soft sediments accumulated on basin beds mitigated by short-term exposure to molluscicides during water systems. As hard substrata is required for attachment, still in development. Embayment mussel infestations may also from source and basin mussel populations could settle in raw from intake walls and large diameter piping (26), but these are tubing in condensers and heat exchangers. Entrained veligers from surfaces. Robotic devices may be used to remove mussels harboring mussel populations. Shells or shell clusters released to remove from intake structures by diver operated suction coolings tower basins if makeup water is drawn from a source Attachment by byssal threads, makes zebra mussels difficult.

In service water system (SWS) piping, formation of mats of mussels could reduce sustainable flow rates particularly in small diameter components (2, 22). Flow restriction by mussel mats will cause accumulation of sediments and reduction of O2 oxygen tension at the pipe surface, potentially exacerbating corrosion. Typical low-flow areas (< 1.5-2.0 m/sec) susceptible to mussel fouling include: low-flow piping; heat exchanger water boxes and tube sheets; dead-end piping; fire protection systems; valve plates, downstream areas behind partially opened valves; pipe bends; reservoir tanks; and joints of unequal pipe diameter. Redundant SWS systems with low-flows during nonoperational periods will be highly susceptible to mussel fouling. Once attached, mussels are unlikely to be dislodged by periodic exposure to high operational flows.

Large populations of zebra mussels could also develop in cooling tower basins if makeup water is drawn from a source harboring mussel populations. Shells or shell clusters released from basin mussel populations could foul small diameter tubing in condensers and heat exchangers. Entrained veligers from source and basin mussel populations could settle in raw water systems. As hard substrata is required for attachment, mussels will not settle in soft sediments accumulated on basin floors, limiting basin infestations to hard surfaces.

**MONITORING**

Monitoring of raw water systems and source waters for zebra mussels will provide early warning of potential macrofouling. Monitoring should also be part of subsequent mitigation and control programs (see Mitigation and Control below).

The zebra mussel veliger is distinct and readily identified in source waters. Identifying characteristics are its rounded bivalve shell and ciliated velum (Fig. 4). Veligers can be detected by examining zooplankton net samples of source waters (mesh size < 40 μm) or by passing a known volume of water (500-3,000 gal depending on veliger density) from the CWS or SWS through a zooplankton net. This latter technique allows determination of veliger densities. Sampling should be initiated before water temperatures reach the 14-16°C (57-61°F) lower limit for spawning and be continued until water temperatures fall well below that level or veligers disappear from the water column for a prolonged period (2).

Juvenile mussel settlement may be monitored with concrete blocks or other hard substrata set out in intake waters or embayments prior to spawning followed by periodic inspection. Submerged floats and nets (16) also make good settlement substrata for juvenile mussels. Sidestream devices may be used to monitor settlement and include boxes or pipe sections plumbed to receive condenser or service water at suitable settlement velocities (< 1.5 m/sec). Such monitors should be easily inspected for settled juveniles and able to accommodate a variety of substrata representing the construction materials of the raw water system(s) at risk.

Raw water system components can be visually inspected for newly settled juvenile and adult mussels during planned or unplanned outages. Video technologies allow on-line inspection for mussel infestations.

Source waters should be routinely monitored for adult mussel populations. Dead mussel shells accumulate on the shore. Hard substrata below 2-3 m can be inspected by SCUBA. During outages, intake structures can be inspected by SCUBA, video, or dewatering and visual inspection. Shell traps installed in water lines (23, 24, 25) can be inspected for mussels without interrupting operation. Radiography can also reveal accumulations of mussel shells.

**MITIGATION and CONTROL**

Attachment by byssal threads, makes zebra mussels difficult to remove from intake structures by diver operated suction devices. They may have to be manually scraped from infested surfaces. Robotic devices may be used to remove mussels from intake walls and large diameter piping (26), but these are still in development. Embayment mussel infestations may also be mitigated by short-term exposure to molluscicides during outages. High concentrations of sodium-meta-bisulfite (Na2S2O3) and hydrogen sulfide applied to embayments during outages kill bivalves by reducing O2 concentrations below tolerated levels (27). High concentrations of non-oxidizing biocides [n-alkyl dimethylbenzyl ammonium chloride (or benzalkonium) & dodecylquainidine hydrochloride (or DGH)] have used to mitigate bivalve infestations in embayments (28).

Maximum effectiveness in controlling zebra mussels in intake structures is likely to be achieved by continual application of biocides over spawning periods. A number of biocides have been tested for efficacy against zebra mussels (Table 1). Among these, chlorination is commonly used in Europe with continuous exposures to 0.5 ppm for more than seven days (6) or 0.3 ppm for greater than 14-21 days inducing near complete kills (7). Bromination may also be effective against zebra mussels, particularly at pH greater than 8.0 (34). Ozonation prevented mussel settlement and growth in municipal water utility piping receiving water from Lake Erie (35). Laboratory testing indicates that the nonoxidizing biocides poly(oxyethylene(dimethyliminio)ethylene-

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Backwashing or recirculation of heated water into intake structures can mitigate zebra mussel infestations (2). Instant mortality occurs at 40°C (104°F) while 36°C (90°F) is 100% lethal after 1 h (7) and 32.5°C (91°F), lethal after 5 h (21). Such techniques may reduce generation efficiency, but loss of efficiency may be offset by their effectiveness.

Antifoulant, biocidal surface coatings can prevent mussel settlement (7). Copper is relatively lethal to zebra mussels (Table 1), thus copper-based antifoulant coatings may deserve further attention. Nontoxic silicone antifoulant coatings may control mussels by preventing successful formation of byssal thread hold-fasts (36, 37). Electrical pulses passed through metallic intake structures kill juvenile mussels at exposure intensities of 7-9 V/cm for 27-31 h (8). As veligers and adults do not generally occur below the thermocline (2), relocation of intake structures to deeper waters may prevent their entrainment on intake water.

In condenser water systems (CWS), adult mussels may have to be manually removed from large diameter piping, water boxes, and tube sheets during outages. Frequency of removal will depend on mussel settlement and growth rates. In some systems, annual cleaning should prevent individuals from reaching sizes or densities resulting in fouling. Similarly, annual mitigation with molluscicides may also be effective. The most efficacious annual treatment time is likely to be just after reproduction ceases in the fall as it would kill all mussels settled during the prior spawning season, leaving the CWS mussel-free until spawning the following spring.

Soon after death, mussel shells fall free of the byssus hold-fast. Therefore, they should flush through a raw water system after mitigation with a biocide (4, 6). However, when mussels form thick mats upstream of condensers, biocide treatment may induce sloughing of shell clusters, that foul downstream components (3). Thus, where juvenile settlement rates are high, a CWS may have to be cleaned or treated with biocides more frequently than annually to avoid development of mussel mats.

In addition to manual scraping, adult mussels may be removed from a CWS by water jetting techniques or line pigs. Several robotic cleaning devices are being developed to clean large diameter intake and discharge piping (26). Once mussels are removed, exposed surfaces may be covered with silicone based nontoxic surface coatings to prevent resettlement (36, 37). Debris strainers will prevent shells originating in intake structures from entering condensers (25, 38, 39). Nozzle brushes may dislodge shells from condenser tubing. Sponge balls cannot remove lodged shells; instead, they lodge behind shells, increasing tube fouling (38).

Backwashing systems are unlikely to free condenser tubing of wedged shells or attached mussels and may leave shells in inlet water boxes to refoul condensers on return to operation. Thermal backwashing (38) can kill newly settled mussels in a CWS (7) and should be carried out often enough to prevent can close the shell valves tightly, sealing themselves off from the toxic effects of short-term (1-2 h) biocide exposures (22).

### Table 1

Molluscicide Applications for Mitigation and Control of Zebra Mussel Macrofouling

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Application</th>
<th>Effect</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chlorination</td>
<td>0.5 ppm for 7 days</td>
<td>75% kill</td>
<td>(6)</td>
</tr>
<tr>
<td></td>
<td>0.3 ppm for 14-21 days</td>
<td>&gt;95% kill</td>
<td>(7)</td>
</tr>
<tr>
<td>Tri-butyl tinoxide</td>
<td>Surface coatings reapplied every 1-2 yr</td>
<td>High success</td>
<td>(7)</td>
</tr>
<tr>
<td>Copper ions</td>
<td>5 ppm for 24 hr</td>
<td>100% kill</td>
<td>(29)</td>
</tr>
<tr>
<td>Silver ions</td>
<td>5 ppm for 24 hr</td>
<td>72% kill</td>
<td>(29)</td>
</tr>
<tr>
<td>Mercury ions</td>
<td>5 ppm for 24 hr</td>
<td>57% kill</td>
<td>(29)</td>
</tr>
<tr>
<td>Zinc ions</td>
<td>5 ppm for 24 hr</td>
<td>54% kill</td>
<td>(29)</td>
</tr>
<tr>
<td>Lead ions</td>
<td>5 ppm for 24 hr</td>
<td>0% kill</td>
<td>(29)</td>
</tr>
<tr>
<td>Copper Sulphate</td>
<td>100 ppm for 5 hr</td>
<td>41% kill</td>
<td>(29)</td>
</tr>
<tr>
<td></td>
<td>at 22.5°C</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>300 ppm for 5 hr</td>
<td>55% kill</td>
<td>(4)</td>
</tr>
<tr>
<td></td>
<td>at 22.5°C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Poly[oxyethylene-(dimethylamino)-ethylene(dimethylamino)ethyl] dichloride</td>
<td>0.3 ppm for 826 hr</td>
<td>100% kill</td>
<td>(30)</td>
</tr>
<tr>
<td></td>
<td>1.2 ppm for 313 hr</td>
<td>100% kill</td>
<td>(30)</td>
</tr>
<tr>
<td></td>
<td>4.8 ppm for 197 hr</td>
<td>100% kill</td>
<td>(30)</td>
</tr>
<tr>
<td>2-(Thiocyanomethylthio)benzothiol</td>
<td>0.15 ppm for 758 hr</td>
<td>100% kill</td>
<td>(30)</td>
</tr>
<tr>
<td>ammonium chloride &amp; Dodecylguanidine hydrochloride</td>
<td>0.6 ppm for 313 hr</td>
<td>100% kill</td>
<td>(30)</td>
</tr>
<tr>
<td></td>
<td>1.2 ppm for 260 hr</td>
<td>100% kill</td>
<td>(30)</td>
</tr>
<tr>
<td>Dimethylbenzylsulfoxide &amp; Dodecylguanidine hydrochloride</td>
<td>15 ppm for 12 h at 11°C</td>
<td>100% kill</td>
<td>(31)</td>
</tr>
<tr>
<td></td>
<td>after 4 h</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>15 ppm for 14 h at 14°C</td>
<td>100% kill</td>
<td>(31)</td>
</tr>
<tr>
<td></td>
<td>after 4 h</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>15 ppm for 6 h at 20°C</td>
<td>100% kill</td>
<td>(31)</td>
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<tr>
<td></td>
<td>after 24 h</td>
<td></td>
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<tr>
<td></td>
<td>15 ppm for 14 h at 20°C</td>
<td>100% kill</td>
<td>(31)</td>
</tr>
<tr>
<td></td>
<td>after 24 h</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dichloro-2-nitro-4-salicylanilide</td>
<td>0.05 ppm for 24 hr</td>
<td>70% kill</td>
<td>(32)</td>
</tr>
<tr>
<td></td>
<td>0.1 ppm for 24 hr</td>
<td>100% kill</td>
<td>(32)</td>
</tr>
<tr>
<td>M-triphenylmethyloxopholine</td>
<td>0.5 ppm for 24 hr</td>
<td>70% kill</td>
<td>(32)</td>
</tr>
<tr>
<td></td>
<td>0.9 ppm for 24 hr</td>
<td>100% kill</td>
<td>(32)</td>
</tr>
<tr>
<td>Cyanuric acid</td>
<td>2000 ppm for 17 days</td>
<td>50% kill</td>
<td>(33)</td>
</tr>
</tbody>
</table>
formation of mussel mats. Treatment times will depend on ability to achieve a lethal temperature of $\geq 30^\circ$C (86°F).

Control of condenser fouling by zebra mussels may be best achieved by treating all upstream areas by the methods described above such that mussels do not settle or reach sizes or densities that could foul condenser tubing. Such control will require monitoring for presence of veligers in source waters to determine application schedules (2).

Zebra mussel fouling problems are likely to be most severe and difficult to mitigate in service water systems (SWS), portions of which are difficult to access for mussel removal. Once adult mussels form dense mats, large quantities of shells will have to be removed from an SWS after mitigation. A number of off-line technologies can remove mussels from pipe walls. Water jetting could be effective in larger piping (40), but dislodged shells will have to be flushed from cleaned piping to prevent fouling of downstream components. Cutting or scraping line pigs may remove mussels from specific lines, but are unlikely to be effective in a large portion of an SWS. Off-line, in-situ abrasive blast cleaning (41) could remove mussel shells and byssal threads from specific pipe sections. Chemical cleaning technologies, utilizing mineral or organic acids (42), will dissolve shells, but are unlikely to remove byssal threads. In small diameter components such as heat exchangers, manual removal techniques may be required.

Biocide treatment can mitigate SWS zebra mussel infestations. Treatment protocols are essentially those for intake structures or a CWS as described above. Potentially effective biocides include chlorination (6, 7), bromination at higher pH ($> 8.0$) (34) or ozonation (35). The efficacy of CO$_2$ exposure as a biocide and use of surfactants and/or penetrants to disrupt byssal thread attachment require investigation. Several nonoxidizing molluscicides are potentially effective in mitigation and control of mussels in an SWS (Table 1).

Two molluscicide application strategies may be used to control SWS zebra mussel infestations. Chemical agents can be applied at very high concentrations for relatively short periods, but may require detoxification of discharge waters. Alternatively, agents can be applied for longer periods at minimal effective concentrations precluding necessity for detoxification. That zebra mussels may be more resistant to both chlorination and nonoxidizing biocides than other bivalves (30), suggests that higher concentrations or longer durations of molluscicide application could be required.

Although molluscicides can mitigate SWS mussel infestations, shell removal remains a problem. Smaller shells may simply be flushed through an SWS once released from byssal hold-fasts. However, dislodged shells could accumulate in low flow areas, aggravating sedimentation and corrosion. Dislodged larger shells and shell clusters could foul small diameter components such as heat exchangers or fire protection systems. Thus, chemical mitigation will probably require subsequent shell removal. Small diameter components can be protected from shell fouling by in-line shell traps (23, 24, 25).

Molluscicide treatment will not immediately remove byssal threads which can also increase sedimentation and corrosion rates. Use of penetrants to loosen byssal thread attachment should be investigated. Presently, water jetting, abrasive blasting or scraping and cutting pigs could be used to remove byssal threads from piping after biocide treatment.

Maintenance of constant or frequent flow in fire protection systems allows mussels to settle and grow. If fire protection systems are stagnant, mussel infestations will be prevented. Biocide injection during testing or when flowing prevents mussel settlement. In-line traps or strainers can prevent fouling of small diameter fire protection piping by shells dislodged from upstream components. Biocide application during flow will prevent mussel fouling of underground raw water irrigation (lawn watering) systems.

Efficacious molluscicides and application protocols for control of SWS fouling by zebra mussels are essentially those described for intakes and CWS above (Table 1). Generally molluscicides need only be applied to an SWS during spawning seasons, frequency of application dependent on the severity of mussel settlement and growth (minimally, once per year).

As in a CWS, total prevention of mussel settlement will provide the best protection against SWS fouling and can be achieved by continual biocide application during spawning season. Continual chlorination at 0.3 ppm residual is effective (7) as are other oxidizing biocides (Table 1). Continuous application of nonoxidizing biocides could also prevent SWS fouling (30). Daily biocide slug dosing is a cost-effective method for continual protection from bivalve fouling, but its efficacy in controlling zebra mussels remains to be determined. Slug dosing with a nonoxidizing biocide mitigated SWS fouling by Asian clams (28).

Nonchemical technologies to control zebra mussel SWS fouling include: sand-filtration of veligers from intake waters and high voltage electrical fields to kill entrained veligers (225-400 V/cm for 0.02-0.1 sec depending on environmental conditions and degree of veliger shell valve opening) (43, 44). Thermal backwashing of an SWS for several hours at 32-36°C (90-97°F) could kill recently settled juveniles (7). Nontoxic silicone-based antifoulant coatings could be used to prevent mussel attachment in various SWS components (36, 37).

Mitigation of zebra mussel infestations in cooling tower basins will primarily involve manual removal during outages. Robotic systems may also be utilized for off-line or on-line mussel removal. Annual application of biocides at the end of the spawning season should prevent growth and accumulation of mussels to levels that foul systems drawing water from tower basins unless mussel settlement and growth rates are high, necessitating more frequent mitigation. Control could be affected by treatment of makeup water with biocides, sand-filtration or high voltage electric fields. Nontoxic silicone-based antifoulant coatings could be used to prevent settlement on exposed surfaces.
Control of zebra mussel populations in source waters could reduce the number of veligers entrained on intake waters and, thus, fouling rates. As zebra mussels are restricted to relatively shallow waters (depth of maximum abundance is 2-14 m) (2), source water level draw-down may kill the majority of exposed mussels as this species is unable to survive more than 4 days in air at 20-22°C (68-72°F) (19). Therefore, annual cooling impoundment draw-down could not only reduce mussel populations but, could limit them to deeper, less hospitable habitats.

Biological controls may reduce zebra mussel densities in source waters. Adult crayfish ate an average of 93-114 juvenile mussels/day (45). A number of European fish species feed on zebra mussels (46, 47). Fish predation can reduce Asian clam populations by 96.6% (48) thus, could reduce mussel densities in source water. Three North American fish species feed on large (> 7 mm SL) bivalves including: Cyprinus carpio, the common carp; Ictalurus punctatus, the channel catfish; and Aplodinotus grunniens, the common drum (49). Of these, the drum feeds exclusively on bivalves making it a likely candidate for biological control of mussel populations.

Diving ducks and other water fowl feed on zebra mussels in Europe (50, 51, 52). Duck feeding reduced Asian clam population densities by 67-80% (53), suggesting that it may also regulate mussel populations. Heavy feeding by diving ducks on zebra mussels is reported in western Lake Erie (54).

The effects of predators on the eventual distribution and density of zebra mussels in North America is unknown. The likely pattern, based on European experience (2) and invasion of North America by the Asian clam (55), is attainment of extremely high densities during the first 5-10 yr after invasion, followed by reduction in density to lower, stable levels as predator species and disease organisms increase.

CONCLUSIONS

Because zebra mussels are rapidly expanding their North American range, power plants with potential for infestation should initiate monitoring programs for presence of adults and veligers in source and intake waters. Such monitoring permits advance warning of invasion by zebra mussels and initiation of mitigation and control programs before serious macrofouling problems can occur. Every effort should be made to prevent establishment of adult mussel populations as their subsequent removal is both difficult and expensive.

Because zebra mussels are only capable of entering and settling in raw water systems in the planktonic veliger stage, control measures need only be applied during that portion of the year when veliger larvae are present in source water (generally when water temperatures are above 14-16°C or 57-61°F).

EPRI is beginning a new project to develop a "Zebra Mussel Monitoring and Control Guide." This state-of-the-art document is intended to provide utility engineers guidance on applying a wide variety of zebra mussel monitoring and control measures in fossil and nuclear power plants. The focus will be on field-proven monitoring and control techniques. Sufficient details of costs and other impacts (e.g., corrosion) of the various monitoring and control technologies will be provided. The plant personnel can use these methods to select the appropriate technology for application. The expected publication date for this document is December 1990.

Since zebra mussels have the potential to spread to most parts of the U.S. (Fig. 6), EPRI has formed an inter-divisional task force, which consists of members from the Environment, Generation and Storage, and Nuclear Divisions, to coordinate R & D efforts in this area. EPRI has also formed a Utility Zebra Mussel Advisory Group to assist EPRI in planning long term strategy for developing environmentally acceptable solutions to the problem. In addition, EPRI is also coordinating R & D works with other groups which include the American Water Works Association Research Foundation, Empire State Electric and Energy Research Corporation, and Lake Erie Consortium.

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REFERENCES


