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Improving the Reliability of Open-Cycle Water Systems

An Evaluation of Biofouling Surveillance and Control Techniques for Use at Nuclear Power Plants

Prepared by D. A. Neitzel, K. I. Johnson, P. M. Daling

Pacific Northwest Laboratory
Operated by
Battelle Memorial Institute

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U.S. Nuclear Regulatory Commission

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PREFACE

The U.S. Nuclear Regulatory Commission (NRC), Division of Safety Review and Oversight is compiling information that can be used to improve the reliability of open-cycle water systems at nuclear power plants. The reliability of open-cycle water systems is compromised by fouling or clogging of pipes, heat exchanger tubing, and other constricted components within the systems. Fouling has resulted from the presence of bivalves, mud, silt, and corrosion products. Fouling by bivalves and other aquatic animals has been reviewed to determine the biological characteristics of bivalves and the engineering characteristics of open-cycle water systems that promote or enhance fouling. Biofouling and clogging surveillance and control techniques are reviewed in the document to provide data that the NRC can use to address mud, silt, and corrosion product fouling and clogging at operating facilities. This information will also be used during Office of Nuclear Reactor Regulation safety evaluations.

The compilation of information is being accomplished with four tasks:

1) a review of biofouling surveillance and control techniques for use at nuclear power plants;
2) a study of biofouling surveillance and control techniques and their applicability for use in controlling fouling and flow blockage by mud, silt, and corrosion products;
3) a study of proposed techniques for their applicability to systems and component configurations in nuclear power plants; and
4) preparation of a final report.

These four topics will be covered in four separate volumes. The scope of this report satisfies Task 1.

ABSTRACT

Nine surveillance and 11 control techniques were reviewed for their applicability to open-cycle water systems at nuclear power plants. Journal articles and technical reports were reviewed to collect information about the surveillance and control techniques. Power plant personnel that are using or have used some of the techniques were interviewed to get data on the effectiveness of the techniques. A computerized decision support program was used by the review staff to evaluate the techniques. The review results indicate all the techniques are used in open-cycle water systems to survey for or control biofouling and could be applied to the open-cycle water system at nuclear power plants.

The surveillance techniques reviewed include monitoring water and substrate samples outside the plant by SCUBA diver inspection, monitoring growth panels, inspecting dismantled equipment, examining samples from side-stream monitors, inspecting water samples from inside the plant, measuring pressure differentials, measuring temperature differentials, and measuring flow differentials. The control techniques reviewed include chlorinating the water using the AMERTAP system (AMERTAP Corporation), using the MAN system (MAN Corporation), installing tube scrapers, hydroblasting, applying antifoulant coatings, thermal backwashing, using oxygen scavengers, using screens and strainers, using hand scrapers, and nonthermal backflushing.

EXECUTIVE SUMMARY

Essential components of the open-cycle water systems of nuclear power plants are fouled and clogged with accumulations of mud, silt, corrosion products, and other inorganic materials (inorganic fouling), or from the presence of plants and animals (biofouling) in the service water. The Pacific Northwest Laboratory (PNL) conducted a review of 9 biofouling surveillance and 11 biofouling control techniques to evaluate their use at nuclear power plants. These techniques are used in open-cycle water systems to control or detect biofouling and could be applied to the open-cycle water system at nuclear power plants. The surveillance techniques reviewed include monitoring by SCUBA divers, inspecting water and substrate samples from outside the plant, monitoring growth panels, inspecting dismantled equipment, examining samples from side-stream monitors, inspecting water samples from inside the plant, measuring pressure differentials, measuring temperature differentials, and measuring flow differentials. The control techniques reviewed include chlorinating the water, using the AMERTAP system (AMERTAP Corporation), using the Man system (MAN Corporation), installing tube scrapers, hydroblasting, applying antifoulant coatings, thermal backwashing, using oxygen scavengers, installing screens and strainers, using hand scrapers, and nonthermal backflushing. Additionally, eight control techniques were reviewed that may be used to control biofouling, but are not yet tested for use at nuclear power plants.

The information collected during this review was used to propose an effective biofouling surveillance and control program at nuclear power plants. An important preliminary means for developing an effective program is a thorough system evaluation to determine which components and/or subsystems are most likely to foul and where fouling will have the greatest impact on plant safety. Although it is recommended that fouling be minimized throughout the entire open-cycle water system, a system evaluation will help to focus biofouling surveillance and control on those areas of the water system that have the highest impact on plant safety and efficient operation.

Surveillance and control programs have been somewhat ineffective in controlling biofouling at many power plants partly because the potential impact of bivalve fouling was not fully anticipated, and thus, adequate measures to detect and control biofouling were not included in the original plant design. Asiatic clam fouling at power plants using freshwater has been difficult to control since this bivalve species has only recently invaded many lakes and river systems in the United States. Plants using saltwater have generally been better prepared to detect and control bivalve fouling because of the well-known problems involving marine slimes, films, and microinvertebrates. However, several saltwater plants have been affected by bivalve fouling in recent years, indicating that surveillance and control practices at these plants have similar shortcomings.

The reliability of open-cycle water systems can be improved with a comprehensive and effective surveillance and control program at the nuclear power plant. The results of this study indicate four recommendations for improving biofouling surveillance and control programs: 1) thoroughly evaluating the system to determine which components and/or subsystems are most likely to foul and where fouling will have the greatest impact in plant safety and operation, 2) revising the plant technical specifications to reflect improved surveillance and control procedures for biofouling, 3) monitoring the effectiveness of the control procedures as part of the surveillance program, and 4) including biofouling surveillance in the routine maintenance program.

OPEN-CYCLE SYSTEM EVALUATION

The potential correlation between biological characteristics and plant design has to be evaluated in order to predict the effectiveness of a surveillance and control program. Biofouling by macroinvertebrates occurs when the biological characteristics of bivalves are compatible with the environment in the open-cycle system. Both physical design and operating procedures of open-cycle systems can promote or restrict fouling.

A numerical scoring or evaluation system is recommended by Neitzel et al. (1984). The biological characteristics of bivalves are listed along with the design characteristics of the power plant. A maximum score for each correlation is suggested. By comparing the maximum values with the score of the assessor, a 'fouling index' can be developed for each system or component. The fouling index can help a plant operator identify those systems or components that require the closest surveillance.

REVISION OF PLANT TECHNICAL SPECIFICATIONS

The revision of plant technical specifications to reflect improved surveillance and control procedures for biofouling is an important part of an effective biofouling control strategy. Interviews with nuclear plant personnel indicate that maintenance and testing required by technical specifications receive higher priority than other activities. Technical specifications can be written to make some surveillance and control systems critical path items in order to ensure their correct operation during plant operation. An example would be a technical specification requiring the chlorination system to remain in operable condition at all times, and requiring chlorination schedules to be maintained during extended outages. Plants that have implemented improved surveillance and control techniques have noted substantial decreases in the severity of their fouling problems. In several cases, the difference has been the increased attention given to control systems already in place.

INCLUDING BIOFOULING SURVEILLANCE IN REGULAR MAINTENANCE PROGRAM

Many components of the open-cycle system are regularly inspected. Rains et al. (1984) have made some specific recommendations for increasing these inspections to improve the reliability of open-cycle systems. These inspections could be improved further by including a survey for potential biofouling problems. The inspection should include a survey for bivalve shells, an inspection of surfaces for attached bivalves, and a collection of mud, silt, and water to survey for bivalve larvae. Some of these inspections are straightforward; others may require the attention of the plant biologists.

MONITORING CONTROL EFFECTIVENESS

One of the most important uses of some surveillance techniques is to monitor control techniques. SCUBA divers should make regular inspection of intake bays and forebays to monitor the accumulation of bivalves, mud, or silt. Growth panels should be used to monitor for the presence of bivalves. Growth panels also serve to monitor the effectiveness of thermal backwash control programs. The panels can be useful in determining the timing of thermal backwash programs. Bivalves that are being killed and washed through the open-cycle system should be small enough to clear the condenser tubing; otherwise, an effective control program can become a clogging problem. The size of bivalves can be monitored on growth panels. Similar monitoring functions can be assigned to side-stream monitors. Water sampling should be conducted throughout the open-cycle system to ensure that chlorine, or the control chemical, levels are toxic throughout the system.

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INTRODUCTION

Fouling and clogging of open-cycle water systems is a safety concern of power generating utilities and the U.S. Nuclear Regulatory Commission (NRC). This concern is the result of several fouling incidents that have occurred in safety-related equipment at nuclear power plants. Fouling occurs when organisms attach themselves to available substrate or corrosion products accumulate. Clogging occurs when organisms, mud, silt, or corrosion products are pumped or washed into a pipe, valve, strainer, screen, or any other constriction in a quantity that obstructs normal flow. In response to this concern, the NRC contracted with the Pacific Northwest Laboratory (PNL) to review information that will lead to the improvement of the reliability of open-cycle water systems in nuclear power plants.

Improving the reliability of the open-cycle water systems at nuclear power plants requires development of surveillance and control information. This information would be used to 1) detect fouling organisms in source water; 2) detect fouling organisms in open-cycle systems; 3) detect the presence of mud, silt, and corrosion products; and 4) develop control and removal techniques for biofouling organisms, mud, silt, and corrosion products. Information on biofouling by macroinvertebrates has been reviewed (Neitzel et al. 1984; Daling and Johnson 1985; Henager et al. 1985). These documents review information on the biological characteristics of bivalves that enhance their ability to infest raw-water and fire protection systems, the engineering characteristics of raw-water systems that provide suitable bivalve habitat, the current status of biofouling surveillance and control techniques, and factors that might interact with 'normal' levels of plant biofouling to exacerbate problems not related to fouling.

It is possible that biofouling surveillance and control strategies might be applicable to the fouling and clogging problems caused by mud, silt, and corrosion products. The first step in evaluating this possibility is to review the biofouling surveillance and control techniques to determine which of these techniques might be applicable at nuclear power plants to improve the reliability of open-cycle water systems. This report contains our review of biofouling surveillance and control techniques, evaluation of their applicability at nuclear power plants, and suggests procedures that might be the basis for a surveillance and control program to improve the reliability of open-cycle water systems at nuclear power plants.

RECOMMENDATIONS

Based on the review of biofouling surveillance and control techniques, two sets of recommendations were made. The first set concerns improving biofouling surveillance and control programs at nuclear power plants. The second set relates to how further information should be reviewed and presented to improve the reliability of open-cycle water systems.

IMPROVEMENT OF BIOFOULING SURVEILLANCE AND CONTROL PROGRAMS

1. The components and subsystems of an open-cycle water system should be thoroughly evaluated to determine which components are most likely to foul and in which areas fouling will have the greatest impact on plant safety and operation.

2. Plant technical specifications should be revised, where appropriate, to include biofouling surveillance and control as an important part of the procedure.

3. Regular maintenance inspection should include a survey for the presence of bivalves or mud and silt in which bivalves could settle and grow.

4. Biofouling surveillance programs should be designed to help evaluate the effectiveness of biofouling control programs.

RELIABILITY OF OPEN-CYCLE WATER SYSTEMS

1. It should be determined whether or not biofouling surveillance and control techniques in open-cycle systems may be used for surveillance and control of fouling by mud, silt, and corrosion products.

2. The potential for increasing corrosion in open-cycle water systems from the implementation of proposed surveillance and control techniques should be evaluated.

3. All proposed surveillance and control techniques should be evaluated to ensure their applicability to specific systems and configurations at nuclear power plants.

4. Any surveillance and control methods that are developed during this study or that are under development should be reviewed to determine whether they might improve the reliability of open-cycle water systems.

5. It should be determined if recommended surveillance and control techniques are in compliance with the Clean Water Act of 1977 and other discharge regulations.

6. The information developed for this report and any subsequent information developed for improving the reliability of open-cycle water systems should be incorporated into a single report. This compilation will provide guidance to utility staff who implement the surveillance and control techniques and to NRC staff who may use the information to develop technical specifications for surveillance of open-cycle systems at nuclear power plants.

REVIEW OF BIOFOULING SURVEILLANCE AND CONTROL TECHNIQUES

The NRC provided PNL staff with six documents to review. These documents present information on the current status of macrobiofouling surveillance and control techniques (Table 1). Each document was reviewed to compile a comprehensive list of biofouling surveillance and control techniques. Many of these techniques are currently used in operating power plants (nuclear and non-nuclear), while others have been shown to be effective in laboratory and pilot-scale tests.

Brief descriptions are given for each surveillance and/or control technique. The applicability of the surveillance and control techniques for use in open-cycle water systems at nuclear power plants is discussed.

BIOFOULING SURVEILLANCE TECHNIQUES

Surveillance is an important part of any biofouling prevention program. As used in this report, the term 'surveillance technique' refers to activities designed to detect fouling and to monitor the growth and development of fouling organisms both inside and outside the open-cycle water system. The surveillance techniques described in the following pages are divided into three general categories: 1) techniques for monitoring fouling organisms outside the plant in the source waterbody, 2) techniques for monitoring fouling organisms inside the plant, and 3) techniques for monitoring plant performance characteristics that provide an indication that biofouling organisms may be present.

1. Techniques For Monitoring Fouling Organisms Outside The Plant

Bivalve populations are sampled outside the plant in order to monitor the organism density and movement. Monitoring of movement is especially important for Asiatic clams because they continue to move into new areas. The reproductive status of bivalve populations near a plant can also be monitored. These data are important when control techniques are targeted at specific early life stages. Techniques of monitoring bivalve populations in the intake structure and source waterbody include the use of SCUBA divers, water and substrate sampling, and growth panels.

Visual Inspection by SCUBA Divers

At many of the nuclear plants surveyed in the NRC-sponsored biofouling study (Neitzel et al. 1984; Daling and Johnson 1985; Henager et al. 1985), divers monitored bivalve populations in the water source and in the intake structure of the plant. Some plants use divers to survey the effectiveness of fouling control techniques (e.g., chlorination, thermal backwashing, oxygen scavengers) in the intake structure. When diving is conducted in the intake structure, it must be scheduled to coincide with plant outages

TABLE 1. NRC-Provided Documents Reviewed by PNL Staff for Information to Improve the Reliability of Open-Cycle Water Systems

NUREG/CR-4070, "Bivalve Fouling of Nuclear Power Plant Service-Water Systems. Volumes 1 - 3.

Volume 1. "Correlation of Bivalve Biological Characteristics and Raw-Water System Design."

Volume 2. "Current Status of Biofouling Surveillance and Control Techniques."

Volume 3. "Factors That May Intensify the Safety Consequences of Biofouling."

Memorandum from Carlyle Michelson to Harold R. Denton and Richard DeYoung, Subject: "Service Water System Flow Blockage by Bivalve Mollusks at Arkansas One and Brunswick," dated February 12,1982.

Memorandum from Darrell G. Eisenhut to Stephen H. Hanauer, Subject: "Proposed Recommendations for Improving the Reliability of Open Cycle Service Water Systems," date March 19, 1982.

NUREG/CR-3054, "Closeout of IE Bulletin 81-03: Flow Blockage of Cooling Water to Safety System Components by Corbicula sp. (Asiatic Clam) and Mytilus sp. (Mussel), June 1984.

or when an individual intake bay is out of service. Divers should also clean accumulations of bivalves and sediment from the intake structure and large intake piping using vacuum dredges and/or hand scrapers.

Water and Substrate Sampling

Water and substrate samples taken from outside the plant can be used to monitor the presence of early life stages of fouling organisms, determine when bivalve spawning seasons occur, and monitor the amount of suspended solids in the water entering the plant. These samples, taken from outside the plant, could be compared with water samples taken in the plant to estimate the amount of sediment accumulating in plant water systems. Substrate sampling can also be used to monitor the occurrence and population density of bivalves growing in the vicinity of the plant.

Growth Panels

Growth panels are used to monitor bivalve populations in the intake structure and in the vicinity of the plant. Growth panels are inexpensive, simply designed, and easy to monitor during normal plant operation. The panels are made of a variety of materials including substrates found in the intake structure (concrete) and inlet piping (either steel or lining materials such as concrete or rubber). Growth panels can also be used to monitor the effectiveness of bivalve control practices.

2. Techniques For Monitoring Fouling Organisms Inside The Plant

The second form of biofouling surveillance is monitoring biofouling within piping and heat exchangers inside the plant. In-plant monitoring provides information to help determine where biofouling is most likely to occur in the plant. In-plant surveillance also helps identify operating conditions that enhance the potential for fouling. In-plant monitoring techniques described in this section include 1) dismantling equipment for visual inspection, 2) side-stream monitors, and 3) water sampling techniques.

Dismantling Equipment for Visual Inspection

Visual inspections are performed by removing access covers from heat exchangers and water supply headers. The inspections can identify locations where fouling and clogging have actually occurred in the plant. Such inspections are restricted to plant outages or to cooling loops that can be isolated during normal operation. Many plants currently have visual inspection programs that examine for mud, silt, and corrosion products; damage to heat exchange tubes and baffle plates; and accumulations of bivalves. Inspection schedules, however, often allow sufficient time between inspections (typically 2 to 3 years) for bivalve fouling to seriously degrade. For visual inspections to effectively monitor biofouling, key portions of the open-cycle water system need to be thoroughly inspected annually (Rains et al. 1984). For plants with existing biofouling problems or a high potential for problems, Rains et al. (1984) suggest that the NRC consider an extensive quarterly inspection program covering all safety-related systems including fire protection systems. Such frequent inspections could be scheduled to coincide with refueling or maintenance outages when possible, however, other provisions (retrofitting of isolation valves, access ports, etc.) may have to be made to allow for such extensive inspections during normal operation.

The present visual inspection programs could be improved by using inspection reports to record the condition of heat exchangers and piping during inspections. The reports provide a written record of the damage and amount of fouling observed during the inspection. An example heat exchanger report form is given in Daling and Johnson (1985).

Side-Stream Monitors

Side-stream monitors are growth chambers used to monitor the potential for bivalve growth in open-cycle cooling loops at various locations in the plant (Figure 1). Water from the open-cycle system is circulated through the side-stream monitor to provide environmental conditions that approximate those in the water system piping. Side-stream monitors are designed to provide 'ideal' conditions for bivalve settlement and growth.

Side-stream monitors are inexpensive, simply designed, and they are easily monitored during normal operation. They are used to monitor the effectiveness of bivalve control practices such as chlorination and thermal backwashing.

Water Sampling Techniques

Water within the plant can be sampled to test for compounds given off by fouling organisms (e.g., hormones, pheromones, feces, gases from decaying bivalves). This technique may require the skill of a chemist or biologist rather than plant maintenance personnel. It should be possible, however, to devise a simplified procedure that could be used by unskilled personnel (a litmus test equivalent). Water sampling may also be used to test for silt and corrosion products in the water. Water sampling techniques may be restricted to cooling loops that are nearly stagnant to obtain concentrations of organic compounds or corrosion products that are high enough to detect easily.

3. Monitoring to Detect Changes in Plant Performance

Monitoring the cooling-loop performance characteristics can provide an early warning of changes due to biofouling or the presence of mud, silt, and corrosion products. Performance characteristics discussed in this section include 1) differential pressure measurements, 2) differential temperature measurements across heat exchangers, and 3) flow velocity measurements.

Differential Pressure Measurement

Differential pressure measurements are used to monitor trends that estimate the extent of flow degradation due to biofouling or mud, silt, and corrosion products. Plant technical specifications often require differential pressure measurements across heat exchangers as an indication of flow blockage in cooling loops. Differential pressure is measured between pressure lines that sample the pressure from the inlet and outlet sides of the cooling loop. Pressure lines can foul, and thus pressure measurements may not always be a reliable technique for determining flow degradation. Also, differential pressure measurements cannot detect internal bypass leakage such as that which occurred in the residual heat removal (RHR) heat exchangers at Brunswick 1 and 2 (Imbro and Gianelli 1982) and in the reactor building closed cooling-water (RBCCW) heat exchangers at Pilgrim 1 (Imbro 1982). Differential pressure measurements are usually taken once per shift, and they are easily performed during normal operation if pressure taps have been provided.

Differential Temperature Measurement

Differential temperature measurements can indicate trends that can be used to detect degradation of water flow. Temperatures are measured across both the shell and tube sides of heat exchangers in order to estimate the

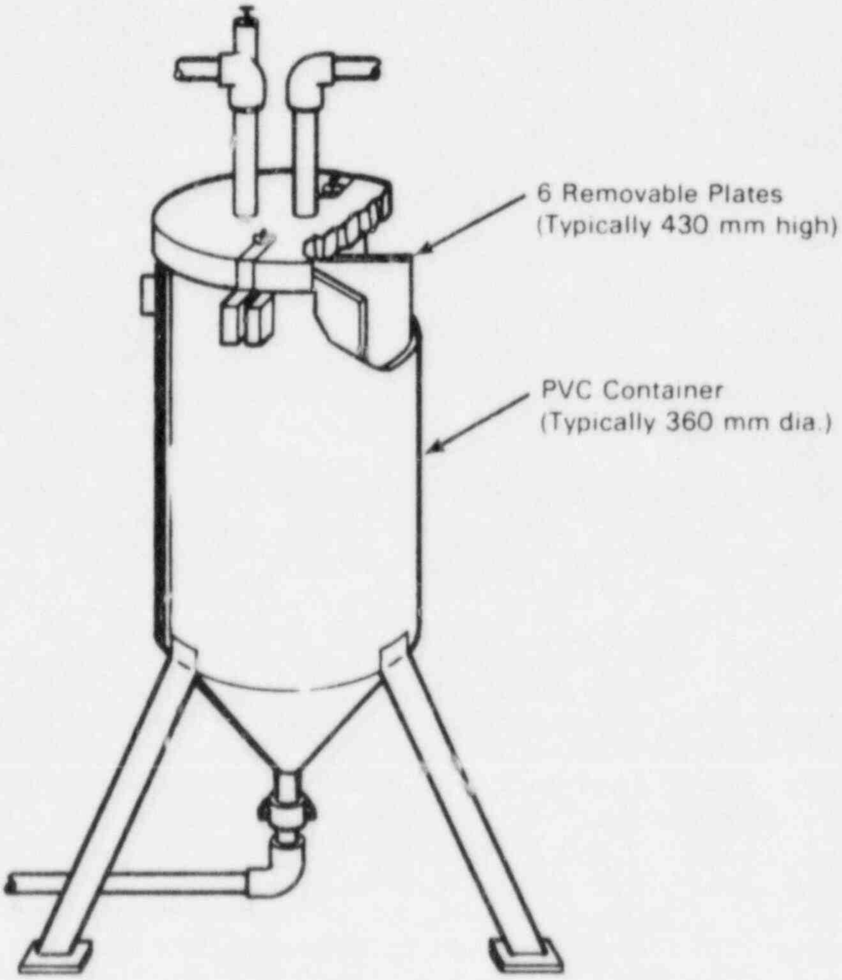

FIGURE 1. Illustration of a Typical Side-Stream Monitor Used at Nuclear Power Plants to Monitor Bivalve Settlement and Growth (Scotton et al. 1983)

overall heat transfer coefficient of a heat exchanger. The overall heat transfer coefficient, as defined in Daling and Johnson (1985), provides a more quantitative estimate of the heat transfer capabilities of a heat exchanger. Temperatures are easily measured without disrupting normal plant operation, and the overall heat transfer coefficient provides a sound indication of internal bypass leakage within a heat exchanger. The temperatures of components being cooled by the open-cycle system are commonly measured at nuclear power plants. These measurements, however, are insensitive to detecting the onset of fouling and, therefore, indicate only that serious flow degradation has already occurred.

Flow Velocity Measurements

Flow velocity is measured to estimate the flow rate through cooling loops. This information has been used as an indication that cooling loops are performing to the minimum flow requirement given in plant technical specifications. Flow velocity is an important environmental condition that controls the settlement and growth of bivalve larvae in open-cycle water systems. Flow velocities in cooling loops that are used intermittently and have valves that leak excessively often provide habitats that enhance bivalve settlement and growth. It is important that flow velocity be measured during normal operating conditions both on the cooling loops that are in use and on those that remain on standby status. Permanent flow measuring devices (e.g., venturi meters) are installed on many cooling loops in open-cycle water systems. Portable, ultrasonic flow meters are also used at some nuclear power plants. An advantage of the portable meters is that they can be clamped or strapped to piping and therefore require no piping modifications. They are less accurate than conventional methods, but they are accurate enough to estimate valve leakage and to develop trends in flow velocity. Portable flow meters could be used effectively to ensure that valve leaks do not occur in the fire protection system.

Several problems have occurred with typical flow velocity measurement techniques used in nuclear power plants. Flow velocity is sometimes measured at the inlet header to a series of heat exchangers and provides flow measurement for the series of heat exchangers, but does not indicate the flow through individual heat exchangers. Flow velocity can also be misleading because in instances where bivalves, primarily blue mussels and American oysters, have attached to the inside of supply piping (reducing the flow area) the velocity may actually increase while the flow rate remains relatively constant or decreases. Thus, serious bivalve fouling could be present and the minimum required flow velocity still be met.

BIOFOULING CONTROL TECHNIQUES

The second major element of an effective biofouling prevention program is control of the infestation and growth of fouling organisms. As used in this report, the term 'control technique' refers to techniques that are used to limit biofouling to a safe and acceptable level. The goal of biofouling control techniques is not to eliminate biofouling completely, but rather to reduce its safety risk or consequences. The following pages give brief descriptions of control techniques that are either in use at power plants or that have been effective in laboratory or pilot-scale tests. These descriptions are divided into control techniques for 1) microfouling slimes, 2) bivalve larvae, 3) juvenile and adult bivalves, 4) collection and removal of debris, 5) implementation in new plant designs, and 6) unproven control techniques.

1. Control Techniques For Microfouling Slimes

Microfouling slimes and algae affect plant operation and safety by reducing heat exchanger performance. Slimes and algae are also the precursor to macroinvertebrate settlement. Although plant safety is important, the primary emphasis of slime control is to maintain high turbine efficiency and thus increase power production. Techniques for controlling slime buildup in heat exchanger tubes include 1) intermittent chlorination, 2) the AMERTAP on-line tube cleaning system, 3) the MAN on-line tube cleaning system, 4) tube scrapers, and 5) hydroblasting.

Intermittent Chlorination

A review of utility responses to Inspection and Enforcement Bulletin 81-03 indicates that chlorination was the most common slime control technique used by utilities (Rains et al. 1984). Chlorine is also used to control settlement and survival of bivalves. Most nuclear power plants are equipped with chlorination systems for controlling microfouling. A typical slime control program used at one nuclear plant specifies weekly chlorination for a 2-hour period at 0.2 parts per million (ppm) free residual chlorine. Although effective in controlling slime buildup on condenser and heat exchanger tubes, intermittent chlorination has to be augmented with continuous chlorination during periods of bivalve spawning to control bivalve fouling.

Three different sources of chlorine are used at nuclear power plants: sodium or calcium hypochlorite solution, compressed chlorine gas, or sodium hypochlorite generated electrolytically from saltwater. According to Bour (1980), 70% of the stations that have chlorination programs use chlorine gas, presumably because the gas and associated injection system are less expensive (Battaglia et al. 1981). The remaining 30% inject hypochlorite solutions into the open-cycle water system. Hypochlorite is less hazardous to store onsite than is chlorine gas, because it is a liquid rather than a compressed gas. The St. Lucie nuclear plant uses electrolytic generation to produce sodium hypochlorite solution from seawater. An advantage of this technique is that the electrodes can be placed directly in the intake structure and therefore no distribution system is required.

The AMERTAP Online Tube Cleaning System

The AMERTAP system is the most common continuous mechanical tube cleaning system in use at power plants (Torbin and Mussalli 1980; Drake 1977). The AMERTAP system cleans heat exchanger tubes by circulating sponge balls through the tubes to remove microfouling slimes from the inner surface (Figure 2). This form of mechanical cleaning is most commonly used in the main condensers to maintain high heat transfer efficiency in the condenser tubes and therefore high turbine efficiency. This system is not effective for removing bivalve shells lodged in condenser tubes because the balls themselves often become lodged behind shells blocking the tubes. The AMERTAP system's most useful feature for bivalve fouling control is its ability to indicate when a large number of tubes are blocked by showing an excessive loss of balls. The AMERTAP system can be retrofitted to most existing condensers and it operates during normal plant operation.

The MAN Online Tube Cleaning System

The MAN system provides intermittent tube cleaning that removes debris and slime by reversing the cooling water flow and passing nylon brushes through the tubes (Figure 3). This system, like the AMERTAP system, is designed primarily for microfouling control in the main condensers. The cages on the ends of the tubes also collect debris and bivalves and increase the fouling problem. Extensive piping modifications are required in existing plants to provide the flow reversal capabilities needed to operate this system. Also, typical condenser tubes would have to be lengthened to install the brush cages. These restrictions essentially limit the MAN system to new plants.

Tube Scrapers

Tube scrapers are used to remove shells and other debris from condenser and heat exchanger tubes. This technique can only be used during outages because access to the heat exchanger tubes is required. The scrapers are forced down the tubes by a high-pressure water gun, a rotating flexible shaft, or by high-pressure air (Torbin and Mussalli 1980). Several types of scrapers are available including smooth metal scrapers, bristled metal scrapers, nylon brushes, and rubber plugs. The smooth metal scrapers clean down to bare metal and remove a certain amount of the tube wall, slightly reducing its thickness. The smooth metal scrapers appear to be more effective than bristled scrapers on shells and debris lodged in tubes, but they also remove more metal and thus reduce tube life more rapidly. Nylon brushes and rubber plugs remove less of the metal surface than do metal scrapers, but they are also less effective in removing bivalve shells. Tube scrapers have the added disadvantage that they can become lodged in the tubes.

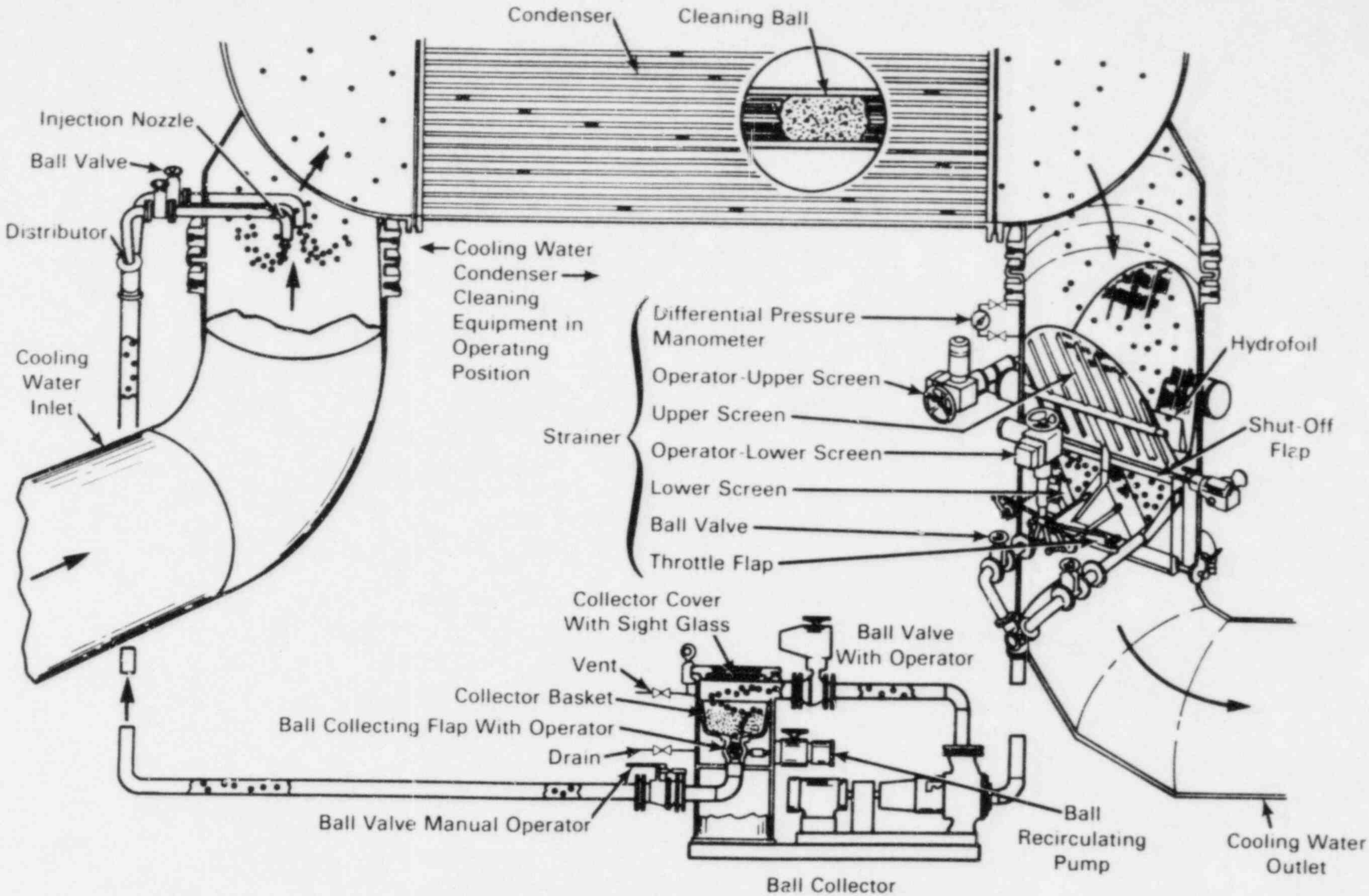

FIGURE 2. Illustration of an AMERTAP Condenser Tube Cleaning System Used at Nuclear Power Plants to Control Slime and Algae (Drake 1977).

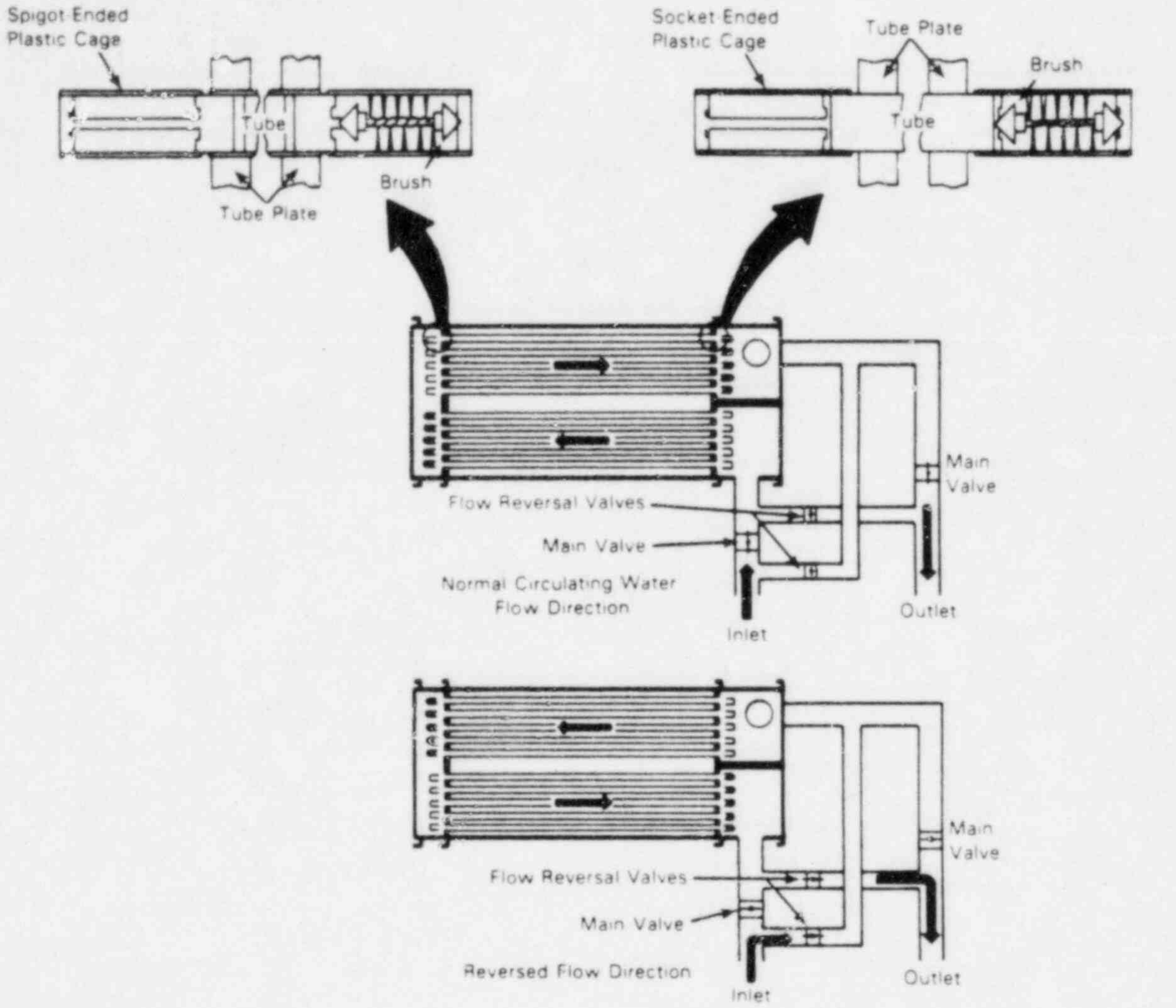

FIGURE 3. Illustration of a MAN Tube Cleaning System Used at Nuclear Power Plants to Control Slime and Algae (Torbin and Mussalli 1980)

Hydroblasting

Hydroblasting relies on high-pressure water directed through specially-designed nozzles to loosen and flush slime buildup from inside tubes (Torbin and Mussalli 1980). Hydroblasting (or hydrolazing) is a relatively new and inexpensive technique, and in addition to slime buildup, it is used to remove bivalves and other debris from inside condenser tubes (Torbin and Mussalli 1980). An advantage of hydroblasting over other tube cleaning techniques is that it causes less damage to the tubes. Hydroblasting has also been used effectively to remove attached bivalve shells from surfaces in the intake structure and intake piping. This technique is also restricted to outages because access is required to the heat exchanger tubes and/or the intake structure.

2. Control Techniques For Bivalve Larvae

Controlling bivalve larvae is an important phase of an effective bivalve control strategy. Bivalves found in open-cycle systems in the plant undoubtly entered as larvae or were spawned inside the plant and have found suitable conditions for growth. Methods of controlling bivalve larvae include 1) continuous chlorination and 2) antifoulant coatings.

Continuous Chlorination

Intermittent chlorination used to control slime is ineffective in controlling bivalve larvae because chlorine concentrations and application frequencies are low enough to allow larvae to attach and grow within water systems. After the larvae have grown to a shelled stage, bivalves are able to minimize exposure to chlorinated water by closing their shells (they 'clam-up') and by burrowing into sediment layers. The Tennessee Valley Authority (TVA) has implemented an Asiatic clam control program that calls for continuous chlorination during clam spawning periods to control Asiatic clam larvae (Daling and Johnson 1985, Rains et al. 1984). This program apparently has been successful at several of their nuclear facilities.

Continuous chlorination programs may not be practical when limited by environmental discharge limitations. U.S. Environmental Protection Agency regulations (40 CFR Parts 125 and 423, vol. 25 No. 200, October 14, 1980) limit chlorine discharges from steam electric power stations. These regulations require that total residual chlorine (TRC) not exceed 0.14 ppm at the point of discharge and that TRC may not be discharged from any point-source for more than 2 hours per day (Rains et al. 1984). The EPA has, however, allowed power plants to increase chlorine discharge to the amount necessary for effective control. Necessary discharge increases are determined by chlorine minimization studies at the plant. Rains et al. (1984) indicate that several licensees have performed chlorine minimization studies and that it may be beneficial for other licensees to do so considering the effectiveness of chlorination in controlling bivalve fouling.

Another problem, often encountered with continuous chlorination programs, is the system's reliability. Chlorination systems intended for intermittent application are often inadequately designed to provide the continuous chlorination needed to control bivalve larvae. Utility personnel indicate that chlorination system reliability has been a problem.

Antifoulant Coatings

Antifoulant coatings, although used extensively in the marine industry, have seen little use in power plants. This is due to their poor durability when compared to the operating life of power plants (several years versus the 40-year design life of nuclear plants) and because of uncertainties of their impact on the environment. The most common antifoulant toxicants include copper, copper alloys, and organometallic materials. These compounds are applied to surfaces in the form of nylon- or rubber-based paints, elastomeric lining materials, and metallic plating. Elastomeric linings (commonly neoprene or nylon sheeting 0.5 in. thick) are chemically bonded to surfaces.

Extensive surface preparation is required to ensure a firm bond of all types of coatings. Even so, typical life expectancies of these coatings only range from 15 to 30 months. Another disadvantage is that the coating may contribute to fouling when it works loose and is pumped or washed through the open-cycle system. Antifoulant coatings may be an effective control technique in plants that already use rubber or concrete lined intake piping. Antifoulant coatings may also be an effective control technique for preventing oysters from permanently bonding to intake structures and piping. Additional research is needed to better determine the durability and effectiveness of coatings in a power plant environment.

3. Control Techniques for Juvenile and Adult Bivalves

Once bivalves have infested the open-cycle water system, measures must be taken to control shelled, juvenile, and adult bivalves. Shelled bivalves are able to avoid chemical treatment by tightly closing their shells for extended periods of time. Effective methods of controlling shelled bivalves include 1) thermal backwashing and 2) oxygen scavengers.

Thermal Backwashing

Thermal treatment is an effective technique of killing bivalves. Mattice et al. (1982) reported that 30-min exposures to temperatures of 43°C or higher kills virtually all Asiatic clams. Time-temperature mortality tests on blue mussels indicate that exposure to 41°C or higher temperatures for 10 min causes 100% mortality (Scotton et al. 1983). The Millstone nuclear plants use thermal treatments of 20 min at 39°C to control blue mussels (Johnson et al. 1983).

Thermal backwashing has been used during normal operation by several utilities to control blue mussel fouling in the circulating-water intake structure and in the main condensers. Common procedures are to route hot water from an on-line condenser back through the outlet of an off-line condenser and into the intake bay. This procedure allows treating both the condenser and the intake bay. The thermal treatments are performed frequently enough so as not to allow bivalves to grow to a size that causes clogging problems. The plant must reduce power during thermal backwashing, however, this lost production is recovered several times because of the reduced downtime and increased turbine efficiency.

This technique has not been used to control blue mussels in the safety-related service-water system because water temperature limits would be exceeded. Use of thermal backwashing in the service water system would require some retrofitting of equipment (installing cross-over lines) to allow backflushing the redundant train with heated water from the on-line train. Plants using thermal backwashing in the circulating-water system normally use chlorination to control bivalves in the service-water system. The effluent from the service-water system is diluted with the unchlorinated effluent from the circulating-water system to minimize the concentration of chlorine in the total plant effluent.

Oxygen Scavengers

An oxygen scavenger system developed by Smithson (1981) uses sodium metabisulfite ($Na_2S_2O_5$) to create anaerobic conditions in the intake structure to kill Asiatic clams. This technique uses cobalt chloride ($CoCl_2$) as a catalyst and hydrogen sulfide gas (H_2S) can be used to increase the effectiveness and reduce the duration of the treatment. This technique has been used successfully at the fossil-fueled, Baldwin Station operated by Illinois Power Company, but it has not been used at nuclear power plants.

The use of an oxygen scavenger requires still water conditions for periods of 60 to 72 hours. This time requirement limits the use of oxygen scavengers to periods during plant outages and to systems that can be easily isolated. Oxygen scavenger techniques have not been used for blue mussel and American oyster control.

4. Techniques For Collecting and Removing Bivalves and Debris

Once bivalves have infested the open-cycle system, they must be removed to prevent clogging of heat exchangers tubes and small piping. Techniques used to remove bivalves include 1) screens, 2) strainers, 3) hand scrapers, 4) hydroblasting, and 5) backflushing.

Screens

Intake screens at power plants typically have mesh sizes ranging from 3/16 to 3/8 inch. As part of their Asiatic clam control program, the TVA has installed screens of 1.26-mm (0.05 in.) mesh size. Although bivalve larvae are too small to be effectively screened out, Daling and Johnson (1985) indicate that fine-mesh screens may reduce the number of larvae entering the plant because larvae may cling to the increased amount of debris on the finer screens.

Strainers

Several types of in-line strainers are used in power plants to filter water flowing through the open-cycle water system. All plants are equipped with manual or automatic cleaning strainers directly downstream from the intake pumps to the service-water and circulating-water systems. Typical strainers filter debris larger than 3.2 mm (1/8 in.), although strainers as small as 0.4 mm (1/64 in.) have been used (Power 1982). Fine-mesh strainers can be retrofitted into most piping systems, however, the additional head loss due to reduced flow area increases station pumping costs (Torbin and Mussalli 1980). Service-water strainers have failed at Indian Point and Salem 1 and 2 (Henager et al. 1985). Clogging by ice, grass, and other debris caused high pressure differentials across several strainers and broke the shear pins on the motor shafts of several strainers. Sudden macroinvertebrate fouling could produce the same effect.

A second type of strainer (Figure 4) removes organisms and debris by a cyclone separator effect (Power 1982). Cyclonic separators force water into cyclonic flow which deposits solid debris into a collection box. The debris is removed by opening a valve to evacuate the collection box. These strainers are reported to be performing successfully with minimal head loss. Little maintenance is required because the strainers have no moving parts. These strainers are generally designed for large-volume, high-velocity systems such as the circulating-water system.

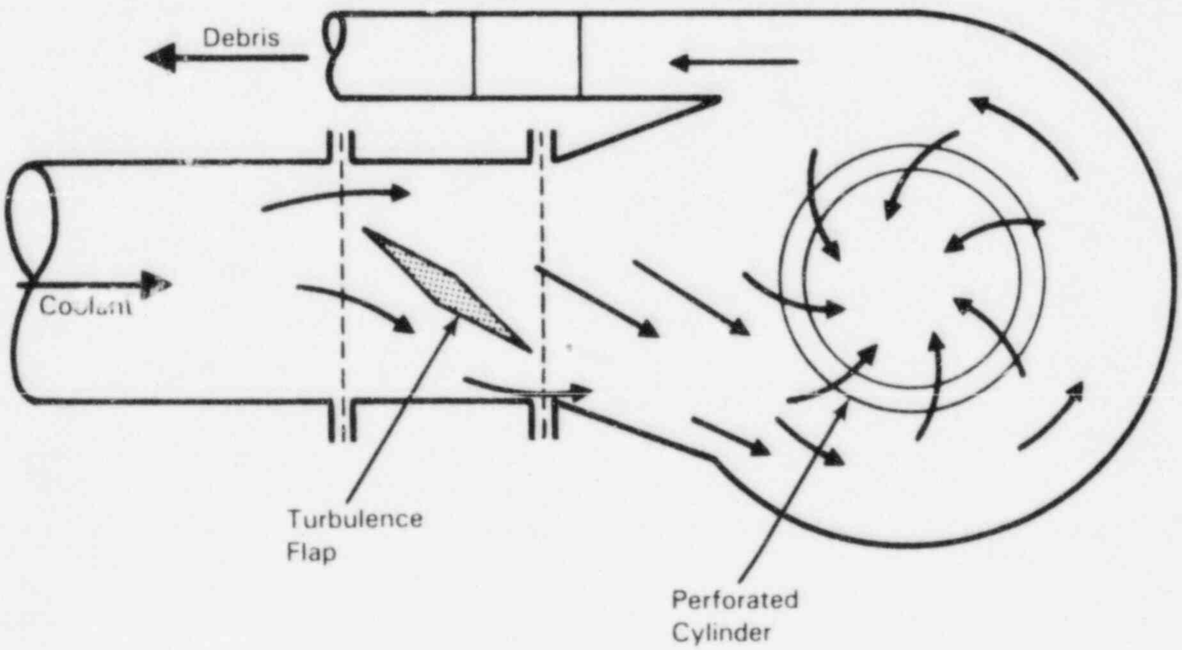

FIGURE 4. Illustration of a Cyclonic Debris Filter to Control Bivalve, Corrosion Product, and Other Debris Buildup at Nuclear Power Plants (Power 1982)

A third type of strainer (Figure 5) has been used in the inlet piping of small cooling loops to strain the water before it passes through heat exchangers. These strainers are effective in removing adult bivalves that could plug the heat exchanger tubes. The strainers, sometimes called 'clam traps', typically filter out debris and shells greater than 3.2 mm (1/8 in.) (Goss and Cain 1977). Flushing connections at the bottom of the strainers allow for easy cleaning during normal operation. This type of strainer has been used by TVA at several of its fossil-fueled plants, and the Arkansas Power and Light Company has recently retrofitted seven of these strainers in Arkansas Nuclear One, Unit ?. The strainers were installed in 50-mm (2-in.) inlet piping to small heat exchangers.

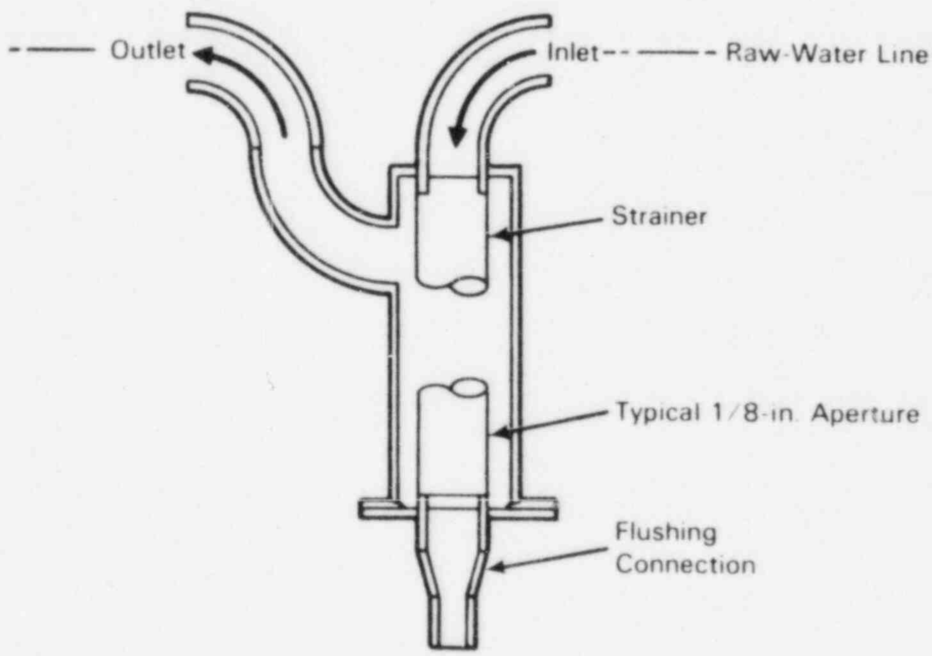

FIGURE 5. Illustration of an On-Line Strainer to Control Bivalve, Corrosion Products, and Other Debris Buildup at Nuclear Power Plants (MacPhae 1983)

Hand Scrapers

Hand scrapers are used to remove accumulations of bivalves attached to the surfaces of the intake structure, large intake piping, and the condenser water-boxes. This technique is most commonly used to remove blue mussels and American oysters. This cleaning technique is restricted to outages because large portions of the open-cycle water system must remain out of service. Hand cleaning the intake piping and the condensers requires that they be drained and partially dismantled.

Hydroblasting

Hydroblasting (or hydrolazing) relies on high-pressure water to loosen bivalves and debris from the intake structure and large intake piping. This technique is more effective than hand scraping in removing bivalves from surfaces. Hydroblasting is restricted to outages because access to the intake structure is required.

Backflushing

Backflushing is performed by reversing the water flow in a cooling loop to help remove lodged shells and debris from within heat exchanger tubes and supply piping. Backflushing is often used in conjunction with other control strategies such as thermal treatment to kill and remove bivalves from the system. Backflushing capabilities are best provided in the initial design of the plant because major piping changes may be required to retrofit such a system. In some instances it may be feasible to install cross-over and flushing connections to allow backflushing certain heat exchangers where fouling has been a particular problem.

5. Control Techniques for New Power Plants

Certain control techniques require extensive modifications to retrofit them to existing plants; therefore, these are recommended only for new plant designs. Control techniques recommended for new plants include 1) contoured intake bays, 2) intermediate cooling loops, and 3) center-flow screens.

Contoured Intake Bays

Bivalve populations flourish in intake bays because low-velocity flow areas exist there. Low-velocity flow areas could be reduced by designing contoured intake bays to improve flow characteristics. Such an approach has been used with success at a French plant (the Paluel nuclear station) located on the English Channel, in an area famous for its shellfish fishery (Power 1982). The water velocity in the intake of this plant is maintained at approximately 3 mps (10 fps) by the streamlined pump intake bays. This has helped eliminate outages due to bivalve fouling at the plant. Modifications could be made to existing plants to improve flow characteristics by pouring concrete on the floor and in the corners of square intake bays; however, such modifications would be considered extensive. Contour plots of typical sediment buildups in the intakes could be taken to determine the correct profile of the added concrete.

Intermediate Cooling Loops

The addition of a large, intermediate cooling loop between the open-cycle system and smaller, individual cooling-loops would restrict the flow of raw water and limit biofouling to only a few large heat exchangers fed by the open-cycle water system. This type of system is currently in use at most saltwater-cooled plants because of the known threat of marine fouling. Intermediate cooling loops are also used at several of the newer freshwater plants including the Oconee and Palo Verde plants (Neitzel et al. 1984). In a freshwater environment, the major advantage of the intermediate loop is the reduced number of heat exchangers where Asiatic clams and silt can accumulate. The intermediate heat exchangers are substantially larger than most heat exchangers in typical open-cycle systems and the flow velocity through them is higher. Both factors make it harder for Asiatic clams and silt to settle in the system. This control technique is restricted to new plant designs because of the extensive modifications required to retrofit an intermediate cooling loop to an existing plant.

Center-Flow Intake Screens

Center-flow intake screens are designed differently than intake screens found in most power plants. The screen panels are set parallel to the direction of flow allowing water to flow through both the ascending and descending screen panels (Figure 6). This increases flow area and allows finer mesh screens to be used. Torbin and Mussalli (1980) report that a center-flow screen with 1-mm (0.04-in.) mesh has been operating successfully at a nonnuclear power plant on the Gulf of Mexico. Center-flow screens would require extensive modification to the intake structure to retrofit them to existing plants. Because of this, their use in nuclear power plants is essentially restricted to future plants.

6. Unproven Biofouling Control Techniques

Several techniques for controlling biofouling have been effective in laboratory tests, but they have not been developed for large-scale use at power plants. These techniques include treatments using 1) high voltage, 2) ultrasonic vibrations, 3) osmotic shock, 4) the CATHELCO system, 5) ozone, and 6) carbon dioxide.

High Voltage Treatments

Exposure to high voltage has been used to kill *Dreissena polymorpha*, in laboratory tests (Mattice et al. 1982). This treatment may be practical in a low-volume system that stands idle for long period before being tested or used; however, the technique has not been field tested and appears to be impractical for a large-volume, high-velocity system.

Ultrasonic Vibrations

Burton (1980) reports that ultrasonic techniques have been used to prevent barnacle fouling on ship hulls. This technique does not inhibit slime formation, and thus another control technique, such as chlorination, would also be needed. Ultrasonic cleaning techniques have not been field tested at power plants (Mattice et al. 1982).

Osmotic Shock

Osmotic shock consists of flooding saltwater into freshwater systems (or vice versa) and allowing the water to remain for several days (Burton 1980). Disadvantages of this technique are that water in the intake structure must remain stagnant for several days and that osmotic shock may not be effective against brackish-water organisms such as Asiatic clams.

The CATHELCO System

The CATHELCO system was developed to control slime and corrosion on ships and offshore platforms. This system could also be used to protect the inlet piping and condensers from slime buildup in power plants (Blume and Kirk 1980). The system uses cathodic protection principles to introduce Cu^{+2} ions into the environment. A sacrificial copper anode is submerged in the water and a DC current is applied to release the copper ion. This technique has not been applied in a large-volume, high-flow system such as the open-cycle system. Also, it has not been demonstrated that the low levels of copper ion released are effective in controlling Asiatic clams, blue mussels, or American oysters.

Ozone as a Biocide

Ozone (O_3) is a strong oxidizing agent that has been shown to be toxic to bivalves in laboratory tests; however, it has not been used as a biocide in industrial or power plant applications. Some evidence showed that ozone may be more effective than chlorine, but it may also cost more to implement (Daling and Johnson 1985). Ozone may also have a serious environmental impact when used in saltwater because other toxic compounds are formed when ozone decomposes in saltwater. A potential problem with ozone is that little is known about the corrosive nature of ozonated water on heat exchanger and piping materials (Daling and Johnson 1984). Advantages of ozone include safety and storage requirements: ozone must be generated onsite due to its short half-life, and O_3 is generally stored at atmospheric pressure making it safer to store than liquid chlorine gas.

Carbon Dioxide Treatments

The Commonwealth Edison Company has experimented with carbon dioxide injection as a means of Asiatic clam control (Rains et al. 1984). Exposure to carbon dioxide produces an anesthetizing effect on Asiatic clams, and if held in this condition long enough, it could prove toxic. Carbon dioxide

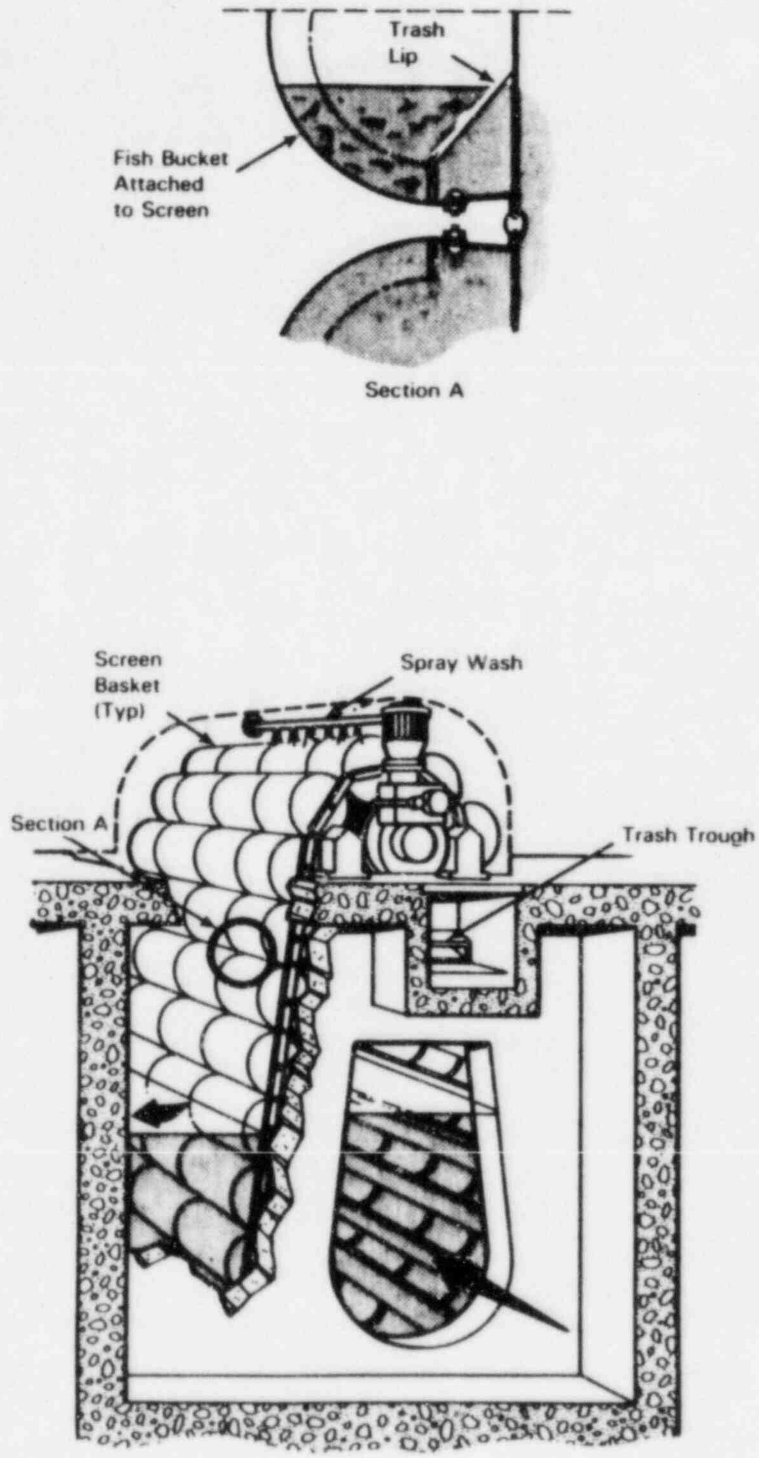

FIGURE 6. Illustration of a Center-Flow Travelling Screen on a Water Intake Structure (Torbin and Massalli 1980)

may also be effective in causing the Asiatic clams to 'open up' in which case it would be useful as a pretreatment before chlorination or other chemical treatment. To date, this work has been experimental and carbon dioxide injection has not been used in a bivalve control program.

EVALUATION OF SURVEILLANCE AND CONTROL TECHNIQUES

PNL staff reviewed the surveillance and control techniques that are currently being used at nuclear power plants. The objective of the review was to evaluate each of the techniques using a common set of evaluation criteria and to determine the applicability of the techniques for use at nuclear power plants. A common set of criteria allows the evaluators the opportunity to determine which criteria are the most important for ranking the techniques. The evaluators included a civil engineer, a mechanical engineer, two biologists, and a systems safety engineer. The evaluation was aided by the use of a computerized decision support program (States 1980; Fickeisen et al. 1983). The program enables the evaluators to list, rank, and analyze the techniques and the evaluation criteria.

EVALUATION TECHNIQUE

The evaluation involved four steps. In Step 1, the evaluators listed the surveillance and control techniques (Tables 2 and 3) as listed in the NRC furnished references (Table 1). These techniques were discussed to develop a common understanding of the techniques and the basis for inclusion on the list. In Step 2, the evaluators developed a list of criteria for ranking the applicability of the techniques to open-cycle water systems at nuclear power plants. Each of the criteria (Table 4) included a rating scale (0 to 9) with an indication of the endpoints of the scale (e.g., a 9 indicated the technique would rank high). Like the techniques, each criterion was discussed by the group to develop a common understanding of its meaning and to develop the scale for evaluating techniques against that criterion.

In Step 3, paired comparisons of the criteria were made by each participant to determine the relative importance of the criteria to ranking the surveillance and control techniques. Each possible pair of the criteria was evaluated. The paired comparisons provided the basis for assigning weighting factors to the criteria.

In Step 4, each of the surveillance and control techniques was evaluated against each criterion. The scores of the five participants used the subjective measurement scale assigned to each of the criteria. These scores, weighted by the factors developed in Step 3, provided the data for assessing and determining the applicability of the surveillance and control techniques to open-cycle water systems at nuclear power plants.

TABLE 2. Biofouling Surveillance Techniques for Improving the Reliability of Open-Cycle Water Systems at Nuclear Power Plants

SURVEILLANCE TECHNIQUE	PAGE DISCUSSED IN TEXT	COMPONENT OR SYSTEM MOST OFTEN SURVEYED AT NUCLEAR POWER PLANTS
SCUBA divers to visually inspect system	5	Water intake structures Raw water environment
Water and substrate sampling outside plant to monitor bivalve populations	6	Raw water environment
Growth panels to monitor bivalve populations	6	Water intake structures Raw water environment
Dismantle equipment to visually inspect system	7	Heat exchangers Water supply headers Pipes
Side-stream monitor to survey bivalve populations	7	Open-cycle cooling loops Piping in the plant
Water sampling within plant to detect presence of bivalves	8	Pipes with stagnant or near stagnant water
Differential pressure to monitor flow degradation	8	Pressure lines Cooling loops
Differential temperature to estimate heat transfer coefficients	8	Heat exchangers
Flow meters to monitor changes in flow rates	10	Cooling loops

TABLE 3. Biofouling Control Techniques for Improving the Reliability of Open-Cycle Water Systems at Nuclear Power Plants

CONTROL TECHNIQUE	PAGE DISCUSSED IN TEXT	COMPONENT OR SYSTEM IN WHICH TECHNIQUE IS MOST OFTEN USED AT NUCLEAR POWER PLANTS
Chlorinate water to control slime and kill bivalves	11,15	Raw water system
AMERTAP system to control slime	12	Heat exchangers Main condensers
MAN system to control slime	12	Condenser tubes
Tube scrapers to remove attached bivalves	12	Condenser tubes Heat exchanger tubes
Hydroblasting to control slime and to remove attached bivalves	14,20	Condenser tubes Walls of intake structures
Antifoulant coatings to prevent bivalve attachment	15	Pipes Intake structures
Thermal backwashing to kill bivalves	16	Intake structures Main condensers
Remove oxygen to kill bivalves	17	Intake structure
Screens and Strainers to prevent bivalves from entering the raw water system	17	Raw water systems
Hand scrappers to remove attached bivalves	20	Intake structures Large intake pipes Condenser water-boxes
Backflushing to remove attached bivalves	20	Heat exchanger tubes Pipe

EVALUATION CRITERIA

The surveillance and control techniques were evaluated by comparing a common list of criteria. The criteria are presented as questions with the 'answers' representing the information the PNL evaluators required to assess the applicability of using a technique in an open-cycle water system at a nuclear power plant. The criteria are listed in Table 4.

TABLE 4. Criteria Used to Evaluate Biofouling Surveillance and Control Techniques That Are Used in Open-Cycle Water Systems at Nuclear Power Plants

Will application of this technique affect the operational efficiency of the plant? (likely to reduce efficiency = 0; no probable decrease = 9)

Will application of this technique affect safety (not limited to radiation exposure) at the plant? (likely reduction in plant safety = 0; plant safety not affected or improved = 9)

Will application of this technique be environmentally acceptable? (technique not environmentally permitted = 0; no known environmental effect = 9)

Can this technique be retrofitted to an existing plant? (must be built into the original plant design = 0; easily retrofitted = 9)

Is this technique easy to operate? (high degree of training required = 0; minimal training required = 9)

Are there aspects of this technique that limit its use in or near a radiation area? (cannot be used near radiation = 0; radiation not a consideration = 9)

Do the staffing requirements to operate this technique limit its utility? (more than 20 workers required to complete task = 0; one worker required to complete task = 9)

EVALUATION RESULTS

The evaluation program that was used produces two evaluation forms. The first is a random list of all possible pairs of the criteria. The participants indicate which member of each pair of the criteria is most important for assessing the applicability of the surveillance and control techniques to open-cycle water systems. The program algorithms distribute a total of 100 points among the criteria based on the responses to the paired comparisons. The distributed points are the criteria weights. The weights for the criteria as determined by the PNL evaluators are presented in Table 5.

TABLE 5. Evaluation Criteria and Weights Used to Assess the Applicability of Surveillance and Control Techniques to Open-Cycle Water Systems

WEIGHTS	CRITERION
28.5	Will application of this technique reduce safety (not limited to radiation exposure) at the plant?
19.0	Will application of this technique reduce the operational efficiency of the plant?
16.1	Will application of this technique be environmentally acceptable?
14.2	Are there aspects of this technique that limit its use in or near a radiation area?
9.5	Can this technique be retrofitted to an existing plant?
8.5	Do the staffing requirements to operate this technique limit its utility?
3.8	Is this technique easy to operate?

The participants placed the most weight on the safety aspects of the surveillance and control techniques. Application of any technique that reduces the safe operation of an open-cycle water system would have less use at a nuclear power plant than a technique that did not reduce safety. Operational efficiency, environmental acceptability, and radiation considerations were also heavily weighted.

The evaluation exercise continued by scoring each weighted criterion from 0 to 9 for each technique. The raw scores for all of the participants were averaged. The mean raw scores were multiplied by the criteria weights and summed across all of the criteria for each of the techniques to obtain a total score, which ranged from 0 to 900.

Evaluation Of Biofouling Surveillance Techniques

All of the surveillance techniques evaluated by the PNL staff are used at nuclear power plants to improve the reliability of open-cycle water systems. The range in the evaluation scores (Table 6) is a reflection of the importance of plant safety as perceived by the PNL evaluators.

TABLE 6. Evaluation Scores for Biofouling Surveillance Techniques as Determined by PNL Staff (The score can range from 0 to 900)

SCORE	SURVEILLANCE TECHNIQUE
780	Environmental sampling outside plant to monitor bivalve populations
774	Differential pressure measurements to monitor flow degradation
771	Flow velocity measurements to estimate flow rates
770	Differential temperature measurements to estimate heat transfer coefficients
764	Side stream monitor to monitor bivalve populations
751	Growth panels to monitor bivalve populations
734	Water sampling within or near plant to detect presence of bivalves
633	SCUBA divers to visually inspect system
560	Dismantling equipment to visually inspect system

Techniques for Monitoring Fouling Organisms Outside The Plant

Environmental monitoring provides information about the presence of potential fouling organisms near a plant, and the monitoring can be conducted without affecting plant safety or operations. Monitoring is conducted to assess the organism density near the plant and organism movement. Monitoring movement of Asiatic clams is especially important because of their recent introduction into North American waters (Britton and Morton 1982; Burch 1944) and their potential movement into new areas. The reproductive status of bivalve populations near a plant can also be monitored. These data are important when control techniques are targeted at specific early life stages.

Each of the techniques for monitoring fouling populations outside the plant (SCUBA divers, water and substrate sampling, and growth panels) have been used successfully at nuclear power plants. Using SCUBA divers for visual inspection was scored lower than the highest ranked surveillance techniques because of perceived safety considerations relative to the other techniques and potential effects on the operation of the plant. Water and sediment sampling and growth panels received scores similar to most of the evaluated techniques.

Techniques for Monitoring Fouling Organisms Inside the Plant

Each of the techniques for monitoring bivalve fouling inside the plant described in this report (dismantling equipment for visual inspections, side-stream monitors, and water sampling) have been successfully applied at nuclear power plants. Many plants currently have visual inspection programs to monitor corrosion and fouling. Pilgrim 1 uses side-stream monitors to estimate the growth of blue mussels in the open-cycle water system. The TVA has used water sampling techniques to help determine the cause of corrosion in the fire protection system on one plant.

The extensive quarterly inspection schedule suggested by Rains et al. (1984) would undoubtedly increase plant downtime and require plant modifications. A surveillance program combining each of the techniques described in this section may be more effective and affect plant operations less than quarterly inspections. The use of side-stream monitors may be a particularly attractive form of in-plant monitoring because these monitors can be designed to provide ideal conditions for bivalve growth and thus should provide an early warning of possible fouling. Their initial use could be coordinated with a detailed in-plant inspection program to ensure that the monitors fouled more readily than locations in the open-cycle system. Once the monitors were in place and their correct operation verified, the scope and frequency of the in-plant inspection program could be reduced. Such an in-plant monitoring strategy could provide an early warning of potential fouling with a minimal impact on plant operations.

Water sampling techniques could help to determine the cause of fouling in the plant. This technique is best used in systems that remain stagnant for an extended period in order to obtain concentrations of organic compounds and corrosion products that are easily detected. Such systems include the fire protection system, redundant cooling loops, and other cooling loops that are used infrequently. Because of the technical expertise required by current water sampling methods, this technique is not recommended for wide-spread use throughout the plant.

Techniques for Monitoring Changes in Plant Performance

Each of the techniques for monitoring changes in plant performance is used at nuclear power plants. These techniques can provide a warning of possible fouling; however, in some situations, one method may be preferred. Differential temperature measurements across both the shell and tube sides of heat exchangers are used to calculate the overall heat transfer coefficient. This procedure is recommended for multi-pass heat exchangers because the overall heat transfer coefficient can provide an indication of internal bypass leakage. Differential temperature measurements should also be made for heat exchangers that are critical to plant safety because the overall heat exchanger coefficient provides a more sensitive measure of heat transfer capacity than do either flow velocity or differential pressure measurements. Temperature measurements are easily recorded during normal operation; however, minor retrofitting is required to include additional temperature sensors on the shell sides of heat exchangers.

Flow velocity measurements can identify conditions that allow bivalve settlement and growth within the open-cycle water system. These same conditions often allow sediment to settle. Portable, ultrasonic flow meters are an attractive alternative to conventional venturi meters because they require no piping modifications. Measurements of flow velocity cannot detect internal bypass leakage.

Differential pressure measurements can indicate flow degradation; however, they are less accurate than either the overall heat transfer coefficient or flow velocity measurements. Differential pressure measurements cannot detect internal bypass leakage.

Evaluation Of Biofouling Control Techniques

Eleven of the control techniques evaluated by the PNL staff are used in the open-cycle water system of nuclear power plants. The AMERTAP system ranked the highest because it has little negative effect on safety and efficiency relative to other techniques. The range in scores for the other techniques results from perceived differences in the effect on plant safety and operations (Table 7).

TABLE 7. Evaluation Scores for Biofouling Control Techniques Determined by PNL Staff (The score can range from 0 to 900)

SCORE	CONTROL TECHNIQUE
784	AMERTAP system to remove attached bivalves
699	MAN system to remove attached bivalves
673	Screens and strainers to prevent bivalves from entering the raw water system
668	Chlorination to kill bivalves
618	Hydroblasting to remove bivalves
615	Tube scrapers to remove bivalves
603	Oxygen scavengers to kill bivalves
586	Backflushing to remove attached bivalves
576	Thermal backwashing to kill bivalves
567	Antifouling coatings to prevent bivalve attachment
558	Hand scrapers to remove bivalves

Slime Control Techniques

Of the five slime control techniques described in this report, intermittent chlorination is the one most commonly used at power plants. Intermittent chlorination is effective, economical, and can be performed during normal operations. Of the two on-line tube cleaning systems, the AMERTAP system is more commonly used. The AMERTAP system was retrofitted to one plant where chlorination was inadequate for controlling slime buildup. Both AMERTAP and MAN systems are commonly used in the circulating water system to clean condenser tubes. Compared with the AMERTAP system, the MAN system has two disadvantages: flow must be reversed to force the cleaning brushes through the tubes, and the cages on the ends of the tubes can become clogged with bivalve shells and debris. Tube scrapers are used to remove slime, scale, and bivalve shells from heat exchanger tubes. Their use is restricted to outages because access to the heat exchanger tubes is required.

Larvae Control Techniques

Continuous chlorination appears to be more applicable for controlling bivalve larvae than are antifoulant coatings. The EPA has allowed continuous chlorination for plants that can demonstrate the need for continuous chlorination to control biofouling and are willing to perform a chlorination minimization study. Antifoulant coatings have not been used widely at power plants because of poor durability and uncertainties concerning their impact on the environment.

Techniques for Controlling Juvenile and Adult Bivalves

Thermal backwashing and oxygen scavengers are both effective techniques for killing shelled bivalves. Thermal backwashing has been used more than oxygen scavengers because it kills bivalves much more quickly (approximately 30 min versus several days) and its effectiveness has been known for many years. Thermal backwashing is used at Millstone 1 and 2 and at Pilgrim 1 to control blue mussel fouling in the circulating water system. These plants are equipped with the cross-over piping required to allow thermal backwashing of the condensers and intake bays during normal operation. Thermal backwashing is not used in the service water systems at these plants because temperatures lethal to blue mussels would exceed temperature limits for the service water system. Continuous chlorination is used in the service-water systems of these plants to prevent mussel larvae from attaching.

Techniques for Removing Bivalve Shells and Debris

Three of the techniques described for removing bivalve shells and debris (screens, strainers, and nonthermal backflushing) can be used during normal plant operation. Intake screens prevent large debris from entering the intake bays, but do not prevent bivalve larvae from entering the plant. Pump strainers remove bivalves and debris that are entrained by the intake pumps, but they too allow larvae to enter the plant. In-line strainers ('clam traps') have been used successfully to remove Asiatic clams from cooling loops before they can clog heat exchangers. These strainers may be particularly effective in cooling loops that are known to clog with shells and in others that are critical to plant safety. Backflushing can be performed during normal operations provided that cross-over piping is in place to allow reverse flow through heat exchangers.

Other techniques for removing bivalve shells and debris (hand scrapers and hydroblasting) can only be used during plant outages because they require access to areas where bivalves have accumulated. Hydroblasting requires less physical labor than do hand scrapers because a high-pressure water jet is used to remove bivalves from surfaces.

Evaluation of Control Techniques Not In Use At Nuclear Power Plants

Nine of the control techniques (Table 3) that were reviewed were not evaluated relative to the other techniques. These techniques are not currently used at nuclear power plants; the techniques would require extensive modification of existing facilities and are unproven in large scale water systems.

Control Techniques for New Plants

Each of the control techniques recommended for new plants (contoured intake bays, intermediate cooling loops, and center-flow screens) are considered improvements on the techniques in use at power plants. They are recommended only for new plants because extensive modifications would be required to retrofit them to existing plants. Contoured intake bays reduce areas where bivalves can settle and grow. Intermediate cooling loops reduce the number of heat exchangers where fouling can occur and they maintain a constant, high-velocity flow that helps to prevent bivalves from attaching to surfaces in the open-cycle system. Center-flow screens allow the use of finer meshed screens because of their larger screen area compared to conventional screen assemblies of similar size.

Unproven Control Techniques

The control techniques described as 'unproven' (high voltage, ultrasonic vibrations, osmotic shock, the CATHELCO system, ozone, and carbon dioxide) have been shown to be effective in controlling biofouling; however, these have not been developed for large-scale use at power plants. The power requirements for high-voltage treatments make them impractical on a large scale. Ultrasonic vibrations have been used in marine applications, but they have not been field tested at power plants. Osmotic shock techniques suffer from long application times, and they may not be effective on brackish water organisms such as the Asiatic clam. The CATHELCO system has been used to control slime and corrosion on ships and offshore structures, but it has not been tested for bivalve control at power plants. Ozone has not been used in an industrial or power plant application and its use in saltwater may be prohibited because of other toxic compounds that form when it decomposes. Carbon dioxide has been used to anesthetize Asiatic clams in experiments, but to date, it has not been used in a bivalve control program.

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Nine surveillance and 11 control techniques were reviewed for their applicability to open-cycle water systems at nuclear power plants. Journal articles and technical reports were reviewed to collect information about the surveillance and control techniques. Power plant personnel that are using or have used some of the techniques were interviewed to get data on the effectiveness of the techniques. A computerized decision support program was used by the review staff to evaluate the techniques. The review results indicate all the techniques are used in open-cycle water systems to survey for or control biofouling and could be applied to the open-cycle water system at nuclear power plants.

The surveillance techniques reviewed include monitoring water and substrate samples outside the plant by SCUBA diver inspection, monitoring growth panels, inspecting dismantled equipment, examining samples from side-stream monitors, inspecting water samples from inside the plant, measuring pressure differentials, measuring temperature differentials, and measuring flow differentials. The control techniques reviewed include chlorinating the water using the AMERTAP system (AMERTAP Corporation), using the MAN system (MAN Corporation), installing tube scrapers, hydroblasting, applying antifoulant coatings, thermal backwashing, using oxygen scavengers, using screens and strainers, using hand scrapers, and nonthermal backflushing.

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