NUREG/CR-5210
PNL-6623

Technical Findings Document for Generic Issue 51: Improving the Reliability of Open-Cycle Service-Water Systems

Prepared by D.A. Neitzel, K.I. Johnson

Pacific Northwest Laboratory
Operated by
Battelle Memorial Institute

Prepared for
U.S Nuclear Regulatory
Commission

NOTICE

Availability of Reference Materials Cited in NRC Publications

Most documents cited in NRC publications will be available from one of the following sources:

1. The NRC Public Document Room, 1717 H Street, N.W.
   Washington, DC 20555
2. The Superintendent of Documents, U.S. Government Printing Office, Post Office Box 37082, Washington, DC 20013-7082
3. The National Technical Information Service, Springfield, VA 22161

Although the listing that follows represents the majority of documents cited in NRC publications, it is not intended to be exhaustive.

Referenced documents available for inspection and copying for a fee from the NRC Public Document Room include NRC correspondence and internal NRC memoranda; NRC Office of Inspection and Enforcement bulletins, circulars, information notices, inspection and investigation notices; Licensee Event Reports; vendor reports and correspondence; Commission papers; and applicant and licensee documents and correspondence.

The following documents in the NUREG series are available for purchase from the GPO Sales Program: formal NRC staff and contractor reports, NRC-sponsored conference proceedings, and NRC booklets and brochures. Also available are Regulatory Guides, NRC regulations in the *Code of Federal Regulations*, and *Nuclear Regulatory Commission Issuances*.

Documents available from the National Technical Information Service include NUREG series reports and technical reports prepared by other federal agencies and reports prepared by the Atomic Energy Commission, forerunner agency to the Nuclear Regulatory Commission.

Documents available from public and special technical libraries include all open literature items, such as books, journal and periodical articles, and transactions. *Federal Register* notices, federal and state legislation, and congressional reports can usually be obtained from these libraries.

Documents such as theses, dissertations, foreign reports and translations, and non-NRC conference proceedings are available for purchase from the organization sponsoring the publication cited.

Single copies of NRC draft reports are available free, to the extent of supply, upon written request to the Division of Information Support Services, Distribution Section, U.S. Nuclear Regulatory Commission, Washington, DC 20555.

Copies of industry codes and standards used in a substantive manner in the NRC regulatory process are maintained at the NRC Library, 7920 Norfolk Avenue, Bethesda, Maryland, and are available there for reference use by the public. Codes and standards are usually copyrighted and may be purchased from the originating organization or, if they are American National Standards, from the American National Standards Institute, 1430 Broadway, New York, NY 10018.

NUREG/CR-5210
PNL-6623
RG

Technical Findings Document for Generic Issue 51: Improving the Reliability of Open-Cycle Service-Water Systems

Manuscript Completed: July 1988
Date Published: August 1988

Prepared by
D.A. Neitzel, K.I. Johnson

Pacific Northwest Laboartory
Richland, WA 99352

Prepared for
Division of Engineering
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555
NRC FIN B2977

PREFACE

The U.S. Nuclear Regulatory Commission (NRC), Office of Nuclear Regulatory Research, 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. 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 that promote or enhance fouling. The engineering characteristics of open-cycle water systems were reviewed to determine the components and characteristics of the open-cycle systems that promote or enhance fouling. Techniques for surveillance and control of fouling and clogging were reviewed to provide data that will give NRC staff the required basis for adequately assessing fouling and clogging when it occurs at operating facilities and during Office of Nuclear Reactor Regulations safety evaluations.

The compilation of information was accomplished with five tasks:

1. a review of the biological characteristics of bivalves and the engineering characteristics of open-cycle water systems that promote or enhance fouling
2. a review of biofouling surveillance and control techniques for use at nuclear power plants
3. a review of service-water system fouling and the relation to nuclear power plant safety
4. a study of biofouling surveillance and control techniques and their applicability for use in controlling fouling and flow blockage by mud, silt, and corrosion
5. a study of proposed fouling and control techniques for their applicability to systems and component configurations in nuclear power plants.

The data and information for these five tasks are presented in NUREG/CR-4070 Volumes 1 through 3 and NUREG/CR-4626 Volumes 1 and 2. The technical findings document presents a summary of the information and provides the criteria for using this information to prepare a fouling surveillance and control program at a nuclear power plant.

ABSTRACT

This report summarizes information needed to prepare a fouling surveillance and control program for a nuclear power plant. The safety significance of bivalve and other fouling is reviewed. Many safety-related systems are cooled either directly by the open-cycle water system or indirectly through intermediate cooling loops. Residual heat-removal heat exchangers, containment cooling units, diesel-generator coolers, fire-protection systems, and safety-related equipment coolers have been fouled by bivalves, sediment, or corrosion.

The biological characteristics of bivalves enhance their ability to foul service-water systems. The design of the service-water system provides areas where sediments can accumulate and where bivalves can settle and grow.

Surveillance and control systems are available to reduce the occurrence of bivalve, sediment, and corrosion fouling. No one technique seems to provide the best answer. A workable surveillance and control program requires using several surveillance and control alternatives. Utility experience has shown that continuous low-level chlorination of the service-water system is one of the most effective means of minimizing the safety significance of macrofouling.

EXECUTIVE SUMMARY

The Pacific Northwest Laboratory has reviewed service-water system fouling and the techniques for monitoring and controlling fouling. This information, which is presented in this report, can be used to develop a series of fouling surveillance and control programs for application at nuclear power plants. The information was developed from data acquired during site visits to nuclear power plants where effective fouling programs are in place, and from the published literature on fouling programs that have been implemented by utilities. The alternative programs are evaluated in a subsequent task of this study to estimate the value/impact of implementing each alternative.

There is no single solution to biological, sediment, and corrosion fouling at nuclear power plants. Effective fouling programs must include both surveillance and control techniques covering the many subsystems of the open-cycle water system and the different types of fouling that occur. Criteria that are given in this report form the basis for an effective fouling surveillance and control program.

A review of effective fouling programs implemented by utilities demonstrates several common factors. Effective fouling programs are based on a detailed understanding of the life history of fouling species and their distribution in the water source to the plant. Some form of control should be applied continuously to the service-water system. Chlorine is effective for preventing or retarding the settlement and growth of biofouling organisms in the service-water system. Performance trending is an effective method of detecting fouling buildup, and it also helps to make plant personnel aware of the cause-and-effect relationships between specific operating procedures and fouling severity. Performance trending can also be used to evaluate the performance of the fouling program so that improvements can be recommended.

Effective fouling programs have a multilayered structure that calls for more frequent inspection or treatment during times when fouling species are known to be spawning or when fouling is discovered in the critical areas of the water system. Finally, utilities that are making progress in minimizing fouling most often have strong support from management (as time and money) to ensure that 1) plant personnel are educated about the safety and economic consequences of fouling, 2) equipment used for surveillance and control of fouling is properly maintained, and 3) surveillance and control procedures are followed.

Information was compiled on the application of surveillance and control techniques at nuclear power plants and the approximate costs involved in implementing the techniques. Much of the information was obtained from site visits and interviews with utility personnel. Other information was obtained from vendors and contractors who provide equipment and services used for fouling surveillance and control. These data will be used later in the value/impact analysis to estimate the cost of implementing the alternative programs.

The radiation exposure associated with operating and maintaining the open-cycle water system is minimal. Personnel at two of four nuclear plants visited reported no radiation exposure from operating and maintaining the open-cycle water system. Personnel at the two remaining plants conservatively estimated the total exposure to all employees associated with the maintenance of the open-cycle system to be less than 500 millirems per year.

ACKNOWLEDGMENTS

This report was prepared by the Pacific Northwest Laboratory, operated by Battelle Memorial Institute for the U.S. Department of Energy under Contract DE-AC06-76RLO 1830. The work was performed for the U.S. Nuclear Regulatory Commission (NRC), Office of Nuclear Regulatory Research, NRC FIN B2977. The review and preparation of this report were under the guidance of Jerry E. Jackson, NRC.

Thomas L. Page was the project manager, and, with Philip M. Daling, reviewed this report and provided input. The authors would also like to acknowledge the editorial assistance of Susan A. Kreml.

CONTENTS

FIGURES

TABLES

INTRODUCTION

Fouling and clogging of open-cycle water systems is a safety concern to the U.S. Nuclear Regulatory Commission (NRC) and to power-generating utilities. This concern is the result of several fouling incidents that have occurred when bivalves have accumulated in safety-related equipment at nuclear power plants. Fouling caused by sediment and corrosion is of equal concern because of its wide occurrence and its potential impact on plant safety and reliability. In response to these concerns, the NRC contracted with the Pacific Northwest Laboratory to compile the information needed to develop surveillance and control programs. A surveillance and control program must minimize the effects of fouling on plant safety. The information compiled to develop surveillance and control programs will help NRC staff develop regulations for improving the reliability of open-cycle water systems in nuclear power plants.

Effective fouling programs must include both surveillance and control measures that consider the many subsystems within the open-cycle water system and the different types of fouling that occur. Utility personnel indicate that other requirements for an effective fouling program include a detailed understanding of the life history of fouling species and strong management support to ensure that effective procedures are developed and enforced.

This report discusses fouling surveillance and control techniques used at nuclear power plants. These techniques and information about surveillance and control programs are used to develop a set of criteria that form the basis for an effective fouling program. Effective fouling programs used at power plants are summarized to give examples of the extensive measures that utilities are willing to implement to keep fouling under control. The report also contains application and cost data for the individual surveillance and control techniques. These data will be used in a later task to estimate the value/impact of implementing alternative programs.

Much of the information presented in this report was compiled from site visits and interviews with utility personnel. An informal questionnaire (Appendix) was used during the site visits to help compile a consistent set of information. Other data were obtained from vendors and contractors who provide equipment and services used to monitor and control fouling at power plants. A third source of information was the current literature on fouling surveillance and control.

Five sets of information have been collected and presented: safety, biological, design, surveillance techniques, and control techniques. Each of these sets is summarized in the respective sections of the report. This information is essential to understanding a fouling problem and developing a program to control the problem.

A surveillance and control program is a dynamic procedure of development, implementation, and evaluation (Figure 1). If a problem exists and safety is compromised, then surveillance and control are required. To develop the program, an understanding of the biology of the fouling organisms, the design of the fouled component or system, and the availability of the techniques to detect and control is essential. This report describes one method of evaluating fouling potential. Other sections present the types of surveillance and control techniques that are available. Using a set of evaluation criteria, a surveillance and control program can be developed. The criteria must include

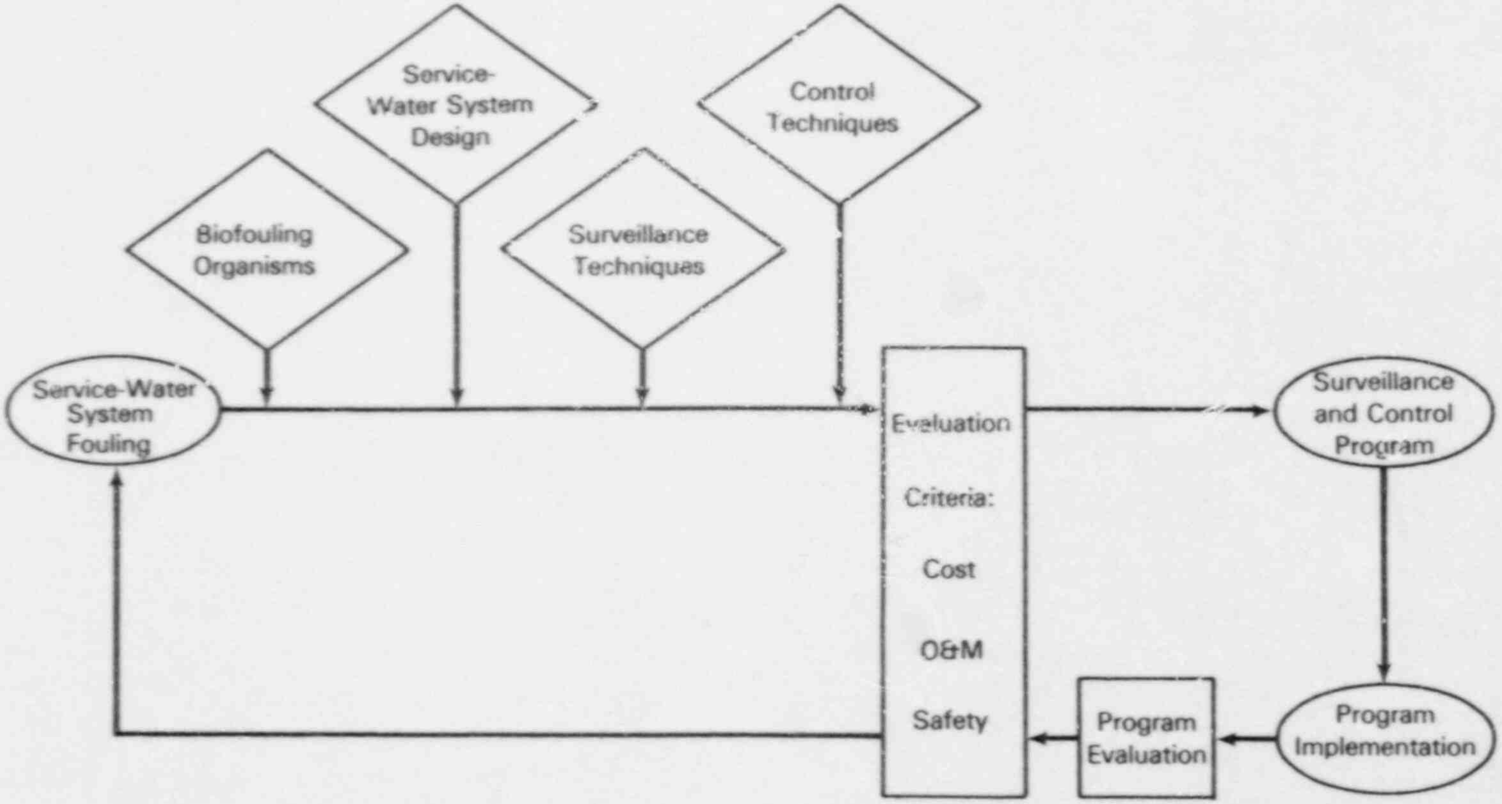


FIGURE 1. Flow Chart to Illustrate the Iterative Process Needed to Develop a Fouling Surveillance and Control Program for Service-Water Systems

effectiveness, plant safety, operations and maintenance, and cost. After the program is set up and implemented, the program effectiveness must be evaluated. Evaluation can lead back to the assessment of the problem or continuation of the program.

RECOMMENDATIONS

Recommendations for developing an effective surveillance and control program include these:

- A dynamic set of criteria must be developed to guide implementation and evaluation of the surveillance and control program. The criteria for an effective fouling surveillance and control program that are presented in this report could be used to evaluate programs that are currently being used at power plants.
- Effective fouling programs have a multilayered structure that calls for more frequent inspection and treatment during times when fouling species are known to be spawning or when fouling is discovered in critical areas of the water system.
- Fouling score sheets (such as presented in this report) can be used to estimate the potential for fouling in components of the open-cycle system.
- Effective fouling programs must be composed of both surveillance and control techniques that cover the many subsystems of the open-cycle water system and the different types of fouling that occur.
- Effective fouling programs are based on a detailed understanding of the life history and distribution of fouling species in the water source to the plant.
- Some form of control should be applied continuously to the service-water system. Chlorine is an effective means of excluding biofouling organisms from the service-water system.
- Performance trending is an effective method of detecting fouling buildup and also helps to make plant personnel aware of the cause-and-effect relationships between specific operating procedures and fouling severity. Performance trending can also be used to evaluate the performance of the fouling program so that improvements can be recommended.
- Support from utility management is necessary for good fouling surveillance and control practices to be developed, implemented, and enforced.

THE SIGNIFICANCE OF FOULING FOR SAFETY

The NRC has identified fouling of open-cycle water systems as a safety concern because severe fouling incidents have occurred where bivalves, sediment, and corrosion have rendered safety-related equipment inoperable. Such fouling represents a common-cause failure mode because it has the potential of affecting all open-cycle systems, including the backup cooling loops provided for the safety-related cooling systems. Henager et al. (1985) reviewed the safety aspects of bivalve fouling to identify: 1) safety-related fouling events that have occurred; 2) environmental and operating events that could exacerbate fouling; 3) safety-related components that are vulnerable to fouling; and 4) the safety significance or fouling scenarios. This section summarizes their work.

SAFETY-RELATED FOULING EVENTS THAT HAVE OCCURRED

Serious fouling events that have occurred at several nuclear plants have prompted the NRC to issue IE Bulletin 81-03, which requires all nuclear plants to determine the extent of bivalve fouling and to outline their strategy for controlling it. The following examples demonstrate the range of systems that have been affected by bivalve fouling.

1. Loss of Residual Heat-Removal (RHR) Capacity

Brunswick 1 and 2 (Southport, North Carolina) reported blockages of their residual heat-removal (RHR) heat exchangers in 1981 (Imbro and Gianelli 1982). American oyster (*Crassostrea virginica*) shells blocked the RHR 1A heat-exchanger tubes, which produced high differential pressures across the divider plate and caused the plate to buckle. The result was a total loss of the RHR system because the RHR 1B heat exchanger was out of service for maintenance. The plant was forced to provide alternate cooling, first with the spent fuel pool heat exchangers, the condensate storage tank, and core spray system, and later with the main condensers as a heat sink. The oysters had accumulated in the inlet piping to the RHR heat exchangers because the chlorination schedule had been suspended for an extended period. Both RHR heat exchangers at Unit 2 were also severely fouled and plugged.

2. Flow Blockages to Containment Fan Cooling Units

Salem 2 (Salem, New Jersey) reported 13 flow blockages to containment fan cooling units from 1982 to 1984 (NRC 1984). In one instance, relict shells from a recent service-water cleaning operation were found plugging a back-pressure control valve, which restricted flow to the containment fan cooling units (S. M. Stoller Corp. 1983). A similar event occurred at Arkansas Nuclear One 2 (Russelville, Arkansas) in September 1981 when the containment cooling units (CCUs) could not pass the minimum flow required by plant technical specifications (Haried 1982). This incident shut the plant down for about 1 month and prompted NRC to issue IE Bulletin 81-03.

3. Loss of Fire-Protection System Capability

A nonnuclear, industrial plant experienced severe Asiatic clam (*Corbicula fluminea*) fouling in its fire-protection piping because of frequent flow testing (biweekly or monthly) at flow rates that were much less than those required for full operation during a fire. Procedures at the plant did not call for chlorinating the fire-protection system. When the system was later tested at full flow conditions, the sudden flow surge caused severe blockage of the fire mains and branch piping with Asiatic clams (Neitzel et al. 1984). Minor clam fouling has also occurred in the fire-protection systems at the Browns Ferry (Decatur, Alabama) and McGuire (Cornelius, North Carolina) nuclear plants (Tennessee Valley Authority 1981[a]; Duke Power Co. 1981[b]).

4. Fouling in the Water Jacket Coolers of a Diesel Generator

Fouling in these heat exchangers can cause the diesel generator to overheat and subsequently trip off. This occurred at Salem 1 during a 1-hour surveillance test (NRC 1984), and at Millstone 2 (Waterford, Connecticut) where blue mussel shells were accumulating in the diesel-generator heat exchangers (S. M. Stoller Corp. 1977).

5. Decreased Main Condenser Capacity

The main condenser at Browns Ferry 1 fouled with Asiatic clams only a few months after the plant began operation in 1974. The growth and spreading of clams were enhanced by allowing the cooling-water systems to remain full of water during the final stages of construction (Rains et al. 1984).

6. Loss of Reactor Building Closed Cooling-Water (RBCCW) Heat-Exchanger Capacity

At Pilgrim 1 (Plymouth, Massachusetts), blue mussels blocked cooling-water flow and caused an increase in differential pressure across the divider plates, forcing the plates out of position. The cooling water then bypassed the heat-exchanger tubes (Imbro 1982).

7. Partial Plugging of Spare Turbine Bearing Lube Oil Cooler

At Trojan (Prescott, Oregon), Asiatic clams plugged one of the heat exchangers that cools the lube oil to the main turbine bearings. The combination of an open valve on the inlet side of the idle heat exchanger and a leaking valve downstream allowed a steady, low-velocity flow that deposited silt and allowed Asiatic clams to grow in the heat-exchanger waterbox during a 9-month period (Portland General Electric Co. 1981[c]).

Aquatic organisms other than bivalves have also caused fouling. In recent years, organisms such as fish, jellyfish, and goose barnacles have fouled the service-water and circulating-water systems at nuclear power plants. Several examples of such fouling are given here because of their similarities to bivalve fouling.

(a) Tennessee Valley Authority. 1981. Letter from L. M. Mills to J. P. O'Reilly transmitting TVA's response to the NRC IE Bulletin 81-03 for the Browns Ferry Nuclear Plants, May 26, 1981.

(b) Duke Power Co. 1981. Letter from W. O. Parker to J. P. O'Reilly transmitting Duke Power Company's response to the NRC IE Bulletin 81-03 for the McGuire Nuclear Plants, May 22, 1981.

(c) Portland General Electric Co. Letter from B. D. Withers to R. H. Engelken transmitting Trojan Nuclear Plant's response to IE Bulletin 81-03, July 20, 1981.

1. Loss of Component Cooling-Water Heat-Exchanger Capacity

Suspension of normal preventative maintenance during an extended plant shutdown at San Onofre 1 (San Clemente, California) allowed goose barnacles (*Pollicipes polymerus*) to incapacitate a component cooling-water heat exchanger (Eisenhut 1982[a]).

2. Butterfly Valve Malfunction

A butterfly valve malfunction at San Onofre 1 on the saltwater discharge side of a component cooling-water heat exchanger occurred because goose barnacles had reduced the effective diameter of the pipe and impeded valve movement (Eisenhut 1982[a]).

3. Intake Screen Plugging by Jellyfish

In September 1984, St. Lucie (Hutchinson, Florida) reported plugging of its intake screen by jellyfish.

4. Intake Screen Plugging by Live Fish

On August 31, 1983, Clavert Cliffs 1 (Lusby, Maryland) tripped manually to avoid an automatic turbine/reactor trip from low condenser vacuum. The low condenser vacuum resulted from shutting down two of six circulating raw-water pumps because their inlet screens had become plugged with fish (6- to 8-inch croaker) (NRC 1984).

ENVIRONMENTAL AND OPERATING EVENTS THAT COULD EXACERBATE FOULING

Events that occur inside and outside of nuclear power plants may increase the severity of a fouling incident. Severe storms, changes in the salinity of the water source, dynamic shocks, and chemical spills could kill bivalves and/or cause them to break loose and clog the plant downstream. Sudden flow changes, water hammer, thermal shock, leaking valves, damaged screens and strainers, and the accumulation of bivalves and shells in the system can also enhance the potential for serious fouling. Surveillance and control procedures that are intended to reduce fouling can, in some cases, become the cause of fouling and clogging. Events such as inadequate cleanup after thermal backwashing, flow surges during flow testing, and initial flow testing after a system has been down for a long period all can cause bivalves to break loose and clog components downstream. Infrequent or inadequate chlorination can also allow bivalves to survive in open-cycle water systems.

FOULING SCENARIOS THAT SIGNIFICANTLY IMPACT PLANT SAFETY

One of the most serious fouling scenarios that involves fouling in the open-cycle water system is the loss of cooling to the RHR heat exchangers and the resulting inability to provide adequate shutdown cooling. In boiling water

---

(a) Eisenhut, D. G. 1982. "Proposed Recommendations for Improving the Reliability of Open Cycle Service Water Systems." Memo from NRC Operating Reactors Assessment Branch to S. H. Hanauer, March 19, 1982.

reactor (BWR) plants, the RHR heat exchangers are often cooled directly by raw water. In pressurized water reactor (PWR) plants, the RHR system is cooled indirectly through the component cooling-water loop, and RHR system performance can be compromised by fouling in the component cooling-water heat exchangers or in the coolers to the component cooling-water pumps or RHR pumps.

The loss of cooling to safety-related pumps and room coolers in the emergency core cooling system is also important to safety. Fouling of these small, infrequently used heat exchangers is common in freshwater plants where Asiatic clam fouling has occurred. Both the normal and backup cooling loops are equally susceptible to fouling because both remain in standby condition during normal operation. This constitutes a common-cause failure because both the normal and backup loops are affected by fouling.

Fouling of the diesel-generator coolers is also serious because it jeopardizes the availability of AC power during a loss of offsite power transient. The diesel generators at both freshwater- and saltwater-cooled plants are cooled directly by the open-cycle system.

A rapid loss of condenser vacuum, which could be caused by severe condenser fouling, results in a severe pressure transient (a turbine trip) in BWR plants. This would be especially serious if either the bypass valves failed to open or the reactor did not scram immediately [i.e., an anticipated transient without scram (ATWS) occurs]. In the bypass valve scenario, the rapidly increasing pressure would cause a sudden loss of voids in the reactor vessel that in turn would cause a power spike and drive the pressure even higher. This transient has the potential to cause damage to fuel elements.

Asiatic clam fouling in the water-charged, fire-protection system may be serious because of the potential loss of fire protection in critical areas of the plant and because of the possible consequences that even minor fouling could have. Because of their small size, fire spray nozzles could be completely blocked by only one shell. In a worst-case scenario, only a handful of shells could severely disable the fire-protection system in an area where safety-related equipment is located.

Malfunctioning service-water pump strainers or isolation and check valves could severely reduce flow to all components cooled by service water. If the isolation and check valves to an offline pump were to stick open, water from the online pumps would flow backward through the open valve and out through the offline pump. This reduction in service-water flow may not be readily apparent from the standard indicators such as a high pressure differential across the pump strainers or similar readings across heat exchangers farther downstream.

Although fouling can itself be the cause of many transient scenarios, an equal if not more important safety concern is the impact that fouling may have on transients that initiate from other equipment malfunctions or from an operator error. The quick action of reactor operators to diagnose the problem and the reliable operation of the required safety systems are both key factors in mitigating the consequences of a potential accident. If the functions of one or more safety systems are impaired by fouling, then considerable confusion may result while the operator attempts to determine the most effective response to the transient. This confusion may be further multiplied when, for example, an injection pump begins to overheat because its coolers are fouled or when cooling through the RHR loops suddenly decreases to an insignificant level because of fouling.

A transient can progress to a serious condition within a short period of time, as is evident from several serious transients that have occurred at operating nuclear plants. The major events leading to the Three Mile Island 2 (Londonderry, Pennsylvania) accident occurred within approximately 12 seconds. Less than 8 minutes later, the temperature and pressure in the vessel were at levels that suggested part of the reactor coolant had flashed to steam. During the Davis-Besse 1 (Oak Harbor, Ohio) small LOCA, the primary pressure dropped to one-half its normal operating value in less than 10 minutes, and within 20 minutes, nearly 10,000 gallons of primary coolant had been released to the containment building (Texas Utilities Generating Company 1982). Neither of these transients was exacerbated by fouling, but to bring the transient under control both used safety systems that rely on the service-water system for cooling. If severe fouling had affected the performance of these safety systems, the consequences of these transients could have been much worse.

BIOLOGICAL AND ENVIRONMENTAL CHARACTERISTICS THAT ENHANCE FOULING IN OPEN-CYCLE WATER SYSTEMS

To determine the best surveillance and control techniques for a comprehensive fouling control strategy, it is necessary to identify the important biological and environmental conditions that lead to the major types of fouling. This section summarizes the important characteristics of bivalve fouling, microbiological fouling, sedimentation, and corrosion that impact the effectiveness of fouling surveillance and control techniques.

BIVALVE FOULING

Bivalve fouling occurs because environmental conditions within the open-cycle water system allow bivalves to settle, attach, and grow there. The conditions that encourage bivalve fouling are species specific. The following paragraphs summarize information found in Neitzel et al. (1984) that relates fouling by the Asiatic clam (*Corbicula fluminea*), the blue mussel (*Mytilus edulis*), and the American oyster (*Crassostrea virginica*) to environmental conditions that are often found in the open-cycle water system.

Asiatic Clam Fouling

The Asiatic clam can be found in virtually every major river system in the United States south of latitude 40 degrees (Figure 2). Their typical life span is about 14 to 17 months, during which time they grow to an average shell length of about 35 millimeters (mm) [1.4 inch (in.)]. Water temperatures between 2°C and 35°C (36°F and 95°F) support Asiatic clam growth. Optimum temperatures for growth are 20°C to 30°C (72°F to 82°F), and optimum temperatures for reproduction range from 15°C to 28°C (59°F to 84°F). Asiatic clams prefer sandy or gravelly substrata, but they can also be found among large rocks or in sediment layers (Britton 1982). Water velocities in the range of 0 to 0.3 meters per second (mps) [0 to 1 feet per second (fps)] allow Asiatic clam larvae to settle. As juveniles, they can attach to substrata by secreting a byssal thread. They lose the ability to attach soon after the 5-mm (0.2-in.) stage, and flow velocity becomes an important factor influencing their movement. Asiatic clams are able to tolerate reduced levels of dissolved oxygen and high levels of suspended solids in the water column. Common areas where clams are found in open-cycle water systems include the corners of pump bays, redundant cooling loops that are used infrequently, condenser water boxes, low-velocity flow areas, and where silt has deposited. Utility personnel indicate that "where you find silt, you'll also find clams."

Blue Mussel Fouling

In North America the blue mussel ranges from Greenland to the Carolinas in the Atlantic, and from Alaska to Baja, California in the Pacific (Figure 3; Wells and Gray 1960; WHOI 1952). Water temperatures between 1°C and 26°C (34°F and 79°F) support blue mussel growth. Optimum temperatures for growth range between 10°C and 20°C (50°F and 68°F), and the optimum temperature for reproduction is about 15°C (59°F). Blue mussels are more likely to settle on rough substrata than on smooth ones, provided the substrata are not fouled by soft organisms or sediment. Blue mussels also tend to attach to each other, forming clusters and mussel beds. Water velocities in the range of 0 to 1.2 mps

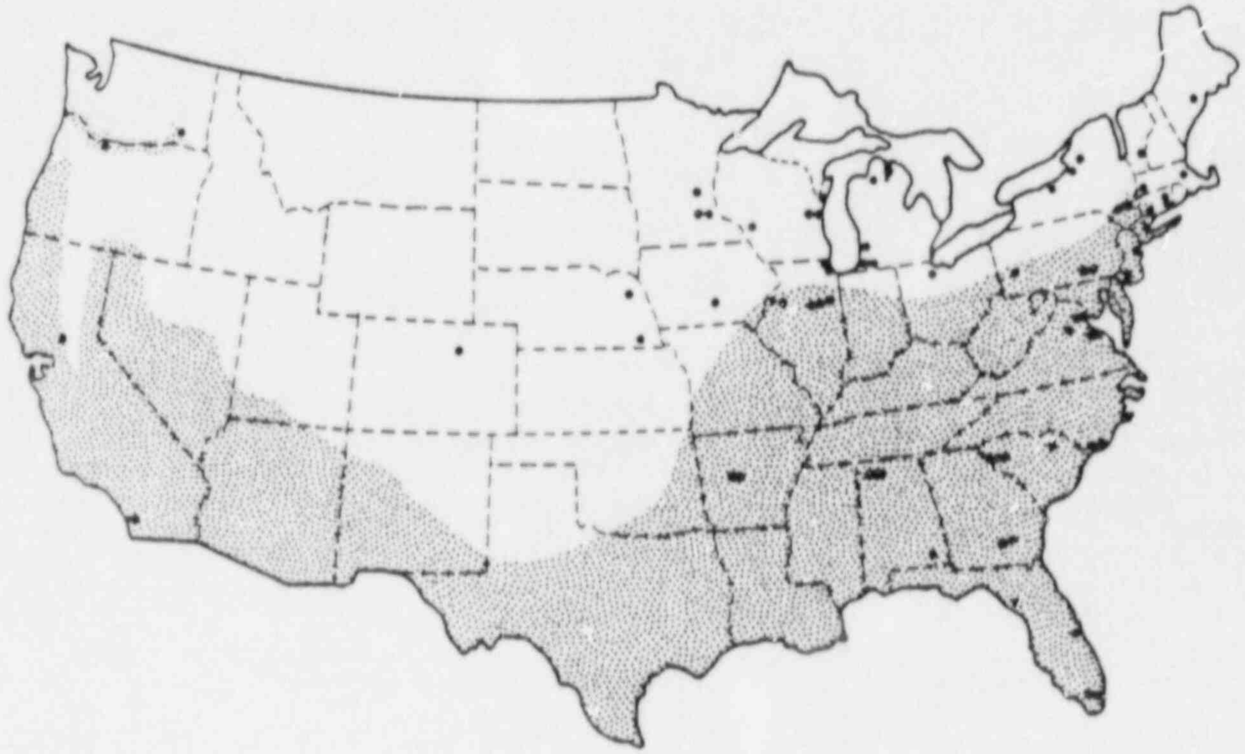


FIGURE 2. Distribution of Asiatic Clams in the Continental United States

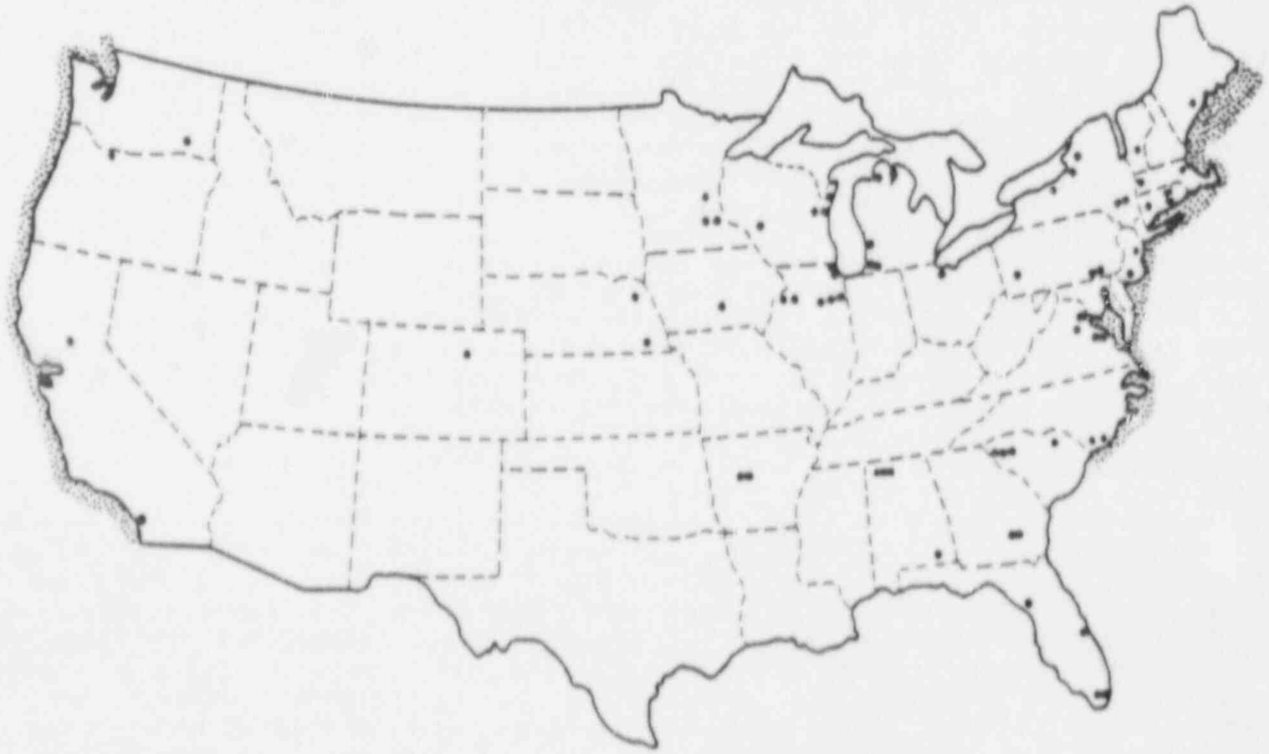


FIGURE 3. Distribution of Blue Mussels in the Continental United States

(0 to 4 fps) allow blue mussels to settle and attach to substrata. Blue mussels are able to firmly attach to substrata using byssal threads. Common locations where blue mussels are found in open-cycle water systems include the floor and walls of intake structures, raw-water supply piping, heat-exchanger water boxes, and locations where the flow is continuous and the velocity is less than 1.2 mps (4 fps). Mussels will completely cover surfaces in an open-cycle water system that is left untreated.

American Oyster Fouling

The American oyster is common to the eastern seaboard of North America, ranging from northern New Brunswick south along the Eastern and Gulf Coasts to Mexico, and is also found in parts of the West Indies (Figure 4; MacKenzie 1975). American oysters may mature sexually during their first year; they can live as long as 40 years, and they grow to more than 20 cm (8 in.) in shell length. Water temperatures between 1°C and 36°C (34°F and 97°F) support oyster growth. The optimum temperature for growth is about 25°C (77°F), and the optimum temperature for reproduction is about 15°C (59°F). Larvae generally set on dead American oyster shells but they will also attach to rocks and other surfaces. Butler (1954) observed the following order of substrata preference: cement board; American oyster shell; frosted glass; black Plexiglas; and white Plexiglas. As little as 4 mm (0.16 in.) of sediment on a surface will prevent setting. Oyster larvae can settle and attach in water velocities up to about 1.2 mps (4 fps). Oysters firmly cement themselves to substrata, making their removal very difficult. Shaw and Merrill (1966) indicate that continuous flow stimulates oyster growth because the current brings in fresh food. Severe fouling by American oysters in two nuclear

FIGURE 4. Distribution of the American Oyster in the Continental United States

power plants located on estuaries with high sediment levels suggests that oysters can tolerate high levels of suspended solids. Common locations where American oysters are found in open-cycle water systems include completely covering the floors and walls of intake structures, in supply piping to the service-water and circulating-water systems, and in virtually all open-cycle cooling loops.

MICROBIOLOGICAL FOULING

According to a study funded by the Electric Power Research Institute, microbiological fouling is a common problem affecting more than 70% of U.S. power plants having experienced fouling of any type (Strauss 1985). The major concern with microfouling slimes in the utility industry has been reduced condenser efficiency and the associated loss in power production. In recent years, utilities have become more aware of the interaction of microfoulants and sediment in causing pitting corrosion in piping and heat-exchanger tubes. Biofouling (macro- and microfouling) increases rapidly at average water velocities less than 0.9 mps (3 fps) (Tuthill 1985). However, microfouling also occurs in circulating-water systems where the average water velocity through the condenser tubes is in the range of 1.8 to 2.4 mps (6 to 8 fps). Microfouling occurs in all areas of the open-cycle system.

SEDIMENTATION

Sedimentation results whenever flow velocities fall below approximately 0.9mps (3 fps). Circulating-water systems are often designed with an average flow velocity through condenser tubes in the range of 1.8 to 2.4 mps (6 to 8 fps). Smaller heat exchangers (such as those in service-water systems), however, typically have much lower design velocities, often as low as 0.3 to 0.6 mps (1 to 2 fps) (Tuthill 1985). One reason for the lack of attention to flow velocity in small heat exchangers is the tendency to use standard-size heat exchangers with extra capacity rather than to apply a functional design approach that considers minimum flow velocity (Tuthill 1985). Overdesign adds to the problem by allowing sediment to accumulate for an extended period of time before heat transfer capacity is reduced to a level that is noticed by utility personnel. This dramatically enhances the potential for under-sediment corrosion to attack heat-exchanger tubes. Of the utilities contacted during this study, all indicated that sedimentation was a problem at their plants. Sedimentation has even been a problem in plants where the raw water appears visibly clean.

Sedimentation is often self-limited by flow velocity. That is, sediment will build up until the flow area is sufficiently reduced to increase the local velocity enough that further sedimentation is prevented. This is evident in corners of the intake structure and near geometric discontinuities in the open-cycle system where the velocity is low. Sediment accumulates in these areas until a steady-state flow condition develops where no further sedimentation occurs. This suggests that sedimentation could be substantially reduced in such areas of the intake structure if they were filled with concrete (after the fact) that conformed to the shape of the sediment deposit. Sedimentation commonly occurs in fire-protection systems, cooling loops that are used infrequently, and anywhere the local flow velocity is less than 0.9 mps (3 fps).

CORROSION

Three types of corrosion are common in open-cycle water systems: galvanic corrosion, concentration cell corrosion, and microbiologically influenced corrosion (often referred to as MIC). Of these three types, both concentration cell corrosion and microbiologically influenced corrosion are strongly linked to sedimentation in the open-cycle water system. Microbiologically influenced corrosion is of particular concern to the utility industry because it has caused through-wall pitting of condenser tubes in a matter of weeks.

Galvanic corrosion occurs when two dissimilar metals are in contact in the presence of an electrolytic solution. In open-cycle water systems, one metal becomes anodic with respect to the other metal (the cathode), and water acts as the electrolyte. Corrosion occurs at the anode where metal ions are liberated and deposited on the cathode. A hierarchical list of metals known as the galvanic series has been compiled to identify which metals will corrode in the presence of other metals (Strauss and Puckorius 1984). Two examples of dissimilar metal joints in open-cycle water systems are steel piping joined to brass valves and copper alloy tubesheets in contact with steel condenser water boxes. In both examples, steel is the metal that would corrode. Galvanic corrosion is more pronounced in seawater and in recirculating condenser systems where the ionic content of the cooling water is higher than in once-through, freshwater cooling systems. The effects of galvanic corrosion are well known in the marine industry, and this factor is considered in the design of marine power plants.

Concentration cell corrosion is similar to galvanic corrosion; however, the electrochemical potential results from localized environmental conditions rather than dissimilar metals. Concentration cell corrosion often occurs in tight crevices and under sediment and fouling layers where dissolved oxygen levels have been depleted. The area of low oxygen content becomes anodic compared to the nearby clean surface, and corrosion occurs in the crevice or under the sediment layer.

Under-sediment corrosion can also be biologically induced by the breakdown of organic matter. Although sediment is sometimes thought of as an inorganic foulant, it is a combination of silt, mud, organic matter, and microbiological foulants such as algae, bacteria, and fungi (Wetzel 1976; Ruttner 1952). Pitting corrosion most often occurs in fouled areas, and, in the majority of cases, it is attributable to the bacteria, *Desulfovibrio desulfuricans* (McCoy 1980). This sulfur-reducing bacteria, found in both saltwater and freshwater, uses organic nutrients as food. It can be distinguished by a sulfur odor, a black layer of slime under sediment, and its distinctive fingerprint-like corrosion pattern (McCoy 1980; Strauss and Puckorius 1984). Sulfur-reducing bacteria thrive in the anerobic conditions found under sediment layers, where they convert water-soluble sulfate compounds to hydrogen sulfide (Strauss and Puckorius 1984). Hydrogen sulfide dissolves in water to form sulfuric acid, which causes corrosion of mild steel, stainless steel, and copper alloys. This is an aggressive corrosive agent that has caused through-wall pitting in mild steel condenser tubing in as little as 6 weeks (Strauss and Puckorius 1984).

Utility personnel indicate that the problem of through-wall pitting in condenser and heat-exchanger tubes is now perceived to be as critical, if not more so, than bivalve fouling in affecting plant reliability. In some cases, condenser units in seawater service that are made with 90/10 copper/nickel tubes are lasting only half of their 40-year design life (Boffardi 1985).

INTERACTION OF DIFFERENT FOULANT TYPES

A comparison of the conditions that allow different foulants to accumulate shows that similar flow conditions allow all types of fouling to occur simultaneously or in close sequence. Also, fouling of one type will enhance the potential for other types of fouling to occur by increasing the surface roughness, decreasing the flow area, and changing flow velocities. Similar velocity ranges allow the settlement of bivalves, microfoulants, and sediment, and sediment often leads to corrosion. The correlation of sedimentation and bivalve accumulations may be especially true with Asiatic clams because adult clams are unable to attach to surfaces and are easily moved by currents. Conversely, mussel and oyster fouling may be more dense in conditions where sedimentation is minimal because sediment inhibits mussel and oyster setting. Mussels and oysters are also able to firmly attach to surfaces, and continuous flow (bringing a steady supply of food and oxygen) accelerates their growth. Continuous flow also accelerates Asiatic clam growth; however, clams are not likely to be found in these conditions because of their tendency to be moved with the flow. As noted previously, sediment is most often a mixture of inorganic solids, organic matter, and microorganisms such as bacteria, algae, and fungi. Sulfur-reducing bacteria, coupled with organic matter as a food source and a sediment layer to provide anaerobic conditions, cause pitting corrosion of piping and heat-exchanger tubes.

Corrosion may also be accelerated by decaying bivalves in cooling loops and fire-protection systems that normally remain full of stagnant water. One utility reported that corrosion was severe in carbon steel piping connected to small heat exchangers that were normally in standby condition. Another utility described corrosion of their fire-protection systems that are normally filled with stagnant water. Utility personnel contacted during this study indicated that current fouling surveillance and control practices do not distinguish between the different types of fouling. Fouling of all types has often been referred to as "debris" in inspection and maintenance reports. Surveillance techniques are capable of detecting fouling, but they are often incapable of providing an early warning of fouling or determining the specific cause or type of fouling. Fouling control techniques have been directed primarily at maintaining high condenser efficiency.

Historically, fouling control was directed at slime in both freshwater and saltwater power plants and at bivalves in saltwater plants. Before the occurrence of Asiatic clam fouling, bivalve fouling was not considered to be a problem in freshwater plants. Sedimentation and corrosion were also not considered to be a problem in the service-water or fire-protection systems of freshwater plants because of the relative cleanliness and low corrosiveness of freshwater compared to saltwater. This is evident when comparing the service-water system designs used in saltwater- and freshwater-cooled nuclear plants. Saltwater plants cool the many small heat exchangers of the service-water system through two or three large intermediate cooling loops that interface with the open-cycle water system, but freshwater plants typically cool the service-water system directly with raw water. This, coupled with the fact that nearly 80% of the service-water cooling loops are normally stagnant, suggests a high potential for sedimentation and corrosion in service-water systems at freshwater plants.

SYSTEM DESIGN CHARACTERISTICS THAT ENHANCE FOULING OF OPEN-CYCLE WATER SYSTEMS

Design characteristics of open-cycle water systems may allow or even increase the rate of fouling by promoting conditions that are conducive to sedimentation, the growth of bivalves and slime, and corrosion. Neitzel et al. (1984) reviewed the interaction of system design characteristics and the occurrence of bivalve fouling. This section summarizes the following design characteristics that affect fouling in open-cycle water systems: 1) flow velocity, 2) flow patterns, 3) frequency of use, 4) valve leaks, 5) unreliable and ineffective chlorination systems, 6) component size, 7) system configuration, and 8) water temperature.

FLOW VELOCITY

Flow velocity is the major design factor that determines whether or not fouling will occur (Jenkins 1978; Strauss and Puckorius 1984; Tuthill 1985; Johnson et al. 1986). Flow velocities less than 0.9 mps (3 fps) allow sedimentation and microfouling to occur. Flow velocities greater than 0 but less than 0.3 mps (1 fps) allow Asiatic clam larvae to settle. Flow velocities greater than 0.1 mps but less than 1.2 mps (0.3 to 4 fps) allow blue mussel and American oyster larvae to settle. Tuthill (1985) suggests that a minimum design velocity of 1.5 mps (5 fps) be used to ensure that the velocity through all heat-exchanger tubes is at least 0.9 mps (3 fps).

Circulating-water systems are often designed with an average flow velocity through condenser tubes in the range of 1.8 to 2.4 mps (6 to 8 fps). Smaller heat exchangers such as those in service-water systems typically have much lower flow velocities, often as low as 0.3 to 0.6 mps (1 to 2 fps). One reason for the lack of attention to flow velocity is the tendency to use standard-size heat exchangers with extra capacity rather than to apply a functional design approach that considers minimum flow velocity (Tuthill 1985).

FLOW PATTERNS

Flow patterns and changes in flow patterns have been known to allow fouling to accumulate in open-cycle water systems (Figures 5 and 6). Flow patterns are determined by local flow geometries and the arrangement of components in systems. Changes in flow patterns occur when redundant cooling loops are used alternately, infrequently used systems are flow tested or put into use, the circulating-water system is thermally backwashed, or other operating transients occur.

Clogging of heat exchangers with Asiatic clams has been related to changes in flow configuration in the service-water system. Fouling at one plant became apparent soon after cooling water was diverted to redundant heat exchangers or to infrequently used cooling loops for flow testing. Clams that may have grown in the branch lines to the cooling loops were washed into the heat exchangers and became trapped in the tubes and against the tubesheets.

Thermal backwashing is used at several coastal plants to control blue mussel growth in circulating-water systems. The initial thermal backwashing treatment at one plant caused a massive blue mussel kill in the intake structure

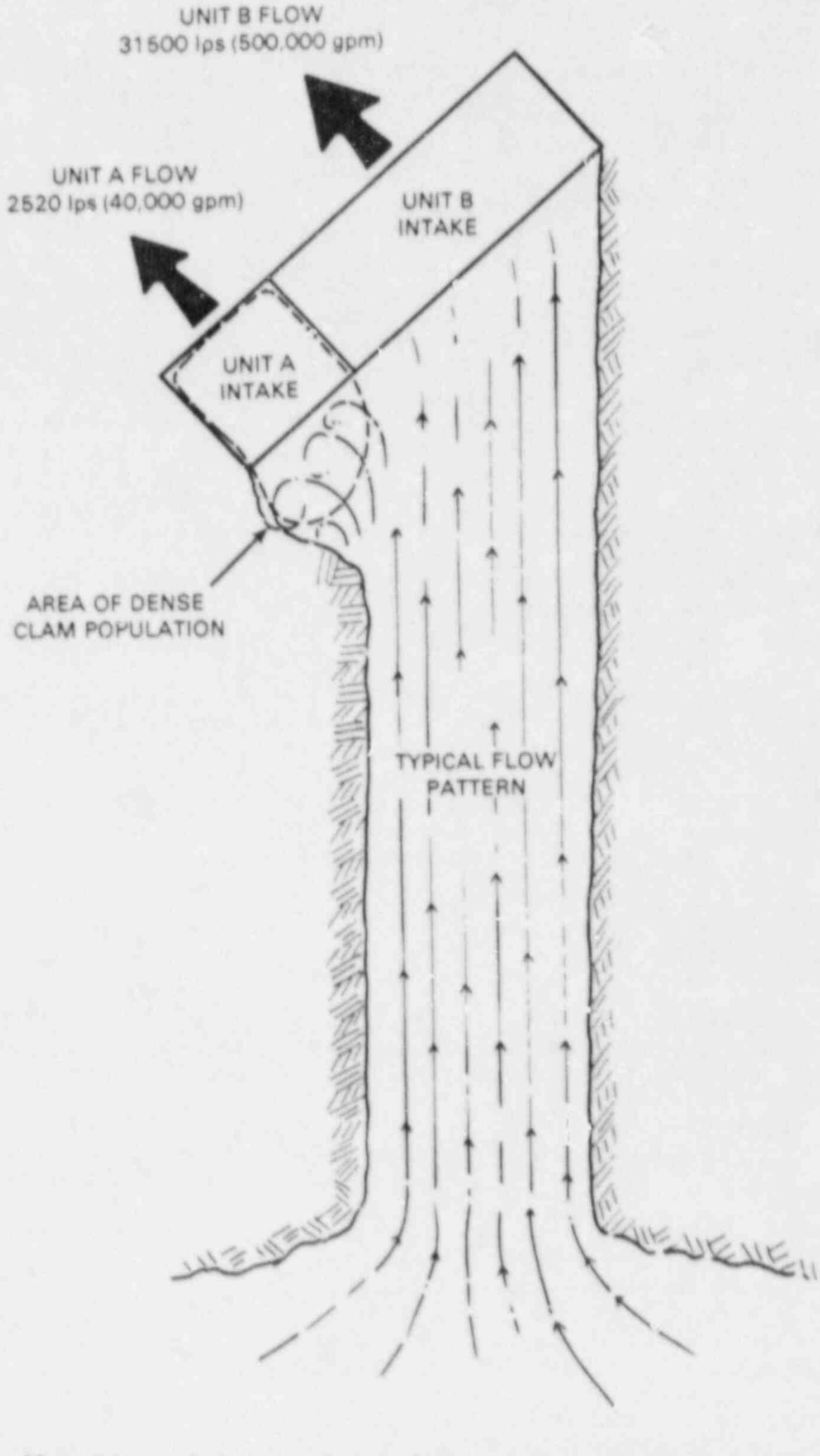


FIGURE 5. Plan View of Intake Canal Showing Typical Flow Patterns and Area of Dense Asiatic Clam Population

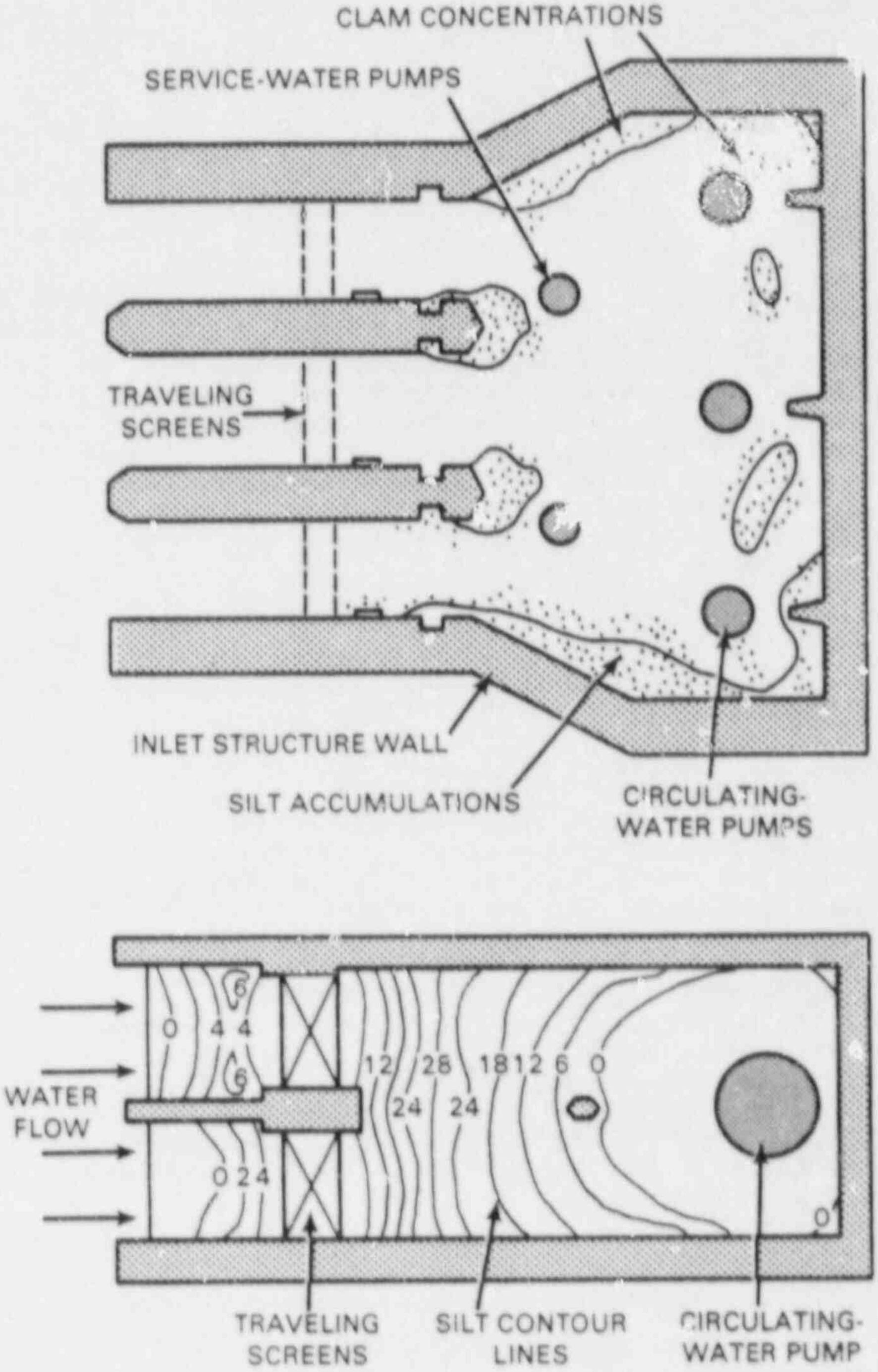


FIGURE 6. Typical Locations Where Silt and Asiatic Clams Settle in Intake Structures (silt contour lines are depth in inches)

and piping to the condensers. For the next 3 months the plant was forced to operate at approximately 30% power while blue mussel shells continued to clog the main condensers and the reactor and turbine building closed cooling-water (RBCCW and TBCCW) heat exchangers.

Water hammer can occur when flow in a pipe is stopped suddenly by a fast-acting valve. Utilities indicate that large accumulations of Asiatic clam and American oyster shells have clogged heat exchangers shortly after water hammer events have occurred.

FREQUENCY OF USE

A factor that encourages Asiatic clam fouling is that as many as 80% of the heat exchangers in service-water systems at freshwater plants are used infrequently and remain nearly stagnant during normal plant operation. The near-stagnant conditions allow sediment to deposit in the system and provide a protected environment in which Asiatic clam larvae can grow. Utilities indicate that Asiatic clam fouling has occurred more frequently in heat exchangers that are used infrequently.

Blue mussel and American oyster fouling is often more dense in areas where the flow is continuous. Mussels and oysters are able to firmly attach to surfaces and the continuous flow, bringing a steady supply of food and oxygen, accelerates their growth. Near-stagnant conditions do not provide adequate food and oxygen for dense mussel and oyster fouling.

Valve leaks are a common cause of low velocity, continuous flow in infrequently used cooling loops. Although these leaks may be considered minor from an engineering standpoint, the flow rate may be high enough to provide bivalves with a continuous supply of food and oxygen. Such conditions may not be ideal for bivalve growth, but they can allow bivalve populations to become established in the system. Utility personnel say that strictly stagnant conditions rarely exist in open-cycle systems during normal operation.

Different types of valves are designed for different applications, and each has different leak characteristics. Butterfly valves are often used to throttle flow in water systems where leakage is relatively unimportant. Gate valves are commonly used as shut-off valves and may be subject to accelerated wear if used in the partially open position to throttle flow. Gate valves are the second most common valve type to develop leaks. Ball and globe valves are used either as throttle or shut-off valves, and are less likely to develop leaks than are butterfly or gate valves.

UNRELIABLE AND INEFFECTIVE CHLORINATION

Chlorination can be an effective control technique for both bivalves and slime. However, personnel at 8 of the 10 nuclear power stations visited during this and previous fouling studies for the NRC described the unreliable operation of chlorination systems and the ineffectiveness of chlorination schedules as primary causes of fouling in open-cycle water systems. Intermittent chlorination effectively controls slime, but chlorine must be applied continuously at least during spawning seasons to control bivalves. A common problem at nuclear power plants is that chlorination systems that were intended for intermittent application are inadequately designed to provide the continuous chlorination required to control bivalves. Other problems, including the low maintenance priority often given to chlorination systems and failure to maintain spare metering pumps and other parts on hand, have caused the chlorination systems at many plants to be out of service for periods ranging from several weeks to several months.

Intermittent chlorination is an effective technique for controlling micro-fouling slime in heat-exchanger tubes. The U.S. Environmental Protection Agency (EPA) allows chlorinating open-cycle, circulating-water systems for periods up to 2 hours per unit per day at chlorine concentrations not to exceed 0.5 milligrams per liter (mg/l) maximum and 0.2 mg/l average free available chlorine (FAC). Simultaneous chlorine discharge from multiple units is not allowed unless the utility can demonstrate that the units cannot operate at or below this level of chlorination. Some plants divide the 2-hour maximum into 15-minute intervals spread throughout the day.

Effective bivalve control using chlorine requires continuous application, at least during bivalve spawning seasons. EPA has allowed several plants to use continuous, low-level chlorination to control bivalve fouling in their service-water systems (designated by EPA as low-volume waste systems). EPA has, however, required that plants perform a chlorine minimization study to determine the minimum chlorine level required to effectively control bivalves. When the service-water discharge is mixed with the much larger flow from the circulating-water system, the residual chlorine level is often too low to measure. Continuous chlorination of the circulating-water system is prohibited. The upper bounds for chlorine concentrations used at power plants for bivalve control are 0.6 to 0.8 mg/l for Asiatic clam control, 0.2 mg/l for blue mussel control, and 0.2 mg/l for oyster control.

Correct measurement of residual chlorine levels is necessary to ensure the effectiveness of chlorination. Organic and inorganic particles suspended in raw water have a chemical demand for chlorine that makes residual chlorine levels both time- and space dependent. Free available chlorine levels measured near the point of injection will be unrealistically high compared to levels measured farther downstream. Chlorine levels should therefore be measured at the service-water and circulating-water discharges. Several plants have noted wide variations in chlorine concentration throughout the plant. Several causes of these variations are poor placement of chlorine injection manifolds in the intake, poor mixing in systems where chlorine is injected downstream of the intake pumps, and failure to ensure that infrequently used cooling loops are laid up with chlorinated water. Chlorine measurements should be taken at several locations in the open-cycle system to ensure that all areas are receiving adequate chlorine to control fouling.

COMPONENT SIZE

Bivalve larvae, sediment, and bacteria that cause MIC are all small enough to pass through the screens and strainers of open-cycle water systems. Once inside the plant, bivalve larvae can grow to a size that will clog heat-exchanger tubes, and sedimentation and corrosion can occur.

Utility experience at freshwater plants has shown that Asiatic clam fouling, sedimentation, and MIC corrosion often occur together in small-diameter components of the service-water, auxiliary cooling-water, and fire-protection systems. Fouling has been more prevalent in cooling loops with inlet and outlet piping less than 100 mm (4 in.) in diameter, and chronic fouling has occurred in some cooling loops with 50-mm (2-in.) and smaller piping. Fouling has also been more severe in heat exchangers with 12-mm- (1/2-in.-) diameter tubes than in those with 22- to 25-mm (7/8- to 1-in.) tubes. Many cooling loops that have small piping and heat-exchanger tubes are in standby condition during normal operation. The infrequent use of these systems also makes them more prone to fouling and clogging.

It is not known whether Asiatic clams settle and grow in small-diameter components or whether these are simply the locations where they accumulate. Asiastic clams lose the ability to attach to surfaces soon after the 5-mm (0.2-in.) stage, and flow velocity becomes an important factor influencing their movement. Debris removed from heat exchangers often consists largely of relict shells, suggesting that clams have grown elsewhere in the system and have been flushed into the heat exchangers.

Blue mussels and American oysters are able to attach firmly to piping and intake structures, and are not limited to a specific range of component sizes. Relict shells from these bivalves have, however, been found fouling in small-diameter piping and have clogged heat-exchanger tubes and tubesheets.

SYSTEM CONFIGURATION

The design of flow channels and the configuration of components in open-cycle systems can affect fouling. Asiatic clam fouling in the intakes of two adjacent units at a nuclear station is more severe in one unit than in the other. When the second unit was built, the intake channel was widened near the plant to make room for the additional intake bays (Figure 5). The abrupt change in channel width coupled with a much smaller flow rate to the second plant (the first plant uses once-through condenser cooling and the second has a cooling tower) has caused Asiatic clams and sediment to accumulate more rapidly in the intake of the second plant. Clams and sediment also accumulate more readily in the corners of intake structures where nearly stagnant areas exist.

Small, infrequently used heat exchangers that are located in low spots of open-cycle water systems are often the first to foul with bivalves, sediment, and later corrosion. Utilities have also found that if several heat exchangers are stacked on top of each other, the lower one will often foul more readily than the others. Deadlegs and inlet piping to infrequently used cooling loops are also prime locations where fouling can occur.

WATER TEMPERATURE

Water temperatures greatly influence the presence and growth of bivalve populations. Assessments of bivalve presence in or near power plants must consider both the temperature of the water source and water temperatures attained during different operating conditions of the plant. Water temperatures in the open-cycle system can range from ambient (water source) to more than 30°C.

Water temperatures between 2°C and 35°C (36°F and 95°F) support Asiatic clam growth. Optimum temperatures for growth are in the 20°C to 30°C range (72°F to 82°F), and optimum temperatures for reproduction range from 15°C to 28°C (59°F to 84°F). Favorable temperature conditions for Asiatic clam growth are found on the inlet side of heat exchangers and in system components inside reactor or reactor support buildings where water temperatures can warm to room temperature.

Water temperatures between 1°C and 26°C (34°F and 79°F) support blue mussel growth. Optimum temperatures for growth range between 10°C and 20°C (50°F and 68°F), and the optimum temperature for reproduction is about 15°C (59°F). Optimum temperatures depend on the mussels' normal seasonal temperature range, which varies with latitude. Favorable temperatures for mussel growth are found from the intake structure to the inlet sides of the condensers and the service-water heat exchangers. Temperatures downstream of the condensers and service-water heat exchangers are often high enough to preclude mussel growth.

Water temperatures between 1°C and 36°C (34°F and 97°F) support American oyster growth. The optimum temperature for growth is about 25°C (77°F), and the optimum temperature for reproduction is about 15°C (59°F). Favorable temperatures for oyster growth are found from the intake structure to the inlet sides of the condensers and the service-water heat exchangers. Temperatures downstream of the condensers and service-water heat exchangers are often high enough to preclude oyster growth.

OPEN-CYCLE WATER SYSTEM DESIGNS AT NUCLEAR POWER PLANTS

Open-cycle water systems typically provide cooling to 1) reactor support systems, 2) turbine-generator support systems, and 3) the main condensers of the circulating-water system. Although there are many plant-to-plant differences, these three general categories apply to most commercial boiling water reactors (BWR) and pressurized water reactors (PWR). The information presented in this chapter is summarized from Neitzel et al. (1984). Only those open-cycle systems that cool the reactor support systems are designated nuclear safety related. The majority of these systems and components are classified as Nuclear Safety Class 3, which corresponds to the group C safety classification detailed in Regulatory Guide 1.26 (AEC 1974).

Nuclear safety-related cooling loops within the open-cycle system are designed to meet the single-failure criterion. That is, redundant cooling loops are provided to ensure that failure of a single component in any cooling loop will not jeopardize the required heat-removal capacity of the system. Redundant cooling loops are also provided to several nonsafety-related components associated with the turbine-generator set, such as the heat exchangers that cool the lubricating oil to the turbine bearings.

The following sections describe the open-cycle systems of typical freshwater-cooled PWR and BWR plants where Asiatic clam fouling has occurred. A later discussion addressed the major differences between the open-cycle systems at freshwater- and saltwater-cooled plants. BWRs and PWRs have similar main circulating-water systems and fire-protection systems, and therefore these systems are treated alike in the following discussions.

OPEN-CYCLE SYSTEMS IN FRESHWATER-COOLED PWRs

Open-cycle systems that provide cooling to reactor support systems in a PWR are often designated as the service-water system. Open-cycle systems that cool turbine-generator support systems are often designated as the auxiliary cooling-water system.

The Service-Water System in a Freshwater-Cooled PWR

Figure 7 shows a simplified diagram of a PWR service-water system that includes the parallel (redundant) flow paths (trains A and B), inlet piping diameters, and the location of valves. Inlet valves to heat exchangers are included to show which are normally open (NO), normally closed (NC), or used on demand (OD). Valves that are used on demand include those to room coolers and other heat exchangers that are only used when certain temperature limits are exceeded (Table 1).

During normal operation, only a fraction of the total number of heat exchangers in Train A of Figure 7 are used continuously. The rest are either used intermittently during normal operation or are only used during shutdown or emergency conditions. Train B is a 100%-capacity backup system provided to meet the single-failure criterion. Heat exchangers in Train A that are used either continuously or intermittently during normal operation are listed in Table 2. Five heat exchangers are used continuously, and six are used during

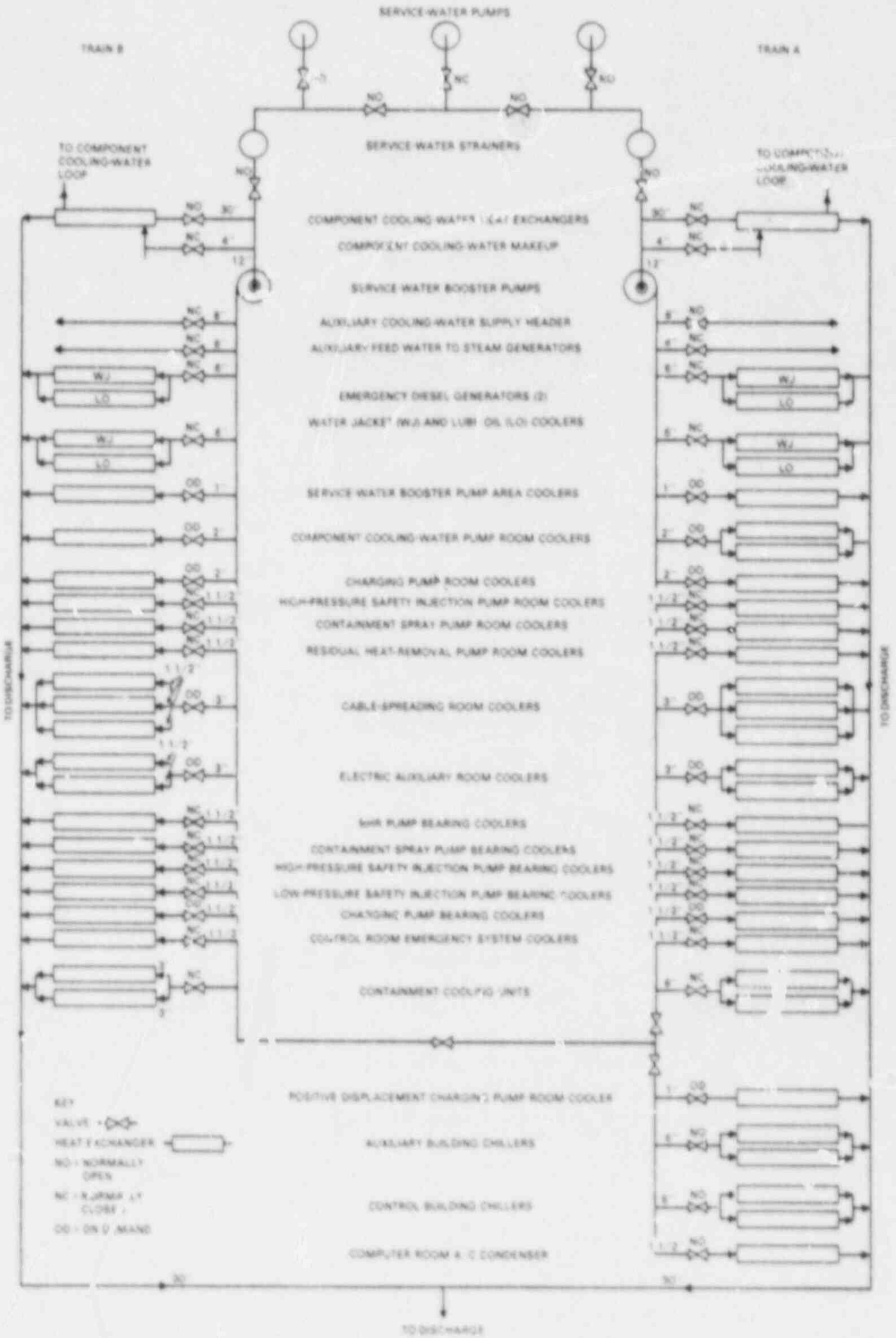


FIGURE 7. Typical PWR Service-Water Flow Design

TABLE 1. Nuclear Safety-Related Components Typically Supplied with Service Water in a Freshwater-Cooled PWR

- Component Cooling-Water Heat Exchangers
- Emergency Diesel Water Jacket and Lube Oil Coolers
- Containment Cooling Units
    - Auxiliary Building Room Coolers to:
    - Component cooling-water pumps
    - Service-water booster pumps
    - Safety injection pumps
    - Charging pumps
    - Containment spray pumps
    - Residual heat-removal pumps
    - Cable-spreading room
    - Electrical auxiliary room

    - Bearing Coolers to:
    - RHR pumps
    - Containment spray injection pumps
    - Low-pressure safety injection pumps
    - Low-pressure safety injection pumps
    - Charging pumps

- Control Room Emergency System Coolers
- Control Building Chillers
- Computer Room A/C Condenser
- Auxiliary Building Chillers

TABLE 2. Heat Exchangers Used During Normal Operation in a Freshwater-Cooled PWR

Continuous Use

- Component cooling-water heat exchangers (A and B)
- Auxiliary building chillers
- Control building chillers
- Computer room A/C condenser

Intermittent Use

- Service-water booster pump area coolers
- Component cooling-water pump room cooler
- Cable-spreading room cooler
- Charging pump room cooler
- Charging pump bearing cooler

normal operation. Considering both Trains A and B, only 11 of 55 (20%) of the heat exchangers are used during normal operation. The large percentage of heat exchangers not used during normal operation (80%) is an important factor contributing to fouling by the Asiatic clam.

The Auxiliary Cooling-Water System in a Freshwater-Cooled PWR

Figure 8 shows a diagram of the heat exchangers that are typically included in the auxiliary cooling-water system. These components are not safety related and are generally classified as power-conversion systems.

OPEN-CYCLE SYSTEMS IN FRESHWATER-COOLED BWRs

The open-cycle systems serving the reactor and turbine-generator support systems in typical freshwater BWR plants can be divided into three functional groups: 1) the raw cooling-water (RCW) system; 2) the residual heat-removal, service-water (RHRSW) system; and 3) the emergency equipment cooling-water (EECW) system. In general, the RCW system is used during normal operating conditions, the RHRSW system is used during normal and emergency conditions, and the EECW system in used during emergency conditions. Table 3 lists heat exchangers that are cooled by raw water in several BWR plants. Figure 9 shows the heat exchangers of Table 3 in a simplified flow diagram.

The Raw Cooling-Water System in a Freshwater-Cooled BWR

During normal operation, the RCW system removes heat from the reactor building and turbine building closed cooling-water (RBCCW and TBCCW) heat exchangers and other equipment associated with the reactor and turbine generators. A flow diagram of a typical RCW system is shown in Figure 10. The RCW system is typically not safety related nor is it essential to safe shutdown of the plant.

The Residual Heat-Removal Service-Water System in a Freshwater-Cooled BWR

The RHRSW system operates in several different modes under different conditions. During shutdown, the system supplies raw water to the RHR heat exchangers, which remove decay heat from the primary coolant system. The system can also operate in a standby cooling mode to provide an inexhaustible source of makeup water to flood the reactor vessel and containment building after a loss-of-coolant accident. The RHRSW system can also be used to cool the suppression pool, flood the reactor core, provide spray cooling to the drywell and suppression chamber, and augment fuel pool cooling. Figure 11 shows a simplified flow diagram of the combined RHRSW and EECW systems. The RHRSW system is nuclear safety related.

The Emergency Equipment Cooling-Water System in a Freshwater-Cooled BWR

The primary function of the EECW system is to provide long-term, post-accident cooling to emergency systems. The EECW and RHRSW systems are often closely associated with each other (e.g., both systems may share common pumps) and may serve as backups for each other. The EECW system supplies cooling water to

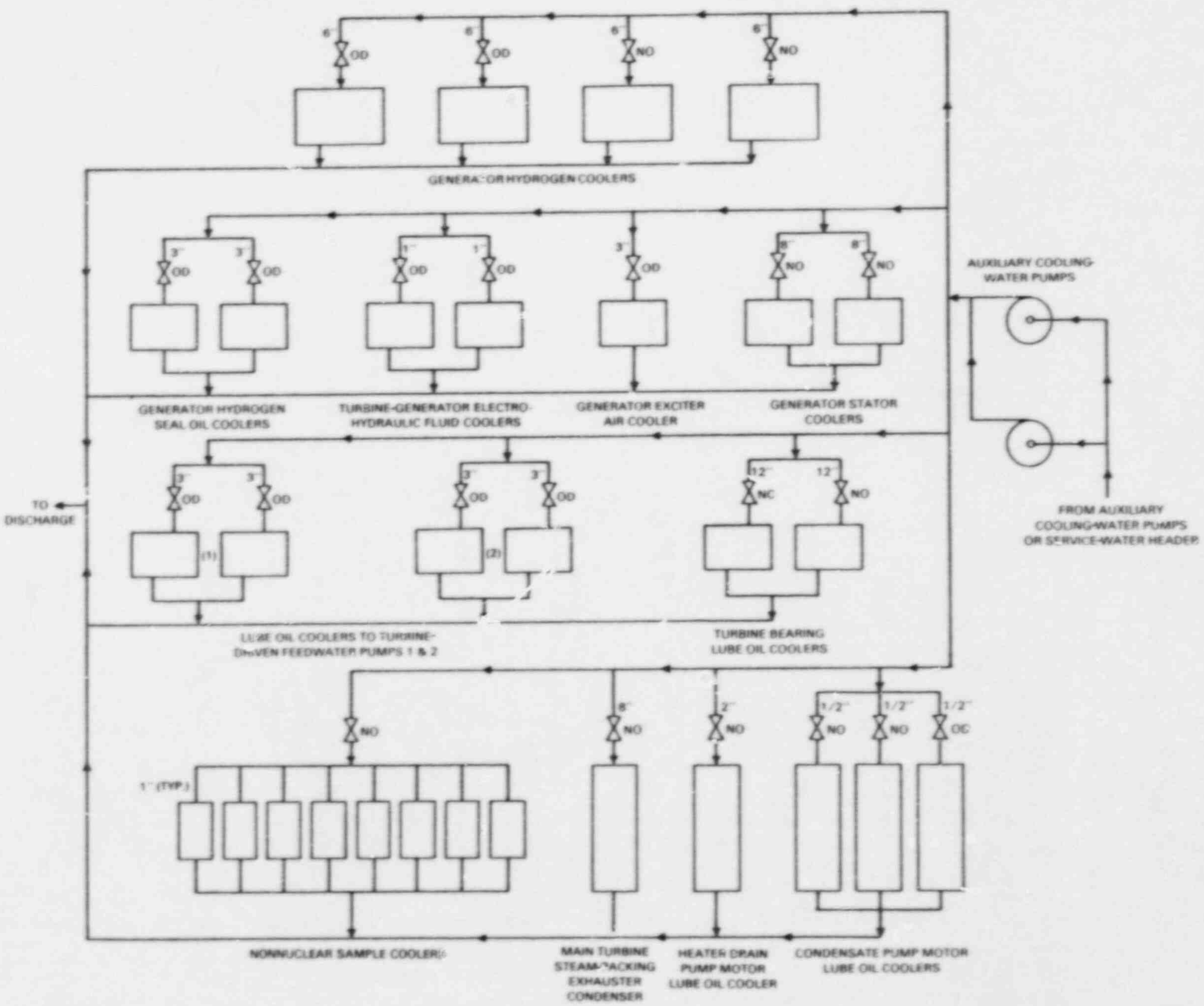


FIGURE 8. Flow Design of an Auxiliary Cooling-Water System in a Freshwater-Cooled PWR

TABLE 3. Heat Exchangers Cooled by Raw Water at Various Freshwater-Cooled BWR Plants

Residual Heat-Removal (RHR) Heat Exchangers(a)
Reactor Building Closed Cooling-Water (RBCCW) Heat Exchangers
RBCCW System Pump and Room Coolers
RHR Pump Seal and Bearing Coolers(a)
RHR Pump Room Coolers(a)
Control Rod Drive Pump Motor, Oil, and Bearing Coolers
Control Air Compressors
Station Service Air Compressors
Core Spray Pump Bearing Coolers(a)
Core Spray Room Coolers(a)
Diesel-Generator Water Jacket and Lube Oil Coolers(a)
Containment Cooling Units (Drywell Cooling Units)(a)
Reactor Water Cleanup Pump Coolers
Control Room Air-Conditioning Chilled Water Condensers(a)
Reactor Water Cleanup Pump Coolers
Control Room Air-Conditioning Chilled Water Condensers(a)
Reactor Building Standby Ventilation System Condensers
Relay Room, Emergency Switchgear, and Computer Room A/C System(a)
Turbine Building Closed-Loop Cooling-Water Heat Exchangers
Main Turbine Lube Oil Coolers
Reactor Feed Pump Turbine Oil Coolers
Recirculation Pump Motor-Generator Set Coolers
Recirculation Pump Motor Bearing and Seal Coolers
Generator Hydrogen Coolers
Condensate Booster Pump Lube Oil Coolers
Generator Leads Coolers

(a) Denotes nuclear safety-related component.

operate safety-related components in the core spray, RHR, and diesel-generator systems. The EECW system can supply cooling water to the standby ventilation system in the reactor building, to the chilled water condensers in the control room air-conditioning system, to the RBCCW system, and to the service air compressors and after-coolers. The EECW system is nuclear safety related.

OPEN-CYCLE SYSTEMS IN SALTWATER-COOLED PLANTS

Saltwater-cooled plants are designed to minimize the number of components that interface directly with seawater because of the corrosive nature of seawater and the known threat of biofouling in marine environments. Intermediate, closed-cycle loops filled with clean water are used to cool the majority of heat exchangers serving the reactor and turbine-generator system. These closed-cycle loops are, in turn, cooled by saltwater. Saltwater-cooled plants

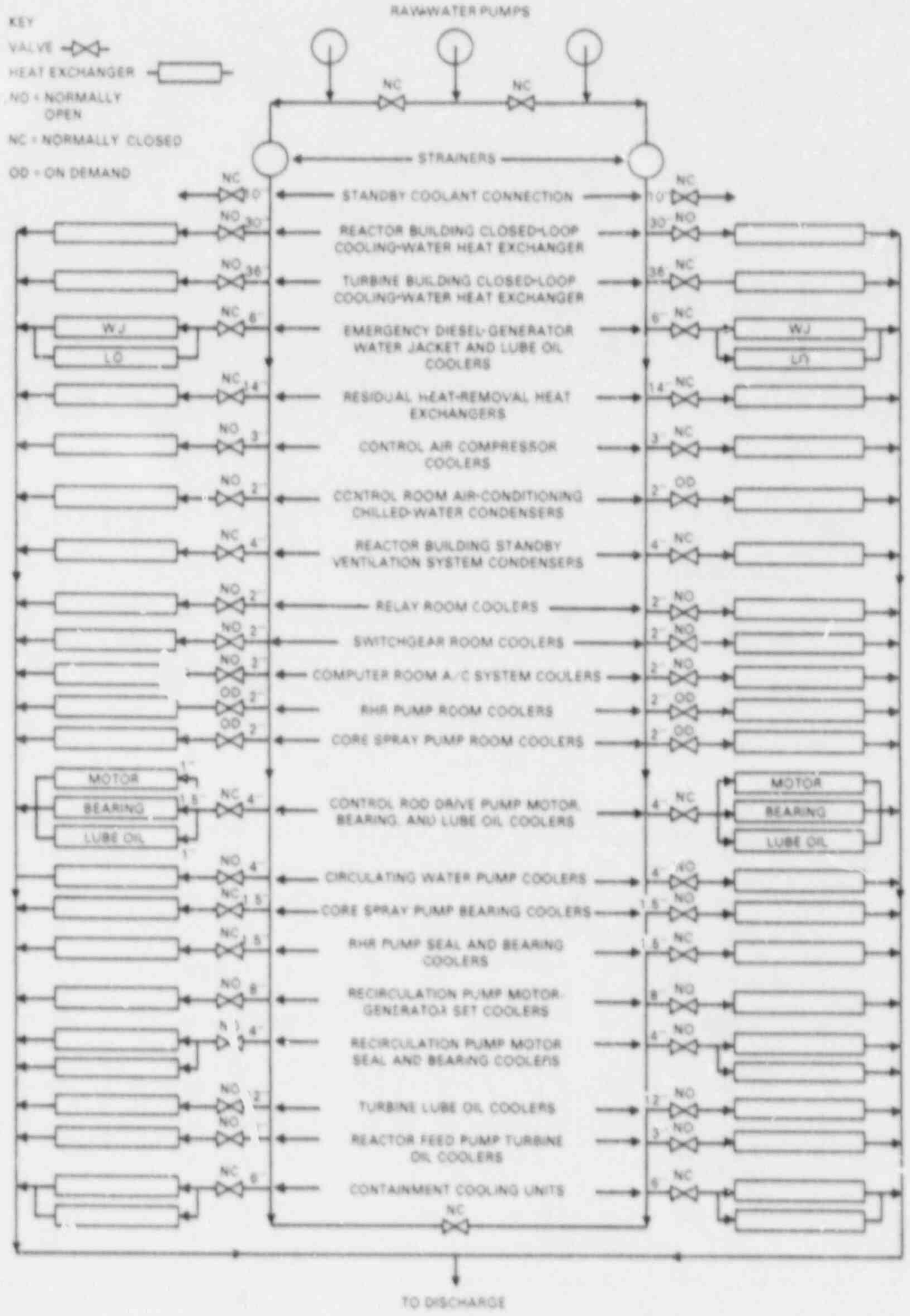


FIGURE 9. Flow Diagram Showing Typical BWR Components Cooled by Raw Water in a Freshwater Plant

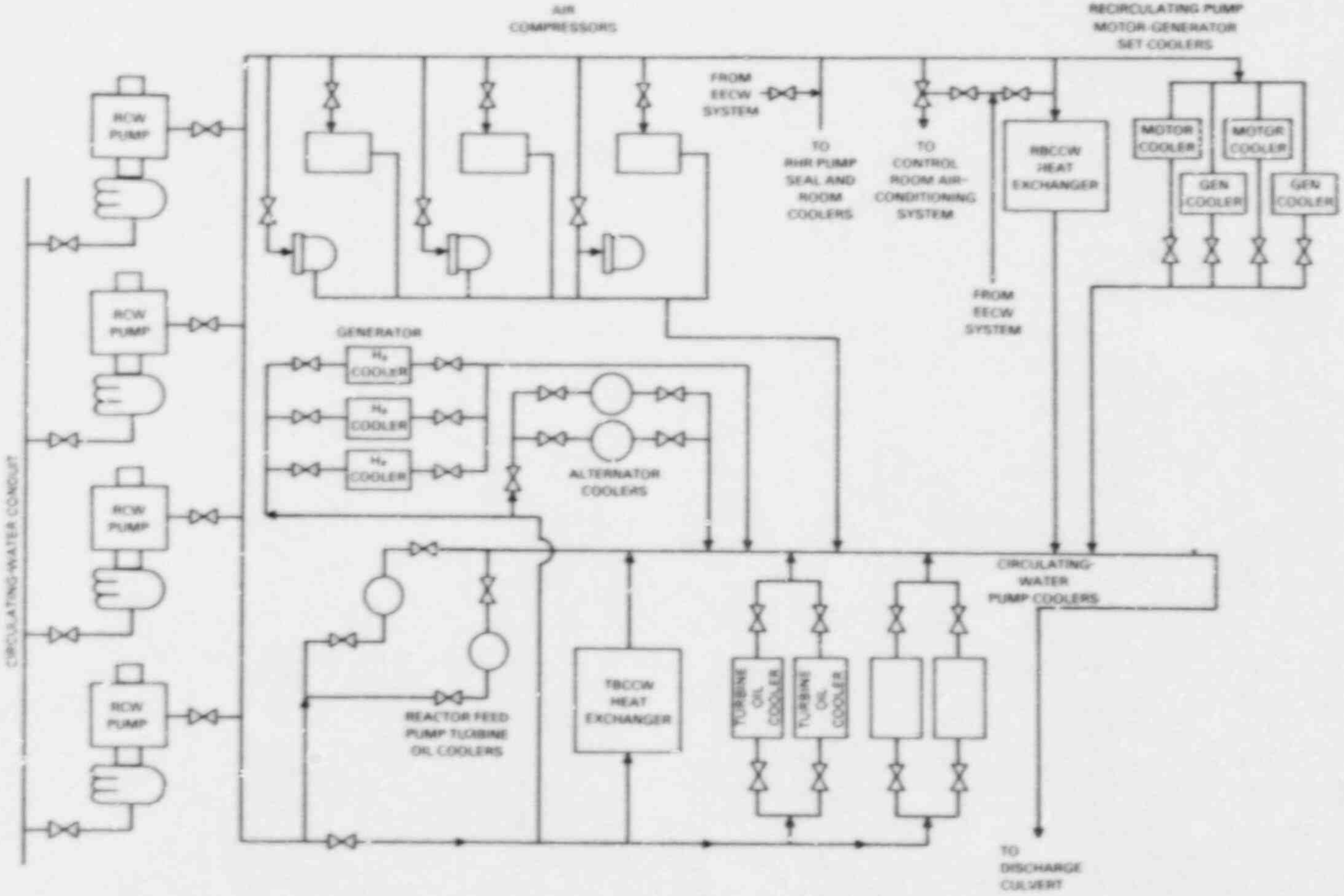


FIGURE 10. Flow Diagram of a Typical BRW Raw Cooling-Water System in a Freshwater Plant

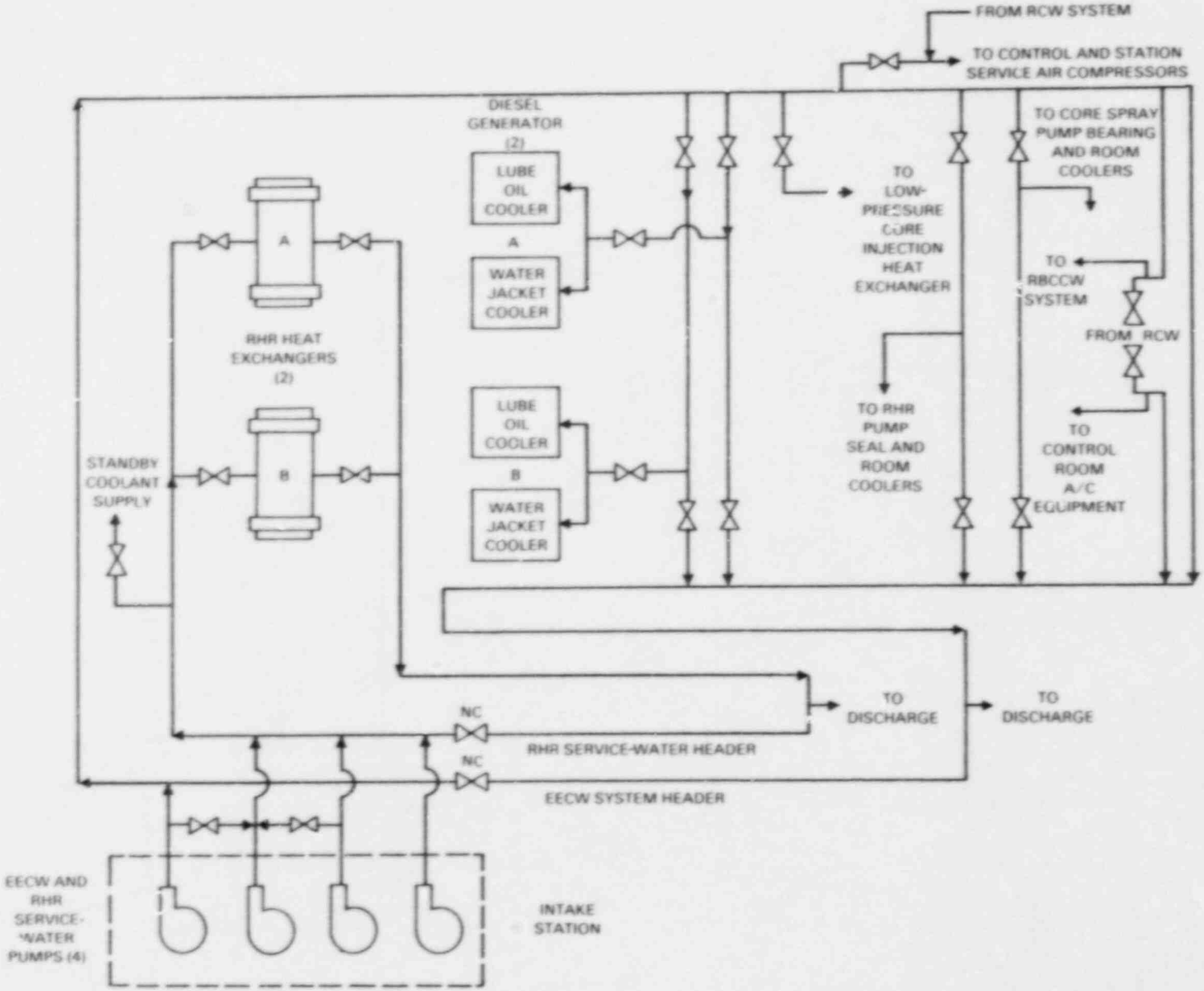


FIGURE 11. Flow Diagram of the Residual Heat-Removal Service-Water System Emergency Equipment Cooling-Water System

typically have 12 to 15 large, continuous-flow heat exchangers that are cooled directly by seawater. This is in contrast to the open-cycle systems at most freshwater plants, where 50 or more small heat exchangers are cooled directly by raw water. The reduced number of heat exchangers in saltwater plants confines corrosion and marine fouling to fewer components. The flow diagram in Figure 12 shows an open-cycle system that is typical of both saltwater-cooled PWR and BWR plants. Three 50%-capacity heat exchangers (the third is a backup) are provided for the reactor building closed cooling-water (RBCCW)

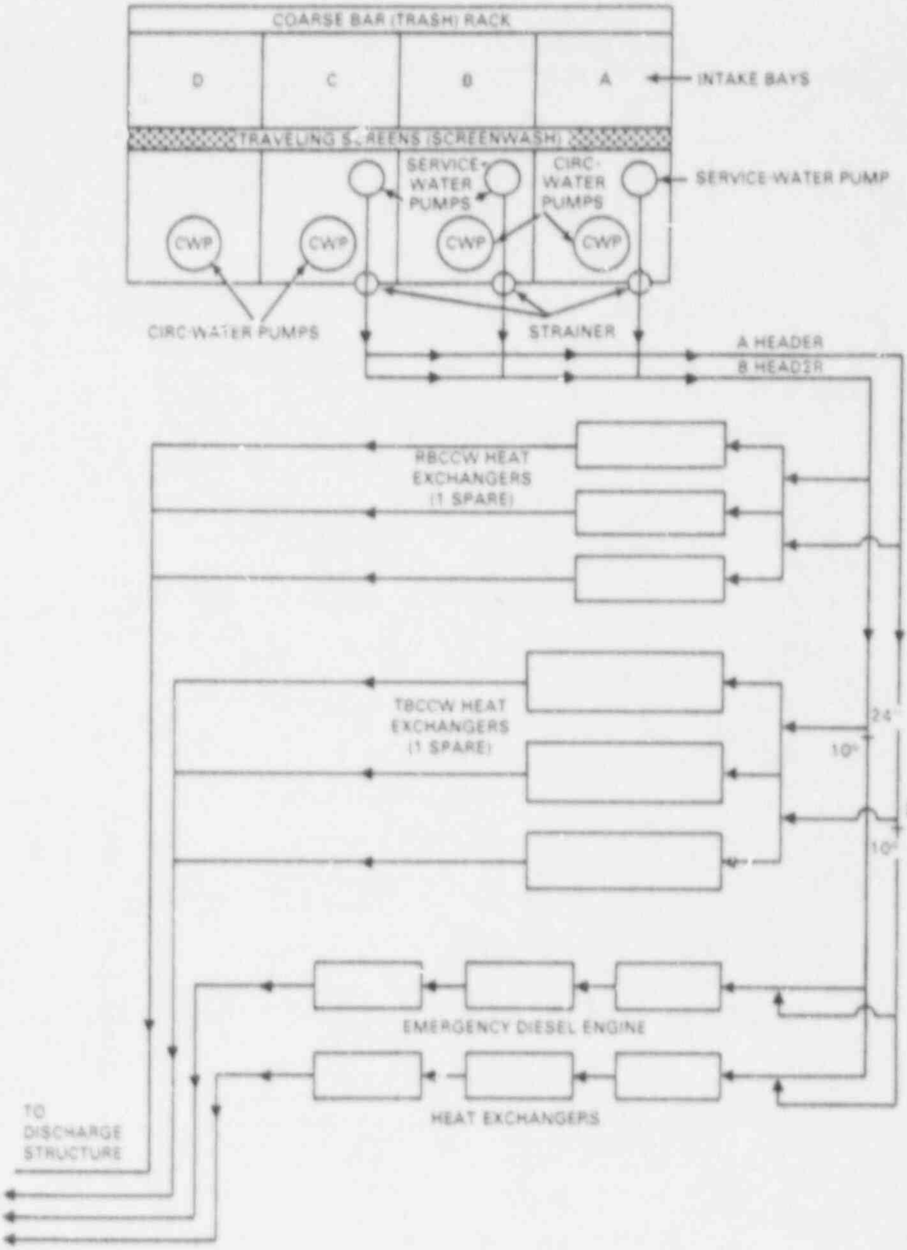


FIGURE 12. Flow Diagram of a Typical Closed-Cycle System at a Saltwater-Cooled Plant

system, the turbine building closed cooling-water (TBCCW) system, and each of the two emergency diesel generators. The RBCCW and TBCCW heat exchangers cool all heat exchangers that serve the reactor and turbine-generator systems, respectively. In addition, the RHR heat exchangers in saltwater-cooled BWRs are often cooled directly by seawater. Several of the newer freshwater plants have been designed with open-cycle systems similar to those in saltwater-cooled plants. Two examples are the Oconee (Seneca, North Carolina) and Palo Verde (Wintersburg, Arizona) plants. In a freshwater environment, the major advantage is the reduced number of heat exchangers in which Asiatic clam fouling, sedimentation, and MIC can occur. Additionally, the heat exchangers are substantially larger than most heat exchangers in typical freshwater plants and the flow velocity is much higher. Both factors make it harder for Asiatic clams and sediment to settle in the system.

MAIN CIRCULATING-WATER SYSTEMS AT NUCLEAR POWER PLANTS

The main circulating-water system (CWS) removes heat from the main condensers and dissipates it to the environment. The condensers condense steam from the turbine exhaust and the turbine bypass system. The main circulating-water system is classified as nonnuclear Safety Class 4.

Circulating-water systems are designed for one of three types of operation: 1) once-through cooling, 2) closed-cycle cooling, or 3) a combination of both ("helper" mode). Figure 13 shows a flow diagram of a circulating-water system that is capable of operating in all three modes. Once-through cooling systems are common in both freshwater and saltwater plants, whereas closed-cycle cooling is more common in freshwater plants. In once-through systems, raw water is pumped from the source water body, passed through the condensers, and returned to the water body. Closed-cycle systems use cooling towers or large cooling ponds in a closed loop that in turn provides cooling to the condensers. Makeup water to the closed loop is provided from the raw-water intake.

FIRE-PROTECTION SYSTEMS AT NUCLEAR POWER PLANTS

The high-pressure fire-protection (HPFP) system is designed to provide a reliable source of water for use in the event of fire. The source of water for the fire-protection system is most often raw water from the open-cycle system in freshwater plants and ground wells or domestic water in saltwater plants. Bivalve fouling in fire-protection systems has been restricted to Asiatic clam fouling in freshwater plants. Figure 14 shows a flow diagram of a typical fire-protection system in a nuclear power plant. The fire-protection system is classified as nonnuclear Safety Class 4. Table 4 lists the safety- and nonsafety-related areas where fire protection is provided.

OPEN-CYCLE INTAKE STRUCTURES

Open-cycle intake structures vary from plant to plant depending on environmental considerations, flow requirements, and the judgment of the architect/engineer. Figure 15 shows a plan and elevation view of a typical intake structure design. Most plants use a common intake structure for the circulating-water pumps, service-water pumps, and fire-protection pumps. Fouling is initially controlled in the intake structure. Floating debris (driftwood, seaweed, ice, etc.) is removed by trash racks at the opening of

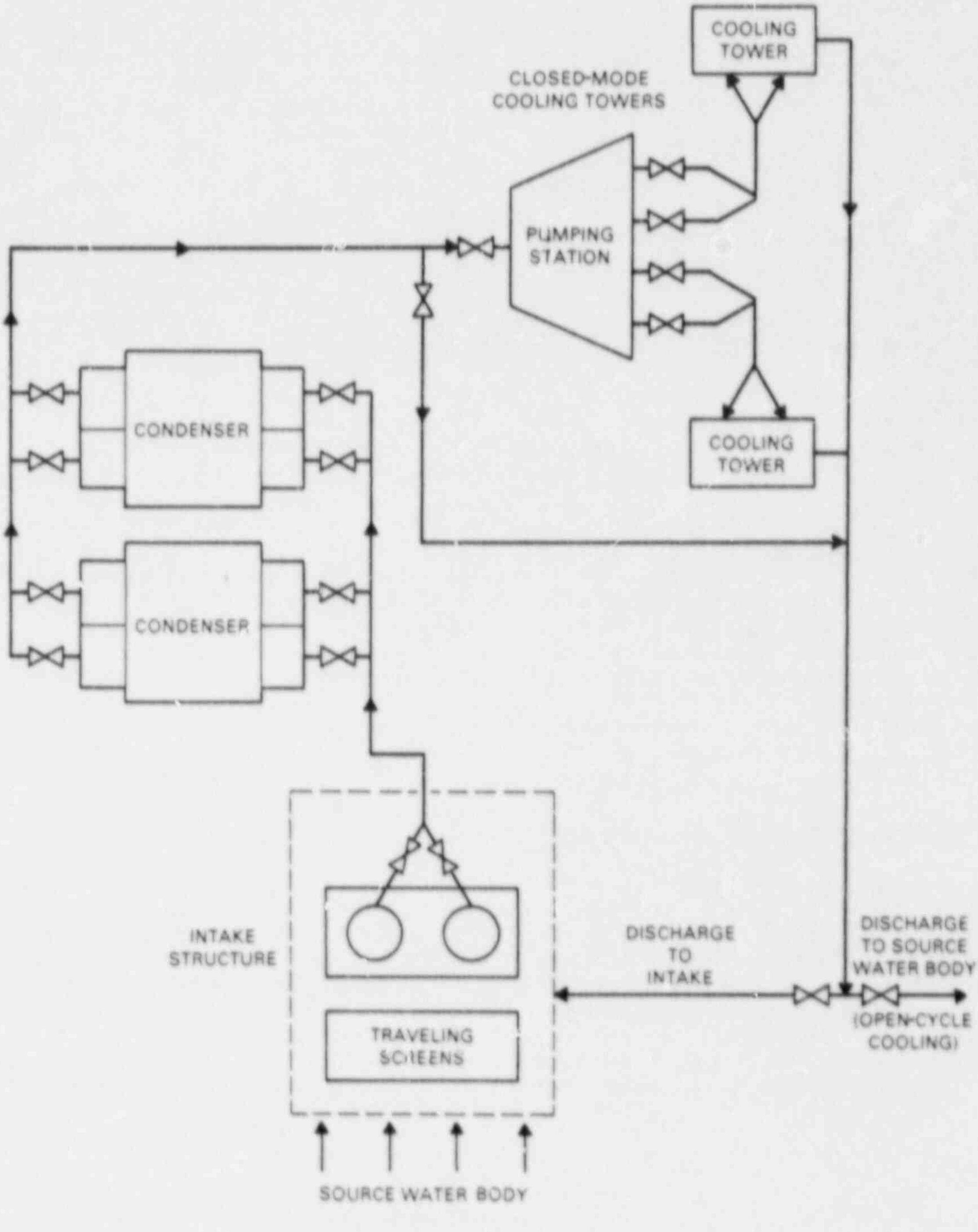


FIGURE 13. Flow Diagram of a Circulating-Water System Capable of Once-Through, Closed-Cycle, and Helper Modes of Operation

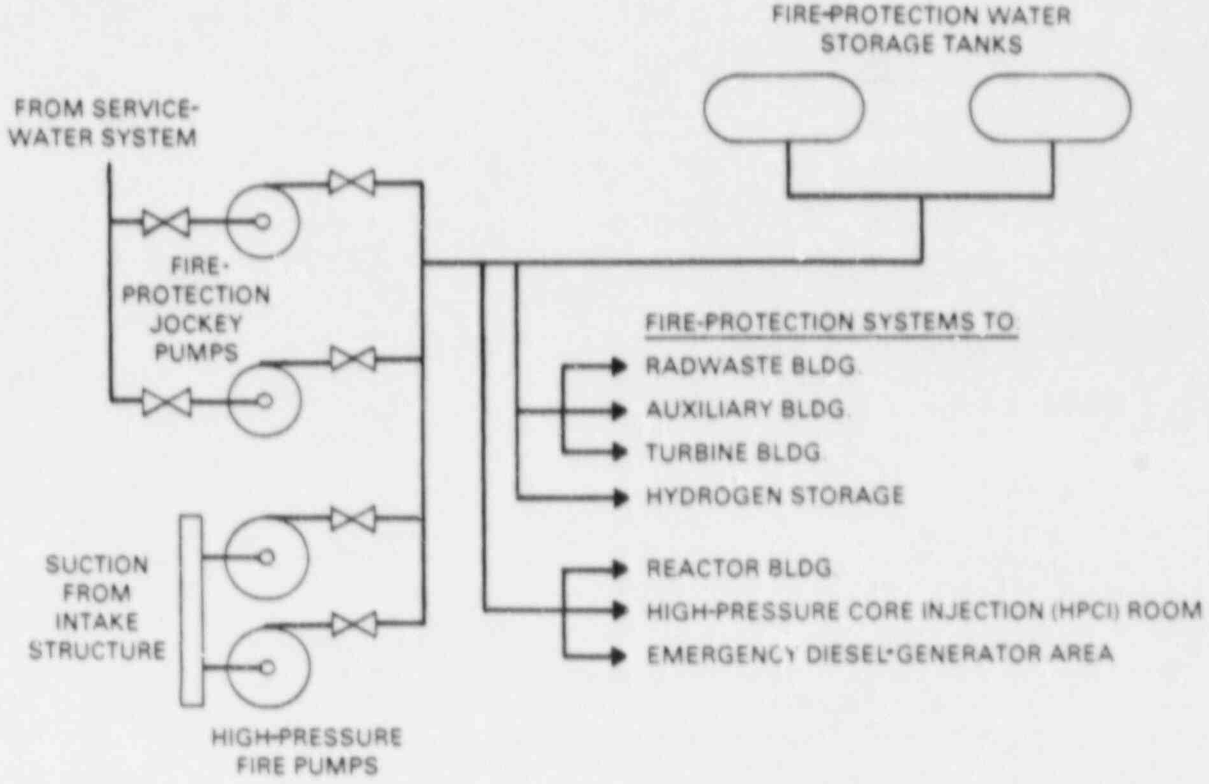


FIGURE 14. Flow Diagram of High-Pressure Fire-Protection System

the intake structure. After entering the intake, fish and smaller debris are removed by the traveling screens. Typical screens have mesh sizes in the 4- to 13-mm (3/16- to 1/2-in.) range. Downstream of the service-water pumps, the water passes through basket strainers (either manual or self-cleaning), which remove particles greater than 1.6 to 3 mm (1/16 to 1/8 in.) in diameter. Bivalves larger than 3 mm that are found downstream of the strainers have, therefore, come in as larvae and have found suitable conditions for growth inside the service-water system.

TABLE 4. Major Plant Areas with Fire-Protection Water Systems

Nonsafety-Related Areas

Outside Areas: main transformers, service transformers, auxiliary transformers, startup transformers, auxiliary boilers, and lube oil storage
Turbine Building: areas under turbine pedestal where lube oil piping runs and all areas where oil may spread in event of oil line break, areas around turbine lube oil reservoirs, and hydrogen seal oil unit
Service Building: automotive shop, warehouse, paint shop, and laundry area
Radwaste Building: truck bay, cable shaft areas, radwaste control room, radwaste storage areas, and incinerator room

Safety-Related Areas

Control Building: chiller rooms, DC equipment rooms, engineered safety features (ESF) room, cable-spreading rooms, and cable shafts
Auxiliary Building: LPSI and HPSI pump rooms (PWRs), reactor feedwater pump areas, core spray pump areas, and HPCI tank areas (BWRs), RHR heat-exchanger and pump rooms, condensate pump room, piping penetration areas, cable penetrations, cable-spreading areas, and containment spray pump areas
Diesel-Generator Building: diesel generators, fuel oil pump areas, fuel oil day tank vaults, control room, air filters, and switch-gear room
Containment Building: steam-generator cavities (PWRs), cable trays, control rod drive areas, air-handling units, and recirculating pump motor-generator area
Fuel Building: spent fuel pool heat exchangers and pumps, new fuel storage areas, railroad bay, and charcoal filtration units

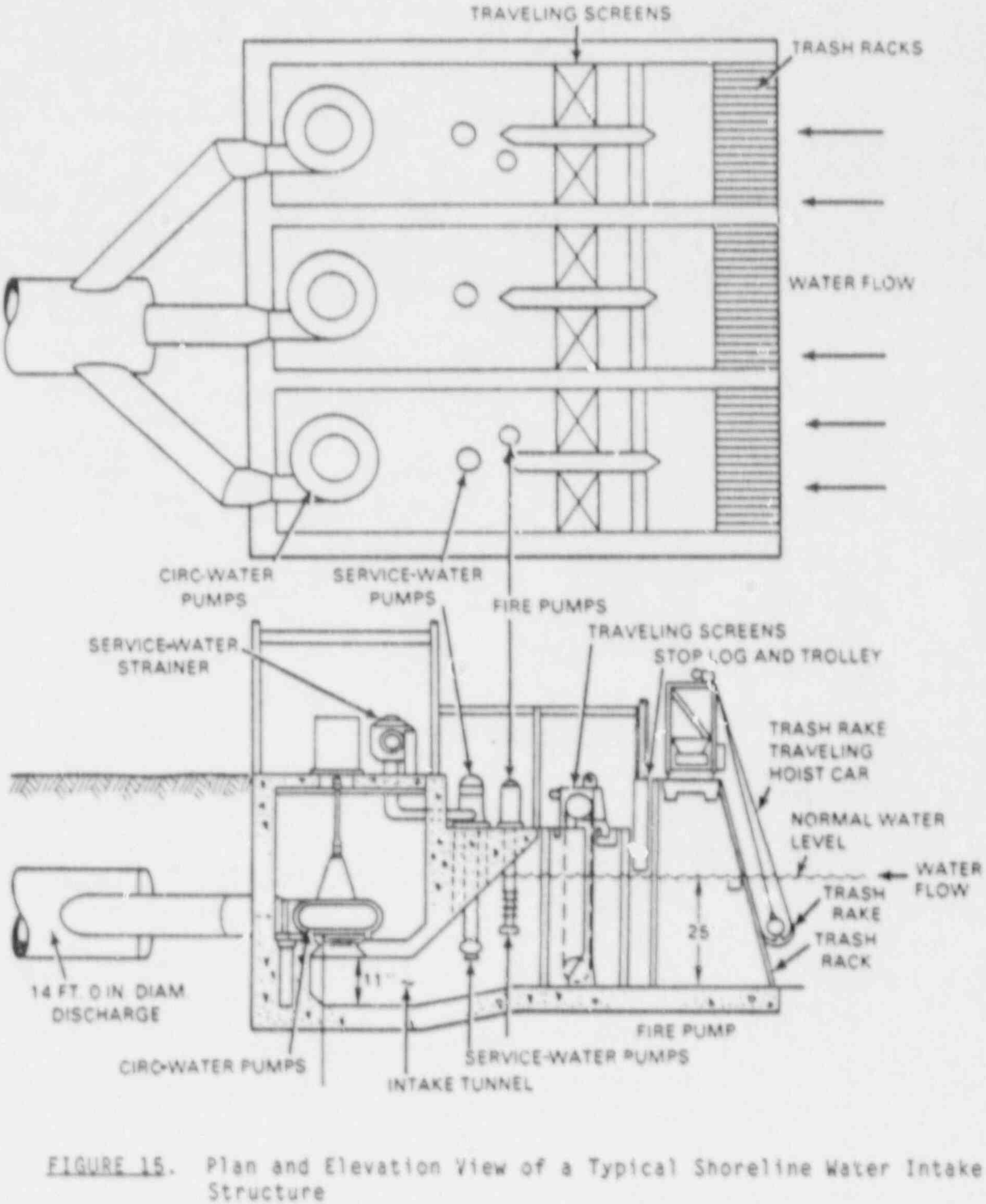


FIGURE 15. Plan and Elevation View of a Typical Shoreline Water Intake Structure

SCORE SHEETS FOR ASSESSING THE FOULING POTENTIAL OF COMPONENTS IN THE OPEN-CYCLE SERVICE-WATER SYSTEM

Score sheets can be used to assess the relative fouling potential of specific systems and components within the open-cycle service-water system. The score sheets to evaluate fouling by Asiatic clams, blue mussels, and American oysters (Figures 16, 17, and 18, respectively) are summarized from Neitzel et al. (1984). The scoring system gives high scores to systems and components that exhibit conditions which are known to cause fouling and low scores to systems and components that exhibit conditions which are known to inhibit fouling.

The score sheets distinguish between primary and secondary fouling characteristics. The primary characteristics represent environment conditions that must occur for fouling to exist. The primary fouling characteristics that are considered include:

- Presence of bivalves in the water source
- Minimum flow velocity during all operating conditions
- The inlet and outlet water temperatures to components
- Chlorination concentration, schedule, and system reliability.

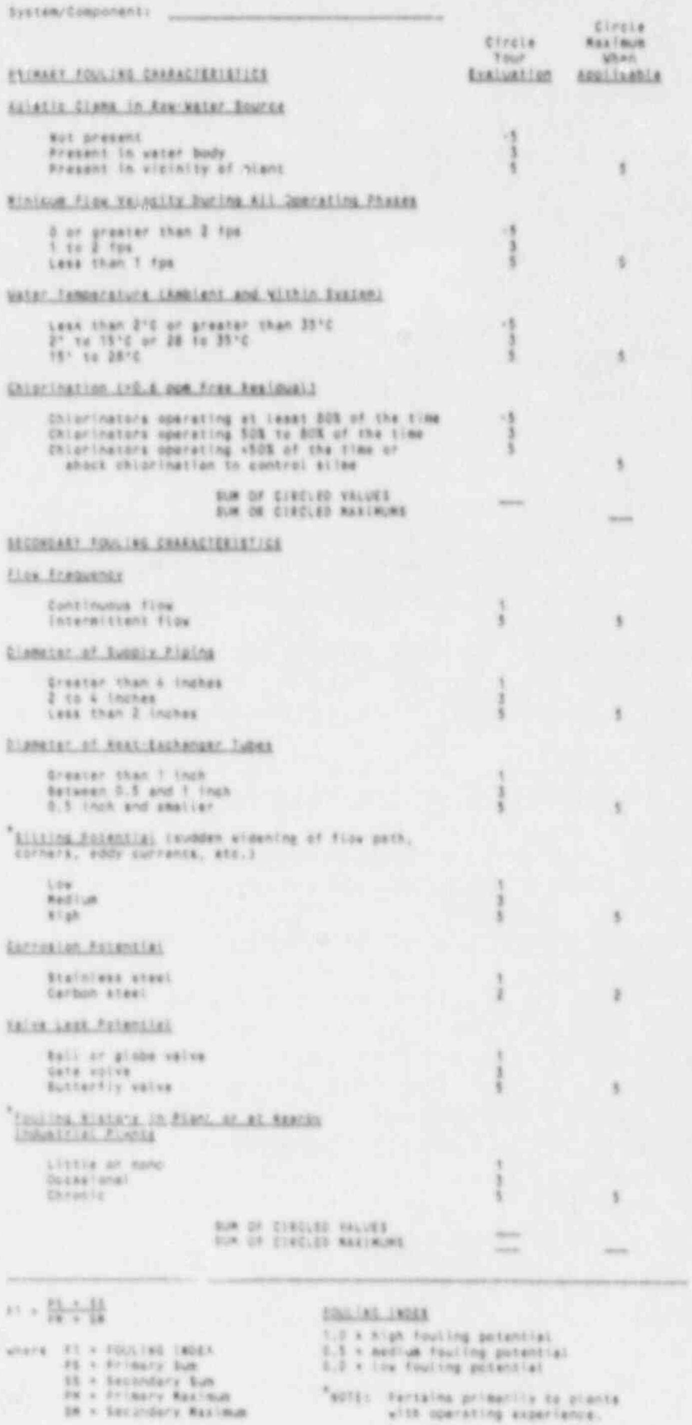
The secondary characteristics include conditions that are known to enhance the potential for fouling but that do not have as pronounced an effect on fouling as do the primary characteristics. The secondary fouling characteristics that are considered include:

- Whether flow is continuous or intermittent, or the system is normally stagnant
- Size of supply piping and heat-exchanger tubing
- Silting and corrosion potential of systems
- Potential for valve leakage
- Fouling history in the plant or at nearby industrial plants.

The score sheets for blue mussel and American oyster fouling are less detailed than the score sheets for Asiatic clam fouling because fewer system-related characteristics influence fouling by these two species. Blue mussel and American oyster fouling occurs throughout the open-cycle system, making it more difficult to differentiate between systems that are more or less likely to foul. Also, marine plants typically have open-cycle water systems that are much more simply designed (substantially fewer components served directly by raw water) than are open-cycle systems in freshwater plants. The flow conditions are more uniform throughout the various cooling loops in marine plants and provide similar conditions for fouling. Also, blue mussels and American oysters are less sensitive to changes in flow velocity than are Asiatic clams because they are better able to attach to substrates than are clams.

Numerical Values for Rating Fouling Potential

Because each primary characteristic relates to a basic requirement for bivalve survival or growth, one or more scores of -5 indicate a low overall fouling potential. For example, if the flow velocity in a system were consistently higher than the upper limit conducive to bivalve settlement, then the potential for fouling would be low regardless of the values of other primary



System/Component: ____________________

	Circle Your Evaluation	Circle Maximum When Applicable
PRIMARY FOULING CHARACTERISTICS		
Asiatic Clams in Raw-Water Source		
Not present	-5	
Present in water body	3	
Present in vicinity of plant	5	5
Minimum Flow Velocity During All Operating Phases		
3 or greater than 2 fps	-5	
1 to 2 fps	3	
Less than 1 fps	5	5
Water Temperature (Ambient and Within System)		
Less than 2°C or greater than 35°C	-5	
2° to 15°C or 28 to 35°C	3	
15° to 28°C	5	5
Chlorination (>0.5 ppm Free Residual)		
Chlorinators operating at least 80% of the time	-5	
Chlorinators operating 50% to 80% of the time	3	
Chlorinators operating <50% of the time or shock chlorination to control slime	5	5
SUM OF CIRCLED VALUES	___	
SUM OR CIRCLED MAXIMUMS		___
SECONDARY FOULING CHARACTERISTICS		
Flow Frequency		
Continuous flow	1	
Intermittent flow	5	5
Diameter of Supply Piping		
Greater than 4 inches	1	
2 to 4 inches	3	
Less than 2 inches	5	5
Diameter of Heat-Exchanger Tubes		
Greater than 1 inch	1	
Between 0.5 and 1 inch	3	
0.5 inch and smaller	5	5
*Silting Potential (sudden widening of flow path, corners, eddy currents, etc.)		
Low	1	
Medium	3	
High	5	5
Corrosion Potential		
Stainless steel	1	
Carbon steel	2	2
Valve Leak Potential		
Ball or globe valve	1	
Gate valve	3	
Butterfly valve	5	5
*Fouling History in Plant or at Nearby Industrial Plants		
Little or none	1	
Occasional	3	
Chronic	5	5
SUM OF CIRCLED VALUES	___	
SUM OF CIRCLED MAXIMUMS	___	___

$$FI = \frac{PS + SS}{PM + SM}$$

where FI = FOULING INDEX
PS = Primary Sum
SS = Secondary Sum
PM = Primary Maximum
SM = Secondary Maximum

FOULING INDEX

1.0 = high fouling potential
0.5 = medium fouling potential
0.2 = low fouling potential

*NOTE: Pertains primarily to plants with operating experience.

FIGURE 16. Score Sheet to Assess Fouling by Asiatic Clam (*Corbicula fluminea*) in a Nuclear Plant Raw-Water System

System/Component: ____________________

PRIMARY FOULING CHARACTERISTICS	Circle Your Evaluation	Circle Maximum When Applicable
Blue Mussels in Raw-Water Source		
Not present	-5	
Present in water body	3	
Present in vicinity of plant	5	5
Minimum Flow Velocity During All Operating Phases		
0 or greater than 6 fps	-4	
3 to 6 fps	3	
Greater than 0 but less than 3 fps	5	5
Water Temperature (Ambient and Within System)		
Less than 1°C or greater than 36°C	-4	
1° to 9°C or 21° to 36°C	3	
10° to 20°C	5	5
Chlorination (>0.25 ppm Free Residual)		
Chlorinators operating at least 80% of the time	-4	
Chlorinators operating 50% to 80% of the time	3	
Chlorinators operating <50% of the time	5	5
SUM OF CIRCLED VALUES	___	
SUM OF CIRCLED MAXIMUMS		___
SECONDARY FOULING CHARACTERISTICS		
Flow Frequency		
Normally stagnant (near-stagnant)	1	
Intermittent	4	
Continuous	5	5
Valve Leak Potential		
Ball or globe valve	1	
Gate valve	3	
Butterfly valve	5	5
*Natural Traps for Relict Shells		
Piping 4 inches in diameter and smaller	3	
Low spots in cooling loops	4	
Heat-exchanger tubes, tubesheets, or other flow constrictions 2 inches in diameter and smaller	5	5
*Fouling History in Plant or at Nearby Plants		
Little or none	1	
Occasional	3	
Chronic	5	5
SUM OF CIRCLED VALUES	___	
SUM OF CIRCLED MAXIMUMS		___

$$FI = \frac{PS + SS}{PM + SM}$$

where FI = FOULING INDEX
PS = Primary Sum
SS = Secondary Sum
PM = Primary Maximum
SM = Secondary Maximum

FOULING INDEX

1.0 = high fouling potential
0.5 = medium fouling potential
0.0 = low fouling potential

*NOTE: Pertains primarily to plants with operating experience.

FIGURE 17. Score Sheet to Assess Fouling by Blue Mussel (*Mytilus edulis*) in a Nuclear Power Plant Raw-Water System

System/Component: ______________________________

PRIMARY FOULING CHARACTERISTICS	Circle Your Evaluation	Circle Maximum When Applicable
American Oysters in Raw-Water Source		
Not present	-5	
Present in water body	3	5
Present in vicinity of plant	5	5
Minimum Flow Velocity During All Operating Phases		
0 or greater than 4 fps	-5	
2 to 4 fps	3	
Less than 2 fps	5	5
Water Temperature (Ambient and Within System)		
Less than 1°C or greater than 36°C	-5	
1° to 9°C or 21° to 36°C	3	
10° to 20°C	5	5
Chlorination (>0.2 ppm Free Residual)		
Chlorinators operating at least 80% of the time	-5	
Chlorinators operating 50% to 80% of the time	3	
Chlorinators operating <50% of the time	5	5
SUM OF CIRCLED VALUES	___	
SUM OR CIRCLED MAXIMUMS		___
SECONDARY FOULING CHARACTERISTICS		
Flow Frequency		
Normally stagnant (near-stagnant)	3	
Intermittent	4	
Continuous	5	5
Valve Leak Potential		
Ball or globe valve	1	
Gate valve	3	
Butterfly valve	5	5
*Natural Traps for Relict Shells		
Piping 4 inches in diameter and smaller	3	
Low spots in cooling loops	4	
Heat-exchanger tubes, tubesheets, or other flow constrictions 2 inches in diameter and smaller	5	5
*Fouling History in Plant or at Nearby Industrial Plants		
Little or none	1	
Occasional	3	
Chronic	5	5
SUM OF CIRCLED VALUES	___	
SUM OF CIRCLED MAXIMUMS		___

$$FI = \frac{PS + SS}{PM + SM}$$

where FI = FOULING INDEX
PS = Primary Sum
SS = Secondary Sum
PM = Primary Maximum
SM = Secondary Maximum

FOULING INDEX

1.0 = high fouling potential
0.5 = medium fouling potential
0.0 = low fouling potential

*NOTE: Pertains primarily to plants with operating experience.

FIGURE 18. Score Sheet to Assess Fouling by American Oyster (*Crassostrea virginica*) in a Nuclear Power Plant Raw-Water System

or secondary characteristics. Numerical values assigned to the secondary characteristics range from 1 to 5. Scores less than 1 were not assigned to the secondary characteristics because secondary characteristics are subjugated by the primary characteristics.

Considerations in Scoring Fouling Potential

Actual operating conditions should be used when assigning numerical values to the fouling characteristics. This is especially important for estimating the contribution of flow velocity to the fouling potential, because actual flow rates may vary substantially from the design values. During conditions such as cold shutdown or low-power testing, flow velocities may be one-half the average design rates. Thus, design flow velocities may be high enough to preclude fouling by bivalves, whereas the actual flow velocities may be ideal for fouling. If valve leaks are known (or suspected) to allow flow in intermittently used systems, then the estimated leakage rate should be used to determine the flow velocity.

In some cases, one or more of the fouling characteristics may not apply to the system or component being evaluated. In other cases, it may be difficult to estimate characteristics such as flow velocity or the potential for silting. The score sheets have been developed so that characteristics that either do not apply or are difficult to estimate with available data can be omitted. Some characteristics only pertain to plants with previous operating experience (see those marked with asterisks in Figures 16, 17, and 18) and should be omitted when estimating the fouling potential of plants that are currently in the design or construction phase.

The scores for primary and secondary characteristics may be, in some cases, more revealing if they are interpreted separately, before the combined score is tabulated. This gives an idea of how suitable the basic environment is for fouling, as well as the ability of the system to enhance the fouling environment. The individual scores may be especially useful in determining what changes in operating conditions could cause fouling to be more or less acute.

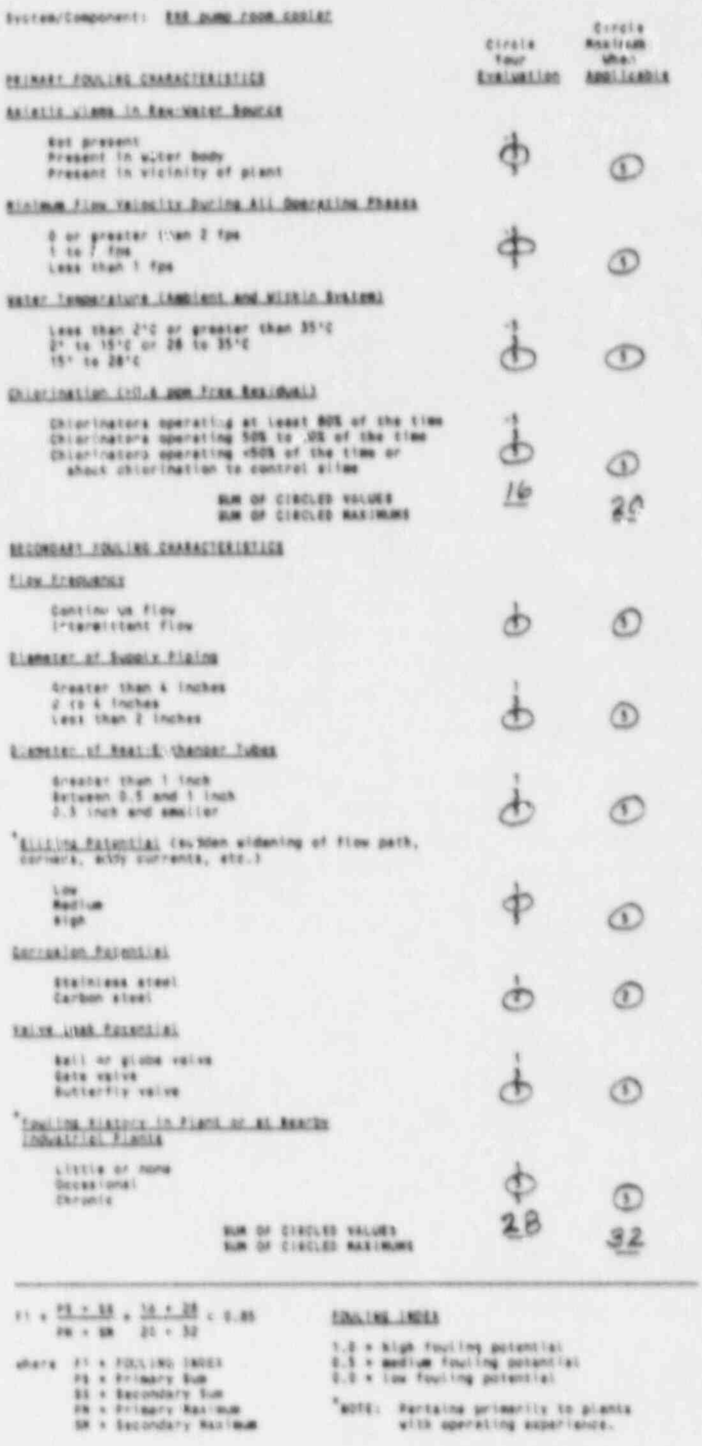
Calculating the Fouling Index

A fouling index can be calculated as the ratio of the sums of the actual scores to the maximum scores. The index can range from 1.0 to less than 0. The closer the index is to 1.0, the greater the fouling potential of the system or component. Values less than 0 can occur when there is more than one -5 evaluation score. The lowest score does not guarantee, however, that fouling will not occur, only that the potential for fouling by bivalves is low.

Example of Score Sheet Usage

The following example shows how a score sheet (Figure 19) can be used to evalute the potential of Asiatic clam fouling in an RHR pump room cooler. Additional examples are given in Neitzel et al. (1984), using the score sheets for blue mussel and American oyster fouling. The environmental and operating conditions important to the evaluation are:

- The temperature of the source water varies between 5°C and 28°C throughout the year.



System/Component: RHR pump room cooler

PRIMARY FOULING CHARACTERISTICS	Circle Your Evaluation	Circle Maximum When Applicable
Asiatic Clams in Raw-Water Source		
Not present		
Present in water body		
Present in vicinity of plant		5
Minimum Flow Velocity During All Operating Phases		
3 or greater than 2 fps		
1 to 2 fps		
Less than 1 fps		5
Water Temperature (Ambient and Within System)		
Less than 2°C or greater than 35°C		
2° to 15°C or 28 to 35°C		
15° to 28°C		5
Chlorination (>0.4 ppm Free Residual)		
Chlorinators operating at least 80% of the time		
Chlorinators operating 50% to 80% of the time		
Chlorinators operating <50% of the time or shock chlorination to control slime		5
SUM OF CIRCLED VALUES	16	
SUM OF CIRCLED MAXIMUMS		20
SECONDARY FOULING CHARACTERISTICS		
Flow Frequency		
Continuous flow		
Intermittent flow		5
Diameter of Supply Piping		
Greater than 4 inches		
2 to 4 inches		
Less than 2 inches		5
Diameter of Heat-Exchanger Tubes		
Greater than 1 inch		
Between 0.5 and 1 inch		
0.5 inch and smaller		5
*Silting Potential (sudden widening of flow path, corners, eddy currents, etc.)		
Low		
Medium		
High		5
Corrosion Potential		
Stainless steel		
Carbon steel		2
Valve Leak Potential		
Ball or globe valve		
Gate valve		
Butterfly valve		5
*Fouling History in Plant or at Nearby Industrial Plants		
Little or none		
Occasional		
Chronic		5
SUM OF CIRCLED VALUES	28	
SUM OF CIRCLED MAXIMUMS		32

$$FI = \frac{PS + SS}{PM + SM} = \frac{16 + 28}{20 + 32} = 0.85$$

where FI = FOULING INDEX
PS = Primary Sum
SS = Secondary Sum
PM = Primary Maximum
SM = Secondary Maximum

FOULING INDEX

1.0 = high fouling potential
0.5 = medium fouling potential
0.0 = low fouling potential

*NOTE: Pertains primarily to plants with operating experience.

FIGURE 19. Assessment of Asiatic Clam Fouling in a Nuclear Power Service-Water System Residual Heat-Removal Pump Room Cooler

- The service-water system is chlorinated once per week for 30 minutes at a concentration of 0.5 ppm free residual chlorine.
- Asiatic clam larvae have been found in the water source during the past year.
- The minimum flow velocity through the 38-mm- (1.5-in.-) diameter inlet pipe to the cooler is about 0.5 mps (1.6 fps).
- Heat-exchanger tubes in the RHR pump room cooler are 13 mm (0.5 in.) in diameter.
- Flow through the cooler is infrequent, and only occurs when the temperature limit in the RHR pump room is exceeded.
- A butterfly valve is used to throttle flow.
- Silt, corrosion, and occasional relict shells have been found in the coolers during previous inspections.

Figure 19 shows the RHR pump room cooler received an overall fouling index of 0.85. This suggests that the potential for Asiatic clam fouling is quite high in the RHR pump room cooler. Asiatic clam fouling has indeed occurred in this type of heat exchanger and in other small, infrequently used heat exchangers in freshwater plants.

Summary of Score Sheet Advantages and Disadvantages

The use of a score sheet to assess fouling or clogging has the following advantages:

- The fouling index can predict the relative fouling potential of numerous systems or components in the open-cycle system.
- A surveillance program based on the relative fouling potential could be developed to give an early warning of future fouling problems.
- The generality of the fouling characteristics makes them relatively easy to determine.
- The fouling characteristics are not plant specific, and this applies to plants over a wide geographic region.
- Utilities that have fouling problems can use the score sheets presented here as a guideline for developing a more detailed, site-specific system for evaluating their fouling problems.

The use of a score sheet to assess fouling or clogging has the following disadvantages:

- The score sheet may not accurately predict fouling potential for all systems or components under all operating conditions.
- The score sheet may not address uncommon operating conditions that occur at certain plants.

- The general nature of the fouling characteristics does not consider the effect of parameters such as dissolved oxygen content, pH, salinity, etc. on fouling levels.

- The general approach is necessitated partly by the lack of detailed operating data concerning the history of events leading up to fouling events.

- The overall fouling index may not accurately reflect the dominant characteristic that causes or inhibits fouling or clogging within a specific system or component.

USE AND EFFECTIVENESS OF SURVEILLANCE TECHNIQUES

The selection of surveillance techniques depends on several factors, such as the location of fouling, the engineering design of the plant, and the overall cost of using the technique. Equally important is the effectiveness and reliability of the techniques in detecting fouling. This chapter describes the pros and cons of numerous surveillance techniques and presents methods for evaluating their effectiveness.

SCUBA DIVERS

Many power plants use SCUBA divers for their surveillance programs. Because divers inspect only large, accessible components of the plant (such as the intake conduits and pump bays), the surveillance programs at these plants are augmented by other surveillance techniques. The effectiveness of using SCUBA divers for detecting fouling depends largely on the degree of inspection you request and the extent of documentation you require concerning the results of the inspection.

What to Consider Before Selecting This Technique

SCUBA divers visually inspect the intake system and conduits or large pipes for signs of damage to components and for bivalve fouling, sediment, and corrosion. The following list of considerations is designed to help you determine whether to include SCUBA inspection in your surveillance program.

Availability of Dive Team. If a dive team is not available in house, you need to contract for one. The names and addresses of diver contractors can be obtained from the Yellow Pages in your local phone directory. Personnel at other power plants may be able to identify SCUBA divers available for this work and give you recommendations about their performance as well.

Size of Dive Team. According to Occupational Safety and Health Administration (OSHA) standards, a dive team has a minimum of four persons: a supervisor, working diver, dive-equipment tender, and standby diver. Additional divers may be required in some areas of the open-cycle water system to ensure that the working diver's air line remains free. Check with dive contractors for assistance in determining the number of divers needed to conduct your work.

Inspection Schedule. Plants contacted during this study use various schedules for diver inspections. Several plants in which thermal backwashing is used to control blue mussel fouling in the intake structure use divers to check the effectiveness of the treatments. Some plants inspect the intake conduits and pump bays yearly. As a minimum, the intake system should be inspected each refueling outage (approximately once every 18 months) to monitor the level of fouling and the condition of the system.

Cost of This Technique. Costs will be influenced by several factors: 1) union versus nonunion wages, 2) insurance fees for the divers, 3) per diem and travel expenses for dive teams obtained through an offsite contractor, and 4) equipment rental charges. Check with dive contractors for assistance in estimating costs.

Evaluating the Effectiveness of This Technique

SCUBA diver inspections provide a first-hand look at the condition of the intake water system. Divers should be instructed as to the specific types of fouling or damage they should look for. The results of diver inspections should be recorded immediately following the inspection (including photographs where applicable) to ensure that this information is available for comparison with the results of future inspections.

Additional Reading

The following materials provide additional information on using SCUBA divers at nuclear power plants:

Drew, E. A., J. N. Lythgoe and J. D. Woods. 1976. *Underwater Research*. Academic Press, New York.

Scotton, L. N., W. J. Armstrong, J. F. Garey and D. J. McDonald. 1983. "Development and Future Trends of the Mussel Control Program at Pilgrim Nuclear Power Station." In *Proceedings of the Symposium on Condenser-Macrofouling Control Technologies - The State-of-the-Art*. Electric Power Research Institute, Palo Alto, California.

U.S. Navy 1975. *U.S. Navy Diving Manual*. Vol. 1, *Air Diving*. NAVSEA 0994-LP-001-9010. Best Bookbinders, Carson, California.

VISUAL INSPECTION

Visual inspection is the most effective and most widely used method of detecting all types of fouling. There is no better method for determining the type and extent of fouling than to open the water system and look inside. Visual inspection, however, is labor intensive and often requires maintenance personnel to dismantle equipment. Inspection of some components can only be done during plant outages, and inspection of equipment in radiation zones increases the radiation exposure to workers.

What to Consider Before Selecting This Technique

Visual inspection provides a first-hand look at the level of bivalve fouling, sediment, and corrosion present in heat exchangers, piping, and valves. The following list of considerations will help you determine whether to include visual inspection in your surveillance program.

Accessibility of Components. Visual inspection requires that components be accessible at the time when inspection is scheduled. If the plant is operating, provisions must be available (i.e., valves, redundant cooling loops, etc.) to isolate the components from the rest of the water system.

Inspection Schedule. Factors that you should consider when determining the frequency of inspection for specific components include past fouling experience, the susceptibility to fouling, and the safety classifications of the component and other equipment that it supports. If fouling has been noted in past inspections, then this component is a candidate for more frequent inspection than others where fouling has never been found. Certain design factors such as flow velocity and component size can indicate whether fouling is likely to occur. The preceding chapter of this report gives example score sheets to help you determine the susceptibility to fouling. The safety significance of component failure caused by fouling must also be considered. For example, heat exchangers that cool components in the emergency core cooling and residual heat-removal systems should be inspected more often than those that cool the lubricating oil to the turbine. Current inspection schedules at plants vary from once per quarter to every refueling outage depending on the component. As a minimum, we suggest that all heat exchangers (including the inlet and outlet piping), valves, and strainers in the nuclear-related service-water system be inspected once per year using a rotating inspection schedule such that at least one-fourth of the system is inspected each quarter.

Technical Specification Requirements. Plant technical specifications describe when and how long specific systems or components can be out of service. These specifications must be consulted before determining if and when inspections can be made.

Cost of This Technique. Visual inspections are performed by plant maintenance personnel. Inspections are often labor intensive because components must be drained and dismantled to allow access. Personnel at one nuclear plant indicate that inspecting and cleaning two 1,000-tube heat exchangers typically requires about 4 hours for a four-man crew to complete. Consult your maintenance supervisor and past maintenance records to estimate the time required for inspection.

Evaluating the Effectiveness of This Technique

The effectiveness of a visual inspection program hinges on the prompt and complete recording of the results of the inspection. A sample heat-exchanger inspection report form is included in the preceding chapter (Figure 19). Photographs should be included with the inspection report. Maintenance personnel should be instructed as to what to look for during the inspection. Cognizant biologists and/or engineers should be present to observe the types and extent of fouling and the condition of the components.

Additional Reading

The following materials provide additional information on using visual inspection at nuclear power plants. Pope (1986) gives valuable guidance concerning methods of preserving corrosion samples for later analysis.

Daling, P. M., and K. I. Johnson. 1985. Current Status of Biofouling Surveillance and Control Techniques. Vol. 2 of Bivalve Fouling of Nuclear Power Plant Service-Water Systems. NUREG/CR-4070, Vol. 2/PNL-5300, Vol. 2, U.S. Nuclear Regulatory Commission, Washington, D.C.

Pope, D. H. 1986. A Study of Microbiologically Influenced Corrosion in Nuclear Power Plants and a Practical Guide for Countermeasures. EPRI-NP-4582. Prepared by Rensselaer Polytechnic Institute for the Electric Power Research Institute, Palo Alto, California.

WATER AND SUBSTRATE SAMPLING

Water samples taken inside and outside the plant are used to monitor amounts of bivalve larvae, sediment, and organic matter entering the open-cycle water system. Substrate sampling provides information on bivalve populations and sediment accumulation in the vicinity of the plant intake. This information is valuable in determining when bivalve spawning is occurring (and when to chlorinate) and when sedimentation is likely to be heaviest.

What to Consider Before Selecting This Technique

The following list of consider substrate sampling in your surveillance program.

Sampling Frequency. The initial water and substrate sampling schedules should be sufficiently frequent to allow developing a seasonal history that includes the times when bivalve larvae are present in the water and the seasonal variation in suspended solids content. After several years of data have been collected, less frequent sampling would be required during periods when larvae are known to be absent from the water source. One plant currently under construction has proposed such a schedule. The utility compiled 12 years of sampling data on the population dynamics of Asiatic clams in the river near the plant site. Sampling at the plant includes monthly sampling near the intake structure. Sampling for clam larvae is conducted semimonthly from April through October and monthly from November through March.

Sampling Procedure. Larvae are small, and appropriate collecting methods must be used: 150-μm plankton nets as suggested in the River Bend plan. For substrate sampling, use a standard method such as the Peterson grab sample.

Cost of This Technique. Water sampling programs are in place at all nuclear power plants. Additional costs will only include evaluating current procedures and implementing changes in schedule.

Evaluating the Effectiveness of This Technique

Water and substrate sampling provides an indication of the types of fouling that may occur in the future. Sampling programs can be effective when proper fouling schedules and sampling procedures are developed and practiced. Plant personnel indicate that results from water sampling programs can be erratic, and that a consistent, proven sampling procedure must be used to ensure accurate trends.

Additional Reading

The following materials provide additional information on using water and substrate sampling at nuclear power plants:

Hamm, P. J. 1982. "What Are We Doing About the Asiatic Clam?" Power 126(1):25-28.

Sinclair, R. M., and B. G. Isom. 1963. Further Studies on the Introduced Asiatic Clam (Corbicula) in Tennessee. Tennessee Stream Pollution Control Board, Tennessee Department of Public Health, Cordell Hull Building, Nashville, Tennessee.

Smithson, J. A. 1981. "Control and Treatment of Asiatic Clams in Power Plant Intakes." In Proceedings of the American Power Conference, Vol. 43. Illinois Institute of Technology, Chicago, Illinois.

GROWTH PANELS

Growth panels are artificial or natural substrates placed into the aquatic environment in or near the intake of the power plant. The growth panel is placed to study the colonization by indigenous organisms. Although the growth panel may not be natural or may be placed in a location different than that preferred by the natural macroinvertebrate community, most of the biological processes that occur on it will be similar to those occur in the plant intake. Settlement and growth in the intake and throughout the circulating raw-water system provide information that is useful to the control and surveillance of macrofouning organisms.

What to Consider Before Selecting This Technique

Growth panels offer a simple and effective method for monitoring the development of most marine fouling organisms. Artificial substrate panels immersed in the source water body provide a location for the organisms to settle and grow. Various materials, including concrete, wood, and metal, can be used for the artificial substrate.

Accessibility of Components. The intake structure in the most likely component in which to place growth panels. Accessibility should not be a major consideration here. Placement, removal, and monitoring of growth panels within the CRW system may be more difficult and will require a site-specific evaluation.

Cost of This Technique. Cost of using growth panels includes procurement of materials to construct panels; construction; plant staff to place, monitor, and sample the panels; and analysis of the samples.

Evaluating the Effectiveness of This Technique

The effectiveness of growth panels for control and surveying macrofouling organisms depends on the community that is being monitored and on location of the panel to provide the growth information that is most useful for controlling fouling. The age of a natural community may not be known, but this can be determined with growth panels. Community age and progression are important to fouling control. Growth panels may not be the same structure, composition, and surface area as the intake of a power plant. It is possible to control the water quality of the area in which the growth panels are placed. Growth panels can be positioned so that the exposure to current, amount of sunlight, and other important characteristics are as similar as possible to those of the environment that should be monitored.

Additional Reading

The following materials provide additional information on using growth panels at nuclear power plants:

Cairns, J., Jr., ed. 1982. Artificial Substrates. Ann Arbor Science, Ann Arbor, Michigan.

Hillman, R. E. 1977. "Techniques for Monitoring Reproduction and Growth of Fouling Organisms at Power Plant Intakes." In Biofouling Control Procedures Technology and Ecological Effects. Marcel Dekker. New York.

Richards, B. R. 1977. "The Use of Artificial Substrates for Studies of the Biofouling Community." In Biofouling Control Procedures Technology and Ecological Effects. Marcel Dekker, New York.

SIDE-STREAM MONITORS

Side-stream monitors are growth chambers used to monitor the settlement and growth of macrofouling organisms. They are inexpensive and easy to operate because of their simple design, and they do not interfere with system operation. A small flow of raw water is circulated through the monitors allowing bivalve larvae to settle and grow in the monitor. Periodic examination of the removable plates enables plant personnel to determine the presence of bivalves and to monitor their growth.

What to Consider Before Selecting This Technique

The following list of considerations is intended to help you determine whether to include side-stream monitors in your surveillance program.

Simplicity and Versatility of Design. Side-stream monitors are very simple in design. Commercial models are available from a manufacturer in the Netherlands, but several plants have adapted plastic buckets and PVC piping to serve the same purpose. Besides monitoring biofouling populations, side-stream monitors could also be used to monitor sedimentation and corrosion coupons (samples of piping and heat-exchanger materials) could be included to check for microbiologically influenced corrosion (MIC).

Water Supply from Open-Cycle System. A water supply from the open-cycle system is required to feed into the monitor. Access to a drain is also required to maintain flow through the monitor.

Location. Monitors should be positioned at several locations in the open-cycle system to account for variations in chlorine concentration that occur because of poor mixing and the biological demand for chlorine. Monitors should be located near the intake, in the middle of the open-cycle system, and near the discharge.

Chlorine Minimization Studies. Plant personnel have used side-stream monitors effectively during in-plant chlorine minimization studies to determine the actual chlorine levels required to control bivalve fouling. Monitors are stocked with populations of bivalves at several locations in the plant, and mortality data are compared to control populations.

Cost of This Technique. Side-stream monitors are inexpensive to buy or build and to maintain. Commercial models sell for approximately $1,000 each, but plant personnel indicate that their availability from the Dutch manufacturer can be a problem.

Evaluating the Effectiveness of This Technique

Analyses of the data generated by side-stream monitors are used to indicate when the fouling organisms are settling and spawning, to determine the appropriate times for treating raw-water systems, and to determine the effectiveness of the various control strategies. Generally, side-stream monitors are placed in two types of locations: a control location normally on the outboard side of water treatment points (e.g., outboard of the raw-water system chlorination point), and at heat exchangers and coolers that are supplied with raw water. Comparison of the data from the control and test monitors is used to evaluate the effectiveness of biofouling control programs.

Additional Reading

The following materials provide information on using side-stream monitors at nuclear power plants. Each paper provides information on the use of the commercially available monitors. Jenner (1983) describes the experience of a Dutch power plant and how the monitors were used to reduce chlorine usage.

Hillman, R. E., D. Anson, J. M. Coriss, B. W. Vigon, R. H. Gray and H. J. Bomelberg. 1985. Biofouling Detection Monitoring Devices: Status Assessment. EPRI-CS-3914. Prepared by the Battelle/Marine Research Laboratory for the Electric Power Research Institute, Palo Alto, California.

Jenner, H. A. 1983. "A Microcosm Monitoring Mussel Fouling." In Proceedings of the Symposium on Condenser Macrofouling Control Technologies - The State-of-the-Art. Electric Power Research Institute, Palo Alto, California.

Scotton, L. N., W. J. Armstrong, J. F. Garey and D. J. McDonald. 1983. "Development and Future Trends of the Mussel Control Program at Pilgrim Nuclear Power Station." In Proceedings of the Symposium on Condenser Macrofouling Control Technologies - The State-of-the-Art. Electric Power Research Institute, Palo Alto, California.

DIFFERENTIAL PRESSURE MEASUREMENT

Measuring the difference in pressure across a heat exchanger or other component provides an indication of the level of fouling or clogging that is present. Limits on differential pressure are often used to signal when components must be cleaned.

What to Consider Before Selecting This Technique

The following list of considerations is intended to help you determine whether to include differential pressure measurement in your surveillance program.

Reliability. Differential pressure gauges used in power plants measure the pressure difference between two pressure taps, one upstream and one downstream of the component. These pressure taps often become clogged, and therefore pressure readings can be unreliable. Pressure taps should be flushed before each measurement is taken to ensure the accuracy of readings. Differential pressure gauges that include this feature are available. Consult the Thomas Register of American Manufacturers under Gauges: Pressure.

U-Tube or Multipass Heat-Exchanger Designs. Several fouling events have occurred in which differential pressure measurements alone did not warn of the severe level of fouling that had occurred. In one case the differential pressure across a U-tube heat exchanger became so high that the divider plate separating the inlet and outlet water boxes was bent sufficiently to allow flow to bypass the heat-exchanger tubes. A similar event happened in a multipass heat exchanger where fouling caused damage to several internal baffle plates and allowed cooling water to bypass some of the tubes.

Evaluating the Effectiveness of This Technique

Steps must be taken to ensure that the readings that are taken are accurate. Pressure taps must be flushed before each reading is taken to ensure that they are not plugged.

Additional Reading

The following source provides additional information on using differential pressure measurement to detect fouling:

Neitzel, D. A., K. I. Johnson, T. L. Page, J. S. Young and P. M. Daling. 1984. Correlation of Bivalve Biological Characteristics and Service-Water System Design. Vol. 1 of Bivalve Fouling of Nuclear Power Plant Service-Water Systems. NUREG/CR-4070, Vol. 1/PNL-5300, Vol. 1, U.S. Nuclear Regulatory Commission, Washington, D.C.

FLOW VELOCITY MEASUREMENT

Flow velocity is the most reliable indicator of potential biofouling, sedimentation, and corrosion within open-cycle water systems. Sedimentation and general fouling will occur in flow velocities less than 0.9 mps (3 fps). Monitoring flow velocity can identify cooling loops where fouling is most likely to occur. Trends in velocity data can indicate where fouling has occurred.

What to Consider Before Selecting This Technique

There are several methods of measuring flow velocity in water systems. Some require permanent installation and others can be strapped to the outside of piping. The following list of considerations is designed to help you determine how best to include flow velocity measurement in your surveillance program.

Permanently Installed Meters. Flowmeters that measure flow by relating velocity to a change in pressure (pitot tubes, flow orifices, or venturi meters) must be installed in the piping system. Flow orifices have the added disadvantage of contributing a substantial pressure drop across the meter itself. Such a flow constriction could also be a likely site for fouling to occur.

Portable Ultrasonic Flowmeters. Portable ultrasonic flowmeters are also available that can be strapped to the outside of piping. Two types of flowmeters are available: doppler and transit-time meters. Doppler-type meters bounce sound waves off particles in the fluid. These meters are not recommended for use in open-cycle water systems because of unpredictable variations in the solids content of raw water. Transit-time meters measure the difference in time required to transmit signals upstream and downstream between two transducers. Wetted transducers are more accurate than clamp-on types, but they require modifications to the piping system. Clamp-on transducers usually give results within 2 to 5% of wetted transducers, and require no modifications to piping.

Placement of Flowmeters. Most flowmeters assume that a standard, reproducible, velocity profile exists within the piping. Flowmeters should therefore be mounted in (or on) long, straight, piping runs at least three pipe diameters away from flow disturbances that occur near elbows, valves, or changes in pipe diameter.

Cost of This Technique. A major cost factor of permanently installed meters is the modification of the piping system. The current cost of a portable ultrasonic meter that is able to measure flow velocity in pipes 50 to 500 mm (2 to 20 in.) in diameter is approximately $11,000. Consult the Yellow Pages and the Thomas Register for vendors of flowmeters located in your area.

Evaluating the Effectiveness of This Technique

Flowmeters that use differential pressure to indicate flow (pitot tubes, orifice meters, venturi meters, etc.) can give inaccurate results if the pressure tubes become clogged. The pressure taps should therefore be flushed on a regular schedule. Flowmeters must also be located in long straight piping runs to ensure that measurements are not biased by flow disturbances that occur near elbows, valves, or sudden changes in pipe diameter. The effectiveness of transit-time flowmeters can change under various conditions (Table 5).

Additional Reading

Daling, P. M., and K. I. Johnson. 1985. *Current Status of Biofouling Surveillance and Control Techniques*. Vol. 2 of *Bivalve Fouling of Nuclear Power Plant Service-Water Systems*. NUREG/CR-4070, Vol. 2/PNL-5300 Vol. 2, U.S. Nuclear Regulatory Commission, Washington, D.C.

DIFFERENTIAL TEMPERATURE MEASUREMENT

Measuring the change in fluid temperature across both the tube and shell sides of a heat exchanger provides the data required to calculate the overall heat transfer coefficient. The overall heat transfer coefficient gives a more accurate prediction of heat-exchanger performance than does differential pressure. The overall heat transfer coefficient, unlike differential pressure measurements, can indicate when internal bypass leakage is occurring in U-tube and multipass heat exchangers.

TABLE 5. Application Data for Transit-Time Ultrasonic Flowmeters[a]

GOOD (Likely to Work)	QUESTIONABLE (May or May Not Work)	BAD (Likely to Fail)
FLUID		
Clean, nonresidue	Contaminants small, only minor residue on pipe	Immiscible bearing residue-bearing mixture
Single-phase flow	Second phase small or present occasionally	Foamy
Composition constant	Composition varies widely	Composition unknown
Low viscosity (water)	Viscosity <100 cps	High viscosity
Percent solids small (<1% by volume)	Percent solids significant (1-10% by volume)	Percent solids large (>10% by volume)
Percent of gas small (<1% by volume)	Gas phase significant (1-10% by volume)	Gas phase large (>10% by volume)
No cavitation	Cavitation	Cavitation
FLOW CONDITIONS		
Steady flow	Unsteady flow	Oscillatory or transient
Standard or reproducible profile	Profile repeatability uncertain	Uncontrolled profile
PIPE CONDITIONS		
Clean	Deposits on walls	Scaled or heavily coated with residues
Smooth inside and outside	Not smooth	Very rough outside
Long, straight, and continuous location	Disturbances within 3 diameters of measuring	Inlet and outlet disturbances very close to measuring location
Unlined	Lining contacts well	Loose or attenuating lining
Wall attenuation small	Wall attenuation moderate	Wall attenuation large

---

(a) Panametrics. 1986. "Introducing Model 6002." Product brochure, Panametrics Company, Waltham, Massachusetts.

What to Consider Before Selecting This Technique

Heat-Exchanger Type. Differential temperature measurements should be taken on both the shell and tube sides of U-tube and multipass heat exchangers to ensure that an excessive pressure differential has not damaged the divider plates and allowed flow to bypass the heat-exchanger tubes.

Safety Significance. Heat exchangers in the open-cycle water system that support the emergency core cooling system, the residual heat-removal system, the emergency diesel generators, and other nuclear safety systems should be considered for installation of equipment to monitor the differential temperature measurement.

Flow Rate Measurement The flow rate (flow velocity times flow area) must also be measured to calculate the overall heat transfer coefficient.

Cost of This Technique. Factors affecting the cost of differential temperature measurement include equipment and installation costs. Installation will likely be required during an outage or other time when systems can be out of service. For further cost information, consult the Thomas Register and your local Yellow Pages for vendors of industrial gauges and instruments.

Evaluating the Effectiveness of This Technique

Temperatures should be monitored frequently enough to develop a performance history that reflects heat-exchanger performance immediately after cleaning and at various degrees of fouling. One nuclear power plant has specified daily temperature monitoring for their emergency diesel-generator coolers and RHR heat exchangers and monthly review of these data to identify fouling trends. Consult the manufacturer of your heat exchangers to obtain design performance data.

Additional Reading

The following source provides additional information on using differential temperature measurement at nuclear power plants. Pages 17 to 19 of Daling and Johnson (1985) describe a method of calculating the overall heat transfer coefficient.

Daling, P. M., and K. I. Johnson. 1985. Current Status of Biofouling Surveillance and Control Techniques. Vol. 2 of Bivalve Fouling of Nuclear Power Plant Service-Water Systems. NUREG/CR-4070, Vol. 2/PNL-5300 Vol. 2, U.S. Nuclear Regulatory Commission, Washington, D.C.

SIDE-STREAM CONDENSER MONITORS

Side-stream condenser monitors have been developed to monitor the growth of microfouling slimes in condenser tubes. Most measure the decrease in heat transfer rate as a slime layer forms on a test section within the monitor.

Hillman et al. (1985) reviewed the performance characteristics of 14 microfouling monitors and judged that only 2 were capable of providing early warning of fouling problems. The success of these 2 monitors was attributed to their ability to correctly model flow conditions that exist within condenser tubes.

What to Consider Before Selecting This Technique

Side-stream condenser monitors have been developed on the basis of several designs. The following list of considerations is intended to help you determine whether to include side-stream condenser monitors in your surveillance program.

Annular Flow Monitors. Annular flow devices monitor slime buildup on the outside of a heated tube located inside a larger tube. Annular devices do not provide similar flow conditions to condenser tubes because water flows over the outside of the fouling surface rather than through it. Annular fouling monitors would not be effective in detecting sedimentation because little or no sediment would accumulate on the outer surface of the heated tube.

Externally Heated Tube Monitors. Some monitors pass water through an externally heated tube and measure the degradation in heat transfer as slime forms inside the tube as it would in actual condenser tubes. These monitors may also be effective for modeling sedimentation provided that flow conditions within the monitor and condenser tubes are sufficiently similar to provide meaningful results. One of the two side-stream condenser monitors with early warning capability was of the externally heated tube design.

Condenser Simulators. Condenser simulators use pilot-scale condensers to monitor slime buildup in the condensers. Public Service Electric and Gas (PSE&G) has developed a mobile laboratory that includes three pilot-scale condensers. This represents an effort to model actual conditions within the condensers, and field tests indicate that it provides an early warning of condenser fouling problems.

Length of Tubing. The tubing used in a side-stream condenser monitor must be of sufficient length to ensure that end effects do not bias the results. The externally heated tube monitor with early warning capability requires a minimum entry length of 50 tube diameters before the heated test section (Hillman et al. 1985). Present models in use have a total tube length of 1.8 m (6 ft), and the heated length is about 0.3 m (1 ft).

Cost and Availability of This Technique. Many of the monitors reviewed by Hillman et al. (1985) were not available for purchase. Some are research models and others are part of a fouling detection service provided by vendors. The externally heated tube monitor referred to here is available from the manufacturer. Refer to Hillman et al. (1985) for vendors and cost information.

Evaluating the Effectiveness of This Technique

The effectiveness of side-stream condenser monitors is largely dependent on how well each monitor simulates the actual flow conditions within the condensers at a specific plant. Utility personnel indicate that condenser monitors have been used in the past, but that fouling data obtained often does not correlate well with actual condenser fouling. The effectiveness of condenser monitors must be determined on a case-by-case basis by comparison with fouling observed in the condensers.

Additional Reading

The following materials provide additional information on using side-stream condenser monitors at power plants. Hillman et al. (1985) present a review of 14 microfouling monitors, and Johnson and Neitzel (1987) present an update on the condenser simulator developed by PSE&G.

Hillman, R. E., D. Anson, J. M. Coriss, B. W. Vigon, R. H. Gray and H. J. Bomelberg. 1985. Biofouling Detection Monitoring Devices: Status Assessment. EPRI-CS-3914. Prepared by the Battelle/Marine Research Laboratory for the Electric Power Research Institute, Palo Alto, California.

Johnson, K. I., and D. A. Neitzel. 1987. Application of Biofouling Surveillance and Control Techniques to Sediment and Corrosion Fouling at Nuclear Power Plants. Vol. 2 of Improving the Reliability of Open-Cycle Water-Systems. NUREG/CR-4626, Vol. 2/PNL-5876-2, Vol. 2, U.S. Nuclear Regulatory Commission, Washington, D.C.

USE AND EFFECTIVENESS OF FOULING CONTROL TECHNIQUES

The selection of fouling control techniques depends on factors such as the type of fouling to be controlled, state and federal environmental regulations, the location of fouling in the plant, and the overall cost of the technique. Equally important is the technique's effectiveness and reliability in controlling fouling. This chapter describes the pros and cons of the control techniques and presents methods for evaluating their effectiveness.

CHLORINATION

Chlorination is an effective control technique for bivalves, slime, and, to a lesser extent, MIC. Chlorine is the biocide most widely used in the power-generating industry. Intermittent chlorination effectively controls slime, but chlorine must be applied continuously, at least during bivalve spawning seasons, to control bivalves.

What to Consider Before Selecting This Technique

The following list of considerations is designed to help you determine how best to use chlorination in your control program.

Slime Control. Microfouling slime can be controlled with intermittent applications of chlorine. A typical schedule used at several plants calls for chlorinating the circulating-water system at a concentration of 0.2 mg/l for 2 hours per day per plant. Some plants break the 2-hour total into 15-minute intervals distributed throughout the day.

Bivalve Control. Effective bivalve control using chlorine requires continuous application, at least during bivalve spawning seasons. The upper bounds of chlorine concentrations used at power plants for bivalve control are 0.6 to 0.8 mg/l for Asiatic clam control, 0.2 mg/l for blue mussel control, and 0.2 mg/l for oyster control.

MIC Control. Continuous low-level (0.5 mg/l) chlorination and shock chlorination (5 to 20 mg/l for periods of several minutes to 1 hour per day) have been effective in controlling organisms that cause MIC in systems that are initially clean. Chlorine is less effective than ozone in penetrating films, corrosion nodules, etc. to control MIC. Pope (1986) provides an in-depth discussion of MIC control.

Targeted Chlorination. The Tennessee Valley Authority (TVA) has tested targeted chlorination in two of its fossil-fueled plants. Targeted chlorination uses a moving manifold to apply a concentrated chlorine solution to only a few tubes at a time. The TVA tests have shown targeted chlorination to be effective and quite reliable; however, only limited plant experience (1 year each at two plants) is available.

System Reliability. The chlorination system must operate reliably for chlorination to be an effective control technique. Personnel at 8 of 10 nuclear plants visited described maintenance and system reliability problems associated with the chlorination system. Chlorination systems intended for intermittent use are often inadequately designed to provide the continuous chlorination required to control bivalves.

Regulations on Chlorine Discharge. The U.S. Environmental Protection Agency (EPA) restricts the discharge of chlorine from power plants. Free available chlorine (FAC) is limited to a maximum concentration of 0.5 mg/l, and an average concentration during a single period of chlorine release of 0.2 mg/l. Discharges of FAC and total residual chlorine (TRC) are limited to 2 hours per day per unit, and simultaneous multiunit discharges are prohibited unless the utility can demonstrate that the units cannot operate at or below this level of chlorination. Both once-through condenser cooling water and cooling tower blowdown are regulated, and these regulations can affect the control of bivalves. These regulations prohibit continuous chlorination of the condenser cooling-water system. Service-water and auxiliary cooling-water systems are often designated as low-volume waste systems, and their regulation is treated on a case-by-case basis. Several plants have obtained waivers that allow continuous chlorination of these systems for bivalve control.

Cost of This Technique. Chlorine is the most common biocide used at power plants because it is cost-effective, and this has precluded large-scale use of other chemical controls. Factors that affect capital equipment costs include: the type of chlorine used (gaseous, hypochlorite generated onsite, or purchased hypochlorite), the size of the system, and additional equipment such as bulk storage facilities, controls, etc. Kasper et al. (1983) present an in-depth survey of chlorine usage and costs based on data collected at U.S. steam electric stations. Johnson and Neitzel (1987) describe dechlorination costs at a nuclear power plant, and the cost of replacing the chlorination system at a nuclear plant. Moss et al. (1985, 1986) summarize the cost of the TVA's targeted chlorination work.

Evaluating the Effectiveness of This Technique

The effectiveness of the chlorination program must be verified by plant biologists and engineers. Verification can be accomplished by keeping detailed records that include the chlorine concentrations applied and when the chlorination system is out of service. These data should be reviewed when trending fouling data to correlate chlorination system performance with fouling observed in the plant.

Additional Reading

The following materials provide additional information on using chlorination at nuclear power plants:

> Hogan, J. E. 1983. "EPA Regulations on Chlorination and Toxic Coating: The Impact on Power Plant Operation." In Proceedings of the Symposium on Condenser Macrofouling Control Technologies - The State-of-the-Art. Electric Power Research Institute, Palo Alto, California.
>
> Isom, B. G., C. F. Bowman, J. T. Johnson and E. B. Rodgers. 1986. "Controlling Corbicula (Asiatic Clams) in Complex Power Plant and Industrial Water Systems." In Proceedings of the Second International Corbicula Symposium, pp. 95-98. American Malacological Union, Houston, Texas.

Johnson, K. I., and D. A. Neitzel. 1987. Application of Biofouling Surveillance and Control Techniques to Sediment and Corrosion Fouling at Nuclear Power Plants. Vol. 2 of Improving the Reliability of Open-Cycle Water Systems. NUREG/CR-4626, Vol. 2/PNL-5876-2, Vol. 2, U.S. Nuclear Regulatory Commission, Washington, D.C.

Kasper, J. R., W. Chow, J. Graham and Y. G. Mussalli. 1983. "Cost of Chlorination." In Proceedings of the Symposium on Condenser-Macrofouling Control Technologies - The State-of-the-Art. Electric Power Research Institute, Palo Alto, California.

Moss, R. D., P. A. March and S. P. Gautney. 1986. Field Experiences and Results of Two Targeted Treatment Systems. IWC-86-34. Presented at the 47th annual meeting of the International Water Conference, Pittsburgh, Pennsylvania, October 27-29, 1986. Tennessee Valley Authority, Chattanooga, Tennessee.

Scotton, L. N., W. J. Armstrong, J. F. Garey and D. J. McDonald. 1983. "Development and Future Trends of the Muscel Control Program at Pilgrim Nuclear Power Station." In Symposium on Condenser-Macrofouling Control Technologies - The State-of-the-Art. Electric Power Research Institute, Palo Alto, California.

SPONGE-BALL TUBE-CLEANING SYSTEMS

Sponge-ball tube-cleaning systems circulate abrasive sponge balls through the condenser tubes to remove slime and sediment. The system collects the balls downstream of the condensers and pumps them back to the distribution manifolds located upstream of the condensers. Research supported by a manufacturer of sponge-ball systems suggests that a system that operates properly can maintain condenser tubes at about 95% of the maximum heat transfer capacity as compared to 85% for tubes where chlorination is used alone and 50% for tubes that are in need of manual cleaning. To our knowledge, sponge-ball systems have only been installed on the condenser cooling-water systems at power plants. None have been installed in service-water systems.

What to Consider Before Selecting This Technique

The following list of considerations is intended to help you determine whether to include a sponge-ball tube-cleaning system in your control program.

Retrofitting a System. Retrofitting a sponge-ball cleaning system in an existing plant where no initial plans were made for later installation would require extensive modifications to the inlet and outlet piping of the condensers and possibly to the building that houses the condensers. Such extensive work would overshadow the cost of the system components and in most cases remove the sponge-ball system from consideration. Several newer plants have included spool pieces that can be removed so that the sponge-ball system can be installed in their place.

Improved Ball Collection Screens. Loss of sponge balls because of misaligned or malfunctioning ball collection screens is a common occurrence. Several manufacturers of sponge-ball systems sell improved collection screens that are designed to reduce the potential for ball loss.

Debris Fouling. The operation of sponge-ball cleaning systems is adversely affected by debris fouling (seaweed, bivalve shells, sticks, etc.). Debris can clog the condenser tubesheet and block the sponge balls from entering the tubes, and it has also clogged the ball collection screens and forced them out of alignment, resulting in excessive ball loss. One manufacturer of sponge-ball systems also sells a debris filter that is designed to minimize these problems. The filter removes debris upstream of the ball distribution manifold and the condensers.

Cost of This Technique. The cost of a ball cleaning system depends on the number of condenser inlet and outlet pipes you have (often one inlet and outlet header per condenser). The manufacturer suggests that a ball distribution and collection system be installed in each set of inlet and outlet headers. The current equipment cost per condenser inlet and outlet is about $300,000. Consult the Thomas Register under Cleaners, Tube for manufacturers of sponge-ball tube-cleaning systems.

Evaluating the Effectiveness of This Technique

If the sponge-ball cleaning system is operating correctly, you should see a lower back pressure on the shell side of the condenser than if it were not operating or operating poorly, all else being equal. A way to test the effectiveness of the system would be to turn off the sponge-ball system on one condenser. The condenser back pressure should gradually become higher in the condenser with the sponge-ball system turned off. Determining whether the ball collection screens are misaligned is easy. Keep an eye out for tens of thousands of sponge balls floating in your discharge canal.

Additional Reading

The following materials provide additional information on using sponge-ball cleaning systems as a means of fouling control.

Daling, P. M., and K. I. Johnson. 1985. Current Status of Biofouling Surveillance and Control Techniques. Vol. 2 of Bivalve Fouling of Nuclear Power Plant Service Water Systems. NUREG/CR-4070, Vol. 2/PNL-5300, Vol. 2, U.S. Nuclear Regulatory Commission, Washington, D.C.

Drake, R. C. 1977. "Increasing Heat Exchanger Efficiency Through Continuous Mechanical Tube Maintenance." In Biofouling Control Procedures: Technology and Ecological Effects. Marcel Dekker, New York.

Huber, E. R., and R. A. Plant. 1984. Upgrade Replacement of Existing On-Line Condenser Tube Cleaning Systems. 84-JPGC-PWR-23, American Society of Mechanical Engineers, New York.

Torbin, R. N., and Y. G. Mussalli. 1980. "The Cost-Effectiveness of Alternative Condenser Biofouling Control Methods." In Condenser Biofouling Control. Ann Arbor Science, Ann Arbor, Michigan.

MANUAL TUBE CLEANING

Manual tube cleaning is often performed during outages to remove slime, sediment, scale, and lodged debris from inside heat-exchanger tubes. Tube cleaning is performed by forcing sponge balls, rubber plugs, brushes, or metal scrapers through the tubes with a high-pressure water gun. A technique called hydroblasting, which relies on a high-pressure water lance to remove fouling from tubes, is also used.

What to Consider Before Selecting This Technique

The following list of considerations is intended to help you determine how best to use manual tube-cleaning methods in your control program.

Scheduling. Manual tube cleaning requires access to the inlet and outlet tube sheets of heat exchangers and therefore must be done when the heat exchanger can be isolated and drained. Plants often call for condenser cleaning to be done every refueling outage. Cleaning could also be done during scheduled visual inspections.

Choosing the Right Type of Cleaner. Different types of tube cleaners provide different levels of tube cleaning. Sponge balls, rubber plugs, and nylon brushes remove soft fouling deposits, but have little effect on mineral scales or corrosion products. Metal scrapers can remove scale and corrosion products, leaving a smooth, bright, metal surface.

Tube Scraping Slows Pitting Caused by MIC. Tube pitting can be slowed by cleaning tubes down to bright metal using metal tube scrapers. The scrapers remove the localized corrosive environment at the tube surface where MIC occurs.

How Many Tube Cleaners Do I Need? Contractors that provide tube-cleaning services suggest purchasing cleaners for at least one-fourth the total number of tubes to be cleaned. By using a large number of cleaners, less time is spent retrieving the cleaners from the discharge waterbox of the heat exchanger.

Tube Cleaners Are Reusable. Nylon brushes can be used up to 6 times and metal scrapers as many as 12 times. The severity of fouling impacts the life of tube cleaners; the thicker the fouling, the faster the cleaners wear out.

Hydroblasting Versus Shooting Tube Cleaners. Hydroblasting is an effective method of cleaning heat-exchanger tubes. It is more time consuming than shooting tube cleaners because the water lance must be inserted and withdrawn from each tube individually.

Cost of This Technique. The current cost of cleaning heat-exchanger tubes ranges from about $0.40 to $1.00 per tube. The lower cost is typical of tube cleaning performed by utility personnel or by contractors located near the plant. The higher cost is typical of cleaning performed by contractors where personnel and equipment transportation costs become a factor. The cost of different tube cleaners is another factor. Hydroblasting tubes typically costs between $0.75 and $1.10 per tube depending on the tube length and the extent of fouling. Consult tube-cleaning contractors for more detailed cost information.

Evaluating the Effectiveness of This Technique

The effectiveness of tube-cleaning methods could be evaluated by collecting the debris removed from several tubes and calculating an equivalent fouling thickness for comparison with the level of fouling noted in tubes that have not been cleaned. Once the plant reaches full power after cleaning, there should be a noticeable improvement in the heat transfer capability of the heat exchangers that have been cleaned. The overall heat transfer coefficient could be calculated (for heat exchangers where the shell and tube inlet and outlet temperatures are recorded) before and after cleaning and compared to estimate the improvement in heat transfer capability.

Additional Reading

The following materials provide additional information on using manual tube cleaning in power plants:

Hovland, A. W. 1978. "Effective Condenser Cleaning Improves System Heat Rate." Power Engineering, January 1978, pp. 49-50.

Pope, D. H. 1986. A Study of Microbiologically Influenced Corrosion in Nuclear Power Plants and a Practical Guide for Countermeasures. EPRI-NP-4582. Prepared by Rensselaer Polytechnic Institute for the Electric Power Research Institute, Palo Alto, California.

INLINE DEBRIS STRAINERS

Inline debris strainers are manufactured in several styles and are available for pipe diameters ranging from approximately 25 mm (1 in.) to 3.3 m (130 in.). The strainers remove debris from the raw water and flush it out of the system.

What to Consider Before Selecting This Technique

The following considerations are intended to help you determine whether to include inline strainers in your control program.

Small Strainers. Small strainers (sometimes called "clam traps") in the 25- to 150-mm (1- to 6-in.) range have been installed in nuclear power plants to remove bivalve shells and debris upstream of heat exchangers that have been prone to fouling. Heat exchangers that accumulate a higher-than-average amount of debris are often located in low areas of the service-water system and used infrequently.

Large Intake Strainers. Large strainers are used downstream of the circulating-water and service-water pumps to remove debris before it enters the plant. Service-water systems at freshwater plants often include strainers In most cases, large strainers for the circulating-water system must be included in the original design of the open-cycle water system because of their size (typically a cylinder of 3 to 4 m in diameter and 3 to 4 m in length).

Cost of This Technique. Factors that affect the cost of strainers include the size of the strainer, the extent of modifications required to install it, and design and analysis required to implement the design change. MacPhee (1986) describes the costs of installing seven strainers in the service-water system of a nuclear plant. Consult vendors of nuclear-grade strainers for specific cost information.

Evaluating the Effectiveness of This Technique

The effectiveness of strainers can be evaluated by comparing the amount of fouling observed in components before and after the strainers were installed. The volume of bivalve shells and debris collected by the strainers should be recorded because it can provide a qualitative view of strainer effectiveness.

Additional Reading

The following material provides additional information on using inline strainers in nuclear plants:

> MacPhee, D. D. 1986. "A Mechanical Strainer Design for Corbicula Fouling Prevention in the Service Water System at Arkansas Nuclear One, Unit 2." In Proceedings of the Second International Corbicula Symposium, pp. 59-61. American Malacological Union, Houston, Texas.

IMPROVED TRAVELING WATER SCREENS

All steam electric stations that use raw water for direct cooling have traveling water screens for removing fish, adult bivalves, and other debris before it enters the pump intake bays. Traveling screens typically remove debris greater than 6 mm (1/4 in.) in size.

What to Consider Before Selecting This Technique

Several utilities have modified or replaced their traveling water screens to reduce the amount of debris that passes the screens. The following list of considerations is intended to help you decide whether to upgrade your traveling water screens.

Fine-Meshed Screens. The TVA has implemented a program to minimize Asiatic clam fouling that calls for installing 0.8-mm (1/32-in.) mesh screen panels in the existing traveling screens (Isom et al. 1986). Fine-meshed screens reduce the flow area into the pump bays. The effect of this on the intake pumps should be determined before implementing such a change. Fine-meshed screens will also collect more debris, and you should determine whether your spray wash system can handle the additional load.

Higher Speed Screens. Screen plugging at one plant has been caused by excessive debris buildup on the slow-moving screens. The utility has modified the screens to include a high-speed setting [available speeds are 4.9 and 15.2 mpm

(16 and 50 fpm)]. The higher screen speed allows less debris to collect on each screen panel before it is removed by the spray wash system.

Multipressure Spray Wash Systems. The aforementioned utility also modified their spray wash system to reduce the amount of debris carried over the screens. This necessitated installing additional sets of wash nozzles to give low-, medium-, and high-pressure wash settings.

Dual-Flow Screens. Dual-flow screens pass water from the outside of a continuous loop of screen panels through to the inside of the loop where it then flows into the pump bay. This eliminates a path for carryover of debris into the pump bays. The design screens water through both the ascending and descending screen panels and therefore has twice the screen area of a similarly sized conventional screen (allowing for a finer screen mesh). Dual-flow screens that require no modification of existing concrete intake bays are available.

Cost of This Technique. Installing fine-meshed screen in the panels of existing screens is the least expensive of the modifications described here. Increasing the screen speed and installing additional wash nozzles cost the utility about $130,000 per screen. Replacing the existing screens with dual-flow screens cost one plant about $240,000 per screen. Consult screen manufacturers for more detailed cost data.

Evaluating the Effectiveness of This Technique

The improvements to traveling water screens just described should noticeably reduce the amount of debris found in the intake bays during scheduled inspections. They should also reduce the frequency of plant shutdowns resulting from severe screen plugging if this has been a problem in the past.

Additional Reading

The following source provides additional information on improving the performance of traveling water screens:

> Isom, B. G., C. F. Bowman, J. T. Johnson and E. B. Rodgers. 1986. "Controlling Corbicula (Asiatic Clams) in Complex Power Plant and Industrial Water Systems." In Proceedings of the Second International Corbicula Symposium, pp. 95-98. American Malacological Union, Houston, Texas.

THERMAL BACKWASHING

Thermal backwashing is practiced by marine power plants to kill biofouling (primarily blue mussels and barnacles) that accumulates in the intake conduits and the intake structure.

What to Consider Before Selecting This Technique

The following considerations are intended to help you determine whether to use thermal backwashing in your control program.

Plant Design. Plants must be designed with crossover piping that allows directing the heated water from one condenser backward through another separate condenser, pump, and intake bay that is temporarily out of service. The extensive modifications necessary to a retrofit such piping in a plant would in most cases eliminate thermal backwashing from consideration.

Limits on Thermal Discharge. The EPA limits the amount of heat that power plants can discharge into the environment. Thermal backwashing temperatures at some coastal plants are limited to 40.6°C (105°F) at the point of discharge to the receiving water. At one plant the maximum temperature differential across the condensers was limited to 17.8°C (32°F). All plants surveyed by Hogan (1983) were required to perform a "316(a) demonstration" before using thermal backwashing. Section 316(a) of the Clean Water Act allows for waivers from specified limits if the plant can demonstrate that the new limits will not adversely affect the balanced indigenous populations of fish, shellfish, and wildlife.

Limits on System Temperatures. In most cases thermal backwashing of service-water systems is not allowed because the water temperature required to kill bivalves is greater than allowed by plant technical specifications. Plants that use thermal backwashing to control bivalve fouling in the circulating-water system often use continuous low-level chlorination to control bivalves in the service-water system. Consult your plant technical specifications to determine what limitations apply.

Scheduling Thermal Backwashing. Thermal backwashing should be scheduled such that the governing fouling organisms do not reach a size greater than one-third the diameter of the smallest tubing in the system. Methods of monitoring fouling growth include growth panels, side-stream monitors, and empirical growth models based on a history of growth data taken in the vicinity of the plant.

Nonthermal Backwashing. Backwashing with unheated water is practiced by a few plants to loosen bivalve shells and other debris that have lodged against the inlet tubesheets of heat exchangers. A temporary backflushing capability was devised at one plant to help remove Asiatic clams from the containment cooling units. Backflushing on a regular basis, however, requires that piping be permanently installed to allow reversing the flow through heat exchangers.

Cost of This Technique. Utilities that use thermal backwashing indicate that overall it represents a cost savings. Some generating capacity is lost because plants have to power down to perform the backwashing procedure, but this is more than recovered by the increased performance and reliability of the circulating-water system. The high cost (equipment, construction, and, most important, replacement power costs) of retrofitting the piping necessary to perform backwashing is the main drawback of retrofitting such a system.

Evaluating the Effectiveness of This Technique

The effectiveness of thermal backwashing can be evaluated by comparing fouling trends before and after thermal backwashing is installed. Plant personnel indicate that thermal backwashing is very effective in controlling mussel and barnacle growth provided that it is done on schedule. Postponement because of scheduling conflicts has led to excessive amounts of shells accumulating in the intake trash baskets and screens.

Additional Reading

The following materials provide additional information on using thermal backwashing at nuclear power plants:

Hogan, J. E. 1983. "EPA Regulations on Chlorination and Toxic Coating: The Impact on Power Plant Operation." In Proceedings of the Symposium on Condenser Macrofouling Control Technologies - The State-of-the-Art. Electric Power Research Institute, Palo Alto, California.

Johnson, G., J. Foertch, M. Kes[illegible] and B. Johnson. 1983. "Thermal Backwash as a Method for Macrofouling Control at the Millstone Nuclear Power Station." In Proceedings of the Symposium on Condenser Macrofouling Control Technologies - The State-of-the-Art. Electric Power Research Institute, Palo Alto, California.

Scotton, L. N., W. J. Armstrong, J. F. Garey and D. J. McDonald. 1983. "Development and Future Trends of the Mussel Control Program at Pilgrim Nuclear Power Station." In Proceedings of the Symposium on Condenser Macrofouling Control Technologies - The State-of-the-Art. Electric Power Research Institute, Palo Alto, California.

Stock, J. N., and R. A. De La Parra. 1983. "Use of Thermal Backwash to Control Marine Biofouling at San Onofre Nuclear Generating Station." In Proceedings of the Symposium on Condenser Macrofouling Control Technologies - The State-of-the-Art. Electric Power Research Institute, Palo Alto, California.

ANTIFOULANT COATINGS

Antifoulant coatings release chemical toxicants that inhibit fouling and are widely used in the marine industry. Common antifoulant toxicants include copper, copper alloys, and organometallic toxicants dissolved in elastomeric materials. Antifoulant coatings using organometallic toxicants have received only limited testing in power plant conditions.

What to Consider Before Selecting This Technique

EPA Regulations. The EPA strictly regulates the use of antifoulant chemicals. Nontoxic coatings may not be regulated; however, toxic coatings are probably restricted from use. Toxic coatings have been used under provisional permits that limit the total surface area that could be covered (Johnson and Neitzel 1987).

Copper as an Antifoulant. Copper and copper-nickel alloys resist the buildup of biofouling by means of formation of a cuprous oxide film that is toxic to marine life. Copper-nickel alloys (typically 90-10 and 70-30) are often used to make heat-exchanger tubes and tubesheets, and as lining materials in the open-cycle water system, because they have a high thermal conductivity and resist fouling.

Durability of Elastomeric Coatings. A drawback to elastomeric coatings is their poor durability compared to the operating life of power plants (several years compared to the 40-year design life of nuclear plants). Extensive surface preparation is required to ensure a firm bond of all types of coatings. Even so, the typical life expectancy of these coatings only ranges from 15 to 30 months. Coatings may also contribute to the fouling problem when they work loose and become impinged against heat-exchanger tubesheets and other constrictions in the open-cycle system.

Cost of This Technique. Factors that affect the cost of antifoulant coatings include the type of coating being used, the type of toxicant, and the regulatory requirements that must be satisfied. Copper-nickel alloys have a long history of use in heat exchangers and are not regulated by the EPA. The cost of using elastomeric coatings impregnated with organometallic toxicants may not even be a factor if the EPA does not allow their use in power plants. Consult vendors for estimating the cost of using antifoulant coatings.

Evaluating the Effectiveness of This Technique

If antifoulant coatings are working properly, they should inhibit most fouling from attaching to the surfaces on which they are applied. This is especially true of the organometallic toxicants. A layer of slime will form on copper-nickel heat-exchanger surfaces, but it should occur more slowly than on stainless steel or titanium.

Additional Reading

The following materials provide additional information on using antifoulant coatings in nuclear power plants:

Hogan, J. E. 1983. "EPA Regulations on Chlorination and Toxic Coating: The Impact on Power Plant Operation." In Proceedings of the Symposium on Condenser Macrofouling Control Technologies - The State-of-the-Art. Electric Power Research Institute, Palo Alto, California.

Holl, C. H., R. L. Martin and R. E. Hillman. 1983. "Antifoulant Coatings: Potential for Controlling Macrofouling in Operating Coastal Power Plants." In Proceedings of the Symposium on Condenser Macrofouling Control Technologies - The State-of-the-Art. Electric Power Research Institute, Palo Alto, California.

OXYGEN SCAVENGERS

Oxygen scavengers has been used at the fossil-fueled Baldwin Station (Baldwin, Illinois; Illinois Power Company) to kill Asiatic clams in the intake structure (Smithson 1981). Sodium metabisulfite ($Na_2S_2O_5$) and hydrogen sulfide (H_2S) are used to create anerobic conditions, which are lethal to the clams, in the intake bays.

What to Consider Before Selecting This Technique

The oxygen scavenger used by Smithson has been an effective means of controlling clams at the Baldwin Station. The following list of consideration is intended to help you determine whether to use an oxygen scavenger in your control program.

Limited Use. To our knowledge, the Illinois Power Company is the only utility using this technique to control clams. Other oxygen scavengers have not been developed for controlling blue mussels and American oysters. Oxygen scavengers have not been used at nuclear power plants.

System Isolation Required. The intake bay or system where this method is applied must be isolated to provide still water conditions for 60 to 72 hours. Isolating the intake bays often requires installing the stoplogs.

Chemical Discharge Regulations. The chemicals used by Smithson are not harmful to the environment, and the anoxic effects can be neutralized by aerating the intake basin after the treatment is completed. Oxygen scavengers developed for other applications must be based on chemicals that can be safely discharged from the plant. An EPA 316(a) demonstration may be required. Consult your NPDES permit and EPA regulations.

Chemical Distribution System. A distribution system must be available for injecting chemicals into the intake bay or other system being treated. An inexpensive distribution system was installed in the bottom of the intake bays at the Baldwin Station using plastic piping. This system is used to apply the chemicals and to reaerate the intake.

Cost of This Technique. Smithson reports that the annual cost of treating each unit at the Baldwin Station is about $1,000 per year for the necessary chemicals. The size of the intake structure will determine the amount of chemicals required. Consult chemical distributors to estimate the cost of applying oxygen scavengers in your plant.

Evaluating the Effectiveness of This Technique

Smithson evaluated the effectiveness of this technique by collecting clams and comparing condenser fouling problems of treated and untreated units. The size of live clams collected before treatment indicates the success of the previous treatment. The percentage of live clams found in samples taken before and after treatment indicates the effectiveness of the present treatment. Smithson reports that the frequency of condenser fouling caused by clams has been reduced since initiating yearly treatments.

Additional Reading

James Smithson is the authoritative author on oxygen scavengers, and his papers fully describe the treatment methods used by the Illinois Power Company:

> Smithson, J. A. 1981. "Control and Treatment of Asiatic Clams in Power Plant Intakes." In Proceedings of the American Power Conference, Vol. 43, pp. 1146-1151. Illinois Institute of Technology, Chicago, Illinois.

Smithson, J. A. 1986. "Development of a Corbicula Control Treatment at the Baldwin Power Station." In Proceedings of the Second International Corbicula Symposium, pp. 59-61. American Malacological Union, Houston, Texas.

CONTOURED INTAKE STRUCTURES

Contoured intake structures have been constructed at French nuclear plants to minimize the buildup of marine growth and sediment in the intake bays. Modifications could be made to existing intake structures to fill in dead areas where sediment and bivalves accumulate. Contoured intakes should also be considered for new plant designs.

What to Consider Before Selecting This Technique

The following list of considerations is intended to help you determine whether to use contoured intake structures in your fouling control program.

Flow Testing. Flow tests using scale models of the intake should be conducted to ensure that the intake geometry is compatible with the pumps being considered. Flow tests especially should be done before considering this technique as a retrofit in existing intake systems.

Modifying Existing Intakes. Modifying existing intake structures would involve pouring concrete on the floor and in the corners of rectangular intake bays to eliminate dead areas. Contour plots of typical sediment buildups in each bay could be used to determine the correct profile of the added concrete. Modifying existing intakes would require an extended outage to complete.

New Plants. Contoured intake structures have been used successfully at the Paluel nuclear station (France) located on the English Channel in an area famous for its shellfish fishery (Anonymous 1982). The streamlined intakes maintain the average flow velocity at approximately 3 mps (10 fps). This design has helped eliminate outages caused by bivalve fouling at the plant.

Cost of This Technique. Factors that would determine the cost of retrofitting contoured intakes include flow testing, design, construction, and replacement power costs. Consult your architect/engineer for estimating the cost of retrofitting contoured intakes at new and existing plants.

Evaluating the Effectiveness of This Technique

If the pump bays are contoured properly, they should not collect sediment or allow marine growth to form as readily as do typical rectangular intakes.

Additional Reading

The following materials provide additional information on the use of contoured intake structures in nuclear power plants:

Anonymous. 1982. "Good News: *Corbicula fluminae* Is Brought Under Control." Power 125:61-63.

Gauthier, H., R. Simon, A. Le Grand and P. E. Jackson. 1983. "Cooling Water Screens and Pumps in French Power Plants." In Proceedings of the Symposium on Condenser Macrofouling Control Technologies - The State-of-the-Art. Electric Power Research Institute, Palo Alto, California.

INTERMEDIATE COOLING LOOPS

Intermediate cooling loops are used at marine power plants to cool many small heat exchangers that would foul readily if directly exposed to ocean water. The intermediate loops are cooled by ocean water through a small number (12 to 15 total) of large, continuous-flow heat exchangers that are less likely to foul. In contrast, the open-cycle systems of some freshwater plants have more than 50 heat exchangers that are cooled by raw water. As many as 80% of these heat exchangers are used infrequently and are susceptible to sedimentation, corrosion, and biofouling. The reliability of open-cycle systems in freshwater plants could be improved if they were designed with intermediate cooling loops.

What to Consider Before Selecting This Technique

The following considerations are intended to help you determine whether to use intermediate cooling loops in your control program.

Impractical to Retrofit. The modifications required to install intermediate cooling in an existing freshwater plant would be so extensive that this technique should not be considered as a retrofit.

New Plants. Intermediate cooling loops have been included in several newer freshwater plants such as the Oconee and Palo Verde plants. The heat exchangers that interface with the open-cycle water system are much larger and the flow velocity much higher than many heat exchangers in typical freshwater plants. Both factors make it harder for Asiatic clams and sediment to accumulate in the system.

Cost of This Technique. The cost of using intermediate cooling loops in a new plant could be estimated by comparing the costs of the open-cycle water systems in similar marine and freshwater plants. The basic idea is to construct a freshwater plant with a typical marine cooling-water system. Consult your architect/engineer for additional cost information.

Evaluating the Effectiveness of This Technique

The construction of intermediate cooling loops would reduce the number of small and intermediate-size heat exchangers that need to be serviced by raw water. [illegible]vicing small- and intermediate-size heat exchangers with "clean" water [illegible] prevent fouling and clogging. Fouling and clogging are less likely to [illegible] the intermediate cooling loop because flow is greater and more reg[illegible] sm[illegible] intermediate-size heat exchangers.

Add[illegible]

The fo[illegible] provide additional information concerning the application o[illegible] cooling loops as part of a fouling control program at nuclear power [illegible]

Neitzel, D. A., K. I. Johnson, T. L. Page, J. S. Young and P. M. Daling. 1984. *Correlation of Bivalve Biological Characteristics and Service-Water System Design*. Vol. 1 of *Bivalve Fouling of Nuclear Power Plant Service-water Systems*. NUREG/CR-4070, Vol. 1/PNL-5300, Vol. 1, U.S. Nuclear Regulatory Commission, Washington, D.C.

HIGH-VELOCITY FLUSHING

Flow velocity is the major design factor that determines whether or not fouling will occur. Many small cooling loops in the service-water systems of nuclear plants have design velocities in the range at which sedimentation occurs [less than 0.9 mps (1 fps)]. Periodic high-velocity flushing [water velocities from 1.5 to 3.0 mps (5 to 10 fps)] of stagnant or infrequently used cooling loops will help to remove sediment and bivalve larvae. High-velocity flushing in combination with continuous low-level chlorination may be a very effective and economical method of controlling all forms of fouling. A further benefit of high-velocity flushing is that few or no piping modifications would be required to implement such a procedure.

What to Consider Before Selecting This Technique

The following considerations are intended to help you determine whether to use high-velocity flushing in your control program.

Sediment Composition. The effectiveness of high-velocity flushing depends on the composition of sediment found in the open-cycle water system. The velocity required to resuspend fine-textured sediments (consisting mainly of silt and clay) can be higher than that for coarser sediments (coarse silt and sand) because of the cohesive properties of the finer particles. Different plants report different levels of success using flushing to remove sediment. You should develop a test program for flushing several cooling loops to test this technique before equipment is modified or extensive flushing schedules are established.

Flushing Schedule. A flushing schedule should be developed to sequentially flush all heat exchangers in the service-water system. Seasonal variations in water turbidity and bivalve growth rates should also be considered to ensure that flushing is scheduled frequently enough that sediment and small bivalves can be easily washed through heat-exchanger tubes. Flushing should coincide with scheduled performance testing of service-water components when practical.

Pumping Capacity. The capacity of the service-water pumps should be checked to ensure that flushing is a feasible alternative. Some plants are equipped with a sufficient number of backup pumps (in some cases a complete set of backup pumps) that simultaneous flushing of the service-water system may be possible.

Cost of This Technique. The factors affecting the cost of high-velocity flushing are 1) the time required by maintenance personnel to flush each cooling loop in the service-water system and 2) the frequency of flushing. Consult your maintenance supervisor for estimating the time required to flush the system.

Evaluating the Effectiveness of This Technique

The effectiveness of high-velocity flushing should be initially tested before implementing a comprehensive schedule. Freshwater plants have cooling loops with backup heat exchangers that are not used during normal operation. The effectiveness of high-velocity flushing can be tested by periodically flushing one of the two heat exchangers and later comparing the amount of sediment and other debris found in the two. The effectiveness of a comprehensive flushing program can be evaluated by comparing maintenance and fouling records taken before and after flushing was started.

Additional Reading

The following materials provide additional information on using high-velocity flushing in a fouling control program:

Johnson, K. I., and D. A. Neitzel. 1987. *Application of Biofouling Surveillance and Control Techniques to Sediment and Corrosion Fouling at Nuclear Power Plants*. Vol. 2 of *Improving the Reliability of Open-Cycle Water-Systems*. NUREG/CR-4626, Vol. 2/PNL-5876-2, Vol. 2, U.S. Nuclear Regulatory Commission, Washington, D.C.

Strauss, S. D., and P. R. Puckorius. 1984. "Cooling-Water Treatment for the Control of Scaling, Fouling, and Corrosion." *Power*, June 1984, pp. S1-S24.

Tuthill, A. H. 1985. "Sedimentation in Condensers and Heat Exchangers: Causes and Effects." *Power Engineering*, June 1985, pp. 46-49.

CLARIFIERS AND SEDIMENT BASINS

Clarifiers use chemical flocculants to bind up suspended solids so that mechanical skimmers can remove them from the water. Sediment basins use low-velocity flow to allow solids to settle out before the water enters the plant.

What to Consider Before Selecting This Technique

The following list of considerations is intended to help you determine whether to include clarifiers or sediment basins in your control program.

Plant Design. To our knowledge, clarifiers are only used to clean up makeup water to cooling tower systems where the flow rate of makeup water is small compared to that used in a once-through cooling system. A system of clarifiers large enough to treat the intake flow to a once-through system would in most cases be so expensive and require so much area that such an installation would be impractical.

Sediment Basins. One plant contacted during this study uses the intake canal as a sediment basin and periodically dredges the canal to remove sediment that accumulates. Another plant has proposed dredging a large hole in front of their intake structure to trap silt before it enters the plant.

Cost of This Technique. The major factor affecting the cost of clarifiers is the flow rate of water required. The flow rate determines the size of the clarifier and the amount of chemicals required. Dredging costs are the major factor affecting the cost of sediment basins.

Evaluating the Effectiveness of This Technique

A nuclear plant that uses a clarifier to clean up makeup water to the cooling tower basin has developed a surveillance program for determining the effectiveness of the clarifier in removing Asiatic clam larvae. The plan calls for sampling the water flowing into and out of the clarifier to allow comparing the concentrations of clam larvae found in each. Sampling is to be conducted semimonthly during the peak spawning periods (April through October) and monthly during the rest of the year.

Additional Reading

The following source provides additional information on using clarifiers and sediment basins at nuclear power plants:

> Strauss, S. D., and P. R. Puckorius. 1984. "Cooling-Water Treatment for the Control of Scaling, Fouling, and Corrosion." Power. June 1984, pp. S1-S24.

SPARGER LINES

Sparger lines maintain flow velocities high enough to keep sediment from accumulating in stagnant areas of intake pump bays. Water from the open-cycle system is pumped through a distribution system located near the floor of the intake structure.

What to Consider Before Selecting This Technique

The following list of considerations is intended to help you determine whether to use sparger lines in your control program.

Limited Power Plant Usage. Utility personnel indicate that sparger lines are not commonly used at power plants.

Flow Requirements. The flow velocity and pressure required to keep the floor of the pump bays clean should be estimated to allow sizing the pumps and distribution system. The general rule is that sediment and fouling will occur at flow velocities less than 0.9 mps (3 fps).

Cost of This Technique. Factors affecting the cost of sparger lines include the size and number of intake bays to be treated and the flow velocity and pressure required. Consult your architect/engineer for specific information on estimating the cost of a system.

Evaluating the Effectiveness of This Technique

The effectiveness of sparger lines could be determined by comparing the amount of sediment found in the intake bays before and after the sparger lines are installed.

Additional Reading

The following source gives additional information on the use of sparger lines and sediment basins at nuclear power plants.

> Strauss, S. D., and P. R. Puckorius. 1984. "Cooling-Water Treatment for the Control of Scaling, Fouling, and Corrosion." Power, June 1984, pp. S1-S24.

CHEMICAL ADDITIVES (DISPERSANTS, FLUIDIZERS, AND SCALE INHIBITORS)

Chemical dispersants and fluidizers are sometimes used to help remove sediment from industrial and power plant water systems (Strauss and Puckorius 1984). Dispersants break up sediment deposits and keep them suspended in the cooling water. Fluidizers work in an opposite manner to fluidizers. They bind up (flocculate) fine suspended particles into larger particles that more easily flow through the system. Scale inhibitors are often used in recirculating condenser cooling systems to maintain a high heat transfer efficiency in the condenser tubes.

What to Consider Before Selecting This Technique

The following list of considerations is intended to help you determine whether to use dispersants and fluidizers in your control program.

Limited Use in Open-Cycle Systems. The power plants contacted during this study indicate that dispersants and fluidizers are not commonly used to control sedimentation in once-through water systems because of discharge limitations and the cost of continually treating such a large volume of water. These chemical additives have, however, been used on a one-time basis to clean sediment out of open-cycle systems (Electric Light and Power 1978).

Cooling Tower System. Dispersants, fluidizers, and scale inhibitors are more commonly used in cooling tower systems to maintain high water quality than in open-cycle systems. Cooling towers recirculate water from a closed basin and only a small fraction of the water and chemical additives are discharged from the plant as blowdown. This reduces the amount of chemical additives required.

Common Types of Dispersants. Synthetic polymers (typically polyacrylates) are favored over naturally derived dispersants because 1) they can be made to a specific molecular weight, 2) they are not easily degraded and used as a food source by biological organisms, 3) they do not react with chlorine or iron salts, and 4) they are less expensive. The molecular weight most effective for dispersing and suspending sediment is in the 1000 g/mol range.

Common Types of Fluidizers. Common fluidizers are polyacrylimides with molecular weights in the millions. Consult vendors of water treatment chemicals for additional information.

Cost of This Technique. Factors that affect the cost of chemical additives include the type of chemicals to be used and the amount of water to be treated. Consult vendors of water treatment chemicals for additional information.

Evaluating the Effectiveness of This Technique

The effectiveness of dispersants and fluidizers can be evaluated by monitoring sediment levels before and after chemical treatment is initiated. Another method would be to measure the sediment content of water samples before and after treatment. If sediment deposits are to be flushed away using a dispersant, the sediment content should go up after treatment is started.

Additional Reading

The following materials provide additional information on using chemical additives to reduce sedimentation at a power plant:

> Strauss, S. D. 1985. "Condenser-Biofouling Control Looms Large in Light of Toxic-Discharge Deadline." Power, September 1985, pp. 83-85.
>
> Strauss, S. D., and P. R. Puckorius. 1984. "Cooling-Water Treatment for the Control of Scaling, Fouling, and Corrosion." Power, June 1984, pp. S1-S24.
>
> Tuthill, A. H. 1985. "Sedimentation in Condensers and Heat Exchangers: Causes and Effects." Power Engineering, June 1985, pp. 46-49.

ALTERNATE BIOCIDES

Alternate biocides have been investigated for general fouling control at power plants; however, none has proven as effective and economical as chlorine. Recent research suggests that biocides such as ozone, hydrogen peroxide, and 2,2-dibromo-3-nitrilo propionamide (DBNPA) may be required to control MIC.

What to Consider Before Selecting This Technique

The following list of considerations is intended to help you determine whether to use alternate biocides in your control program.

Fouling Type. Chlorine is the biocide most commonly used at power plants for slime and bivalve control. A review of biocides for MIC control suggests that only strong oxidants such as ozone, hydrogen peroxide, DBNPA, and strong concentrations of chlorine are effective in penetrating biofilms, corrosion nodules, and pits to control MIC.

Alternatives to Chlorine. Daling and Johnson (1985) reviewed several biocides that have been suggested as alternatives to chlorine. Table 1 on page 37 of their report lists the advantages and disadvantages of six alternatives. The most promising alternative appears to be bromine chloride.

Interaction with Source Water. Some biocides may [illegible] be applicable to all types of source water. For example, ozone may not [illegible] applicable in marine or estuarine power plants because hypobromous acid (another powerful biocide) can form when ozone decomposes in saltwater.

EPA Discharge Limits. EPA sets case-by-case limits on biocides other than chlorine. The use of alternative biocides will likely require performing an

EPA section 316(a) demonstration to show that the proposed biocide application program will not adversely affect the balanced indigenous populations of fish, shellfish, and wildlife.

Testing Required in Actual Water System Conditions. The literature available from commercial water treatment companies claims that many types of biocides are effective against MIC; however, independent confirmation is lacking for most of these claims (Pope 1986). The testing that supports these claims is often done in the laboratory using pure cultures, stagnant conditions, and nonattached populations of organisms. Biocides must be tested in conditions as similar as possible to the water system where fouling is occurring to evaluate their effectiveness under real-world conditions.

Cost of This Technique. The popularity of chlorine as a biocide is largely based on its low cost, high effectiveness, and relatively low impact on the environment. Alternate biocides for general fouling control appear to be either more costly, less effective, or more harmful to the environment than chlorine. Periodic applications of alternate biocides for MIC control are more costly than chlorination; however, they may be very economical compared to replacing water system piping. Consult vendors of water treatment chemicals and metering systems for estimating the cost of specific treatment plans.

Evaluating the Effectiveness of This Technique

Alternate biocide treatments must be tested in conditions as near as possible to those in the fouled water system. Pope (1986) suggests that water monitoring programs, test coupons, side-stream monitors, and online probes can be used to determine the effectiveness of MIC control measures. These surveillance techniques can also be used to evaluate the effectiveness of alternate biocide treatments directed at other fouling types.

Additional Reading

The following materials provide additional information on using alternate biocides at nuclear power plants:

Daling, P. M., and K. I. Johnson. 1985. Current Status of Biofouling Surveillance and Control Techniques. Vol. 2 of Bivalve Fouling of Nuclear Power Plant Service-Water Systems. NUREG/CR-4070, Vol. 2/PNL-5300, Vol. 2, U.S. Nuclear Regulatory Commission, Washington, D.C.

Hogan, J. E. 1983. "EPA Regulations on Chlorination and Toxic Coating: The Impact on Power Plant Operation." In Proceedings of the Symposium on Condenser Macrofouling Control Technologies - The State-of-the-Art. Electric Power Research Institute, Palo Alto, California.

Pope, D. H. 1986. A Study of Microbiologically Influenced Corrosion in Nuclear Power Plants and a Practical Guide for Countermeasures. EPRI-NP-4582. Prepared by Rensselaer Polytechnic Institute for the Electric Power Research Institute, Palo Alto, California.

Strauss, S. D. 1985. "Condenser-Biofouling Control Looms Large in Light of Toxic-Discharge Deadline." Power, September 1985, pp. 83-85.

Strauss, S. D., and P. R. Puckorius. 1984. "Cooling-Water Treatment for the Control of Scaling, Fouling, and Corrosion." Power, June 1984, pp. S1-S24.

CATHODIC PROTECTION

Cathodic protection is often used to limit galvanic corrosion that occurs at dissimilar metal joints. Galvanic corrosion occurs in open-cycle water systems when one metal becomes anodic with respect to the other metal (the cathode) and water acts as the electrolyte. Corrosion occurs at the anode where metal ions are liberated and deposited on the cathode.

What to Consider Before Selecting This Technique

The following list of considerations is intended to help you determine whether to use cathodic protection in your control program.

The Galvanic Series. The galvanic series is a hierarchical list of metals that has been compiled to identify which metals will corrode in the presence of other metals. Strauss and Puckorius (1984) include the galvanic series in their article. This will help you determine how severe is the potential for galvanic attack in your system.

The Water Source. Galvanic corrosion is more pronounced in seawater and in recirculating condenser systems where the ionic content of the cooling water is higher than in once-through, freshwater cooling systems. The effects of galvanic corrosion are well known in the marine industry, and this factor is considered in the design of marine power plants.

Impressed Current Systems Versus Sacrificial Anodes. Impressed current systems use a current source to neutralize the galvanic potential between the two metals in contact. Sacrificial anodes refer to pieces of metal that are attached to the metal surface to be protected. The sacrificial anode is more anodic than the metal it is protecting, and corrosion occurs on the sacrificial anode. Common anode materials are zinc and magnesium. Zinc anodes have the advantage of contributing zinc ions to the cooling water, which acts as a chemical corrosion inhibitor. Strauss and Puckorius (1984) state that cathodic protection using sacrificial anodes is usually preferred over impressed current systems.

Cost of This Technique. The cost of applying cathodic protection depends on whether impressed current or sacrificial anodes are used and the surface area to be protected. Consult vendors of corrosion-protection equipment for detailed cost information.

Evaluating the Effectiveness of This Technique

The effectiveness of cathodic protection can be estimated by monitoring corrosion of the protected surface before and after cathodic protection is applied. Corrosion coupons can also be used to measure the reduction in weight of the coupon as corrosion takes place over time.

Additional Reading

The following source provides additional information on using cathodic protection in open cycle water systems at power plants:

> Strauss, S. D., and P. R. Puckorius. 1984. "Cooling Water Treatment for the Control of Scaling, Fouling, and Corrosion." *Power*, June 1984, pp. S1-S24.

MODEL FOULING PROGRAMS FOR USE AT NUCLEAR POWER PLANTS

Several utilities have developed fouling surveillance and control programs that have proven effective in minimizing fouling. Other utilities have developed comprehensive fouling programs for use at nuclear plants that are soon to be completed. This section summarizes several of these programs to provide examples of the extensive programs that utilities are willing to implement to keep fouling under control. A proposed surveillance and control program for microbiologically influenced corrosion is also presented in this section, which has been summarized from the current literature.

The lessons provided by those who have programs in place offer valuable information for developing the criteria needed to set up a new program. The criteria that are presented in the following chapters of this report are in large part based on the experiences provided by these model programs.

ASIATIC CLAM CONTROL PROGRAM DEVELOPED BY THE TENNESSEE VALLEY AUTHORITY

During the 1970s, the Tennessee Valley Authority (TVA) assembled an interdisciplinary team of scientists and engineers to develop a surveillance and control program for Asiatic clam fouling at their power plants. Over the past several years the program has proven to be effective in minimizing clam fouling at the TVA's fossil-fueled plants, except where mechanical or operational problems have interrupted the chlorination schedule. The TVA program is based on knowledge of the life history of Asiatic clams, including the size of benthic veligers at spawning and the time when clam spawning occurs. The program calls for straining all raw water through 0.8-mm (1/32-in.) media, chlorine injection, and increased attention to general "housekeeping" methods to keep the open-cycle water systems clean. The following description of the TVA program is summarized from Isom et al. (1986).

The open-cycle water systems at TVA nuclear plants are composed of the following subsystems: the condenser circulating-water (CCW) system; the raw cooling-water (RCW) system; the raw service-water (RSW) system; the essential raw cooling-water (ERCW) system; and the high-pressure fire-protection (HPFP) system. The TVA program requires continuous chlorination of the ERCW system at 0.6 to 0.8 ppm total residual chlorine (TRC) during the entire clam spawning season. The RSW and RCW systems must be continuously chlorinated for two 3-week periods marking the beginning and end of the clam spawning season. At plants where the HPFP system is fed by the RSW system, the RSW system must be chlorinated continuously throughout the clam spawning season. The CCW system is not normally chlorinated because of the high flow rate of the system. The combined flow of the other subsystems is small relative to the CCW system, and when mixed at the plant discharge, the chlorine concentration is maintained within the NPDES discharge limit.

Previous studies by TVA have shown that clam spawning occurs in the vicinity of their plants when the temperature of the inlet water exceeds about 16°C (60°F). The TVA program calls for chlorination to be initiated in the spring when the water temperature exceeds 16°C (60°F) and discontinued in the fall when the temperature drops below 16°C (60°F). Isom et al. (1986) report that the concentration and duration of chlorine treatments specified in the TVA plan represent a very conservative approach to clam control, but that it is warranted because the lost revenue associated with clam fouling is high. More recent discussions with personnel from other utilities indicate that chlorine concentrations as low as 0.2 to 0.3 ppm TRC applied continuously during three 5-week periods throughout the clam spawning season (at the beginning, middle, and end of clam spawning) can kill 90% of the clams in the system. Such variations in concentration and treatment frequency emphasize the importance of site-specific chlorine minimization studies to determine the chlorine levels needed to provide adequate fouling control. TVA has made provisions for periodic measurement of the chlorine concentration at locations near the discharge of water systems that are normally in service. Provisions have also been made to measure chlorine concentrations in systems that are normally stagnant. Systems have been designed or modified to allow flushing stagnant lines with chlorinated water when an inadequate chlorine level is found during sampling. The chlorine program calls for initial sampling to be done weekly. Longer intervals may be adopted later if data from the sampling program show that target concentrations are consistently being met.

In addition to the standard control measures listed, there are several requirements that are specific to subsystems in the open-cycle water system. Areas of the ERCW system that are normally stagnant have been modified to include "mini-flow" lines that allow sufficient flow through the system to maintain the chlorine residual. Provisions have also been made to allow flushing the main supply headers of the fire-protection system.

Guidelines have also been written that outline clam control procedures that must be followed when the open-cycle system is initially filled with water, during extended outages, and during temporary construction. Unchlorinated raw water is not allowed to lie stagnant in any system at any time. Where possible, systems are designed to allow draining them after initial testing. If the system is to be used frequently or if draining is not feasible, temporary provisions must be made to inject chlorine into the system. The procedures must be followed regardless of the inlet water temperature.

ASIATIC CLAM CONTROL AT A PLANT UNDER CONSTRUCTION

A surveillance and control program for Asiatic clams has been developed for a nuclear power plant located on the Mississippi River that is currently in the final construction phase. All makeup water to the open-cycle water system at this plant is passed through a clarifier to remove debris, including clam larvae, before it enters the cooling tower basin. Both the circulating-water system and the service-water system take suction from the common cooling tower basin.

The fouling program at this plant is based on a utility-sponsored study that compiled 12 years of historical data on the distribution of Asiatic clams in the river near the plant site. Data were collected to describe the distribution of substrate-associated juvenile and adult clams as well as drifting juveniles in the area of the plant. The historical data indicate that benthic Asiatic clams have been declining in number over the 12-year test period. The data have also established that the concentration of drifting larvae and early life stages peaks in June and August and that population densities differ for each side of the river. Such a comprehensive data base on clam population dynamics gives the utility a strong base on which to develop effective procedures and incorporate the fouling program into the initial design of the water system.

Surveillance Program

The intake embayment and the river near the site are sampled for juvenile and adult Asiatic clams once per month. Sampling for clam larvae near the intake is conducted semimonthly from April through October and monthly from November through March using 150-µm plankton nets. Sampling for clam larvae will also be conducted in the clarifier effluent to determine the quantities entrained in the makeup water. Although the clarifiers are expected to remove practically all larval clams, samples of the clarifier will be taken weekly from April through October (the period when clam larvae are most likely to be in the river water) and monthly from November through March. Additional sampling for larger juveniles and adult clams will be conducted monthly in various exposed portions of the circulating-water system such as the cooling tower basins.

The sampling program was begun when the cooling tower basin was initially filled, with river water, and it will continue through two complete clam reproductive seasons beyond commercial operation. At the end of this period there will be data reflecting 1) ambient densities of larval and adult clams in the river, 2) numbers of clams entrained in the intake water, and 3) numbers of larvae introduced into the service- and circulating-water systems (i.e., a measure of clarifier performance). If the data show minimal Asiatic clam infestation in the plant, then the sampling schedule may be reduced. A sufficient program will be retained, however, to monitor clam populations in the river and to continue semimonthly and monthly sampling of the clarifier discharge.

If the data indicate that Asiatic clams are in the service- and circulating-water systems, the emphasis of the surveillance program will shift to address: 1) the adequacy of the chlorination program; 2) the growth, reproduction, and distribution of clams in the water systems; and 3) the relationship between the number of clams and the biofouling problems observed. These data will be used to determine if the control program has to be modified.

The surveillance program will also include performance monitoring of the safety-related heat exchangers in the service-water system. Differential temperature and differential pressure measurements will be used to indicate flow degradation in most heat exchangers. Heat balance calculations will also be performed for several heat exchangers that are critical to safe plant operation (the RHR heat exchangers and the emergency diesel-generator coolers).

Technical staff will regularly review the daily data and calculate component fouling monthly. The results of the calculations will be plotted to determine trends in fouling for the service-water components. If the performance of a component does not meet standards, the component will be taken out of service, opened, and visually inspected for evidence of clam fouling.

A schedule of visual inspections will be conducted in accordance with the preventative maintenance program. If fouling is noted, the system will be flushed and clams and debris will be removed before the system is put back in service. If clams large enough to clog the system are found, then performance testing of all other safety-related components served by the service-water system will be conducted. If standards are exceeded, then components will be visually inspected and cleaned, and performance trends will be monitored more frequently.

Control Program

The first level of control is the exclusion of clams from the plant. Screens are used to keep adult clams out of the inlet piping to the makeup water system. Clarifiers are also provided to remove suspended matter (including clam larvae) from the makeup water before it enters the cooling tower basin. Continuous chlorination will be used to kill clams that do get into the service-water system. A total residual chlorine concentration of 0.6 to 0.8 ppm will be used initially. Operating experience will be used to determine if this dose rate can be decreased without decreasing the effectiveness of the clam control program. The residual chlorine level will be measured at the outlet of the service-water system to ensure that the entire service-water system is receiving the required dose.

The redundant, safety-related components of the service-water system will be operated monthly to ensure that the contained water will be periodically exchanged with freshly chlorinated water. Operation of intermittent flow systems will prevent clams from surviving. This will also provide operating data from which to calculate performance trends.

THERMAL BACKWASHING TO CONTROL MACROFOULING AT MILLSTONE NUCLEAR POWER STATION

Biofouling control at the Millstone Power Plants (Waterford, Connecticut) is multiphased. In addition to mechanical filtration and chlorination, plant operators emphasize thermal backwashing to kill macrofouling (primarily blue mussels) that grow in the intake bays and the intake piping to the condensers. A description of the thermal backwash program reported by Johnson et al. (1983) illustrates the surveillance and control criteria and alternatives that were developed in this report.

Blue mussels (*Mytilus edulis*) are common in the source water to the open-cycle water system at Millstone. Effectively controlling the settlement and growth of blue mussels requires knowledge of the biology of the organism. Blue mussel response to various control regimes depends on size, life stage, reproductive status, and time of the year. Northwest Utilities Laboratory has evaluated and developed antifouling techniques for use at Millstone to optimize control of blue mussels throughout the year.

The thermal backwash system is used to control blue mussels in the circulating-water system. All intake bays can be chlorinated, but station service-water temperature cannot exceed 95°F. To determine the most effective thermal control program, larval densities and settlement, growth rates, and time/temperature tolerances were studied. Larval densities were estimated from entrainment plankton samples. Settlement data were collected from shore surveys, exposure panel studies, and experimental settlement ropes placed near the plant. Data were used to determine seasonal and year-to-year variability.

Biologists from Millstone perform SCUBA diving observations of the intake before and after each thermal backwash to visually assess the effectiveness of the treatment method.

The thermal backwash has been successful and cost effective at Millstone. Johnson et al. (1983), who have estimated a cost savings of $230,000 per year, are optimistic about this program for controlling blue mussels but caution that optimum antifouling schedules and procedures for any power plant will be site specific. The population characteristics of the fouling organisms, and their response to environmental conditions, vary from site to site.

Other nuclear plants that use thermal backwashing to control blue mussel fouling are the Pilgrim Nuclear Power Station and the San Onofre Nuclear Generating Station. Scotton et al. (1983) report that chlorination of the service-water system and thermal backwashing of the circulating water system at Pilgrim saved approximately $2.4 million in 1982 because of reduced maintenance and increased operating efficiency. A similar thermal backwashing program is in effect at the San Onofre Nuclear Generating Station (Stock and De La Parra 1983). The San Onofre program uses a computerized growth model to determine the frequency of thermal treatments.

DETECTION, TREATMENT, AND PREVENTION OF MICROBIOLOGICALLY INFLUENCED CORROSION

A study of the detection, treatment, and prevention of microbiologically influenced corrosion (MIC) was conducted by Pope (1986) for the Electric Power Research Institute. This study and the recommendations for surveillance and control program illustrate the use of the selection criteria and techniques that are discussed in this report. Pope's guide is summarized here.

Site Conditions

The conditions at the power plant that affect MIC should be determined. These include operational parameters, the content of water samples, the content of sediments, and the condition of corroded materials. Operational conditions that should be surveyed are flow rates, pH, temperature, levels of debris in the water, interruptions to operations, and the type, frequency, and concentration of chemicals added to the system. Low flow, interrupted flow, debris, and sediment enhance the growth of bacteria in the service-water system.

Water should be collected from the service-water system for analysis. Care must be taken in collecting and handling the sample because it may be used for bacteriological analysis. Chemical characteristics that are of particular interest are organic carbon, microbes, dissolved solids, salinity, alkalinity, iron, manganese, chloride, nitrate, ammonia, nitrate, phosphorus, sulfur, carbonates, and dissolved oxygen. Pope (1986) stresses that MIC is often associated with "dirty" systems; however, cases of MIC have been associated with the use of deionized water, distilled water, steam condensate, or well water.

Debris and sediment samples should be collected from the system. Much of the same information collected for water samples is important to the analysis of sediment as well. The color and odor of the sediment is important. Black sediment with a sulfur smell indicates the presence of sulfate-reducing bacteria. Corroded materials should be sampled from the system to estimate the probability of MIC being the cause. The presence of discrete deposits (nodules) on corroded surfaces is indicative of MIC.

Sampling for MIC

Sampling for MIC is difficult. Contamination of the sample must be kept to a minimum. Samples should be collected in sterile, glass containers, kept on ice, and held for no longer than 1 day before analysis. Samples should be collected for chemical and metallurgical analysis also. Deposits should be analyzed for iron, manganese, sulfur, phosphorus, chloride, total and organic carbon, and metallic constituents of the alloy on which the corrosion was collected. Metallurgical analysis should determine the type of corrosion, the nature of the deposit, the material in the cracks and pits on the corrosion site, and the presence of iron, manganese, sulfur, and chloride.

Collection of Samples Within the Service-Water System

There are several methods that can be used to determine the collection location within the system. Water samples can be collected at locations near the entrance to the service-water system and again at locations where water leaves the service-water system. This may help determine if the number of microbes entering the system is different than those leaving the system. Corrosion coupons can be used to monitor for MIC. Coupons are pieces of material like those in the system that can be placed at specific locations in the system for later removal and testing. Probable coupon locations include dead legs, low points, areas of flow, and areas where debris accumulates. The corrosion coupons must be of the same material as the component being tested.

Side-stream monitors and online corrosion probes are other means of collecting samples. Side-stream monitors of the type used to monitor heat transfer and biofouling can be used to house corrosion coupons. Care must be taken to ensure that the monitors duplicate the actual flow conditions that exist in the water system. Pope (1986) suggests that corrosion probes may be of value, but cautions that probes are not available that can discriminate MIC from other types of corrosion. Probes are useful, however, when the source of corrosion is not in question.

Prevention and Treatment of MIC

Systems in which MIC occurs should be treated to kill or inhibit the organisms that cause MIC. Pope (1986) cautions, in his summary of MIC prevention and treatment, that there are many claims for biocides that have not been tested under field conditions. Any proposed treatment system should be tested under conditions as close as possible to those in the system before being implemented. Ozone is the most effective agent in penetrating films, nodules, debris, and greases, and in killing the microbes that cause MIC. Ozone is effective at residual concentrations as low as 0.1 ppm. Ozone should be used continuously at 0.1 ppm or at levels as high as 0.5 ppm for a few minutes each day.

Hydrogen peroxide is another effective biocide for microbes that cause MIC. Hydrogen peroxide is useful where water is left in contact with metal for long periods. Chlorine is effective when used continuously at low levels (0.5 ppm) or intermittently at high doses (5-20 ppm). The effectiveness of the treatment program should be monitored at least once each month.

CRITERIA FOR AN EFFECTIVE SURVEILLANCE AND CONTROL PROGRAM

There is no single solution to biological, sediment, and corrosion fouling at nuclear power plants. Effective fouling programs must include both surveillance and control techniques that cover the different areas of the open-cycle system and the different types of fouling that occur. Such a comprehensive program is required to keep fouling to a level that will not jeopardize the safe operation of nuclear power plants. An effective surveillance and control program must therefore satisfy a set of criteria that address the major areas of the open-cycle water system that must be monitored for fouling and the major fouling types that must be controlled. The alternative surveillance and control programs presented in this section will be evaluated to estimate the probabilistic risk reduction associated with implementing each alternative. A basic assumption in the probabilistic risk analysis is that, if implemented properly, each alternative program will resolve the NRC Generic Issue 51 (Improving the Reliability of Open-Cycle Water Systems). The criteria provided here form the basis for effective surveillance and control programs that satisfy this inherent assumption.

For fouling surveillance to be effective, nuclear power plants have these capabilities:

- monitoring fouling species and sediment movement in the intake system of the open-cycle water system
- monitoring fouling species, sediment, and corrosion inside the open-cycle water system
- monitoring biological, sediment, and corrosion fouling in the fire-protection system
- monitoring the performance of cooling loops in the safety-related portion of the open-cycle water system using differential pressure, differential temperature, and flow measurements
- periodically evaluating the performance of the open-cycle water system to establish operating trends and to estimate the most likely components in which fouling will occur.

For fouling control to be effective, nuclear power plants must have these capabilities:

- controlling microfouling slime
- controlling larval bivalves
- controlling juvenile and adult bivalves
- controlling microbiologically influenced corrosion
- controlling sediment
- removing bivalve shells, sediment, and corrosion products
- periodically evaluating fouling surveillance and control programs to estimate program effectiveness and to propose improvements.

Surveillance and control techniques that combine to meet these criteria are described in reports written for this study and for the previous fouling study sponsored by the NRC Research Branch (Daling and Johnson 1985; Neitzel et al. 1986; Johnson and Neitzel 1987). These reports describe physical techniques that are effective when implemented correctly. There are several "nonphysical" reasons why these techniques have not been effective when applied at power plants.

Trend analysis of plant performance data is an important criterion for effective fouling surveillance and control that has been underutilized by many utilities. Valuable insights can be gained by studying the relationship between plant performance and various operating events. In the case of open-cycle water systems, performance trends can warn of system flow degradation and associated fouling. Performance trends can also be used to develop cause-and-effect relationships between fouling and operating events such as switching over to redundant cooling loops that have been out of service, postponement of scheduled fouling treatments, or rapid valve closures. Understanding these relationships helps plant personnel to be aware of operating events that may intensify the significance of fouling in affecting plant safety and availability.

Utility personnel at several plants visited during this study indicate that support from utility management plays a key role in building an effective fouling surveillance and control program. If management is aware of the safety and economic benefits of minimizing fouling in the open-cycle water system, then sufficient money, time, and manpower are allotted to successfully monitor and control fouling. In an independent study for the NRC, Morgenstern et al. (1985) conclude that the lack of management support underlies many of the deficiencies found in existing nuclear power plant maintenance procedures. Well-developed and effective maintenance procedures do not occur without management support in the form of 1) explicit policies to guide the development of procedures, 2) a willingness to dedicate the necessary resources, and 3) a commitment to enforce sanctions for not following procedures. Without the incentive of vigorous management oversight, other expenditures take precedence over the development and implementation of high-quality procedures (Morgenstern et al. 1985). Several plants have increased their commitment to minimizing fouling and have noted significant decreases in the severity of fouling-related problems as a result. In some cases, the difference has been the increased attention given to surveillance and control systems already in place.

A management style that has been implemented effectively by some utilities has been delegation of the responsibility of correctly maintaining and operating specific plant systems to individual employees. Designating responsible, or cognizant, engineers to systems provides a link between employee performance and system performance, and it provides an additional incentive for the responsible persons to understand the subtleties of maintaining and operating each system.

REFERENCES

AEC (U.S. Atomic Energy Commission). 1974. "Quality Group Classification and Standards for Water-, Steam, and Radioactive-Waste-Containing Components of Nuclear Power Plants." In Regulatory Guide 1.26, Rev. 1. U.S. Atomic Energy Commission, Washington, D.C.

Anonymous. 1982. "Good News: *Corbicula fluminae* is Brought Under Control." Power 125:61-63.

Boffardi, B. P. 1985. "Control the Deterioration of Copper-Based Surface Condensers." Power, July 1985, pp. 57-60.

Britton, J. C. 1982. "Biogeography and Ecology of the Asiatic Clam, Corbicula, in Texas." In Proceedings of the Symposium on Recent Benthological Investigations in Texas and Adjacent States, pp. 21-31. Texas Academy of Science, Austin, Texas.

Butler, P. A. 1954. "Selective Setting of Oyster Larvae on Artificial Cultch." Proc. Natl. Shellfish. Assoc. 45:95-105.

Cairns, J., Jr., ed. 1982. Artificial Substrates. Ann Arbor Science, Ann Arbor, Michigan.

Daling, P. M., and K. I. Johnson. 1985. Current Status of Biofouling Surveillance and Control Techniques. Vol. 2 of Bivalve Fouling of Nuclear Power Plant Service-Water Systems. NUREG/CR-4070, Vol. 2/PNL-5300, Vol. 2, U.S. Nuclear Regulatory Commission, Washington, D.C.

Drake, R. C. 1977. "Increasing Heat Exchanger Efficiency Through Continuous Mechanical Tube Maintenance." In Biofouling Control Procedures: Technology and Ecological Effects. Marcel Dekker, New York.

Drew, E.A., J. N. Lythgoe and J. D. Woods. 1976. Underwater Research. Academic Press, New York.

Electric Light and Power. 1978. "Mud-Flushing Additive Hikes Condenser Heat Transfer." Electric Light and Power 56:7.

Gauthier, H., R. Simon, A. Le Grand and P. E. Jackson. 1983. "Cooling Water Screens and Pumps in French Power Plants." In Proceedings of the Symposium on Condenser Macrofouling Control Technologies - The State-of-the-Art. Electric Power Research Institute, Palo Alto, California.

Hamm, P. J. 1982. "What Are We Doing About the Asiatic Clam?" Power 126(1):25-28.

Haried, J. A. 1982. Evaluation of Events Involving Service Water Systems in Nuclear Power Plants. NUREG/CR-2797/ORNL/NSIC-207, U.S. Nuclear Regulatory Commission, Washington, D.C.

Henager, C. H., Sr., P. M. Daling and K. I. Johnson. 1985. *Factors That May Intensify the Safety Consequences of Biofouling*. Vol. 3 of *Bivalve Fouling of Nuclear Power Plant Service-Water Systems*. NUREG/CR-4070, Vol. 3/PNL-5300, Vol. 3, U.S. Nuclear Regulatory Commission, Washington, D.C.

Hillman, R. E. 1977. "Techniques for Monitoring Reproduction and Growth of Fouling Organisms at Power Plant Intakes." In *Biofouling Control Procedures Technology and Ecological Effects*. Marcel Dekker, New York.

Hillman, R. E., D. Anson, J. M. Coriss, B. W. Vigon, R. H. Gray and H. J. Bomelberg. 1985. *Biofouling Detection Monitoring Devices: Status Assessment*. EPRI-C -3914. Prepared by the Battelle/Marine Research Laboratory for the Electric Power Research Institute, Palo Alto, California.

Hogan, J. E. 1983. "EPA Regulations on Chlorination and Toxic Coating: The Impact on Power Plant Operation." In *Proceedings of the Symposium on Condenser Macrofouling Control Technologies - The State-of-the-Art*. Electric Power Research Institute, Palo Alto, California.

Holl, C. H., R. L. Martin and R. E. Hillman. 1983. "Antifoulant Coatings: Potential for Controlling Macrofouling in Operating Coastal Power Plants." In *Proceedings of the Symposium on Condenser Macrofouling Control Technologies - The State-of-the-Art*. Electric Power Research Institute, Palo Alto, California.

Hovland, A. W. 1978. "Effective Condenser Cleaning Improves System Heat Rate." *Power Engineering*, January 1978, pp. 49-50.

Huber, E. R., and R. A. Plant. 1984. *Upgrade Replacement of Existing On-Line Condenser Tube Cleaning Systems*. 84-JPGC-Pwr-23, American Society of Mechanical Engineers, New York.

Imbro, E. V. 1982. *Engineering Evaluation of the Salt Service Water System Flow Blockage at the Pilgrim Nuclear Power Station by Blue Mussels (Mytilus edulis)*. Office for Analysis and Evaluation of Operational Data, U.S. Nuclear Regulatory Commission, Washington, D.C.

Imbro, E. V., and J. M. Gianelli. 1982. *Report on Service-Water System Flow Blockages by Bivalve Mollusks at Arkansas Nuclear One and Brunswick*. Office for Analysis and Evaluation of Operational Data, U.S. Nuclear Regulatory Commisssion, Washington, D.C.

Isom, B. G., C. F. Bowman, J. T. Johnson and E. B. Rodgers. 1986. "Controlling Corbicula (Asiatic Clams) in Complex Power Plant and Industrial Water Systems." In *Proceedings of the Second International Corbicula Symposium*, pp. 95-98. American Malacological Union, Houston, Texas.

Jenkins, J. F. 1978. "Design Factors Influencing OTEC Biofouling and Corrosion." In *Proceedings of the Ocean Thermal Energy Conversion (OTEC) Biofouling and Corrosion Symposium*. Prepared for the U.S. Department of Energy, Washington, D.C., by Pacific Northwest Laboratory, Richland, Washington.

Jenner, H. A. 1983. "A Microcosm Monitoring Mussel Fouling." In *Proceedings of the Symposium on Condenser Macrofouling Control Technologies - The State-of-the-Art*. Electric Power Research Institute, Palo Alto, California.

Johnson, K. I., and D. A. Neitzel. 1987. *Application of Biofouling Surveillance and Control Techniques to Sediment and Corrosion Fouling at Nuclear Power Plants*. Vol. 2 of *Improving the Reliability of Open-Cycle Water Systems*. NUREG/CR-4626, Vol. 2/PNL-5876-2, Vol. 2, U.S. Nuclear Regulatory Commission, Washington, D.C.

Johnson, G., J. Foertch, M. Keser and B. Johnson. 1983. "Thermal Backwash as a Method for Macrofouling Control at the Millstone Nuclear Power Station." In *Proceedings of the Symposium on Condenser Macrofouling Control Technologies - The State-of-the-Art*. Electric Power Research Institute, Palo Alto, California.

Johnson, K. I., C. H. Henager, T. L. Page and P. F. Hayes. 1986. "Engineering Factors Influencing Corbicula Fouling in Nuclear Service Water Systems." In *Proceedings of the Second International Corbicula Symposium*, pp. 47-52. American Malacological Union, Houston, Texas.

Kasper, J. R., W. Chow, J. Graham and Y. G. Mussalli. 1983. "Cost of Chlorination." In *Proceedings of the Symposium on Condenser-Macrofouling Control Technologies - The State-of-the-Art*. Electric Power Research Institute, Palo Alto, California.

MacKenzie, C. L., Jr. 1975. "Development of a Program to Rehabilitate the Oyster Industry of Prince Edward Island." *Mar. Fish. Rev.* 37:21-25.

MacPhee, D. D. 1986. "A Mechanical Strainer Design for Corbicula Fouling Prevention in the Service Water System at Arkansas Nuclear One, Unit 2." In *Proceedings of the Second International Corbicula Symposium*. pp. 59-61. American Malacological Union, Houston, Texas.

McCoy, J. W. 1980. *Microbiology of Cooling Water*. Chemical Publishing Company, New York.

Morgenstern, M. H., V. E. Barnes, L. R. Radford, W. A. Wheeler and R. V. Badalamente. 1985. "Improving the Development, Use and Control of Maintenance Procedures." PNL-SA-13603. Paper presented at the International Meeting on Nuclear Power Plant Maintenance, March 23-27, 1986, Salt Lake City, Utah.

Moss, R. D., S. P. Gautney and P. A. March. 1985. "Targeted Chlorination is Viable and Environmentally Acceptable." *Power*, February 1985, pp. 79-81.

Moss, R. D., P. A. March and S. P. Gautney. 1986. *Field Experiences and Results of Two Targeted Treatment Systems*. IWC-86-34. Presented at the 47th annual meeting of the International Water Conference, Pittsburgh, Pennsylvania, October 27-29, 1986. Tennessee Valley Authority, Chattanooga, Tennessee.

Neitzel, D. A., K. I. Johnson and P. M. Daling. 1986. An Evaluation of Biofouling Surveillance and Control Techniques for Use at Nuclear Power Plants. Vol. 1 of Improving the Reliability of Open-Cycle Water Systems. NUREG/CR-4626, Vol. 1/PNL-5876-1, Vol. 1, U.S. Nuclear Regulatory Commission, Washington, D.C.

Neitzel, D. A., K. I. Johnson, T. L. Page, J. S. Young and P. M. Daling. 1984. Correlation of Bivalve Biological Characteristics and Service-Water System Design. Vol. 1 of Bivalve Fouling of Nuclear Power Plant Service-Water Systems. NUREG/CR-4070, Vol. 1/PNL-5300, Vol. 1, U.S. Nuclear Regulatory Commission, Washington, D.C.

NRC (Nuclear Regulatory Commission). 1984. Power Reactor Events. NUREG/BR-0051, Vol. 5, No. 4. U.S. Nuclear Regulatory Commission, Washington, D.C.

Pope, D. H. 1986. A Study of Microbiologically Influenced Corrosion in Nuclear Power Plants and a Practical Guide for Countermeasures. EPRI-NP-4582. Prepared by Rensselaer Polytechnic Institute for the Electric Power Research Institute, Palo Alto, California.

Rains, J. H., W. J. Foley and A. Hennick. 1984. Closeout of IE Bulletin 81-03: Flow Blockage of Cooling Water to Safety System Components by *Corbicula* sp. (Asiatic clam) and *Mytilus* sp. (mussel). NUREG/CR-3054, Parameter IE-138, U.S. Nuclear Regulatory Commission, Washington, D.C.

Richards, B. R. 1977. "The Use of Artificial Substrates for Studies of the Biofouling Community." In Biofouling Control Procedures Technology and Ecological Effects. Marcel Dekker, New York.

Ruttner, F. 1952. Fundamentals of Limnology. University of Toronto Press, Toronto, Ontario, Canada.

Scotton, L. N., W. J. Armstrong, J. F. Garey and D. J. McDonald. 1983. "Development and Future Trends of the Mussel Control Program at Pilgrim Nuclear Power Station." In Proceedings of the Symposium on Condenser Macrofouling Control Technologies - The State-of-the-Art, 1983. Electric Power Research Institute, Palo Alto, California.

Shaw, W. N., and A. S. Merrill. 1966. "Setting and Growth of the American Oyster, *Crassostrea virginica*, on Navigation Buoys in the Lower Chesapeake Bay." Proc. Natl. Shellfish. Assoc. 56:67-72.

Sinclair, R. M.. and B. G. Isom. 1963. Further Studies on the Introduced Asiatic Clam (Corbicula) in Tennessee. Tennessee Stream Pollution Control Board, Tennessee Department of Public Health, Cordell Hull Building, Nashville, Tennessee.

S. M. Stoller Corp. 1977. "DG Heat Exchangers Clogged with Mussels - Inadequate Chlorination Schedule." In Nuclear Power Experience, Vol. PWR-2, Section VIII, Subsection B, p. 28. S. M. Stoller Corporation, Boulder, Colorado.

S. M. Stoller Corp. 1983. "SW Filter Drive Motor Shaft Key Sheared, Pump Seized - Excessive Debris." In Nuclear Power Experience, Vol. PWR-2, Section VIII, Subsection B, p. 130. S. M. Stoller Corporation, Boulder, Colorado.

Smithson, J. A. 1981. "Control and Treatment of Asiatic Clams in Power Plant Intakes." In Proceedings of the American Power Conference, Vol. 43. Illinois Institute of Technology, Chicago.

Smithson, J. A. 1986. "Development of a Corbicula Control Treatment at the Baldwin Power Station." In Proceedings of the Second International Corbicula Symposium, June 21-24, 1983, pp. 59-61. American Malacological Union, Houston, Texas.

Stock, J. N., and R. A. De La Parra. 1983. "Use of Thermal Backwash to Control Marine Biofouling at San Onofre Nuclear Generating Station." In Proceedings of the Symposium on Condenser Macrofouling Control Technologies - The State-of-the-Art. Electric Power Research Institute, Palo Alto, California.

Strauss, S. D. 1985. "Condenser-Biofouling Control Looms Large in Light of Toxic-Discharge Deadline." Power, September 1985, pp. 83-85.

Strauss, S. D., and P. R. Puckorius. 1984. "Cooling-Water Treatment for the Control of Scaling, Fouling, and Corrosion." Power, June 1984, pp. S1-S24.

Texas Utilities Generating Company. 1982. "Introduction to Industrial Transients." In Systems Information Manual, Comanche Peak Steam Electric Station, Section XIII, pp. 1.1-1.39. Dallas, Texas.

Torbin, R. N., and Y. G. Mussalli. 1980. "The Cost-Effectiveness of Alternative Condenser Biofouling Control Methods." In Condenser Biofouling Control. Ann Arbor Science, Ann Arbor, Michigan.

Tuthill, A. H. 1985. "Sedimentation in Condensers and Heat Exchangers: Causes and Effects." Power Engineering, June 1985, pp. 46-49.

U.S. Navy. 1975. U.S. Navy Diving Manual. Vol. 1, Air Diving. NAVSEA 0994-LP-001-9010. Best Bookbinders, Carson, California.

Wells, H. W., and I. E. Gray. 1960. "The Seasonal Occurrence of *Mytilus edulis* on the Carolina Coast as a Result of Transport Around Cape Hatteras." Biol. Bull. 119:550-559.

Wetzel, R. G. 1976. Limnology. W. B. Saunders, Philadelphia, Pennsylvania.

WHOI (Woods Hole Oceanographic Institution). 1952. Marine Fouling and Its Prevention. U.S. Naval Institute, Annapolis, Maryland.

APPENDIX

QUESTIONS TO UTILITIES ON BIOLOGICAL, SEDIMENT, AND CORROSION FOULING

IMPROVING THE RELIABILITY OF OPEN-CYCLE SERVICE-WATER SYSTEMS

NAME: ____________________ PHONE: ____________
PLANT: ____________________ DATE: ____________

SPONSOR: Division of Engineering
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555

OBJECTIVE

The objective of this program is to improve the reliability of open-cycle service-water systems in nuclear power plants by preventing serious fouling of these systems. Improving system reliability requires compiling information on effective surveillance methods to detect fouling organisms in source water; detect fouling organisms in open-cycle systems; and detect the presence of mud, silt, and corrosion products in the systems. Improving water system reliability also requires compiling information on effective techniques to control and remove biofouling organisms, mud, silt, and corrosion from the systems. The information compiled during this program will be reported in a form that nuclear power plant personnel can use to develop plant-specific methods or strategies to improve the reliability of open-cycle water systems.

QUESTIONS

1. What techniques do you use to look for sediment and corrosion in your open-cycle water systems? Are they different from those used for biofouling?
2. What techniques do you use to control sediment and corrosion in your open-cycle water systems? Are they different from those used for biofouling?
3. Are you aware of techniques other than those listed in Table A.1 for detection/control of biological, sediment, and/or corrosion fouling?
4. What vendors provide the surveillance and control techniques listed in Table A.1?
5. What do you think would be the most effective techniques for detecting and controlling biological, sediment, and corrosion fouling at your plant?
6. Are there specific systems or system configurations where the surveillance/control techniques listed in Table A.1 cannot be used? What systems are they, and why?
7. Has your utility studied the feasibility of implementing any of the techniques listed in Table A.1? If yes, which techniques were they and what were the approximate implementation costs (materials and equipment, labor, and lost power production)? What was the time required for this

system to pay for itself in improved plant performance? Would the written results of the study be available?

8. What are the exposure times to plant personnel maintaining and monitoring fouling control systems in radiation zones at your plant? What are the approximate dose rates in these areas?

9. What are your written procedures (i.e., plant technical specifications) concerning fouling surveillance and control?

10. Are there surveillance or control techniques that you have considered but abandoned because of regulatory restrictions on their use (i.e., the Clean Water Act of 1977, state regulations, etc.)?

TABLE A.1. Fouling Surveillance and Control Techniques Identified

BIOFOULING SURVEILLANCE TECHNIQUES

SCUBA Divers for Visual Inspection
Water and Substrate Sampling Outside the Plant
Water Sampling Inside the Plant
Growth Panels
Side-Stream Monitors
Visual Inspection
Differential Pressure Measurement
Flow Velocity Measurement
Differential Temperature Measurement

ALTERNATE SURVEILLANCE TECHNIQUES FOR SEDIMENT AND CORROSION FOULING

Side-Stream Condenser Monitors to Detect Microfouling
Condenser Simulators
Ultrasonic Testing

BIOFOULING CONTROL TECHNIQUES

Chlorination (Intermittent, Continuous, and Targeted)
The AMERTAP and MAN Tube-Cleaning Systems
Scraping and Hydroblasting to Remove Fouling
Antifoulant and Protective Coatings
Thermal and Nonthermal Backwashing
Oxygen Scavengers
Screens and Strainers (Fine Mesh, Center Flow)
Contoured Intake Structures
Intermediate Cooling Loops to Isolate Small HXs from Raw Water

ALTERNATE TECHNIQUES TO CONTROL SEDIMENTATION AND CORROSION

High-Velocity Flushing (5 to 10 fps)
Clarifiers and Sediment Basins
Silt Traps
Sparger Lines to Clean Corners of Intake Structures
Chemical Dispersants and Fluidizers
Alternate Biocides (Ozone and DBNPA)
Cathodic Protection

NRC FO
(2-84)
NRCM 11
3201, 3202

U.S. NUCLEAR REGULATORY COMMISSION

BIBLIOGRAPHIC DATA SHEET

SEE INSTRUCTIONS ON THE REVERSE

1. REPORT NUMBER (Assigned by TIDC, add Vol. No., if any)
NUREG/CR-5210
PNL-6623

2. TITLE AND SUBTITLE
Technical Findings Document for Generic Issue 51:
Improving the Reliability of Open-Cycle Service-Water
Systems

3. LEAVE BLANK

4. DATE REPORT COMPLETED

MONTH	YEAR
July	1988

5. AUTHOR(S)
Duane A. Neitzel
Kenneth I. Johnson

6. DATE REPORT ISSUED

MONTH	YEAR
August	1988

7. PERFORMING ORGANIZATION NAME AND MAILING ADDRESS (Include Zip Code)
Pacific Northwest Laboratory
P.O. Box 999
Richland, WA 99352

8. PROJECT/TASK/WORK UNIT NUMBER

9. FIN OR GRANT NUMBER
B2977

10. SPONSORING ORGANIZATION NAME AND MAILING ADDRESS (Include Zip Code)
Division of Engineering
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555

11a. TYPE OF REPORT

b. PERIOD COVERED (Inclusive dates)

12. SUPPLEMENTARY NOTES

13. ABSTRACT (200 words or less)

This report summarizes information needed to prepare a fouling surveillance and control program for a nuclear power plant. The safety significance of bivalve and other fouling is reviewed. Many safety-related systems are cooled either directly by the open-cycle water system or indirectly through intermediate cooling loops. Residual heat-removal heat exchangers, containment cooling units, diesel-generator coolers, fire-protection systems, and safety-related equipment coolers have been fouled by bivalves, sediment, or corrosion.

The biological characteristics of bivalves enhance their ability to foul service-water systems. The design of the service-water system provides areas where sediments can accumulate and where bivalves can settle and grow.

Surveillance and control systems are available to reduce the occurrence of bivalve, sediment, and corrosion fouling. No one technique seems to provide the best answer. A workable surveillance and control program requires using several surveillance and control alternatives. Utility experience has shown that continuous low-level chlorination of the service-water system is one of the most effective means of minimizing the safety significance of macrofouling.

14. DOCUMENT ANALYSIS – a. KEYWORDS/DESCRIPTORS
Open-cycle water system fouling, corrosion, silt, Asiatic clams, blue mussels, American Oyster, surveillance techniques, control techniques, service-water system fouling

b. IDENTIFIERS/OPEN-ENDED TERMS

15. AVAILABILITY STATEMENT
Unlimited

16. SECURITY CLASSIFICATION
(This page)
Unclassified
(This report)
Unclassified

17. NUMBER OF PAGES

18. PRICE

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555

120555139217 1 1AN1RG
US NRC-OARM-ADM
DIV FOIA & PUBLICATIONS SVCS
RRES-PDR NUREG
P-210
WASHINGTON DC 20555

NUREG/CR-5210

TECHNICAL FINDINGS DOCUMENT FOR GENERIC ISSUE 51: IMPROVING THE RELIABILITY OF
OPEN-CYCLE SERVICE-WATER SYSTEMS

AUGUST 1988